Linac Coherent Light Source (LCLS) Design Study Report

The LCLS Design Study Group

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Preface

The Stanford Linear Accelerator Center (SLAC), in collaboration with Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and the University of California at Los Angeles, is proposing to build a Free-Electron-Laser (FEL) R&D facility operating in the self-amplified spontaneous emission (SASE) mode in the wavelength range 1.5–15 Å. This FEL, called “Linac Coherent Light Source” (LCLS), utilizes the SLAC linac and produces sub-picosecond pulses of short wavelength x-rays with very high peak brightness and full transverse coherence.

Until about the 1960s x-rays were obtained from Roentgen tubes. After the first observation of synchrotron radiation [1] and the evolution of cyclic electron synchrotrons and then storage rings for high energy physics applications, it was realized that these accelerators could be exploited as much more intense x-ray sources. Storage ring synchrotron light sources have now evolved through three generations. The first-generation sources utilized radiation from storage rings built for high-energy physics purposes. These included Tantalus at the University of Wisconsin, ACO and DCI at LURE, SPEAR and PEP at SLAC, DORIS and PETRA at DESY, Adone at Frascati, VEPP-2M and VEPP-3 in Novosibirsk, and CESR at Cornell. Initially only bending magnet radiation was used and experiments were carried out parasitically during high-energy physics runs. The second-generation machines were purpose built, but still initially used bending magnet radiation. The first round of second-generation sources included the SOR-ring in Tokyo, the SRS at Daresbury, Aladdin in Wisconsin, the Photon Factory at KEK, and the NSLS at Brookhaven. Eventually, insertion devices were added to these facilities, but only in limited number because, in most cases, the magnet lattice did not include a large number of straight sections.

The rapid growth in demand for synchrotron radiation and the successful implementation of wigglers and undulator insertion devices on first- and second-generation sources led to the need for third-generation facilities. These are characterized by a lower electron beam emittance (emittance is the product of the beam transverse size and divergence) and a larger number of straight sections for insertion devices. Presently operating third-generation sources include the ALS and APS in the USA; the SRRC in Taiwan; Super-ACO and the ESRF in France; Elettra in Italy; PLS in Korea; MAX II in Sweden; and SPring-8 in Japan. The lower electron beam emittance of these rings, typically of the order of a 5–10 nm-rad compared with ~100 nm-rad in earlier sources, results in higher radiation brightness, particularly from undulators, and transversely coherent (i.e., diffraction-limited) radiation at wavelengths longer than ~ 50 nm.
Three workshops have been held to discuss fourth-generation light sources, the first at SLAC in 1992 [2], the second at the ESRF [3] in 1996, and a third at APS in 1997. The LCLS was first proposed [4] at the SLAC workshop, leading to several years of continued refinement of the design by a multi-institutional study group. At the ESRF workshop, a consensus developed that short wavelength free electron lasers driven by linear accelerators are the most promising path for the increasing number of applications where high brightness, coherence, and short bunches are important. A similar view was expressed by the 1997 Synchrotron Radiation Light Source Working Group [5] (the Birgeneau/Shen Panel) of the Basic Energy Sciences Advisory Committee of the Department of Energy. This report recognizes that “fourth-generation x-ray sources...will in all likelihood be based on the free electron laser concepts. If successful, this technology could yield improvements in brightness by many orders of magnitude.”

In 1996 a team was formed to produce a detailed design for the LCLS. One of the goals of this Design Study is to show that advances in the technology of electron sources and linear accelerators, as well as improved understanding in the physics of transporting and compressing high brightness beams, are such that an electron beam can be created of sufficiently high quality to drive a single pass free-electron laser operating at wavelengths down to ~1.5 Å in the SASE mode. In this mode, the FEL radiation is created by inducing a longitudinal bunch density modulation at the optical wavelength in a single pass of the electron beam through a long undulator, without the need for high reflectivity mirrors to form an optical cavity, as is used in longer wavelength FEL oscillators. The lack of mirrors adequate to form an optical cavity now limits FEL oscillators to wavelengths longer than ~ 2000 Å.

A free-electron laser has all the characteristics of a fourth-generation source: brightness several orders of magnitude greater than presently achieved in third-generation sources, full transverse coherence, and sub-picosecond long pulses. The technologies needed to achieve this performance are those of bright electron sources, of acceleration systems capable of preserving the brightness of the source, and of undulators capable of meeting the magnetic and mechanical tolerances that are required for operation in the SASE mode.

Starting in FY1998, the first two-thirds of the SLAC linac will be used for injection into the B factory. This leaves the last third free for acceleration to 15 GeV. The LCLS takes advantage of this opportunity, opening the way for the next generation of synchrotron light sources with largely proven technology and cost effective methods.

The LCLS uses an rf photoinjector as the source of electrons. In this device, developed at LANL, the cathode is placed in the accelerating field of a radio-frequency cavity. A laser, shining on the cathode, expels electrons that are rapidly accelerated in the rf field, minimizing emittance growth due to space charge effects. Photoinjectors have been recognized as the most effective method of achieving very bright and short electron pulses,
and their technology has made great progress in recent years. The LCLS makes full use of these advances.

To achieve design performance it is essential that acceleration occur with minimal longitudinal and transverse emittance dilution. Here, the LCLS will exploit the research and progress in the technology and accelerator physics of linear colliders that have produced the tools and knowledge that now find a remarkable application in the realization of fourth-generation light sources. SLAC, a leading laboratory in this research, and the first laboratory to have constructed and operated a linear collider, the SLC (SLAC Linear Collider), is in an ideal position to apply this linear collider technology to a free electron laser.

As a consequence of the enormous growth of synchrotron light sources over the last 20 years, insertion devices have reached a very high level of performance. The LCLS undulator is a state-of-the-art device that is capable of meeting the specifications demanded by the design.

The LCLS would create a photon beam of unprecedented brightness, coherence, and beam power, far surpassing anything available in third-generation sources today. Design goals are a brightness of $1.2 \times 10^{33}$ photons/(s mm$^2$ mrad$^2$ 0.1% bandwidth), a peak power of 9 GW, and sub-picosecond pulse duration. The remarkable features of this facility promise unparalleled potential for the development of completely new capabilities, such as non-linear dynamics, as well as for extending existing fields of study into new dimensions.

**Organization of this Design Study Report**

In this report, the Design Team has established performance parameters for all the major components of the LCLS and developed a layout of the entire system. Chapter 1 is the Executive Summary. Chapter 2 (Overview) provides a brief description of each of the major sections of the LCLS, from the rf photocathode gun, through the experimental stations and electron beam dump. Chapter 3 describes the scientific case for the LCLS. Chapter 4 provides a review of the principles of the FEL physics that the LCLS is based on, and Chapter 5 discusses the choice of the system’s physical parameters. Chapters 6 through 10 describe in detail each major element of the system. Chapters 11 through 13 respectively cover undulator controls, mechanical alignment, and radiation issues.

Several technical challenges that are crucial to achieving the LCLS’s performance goals have received serious attention during the study. Among the most important of these are: (1) the generation and preservation of very low emittance and low momentum spread during acceleration; (2) the understanding of the SASE mechanism and the conditions required for it; (3) the conceptual development and design of a very long undulator; and (4) the control and utilization of radiation at extremely high power densities. These issues are addressed in Chapter 6 through 10.

A research and development program that will provide further support and confirmation of the design has been formulated, and plans are being made to implement this program in
the next 2 years. Construction could begin in FY2001. Concurrent with the Design Study, further work is being carried out to document the eventual applications of the LCLS.

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1 Executive Summary

1.1 Introduction

The Stanford Linear Accelerator Center, in collaboration with Los Alamos National Laboratory, Lawrence Livermore National Laboratory, and the University of California at Los Angeles, is proposing to build a Free-Electron-Laser (FEL) R&D facility operating in the wavelength range 1.5–15 Å. This FEL, called the “Linac Coherent Light Source” (LCLS), utilizes the SLAC linac and produces sub-picosecond pulses of short wavelength x-rays with very high peak brightness and full transverse coherence.

Starting in FY 1998, the first two-thirds of the SLAC linac will be used for injection into the B factory. This leaves the last one-third free for acceleration to 15 GeV. The LCLS takes advantage of this opportunity, opening the way for the next generation of synchrotron light sources with largely proven technology and cost effective methods. This proposal is consistent with the recommendations of the Report of the Basic Energy Sciences Advisory Committee (Synchrotron Radiation Light Source Working Group, October 18–19, 1997). The report recognizes that “fourth-generation x-ray sources...will in all likelihood be based on the free electron laser concepts. If successful, this technology could yield improvements in brightness by many orders of magnitude.” This Design Study, the authors believe, confirms the feasibility of constructing an x-ray FEL based on the SLAC linac. Although this design is based on a consistent and feasible set of parameters, some components require more research and development to guarantee the performance. Given appropriate funding, this R&D phase can be completed in 2 years.

This Executive Summary provides a brief description of the LCLS. A layout of the LCLS is shown in Fig. 1.1-1. The facility is comprised of the following main elements:

a. A photoinjector and a short linac, where a bright electron beam is generated and accelerated to 150 MeV.

b. The main linear accelerator, consisting of the last one-third of the SLAC 3 km linac, where the electron bunch is compressed and accelerated to 14.3 GeV.

c. The transport system to the undulator.

d. The undulator, where the electrons emit FEL and spontaneous radiation.

e. The undulator-to-experimental area transport line.

f. The take-off optics and experimental stations.
The LCLS
(Linac Coherent Light Source)

Figure 1.1-1. Layout of the Linac Coherent Light Source.

A photoinjector will be used to generate a bright electron beam. A bunch of electrons will go through two magnetic compressors that will reduce its length from 10 ps to 280 fs during acceleration to 14.3 GeV. After acceleration to 14.3 GeV, the beam goes through a transport system to a 100 m long undulator, where the FEL radiation is generated and channeled to an experimental area. The transport system and the undulator area use an existing tunnel that presently houses the SLAC Final Focus Test Beam (FFTB).

The projected peak brightness of the produced FEL radiation is 10 orders of magnitude above existing radiation sources. Accompanying this FEL radiation, and independent of the lasing action, the peak spontaneous radiation brightness that will be produced has high bandwidth, comes in sub-picosecond long pulses, and is four orders of magnitude above existing sources. This leap in performance is possible because of major technical advances in some of the experimental tools of high-energy physics and synchrotron radiation. These are the development of photoinjectors, the acceleration and compression without degradation of very high brightness electron beams in linear colliders, and the progress in undulator design and its error control. In the LCLS all these technologies converge to produce a scientific tool of extraordinary performance.
1.2 The Scientific Case

An FEL operating in the hard x-ray region, such as the LCLS, will produce radiation with unique qualities. The peak brightness will exceed that produced by today’s brightest synchrotrons by more than 10 orders of magnitude, an advance similar to that of the synchrotron over a 1960s laboratory x-ray tube. In addition, the FELs sub-picosecond pulse length will be two orders of magnitude shorter than a synchrotron pulse, and the FEL pulse will be highly coherent.

Given the revolutionary properties of the LCLS, accurate projection of its scientific applications is difficult. Nevertheless, major advances can be anticipated in many fields of research, exploiting the short pulse, high brightness and coherence of the FEL. These include fundamental quantum mechanics phenomena using entangled multi-photon states, and atomic physics studies that measure photon interactions with core atomic electrons well into the nonlinear regime. In molecular and plasma physics, ionization and dissociation processes under extremely high-intensity electromagnetic fields will be studied. In chemistry, the x-ray FEL has great potential as a monitor of surface chemical reactions using x-ray fluorescence or photoelectron spectroscopy. In condensed matter science, the brightness of the FEL will be used to apply standard x-ray techniques to sub-micron samples, and to record the signals in less than 1 picosecond. The coherence will allow interference techniques, such as photon correlation spectroscopy, to become powerful tools for studying dynamics in condensed matter. In addition, the FEL should allow the development of completely new ways to study condensed matter, based on nonlinear x-ray interactions. In biology, the sub-picosecond time scale of the FEL pulse will make it possible to observe dynamical interactions between large molecules in some extremely interesting systems.

All of these advances will require much development of detectors, optics, and timing techniques. The LCLS will provide a wonderful tool for carrying out this development, and will be the door that opens into a new world of science.

1.3 FEL Physics and Simulations

Theoretical and computational studies led to a selection of the accelerator and FEL parameters. An exhaustive study was carried out of the sensitivity of the FEL radiation to changes in the values of accelerator parameters and beam characteristics and to unavoidable imperfections of the magnetic elements, alignment, and electron beam monitoring.

The focusing of the electron beam in the undulator plays an important role in the production of the FEL radiation. The LCLS undulator optics has been optimized in terms of its focusing lattice and strength. The electron optics consists of FODO cells, with a cell length of 4.32 m. Focusing is obtained by placing permanent magnet quadrupoles in the interruptions of the undulator sections. Each interruption is 23.5 cm long, and also includes focusing quadrupoles, beam position monitors, and vacuum ports. The correction of the electron orbit is obtained by a small lateral displacement (up to 0.5 mm) of the quadrupoles.
Simulations indicate that the FEL radiation saturates at a length of ~90 m. The proposed LCLS undulator has a magnetic length of 100 m, as it is a requirement that the FEL operate in the saturation regime. This fact not only gives the maximum output power, but also reduces the pulse-to-pulse fluctuations of the radiation.

1.4 The Injector

The injector for the LCLS is required to produce a single 150 MeV bunch of ~1 nC and ~100 A peak current at a repetition rate of 120 Hz with a normalized rms transverse emittance of ~1 π mm-mrad. The required emittance is about a factor of two lower than has been achieved to date. The design employs a solenoidal field near the cathode of a specially designed rf laser-driven gun which allows the initial emittance growth due to space charge to be almost completely compensated by the end of the injection linac (Linac 0). Spatial and temporal shaping of the laser pulse striking the cathode can reduce the compensated emittance even further. Following the injection linac, the geometric emittance simply damps linearly with energy growth. PARMELA simulations show that this design will produce the desired normalized emittance. In addition to low emittance, there are two additional electron-beam requirements that are challenging—the timing and intensity stabilities must have rms values of 0.5 ps and 1% respectively. The desired laser-pulse energy stability will be achieved by stabilizing the pumping laser for the amplifiers and by operating the second amplifier in saturation. Although additional R&D is planned to improve the projected performance of the photoinjector, confidence in the present design is based on the performance of existing systems. PARMELA accurately simulates the measured performance of low emittance rf photoinjectors operating near the emittance level of the LCLS. Laser systems have been employed in high-energy physics experiments with timing stability—with respect to the accelerated electron beam—that is within a factor of two of the value required here.

1.5 Acceleration and Compression

In order for the FEL to operate in the saturation regime with a 100 m long undulator, a high electron peak current in a small transverse and longitudinal emittance is required. For the LCLS operating at 1.5 Å, the design values are a peak current of 3.4 kA with a transverse normalized emittance of 1.5 π mm-mrad at 14.3 GeV. This value is 50% higher than is provided by the photoinjector and includes a safety margin against emittance dilution effects. Since the rf photocathode gun produces 1 nC in a length of 3 ps rms, corresponding to a peak current of 100 A, the bunch has to be compressed by a factor of about 50 before it enters the undulator. The compressors consist of a series of magnetic chicanes, arranged and located such that the non-linearities in the compression and acceleration process (longitudinal wakefields, rf curvature, and second order momentum compaction) are partially cancelled. An optimum choice of parameters compensates the correlated energy spread after the final compression and desensitizes the system to phase and charge variations. The energy of the
first compressor is 280 MeV. The choice of energy for the first compressor is set by the need to minimize space charge effects at the lower energy end, while the upper limit is set by the desire to compress the bunch early in the linac to ease transverse wakefields. In the first compressor, the bunch length shrinks from 1mm to 390 µm (rms values). The energy of the second compressor, 6 GeV, was chosen as an optimum between the conflicting requirements of longitudinal emittance dilution due to synchrotron radiation effects and longitudinal wakefields. The design of the second compressor is set by the need to reduce coherent synchrotron radiation effects, which are most pronounced for short bunches. Since the energy spread generated by the coherent synchrotron radiation is correlated along the bunch, its effect on the transverse emittance is compensated by introducing a double chicane and optical symmetry to cancel longitudinal-to-transverse coupling. The coherent synchrotron radiation effect on the beam was calculated both in the steady state and transient regime. In the former, the radiation force is supposed to vanish in between bends. In the transient regime the effect of the transition between bends is included, and found to be important. With the double chicane compensating scheme, the emittance growth in the LCLS, due to coherent synchrotron radiation, is only 3–5%.

Simulations have also been made which calculate emittance dilution effects in the linac due to transverse wakefields and anomalous momentum dispersion, each of which arise with component misalignments. These simulations include realistic correction techniques and successfully demonstrate the level of transverse emittance preservation required.

1.6 The Undulator

After reviewing several possible magnet designs, a planar Halbach hybrid type was adopted, with a period of 3 cm and a fixed 6 mm magnetic gap. The focusing of the electron beam is obtained with a FODO separated function lattice, with quadrupole focusing permanent magnets placed between segments of the undulator. Each segment contains 64 periods and is 1.92 m long. The poles are made of vanadium permendur, and the magnets that drive them are made of NdFeB. The separation between segments is 23.5 cm long. This free space will house the focusing quadrupoles, beam position monitors, and vacuum ports. The quadrupoles are also used to correct the trajectory by moving them transversely. The electron beam trajectory is required to be straight to within 5 µm over a field gain length (11.7 m) to achieve adequate overlap of the electron and photon beams. It is shown that this specification, presently beyond state-of-the-art mechanically, can be achieved with electron beam-based techniques. A suspended wire and mechanical actuator feedback will be used to maintain alignment at the micron level. A small amount of tapering is required to compensate for the small energy loss due to the emission of radiation and to resistive wall effects.

Each undulator section is supported by a girder. A pier supports the ends of two girders, with the quadrupole magnets and other components, such as Beam Position Monitors (BPMs) and vacuum ports, located between the girders.
The BPMs are the primary system for measuring the transverse electron beam position in the undulator. The BPMs must have the ability to detect relative changes in position of 1 \( \mu \text{m} \) at the operating charge of 1 nC. After a review of several BPM technologies, it was decided that a microwave cavity type of detector can provide sub-micron resolution and micron level absolute accuracy, and this is the non-intercepting monitor choice for the LCLS. Carbon wires will be used for emittance measurements and to measure simultaneously the electron and photon beams’ position and size.

Because of the small chamber radius, wakefield effects have to be taken into account in the design. The resistive wall effects can be made small by plating the stainless steel vacuum chamber with copper. It has been estimated that the roughness of the inside pipe surface can cause a momentum spread increase and interfere with the FEL dynamics if it is greater than about 100 nm. With some R&D effort, this value is achievable.

1.7 Undulator-to-Experimental Area

The primary function of the undulator-to-experimental area is to deflect the electron beam away from the radiation exiting the undulator, dump it, and then pass the radiation on through a high-vacuum system of spectral-angular filters and beam lines. This system is required to transport either the spontaneous or coherent photons to the experimental end station, while suppressing as much as possible the transmission of the bremsstrahlung component and any secondary noise generated by it. After the beam has exited the undulator, it will be intercepted by an absorption cell, whose purpose is to attenuate the power to levels manageable with conventional optics and to provide a continuous transition to power densities at which meaningful research on the interaction of LCLS radiation pulses with matter can proceed.

The coherent FEL light (820 eV–8200 eV in the fundamental and up to about 25 keV in the third harmonic) will be spectrally and angularly separated from the spontaneous radiation (extending out to beyond 1 MeV) by an absorption cell, by mirrors or crystals, and by a pair of horizontally/vertically tunable x-ray slits. Two beam lines, one based on crystal take-off optics and the other on mirrors, will deliver photons to experimental end stations. The bremsstrahlung, a concern for both personnel safety and experimental signal-to-noise quality, will be absorbed by stoppers following line-of-sight impact with a mirror or crystal, while the thermal neutrons created by this interaction will be contained with a lead/polyethylene shield wall.

As a future alternative to the absorption cell and the initial location of the experimental hall, siting for a long beam line (up to 780 m) has been assessed as a means of reducing the beam's power density without diluting its brightness.
1.8 Take-off Optics and Beamline Layout

Accurate theoretical understanding and modeling of the source properties of the coherent and spontaneous components are required for the design, operation, support, and interpretation of scientific experiments. The properties of the radiation emitted from an ideal source are well understood, and detailed calculations of the spectral-angular flux and power density distributions have been carried out. More refined source studies and simulations based on departures of the LCLS components and the electron bunch from their ideal parameters will be undertaken as part of the R&D program.

Detailed modeling of the bremsstrahlung gamma flux entering the experimental area has also been carried out and determined to be controllable with standard shielding techniques.

The primary elements in the x-ray optical system are: Differential Pumping Sections (DPSs), x-ray slits, an absorption cell, mirrors, and crystals. The DPSs provide windowless in-vacuum transport and ultra high vacuum environment. Phase-space filtering of the radiation will be accomplished with two sets of horizontal and vertical slits. The absorption cell, designed for variable attenuation of the coherent radiation, will operate with a suitable gas or, alternatively, a liquid. The mirrors, operating at extreme grazing incidence, will provide low-pass spectral filtering and beam deflection. The crystal optics, applicable to wavelengths < 3–5 Å, will employ low-Z materials and asymmetrically cut geometries to minimize absorbed energy density. In addition to the primary optics, special instruments and components need to be developed for both beam diagnostics and selected scientific experiments.

A basic theme underlying the x-ray optics design study has been, and remains, the lack of knowledge regarding the interaction of extremely high peak power levels of radiation pulses with matter. The LCLS will provide the opportunity for experimental studies that will lead to optimal instrumentation and experimental design.

1.9 Instrumentation and Controls

The control system of the LCLS consists of three separate systems. The control system currently running the SLAC facility will control and monitor the operation of the photocathode gun and accelerator systems up to the undulator. A workstation will control and monitor the operation of the undulator systems. Another workstation will control and monitor the operation of the x-ray optics and the acquisition of data from the detectors.

The undulator control system includes movers of the 1.9 m segments and steering magnets, the monitoring of the position of the undulator segments with wire position monitors and the acquisition of the beam position monitors.

Most of the LCLS x-ray experiments require synchronization of the experimental station's equipment with the electron beam. The electron beam, in turn, is phased to the 476 MHz of the SLAC master clock. Temporal jitter between the RF and the beam must be
specified to be less than 0.5 ps. For those experiments that require synchronization with an external laser pulse, the timing system is designed to assure that the synchronization between the user laser and the FEL x-ray pulses have a timing jitter better than 1 ps for time delays of +/- 1 ns, and better than 1 ns for time delays of +/- 10 ms.

1.10 Alignment

The alignment network design philosophy is based on a 3-D design, now widely used in high precision metrology. The network consists of three parts: the linac, undulator, and transport line/experimental area. Since the linac exists already, the network does not need to support construction survey and alignment but will only provide tie-points during the linac straightening (smoothing) procedure. The undulator network’s geometry is dictated by the tunnel and machine layout. The geometry should permit observation of each target point from at least three different stations. A triplet of monuments is placed in the tunnel cross section. The transport line/experimental area network will be constructed and established like the undulator network, with the only difference that each cross section will have only two monuments.

The alignment coordinate system will be a Cartesian right handed system, with the origin placed where the present SLC origin is (Linac Station 100). The instrumentation for the network observation will be a laser tracker/Total Station combination. The laser tracker will be used for position and the Total Station for angle accuracy. The alignment tolerances in the linac tunnel are achievable with an established laser technique.

The undulator requirements are somewhat tighter. Free-stationed laser trackers, oriented to at least four neighboring points, are used for absolute position measurements. The trajectory in the undulator is determined by a string of quadrupoles, supported by magnet movers. For the beam-based algorithm to converge, 100 \( \mu \)m initial placement accuracy of the quadrupoles is required. Laser tracker measurements and hydrostatic level information will provide the required positional accuracy.

The position tolerances of transport line and experimental area components are achievable with standard absolute alignment procedures. A relative alignment is not required.

1.11 Radiation Protection

The radiation concerns fall into three distinct areas: radiation safety, radiation background in experiments, and machine protection. The study covers these concerns in the region downstream of the undulator, since the linac will be taken care of by the existing radiation protection system.

The effect of scattering of the electron beam on the residual gas of the undulator was computed, and no degradation of the undulator is expected from this source of radiation. The photon deposition due to spontaneous emission in the undulator was calculated and does not cause a problem. The effectiveness of the undulator protection collimators was found to be
very good. The emission due to gas bremsstrahlung was estimated using an analytical formula and found to be controllable. Computational estimates of the muon dose rates behind the concrete and iron shielding have been made. All these studies indicate that the radiation is quite manageable.

The dose rates due to induced activity were calculated. With the expected low level of beam loss and activation in the undulator, the resulting personnel exposures are expected to be very low.

### 1.12 Basic Parameters

Table 1.12-1 lists some of the basic parameters of the LCLS electron beam, of the undulator, and of the FEL performance at the shortest operating photon wavelength.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
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<td>Electron beam energy</td>
<td>14.35</td>
<td>GeV</td>
</tr>
<tr>
<td>Emittance</td>
<td>1.5</td>
<td>(\pi \text{ mm mrad, rms})</td>
</tr>
<tr>
<td>Peak current</td>
<td>3,400</td>
<td>A</td>
</tr>
<tr>
<td>Energy spread (uncorrelated)</td>
<td>0.02</td>
<td>% , rms</td>
</tr>
<tr>
<td>Energy spread (correlated)</td>
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<td>% , rms</td>
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<td>Bunch length</td>
<td>67</td>
<td>fsec, rms</td>
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<td>Undulator period</td>
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<td>cm</td>
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<td>Field gain length</td>
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<td>Repetition rate</td>
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<td>Hz</td>
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<tr>
<td>Saturation peak power</td>
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<td>GW</td>
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<tr>
<td>Peak brightness</td>
<td>(1.2 \times 10^{32} - 1.2 \times 10^{33})</td>
<td>Photons/(s mm(^2) mrad(^2) 0.1% bandwidth)</td>
</tr>
<tr>
<td>Average brightness</td>
<td>(4.2 \times 10^{31} - 4.2 \times 10^{32})</td>
<td>Photons/(s mm(^2) mrad(^2) 0.1% bandwidth)</td>
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1.13 Estimated Costs, Proposed Schedule, and Project Execution

The most general expression of the estimated fabrication costs for the Linear Coherent Light Source (LCLS) has been “from $75M to $100M.” This conservative and broad range in the estimated costs reflects the fact that LCLS R&D has not yet been completed. On the other hand, preliminary cost estimates have been prepared, and these estimates indicate that the LCLS fabrication costs should be on the order of $85M, assuming a two-station experimental facility. In addition to fabrication costs, the LCLS project includes $9.9M in R&D costs and $5M in pre-fabrication engineering costs, for a total project cost on the order of $99.9M.

The LCLS has been proposed as a 3-year capital equipment fabrication project with a start date at the beginning of FY 2001. To accomplish this fabrication schedule, R&D activities will be conducted in FY 1999 and FY 2000 and pre-fabrication engineering in FY 2000. With these schedules, commissioning of the major systems would begin in FY 2004 and continue for two quarters. Research and Development using the two experimental stations would be scheduled starting in April 2004.

The LCLS project will be managed by the Stanford Synchrotron Radiation Laboratory (SSRL) division of the Stanford Linear Accelerator Center (SLAC). Formal collaboration will include, but not be limited to, other divisions of SLAC, the High Energy Physics and Accelerator Technology Group of the Lawrence Livermore National Laboratory (LLNL), the Los Alamos Neutron Science Center (LANSC) of the Los Alamos National Laboratory (LANL), and the Particle Beam Physics Laboratory at the University of California, Los Angeles (UCLA).

It is expected that the National Environmental Protection Act (NEPA) determination will be an Environmental Assessment (EA), with an outcome of a Finding of No Significant Impact (FONSI). Because the EA process takes 6 months or more, this effort will begin in early FY 2000.
2 Overview

2.1 Introduction

The SLAC linac presently accelerates electrons to 50 GeV for colliding beams experiments (the SLAC Linear Collider, SLC) and for nuclear and high-energy physics experiments on fixed targets. In the near future, the first two-thirds of the 3 km linac will be used to inject electrons and positrons in the soon-to-be-completed PEP-II B Factory. The last one-third of the linac will be available for the production of an up to 16 GeV electron beam. The design discussed in this paper uses this electron beam to create a Free-Electron Laser (FEL), the Linac Coherent Light Source (LCLS), capable of delivering coherent radiation of unprecedented characteristics at wavelengths as short as 1.5 Å. The LCLS is based on the Self-Amplified Spontaneous Emission (SASE) principle. The SASE mode of operation was first proposed in [1,2] and analyzed for short wavelength FELs in [3]. In the SASE mode of operation, high power transversely coherent, electromagnetic radiation is produced from a single pass of a high peak current electron beam through a long undulator. SASE eliminates the need for optical cavities, which are difficult to build in the x-ray spectral region. However, the resulting requirements on the electron beam peak current, emittance, and energy spread are very stringent and, until recently, difficult to achieve. The LCLS makes use of up-to-date technologies developed for the SLAC Linear Collider Project and the next generation of linear colliders, as well as the progress in the production of intense electron beams with radio-frequency photocathode guns. These advances in the creation, compression, transport and monitoring of bright electron beams make it possible to base the next (fourth) generation of synchrotron radiation sources on linear accelerators rather than on storage rings. These new sources will produce coherent radiation orders of magnitude greater in peak power and peak brightness than the present third-generation sources. Such a large increase in brightness, coupled with the very short pulse duration, will open new and exciting research possibilities in chemistry, physics, biology and other applied sciences. The concept of an x-ray FEL based on the SLAC Linac and a photocathode injector [4] was proposed in 1992 [5,6,7]. This proposal was followed by a period of studies [8] until, in 1996, a Design Study was initiated that will form the basis of a formal construction proposal.

2.2 Principle of Operation

As described in Chapter 4, lasing action is achieved in an FEL when a high brightness electron beam interacts with an intense light beam while travelling through a periodic magnetic field. Under the right conditions, the longitudinal density of the electron beam
becomes modulated at the wavelength of the light. When this occurs, electrons contained in a region shorter than an optical wavelength emit synchrotron radiation coherently; i.e., the intensity of the light emitted is proportional to the square of the number of electrons cooperating, rather than increasing only linearly with the number of electrons, as is the case with normal synchrotron radiation. The increasing light intensity interacting with the electron beam passing through the magnetic field enhances the bunch density modulation, further increasing the intensity of the light. The net result is an exponential increase of radiated power ultimately reaching about ten orders of magnitude above conventional undulator radiation.

The main ingredients of an FEL are a high-energy electron beam with very high brightness (i.e., low emittance, high peak current, small energy spread) and a periodic transverse magnetic field, such as produced by an undulator magnet. Electrons bent in a magnetic field emit synchrotron radiation in a sharp forward cone along the instantaneous direction of motion of the electron, and hence the electric field of this light is predominantly transverse to the average electron beam direction. In most present FELs the light from many passes of the electron beam through the undulator is stored in an optical cavity formed by mirrors. Many of these FELs work in the IR range and some have been extended to the UV range. Extending these devices to shorter wavelengths poses increasing difficulties due primarily to the lack of good reflecting surfaces to form the optical cavity mirrors at these shorter wavelengths. It has recently become possible to consider another path to shorter wavelength, down to the Angstrom range. This new class of FEL achieves lasing in a single pass of a high brightness electron bunch through a long undulator by a process called Self-Amplified Spontaneous Emission (SASE). No mirrors are used. This is the path proposed for the LCLS.

The LCLS reaches the Angstrom range with this approach with a high energy (14.3 GeV), high peak current (3.4 kA), low emittance (1.5 \( \pi \) mm mrad), small energy spread (0.02\%) electron beam passing through a long (100 m) undulator magnet. The spontaneous radiation emitted in the first part of this long undulator, travelling along with the electrons, builds up as the bunch-density modulation begins to take place during a single pass, resulting in an exponential increase in the emitted light intensity until saturation is reached. Usually this occurs after about 10 exponential field gain lengths.

2.3 Overall Layout

Figure 2.3-1 shows the layout of the proposed facility. Note the hexagonal shape of the soon-to-be-completed PEP-II B Factory electron-positron collider that uses the first 2 km of the Linear Accelerator as the injector. The last 1 km of the linac is used by the LCLS.
A new injector consisting of a gun and a short linac is used to inject an electron beam into the last kilometer of the SLAC linac. With the addition of two stages of magnetic bunch compression, it emerges with the energy of 14.3 GeV, a peak current of 3,400 A, and a normalized emittance of 1.5 \( \pi \) mm-mrad. A transfer line takes the beam and matches it to the entrance of the undulator. The 100 m long undulator will be installed in the tunnel that presently houses the Final Focus Test Beam Facility. After exiting the undulator, the electron beam is deflected onto a beam dump, while the photon beam enters the experimental areas.

### 2.4 Performance Characteristics

Table 2.4-1 lists some of the basic parameters of the LCLS electron beam, of the undulator, and of the FEL performance at the shortest operating photon wavelength.

Figure 2.4-1 shows the peak and average brightness as a function of photon energy. The LCLS is designed to be tunable in the photon wavelength range 1.5–15 Å, corresponding to 4.5–14.3 GeV electron energy.
Table 2.4-1. LCLS electron beam parameters.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam energy</td>
<td>14.35</td>
<td>GeV</td>
</tr>
<tr>
<td>Emittance</td>
<td>1.5</td>
<td>π mm mrad, rms</td>
</tr>
<tr>
<td>Peak current</td>
<td>3,400</td>
<td>A</td>
</tr>
<tr>
<td>Energy spread (uncorrelated)</td>
<td>0.02</td>
<td>%, rms</td>
</tr>
<tr>
<td>Energy spread (correlated)</td>
<td>0.10</td>
<td>%, rms</td>
</tr>
<tr>
<td>Bunch length</td>
<td>67</td>
<td>fsec, rms</td>
</tr>
<tr>
<td>Undulator period</td>
<td>3</td>
<td>cm</td>
</tr>
<tr>
<td>Number of undulator periods</td>
<td>3,328</td>
<td></td>
</tr>
<tr>
<td>Undulator magnetic length</td>
<td>99.8</td>
<td>m</td>
</tr>
<tr>
<td>Undulator field</td>
<td>1.32</td>
<td>Tesla</td>
</tr>
<tr>
<td>Undulator gap</td>
<td>6</td>
<td>mm</td>
</tr>
<tr>
<td>Undulator parameter, (K)</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>FEL parameter, (\rho)</td>
<td>4.7 \times 10^{-4}</td>
<td></td>
</tr>
<tr>
<td>Field gain length</td>
<td>11.7</td>
<td>m</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>120</td>
<td>Hz</td>
</tr>
<tr>
<td>Saturation peak power</td>
<td>9</td>
<td>GW</td>
</tr>
<tr>
<td>Peak brightness</td>
<td>(1.2 \times 10^{32} - 1.2 \times 10^{33})</td>
<td>Photons/(s mm^2 mrad^2 0.1% bandwidth)</td>
</tr>
<tr>
<td>Average brightness</td>
<td>(4.2 \times 10^{21} - 4.2 \times 10^{22})</td>
<td>Photons/(s mm^2 mrad^2 0.1% bandwidth)</td>
</tr>
</tbody>
</table>

The curves for the presently operating third-generation facilities indicate that the projected peak brightness of the LCLS FEL radiation would be about ten orders of magnitude greater than currently achieved. Also note that the peak spontaneous emission alone (independent of the laser radiation) is four orders of magnitude greater than in present sources. This, coupled with sub-picosecond pulse length, makes the LCLS a unique source not only of laser, but also of spontaneous radiation. This spontaneous radiation is also transversely coherent at wavelengths of 6 Å and longer.
2.5 The Photoinjector

The design goal of radio-frequency photocathode guns currently under development at various laboratories is a 3 ps (rms) long beam of 1 nC charge with a normalized rms emittance of $1\pi$ mm-mrad.

In a radio-frequency photocathode gun, electrons are emitted when a laser beam strikes the surface of a cathode [9]. The extracted electrons are accelerated rapidly (to 7 MeV) by the field of a radio-frequency cavity. The rapid acceleration reduces the increase in beam emittance that would be caused by the space charge field. The variation of phase space distribution along the bunch, caused by the varying transverse space charge field along the bunch, is compensated with an appropriate solenoidal focusing field [10].

The laser will have a YAG-pumped Ti:sapphire amplifier operating at 780 nm that will be frequency tripled (3rd harmonic). Very restrictive conditions are required for the reproducibility of the laser energy and timing. Stable FEL operation requires a pulse-to-pulse energy jitter of better than 1% and a pulse-to-pulse phase stability of better than 0.5 ps (rms). These tight tolerances are needed to ensure optimum compression conditions.
2.6 Compression and Acceleration

The purpose of the compressors is to reduce the bunch length, thereby increasing the peak current to the 3,400 A required to saturate the LCLS. Accelerating the beam off the crest of the rf waveform in the linac creates an energy-phase correlation that can be used by a chicane to shorten the bunch by appropriate energy-path length dependence. It is preferable to utilize two, rather than one, chicane. This reduces the sensitivity of the final bunch length to the phase jitter in the photocathode laser timing [11]. The rms length of the bunch emitted from the cathode is 1 mm (3 ps). After compression, the bunch shortens to 0.02 mm.

The choice of energies of the various compression stages is the result of an optimization that takes into account beam dynamics effects, the most relevant ones being the space charge forces in the early acceleration stage, the wakefields induced by the electromagnetic interaction of the beam with the linac structure [12], and the coherent synchrotron radiation emitted by a short bunch [13]. With all dynamic effects included, the simulations [14] indicate that the emittance dilution up to the entrance of the undulator should be less than 50%.

From the linac exit a transport system carries the beam to the entrance of the undulator.

2.7 The Undulator

Several candidate undulator types were evaluated, including pure permanent magnet helical devices, superconducting bifilar solenoids, and hybrid planar devices. Superconducting devices require more investment and resources than were available for this study, though they may offer a good solution. A hybrid device has a stronger field, and, therefore, a shorter length, than a pure permanent magnet device. It also offers superior error control. The advantage of a pure permanent magnet system is that it allows superposition of focusing fields. Since the focusing quadrupoles can be placed in the interruptions and need not envelop the undulator, this property of pure permanent magnet undulators is not critical.

The other choice is between a planar and a helical undulator. Helical devices offer a shorter gain length to reach saturation, but are less understood than planar devices, particularly in terms of magnetic errors, a crucial factor in the SASE x-ray situation. Measurements of the magnetic field are also difficult. A planar hybrid undulator was chosen for this design for its superior control of magnetic errors and simplicity of construction and operation. The magnetic length of the undulator is 99.8 m, its period is 3 cm, and the pole-to-pole gap is 6 mm.

2.8 The X-ray Optics and Experimental Areas

After leaving the undulator, the electron beam, carrying an average power of 1.6 kW, will be dumped into a shielding block by a sequence of downward-deflecting permanent magnets, while the FEL radiation will be transported downstream to the experimental areas. The design envisages the construction of two experimental stations in one hutch. To cover
the spectral range of the LCLS, both specular (for the full spectral range) and crystal (for wavelengths shorter than 4.5 Å) optics will be employed. In the initial operation, it is expected that the high peak power and power density will inhibit the utilization of the full FEL flux with conventional focusing and transport optics. On the other hand, there will be a unique opportunity to study the effect of high peak power density on materials and optical elements, thereby opening the path to the full exploitation of the radiation in the LCLS and in future FEL facilities. Consequently, a system will be designed that allows intensity of the radiation to be varied from the level of current third-generation facilities up to the maximum LCLS intensity. This will be achieved by introducing a gas attenuation cell into the path of the FEL radiation. Further reduction factors can be obtained on the beam line optics and instrumentation by operating their crystal or specular optical elements at very low grazing-incidence angles. It is also possible, as a future extension of the LCLS, to construct a long beam line (∼800 m) to reduce the power density without lowering the brightness.

2.9 Applications of the LCLS

The 67 fs (rms) pulses from the LCLS would provide the means for pump/probe x-ray structural studies on a sub-picosecond time scale. Synchronization with external optical lasers should be possible at the picosecond level, and more precise, sub-picosecond synchronization could be achieved by using diffracting crystal optics to split the x-ray pulse into pump and delayed probe pulses. Similar pulse-splitting techniques could be used for time-correlation studies of fast fluctuations in a sample. On a slower time scale, the spatial coherence and pulsed nature of the beam would make time-correlation spectroscopy a powerful technique in the x-ray region. Even intermediate range order fluctuations near the glass transition could be measured, thus providing critical microscopic information about one of the least understood phenomena in condensed matter science.

The 9 GW peak power would make possible non-linear x-ray optical studies of a variety of atomic and solid-state phenomena, including exciton and polariton coherent motions. The spatial coherence of the beam would allow focusing down to sub-micron dimensions, producing tremendous peak electromagnetic fields. While the coherent FEL radiation would be monochromatic, the LCLS would also produce a broadband (1–300 keV) pulse of radiation, incoherent but quite intense and having a sub-picosecond pulse duration. This spontaneous radiation could be used for ultra-fast Laue crystallography. Structures could be derived for very small or unstable samples. The hard x-ray phase-contrast tomographic and holographic imaging techniques pioneered at NSLS and ESRF can provide three-dimensional microscopic images of low-absorption organic and biological materials, which could be produced on biologically and physically important time scales with the coherent LCLS radiation. Similar phase-sensitive techniques could enhance protein crystallography, leading to the determination of presently intractable structures.
2.10 Summary

In summary, this report describes the design of an x-ray Free-Electron Laser operating on the single pass SASE principle. The FEL uses the unique capability of the SLAC linear accelerator to create an intense electron beam of low emittance and a long undulator to produce high brightness coherent radiation down to about 1.5 Å. Theory and computations indicate that the peak brightness from such a device would be about ten orders of magnitude greater than currently achievable in third-generation synchrotron radiation sources. Such performance, coupled with the very short bunch length (67 fsec rms) and full transverse coherence, would allow the exploration of new horizons in material science, structural biology, and other disciplines.

2.11 References


7 Ibid., W. Barletta, A. Sessler and L. Yu, “Using the SLAC two-mile accelerator for powering an FEL,” pp. 376-384.


The Scientific Case

TECHNICAL SYNOPSIS

An FEL operating in the hard x-ray region, such as the LCLS, will produce radiation with unique qualities. The peak brightness will exceed that produced by today’s brightest synchrotrons by more than 10 orders of magnitude, an advance similar to that of the synchrotron over a 1960s laboratory x-ray tube. In addition, the FEL’s sub-picosecond pulse length will be two orders of magnitude shorter than a synchrotron pulse, and the FEL pulse will be highly coherent.

Given the revolutionary properties of the LCLS, accurate projection of its scientific applications is difficult. Nevertheless, major advances can be anticipated in many fields of research, exploiting the short pulse, short wavelength, and high intensity of the FEL. These include fundamental quantum mechanics phenomena using entangled multi-photon states, and atomic physics studies that measure photon interactions with core atomic electrons well into the nonlinear regime. In molecular and plasma physics, ionization and dissociation processes under extremely high-intensity electromagnetic fields will be studied. In chemistry, the x-ray FEL has great potential as a monitor of surface chemical reactions using x-ray fluorescence or photoelectron spectroscopy. In condensed matter science, the brightness of the FEL will be used to apply standard x-ray techniques to sub-micron samples, and to record the signals in less than 1 picosecond. The coherence will allow interference techniques such as photon correlation spectroscopy to become powerful tools for studying dynamics in condensed matter. In addition, the FEL should allow the development of completely new ways to study condensed matter, based on nonlinear x-ray interactions. In biology, the sub-picosecond time scale of the FEL pulse will make it possible to observe dynamical interactions between large molecules in some extremely interesting systems.

3.1 History of Scientific Interest in X-ray Free Electron Lasers

In the mid-1960s the new Stanford Linear Accelerator offered a great leap in accelerator capability, and provided a boost to the rapidly growing field of particle physics. At that time x-ray physics was a stable, mature field, with a solid theoretical base and standardized instrumentation. (The x-rays considered here are hard x-rays, with wavelengths shorter than about 15 Å. This is the region of the spectrum that will be affected by the LCLS.) Though essential to crystallography and materials analysis, the x-ray field had not changed much for
many years, and great future development did not seem likely. Nevertheless, during the intervening 30 years the capability of x-ray sources has increased far more than that of particle accelerators, and x-ray physics has witnessed an explosion of new techniques and applications. The key to this huge change has been the development of synchrotron radiation from high-energy electron storage rings.

The scientific capabilities of synchrotron x-ray sources are reflected in the fact that in the US nine such facilities are operated with a collective annual funding level of about $200 million. Several thousand scientists per year make use of these facilities for their research programs, which range from fundamental physics to materials science to biology and medicine to environmental science. Now, with the LCLS, the Stanford Linear Accelerator can be used to drive an x-ray source whose capabilities outshine those of a modern synchrotron source by nearly as much as the synchrotron does the 1960s laboratory source.

Advances in accelerator technology have been the driving forces in the progress toward brighter synchrotron sources, with scientific applications developing in response to the availability of new sources. The rate of improvement in source capability has been tremendous: for 30 years x-ray source brightness has been increasing exponentially with a doubling time of about 10 months. A modern synchrotron source is eleven orders of magnitude brighter than a 1960s laboratory x-ray source. Seldom if ever in history (perhaps only in the field of visible laser optics) has a scientific discipline seen its tools change so dramatically within the active life of a single generation of scientists. Such change makes it very difficult to predict the future. No one foresaw the huge impact on biomedical research that has come from synchrotron-based EXAFS and protein crystallography, though these techniques had been developed previously using laboratory sources. The new source capability made them qualitatively and unexpectedly more powerful. This history indicates that it should be very difficult to predict the eventual applications of the LCLS, a source more than ten orders of magnitude brighter than today’s synchrotron source.

Nevertheless, recently there has been much speculation about the future of synchrotron radiation. A first workshop on “Fourth-Generation Light Sources,” at SLAC in 1992 [1], concentrated almost exclusively on accelerator technology rather than applications. This workshop served to alert the scientific community to the possibilities for x-ray FELs driven by linacs, including the SLAC linac. It is interesting to note that a workshop earlier in 1992 on “Applications of X-ray Lasers” [2] did not mention FEL sources at all; only conventional lasers were considered. The SLAC workshop directly stimulated the first workshops on scientific applications of x-ray FELs [3,4]. The next “Fourth-Generation Light Sources” workshop, in 1996 at the ESRF [5], included sessions on both sources and applications. The discussions convinced nearly all the participants that linac FELs would be the most effective machines for continuing to improve the performance of x-ray sources, and in particular, would provide the only route to a diffraction-limited hard x-ray source. Subsequent workshops at DESY in 1996 [6,7] and APS in 1997 [8] have assumed that future fourth-generation x-ray user facilities will be based on linac FELs, and have attempted to foresee
the new science that these sources will bring. These workshops form the basis for the ideas presented below.

3.2 Unique Features of X-ray FEL Radiation

Intrinsic to the short-wavelength FEL process are several features which give unique and useful attributes to the radiation that is produced. Because of the difficulty of creating an optical cavity at x-ray wavelengths, a high-gain, single-pass FEL design is used. This implies a very short, high-energy electron pulse (compressed to achieve high peak current) producing a similarly short but very intense FEL radiation pulse. The radiation has a relatively short longitudinal coherence length (limited by the number of undulator periods within a few gain lengths), but complete transverse coherence. The undulator is a high-K device, and so in addition to the FEL radiation, it produces a spontaneous radiation spectrum rich in higher harmonics. Fig. 3.2-1 shows a calculation of the LCLS radiation spectrum with FEL operation at 1.5 Å, and Table 3.2-1 gives some descriptive parameters for the beam. Compared with existing x-ray sources, it has three truly unique aspects:

• The FEL peak intensity and peak brightness are both many orders of magnitude higher than can be produced by any other source (see Fig. 3.2-2). Even the average brightness, though limited by the low repetition rate of the linac, is still orders of magnitude higher than the brightest synchrotron radiation.

• The sub-picosecond pulse length is orders of magnitude shorter than can be achieved with a synchrotron. There exist x-ray sources with comparable pulse lengths (plasma sources and inverse Compton scattering sources), but they have very much lower brightness.

• The FEL radiation has full transverse coherence (it is diffraction limited). In addition, the degeneracy parameter (photons per coherence volume in phase space) is many orders of magnitude greater than one. Only at the longest wavelengths can some synchrotron sources approach the diffraction limit, and no source has a degeneracy parameter much greater than one.

In addition to these features of the FEL radiation, the high-energy spontaneous radiation offers attractive characteristics. The spectrum of this radiation extends to nearly 1 MeV; above about 100 keV it is far brighter than any synchrotron radiation.
Several recent international workshops have discussed the scientific applications of FEL x-ray sources. The following summary has been distilled from the two most recent workshops [7,8]. Many of the techniques mentioned are already in use, or at least proof-of-principle experiments have been done. An attempt has been made to try to project the impact of an FEL source on the future importance of these techniques. However, experience with synchrotron sources indicates that accurate projections are very difficult to make. It is also certain that, once it is available, the FEL source will stimulate the development of completely new techniques, the importance of which is extremely difficult to predict.
Table 3.2-1. Calculated characteristics of the LCLS radiation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEL wavelength</td>
<td>1.5</td>
<td>Å</td>
</tr>
<tr>
<td>FEL bandwidth ($\delta E/E$)</td>
<td>0.002</td>
<td></td>
</tr>
<tr>
<td>Pulse duration (FWHM)</td>
<td>233</td>
<td>fs</td>
</tr>
<tr>
<td>Pulse length (FWHM)</td>
<td>67</td>
<td>µm</td>
</tr>
<tr>
<td>Peak coherent power</td>
<td>9</td>
<td>GW</td>
</tr>
<tr>
<td>Peak coherent power density</td>
<td>$1.5 \times 10^{12}$</td>
<td>W/mm$^2$</td>
</tr>
<tr>
<td>FEL energy/pulse</td>
<td>2.6</td>
<td>mJ</td>
</tr>
<tr>
<td>Peak brightness</td>
<td>$1.2 \times 10^{13}$</td>
<td>Photons/(s mm$^2$ mrad$^2$ 0.1% bandwidth)</td>
</tr>
<tr>
<td>FEL photons/pulse</td>
<td>$2 \times 10^{12}$</td>
<td></td>
</tr>
<tr>
<td>FEL photons/second</td>
<td>$2.4 \times 10^{14}$</td>
<td></td>
</tr>
<tr>
<td>Degeneracy parameter</td>
<td>$3.3 \times 10^9$</td>
<td></td>
</tr>
<tr>
<td>Peak EM field (unfocused)</td>
<td>$3.4 \times 10^{10}$</td>
<td>V/m</td>
</tr>
<tr>
<td>Average FEL power</td>
<td>0.31</td>
<td>W</td>
</tr>
<tr>
<td>Average FEL brightness</td>
<td>$4.2 \times 10^{12}$</td>
<td>Photons/(s mm$^2$ mrad$^2$ 0.1% bandwidth)</td>
</tr>
<tr>
<td>Transverse size of FEL beam (FWHM)</td>
<td>78</td>
<td>µm</td>
</tr>
<tr>
<td>Divergence of FEL beam (FWHM)</td>
<td>1</td>
<td>µrad</td>
</tr>
<tr>
<td>Peak power of spontaneous radiation</td>
<td>81</td>
<td>GW</td>
</tr>
</tbody>
</table>

3.2.1 Fundamental Quantum Mechanics

Nonlinear scattering of the high-brightness FEL beam could be used to produce large numbers of entangled multi-photon states, which could be used to study correlation effects such as the Bell inequality. It would be advantageous to use x-rays for experiments of this type, rather than optical photons, because the high quantum efficiency of x-ray detectors would make it easier to keep track of every photon.

The ability to create intense, short-wavelength electric field patterns using an x-ray FEL would be useful for atom-interferometry experiments. FEL standing wave interference patterns could be used as beam splitters and mirrors for the atom beams. This is achieved today with visible lasers; using the FEL would allow these optics to be created with shorter periods, allowing larger scattering angles for the atom beams, and thereby giving the interferometry experiments much higher sensitivity.
If the full peak power of the x-ray FEL were focused into a submicron spot, the peak electric field could approach $10^{15}$ V/m. This value is high enough to be interesting for tests of quantum electrodynamics.

![Figure 3.2-2. LCLS average brightness and peak brightness compared with some other sources.](image)

### 3.2.2 Atomic, Molecular, and Plasma Physics

The extremely high peak brightness of an FEL x-ray source offers the chance to extend the study of photon interactions with core atomic electrons well into the nonlinear regime. This area cannot be explored using existing sources, since synchrotrons lack the intensity to produce such multi-photon excitations, and atomic x-ray lasers, while intense, are constrained by low repetition rates and lack tunability. The new experimental capability would provide tests of theoretical analysis that go beyond the dipole approximation. For example, it would allow tests of nonlinear processes such as core-resonant ionization in helium, and adiabatic stabilization [9], in which, under certain conditions, transition rates are predicted to decrease with increasing intensity.

In the area of molecular physics, the high brightness and short pulses of the FEL source would contribute to better understanding of ionization and dissociation processes by controlling them coherently. Chemical reactions in the time domain with pump/probe techniques could also be studied.
The plasma physics community is very excited about the ability of an FEL x-ray source to greatly extend their studies of the interactions between matter and extremely high-power-density electromagnetic fields. This would allow new tests of the scaling properties of nanoplasma multiple ionization, and inner-shell excitations.

### 3.2.3 Chemical Physics

With its very high brightness, the x-ray FEL has the potential to become the universal monitor of surface chemical reactions, using x-ray fluorescence or XPS as the system probe. This application has the ability to fully characterize the kinetics (reactants, products, and rates) of surface reactions. The feasibility of the scheme has been demonstrated using a simple model system at the APS; the x-ray FEL will allow the technique to be fully developed and to realize its full potential.

By using the x-ray pulse as a probe beam, a fast-pulse optical laser can be used to set up femtosecond-resolution structural dynamics studies. Local structure would be obtained by EXAFS, and global structure would be obtained via diffraction measurements. Again, the intensity of the FEL allows both dilute and complex systems to be analyzed.

Finally, one can expect that x-ray FEL sources will eventually be developed which have sub-femtosecond time resolution, which would allow probing the next level of temporal dynamics in atomic systems.

### 3.2.4 Condensed Matter Physics and Materials Science

The characteristic distances important for studies of condensed materials typically range from micrometers down to Angstroms, and the typical interaction energy runs from about 1 eV down to 1 μeV (corresponding to interaction times in the femtosecond to nanosecond range). These values match very well with the characteristic length and time scales of an x-ray FEL pulse: Angstrom wavelength with coherence length of many micrometers, and pulse duration measured in femtoseconds.

In addition, the brightness is much higher than that produced by any other x-ray source. This feature will allow a large number of standard x-ray techniques to be applied to smaller samples, and to record the relevant signal in less time. Examples include surface scattering studies of very small samples, diffraction from samples in very high pulsed magnetic fields, time-resolved studies of crack propagation, diffraction from materials undergoing shock wave distortion, diffraction from single grains in complex polycrystalline materials, studies of critical phenomena, and scattering studies of laser pulse-induced charge modulations in materials [10]. One large class of experiments that can take advantage of the x-ray FEL are those involving x-ray photon correlation spectroscopy (XPCS) [11]. This technique today is limited by source brightness to studying length scales larger than 100 nm and time scales longer than 1 ms. Both the length and time limits could be reduced by orders of magnitude with an x-ray FEL. In particular, time scales shorter than 1 ps could be probed, allowing the
XPCS technique to complement energy-resolved inelastic x-ray scattering techniques. Initial FEL designs, such as the LCLS, are particularly suited for XPCS measurements in the ps-ns time range. This range is complementary to that covered by the neutron spin echo technique, which is now being used to study the dynamics of the glass transition. The vastly higher brightness of the FEL source would allow experiments to be performed in much less time and with much smaller samples.

In addition to these extensions of existing techniques, the x-ray FEL should allow the development of some completely new ways to study condensed matter. Some of these new techniques will most likely involve the high degeneracy of the FEL photon state. By analogy with visible laser science, one can envision gaining higher spectroscopic resolution through multi-photon excitations, or nonlinear interactions between the FEL x-rays and synchronized visible laser pulses [12]. If suitable resonances can be identified, x-ray photon echo experiments could provide a new sensitive probe of internal fields in materials.

The very high peak power of the x-ray FEL could also be used to induce desired permanent changes in materials. For example, a spatial interference pattern created from the FEL radiation could have enough intensity to carve a high-quality Fresnel optic into a smooth block of material. The focused FEL beam could also be used to create small holes (microexplosions) deep inside a sample.

3.2.5 Biology

Structural biologists wish to determine the atomic structures and to observe the dynamical interactions between large molecules (mass between 5 kDa and 5 x 10^6 kDa). The dynamical time scales of interest are typically microseconds or longer, but for some extremely interesting systems (e.g., photosynthetic reaction centers, light-harvesting complexes, photosystem II, and light sensors such as photoactive yellow protein and bacteriorhodopsin) the interesting time scale can be as short as a few femtoseconds.

The high brightness of the x-ray FEL would allow structures to be determined using very small samples. It should be possible to study two-dimensionally ordered crystals (e.g., membrane proteins), which are notoriously hard to crystallize in three-dimensions and which are both numerous and of keen biological interest. In addition to conventional crystallographic techniques, it might be possible to exploit the spatial coherence of the FEL radiation to get structural information holographically.

The short time structure of the FEL pulse could be used to probe sample dynamics on a femtosecond to nanosecond time scale. There is interest in both time correlation studies of thermal fluctuations, and pump-probe relaxation studies (using as a pump either an external synchronized laser or the FEL x-ray pulse itself).

The issue of sample damage due to the radiation must be resolved in order for these concepts to lead to practical techniques. At this point too little is known about the damage that FEL pulses will cause in biological samples. From the power density involved, one
would expect significant damage, yet the very short period of the FEL pulse might very well allow scattering information to be collected before damage becomes apparent. For static structure measurements, irreversible damage to the sample is not necessarily a problem, so long as the structure information is retrieved first, in snapshot fashion. The damage issue may be more problematic for dynamical measurements in which the sample must remain undamaged for a longer time. Experiments are needed with high-power, very fast x-ray pulses in order to understand this issue.

3.3 The Role of the LCLS

For the above applications to be realized, much needs to be learned about the interaction between x-ray FEL radiation and matter. This cannot be learned using today’s radiation sources: a recent workshop convened to address this issue [13] concluded that all existing laser and synchrotron sources fail by at least three orders of magnitude in frequency or power density to duplicate the conditions of an x-ray FEL. As mentioned in Section 3.2, the basic interactions between atoms and electromagnetic fields with the strength of the FEL radiation are not well understood. It is not known exactly what kind of damage this radiation will cause in solid samples, or how best to moderate its intensity.

Thus the first scientific contribution of the LCLS will be to provide an understanding of the interactions between very intense, very high frequency electromagnetic radiation and matter. In the process of gaining this understanding, many technical issues must be addressed, such as fast, high dynamic range detectors, high-power optics, and precise synchronization with external probes. These techniques and knowledge can then be used to explore the many other FEL applications mentioned above. It is very likely that as experience with the LCLS grows, further advances in accelerator science will lead to greater control over the FEL radiation. It may become possible to produce even shorter x-ray pulses, energy-chirped pulses, or pulses with special polarization states. All of these will lead to new applications.

Ultimately, it is likely that the US will decide to invest in an FEL x-ray light source user facility. The scientific utility of such a source, and its planning and design, will be greatly influenced by the LCLS operating experience. Just as were the early synchrotron sources of the 1970s, the LCLS is in a sense a door, opening into a wide new world of scientific applications.

3.4 References


10  For elaboration of these applications, see Ref. 7.


4  FEL Physics

TECHNICAL SYNOPSIS

The physics of the x-ray FEL is described. The chapter first presents a review of the historical and technological developments of the Free Electron Laser that led to proposals to operate an FEL in the large gain regime, starting from the spontaneous radiation noise, without using an optical cavity. In this mode, called “Self-Amplified-Spontaneous-Emission” (SASE), lasing is produced in a single pass of an electron beam with high phase-space density through a long undulator, eliminating the need for optical cavities, which are difficult to build in the soft x-ray or x-ray spectral region.

A discussion of the spontaneous radiation produced in the LCLS undulator then introduces the concepts and formulae for the radiation intensity, the number of photons produced per electron, brightness, and peak power. The spontaneous radiation is emitted incoherently, and thus its power increases only linearly with the number of electrons. To increase the peak brightness, one can either increase the electron current or the number of photons produced per electron. An FEL does the latter by increasing the number of photons per electron by many orders of magnitude. This is achieved by microbunching the electrons at the optical wavelength of the radiation. The electron beam interacts with the electric field of the radiation. This interaction produces an electron energy modulation which modifies the electron trajectory in such a way as to produce bunching at the scale of the radiation wavelength. For this collective instability to occur, several conditions must be satisfied and a parameter of paramount importance is the electron density in phase space.

4.1 Introduction

An x-ray laser offers a unique way to explore the structure of matter at the atomic and molecular scale. Among the various schemes proposed to reach this wavelength region, the free-electron laser (FEL), operating without mirrors in a self-amplified spontaneous emission (SASE) mode [1,2], offers a favorable scaling law [3]. It has also been shown [4] that by utilizing state-of-the-art linear accelerators and electron sources, it is possible to build an x-ray SASE FEL, and this has led to two major proposals to build a SASE x-ray FEL, one at SLAC [5], the other at DESY [6]. The SASE x-ray FEL can produce subpicosecond long, high peak power, transversely coherent, photon pulses, with peak brightness about 10 orders of magnitude larger than that obtainable at storage ring based synchrotron radiation sources, the best sources available today. This promises a real breakthrough in the use of photons to
explore matter. The SLAC and DESY proposals are the culmination of many years of theoretical and experimental work on the generation of radiation from relativistic electron beams, going back to the 1950s. The first generators of coherent electromagnetic (EM) radiation from free-electron beams were the microwave tubes; their development received a strong push during World War II. Microwave tubes use slow wave structures, which limit their operation mainly to long wavelengths, in the centimeter region. FELs were developed from the work on free-electron beams. Motz [7] showed in 1951 that an electron beam propagating through an undulator magnet can be used to amplify radiation. The Ubitron, a microwave tube developed in 1960 by Philips [8], is quite similar to the FEL. Theoretical work on the FEL was done in the 1960s and 1970s by Palmer [9], Robinson [10] and Csonka [11].

During the 1960s the research on the generation of short wavelength coherent radiation turned mainly in the direction of atomic and molecular lasers, and optical resonators. While extremely successful in the infrared, visible, and ultraviolet regions, these lasers have limited tunability, and this line of development does not permit them to reach the x-ray region. The use of electron beams and FELs is an alternative when atomic and molecular lasers and microwave tubes cannot be used.

Madey in 1971 [12] analyzed again the possibility of exchanging energy between free electrons and electromagnetic radiation in the small gain regime, using a quantum theoretical approach, and he and coworkers followed this work with successful experimental demonstration of an FEL amplifier [13] at 10 µm, and of an oscillator [14]. This very important step led over the following years to a large interest in FELs, and the successful construction and operation of many FEL oscillators, at wavelengths from the far IR to the near UV. These FEL oscillators operate starting from spontaneous synchrotron radiation (sometimes called noise), and in the small signal gain regime. Soon afterward, additional theoretical work showed that there is also a large gain regime, based on the existence of an exponentially growing solution for the equations describing the interaction of the electromagnetic field and the electron beam, this is called FEL collective instability [15]. (For a review of the FEL collective instability theory see Murphy and Pellegrini [16] and Bonifacio et al. [17].) This work led to the first proposal to operate an FEL in the large gain regime, starting from the spontaneous synchrotron radiation noise, without using an optical cavity, a SASE FEL. In the SASE mode, lasing is produced in a single pass of a high phase-space density electron beam through a long undulator, eliminating the need for optical cavities, which are difficult to build in the soft x-ray or x-ray spectral regions.

The analysis of the FEL in the 1-dimensional (1-D) case has led to a simple theory of the FEL collective instability, which describes most of the FEL physics with one single parameter [18]. The extension of the FEL theory to three dimensions, including the effect of diffraction and optical guiding [19], has been another important step toward a full understanding of the physics of this system. The combination of the 1-D theory of the
collective instability and of the 3-D diffraction effects allows us to obtain a simple scaling law of a SASE-FEL with wavelength, showing a weak dependence of the gain on wavelength [4]. Using this analysis it is possible to show that to reach short wavelengths one needs to attain a large six-dimensional electron beam phase-space density and to provide additional focusing in the undulator. In fact, the requirements on the electron beam’s peak current, emittance, and energy spread are very stringent, and until recently, difficult to satisfy. This situation has been changed by the recent development of high-brightness radio frequency photocathode electron guns [20], and the progress in accelerating and compressing low emittance beams without spoiling their brightness, resulting from the work on linear colliders [21]. As a result, there is now the possibility to make a major extension of FEL operation, from the shortest wavelength yet achieved (240 nm) to 0.1 nm [22].

The theory on which the x-ray SASE-FEL has been developed over many years, but the experimental data to support it are few and incomplete. One characteristic of a SASE-FEL is that the output intensity is proportional to the initial random bunching of the electron beam at the FEL frequency. The output intensity will thus fluctuate from shot to shot [23]. These intensity fluctuations and their distribution, as well as the exponential gain, are important to a full understanding of the SASE-FEL. Very large gain in the SASE mode has so far been observed in the centimeter to millimeter waves [24], and in the medium infrared (IR) at Los Alamos [25]. Recently, gain in the near IR has been observed at Orsay [26], Brookhaven [27], and UCLA [28]. The intensity distribution function has been previously measured for spontaneous undulator radiation [29], with no amplification and long bunches, and more recently for amplified radiation and a short bunch length at UCLA [28]. Large gain (>10^5) and intensity fluctuations at 12 µm, using a 2 m long undulator, have been measured recently in a UCLA-LANL experiment [30]. All these results are in agreement with the FEL theory as described in the next sections.

### 4.1.1 Spontaneous Radiation from the LCLS Undulator

The LCLS is an outstanding source of coherent radiation in the x-ray region even if one neglects the FEL action. For this reason, the spontaneous undulator radiation produced in the LCLS undulator is discussed first. The beam and undulator parameters used are given in Table 4.1-1 and form the baseline design parameters of this report.

When an electron beam traverses an undulator, it emits electromagnetic (EM) radiation at the wavelength

\[
\lambda_v = \lambda_u \left(1 + K^2 / 2\right) / 2\gamma^2 \tag{4.1.1}
\]

and at harmonic wavelengths. \(\lambda_u\) is the undulator period, \(\gamma mc^2\) the beam energy, and 

\[K = ecB_u \lambda_u / 2\pi mc^2\]

is the vector potential normalized to \(mc^2\). A plot of wavelength versus beam energy is given in Fig. 4.1-1.
Table 4.1-1.  Main LCLS parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>14.35</td>
<td>GeV</td>
</tr>
<tr>
<td>Beam emittance, normalized, rms</td>
<td>1.5</td>
<td>mm-mrad</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.95</td>
<td>nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>3.4</td>
<td>kA</td>
</tr>
<tr>
<td>Pulse duration, rms</td>
<td>67</td>
<td>fsec</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>120</td>
<td>Hz</td>
</tr>
<tr>
<td>Undulator period</td>
<td>3.0</td>
<td>cm</td>
</tr>
<tr>
<td>Undulator parameter, $K$</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Number of periods</td>
<td>3328</td>
<td></td>
</tr>
<tr>
<td>$\beta$-function in undulator</td>
<td>18</td>
<td>m</td>
</tr>
<tr>
<td>Radiation wavelength</td>
<td>1.5</td>
<td>Å</td>
</tr>
<tr>
<td>FEL parameter, $\rho$</td>
<td>$4.7 \times 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Cooperation length $L_c$</td>
<td>51</td>
<td>nm</td>
</tr>
</tbody>
</table>

The width of the radiation line (bandwidth) at the fundamental wavelength is related to the number of undulator periods $N_u$ [16] by

$$\frac{\Delta \omega}{\omega} = \frac{1}{N_u}. \quad (4.1.2)$$

**Figure 4.1-1.** Radiation wavelength as a function of the electron energy.
The undulator is an extended linear source, but the coherent part of the radiation, within the bandwidth (Eq. 4.1.2), can be approximately described as an equivalent source at the undulator center, with angular aperture

\[ \theta_r = \frac{2\lambda_r}{\lambda_w N_u}, \]  

and an effective source radius

\[ w = \frac{1}{4\pi} \left( \frac{\lambda_r \lambda_w N_u}{2} \right)^{1/2}. \]  

Notice that the product,

\[ w \theta_r = \frac{\lambda_r}{4\pi}, \]

gives the minimum phase space for a diffraction limited photon beam. For a planar undulator, the intensity of the radiation emitted on axis and at the wavelength \( \lambda_r \) (Eq. 4.1.1) per unit frequency and solid angle is approximately

\[ \frac{d^2I}{d\omega d\Omega} = N_u^2 \frac{e^2}{c} \frac{K^2}{(1 + K^2/2)^2} F_1^2(K), \]  

where \( F_1(K) = \left\{ J_1(K^2/4(1 + K^2/2)) - J_0(K^2/4(1 + K^2/2)) \right\} \). The coherent intensity is obtained by multiplying Eq. 4.1.6 by the solid angle corresponding to Eq. 4.1.3 and the bandwidth (Eq. 4.1.2). Dividing this intensity by the photon energy, the coherent intensity can be written as the number of coherent photons per electron, within the solid angle \( \pi \theta_r^2 \) (Eq. 4.1.3) and bandwidth \( \Delta\omega / \omega \) (Eq. 4.1.2), as

\[ N_{ph} = \pi \alpha \frac{K^2}{1 + K^2/2} F_1^2(K), \]  

where \( \alpha \) is the fine structure constant. For a value \( K = 3.7 \), \( N_{ph} \approx 2.2 \times 10^{-2} \) photons/electron. For an electron beam with \( N_{e,av} \) electrons per second, the number of photons per second is obtained from Eq. 4.1.7 as

\[ N_{ph,av} = \pi \alpha N_{e,av} \frac{K^2}{1 + K^2/2} F_1^2(K), \]  

The photon phase space density, i.e., the beam average brightness in a frequency bandwidth \( 10^{-3} \), is obtained from \( N_{ph} \) (Eq. 4.1.7), the normalized electron beam emittance \( \varepsilon_n \),
(assumed to be the same in both planes), and the undulator beta function \( \beta_{x,y} \) (assumed to be the same in both planes) as

\[
B_{av} = \frac{N_{e,av} N_{ph}}{4\pi^2} \frac{10^{-3}}{\Delta\omega/\omega} \tag{4.1.9}
\]

where

\[
\sum = \left\{ \frac{e_n \beta_{x,y}}{\gamma} + \frac{\lambda_n \lambda_u N_u}{16\pi^2} \right\} \left\{ \frac{e_n}{\gamma \beta_{x,y}} + \frac{\lambda_n}{\lambda_u N_u} \right\}, \tag{4.1.10}
\]

is the effective 4D-phase space area of the photon and electron beams. The peak brightness is obtained substituting \( N_{e,av} \) in Eq. 4.1.9 with \( N_e / \sqrt{2\pi \tau} \) (the number of electrons in a Gaussian bunch over \( \sqrt{2\pi} \) times the rms bunch duration \( \tau \)):

\[
B_{pk} = \frac{N_e N_{ph}}{4\pi^2 \sum} \frac{10^{-3}}{\sqrt{2\pi \tau} \Delta\omega/\omega} \tag{4.1.11}
\]

The peak coherent power, \( P_c \), is given by

\[
P_c = \frac{N_e}{\sqrt{2\pi \tau}} N_{ph} \frac{h}{2\pi} \omega \tag{4.1.12}
\]

Plots of the average and peak brightness based on parameters listed in Table 4.1-1 for the LCLS undulators are given in Fig. 4.1-2 and Fig. 4.1-3. The coherent part of the peak spontaneous radiation power is depicted in Fig. 4.1-4.
To increase the peak brightness for a given wavelength, either the electron current or the number of photons produced per electron can be increased. An FEL achieves the second goal by increasing the number of photons per electron by many orders of magnitude.

In the latter case, many electrons, say $N_e$, are all grouped within a small fraction of a wavelength. The total intensity would then be the single particle intensity times $N_e^2$, and the number of photons per electron would be increased by a factor $N_e$. In practical cases, the electrons are in a bunch much longer than the radiation wavelength, and their position distribution on a scale of $\lambda$, is completely random. As a result, the radiation fields emitted by
different electrons have a random relative phase, the total intensity is proportional to $N_e$, and
the number of photons per electrons is still given by Eq. 4.1.7. Taking advantage of a
collective instability of the electron beam-EM radiation field-undulator system, the number of
photons emitted per electron can be increased. This instability works as follows:

1. The electron beam interacts with the electric field of the radiation; the electric field
is perpendicular to the direction of propagation of the beam (the undulator axis), and
is parallel to the wiggling (transverse) velocity of the electrons produced by the
undulator magnet, of amplitude $K/\gamma$; the interaction produces an electron energy
modulation, on the scale $\lambda_r$.

2. The electron energy modulation modifies the electron trajectory in the undulator, in
such a way to produce bunching of the electrons at the scale $\lambda_r$.

3. Electrons bunched within a wavelength emit radiation in phase, thus producing a
larger intensity. The larger intensity leads to more energy modulation and more
bunching, leading to exponential growth of the radiation until saturation is reached.

The FEL instability has been discussed in detail in the literature. Here are summarized
some of the most important results for the FEL physics in a planar undulator. For the
collective instability to occur there are several conditions that must be satisfied. These
conditions depend on the FEL parameter [18],

$$\rho = \left[ \frac{K \Omega_p \omega_u}{4\sqrt{2\gamma} \omega_u K_i(K)} \right]^{2/3}, \tag{4.2.1}$$

and on the beam emittance, $\epsilon$. $\omega_u = 2\pi c / \lambda_u$ is the frequency associated with the undulator
periodicity;

$$\Omega_p = \left( \frac{4\pi r_e c^2 n_e}{\gamma} \right)^{1/2} \tag{4.2.2}$$

is the beam plasma frequency; $n_e$ is the electron density; $r_e$ is the classical electron radius. The
FEL parameter characterizes the instability, giving the instability inverse growth rate, or
power gain length, which, in the l-D approximation, is

$$L_{G} = \frac{\lambda_u}{4\sqrt{3\pi \rho}}, \tag{4.2.3}$$

and the saturation power

$$P_{sat} = \rho I_{beam} E_{beam} / \epsilon, \tag{4.2.4}$$
where $I_{beam}$ is the beam current, and $E_{beam}$ the beam energy. Saturation occurs after about 20 gain lengths. The conditions for the 1-D approximation to be valid are:

1. Beam emittance smaller than or on the order of the wavelength.

   \[ \varepsilon_e \lesssim \frac{\lambda}{4\pi} \gamma, \quad (4.2.5) \]

2. Beam energy spread smaller than the FEL parameter.

   \[ \sigma_E / E < \rho, \quad (4.2.6) \]

3. Gain length shorter than the radiation Rayleigh range;

   \[ L_G < L_R, \quad (4.2.7) \]

   where the Rayleigh range is defined in terms of the radiation beam radius, $w$, and the wavelength by $\pi w^2 = \lambda_r L_R$.

4. Slippage, $N_u \lambda_r$, is much smaller than the bunch length $\sigma_l$.

   \[ N_u \lambda_r << \sigma_l. \quad (4.2.8) \]

Condition 1 says that for the instability to occur the electron beam must match the angular and transverse phase-space characteristics of the radiation emitted by one electron in traversing the undulator (Eqs. 4.1.3, 4.1.4, 4.1.5). Notice that for wavelengths in the Angstrom region this condition cannot be met at present by storage-ring-based synchrotron radiation sources, but it can be satisfied by electron beams produced by a linac fed by a radio frequency laser-driven electron guns (photoinjectors), as will be discussed in the following sections.

Condition 2 limits the beam energy spread to a value such that the width of the spontaneous radiation line is not increased, and Landau damping does not reduce the growth rate. Condition 3 requires that the beam produce more radiation than is lost through diffraction. Conditions 1 and 3 both depend on the beam radius and the radiation wavelength, and are not independent. If they are satisfied, diffraction and three-dimensional effects are not important, and the one-dimensional model can be used with good approximation. In the case of the LCLS system, Condition 1 is not satisfied and, as a result, the gain length is about a factor of two larger than what predicted by the 1-D model. Condition 4 is well satisfied in the LCLS case, where the slippage is 0.5 $\mu$m, and the bunch length is 70 $\mu$m (fwhm).

If, as it is the case in SASE, there is no input electromagnetic field at the undulator entrance, radiation is still emitted when the longitudinal distribution of the electron beam is
non-uniform, and has a Fourier component \( b(\omega_r) \) at \( \omega_r = 2\pi c / \lambda_r \). This quantity can be written as

\[
b(\omega_r) = \frac{1}{N_e} \sum_{n=1}^{N_e} e^{2\pi i z_{on} / \lambda_r},
\]

and is called the bunching parameter. \( z_{on} \) is the initial electron position at the time \( t = 0 \), when the electron bunch enters the undulator.

The amplitude of the electromagnetic field is then proportional to \( |b(\omega_r)|^2 \). If the bunch length, \( \sigma_z \), is much larger than the resonant wavelength, \( \lambda_r \), and the beam is generated from a thermionic cathode or from a photocathode, the bunching parameter, \( b(\omega_r) \), and thus the amplitude and the intensity of the electromagnetic field are stochastic quantities characterized by a distribution function, which is determined by the random initial longitudinal electron distribution. The dependence of \( |b(\omega_r)|^2 \) on the number of electrons is \( \langle |b(\omega_r)|^2 \rangle = N_e (1 + F(\omega_r) N_e) \), where \( F(\omega_r) \) is the bunch form factor. The intensity term, quadratic in \( N_e \), is called the Coherent Spontaneous Emission (CSE). For \( \sigma_z > \lambda_r \), as in the case of the LCLS, and for a regular charge distribution, \( F(\omega_r) N_e^2 \ll 1 \). Thus, this term can be neglected in the LCLS case. For a long undulator, the electromagnetic field will grow exponentially along the undulator axis, \( z \), with growth rate, \( 1/L_G \), and the intensity, \( I \), will grow as

\[
I = a |b(\omega_r)|^2 e^{2z/L_G}
\]

until saturation is reached. Since the initial bunching is a random quantity, the intensity will vary each time a bunch is sent through the undulator. The average value of the saturation power is still given by Eq. 4.2.4 and the line width by \( 1/N_u \), as in the case of the spontaneous radiation. If the full line width is detected, the distribution of intensities can be reached by a gamma function [23].

\[
p(I) = \frac{M^M}{\Gamma(M)} \langle I \rangle^{-M-1} \exp(-M I / \langle I \rangle),
\]

with a relative standard deviation given by \( 1/\sqrt{M} \), where the quantity \( M \), which can be described as the number of degrees of freedom of the photon system, is

\[
M = \frac{\sqrt{2\pi \sigma_z}}{2\pi L_c} \frac{\Omega_d}{\Omega_c},
\]

where \( L_c \) is the cooperation length, \( \Omega_d \) the solid angle defined by the detector, and \( \Omega_c \) the coherent solid angle. When the observed frequency spread is larger than the FEL line, the
cooperation length is \( L_c = 2L_g(\lambda_r/\lambda_n) \), the slippage in one field gain length. In the LCLS case, and assuming \( \Omega_d = \Omega_n \), \( M = 166 \) and the relative standard deviation of the intensity distribution is expected to be about 7.7%.

The possibility of operating an FEL in the short wavelength region follows from the favorable scaling laws for this system [3]. To obtain and discuss the FEL scaling laws let us write the FEL parameter, \( \rho \), using two quantities, the electron beam emittance, \( \varepsilon \), and the longitudinal brightness, \( B_L \), to characterize the electron beam. The longitudinal brightness is defined as

\[
B_L = \frac{eN_c c}{2\pi \sigma \varepsilon / E},
\]

where \( \sigma / E \) is the rms relative energy spread. The quantity in the denominator of Eq. 4.2.13 is the beam longitudinal phase-space area. The conditions for the validity of the 1-D model, Eq. 4.2.5, 4.2.6, 4.2.7, must all be satisfied assuming \( \sigma / E / \rho / k_i, \varepsilon_n / k_2 \lambda / 4\pi \). The last condition, Eq. 4.2.7, on the optical focusing can be shown to follow from the other two. Using these conditions, the FEL parameter can be written in terms of longitudinal brightness,

\[
\rho = \frac{1}{k_1 k_2 B_L}. \tag{4.2.14}
\]

To obtain a value of \( \rho \) of the order of 5 \( \times \) 10^{-4}, the minimum compatible with a practical undulator, a longitudinal brightness of the order of 1000 \( \mu \) is needed. This value has been exceeded in photoinjector electron sources [30]. The scaling law Eq. 4.2.13 does not depend directly on the radiation wavelength, but only indirectly through the requirements, as given in Eq. 4.2.6. This weak dependence of the FEL scaling law on the radiation wavelength is an important property, and can be used to develop an x-ray FEL. The simple analysis discussed here can be used for an initial design of an x-ray FEL. More detailed calculations, including effects like diffraction and undulator errors, must be performed to predict the system performance. See Chapter 5.

### 4.3 References


11 P. Csonka, Part. Acc. 8, 225 (1978).


27 I. Benzvi, private communication.


30 M. Hogan, R. Sheffield, et al., private communication.
**5 FEL Parameters and Performance**

**TECHNICAL SYNOPSIS**

The FEL theory outlined in Chapter 4 is strictly valid in the one-dimensional approximation. The FEL parameter optimization and performance characterizations that are described in Chapter 5 are based on three-dimensional theory and computer models. The investigation led to a selection of the best parameters and to a study of the sensitivity to changes in values of accelerator components and beam characteristics and to unavoidable imperfections in the settings of the beam characteristics, magnetic and mechanical components and electron beam monitoring. The focusing of the electron beam plays an important role in the production of the FEL radiation. The LCLS undulator optics has been optimized in terms of its focusing lattice and strength. The electron optics consists of FODO cells, with a cell length of 4.32 m. Focusing is obtained by placing permanent magnet quadrupoles in the interruptions of the undulator sections. Each interruption is 23.5 cm long, and also includes beam position monitors and vacuum ports. The correction of the electron orbit is obtained by a small lateral displacement of the quadrupoles; the total movement is 0.5 mm with a resolution of 1 µm. Simulations indicate that the FEL radiation saturates at a length of ~90 m. The proposed LCLS undulator has a magnetic length of 100 m, since it is a requirement that the FEL operate in the saturation regime. This fact not only gives the maximum output power, but also reduces the pulse-to-pulse fluctuations of the radiation.

The possibility of changing (i.e., lowering) the output power was investigated. This may be desirable if the peak power on the sample is excessive and if required for experimental purposes. The reduction in power, by either reducing the electron current or by increasing the beam emittance, is accompanied by an increase in fluctuations of the output power due to fluctuations in the beam characteristics from pulse-to-pulse, since the FEL no longer operates in the saturation regime. For this reason, the best way to reduce the output power is by placing an FEL absorption cell in the path of the radiation, as discussed in Chapter 10.

**5.1 Introduction**

The FEL theory outlined in Chapter 4 is strictly valid in the one-dimensional approximation. Although a three-dimensional theory has been developed [1,2,6,7] and allows us to study the effect of parameters like energy spread, emittance, and diffraction. The effects of magnet errors, misalignment, and lumped alternating gradient focusing can not be treated analytically. For this reason, after one has used the 3-D theory to search and optimize the
fundamental parameters of an FEL, the most important tools for a subsequent and more precise study and optimization are the computer simulation codes. There is no single code at present that can handle all the perturbations that can affect performance. Simulations for this design report used the 3-D codes GINGER [3] (time dependent), FRED-3D [4] (magnet error analysis, beam position control), and TDA3D [5] (effects of lumped focusing). The codes GINGER and FRED-3D were developed about 10 years ago at LLNL for the ELF experiment. They have been extensively cross-checked with experimental results from ELF and are under full control of the author. TDA3D, originally conceived and implemented at MIT, was developed during the last 8 years. This section describes the simulations and the process that led to the selection of the parameter and the sensitivity of the performance to deviations from optimum operating conditions. This section is organized as follows:

- Section 5.2 describes the method used in the analysis.
- Section 5.3 and 5.4 describe the process that led to the choice of the focusing system in the undulator.
- Section 5.5 discusses the sensitivity of the performance to various parameters.
- Section 5.6 describes the structure of the FEL radiation.
- Section 5.7 describes the effect of deviation from the ideal electron orbit.
- Section 5.8 discusses the effect of the emission of the spontaneous radiation on the FEL dynamics.
- Section 5.9 considers ways to control the output power.
- Section 5.10 discusses a realistic beam distribution, as delivered from the linear accelerator.
- Section 5.11 discusses an optical klystron configuration, a method suggested to shorten the undulator.

The LCLS parameters are listed in Appendix A.

### 5.2 Parameter Optimization

The design of the LCLS FEL configuration greatly benefited from an analytical function of a few independent parameters describing FEL physics in the exponential gain regime, based on 3-D FEL theory developed between 1985 and 1995. In 1985, K.-J. Kim developed a dispersion relation which included betatron oscillations [1]. However, this equation did not take all the effects into account and could not be solved. In 1989 L.H. Yu, S. Krinsky and R.L. Gluckstern [6] derived the complete dispersion relation from the Vlasov-Maxwell equations, and solved it for a parabolic electron distribution (waterbag model). They were the first to discover the scaling property of the solution i.e., that the gain length is a universal
function of three dimensionless variables (emittance-to-wavelength ratio, scaled electron focusing strength, and scaled electron-energy spread) and a dimensionless scaling parameter.


\[ F(\eta_d, \eta_\varepsilon, \eta_\gamma) = \frac{L_{G,1D}}{L_G} = \frac{1}{1 + \eta} \]

fitted a 19-parameter polynomial to the function \( \eta \) and published its coefficients [2]

\[
\eta = a_1 \eta_d^{a_2} + a_2 \eta_\varepsilon^{a_4} + a_3 \eta_\gamma^{a_5} + a_4 \eta_d^{a_6} \eta_\varepsilon^{a_7} + a_5 \eta_d^{a_8} \eta_\varepsilon^{a_9} + a_6 \eta_d^{a_{11}} \eta_\varepsilon^{a_{12}} + a_7 \eta_d^{a_{13}} \eta_\varepsilon^{a_{14}} + a_8 \eta_d^{a_{15}} \eta_\varepsilon^{a_{16}} + a_9 \eta_d^{a_{17}} \eta_\varepsilon^{a_{18}} \eta_\gamma^{a_{19}}
\]

(5.2.1)

\( L_G \) and \( L_{G,1D} \) are the three and one-dimensional gain length, respectively. The 19 fit coefficients, \( a_i \), are shown in Table 5.2-1.

<table>
<thead>
<tr>
<th>Table 5.2-1. Fit coefficients.</th>
</tr>
</thead>
<tbody>
<tr>
<td>a_1</td>
</tr>
<tr>
<td>------</td>
</tr>
<tr>
<td>0.45</td>
</tr>
<tr>
<td>a_{11}</td>
</tr>
<tr>
<td>0.95</td>
</tr>
</tbody>
</table>

The scaling parameters express the deviation from the 1-D condition due to diffraction, \( \eta_d \), emittance, \( \eta_\varepsilon \) and energy spread, \( \eta_\gamma \):

\[
\eta_d = \frac{L_{G,1D}}{L_R} ; \quad \eta_\varepsilon = \frac{L_{G,1D}}{L_R} \frac{4\pi c_n}{\lambda_r \gamma} ; \quad \eta_\gamma = \frac{L_{G,1D}}{\lambda_u} \frac{\sigma_E}{E} .
\]

(5.2.2)

Using the 1-D gain length

\[
L_{G,1D} = \frac{\lambda_u}{4\pi \sqrt{3} \rho}
\]

and the total peak beam power

\[
P_{b, pk} = \frac{L}{pk} \gamma mc^2 / e
\]

the peak power at saturation, \( P_{sat} \), can be approximated:

\[
P_{sat} \approx 1.6 \rho \left( \frac{L_{G,1D}}{L_G} \right)^2 P_{b, pk}
\]

(5.2.3)
The results of the fit formula have been checked against 3-D simulation codes and are in excellent agreement. Practical limits exist for a number of parameters: $g$ (undulator gap) $\geq 6$ mm, $E \leq 15$ GeV, $I_{pk} \leq 3400$ A, $\sigma_E \geq 0.0002$ and $L_u \geq 100$ m.

This report uses the terms “slice emittance,” “projected emittance,” and “nominal emittance” to characterize the normalized emittance of the LCLS electron beam. The need for different emittance definitions comes from the fact that electromagnetic fields, produced by space charge, chamber impedance, and coherent synchrotron radiation, create a dependence of the transverse position of the beam centroid on its longitudinal position within the bunch while the local electron density remains unaffected.

The total phase space distribution integrated over the entire bunch along the longitudinal axis is characterized by the term “projected emittance” and will generally increase during beam transport while the electron density at a given bunch location is likely to stay constant.

During the FEL interaction, inside the LCLS undulator, electrons that are further apart than one slippage distance, $L_{slip} = N_u \lambda_s$, will not interact with each other. To understand the production of FEL radiation, it is therefore useful to introduce the term “slice emittance,” as the emittance of the phase space distribution integrated over a distance $L_{slip}$ along the bunch inside the undulator. For the LCLS, simulations and analytical calculations indicate that the increase in slice emittance during beam transport will be negligible. The fact that different slices at different positions in the bunch will arrive with relative transverse offset to each other effects overall beam brightness but not peak FEL radiation power.

Expected lower limits of projected emittance and slice emittance are being reduced as gun and beam transport R&D efforts progress. In order to have a fixed working number for component design and simulations, the LCLS design team decided early on to work with a “nominal emittance.” The nominal emittance was set to a value of 1.5 $\pi$ mm mrad, close to what is expected as projected emittance at the entrance of the undulator. Its use in FEL calculation constitutes a worst case scenario for the FEL saturation length.

A planar hybrid undulator is assumed; this choice is discussed and justified in Chapter 8. Within the above constraints, the optimum operating point (Table 5.2-2) can be found using the fit-formula. Table 5.2-2 lists the parameters that were found to be optimal for the proposed range of LCLS operations.

### 5.3 Electron Beam Focusing

As the electron beam is transported through the undulator, transverse focusing is applied to keep the beam size approximately constant. A planar undulator focuses in the plane perpendicular to the wiggle motion only (in this report, called x-plane, since the undulator, as shown in Chapter 8, has a horizontal field). The focusing strength can be expressed by specifying the “natural” beta-function of the focusing system that is intrinsic to an undulator made of parallel poles.
\[ \beta_{x}^{nat} = \sqrt{2\gamma / k_{w}K}. \]  

(5.3.1)

Table 5.2-2. Basic LCLS parameters at limits of operational range.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
<td>4.54</td>
<td>14.35</td>
<td>GeV</td>
</tr>
<tr>
<td>(\lambda_r)</td>
<td>15</td>
<td>1.5</td>
<td>Å</td>
</tr>
<tr>
<td>(\lambda_u)</td>
<td>0.03</td>
<td>0.03</td>
<td>m</td>
</tr>
<tr>
<td>(g)</td>
<td>6</td>
<td>6</td>
<td>mm</td>
</tr>
<tr>
<td>(B_w)</td>
<td>1.32</td>
<td>1.32</td>
<td>T</td>
</tr>
<tr>
<td>(K)</td>
<td>3.71</td>
<td>3.71</td>
<td></td>
</tr>
<tr>
<td>(\varepsilon_{n})</td>
<td>2.0</td>
<td>1.5</td>
<td>mm mrad</td>
</tr>
<tr>
<td>(I_{pk})</td>
<td>3400</td>
<td>3400</td>
<td>A</td>
</tr>
<tr>
<td>(\sigma_{E}/E)</td>
<td>0.00068</td>
<td>0.00021</td>
<td></td>
</tr>
</tbody>
</table>

By appropriately shaping the pole faces, half the focusing can be directed into the wiggle plane. This type of constant focusing in both planes is called Ted-Pole Focusing [4].

\[ \beta_{x,y}^{TP} = \beta_{x}^{nat} \sqrt{2}. \]  

(5.3.2)

The amount of focusing that can be obtained this way is often smaller than required for optimum FEL performance, especially for high energy and short wavelength applications.

5.3.1 Lattice Design Criteria

The criteria that led to the selection of the average \(\beta\)-function, cell spacing, and quadrupole strength were established by first determining the optimum value of the average \(\beta\)-function, and, after that, the maximum tolerable amplitude of the modulation of the \(\beta\)-function. See Fig. 5.3-1.

5.3.2 Focusing Method (Lattice)

A focusing system stronger than that given by Ted-Pole focusing can be obtained with external quadrupole fields. Possible lattice choices are two (FODO), three (Triplet), or more quadrupole magnets per unit cell. A FODO lattice was selected based on simplicity of design and on the cost-related desire to keep the number of magnets and associated instrumentation small. With quadrupole focusing, the \(\beta\)-function is no longer independent of \(z\) and its variation along \(z\), known as the modulation amplitude, defined as

\[ \Delta \beta_{x,y} / \beta_{x,y} = (\beta_{x,y,\text{max}} - \beta_{x,y,\text{min}}) / \beta_{x,y}, \]

causes the beam envelope to vary also. Ted Scharlemann [4] observed that quadrupole focusing introduces an oscillation in the longitudinal phase of the electrons with respect to the ponderomotive potential well, while
natural focusing maintains a constant phase. Scharlemann found that for the cases that he examined, this phase modulation could lead to de-trapping of particles and thus reduce FEL efficiency. Yu et al. [8], point out that such a reduction in gain can indeed occur for tapered wiggles in which most of the output power is provided by trapped electrons, but that the same effect can actually be beneficial in the exponential gain regime. Here, the reduction of the dependence of the longitudinal velocity on betatron oscillation amplitudes in the case of alternating-gradient focusing tends to offset the effect of longitudinal velocity modulation.

![Graph](image)

**Figure 5.3-1.** Power at saturation, $P_{\text{sat}}$, and saturation length, $L_{\text{sat}}$, in percent of their optimum values, as a function of the average $\beta$-function at 0.15 nm and 1.5 nm radiation wavelength.

### 5.3.3 Optimum Beam Size

The smaller the beam size, the larger the electron density and the value of the FEL parameter $\rho$ and the better the FEL performance. 3-D effects, especially diffraction, will eventually lead to a decrease in FEL performance when the beam size becomes too small. **Fig. 5.3-1** shows relative FEL saturation power and saturation length as a function of the average $\beta$-function in the undulator for 1.5 Å and 15 Å.

At every energy in the proposed range between 4.54 GeV (15 Å) and 14.35 GeV (1.5 Å), the minimum saturation length and the maximum saturation power occur at different values of the average $\beta$-function. While there is plenty of saturation power predicted for the LCLS, the estimated saturation length at the shortest wavelength is longer than desired. It is therefore important at that wavelength to choose the $\beta$-function related to the minimum
saturation length. This minimum occurs at a $\beta$-function of 18 m as is shown in Fig. 5.3-1. This value was chosen for the 14.35 GeV end of the LCLS operations range.

The $\beta$-function value at which minimum saturation length occurs decreases with energy to reach about 3.4 m at 4.54 GeV. As discussed below, the $\beta$-function value chosen for the LCLS at 4.54 GeV is 6 m, which can be reached from the high-energy value with constant gradient focusing. At this $\beta$-function value the saturation power is at its maximum, but the saturation length is about 8% larger than the minimum value, which is much shorter at that energy than at 14.35 GeV. The deviation from the optimum is therefore unimportant at that point.

Note that if Ted-Pole focusing is used alone, the $\beta$-function would be 70 m at 14.35 GeV and 22 m at 4.54 GeV. This situation would give a 22% increase in saturation length at 14.35 GeV.

### 5.3.4 Tolerable Beta-Function Modulation Amplitude

In storage rings and beam transport applications, the strength of the quadrupoles are often optimized to reduce the maximum value of the $\beta$-function for a given FODO cell spacing. In an FEL undulator, the cell spacing should be optimized to reduce the maximum $\beta$-function for a given value of the average $\beta$-function. The strength of the quadrupoles does not strongly depend on the cell spacing as long as the cell spacing is less than about half the targeted average $\beta$-function. See Fig. 5.3-2. For the LCLS, if the FODO cell length is shorter than about 3 m, the required integrated gradient is the same over the 5 to 15 GeV energy range, thus making it possible to use permanent magnet quadrupoles.

![Figure 5.3-2.](image)

**Figure 5.3-2.** Integrated field gradient required to maintain a constant average $\beta$-function in a FODO cell as a function of cell length. The average $\beta$-function values are 18 m at 14.35 GeV and 6 m at 4.54 GeV. 1: Maximum spacing for which both $\beta$-functions can be achieved with same focusing gradient. 2: Maximum spacing for which average $\beta$-function of 6 m can be achieved.
For longer cell lengths, the quadrupole strength would have to be adjusted to keep the β-functions at their optimum values. The β-function modulation amplitude increases with the FODO cell length (see Fig. 5.3-3). The largest cell spacing possible for a given value of the average β-function is $L_{\text{FODO}}^{\text{max}} = \beta_{xy}$ with a phase advance of 90 degrees per cell and a modulation amplitude of about 141%. Small modulation amplitudes could be achieved with small FODO cell lengths but at the expense of shorter quadrupoles with stronger quadrupole gradients, more magnets, and higher overall cost. Long FODO cell lengths are desirable. The question of the maximum allowable FODO cell length can only be answered by computer simulations. The effect of β-function modulation on FEL performance was studied with a version of the TDA3D code as presently maintained at DESY [9]. This version allows the possibility of using lumped focusing optics [10]. The TDA3D analysis carried out so far predicts that the effect of β-function modulation will be rather small. At the largest cell length that would still allow to obtain the optimum β-function at the low energy end, the increase in saturation length is a few percent at 14.35 GeV (with a β-modulation < 30 %) and slightly above 10% at 4.54 GeV (β-modulation ~ 140%). As pointed out above, the increase of saturation length at the lower energy is not as critical, since at that operating point the saturation length is about one-third of the length of the undulator. Based on these considerations, a 4 m cell length was chosen, which still permits us to obtain an average β-function of 6.3 m at 4.54 GeV with permanent magnet quadrupoles. If one uses permanent magnet quadrupoles, as proposed in Chapter 8, the lack of tunability increases the saturation length at the longer wavelength end by about 8%. Here, however, the gain length is so much shorter as to make this not a serious consequence. One additional point to consider is that strong quadrupole focusing causes the longitudinal velocity of the electrons to change as they execute betatron oscillations away from the axis. This effect is negligible for the LCLS.

Figure 5.3-3. β-function modulation amplitude for an average β-function of 18 m at 14.35 GeV and 6.3 m at 4.54 GeV as a function of FODO cell spacing. 1: Maximum spacing for which both β-functions can be achieved with same focusing gradient. 2: Maximum spacing for which average β-function of 6.3 m/rad can be achieved.
5.4 Undulator Sections

The LCLS undulator design uses a modular layout. Identical short sections are combined to form the 100 m device. Analytical studies and computer simulations found the effect of separations on FEL performance to be small [11]. See Table 5.4-1.

Table 5.4-1 summarizes the FRED-3D simulations for the LCLS: \( L_{\text{sat}} \) increases by 6.5 m when a total of 5.17 m of drifts is inserted, each 23.5 cm long. The increase in actual undulator length needed to saturate is therefore only 1.33 m. Separations have to be designed to allow the electron bunches to slip an integral number of wavelengths behind the electromagnetic wave. This can be accomplished by choosing the correct length for the drift space [an integral multiple of \( \lambda_u (1 + K^2 / 2) \), which is 23.5 cm for the LCLS] or by adding a phase shifter that corrects the slippage for a separation of different length. The LCLS design now includes 23.5 cm long separations between undulator sections. The section length (half FODO cell) was chosen to be 1.92 m (64 periods) so that every quadrupole of the 4.32 m FODO cell lattice, together with beam position monitors, orbit correctors and other components, will fit into the separations.

<table>
<thead>
<tr>
<th>Separation Length</th>
<th>Total Inserted Drift to Saturation</th>
<th>( L_{\text{sat}} )</th>
<th>( P_{\text{sat}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001 m</td>
<td>0.022 m</td>
<td>94.5 m</td>
<td>14 GW</td>
</tr>
<tr>
<td>0.235 m</td>
<td>5.170 m</td>
<td>101 m</td>
<td>13.2 GW</td>
</tr>
</tbody>
</table>

5.5 Parameter Sensitivities

Table 5.5-1 shows the sensitivities of the saturation power and length to various FEL parameters at 1.5 Å (14.35 GeV). Notice the strong sensitivities of the saturation length to peak current and normalized emittance. Fig. 5.5-1 shows how peak current can be traded against normalized emittance when keeping the saturation length constant.
Table 5.5-1.  LCLS sensitivities to input parameters.

\[
\begin{align*}
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta \lambda_x}{\lambda_x} &= 1.8 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta \lambda_y}{\lambda_y} &= -0.7 \\
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta \lambda_y}{\lambda_y} &= 4.9 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta \lambda_x}{\lambda_x} &= -0.3 \\
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta a_u}{a_u} &= 2.2 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta a_u}{a_u} &= -0.5 \\
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta \beta_{x,y}}{\beta_{x,y}} &= 0.5 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta \beta_{x,y}}{\beta_{x,y}} &= 0.0 \\
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta \gamma}{\gamma} &= 2.2 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta \gamma}{\gamma} &= -0.5 \\
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta \sigma_y}{\sigma_y} &= -0.6 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta \sigma_y}{\sigma_y} &= 0.2 \\
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta \epsilon_n}{\epsilon_n} &= -1.9 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta \epsilon_n}{\epsilon_n} &= 1.0 \\
\frac{\Delta P_{sat}}{P_{sat}} / \frac{\Delta I_{pl}}{I_{pk}} &= 2.0 & \frac{\Delta L_{sat}}{L_{sat}} / \frac{\Delta I_{pl}}{I_{pk}} &= -0.6
\end{align*}
\]

Figure 5.5-1.  Peak current vs. normalized emittance at constant saturation length.
5.6 Temporal Structure of Laser Power

Figure 5.6-1 shows the simulation results obtained with the time-dependent computer code GINGER. Self-Amplified Spontaneous Emission [12,13] relies on longitudinal electron density fluctuations (shot-noise bunching). Regions where the initial bunching is larger produce more radiation, thus accelerating the lasing process. Due to slippage during the transport through the undulator, those regions will expand to build spikes on the scale of 

\[ 2\pi L_c = 4\pi n_c \lambda_r / \lambda_w \] [14]. The time-dependent simulations clearly show this phenomenon. For the LCLS, the spike structure length is of the order of 0.3 µm at 1.5 Å wavelength and 5 µm at 15 Å.

---

Figure 5.6-1. FEL output power pattern along the bunch.
5.7 Effect of Deviations from the Ideal Electron Trajectory

This section discusses the sensitivity of the FEL performance on the imperfections of the electron orbit in the undulator.

5.7.1 Undulator Steering and Corrector Description

As shown in detail in Chapter 8, the design of the undulator is a planar NdFeB hybrid structure with 1.5 cm long undulator poles (i.e., 3 cm period lengths) and a full gap height of 6 mm. 64 undulator periods form a 1.92 m long segment. Segments are separated by 23.5 cm long gaps that accommodate electron beam position monitors as well as 12 cm long permanent magnet quadrupoles with a gradient of 45.5 T/m. The quadrupoles are used for two purposes, electron beam focusing and steering. Steering is achieved by adjusting the quadrupoles’ x and y positions with stepper motor based systems that allow a total movement of 0.5 mm with a step size of 1 \( \mu \text{m} \). The undulator is built from 52 segments resulting in a total length of 111.825 m, of which 99.84 m is magnet length.

5.7.2 Magnetic Field Errors

One of the most significant sources of FEL performance reduction comes from errors in the on-axis magnetic field of the undulator as well as from dipole components of transversely misaligned quadrupoles. In an ideal magnetic field, the electron beam would execute a sinusoidal movement in the plane perpendicular to the undulator field axis. Error fields can arise from (1) iron pole, permanent magnet, and quadrupole positioning/orientation errors, (2) permanent magnet strength and global/local easy-axis misorientation errors, and (3) iron non-uniformities, including saturation effects. Symmetric field errors \( \Delta B_y(z) \) are perpendicular to the midplane and give a horizontal angular displacement to the beam. Antisymmetric field errors are parallel to the midplane, causing vertical beam steering. Positioning errors of the magnetic structure or variations of the period length give rise to systematic phase errors. If the electron beam is misaligned with respect to the undulator magnetic structure or if the undulator segments are not coaxial with the beam steering, errors can also arise.

5.7.3 Trajectory and Error Control Requirement from Simulations

The effect of magnet errors on the FEL performance has been studied with the FRED-3D simulation code on the NERSC computer systems at LLNL and LBNL. FRED-3D simulates the interaction between the electron beam and the optical field in the undulator. The effects of random pole-to-pole errors in the undulator magnetic field on the centroid motion of the electron beam and on the relative electron-to-radiation phase are included. In each half-period, a transverse momentum increment corresponding to the magnetic field error at that magnetic pole is added to the motion of each particle. The field errors are chosen from a truncated Gaussian distribution. The rms fractional field error and the truncation level are specified as input parameters. Since FRED-3D does not handle lumped quadrupoles or
quadrupole misalignments, quadrupole focusing is implemented as distributed constant gradient focusing. The error field amplitudes from quadrupole misalignments were assumed to be of the same order as the simulated pole-to-pole errors. To estimate the width of the distribution of saturation length and saturation power, a number of different simulation runs were done each with a different set of seed numbers for the generation of magnet errors, initial particle, and seed laser field distribution.

5.7.4 Magnetic Field Error Tolerances

The residual random walk of the electron beam generated by field errors reduces the overlap between the electron and photon beams and also causes dephasing of the electrons with respect to the FEL ponderomotive potential wells. Simulation results shown in Fig. 5.7-1 were obtained with FRED-3D using error-free trajectory corrections spaced 2 m apart. They indicate a threshold in the sensitivity of the saturation length to rms magnet errors. Below an rms distribution of about 0.1%, magnet errors have little or no influence on saturation length. Above the threshold, saturation length increases with error amplitude; therefore, the rms magnet error is specified to 0.1%.

![Graph showing saturation length as a function of RMS magnet error.](image)

Figure 5.7-1. Saturation length as a function of the rms of the magnet error distribution. The line connects the data points.

5.7.5 Steering Algorithm

The random walk can be partially corrected in FRED-3D by introducing “steering stations,” at which the position of the electron beam is measured and a transverse momentum kick is applied to steer the electron beam onto the axis of the next steering station. The position measurement is assumed to be imperfect, with specifiable errors in the accuracy
with which the beam position monitors are aligned and the accuracy with which they can measure the beam position. The positions of steering stations along the undulator axis and the magnitude of the steering errors are inputs to the code. FRED-3D code uses a point-to-point correction steering algorithm.

5.7.6 Steering Error Tolerance

A steering correction that is imprecise because of misalignment errors in the beam position monitors, noise in the processing electronic, or corrector resolution, may reduce the FEL performance. Fig. 5.7-2 shows the effect of four different rms steering error amplitudes on LCLS output power as result of simulations. For the 1.5 Å case (14.35 GeV) with 5 m steering station separation, the absolute reading accuracy of the beam position monitors should be better than 5 µm.

![Graph showing the effect of steering errors on saturation length](image)

**Figure 5.7-2.** Saturation length as a function of the rms of the distribution of the magnet errors at 1.5 Å. In the simulation the orbit was corrected with steering magnets placed 5 m apart.

5.7.7 Optimum Steering Station Separation

If the steering errors become significant, the steering process can degrade as well as improve performance. Fig. 5.7-3 and Fig. 5.7-4 show saturation length and saturation power, respectively, as a function of steering station separation for the 1.5 Å (14.35 GeV), as obtained with the FRED-3D simulations.
Close to optimum performance can be expected if the steering station separation is smaller than 15 m. The trajectory correction process becomes insufficient for larger spacings. For shorter spacing the effect of very large steering errors can reduce the performance. The distance between steering stations should be larger than 4–5 m when the inaccuracy in
determining the electron orbit (due to finite beam position monitor resolution and residual calibration errors) is of the order of $5–10 \mu m$. If the monitors’ accuracy is better or equal than $2 \mu m$, then the separation between correctors could be as close as 2 m. This result also yields the tolerance for the deviation from perfect overlap between the electron and photon beams at those stations. Although this absolute accuracy seems difficult to achieve, it will be shown in Section 8.5 that it is obtainable with a beam-based alignment technique.

### 5.7.8 Undulator Matching Tolerances

The match of the electron trajectory at the entrance and end of each undulator section can be done by adding a series of $\frac{3}{4}$, $\frac{1}{2}$ and $\frac{1}{4}$ period long undulator blocks before the first and after the last period of a 4.32 m long section. The “matching sections,” which are off resonance, do not contribute to lasing but will add a small phase shift, which reduces the space of the actual separation by a few millimeters. Estimates based on beam size arguments indicate that position and angle errors of about $5 \mu m$ and $1 \mu rad$, respectively, should not effect FEL performance. These tolerances can be achieved with state-of-the-art instrumentation (see Section 7.7).

### 5.8 Emission of Spontaneous Radiation

Due to the rather large value of the undulator parameter, $K$, synchrotron radiation from the electron beam in the FEL undulator not only occurs at the resonant frequency and its harmonics but over a wide continuous spectrum of frequencies. As long as micro-bunching can be neglected, the total peak synchrotron power radiated by a bunch is given by [15]

$$
\hat{P}_{spont} = Z_o I_{pk} e^{\frac{2\pi c}{6\lambda u}} \gamma^2 K^2 N_u = 0.663 \cdot 10^{-15} \cdot \frac{s}{T^3 m^3} \cdot (E_e / e)^2 B_u^2 L_u I_{pk}.
$$  \hspace{1cm} (5.8.1)

The power from spontaneous radiation grows linearly along the undulator up to $P_{spont} = 80 \text{ GW}$ after 100 m at 1.5 Å. This is more than eight times as much as can be expected for the fundamental peak of the coherent FEL radiation. While this large amount of incoherent radiation by itself makes the LCLS the brightest x-ray source available, it is undesirable when the LCLS is to be tuned for FEL lasing. Not only can it cause problems for the x-ray optics, but it also reduces the average electron energy, increases the incoherent energy spread and emittance, and adds extra heat load to components that might be installed along the undulator for diagnostics and beam filtering purposes. The detrimental effects on the electron beam need to be taken into account during FEL simulations, but the present computer codes are not yet prepared to handle them.

#### 5.8.1 Average Energy Loss

The average energy loss $\Delta<\gamma>$ from spontaneous synchrotron radiation for each electron is
\[
\Delta \langle \gamma \rangle = -\frac{\hat{P}_{\text{spout}}}{I_{pk}} \frac{e}{mc^2} = -\frac{1}{3} \gamma^2 K^2 k_u^2 \lambda_u,
\]

(5.8.2)

where \( k_u = 2\pi / \lambda_u \), which causes the electrons to move away from the resonance. The resonant frequency of the radiation can be kept constant by reducing the magnetic field along the undulator (tapering). The amount of field taper required is

\[
\Delta B_u / B_u = \frac{1 + K^2 / 2}{K^2 / 2} \Delta \langle \gamma \rangle / \langle \gamma \rangle
\]

(5.8.3)

The actual required change in magnetic field is very small:

<table>
<thead>
<tr>
<th>( \lambda_r )</th>
<th>( I_{pk} )</th>
<th>( \Delta &lt; \gamma &gt; )</th>
<th>( &lt; \gamma &gt; )</th>
<th>( \Delta &lt; \gamma &gt; / &lt; \gamma &gt; )</th>
<th>( \Delta B_u / B_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15 nm</td>
<td>3400 A</td>
<td>-46</td>
<td>28077</td>
<td>-1.64 \times 10^{-3}</td>
<td>-1.9 \times 10^{-3}</td>
</tr>
<tr>
<td>1.5 nm</td>
<td>3400 A</td>
<td>-1.38</td>
<td>8879</td>
<td>-1.56 \times 10^{-4}</td>
<td>-1.8 \times 10^{-4}</td>
</tr>
</tbody>
</table>

At the high end of the energy range, the field reduction needs to be less than twice the rms magnet error tolerance after 100 m, while at the low end the requirement is one-fifth the rms error tolerance after 30 m.

### 5.8.2 Energy Spread Increase

The statistical nature of the synchrotron radiation process increases the incoherent energy spread of the electrons by [16]:

\[
d < \Delta \gamma^2 > \approx \frac{14}{15} \frac{\lambda_c}{2\pi} r_e \gamma^4 k_u^3 K^2 F(K) L_u
\]

(5.8.4)

where \( F(K) \) is \( \approx 1.4K \) for \( K >> 1 \). \( \lambda_c / 2\pi \approx 3.862 \times 10^{-13} \) is the Compton wavelength. The largest influence from this effect on FEL performance for the LCLS occurs at the high-energy end and is shown in Table 5.8-1.

<table>
<thead>
<tr>
<th>( \Delta \gamma )</th>
<th>( L_u )</th>
<th>( \sqrt{d &lt; \Delta \gamma^2 &gt;} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>28077</td>
<td>100 m</td>
<td>6.5</td>
</tr>
<tr>
<td>8879</td>
<td>80 m</td>
<td>0.36</td>
</tr>
</tbody>
</table>

There, the energy spread increase due to incoherent synchrotron radiation will reach the level of the initial rms energy spread which is \( \sigma_{\gamma} = 6 \). This should not affect the LCLS performance significantly. Simulations codes presently available to us do not handle
spontaneous synchrotron radiation, but a 1-D code was recently developed at DESY to study this effect. Running this code with the LCLS parameters showed no reduction in performance [17].

5.8.3 Emittance Increase

Spontaneous synchrotron radiation can cause an increase in rms beam emittance if the radiation occurs at a location with a finite dispersion function [18]. The dispersion function originates in the undulator, is of the order of the wiggle amplitude (∼1 µm), and has a negligible effect on the emittance.

5.9 Output Power Control

For applications that use the x-rays produced by the FEL, it is important that the output power levels be controllable (see Chapter 10). The feasibility of changing the output power by varying the peak current or by the use of a magnetic phase shifter was studied. The conclusion is that neither method is promising. For this reason, a gas absorption cell after the FEL undulator will be used for this purpose.

5.9.1 Peak Current

By changing peak current, either by reducing the amount of charge per pulse or by increasing the pulse length, one can control (reduce) the FEL production over many orders of magnitude. Unfortunately, this action not only reduces the saturation power, but it also increases the saturation length. For reasons of cost optimization, the undulator will be designed to be not much longer than the expected saturation length at the highest achievable peak current. Reduction of the peak current at the highest energy (and shortest wavelength) will move the saturation point beyond the end of the undulator. The FEL output will then be determined by the exponential gain regime, resulting in much higher pulse-to-pulse variations. According to the 1-D FEL theory, the derivative of the peak power with respect to the peak current \( \frac{dP_{sat}}{dI_{pk}} = (1 + z/(3L_G))P_{sat} / I_{pk} \) in the exponential gain regime. The sensitivities can be defined as

\[
\frac{\Delta P_{sat}}{\Delta I_{pk}} / I_{pk} = 4 / 3
\]

(5.9.1)

\[
\frac{I_{pk}}{P_z} \rightarrow \frac{\Delta P_z}{P_z} / I_{pk} = 1 + \frac{1}{3} \frac{z}{L_G}
\]

(5.9.2)

In the exponential gain regime, the sensitivity to fluctuations in peak current increases, as do the sensitivities to fluctuations in normalized emittance and energy spread. The relative sensitivities as obtained from GINGER simulations at 1.5 Å are shown in Table 5.9-1.
Table 5.9-1.  Sensitivities of LCLS performance to electron beam parameters at the end of the 100 m long undulator in the exponential gain regime (at $z/L_G \approx 11.3$ for $I_{pk} = 1500$ A) and at saturation ($I_{pk} = 3400$ A).

<table>
<thead>
<tr>
<th>Sensitivity at $I=3400$ A</th>
<th>Sensitivity at $I=1500$ A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation</td>
<td>Exponential Gain Regime</td>
</tr>
<tr>
<td>$\Delta P / P = \Delta I_{pk} / I_{pk}$ = 1.8</td>
<td>$\Delta P / P = \Delta I_{pk} / I_{pk}$ = 6.4</td>
</tr>
<tr>
<td>$\Delta P / P = \Delta \epsilon_n / \epsilon_n$ = -1.6</td>
<td>$\Delta P / P = \Delta \epsilon_n / \epsilon_n$ = -9.3</td>
</tr>
<tr>
<td>$\Delta P / P = \Delta \sigma_y / \sigma_y$ = 0.2</td>
<td>$\Delta P / P = \Delta \sigma_y / \sigma_y$ = -1.8</td>
</tr>
</tbody>
</table>

The above numbers are larger than those predicted by the 1-D formula, i.e., 1.3 compared to 1.8 at saturation and 4.8 compared to 6.4 at $z/L_G \approx 11.3$. With the expected pulse-to-pulse jitter of the electron beam that is provided by the linac $\Delta I_{pk} / I_{pk} \approx 10-20\%$, $\Delta \epsilon_n / \epsilon_n \approx 5\%$, $\Delta \sigma_y / \sigma_y < 10^{-5}$, the x-ray power jitter will be large when operating at saturation but will be unacceptable when operating in the exponential gain regime. The peak current therefore may not be a suitable variable for controlling FEL output power. The implications of Table 5.9-1 are that the output power at saturation is expected to fluctuate by 20-36%, due mostly to fluctuations in peak current. This fluctuation adds (quadratically) to the natural fluctuations of the SASE process (7.7%; see Section 4.2).

### 5.9.2 Phase Shifter at Saturation

Another method of controlling output power was suggested, which makes use of the relative stability at saturation by changing the relative position between the electron beam and the electromagnetic wave. This could be implemented by installing a chicane after the saturation point of the undulator. The interaction with the electromagnetic field in a second short undulator after the chicane would accelerate the electrons by an amount determined by the phase shift, thus reducing the power of the photon beam. The computed effect is small. Even the 1-D simulations predict about one order of magnitude of output power reduction. This would come at a cost of a 20% increase in undulator length. Thus, this is not a recommended technique for lowering the output power.

### 5.10 Initial Phase Space Distribution (Coupling to Linac Simulation Results)

Various simulation codes are being used to simulate the development of the electron phase space from the gun cathode to the end of the linac. Due to these simulations, which are described elsewhere in this document, transverse and longitudinal phase space distributions...
of macro-particles are available at various positions of the system. Phase-space distributions at the entrance to the undulator can, to some extent, be used to load the particles for the 3-D FEL simulation codes. The longitudinal scale at which the gun and linac simulation codes work (1000–10 \( \mu \)m) is very different from the scale at which the FEL simulation codes operate (1.5–0.00015 \( \mu \)m). While linac simulations consider the entire length of the bunch, for the FEL simulations only transverse and momentum distributions over slices of the order of the slippage length, \( \lambda_r N_u \), are relevant. On the other hand, linac simulations for the LCLS use less than one macro-particle per optical wavelength, while FEL simulations need hundreds if not thousands of particles per optical wavelength, appropriately spaced longitudinally to avoid artificial numerical bunching. Particle seeding for FEL codes based on linac simulation distribution can be done by generating a phase distribution of macro-particles from the macro-particles in bunch slices taken at various positions along the bunch. If the linac simulation is only done in longitudinal distribution, the amount of information that can be extracted is very limited. The following section describes effects related to the initial phase space distributions.

### 5.10.1 Transverse Halo

The effect of transverse halo on FEL performance has been studied with FRED-3D using a model distribution composed of two Gaussian distributions. The total number of macro-particles was distributed on the core Gaussian distribution with nominal emittance and on a halo Gaussian distribution with a 10 times larger emittance. The simulation was done for various ratios of particle numbers between the two distributions. There was no detrimental effect of the FEL process due to the presence of the halo, provided the core current remains unchanged.

### 5.11 Optical Klystron

The great length of the LCLS undulator makes it very desirable to find a mechanism that would shorten the undulator. The suggestion to use an optical klystron configuration has been put forward. The undulator could be converted into an optical klystron by splitting it in two parts and inserting a dispersive section. In the first part the interaction between the electron beam and the emerging electromagnetic wave imprints an energy modulation on the electron beam that is transformed into a spatial modulation in the dispersive section. The bunching created by the dispersive section increases the coherent emission of radiation in the second part of the undulator. The theory of the high-gain optical klystron [19] indicates that the effect is strongly dependent on the initial energy spread and that the condition \( \Delta \gamma / \gamma \ll \rho \) must be fulfilled. For the 1.5 \( \AA \), the energy spread condition is violated: \( \Delta \gamma / \gamma \approx \rho / 2 \), and no improvement of performance can be expected with an optical klystron. This was confirmed by computer simulations, which indicate that the reduction of saturation length can be significant for very small values of energy spread but that the effect vanishes as energy spread approaches the expected value of \( \Delta \gamma / \gamma = 2 \times 10^{-4} \).
5.12 Summary

The operating parameters have been optimized by an analysis of a three-dimensional algorithm and by computer simulations. The results of the study are that the FEL design objectives are reachable with a 100 m long undulator, and with the beam characteristics given in Chapter 2, Table 2.4-1, and in Appendix A (parameter list). A study of the effect of the electron beam optics on the FEL performance led to the choice of the FODO lattice cell length and the quadrupole strength. The sensitivity of the FEL performance to the main undulator and electron beam parameters was studied, and from this, tolerances for the pole-to-pole magnetic field variations and for the electron beam characteristics were derived.

5.13 References


17 S. Reiche, private communication.


### TECHNICAL SYNOPSIS

The injector for the LCLS is required to produce a single 150 MeV bunch of ~1 nC and ~100 A peak current at a repetition rate of 120 Hz with a normalized rms transverse emittance of ~1 \( \pi \) mm-mrad. The required emittance is about a factor of two lower than has been achieved to date. The design employs a solenoidal field near the cathode of a specially designed rf gun which allows the initial emittance growth due to space charge to be almost completely compensated by the end of the booster linac (Linac 0). Spatial and temporal shaping of the laser pulse striking the cathode can further reduce the compensated emittance. Following the booster linac, the geometric emittance simply damps linearly with energy growth. PARMELA simulations show that this design will produce the desired normalized emittance.

In addition to low emittance, there are two additional electron-beam requirements that pose a challenge: the timing and intensity stabilities should have an rms sigma of \( \leq 0.5 \) ps and \( \leq 1\% \), respectively. For an rf photoinjector, these parameters are determined principally by the laser system. Commercial laser oscillators are available with a timing stability of 0.5 ps. The laser system described here uses feedback loops to maintain this stability in the amplification and pulse shaping stages. The desired laser-pulse energy tolerance is achieved by stabilizing the pumping laser for the amplifiers and by operating the second amplifier in saturation. rf systems with a phase stability of 0.5 ps are already routine for the SLC.

Although additional R&D is planned to improve the projected performance of the photoinjector, confidence in the present design is based on the performance of existing systems. PARMELA simulates the measured performance of low-emittance rf photoinjectors operating near the emittance level desired. Laser systems have been employed in high energy physics experiments with timing stability—with respect to the accelerated electron beam—that is within a factor of two of the value required. The photoinjector is divided geographically between the electron source—consisting of an rf gun and laser system—and the booster accelerator. However, to produce the minimal transverse emittance at high energy, the photoinjector as a whole is treated as one unit.
6.1 Electron Source

The electron source for the LCLS consists of a high-gradient 1.6 cell S-band rf gun with a copper photocathode illuminated by intense optical pulses at 260 nm provided by a Nd:YAG-pumped Ti:sapphire laser system whose fundamental frequency is tripled.

For the LCLS, the electron source must produce a nominal 1 nC pulse with low transverse and longitudinal emittances at a pulse repetition rate of up to 120 Hz. The required 1 \( \sigma \) rms emittance for the nominal charge is \( \leq 1 \pi \) mm-mrad. A significant part of the overall emittance produced by the source is expected to be contained in the spatial and temporal halo of the pulse, which can be removed downstream of the photoinjector, if desired, with scrapers.

To meet the emittance requirements, the optical spot size at the cathode has a radius of \(~1\) mm, the pulse duration has an rms sigma of \(~3\) ps, and the rf field at the cathode is 130–150 MV/m.

6.1.1 rf Photocathode Gun

A 1.6 cell low-emittance S-band rf photocathode gun has been designed by the BNL/SLAC/UCLA rf gun collaboration for x-ray FEL applications [1]. The parameters for this gun as applied to the LCLS are listed in Table 6.1-1. The prototype of this design is now installed at the Brookhaven Accelerator Test Facility (ATF). A modified version is installed at the Gun Test Facility at SLAC. Initial measurements at BNL of the gun performance are very encouraging. (See Section 6.1.6, Summary of Experimental Results at ATF.)

Gun Description

The 1.6 cell rf gun design is based on the original 1.5 cell gun designed at BNL [2]. To minimize emittance growth due to the \( E_z \) component of the TM110 mode, the gun has been symmetrized. The original BNL zero-mode-suppressed side-coupling has been replaced by side-coupling rf into the full cell only. This does not completely suppress the zero mode.

Since there is no direct rf coupling from the waveguide to the half cell, the cell-to-cell coupling between the two cells has been improved by increasing the iris size, which also increases the mode separation between the zero and \( \pi \)-modes. This arrangement allows for more precise field balancing during tuning. To provide more rf focusing and decrease the peak field on the cell-to-cell iris, the half-cell length has been slightly increased.

A cross section of the rf gun is shown in Fig. 6.1-1. There are two identical coupling ports in the full cell, located 180° apart. The rf waveguide is connected to one port. A vacuum pump is connected to the second port. For diagnostic purposes, an rf monitoring loop is also located in the second port. The photocathode is located in the geometric center of the end plate of the half-cell. The end plate is removable to facilitate installation of cathode material other than Cu by implantation or by using an insert. As with the original BNL gun,
the laser beam can be brought to the cathode either along the axis of the gun or at a grazing incidence through the 72° side port (not shown in the figure).

**Table 6.1-1. Photoinjector Gun Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode material</td>
<td>Cu (or possibly Mg)</td>
</tr>
<tr>
<td>Usable diameter of cathode</td>
<td>12 mm</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>$10^{-5}$ at 260 nm</td>
</tr>
<tr>
<td>Nominal extraction field</td>
<td>140 MV/m</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>~1 nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>~100 A</td>
</tr>
<tr>
<td>Beam energy at gun exit</td>
<td>~7 MeV</td>
</tr>
<tr>
<td>Energy spread at exit</td>
<td>0.2% rms</td>
</tr>
<tr>
<td>rf frequency</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Bunch repetition rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>rf pulse duration</td>
<td>3–4 μsec</td>
</tr>
<tr>
<td>rf peak power</td>
<td>15 MW</td>
</tr>
<tr>
<td>Number of cells</td>
<td>1.6</td>
</tr>
<tr>
<td>Length</td>
<td>0.168 m</td>
</tr>
</tbody>
</table>

a. Definitions and clarifications. The term “rms” after units indicates a 1 σ value; both the terms “FWHM” (full-width at half-maximum) and “HWHM” (half-width at half-maximum) are used. The laser produces “pulses” and the gun produces “bunches.”

b. Assumes the laser pulse temporal profile is uniform. If Gaussian, then $I_{pk} = Q/(2\pi^{1/2} \cdot \sigma_z)$, or in this case about 130 A.

c. The beam energy is quoted for 130 MV/m extraction field and initial phase of 54° with respect to the crest of the rf.

Electric field maps for the gun were obtained with SUPERFISH. The π-mode fields are shown in Fig. 6.1-2.

**Field Balance**

Because of the deleterious effects of space charge on the beam emittance, it is important to accelerate the beam as rapidly as possible within the gun itself. Field balance tuning is accomplished using the observed mode separation measured during cold testing. Nonetheless, simulations indicate that the transverse emittance decreases as the field increases until about 140 MV/m on the cathode surface.
Symmetrization

The emittance growth due to multipole modes of $E_z$ (dominated by the dipole mode) in a gun cavity with a conventional asymmetric rf coupler is estimated to contribute >1 $\pi$ mm-mrad to the transverse emittance [3]. Any residual dipole mode in the symmetrized gun can be minimized by proper tuning of the adjustable short [4]. This is accomplished during cold testing by measuring the dipole field directly using a needle rotation technique [5]. The same procedure was used to determine that resistive coupling of the waveguide results in a lower dipole component before symmetrization than capacitive coupling. After
symmetrization, the effect of the dipole component on the transverse emittance is estimated to be on the order of 0.1 π mm-mrad or less.

Emittance Compensation

Until the energy of the beam is high enough to eliminate the effects of space charge [6], such effects can result in significant and unacceptable emittance growth. Since the beam diameter is relatively large and the initial acceleration is rapid, the charge from the gun during initial acceleration undergoes something like laminar flow. Under these conditions, the effect of space charge on the transverse emittance of a thin longitudinal slice of the bunch is minimal, and consequently for a single slice the initial emittance is approximately preserved. However, space charge has a significant effect on the shape of the phase space as the bunch progresses through the gun, especially in the first half-cell when the beam energy is lowest. These space charge effects in the center of an electron bunch are significantly greater than at the edges. Consequently, the transverse phase space of the various slices of the bunch evolve differently such that the integrated emittance of the bunch undergoes significant growth.

In 1989 Carlsten [7] pointed out that by simply placing a solenoidal field at the proper location at the gun one can reverse the evolution of the phase space such that at a later point downstream the individual phase spaces of the various slices in the bunch will momentarily be aligned. If this point of alignment occurs at sufficiently high beam energy, then the integrated normalized emittance will be frozen at close to its initial value. Experimentally this realignment of the phase space of the individual longitudinal slices was recently confirmed [8]. The emittance-compensating scheme for this photoinjector is described in Section 6.2, Linac 0.

Summary of Experimental Results at ATF

The beamline at the Accelerator Test Facility (ATF) at BNL consists of a 1.6 cell rf gun with emittance compensating solenoid plus two SLAC-type 3 m sections. The distance from the cathode to the input coupler of the first 3 m section is 0.9 m. The electron beam energy for all beam studies is 40 MeV. Interference with the rf coupler at the gun forces the center of the compensating solenoid to be placed about 5 cm downstream of the optimum position. The laser beam is operated with a longitudinal Gaussian profile (10 ps FWHM) and a uniform transverse profile. It is incident on the cathode at 72° with compensation for the anamorphic magnification and the time slew. Both Cu and Mg cathodes have been tried, but the Mg cathodes have limited the field at the cathode to about 80 MV/m because of excessive rf breakdown.

The normalized rms emittance for a 1 nC bunch after compensation has been measured at the ATF to be 2.5 π mm-mrad at 30 MeV [9]. The “slice” emittance (the emittance of a transverse slice of the bunch that is significantly thinner than the overall bunch length) was <1.5 π mm-mrad. For these ATF measurements, the emittance compensating solenoid was
not at its optimal position, and the intensity of the distribution of the laser pulse was uniform spatial but Gaussian temporal. PARMELA simulations for the ATF configuration yielded an emittance of about $2.0 \pi \text{mm-mrad}$ [10]. Considering that the configuration assumed in this simulation did not exactly match the experimental conditions, there is reasonable agreement between experiment and simulation.

PARMELA simulations also show that if a uniform temporal charge distribution were generated, the emittance of the full beam would be improved by nearly a factor of two. In addition, due to physical constraints, it is not possible to place the compensating solenoid at the optimum position for emittance compensation. The normalized emittance after compensation as calculated with PARMELA for the ATF beamline but with uniform temporal as well as spatial charge distribution is shown in Fig. 6.1-3 as a function of solenoid distance from the cathode [11]. From the figure it can be seen that the final emittance in this case is about 20% higher than optimum. The LCLS design begins with a truncated Gaussian temporal charge distribution, but the laser system is designed to allow experimentation with other distributions including uniform.

![Figure 6.1-3](image)

**Figure 6.1-3.** PARMELA simulation of compensated normalized emittance of ATF gun and beamline as a function of position (defined as the center) of the emittance compensating solenoid. The actual position of the solenoid is shown by the square data point.

PARMELA does not include the initial emittance of the bunch at the cathode—the so-called “thermal emittance.” The thermal emittance for the LCLS photocathode (Cu cathode, 260 nm photons), including the Schottky effect for $\leq 130 \text{MV/m}$, is expected to be $\leq 0.5 \pi \text{mm-mrad}$. Thus, depending on how the emittances combine, at the level of $1 \pi \text{mm-mrad}$, the thermal contribution could be significant. A measurement at the ATF of emittance as a function of charge [12] can be extrapolated to yield a zero-charge upper limit.
of 0.8 π mm-mrad. This measurement includes the rf, multi-pole, and cathode magnetic field as well as thermal contributions to the emittance.

Other factors that can contribute to an emittance larger than calculated by PARMELA include variation of charge density across the cathode and imbalance of the rf fields in the two cells of the gun.

**Photocathode**

A metal photocathode is chosen for the gun for several reasons. Since the source is not required to produce a bunch train (multiple microbunches within each pulse), the lower QE of metal cathodes compared to alkali and semiconductor photocathodes is not a major concern. The QE for Cu illuminated with UV light at normal incidence depends somewhat on surface preparation, but a QE of 10⁻⁵ at 260 nm seems reasonably conservative [13,14,15]. A gain in QE by a factor of two to four can be achieved by illuminating the cathode at a grazing angle. At 260 nm, an optical pulse of ~500 μJ on the cathode is required to produce 1 nC of charge when the QE is 10⁻⁵. A laser system to meet this requirement is relatively straightforward to design. See Section 6.1.2, Laser System.

At extremely high photon intensities, the metal surface will begin to disintegrate. Even with such disintegration, the QE of the cathode tends to remain high, presumably due to the enhancement of field emission along the surface. However, the intensities planned for the LCLS source are well below this regime.

The principal advantage of a metal cathode is that its QE is relatively impervious to exposure to atmospheric air or the vacuum environment of the operating gun. Thus, special cathode preparation and installation (e.g., load lock) techniques are less critical. The photoelectric response time of metal cathodes is on the sub-picosecond level, thus imposing no limitation on any desired temporal pulse shaping. Finally, the use of Cu as the photocathode allows the entire end plate of the half cell to be formed in the standard manner of Cu rf cavities, permitting operation at the highest field values. The use of a cathode plug or insert in an S-band gun has so far limited the cathode field to about 80 MeV/m, whereas simulations indicate the transverse emittance drops with increasing field up to about 140 MV/m.

The most recent measurements of QE for grazing incidence using the ATF rf gun gave a value of 4.4 x 10⁻⁵ for Cu [16]. This value was obtained with a laser injection phase of 90° and high gradient to maximize the Schottky effect [17]. The QE for Mg—after extensive laser-assisted explosive electron emission cleaning—was found to be about an order of magnitude higher than for Cu with similar operating parameters. Since the QE of Mg cathodes is several times higher than that for Cu, the search for a way to use a Mg cathode with fields on the order of 150 MV/m will continue.
The overall layout of the photoinjector system is shown in Fig. 6.2-1. The 15 MW in rf power required for the gun will be provided by the first of the two klystron stations in Linac 0. The rf phase and amplitude out of this station will be adjusted for the gun without the use of a high-power phase shifter or attenuator for the gun, thus avoiding the associated instabilities.

**Emittance Compensating Solenoid**

For emittance compensation, a solenoid with precisely defined field symmetry and positioning will be used at the gun exit. An identical compensation magnet with current flow in the opposite sense will be used to null the magnetic field at the cathode.

The specific solenoid design incorporates several pancake assemblies, each assembly consisting of a pancake coil, a steel flux straightener, a steel flux return, an aluminum alignment tube, a coil spacer, a flux return to coil shim, a ceramic flux straightener spacer, a recessed ceramic yoke-to-flux straightener spacer, and a spacer and compression wave spring. Conventional manufacturing techniques using molded coils will not accommodate the required flux straightener position accuracy therefore the straighteners are positioned independently of the coil positioning. The axial positioning and stability requirement of \( \pm 25 \mu m \) is met by precisely locating the axis of each of the flux straighteners with respect to the yoke bore by the use of a precision ground aluminum tube. Alignment and survey fiducials will be pinned to the gun side of the steel flux return plate. Precision bronze bushings will be located on either side of the solenoid flux return bore axis. The entire solenoid assembly will be suspended off these two bushings in the solenoid flux return by steel pins. An additional pin in the bottom face of the solenoid gun plate will permit the kinematic location of the gun solenoid assembly. The solenoid will be pinned to an aluminum cradle, which will be suspended off the floor by struts with thermal expansion coefficient matched to the gun and linac support system.

**Beamline**

A diagnostic section of about 0.75 m will separate the entrance of Linac 0 from the exit of the rf gun. This drift section will contain two vacuum isolation valves and the following instrumentation: beam position monitor (BPM), current monitor, Faraday cup, profile screen, and steering magnets.

**Vacuum System**

After brazing and before final tuning, the rf gun will undergo a 450°C vacuum bakeout in the Klystron Department's vacuum bakeout facility. This procedure removes excess hydrogen absorbed by the vacuum surfaces of the rf gun during brazing. A 20 l/s ion pump will be located in the rf waveguide near the gun rf input coupler and another near the opposite port. The gun vacuum is separated by the rest of the rf waveguide by rf windows. A third ion
pump of 220 l/s will be located just downstream of the emittance compensating solenoid. Together these three pumps provide a pressure of \( \sim 5 \times 10^{-10} \) Torr at the gun with the field gradient at 140 MV/m. The 220 l/s pump also maintains the vacuum in the diagnostic section following the gun.

A perspective of the gun assembly is shown in Fig. 6.1-4. In the figure, the electron beam exits to the right. Note the emittance compensating solenoid just to the right of the rf coupler. The laser port is at 45° to vertical on the hidden side of the gun.

**Figure 6.1-4.** Perspective of the gun assembly. The beam exits to the right. (Figure by C. Stelmach and S. Pjerov, National Synchrotron Light Source at BNL).

### 6.1.2 Laser System

The laser system for the electron source is required to deliver a 500 \( \mu \)J pulse of UV photons to the photocathode at a repetition rate of 120 Hz. To meet the emittance requirements of the source, the laser pulse must have a pulse length in the range of 3–5 ps rms and radius of \( \sim 1 \) mm hard edge. Pulse shaping is required to optimize both the transverse and longitudinal emittances and as a diagnostic aid. Finally, stability is an important operational requirement, and, as discussed in Chapter 7, the timing stability in particular is
crucial to meeting the longitudinal emittance requirements of the linac and bunch compression system. The design laser parameters are given in Table 6.1-2.

Table 6.1-2. Laser system requirements

<table>
<thead>
<tr>
<th>System</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating wavelength</td>
<td>260-280 nm</td>
</tr>
<tr>
<td>Pulse repetition rate</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Number of micropulses per pulse</td>
<td>1</td>
</tr>
<tr>
<td>Pulse energy on cathode</td>
<td>&gt;500 µJ</td>
</tr>
<tr>
<td>Pulse radius on cathode</td>
<td>~1 mm HWHM</td>
</tr>
<tr>
<td>Pulse risetime</td>
<td>1.0 ps</td>
</tr>
<tr>
<td>Pulse length</td>
<td>~10 ps FWHM</td>
</tr>
<tr>
<td>Longitudinal pulse form</td>
<td>Various</td>
</tr>
<tr>
<td>Transverse pulse form</td>
<td>Uniform</td>
</tr>
<tr>
<td>Homogeneity on cathode</td>
<td>10% ptp</td>
</tr>
<tr>
<td>Pulse-to-pulse optical energy jitter</td>
<td>≤1% rms</td>
</tr>
<tr>
<td>Laser-to-rf phase stability</td>
<td>≤0.5 ps rms</td>
</tr>
<tr>
<td>Spot diameter jitter at cathode</td>
<td>1% ptp</td>
</tr>
<tr>
<td>Pointing stability</td>
<td>&lt;1% ptp</td>
</tr>
</tbody>
</table>

| Requirement                               |

a. Definitions and clarifications: The term “rms” after units indicates a 1 σ value; both the terms “FWHM” (full-width at half-maximum) and “HWHM” (half-width at half-maximum) are used. The laser produces “pulses” and the gun produces “bunches.”
b. The design will be for 18 mJ of IR energy just after the amplifiers, resulting in at least 500 µJ available at the cathode. For a QE of 10^-5, 500 µJ of excitation light at 260 nm at the cathode will produce 1 nC of charge.
c. For a uniform, round, transverse cross section, the FWHM = σ(rms)^6/(2π)^1/2. Thus a 0.9 mm HWHM section has a radius whose rms sigma is 0.75 mm.
d. A risetime of 1 ps (10–90%) is sufficient for pulse shaping requirements, but the system will be designed for 0.5 ps.
e. For a uniform longitudinal cross section, the FWHM = σ(rms)^8/(2π)^1/2. Thus a 10-ps FWHM pulse has an rms sigma of 3 ps.
f. Present simulations in the linac indicate that a timing jitter in the electron beam of 1 ps rms will result in a 10% rms bunch-length variation at the undulator. A stability of 2 ps rms has been achieved in laser-electron collisions for SLAC experiment E-144.

System Description

The titanium-sapphire laser system of Fig. 6.1-5 provides the ultraviolet light pulses for the rf gun. This system is briefly described here and many of its details are elaborated upon.
in subsequent sections. A CW, frequency-doubled, diode-pumped Nd:YAG laser provides energy in the green (532 nm) to pump the CW mode-locked Ti:sapphire oscillator, which delivers a continuous train of 10 nJ, 100 fs FWHM pulses that repeat at 119 MHz. By using this frequency, the 24th subharmonic of the linac’s 2856-MHz rf, timing of the laser pulse is locked to the phase of the rf in the linac and rf gun. This question of timing is discussed in detail below. The wavelength is tuned to 780 nm, which after the amplification is frequency tripled to 260 nm to provide a suitable wavelength for the photocathode of the gun. With the possible exception of the pulse stability requirements at 119 MHz, oscillators of this type are commercially available (e.g., Coherent’s Mira or Spectra-Physics’ Tsunami with modification to 119 MHz).

A Pockels cell and polarizer are used to gate single pulses, at 120 Hz, from the 119 MHz pulse train. The selected pulses are then amplified by two Ti:sapphire crystals, both configured as 4-pass “bow-tie” amplifiers [18]. Both are pumped by a single Q-switched, doubled Nd:YAG laser that can produce a 120 Hz train of 3 ns pulses (again a commercial laser, such as Coherent’s Infinity). The pump output is stabilized. Fourier-relay optics (see below), beginning with a primary aperture between the two amplifiers and continuing to the final optics platform next to the gun, are used to maintain a good transverse mode while efficiently filling the pumped volume of the Ti:sapphire crystals.

In amplifiers for picosecond and especially sub-picosecond pulses, the peak power must be limited to avoid optical damage and nonlinearities. This system uses chirped pulse amplification [19] to keep the peak power in the amplifier small. The large bandwidth of the Ti:sapphire oscillator enables it to produce the 0.1 ps pulse desired for pulse shaping. The dispersion of a grating pair can then stretch the pulse to hundreds of picoseconds, so that the peak power is reduced to avoid nonlinearities and damage during amplification. Different wavelengths take different optical paths through the diffraction gratings. The resulting space, tune and wavelength correlations are then used to stretch—or compress—the pulse. After amplification, the process can be reversed to compress the pulse to the original or any greater width. The large bandwidth of the Ti:sapphire oscillator also allows us to shape the pulse in time (using Fourier-transform pulse shaping, as discussed later). The final shape at the system output can be readily altered under computer control. **Fig. 6.1-5** includes the pulse shaper and stretcher after the oscillator and a compressor after the amplifier. An additional low-power compressor after the oscillator is used as a diagnostic for the pulse shaper. It compresses the pulses from the 119 MHz train that are not selected by the Pockels-cell gate, and a cross-correlator using a portion of the oscillator light can then probe the resulting pulse shape.

After the second amplifier, the transverse shape of the pulse is modified from Gaussian to uniform to better match the requirements for obtaining a low emittance from the gun. Next, two crystals triple the frequency of the light to a wavelength of 260 nm. The flattened pulse also improves efficiency and uniformity in this harmonic-generation process.
Figure 6.1-5. The drive laser for the rf photocathode electron gun for the LCLS. The thick lines show the main beam path, the closely spaced, dashed lines indicate diagnostic beams, and the widely spaced, dashed lines are pump beams.
Finally, the beam is transported through an evacuated tube to an optics platform next to the gun. Because of the long transport tube, the last image plane of the Fourier-relay optical system has a spot size that is too small for the photocathode. The image is magnified onto a plane with a circular aperture that slightly trims the edge of the beam. Since this aperture is subsequently imaged onto the photocathode, the illuminated region of the photocathode is precisely defined without jitter. The imaging includes compensation (discussed below) for the temporal and spatial distortion caused by grazing incidence onto the photocathode.

The energy management of the laser system is as follows: transmission through the spatial flattener ~50%, through the compressor ~50%, through the frequency tripling stage ~25%, and through the optical transport to the gun ~50%. Consequently, starting with 18 mJ after the second amplifier, the required 500 µJ is delivered to the cathode.

The factors that entered into the choice of a CW Nd:YAG-pumped Ti:sapphire oscillator combined with a Q-switched Nd:YAG pumped Ti:sapphire amplifier laser system are given in Section 6.1.3.

Temporal Pulse Shaping

The spatial and temporal shape of the optical (and thus also the electron) pulse is nominally Gaussian. Simulations indicate that an emittance-compensated beam at the exit of the injector will have a lower transverse emittance if uniform temporal and spatial distributions of charge are extracted at the photocathode. However, following the beam downstream through the linacs and compressors, present simulations indicate that the bunch length at the entrance to the undulator for a beam with an initial uniform temporal shape is more sensitive to timing jitter than for an initial Gaussian shape. It is likely that an intermediate shape will in the end prove optimal. Since an experimental variation of the pulse shape will be needed to establish the final operating configuration, the capability to shape (including a uniform shape) the temporal profile of the laser pulse is built into the system.

Temporal shaping of the optical pulse will be accomplished through the well-established technique of frequency domain pulse shaping [20]. This technique takes advantage of the large bandwidth of ultrafast laser pulses. The bandwidth of a laser pulse is determined by the Fourier transform of its electric field

\[ E(\omega) = \int_{-\infty}^{\infty} dt E(t)e^{i\omega t}. \]  

For a laser pulse with an intensity envelope

\[ I(t) = I_0 e^{-\frac{2(t/\tau)^2}{\sigma^2}}, \]  

(6.1.2)
the power spectrum is

\[ I(\omega) = I_0 e^{-\left( \frac{\omega - \omega_0}{\Delta \omega} \right)^2}, \]

(6.1.3)

where \( \Delta \omega = 2/\tau \) is the bandwidth of the pulse. The shorter the pulse the larger the spectral bandwidth. The frequency spectrum is dispersed in space between a pair of diffraction gratings separated by a pair of lenses. By using relay imaging between the gratings, no dispersion is introduced in the pulse. A spatially resolved amplitude and/or phase mask at the dispersion plane modifies the Fourier transform of the laser pulse and permits any pulse shape allowed by the bandwidth to be produced. In principle, a square pulse with a rise time equal to the pulse duration of the original compressed pulse can be produced. In Fig. 6.1-5 pulse shaping is accomplished in a pair of gratings before the amplifier sections. This arrangement reduces the possibility of damage to the pulse shaping optics. The pulse shape will subsequently be modified by the gain properties of the amplifiers and the frequency conversion process. Thus, the Fourier transform produced in the pulse shaping gratings must take these changes into account. To accomplish this, the amplitude and/or phase masks will be made with computer-addressable liquid crystal optics [21]. In this case, the single shot pulse duration measurement will allow immediate feedback on the mask configuration, which can then be modified to produce the desired pulse shape. Thus, the effects of frequency conversion and gain shaping will be readily taken into account, and it will be relatively simple to change the pulse shape if another is found to be advantageous.

**Fourier Relay Optics**

A technique known as Fourier relay imaging combines relay imaging, in which lenses relay an image of an aperture to each pass through an amplifier Ti:sapphire crystal or harmonic-generation crystal, and filtering of the beam’s spatial Fourier transform. This approach can maintain a clean transverse mode and improve pointing stability, while also achieving better utilization of the pump energy. Initially, the oscillator beam is trimmed in an aperture. At each step a lens of focal length \( f_1 \) is placed a distance \( f_1 \) after one of the image planes. The Fourier transform is formed at the focus \( f_1 \) beyond the lens, where higher spatial harmonics are removed by a pinhole. A second lens with focal length \( f_2 \) then recollimates the beam (with magnification \( f_2/f_1 \)) and forms the relay image at a distance \( 2(f_1 + f_2) \) from the previous image plane. Similar imaging takes place at the harmonic-generation crystals, and finally an image of the aperture is relayed to the photocathode to define the area of photoemission.

**Spatial Pulse Shaping**

To shape the pulse in space, a position-dependent attenuation will be applied to the beam [22]. Relay imaging must be used after the flattening to limit diffraction. However, the repeated filtering of the spatial Fourier transform limits the steepness of any uniform pulse at
the output, and so Fourier filtering is not used after the spatial shaper. Also, the initial flattening is lossy, and so the system must have sufficient gain. On the other hand, harmonic generation can be more efficient with a uniform intensity across the beam.

**Frequency Conversion**

The ~780 nm pulses will be frequency tripled to ~260 nm in a pair of frequency conversion crystals using a Type II-Type II tripling scheme [23]. This scheme is called a polarization mismatch scheme because the beam is detuned from optimal in the first crystal to allow efficient conversion to the third harmonic in the second. In Type II doubling, the beam is typically incident with a polarization angle of 45° with respect to the e- and o-axes. For polarization mismatch, the beam is polarized at 35° with respect to the o-axis, allowing approximately 50% conversion to the second harmonic. The unconverted fundamental beam is mixed with the converted beam in the second crystal. Frequency conversion efficiencies in excess of 50% to the third harmonic have been measured with picosecond 1 \( \mu \)m laser pulses. A pair of BBO crystals with phase matching angles of 42° and 54° respectively will be discussed. The cautious estimates of Fig. 6.1-5 assume a day-to-day tripling efficiency of 25%, although twice this efficiency should be achievable.

Because of the intensity and wavelength dependence of the frequency conversion process, one has to be concerned about the pulse distortion during conversion. If the pulse is temporally and spatially uniform (a cylindrical slug), the frequency conversion will maintain the pulse shape. Under these conditions, the frequency conversion efficiency can be optimized. Frequency conversion will also sharpen the edges due to the nonlinearity of the process. On the other hand, a non-uniform shape will be distorted upon frequency conversion. This must be accounted for in the generation of the pulse shape. In addition, any structure on the pulse—ripples in time or space—are likely to grow during the conversion process, again due to the non-linearity [24]. This means that the constraints on the spatial and temporal uniformity before conversion will be more severe than those required at the photocathode.

**Grazing Incidence**

In the rf photocathode guns being developed by the Brookhaven-SLAC-UCLA collaboration, the laser is incident on the photocathode at near-grazing incidence (72° from the normal at Brookhaven’s ATF). When a \( p \)-polarized beam is incident on the photocathode (so that the electric field is nearly normal to the surface), photoemission from metals is enhanced by up to a factor of three over emission at normal incidence. In addition, there is no need to insert a laser mirror directly downstream from the gun, right next to the electron-beam path, where it is an obstacle and a source of wakefields.

However, a circular laser beam incident at a grazing angle illuminates an elliptical spot on the cathode, and, if the spot is millimeters across, the side closer to the laser entry will emit picoseconds earlier than the other side. Corrections for both of these effects are needed.
to minimize emittance. To compensate for the elliptical spot, the last relay of the beam in Fig. 6.1-5, from the final image plane to the cathode, uses a pair of cylindrical lenses, to apply different magnifications horizontally and vertically and so illuminate a circular area. Alternatively, a suitable prism pair can also provide this compensation.

The time slew can be corrected by reflection from a grating or by transmission through an echelon (a staircase of fused-silica plates) in order to add a time delay varying across the beam. By placing the grating in the beam near the final image plane, the time delay is correlated with the position across the cathode. Since gratings are lossy in the ultraviolet, care must be taken to make the beam size large enough on the grating to avoid damage.

**Stability of Laser Pulse**

*Pulse-to-Pulse Timing*

The LCLS design places several strict requirements on laser stability and reproducibility. One of these is pulse-to-pulse timing jitter of the bunch with respect to the rf phase driving the gun and rf accelerating sections. Because of the rf acceleration process in Linac 1, any timing (phase) change at the gun affects the energy slew along the bunch which in turn changes the bunch compression in the subsequent chicane. The energy of the bunch is also affected, which changes the arrival time at Linac 2. The original timing error may in some cases be canceled in the second linac and chicane, but because of the nonlinearities in the compression process, the average bunch length is increased in all cases. Since the peak current varies inversely as the bunch length, the net effect may lead to a serious degradation of FEL performance beginning at the level of a timing jitter of about 1 ps rms. For this reason, a criterion of 0.5 ps rms is adopted for the LCLS. Almost all of the jitter of the laser system originates in the laser oscillator, and this criterion has been met by the stabilization techniques incorporated in advanced commercial oscillators such as those planned for LCLS.

In the design of the laser system presented here, the timing is stabilized twice. Refer to Fig. 6.1-6. First, a measurement is made of the laser oscillator output phase with respect to the accelerator rf phase where the rf is provided by a coupler in the accelerator rf main drive line. The phase error signal, which is first passed through a low-pass filter and then amplified, is used to drive a piezo stage on which the end mirror of the laser oscillator is mounted. The oscillator incorporates a passive mode-locker (using Kerr lens or Fabry-Perot saturable absorber mode-locking techniques), while the lock to the external rf reference is done by tuning the length of the oscillator cavity. Thus the length of the cavity, which is initially set up to match a fraction of the accelerator frequency, can be continuously adjusted to lock the phase of the subsequent laser pulses to the rf. The bandwidth of the method is estimated to be of the kilohertz range. The timing is then restabilized external to the laser oscillator. A prism is mounted on a piezo stage with a fast motor (e.g., a picomotor from New Focus Inc.) which acts as a delay for the laser pulses. As shown in the figure, this delay system uses the same phase error signal as the piezo stage internal to the oscillator, but it
could equally well be made to use the measured phase error signal of either the electrons or
the laser with respect to the rf, both of which are shown in the figure.

The piezo and motor would be computer controlled and would account for all the slow
drifts in the laser optical path length or timing drifts in the rf system. In a recent high-energy
physics experiment, timing stabilization of a laser pulse with respect to the electron beam has
been demonstrated at the level of 2 ps using similar techniques.

Figure 6.1-6. Timing stabilization schematic.

**Pulse Duration**

Like timing jitter, the stability of the pulse duration is important for LCLS performance.
The pulse duration should fluctuate by no more than the allowable timing jitter. A stable
oscillator is again essential. A technique for further control takes advantage of the phase and
amplitude masks used to shape the pulse in time. If the bandwidth of the oscillator pulse is wider than that transmitted by the masks, so that the masks are illuminated almost uniformly, then fluctuations in the oscillator width do not affect the final pulse width or shape, which is determined only by the masks and the pulse compressor following the amplifiers.

**Optical Energy**

The optical energy per pulse should be held constant to the level of 1% rms or less as indicated in Table 6.1-2. This requirement is set by the stability required of the x-ray laser beam. Harmonic generation can compound the difficulty of this criterion, since 1% stability in the third harmonic would require 0.3% stability in the fundamental. Since it is difficult to make a clean Pockels cell trim of a broadband pulse without affecting its temporal shape, the gain is stabilized by using laser diode pumping in the oscillator; by careful control of the beam mode and its pointing through the amplifiers through Fourier relay imaging; and by a combination of feedback loops to stabilize the amplifier pumping to maintain the UV energy at the gun.

To stabilize the pumping, the relatively long upper-state lifetime of Ti:sapphire (3.2 µs) is used to keep the total pump energy constant on a pulse-by-pulse basis. To accomplish this, 10% of the pump beam will be delayed by a 30 ns optical path (the delay chosen to be the minimum necessary to adjust the Pockels cell HV) and used to trim the pumping of the Ti:sapphire for a given primary pulse by up to ±5%. Since the pump has a narrow bandwidth, it is easily trimmed by the Pockels cell shown in Fig. 6.1-5.

To correct for long-term drift in the UV pulse energy as monitored at the gun, a software feedback loop will adjust the set point in the primary feedback loop that stabilizes the amplifier pump energy.

**Spot Size and Position**

To carefully and reproducibly control the distribution of space charge in the gun for optimal emittance, the laser must maintain a 1% variation in the diameter of the laser spot on the photocathode with a centroid location that varies by no more than 1% of the diameter. Position stability can be achieved by trimming the edge of the beam with a circular aperture placed on the final relay plane before the gun; this aperture is then imaged onto the photocathode. A Gaussian beam could still have fluctuations in the position of the centroid within the aperture, but with the uniform pulse shape preferred for LCLS, pointing jitter does not cause any change in cathode illumination (as long as the jitter does not leave any part of the beam-trimming aperture unilluminated).

**Diagnostics**

The laser system is designed with an integral diagnostic beam. (See Fig. 6.1-5.) This beam is used to monitor the shot-to-shot amplifier gain and also is used for diagnosing the pulse shape of the UV pulse to be incident on the photocathode. To obtain the diagnostic beam (lighter line in the figure), a Pockels cell and polarizer are used to gate a second
oscillator pulse that follows the primary pulse by tens of nanoseconds. The diagnostic pulse makes only one pass through each of the amplifiers. A photodiode measures its energy at each stage to check the gain. The unstretched (100 fs) diagnostic pulse is then cross correlated with the UV output pulse (3–10 ps) to measure the pulse shape.

**Cross-correlation Pulse Shape**

The advantage of using a diagnostic beam for a cross-correlation measurement of the UV pulse shape is that the diagnostic beam retains the original ~100 fs duration of the seed beam and so provides a comparable temporal resolution. A cross-correlation provides more information than an auto-correlation because the latter cannot distinguish temporal asymmetries. The diagnostic pulse will be chosen to arrive at a cross-correlator at the same time as a fraction of the primary pulse picked off by a beam splitter. There are a number of techniques for measuring the cross-correlation of an infrared and UV pulse. It is anticipated that a single-shot polarization-gating cross-correlator [25] will be used. This will generate a third-order intensity cross-correlation of the ~100 fs, 800 nm IR pulse and the ~10 ps UV pulse. If the IR pulse is used as the gating pulse, the measured pulse shape is that of the UV pulse with a temporal resolution of approximately 100 fs. The two pulses are incident nearly colinearly on a nonlinear optic. The UV pulse to be detected is incident on a spatially resolving detector through crossed polarizers. In the absence of a gating pulse, no UV light is detected. Between the polarizers there is a Kerr medium, such as a thin piece of fused silica. When the gate pulse is incident on the Kerr medium, it acts as in instantaneous waveplate which allows the portion of the UV pulse passing through the same space-time location to pass through the crossed polarizers and be detected. By choosing the crossing angle, detector and crystal size, and appropriate probe beam energy, the pulse duration can be measured with a resolution approaching the 100 fs duration of the gate pulse.

The effect of the pulse shaping on the low-energy IR pulse will also be measured using cross-correlation. In this case, all of the pulses (other than the primary pulse) from the 119 MHz train out of the shaper-stretcher are selected. After recompression, their shape is measured in the cross-correlator shown in Fig. 6.1-5 in the low-energy area. From the diagnostic beam picked off before the shaper-stretcher (lighter line in the figure), all of the 119 MHz train not selected as the diagnostic pulse is used as the gate pulse. Because both beams entering this cross-correlator are 119 MHz trains (except for the 120 pulses per second selected by the Pockels cells), it can use a simpler swept time delay to scan the overlap of the pulse trains, rather than the single-shot approach of the output cross-correlator where different time delays occur at different spatial locations.

**Energy**

The energy will be monitored using joulemeter probes in combination with calibrated pick-offs at several points in the system: after each amplifier stage, after each harmonic conversion, and just before the beam enters the rf gun’s vacuum to strike the photocathode. These checks allow simple monitoring of amplifier and harmonic-generation efficiency.
Spatial Shape

The spatial shape of the beam on the photocathode can be monitored by picking off a fraction of the beam near the final (cylindrical) lenses and the window leading into the gun. A CCD (without the usual protective glass cover, since it would block the UV laser light), placed at the pick-off image plane (optically the same distance away as the cathode but physically located outside the high-radiation area using an imaging fiber optic relay) and at the same angle to the beam as the cathode surface, would then image the beam spot. Typical CCDs are 4 to 9 mm wide, a good match for the spot needed on the cathode. For a grazing angle on the cathode, it is preferable to get a CCD on a printed circuit board rather than in a camera body since the body does not permit the correct angle. Alternatively, the UV could be incident on a fluorescing surface at the correct angle, and a CCD camera could record the visible glow; however, the response may be somewhat less uniform than that of a direct hit on the CCD. Other CCDs check the beam’s transverse mode after each amplifier and at each harmonic-generation step.

Stability of Spot Centroid

The same camera at the gun can measure the stability of the spot centroid on the photocathode. A digital frame grabber can record the video image, calculate the centroid location, and keep statistics on its stability. For each laser pulse, the centroid can be calculated to better than one pixel, which is typically 8 to 13 μm, about 1% of a typical 1 m-diameter beam. The mean and standard deviation can be calculated with even higher accuracy.

Timing Jitter

Most of the timing jitter is introduced in the laser oscillator. To measure it, some light is picked off with a fast photodiode just after the oscillator, as shown in Fig. 6.1-6. Such diodes are available with rise times down to 7 ps. Jitter can be measured in the time domain using a repetitive-trace sampling oscilloscope triggered by the rf of the gun. After taking many samples, the timing jitter broadens the rising edge of the pulse, which the scope can measure directly, limited to 2–3 ps resolution. In the frequency domain, the same photodiode pulse can be the input to a spectrum analyzer. The timing jitter can be determined from the differences of this spectrum at high and low harmonics using well known techniques [26]. Finally one can mix this diode signal with rf (as already done for control of the end mirror piezo of the oscillator). The phase error (DC) can then be measured with an ordinary oscilloscope, studied in a spectrum analyzer to identify possible noise sources with narrow frequencies, and ultimately recorded by the accelerator control system.

A measurement of the laser pulse jitter with respect to the arrival of the electron beam itself is also possible at a BPM or resonant cavity in the beam-line near the gun exit. In a similar fashion the timing jitter of the electron beam itself with the rf can be also estimated as shown in Fig. 6.1-6.
### 6.1.3 Choice of Laser System

Table 6.1-3 lists four options for the basic laser system that have been considered. The rationale behind these options can be found using the data of Table 6.1-4. Neither Nd:YAG nor Nd:YLF laser systems are suitable as oscillators for the sort of shaped pulses that are desired, since a medium with a bandwidth that can support rise times below 1 ps is required. On the other hand, Nd:glass can support the rise time and so provide a suitable oscillator, but it does not support the 120 Hz repetition rate needed for the amplifier. To achieve both short pulses and a high repetition rate, Option 1 turns to a Ti:sapphire amplifier coupled to a 1.05 μm Nd:glass oscillator. However, this wavelength is on the edge of the Ti:sapphire band which results in inefficient amplification.

<table>
<thead>
<tr>
<th>Option</th>
<th>Element</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oscillator</td>
<td>CW mode-locked Nd:glass</td>
</tr>
<tr>
<td></td>
<td>Oscillator Pump</td>
<td>CW diode laser</td>
</tr>
<tr>
<td></td>
<td>Amplifier</td>
<td>Ti:sapphire</td>
</tr>
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<td></td>
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<td>CW diode laser</td>
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<tr>
<td></td>
<td>Amplifier</td>
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<tr>
<td></td>
<td>Amplifier Pump</td>
<td>Frequency-doubled, flash-lamp-pumped, Q-switched, Nd:YAG or Nd:YLF laser</td>
</tr>
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<td>3</td>
<td>Oscillator</td>
<td>CW mode-locked Cr:LiSAF</td>
</tr>
<tr>
<td></td>
<td>Oscillator Pump</td>
<td>CW diode laser</td>
</tr>
<tr>
<td></td>
<td>Amplifier</td>
<td>Cr:LiSAF</td>
</tr>
<tr>
<td></td>
<td>Amplifier Pump</td>
<td>Several pulsed diode lasers</td>
</tr>
<tr>
<td>4</td>
<td>Oscillator</td>
<td>CW mode-locked Ti:sapphire</td>
</tr>
<tr>
<td></td>
<td>Oscillator Pump</td>
<td>Frequency-doubled CW Nd:YAG laser pumped by several diode lasers</td>
</tr>
<tr>
<td></td>
<td>Amplifier</td>
<td>Ti:sapphire</td>
</tr>
<tr>
<td></td>
<td>Amplifier Pump</td>
<td>Frequency-doubled, Q-switched, Nd:YAG or Nd:YLF laser</td>
</tr>
</tbody>
</table>

The desired wavelength can be obtained by frequency tripling of Ti:sapphire, which has a gain maximum at 790 nm. This leads to Option 4, in which Ti:sapphire is used for both oscillator and amplifier. Ti:sapphire’s main disadvantage is the need for large external pump lasers. The oscillator is the only one of the four that is not pumped by a compact diode laser. Instead, a CW, frequency-doubled, diode-pumped Nd:YAG or Nd:YLF is used to transform diode-laser light into green. As a pulsed amplifier, Ti:sapphire is limited by its short upper-
state lifetime: energy must be pumped in within a few microseconds from when it will be used for amplification. For this application, flashlamps and diode lasers are impractical; instead, a Q-switched (~1 ns), doubled, flashlamp-pumped Nd:YAG or Nd:YLF is used.

The other two options make use of Cr:LiSAF (short for Cr:LiSrAlF$_6$), the newest of these gain media. It supports a short pulse and lasers at a wavelength that is compatible with frequency tripling and with amplification by Ti:sapphire. The wavelength on the cathode is slightly longer (280 vs. 260 nm) than that of the other options, and so will have a reduced quantum efficiency. However, the peak emission of LiSAF occurs at 830 nm, and Time-Bandwidth Products may be able to make an oscillator with a somewhat shorter wavelength than their nominal 850 nm ± 10 nm. The Cr:LiSAF oscillator is compatible with diode pumping. Because the upper-state lifetime (67 µs) is longer than that of Ti:sapphire (but still short compared to the Nd media), the amplifier could be pumped either by a flash-lamp or by a bar of laser diodes. This is the only amplifier on the list without a substantial external pump, and so would be the most compact of the four.

<table>
<thead>
<tr>
<th>Table 6.1-4.</th>
<th>Laser data.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Nd:YAG</td>
</tr>
<tr>
<td>Lasing wavelength(s) [nm]</td>
<td>1064</td>
</tr>
<tr>
<td>Wavelength needed [nm]</td>
<td>1064</td>
</tr>
<tr>
<td>Harmonic required for gun</td>
<td>4</td>
</tr>
<tr>
<td>Gun wavelength [nm]</td>
<td>266</td>
</tr>
<tr>
<td>Fluorescent lifetime [µs]</td>
<td>230</td>
</tr>
<tr>
<td>Thermal conductivity$^b$ [W/mK]</td>
<td>13</td>
</tr>
<tr>
<td>Thermal diffusivity$^b$ [cm$^2$/s]</td>
<td>0.046</td>
</tr>
<tr>
<td>Oscillator power [mW]</td>
<td>&gt;100</td>
</tr>
<tr>
<td>Oscillator pulse duration$^c$ [ps]</td>
<td>18</td>
</tr>
<tr>
<td>Max amplifier rep rate [Hz]</td>
<td>~100</td>
</tr>
</tbody>
</table>

a. Phosphate glass, Hoya LHG-5.
b. At 300 K.
c. For a Lightwave or Time-Bandwidth Products diode-pumped, CW mode-locked oscillator, except for Ti:sapphire, which is pumped by a diode-pumped, doubled Nd:YAG (or an argon-ion) laser and can support various pulse widths. This duration is also typical of what can be supported by an amplifier.
d. Depends on rep rate of pump laser. 100 Hz is typical for a flash-lamp-pumped, Q-switched, doubled Nd:YAG, while rates above 1 kHz (but with correspondingly lower energies per pulse) can be obtained with a CW arc-lamp-pumped, doubled, Q-switched Nd:YAG.
Because LiSAF is a thermally and mechanically weaker crystal than Ti:sapphire, the amplifier may be limited in average power. Table 6.1-4 provides a comparison of some of the thermal properties. Note the wide range of thermal conductivity, $\kappa_t$, with Ti:sapphire being by far the best. The thermal diffusivity, $D_t$, is also provided, where

$$D_t = \frac{k_t}{c_t \rho_m}, \quad (6.1.4)$$

since it is emphasized in some references to LiSAF. Here, $c_t$ is the specific heat and $\rho_m$ is the mass density. The diffusivity is related to the thermal relaxation time, $\tau_t$, by

$$\tau_t = \frac{a^2}{D_t}, \quad (6.1.5)$$

where $a$ is the radius of the laser rod. For a typical 4 mm radius, these materials have relaxation times ranging from 1 to 25 s. At 120 Hz, all of them would be in the steady state, and so the thermal conductivity is the relevant parameter for comparison.

The advantages and disadvantages of the four laser options considered are summarized in Table 6.1-5. Option 3 appears very inviting; however, since Cr:LiSAF amplifiers are not as commercially advanced and would require more development than a Ti:sapphire system, Option 4 is the most suitable system for the LCLS photoinjector.

<table>
<thead>
<tr>
<th>Option</th>
<th>Oscillator</th>
<th>Amplifier</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| 1      | Nd:Glass   | Ti:Sapphire | Diode-pumped oscillator | Edge of Ti:Sapphire band
|        |            |           |            | Big Q-switched pump for amp |
| 2      | Cr:LiSAF   | Ti:Sapphire | Diode-pumped oscillator | Big Q-switched pump for amp
|        |            | Frequency tripling | Oscillator wavelength a bit long |
| 3      | Cr:LiSAF   | Cr:LiSAF   | Diode-pumped oscillator | Wavelength a bit long
|        |            | Diode-pumped amplifier | Not enough output from diode pumping alone? |
|        |            | Frequency tripling | Thermally and mechanically weak (versus Ti:Sapphire): power limit? |
|        |            |           | Least commercial and standard |
| 4      | Ti:Sapphire | Ti:Sapphire | Frequency tripling | Big CW pump for oscillator: less stable than single-platform diode-pumped boxes? |
|        |            |            | Most commercial and standard | Big Q-switched pump for amp |
6.2 Linac 0

6.2.1 Comments on Emittance Compensation

The beam will exit the electron gun with an energy of ~7 MeV. As explained in Section 6.1, Emittance Compensation, the transverse emittance will already have grown significantly, and is susceptible to additional growth. To maintain the high brightness of the beam as extracted from the photocathode, emittance compensation will be employed to minimize the integrated emittance of the beam at high energy [27]. Simulations with PARMELA indicate that at 150 MeV, space-charge effects in the downstream drift and low-energy dog leg are negligible.

Emittance compensation in photoinjectors has been subjected to an extensive analytical treatment by Serafini and Rosenzweig [28]. The evolution of the beam dynamics for the photoinjector can be described in four stages:

1. From the cathode to the end of the gun (i.e., to the second iris).
2. The drift space from the gun to the end of the gun solenoid.
3. The remaining drift space after the solenoid.
4. The following booster accelerator (Linac 0).

In each stage, the dominant forces acting on the beam—space charge, rf, and magnetic field—can be analyzed to understand their effect on the correlated emittance. The analysis is only valid in the regime for which four-dimensional laminarity holds. To provide optimal emittance compensation, it has been shown that these forces should be arranged to match the beam to the invariant envelope (IE). The conditions for satisfying the IE are analogous to those for Brillouin flow—in fact identical in the absence of an rf accelerating field.

In the first stage, especially in the half-cell of the gun where the beam energy is still low, the beam radius will expand rapidly due to the intense space-charge forces. However, since laminarity is maintained, the resulting increase in the transverse emittance will be highly correlated with axial position within the beam pulse. In fact, a given thin, longitudinal slice will be expected to maintain its original uncorrelated (thermal) emittance. A sharp rise in the magnetic field just after the cathode (which in turn requires the gun solenoid to be very close to the cathode) and a strong accelerating gradient are essential to minimize the growth in beam size.

In the second stage, the evolution of the beam size and emittance is reversed by the gun solenoid. The solenoidal field must be strong enough to transform the diverging beam into one that is convergent, overcoming as well the divergent kick received by the beam on exiting the rf field, but not so strong as to destroy the laminarity of the beam. The laminarity is irretrievably destroyed when particle paths cross, creating an uncorrelated group of
particles commonly described as a halo. Since the charge density at the temporal and spatial edges of the pulse varies rapidly between the nominal value and zero, some beam crossover is inevitable. Beam crossover in general can be minimized by two techniques: (1) use of a uniform charge distribution at the cathode; and (2) use of a gentle convergence in stages 2 and 3.

Before describing stage 3, it is useful to state the desired condition for stage 4. In the booster accelerator, the goal is to have the beam match the IE, for which case the phase-space angle (in configuration space), \( \delta \equiv \sqrt{\sigma'} \), is invariant with respect to the beam current and equal to \( -\gamma' \), and remains invariant during acceleration while the beam size and transverse emittance adiabatically damp. (The prime refers to differentiation with respect to the axial coordinate \( z \).) Ideally, this process continues until the beam energy is high enough that the space-charge forces can be ignored. In principle, a completely compensated integrated emittance can be reached, that is, the original uncorrelated (thermal) emittance can be restored and maintained.

The IE requires the beam be slightly convergent at the beginning of the booster accelerator. This convergence is provided by the rf kick the beam receives at the entrance to the booster accelerator if at the end of the drift the beam envelope is at a waist. A relatively gentle waist is required to minimize crossover. To achieve the IE condition, the emittance compensating solenoid must be confined to the gun area and adjusted to match at least one longitudinal slice to the IE at the entrance of the booster accelerator. Those slices that are slightly mismatched will undergo oscillations in the linac that will be damped as \( \gamma^{-1/2} \).

For specific photoinjector designs, simulations with PARMELA have been used to confirm the general validity of this analytical approach [29]. Thus the analytical approach promises to provide the guidance that will permit more rapid convergence with simulations to a photoinjector design having minimum emittance.

The discussion above assumes continuous acceleration in a booster accelerator until 150 MeV is reached. But in fact four separate accelerating sections will be used. If two sections are placed very close together, then presumably the increase in beam size and thus also emittance between the two sections will be minimal and the beam will still be approximately matched in the second section. However, it is possible not only to eliminate the small deterioration of the beam between sections, but even to improve it by placing another solenoid at the exit of a section followed by an appropriate drift. If this drift is treated in a manner similar to stages 2 and 3 discussed above, then in fact the new waist at the entrance to the second section will be smaller, and the resulting emittance of the beam matched to the IE in the following sections will be lower than otherwise. In principle, one can treat each of the three drift spaces between accelerating sections in this manner.

For a non-uniform temporal charge distribution at the cathode, rms emittance matching provides perhaps the closest match for the largest portion of the beam [30]. For rms emittance matching, the solenoidal field is adjusted to match a longitudinal slice close to one
sigma in the charge distribution to the IE. Since the motion of the other slices around the IE is stable, one obtains an emittance correction that is optimum even though the correction for some slices will not result in the real emittance minimum.

This discussion assumes that the initial solenoid is placed so that the axial field extends from \( z = \lambda / 2 \) to \( z = (7/4) \lambda \). Moving the solenoid downstream along the axis will allow the beam to expand more than it would otherwise, resulting in beam oscillations. It is important to keep the amplitude of these oscillations small, since whenever the beam oscillations leave the linear (i.e., perturbative) regime, anharmonic components are introduced in the plasma frequency (i.e., the frequency becomes dependent on the beam size) making it more difficult to correct the emittance for the mismatched slices [31].

### 6.2.2 System Description

Linac 0 consists of four SLAC-type 3-m S-band accelerator sections, associated solenoids, and necessary drift sections with diagnostics. It is preceded by the rf gun and diagnostic section (see **Section 6.1.1, rf Photocathode Gun**) and followed by a second diagnostic section and an achromatic bend system (the low-energy dog leg) and associated instrumentation that brings the beam into Linac 1 (see **Section 7.6.1, Low-Energy Dog Leg**). The overall layout of the photoinjector system is shown in **Fig. 6.2-1**. The overall length of the photoinjector from the photocathode to the last accelerator section output flange is 15.8 m, including 4 drift sections of 75, 47, 105, and 105 cm respectively.

The rf distribution system is also shown in **Fig. 6.2-1**. Two unSLEDed 5045 klystrons are required, one to power the gun and the first two 3 m sections and the other for the last two 3 m sections. As shown in the figure, high power rf phase shifters and attenuators will allow the rf phase and amplitude for the rf gun and the first two 3 m sections to be controlled independently.

**Figure 6.2-1.** Overall layout of the LCLS photoinjector showing the rf gun, Linac 0, and the low-energy dog leg, with drift sections and diagnostics indicated.
The nearest klystron stations to the photoinjector are K20-3 and K20-4. Since these klystrons will not be used by PEP-II, they can be rerouted to the LCLS photoinjector using penetrations P20-5 and P20-7 respectively. In the future, should these stations need to be restored to the 50-GeV linac, two of the downstream stations which will be permanently liberated by the LCLS chicane installations can be moved with modest effort to be near penetrations P20-8 and P20-9 and rectangular waveguide (RWG) of a reasonable length installed to feed the rf gun and Linac 0.

The gun solenoid is 20 cm in length and is located 19.8 cm downstream of the photocathode as shown in Fig. 6.1-3. Two linac solenoids, each 70 cm in length, are located at the end of accelerating sections 2 and 3 respectively.

The beamline diagnostics upstream of Linac 0 are described in Section 6.1.1, Beamline. In Linac 0, after each accelerator section there will be a BPM, a current monitor, and a screen. In addition, between the second and third sections, an X-band cavity will be placed alongside a ceramic gap in the beamline. The charge-normalized rf intensity generated in this cavity as an electron bunch passes can be used as an aid in minimizing the bunch length [32]. The beamline diagnostics downstream of Linac 0 are described in Section 7.7, Transverse Emittance Diagnostics.

6.2.3 Emittance Compensation in Linac 0

Emittance growth in the photoinjector from the rf gun through the end of Linac 0 has been studied using PARMELA simulations. The electric field map of the gun was obtained with SUPERFISH and directly used in PARMELA. SUPERFISH was also used to simulate the fields in the traveling-wave accelerating sections, and space harmonics were calculated to be used in PARMELA. rf fields were assumed to be cylindrically symmetric, which seems to be a reasonable assumption since, as discussed in Section 6.1.1, Symmetrization, the dipole rf fields which are normally dominant in an rf gun will be largely eliminated in this gun.

A magnetic field map for the solenoid magnets at the gun was produced using POISSON and passed to PARMELA. The air core solenoids between the accelerator sections are represented with single coils with appropriate strength to accurately represent the magnetic field from each. The magnetic and electric fields in the gun and accelerator region were adjusted to minimize the normalized emittance at 150 MeV. The peak electric field at the cathode is 150 MV/m. The laser pulse is injected 57° ahead of the peak.

In the first two 3-m sections, where the gradient is 7 MV/m, a 1.5% energy spread for the full beam is introduced to help in emittance compensation by placing the centroid of the beam ~5° ahead of the rf crest. This energy spread is removed in the last two 3 m sections, where the gradient is 17 MeV/m, by phasing the rf such that the beam is slightly behind the crest.
The magnetic field in the emittance compensation solenoid at the gun is slightly less than 3 kG with an effective length of ~20 cm, while the solenoid between the accelerating sections is slightly greater than 3 kG with an effective length of 70 cm.

The edge of the laser spot at the cathode will have a radius of ~0.9 mm. The spot size is dictated by trying to balance the effects of space charge and rf on emittance growth in the gun itself. At the entrance to the third 3 m section, the beam energy is ~50 MeV so that space charge effects are much reduced. On the other hand, the rf field gradient in this section is more than double that of the previous two sections, so for this reason the beam radius is purposely reduced—using a solenoid between the second and third 3 m sections—in order to more nearly balance the space charge and rf effects on emittance growth.

The transverse charge distribution at the cathode is assumed to be uniform, but the temporal shape will be a Gaussian with an rms sigma of 4.4 ps truncated at ±2 sigma, resulting in an overall rms length of 3.8 ps. The use of a truncated Gaussian rather than a uniform distribution is dictated by the beam dynamics of the downstream linac and compressor systems. See Chapter 7.

A summary of the beam parameters at the end of Linac 0 based on PARMELA simulations using the input parameters given in Table 6.2-1 is shown in Table 6.2-2. The beam distribution predicted by PARMELA under these same conditions is shown in Fig. 6.2-2.

Table 6.2-1. Input Parameters for PARMELA Simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge at cathode</td>
<td>1.1 nC</td>
</tr>
<tr>
<td>Longitudinal charge distribution at cathode</td>
<td>Truncated Gaussian</td>
</tr>
<tr>
<td>Transverse charge distribution at cathode</td>
<td>Uniform</td>
</tr>
<tr>
<td>Equivalent rms bunch length at cathode</td>
<td>3.8 ps</td>
</tr>
<tr>
<td>Bunch radius at cathode</td>
<td>0.9 mm HWHM</td>
</tr>
<tr>
<td>Peak rf field at cathode</td>
<td>150 MV/m</td>
</tr>
<tr>
<td>Injection phase</td>
<td>57° ahead of rf peak</td>
</tr>
<tr>
<td>Gradient of accelerator sections 1 and 2</td>
<td>7 MeV/m</td>
</tr>
<tr>
<td>Gradient of accelerator sections 3 and 4</td>
<td>17 MeV/m</td>
</tr>
<tr>
<td>Strength of gun solenoid</td>
<td>~3150 G</td>
</tr>
<tr>
<td>Strength of linac solenoids</td>
<td>~3300 G</td>
</tr>
</tbody>
</table>
Table 6.2-2. Electron Beam Parameters at End of Linac 0.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>1.0 nC</td>
</tr>
<tr>
<td>Halo population</td>
<td>7.7%</td>
</tr>
<tr>
<td>rms pulse length</td>
<td>2.3 (0.69) ps(mm)</td>
</tr>
<tr>
<td>Energy</td>
<td>150.5 MeV</td>
</tr>
<tr>
<td>rms relative energy spread</td>
<td>0.13%</td>
</tr>
<tr>
<td>Normalized rms core emittance</td>
<td>1.1 $\pi$ mm-mrad</td>
</tr>
</tbody>
</table>

The transverse normalized emittance as a function of z is shown in Fig. 6.2-3. Excluding the halo (7.7% of the charge), the normalized emittance of the beam at 150 MeV is 1.1 $\pi$ mm-mrad. If a longitudinally square charge distribution with a rise- and fall-time of <1 ps were produced at the gun, then the emittance at 150 MeV would decrease to 0.95 $\pi$ mm-mrad excluding the halo (only 3% of the charge in this case).
6.3 References


3 D.T. Palmer et al., Proc. of the 1995 Particle Accelerator Conference (1995), p. 982. In this reference it is pointed out that the dipole emittance term has been suppressed by an order of magnitude to the level of 0.1 \( \pi \) mm-mrad, implying that in the unsymmetrized case the dipole emittance term would be 1 \( \pi \) mm-mrad. See also B. Dwersteg et al., “rf Gun design for the TESLA VUV Free Electron Laser,” contributed to FEL ’96, August 26-31, 1996, Rome, Italy.

4 In the case of the symmetrized gun being used at BNL, no significant dipole mode was found. In this case the adjustable short is used for diagnostic purposes only.


6 For the LCLS injector, energies above 150 MeV are taken to be high enough to eliminate the effects of space charge. See Section 6.2.1.


9 I. Ben-Zvi (BNL), private communication (1997).


The crest of the rf is defined as zero phase.

The gain per pass in Ti:sapphire amplifiers is sufficient to get from 1 nJ to a few mJ in eight (8) passes. For example, see S. Backus et al., Opt. Lett. 20 (1995) 2000.


For ultrafast laser pulses, the effects of group velocity walkoff and nonlinear phase effects must be considered when designing the conversion stage.


For the LCLS injector, energies above 150 MeV are taken to be high energy.


L. Serafini, UCLA, private communication (March 1997).

Ibid., Serafini.

TECHNICAL SYNOPSIS

In order for the FEL to operate in the saturation regime with a 100 m long undulator, a high electron peak current in a small transverse and longitudinal emittance is required. For the LCLS operating at 1.5 Å, the design values are a peak current of 3.4 kA with a transverse normalized emittance of 1.5 \( \pi \) mm-mrad at 14.3 GeV. Since the rf photocathode gun can produce 1 nC in a length of 3 psec rms, corresponding to a peak current of 100 A, the bunch has to be compressed by a factor of about 30 before it enters the undulator. The compressors consist of a series of magnetic chicanes, arranged and located such that the non-linearities in the compression and acceleration process (longitudinal wakefields, rf curvature, and second order momentum compaction) are partially cancelled. An optimum choice of parameters compensates the correlated energy spread after the final compression and desensitizes the system to phase and charge variations. The energy of the first compressor is 280 MeV. The choice of energy for the first compressor is set by the need to minimize space charge effects at the lower energy end, while the upper limit is set by the desire to compress the bunch early in the linac to ease transverse wakefields. In the first compressor, the bunch length shrinks from 1 mm to 390 \( \mu \)m rms. The second compressor produces a 20 \( \mu \)m bunch. The energy of the second compressor, 6 GeV, was chosen as an optimum between the conflicting requirements of longitudinal emittance dilution due to synchrotron radiation effects and longitudinal wakefields. The design of the second compressor is set by the need to reduce coherent synchrotron radiation effects, which is most pronounced for short bunches. Since the energy spread generated by the coherent synchrotron radiation is correlated along the bunch, its effect on the transverse emittance is compensated by introducing a double chicane and optical symmetry to cancel longitudinal-to-transverse coupling. With the double chicane compensating scheme, the emittance growth in the LCLS, due to coherent synchrotron radiation, is expected to be 3–5%. Simulations have also been made which calculate emittance dilution effects in the linac due to transverse wakefields and anomalous momentum dispersion, each of which arise with component misalignments. These simulations include realistic correction techniques and successfully demonstrate the level of transverse emittance preservation required.

7.1 Introduction and Overview

In order to reach photon power saturation in a reasonable length undulator, a high electron peak current is required. For a 1.5 Å LCLS with transverse normalized emittances of
1.5 \text{ mm-mrad} (1.5 \text{ \mu m}), a peak current of 3.4 kA at 1 nC and 14.3 GeV is desired. These values correspond to an rms bunch length of \sim 20 \text{ \mu m}, which is not possible in present rf photoinjectors due to space charge limitations. Therefore the bunch is accelerated and compressed in a series of linacs and magnetic chicanes. The accelerator must also preserve the transverse emittance produced by the rf photoinjector. Undulator energy spread requirements at 15 GeV are <0.1% and <0.02% for the rms coherent (correlated) and incoherent (uncorrelated) components, respectively. Fig. 7.1-1 shows a schematic of the LCLS accelerator. Beam energy (E), rms bunch length (\sigma_z), and rms relative energy spread (\sigma_\delta) are indicated at points along the accelerator, as are section parameters, such as length (L), rf phase (\phi_{rf}) , and momentum compaction (R_{56}).

![Figure 7.1-1](image)

Figure 7.1-1. LCLS bunch compression and acceleration schematic. The dog legs (DL1 and DL2) are simple transport lines and have no effect on bunch length. BC2 is a double chicane to decouple coherent synchrotron radiation from the horizontal emittance (see BC2 section). Acceleration crest is at \phi_{rf} = 0.

There are four linac sections and four bending sections. The first linac (Linac 0 or L0) is a new section installed adjacent to the existing SLAC linac in sector-20, which accelerates and emittance compensates the 1 mm long bunch from the rf gun to 150 MeV (Section 6). The first bend section (low energy dog leg or DL1) simply injects the beam into the SLAC linac at the 20-5A location. Linac 1 (L1) accelerates the 1 mm bunch “off-crest” to 280 MeV and generates an energy correlation along the bunch so that the first chicane bunch compressor (BC1 in sector-20) shortens the bunch to 0.4 mm. Linac 2 (L2) then accelerates the bunch to 6 GeV and also generates an energy correlation in order that the double chicane system (BC2 in sector-25) compresses the bunch to its final value of \sim 20 \text{ \mu m}. Finally, Linac 3 (L3) nominally accelerates the beam to 15 GeV (a range of 5-17 GeV is available) and also cancels the correlated energy spread with the geometric longitudinal wakefield of the rf-structures. The high-energy dog leg (DL2) is designed for energy and energy spread analysis, transverse emittance measurement and final beam transport, and matching into the undulator. Each system, its parameters, and design criteria as well as beam dynamics in the LCLS accelerator are discussed in the following sections.
7.2 Compression and Longitudinal Dynamics

To achieve the high peak current and small energy spread in the undulator, the bunch must be compressed in a series of magnetic chicanes. These are arranged and located such that non-linearities in the compression and acceleration process (longitudinal wakefields, rf curvature, and second order momentum compaction) are partially canceled. With a careful arrangement of compression and acceleration parameters, the bunch compression process can be made more linear, which reduces the minimum bunch length achievable. An optimum choice of parameters compensates the correlated energy spread after final compression and desensitizes the system to phase and charge variations.

7.2.1 Bunch Compression Overview

The bunch is compressed by accelerating with an off-crest rf phase, thereby introducing a correlated energy spread along the bunch. This process is followed by a bending section with linear path length dependence on particle energy. The final energy \( E_f \) of a particle, which is at axial position \( z_i \) with respect to bunch center, after nominal acceleration from \( E_{i0} \) to \( E_{f0} \) at an rf phase \( \phi_0 \) (crest at \( \phi_0 = 0 \) and \( \phi_0 \neq \pi/2 \)) is given by

\[
E_f = E_i + (E_{f0} - E_{i0}) \cos(\phi_0 + \Delta \varphi + 2\pi z_i / \lambda) / \cos \phi_0 ,
\]

(7.2.1)

with \( \Delta \varphi \) as a phase error and \( \lambda \) the rf wavelength. The relative energy deviation after acceleration, \( \delta_f \equiv (E_f - E_{i0}) / E_{f0} \), is then

\[
\delta_f \approx \delta_i + \left[ 1 - \frac{E_{i0}}{E_{f0}} \right] \left[ \cos(\phi_0 + \Delta \varphi) - \left( \frac{2\pi z_i / \lambda}{\cos \phi_0} \right) \sin(\phi_0 + \Delta \varphi) - 1 \right] ,
\]

(7.2.2)

where \( \delta_i \equiv (E_i - E_{i0}) / E_{f0} \) represents small injection energy deviations scaled to the final energy. Wakefields are ignored and it is assumed that \( z_i \ll \lambda/2\pi \). From the approximate linear energy dependence, coefficient is defined as

\[
k(\varphi) = \frac{\partial \delta_f}{\partial z_i} = \frac{2\pi}{\lambda} \left[ 1 - \frac{E_{i0}}{E_{f0}} \right] \frac{\sin(\phi_0 + \Delta \varphi)}{\cos \phi_0} .
\]

(7.2.3)

After a bending section with path length dependence, \( R_{56} \), where \( z_f = z_i + R_{56} \delta \), the final bunch length, \( \sigma_{zf} \), and energy spread, \( \sigma_{\delta f} \), are functions of the initial bunch length, \( \sigma_{zi} \), and energy spread, \( \sigma_{\delta i} \), (assuming \( \langle z_i \delta_i \rangle = 0 \)).

\[
\sigma_{zf} = \sqrt{(1 + kR_{56})^2 \sigma_{zi}^2 + R_{56}^2 \sigma_{\delta i}^2} = |1 + kR_{56}| \sigma_{zi}
\]

\[
\sigma_{\delta f} = \sqrt{k^2 \sigma_{zi}^2 + \sigma_{\delta i}^2} = k \sigma_{zi}
\]

(7.2.4)
The injection energy spread, scaled to the final energy, \( \sigma_{\delta i} \), is typically insignificant. Minimum bunch compression is achieved for \( R_{56} = -1/k \), with under-compression at \( |R_{56}| < 1/|k| \) and over-compression for \( |R_{56}| > 1/|k| \). For a magnetic chicane, \( R_{56} > 0 \) (bunch head at \( z > 0 \)) and compression is achieved with \( k < 0 \) (\( 0 < \phi_0 < \pi/2 \), i.e. bunch head at a lower energy than bunch tail).

Since \( k \) is a function of \( \Delta \varphi \), the bunch length is sensitive to phase variations (injector timing jitter). For a single stage compressor, the bunch length change, \( \Delta \sigma_{zf} \) for a phase change, \( \Delta \varphi \), is given by [1]

\[
\frac{\Delta \sigma_{zf}}{\sigma_{zf0}} = -\left( \frac{\sigma_{zf0}}{\sigma_{zf0}} + 1 \right) \Delta \varphi \cot \varphi_0 ,
\]

with under-compression expressed by the minus sign and over-compression by the plus sign. For \( \varphi_0 = 20^\circ \) and a compression ratio of \( \sigma_{zf}/\sigma_{zf0} = 33 \), phase jitter of only \( 0.1^\circ \) S-band (0.1 psec) results in final bunch length (or undulator peak current) jitter of \( \sim 16\% \). Fig. 7.2-1 shows the required \( R_{56} \) and also bunch length sensitivity to phase jitter versus rf phase for a single stage compressor with compression ratios of both 33 and 3.3 (in linear approximation).

![Figure 7.2-1](image.png)

**Figure 7.2-1.** The required \( R_{56} \) (a) and the relative bunch length change per 0.1° phase jitter (b) for a single stage compressor and linac which accelerates a 1 mm bunch from 80 MeV to 250 MeV at an rf phase of \( \varphi_0 \) for a final bunch length of both 30 \( \mu \)m (solid) and 300 \( \mu \)m (dashed).

Clearly, a single stage compressor is too sensitive. Furthermore, the final bunch length of a single stage compressor is limited by non-linearities, such as rf curvature, which make compression from 1 mm to 20 \( \mu \)m very difficult. However, a two-stage compression system brings about cancellations that can reduce this phase jitter sensitivity by an order of magnitude. This arrangement allows the first compressor to be located at relatively low energy so that the next linac accelerates a shorter bunch. The reduced transverse wakefield of the shorter bunch provides looser quadrupole and rf-structure alignment tolerances.
Conversely, a single compression stage would need to be placed at a high enough beam energy so that space charge forces are not significant for a 20 $\mu$m bunch. This system prolongs the acceleration of a long bunch (~1 mm) through more linac, which tightens alignment tolerances. For these reasons, a two-stage compressor is used.

The linear relations for a two-stage bunch compression system are similarly expressible. For a first linac which accelerates from $E_0$ to $E_1$ at rf phase $\phi_1$ followed by a first compressor with $R_{56} \equiv \alpha_1$, then a second linac which accelerates from $E_1$ to $E_2$ at rf phase $\phi_2$ followed by a second compressor with $R_{56} \equiv \alpha_2$, the final bunch length, $\sigma_{z_2}$, and energy spread, $\sigma_{\delta_2}$, are approximately

$$\sigma_{z_2} = \sqrt{\left[(1 + \alpha_1 k_1)(1 + \alpha_2 k_2) + \alpha_2 k_1 E_1 / E_2 \right]^2 \sigma_{z_0}^2 + \left[\alpha_1 (1 + \alpha_2 k_2) E_0 / E_1 + \alpha_2 E_0 / E_2 \right]^2 \sigma_{\delta_0}^2},$$

$$\sigma_{\delta_2} = \sqrt{(1 + \alpha_1 k_1)^2 \sigma_{\delta_0}^2 + (\alpha_1 E_0 / E_1)^2 \sigma_{\delta_0}^2}. \tag{7.2.6}$$

In this case, $\sigma_{\delta_0}$ is the relative energy spread at injection to the first linac (at energy $E_0$) and $\sigma_{z_0}$ is the initial bunch length there. Note, $k_1$ is a function of the rf phase and initial and final energies of Linac 1 as in Eq. 7.2.3. The value for $k_2$, however, depends on the total phase error, which may have contributions from both Linac 1 and Linac 2.

$$k_2 = -\frac{2\pi}{\lambda} \left(1 - \frac{E_1}{E_2}\right) \frac{\sin(\phi_2 + (1 + \alpha_1 k_1) \Delta \phi_1 + \Delta \phi_2)}{\cos \phi_2} \tag{7.2.7}$$

It appears that the above relationships can be used to find a minimum final bunch length sensitivity to injection phase jitter, $\Delta \phi_1$. In fact, longitudinal wakefields, rf curvature, and second order path length dependence, $T_{566}$, complicate these calculations sufficiently to invalidate this simple linear model. The above relationships can help to understand sensitivities, but the optimum stability is best found with a complete computer simulation that includes all non-linearities (see Section 7.2.3).

### 7.2.2 Parameters

The final design parameters for the LCLS two-stage bunch compression system are summarized graphically in Fig. 7.1-1 and numerically in Table 7.2-1 below.

A string of three linacs and two chicane sections are used to compress a 1 mm rms bunch at 150 MeV to 20 $\mu$m at 15 GeV. The final bunch is slightly under compressed, so it is actually possible to compress it even further. However, many severe challenges arise with a shorter bunch, such as coherent synchrotron radiation in BC2 (see Section 7.4) and resistive wall and vacuum chamber roughness wakefields in the undulator (see Section 8.7). These effects can quickly become intolerable as the bunch further shortens. Therefore the final compression is limited to no less than ~20 $\mu$m rms. This achieves the 3.4 kA peak current required and yet allows management of these micro-bunch limitations. A longer bunch is also
operationally possible if the transverse “slice” emittance achieved is less than 1.5 $\pi$ mm-mrad (e.g., 35 $\mu$m at 1.1 $\pi$ mm-mrad, see Fig. 5.5-1).

**Table 7.2-1.** LCLS bunch compression and acceleration parameters per beamline section.

<table>
<thead>
<tr>
<th>Beamline</th>
<th>$E_{\text{in}}$</th>
<th>$E_{\text{out}}$</th>
<th>$\sigma_{z_{\text{in}}}$</th>
<th>$\sigma_{z_{\text{out}}}$</th>
<th>$\sigma_{\delta_{\text{in}}}$</th>
<th>$\sigma_{\delta_{\text{out}}}$</th>
<th>$\varphi_{\text{rf}}$</th>
<th>$R_{56}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac 1</td>
<td>0.15</td>
<td>0.28</td>
<td>1</td>
<td>1</td>
<td>0.2</td>
<td>2.3</td>
<td>40</td>
<td>—</td>
</tr>
<tr>
<td>BC1</td>
<td>0.28</td>
<td>0.28</td>
<td>1</td>
<td>0.39</td>
<td>2.3</td>
<td>2.3</td>
<td>—</td>
<td>27.0</td>
</tr>
<tr>
<td>Linac 2</td>
<td>0.28</td>
<td>6.0</td>
<td>0.39</td>
<td>0.39</td>
<td>2.3</td>
<td>1.1</td>
<td>29</td>
<td>—</td>
</tr>
<tr>
<td>BC2</td>
<td>6.0</td>
<td>6.0</td>
<td>0.39</td>
<td>0.02</td>
<td>1.1</td>
<td>1.1</td>
<td>—</td>
<td>35.5</td>
</tr>
<tr>
<td>Linac 3</td>
<td>6.0</td>
<td>15.0</td>
<td>0.02</td>
<td>0.02</td>
<td>1.1</td>
<td>&lt;0.1</td>
<td>0</td>
<td>—</td>
</tr>
</tbody>
</table>

For this ultra-relativistic beam, the bunch length cannot change through a linac (excluding L0), and the energy spread does not significantly change through the chicanes. Phase and current jitter tolerances are described in Section 7.2.4.

The first compression is from 1 mm to 390 $\mu$m. This is near the limit set by non-linearities due to $T_{566}$ and S-band rf. A shorter bunch is possible, but larger energy tails are generated at 15 GeV. This choice, for the parameters of Table 7.2-1, also best minimizes final bunch length sensitivity to injector timing jitter. Finally, the chosen value of 390 $\mu$m also optimally scales the longitudinal wakefield in Linac 2 so that a cancellation is established between the Linac 2 wake and the non-linearities (rf curvature and $T_{566}$) of the Linac 1/BC1 pair. The parameters are not a unique solution but represent a workable set. A qualitative summary of the effects of changes to the critical compression parameters is listed in Table 7.2-2. The two $R_{56}$ values are not considered free parameters here since their values depend on rf phases and other factors.

The lower limit on the choice for BC1 energy is set by space charge forces of the shorter bunch with 280 MeV at a safe energy. The upper limit is set by the desire to initially compress the bunch early in the linac to ease transverse wakefields. The chosen energy of 280 MeV also desensitizes the system to injector timing jitter and is a practical solution for L1, which consists of three 3-meter S-band sections at an rf phase of 40° and a gradient of 19 MV/m. The location (energy) of BC2 is set by the need to produce a very small energy spread at 15 GeV. This involves a balance between the longitudinal geometric wakefield in L3 (scales with Linac 3 length) and the $\delta_z$ correlation just after BC2. Simulations with BC2 at the 6 GeV location (described below) produce the required beam conditions at 15 GeV. Other factors, including synchrotron radiation, are discussed in more detail in Section 7.4 (BC2) and Section 7.5 (BC1).
Table 7.2-2. Bunch Compression Parameter Trade-Offs: A qualitative summary of the effects of changes to the bunch compression parameters. Only limitations are noted. An “increase” of rf phase, \( \varphi \), refers to moving farther off rf crest and \( \sigma_z \) is the intermediate bunch length (after BC1).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Increase Parameter</th>
<th>Decrease Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_z = 390 \mu m )</td>
<td>• Insufficient L2 wake compensation for L1/BC1 non-linearities.</td>
<td>• Reach BC1 compression limit—bunch begins to fold over itself.</td>
</tr>
<tr>
<td></td>
<td>• Can increase timing jitter sensitivity.</td>
<td>• Can increase timing jitter sensitivity.</td>
</tr>
<tr>
<td>(</td>
<td>\varphi_1</td>
<td>= 40^\circ )</td>
</tr>
<tr>
<td></td>
<td>• Inefficient acceleration.</td>
<td>• Increased BC1 strength and ( \Delta \varepsilon ) due to coherent synchrotron radiation (CSR).</td>
</tr>
<tr>
<td>(</td>
<td>\varphi_2</td>
<td>= 29^\circ )</td>
</tr>
<tr>
<td></td>
<td>• Inefficient acceleration.</td>
<td>• Increased BC2 strength and CSR ( \Delta \varepsilon ).</td>
</tr>
<tr>
<td>( E_1 = 280 \text{ MeV} )</td>
<td>• Longer L1( \rightarrow ) stronger L1 transverse wakes and increased L1 ( \Delta \varepsilon ).</td>
<td>• Smaller ( k_1 \rightarrow ) increase BC1 chicane strength and CSR ( \Delta \varepsilon ).</td>
</tr>
<tr>
<td></td>
<td>• Can increase timing jitter sensitivity.</td>
<td>• Increased space charge forces.</td>
</tr>
<tr>
<td>( E_2 = 6 \text{ GeV} )</td>
<td>• Increase BC2 ( \Delta \varepsilon ) due to incoherent synchrotron radiation or must lengthen BC2.</td>
<td>• Longer L3( \rightarrow ) L3 wake too large—over-compensation of L2 energy spread.</td>
</tr>
<tr>
<td></td>
<td>• Shorter L3( \rightarrow ) insufficient L3 wake for L2 energy spread compensation.</td>
<td>• Shorter L2( \rightarrow ) insufficient L2 wake compensation for L1/BC1 non-linearities.</td>
</tr>
</tbody>
</table>

7.2.3 Longitudinal Wakefields and Non-linearities

Geometric Wakefields

In this section the asymptotic longitudinal geometric wakefield is used in a full tracking simulation. A more detailed description of the wakefields for the SLAC S-band accelerating structures as well as a justification for the use of the asymptotic wake is given in Section 7.8. The simulation [2] includes non-linearities such as \( T_{660} \), longitudinal geometric wakefields of the rf-structures, and sinusoidal rf curvature and proceeds from the LCLS injector to the undulator entrance. Transverse effects do not generally couple back into the longitudinal plane and so are ignored here. The simulation also ignores space charge effects since the compression process takes place at energies above 150 MeV.

Figure 7.2-2 shows the longitudinal phase space, energy distributions, and axial (z) distributions at various points in the compression process. The longitudinal phase space at 150 MeV used in the simulations is similar in both distributions and correlation to the output of space-charge dominated injector simulations using PARMELA [3]. The input beam used is gaussian cut at \( \pm 2\sigma \) in energy and axially with a 1 mm rms bunch length and 0.2% rms energy spread (after cuts) at 10 MeV and a bunch population of \( 6.3 \times 10^9 \) (after cuts). The axial distribution is a truncated gaussian, in order to minimize final bunch length sensitivity to injector timing jitter (see Section 7.2.4). Simulations using an initial uniform distribution
show more severe sensitivities to jitter by up to a factor of three. This choice represents a compromise between jitter sensitivity and transverse emittance compensation in the injector.

As Fig. 7.2-2 shows, the compression process has been arranged so that non-linearities such as rf-curvature and wakefield effects cancel, leaving a flat energy profile at 15 GeV. The final rms bunch length is 18 \( \mu \text{m} \) with >3.4 kA of peak beam current all along the bunch. Long tails exist in the energy distribution (shown at bottom right of Fig. 7.2-2). The core of the beam, however, has an rms energy spread of 0.035% with 85% of the particles contained within a \( \pm 0.15\% \) energy window. The remaining 15% of the beam has been cut out of Fig. 7.2-3 (15 GeV) to show the core beam more clearly while all particles are shown in Fig. 7.2-2. Note, the incoherent component of the final energy spread at any particular slice of the bunch core is <0.01% rms.

Figure 7.2-4 shows a progression of longitudinal phase space, on a fixed scale, through each compressor. The S-band rf and \( T_{566} \) quadratic curvature of L1/BC1 can be seen in Fig. 7.2-4(a-b). Wakefields in L2 produce mostly a quadratic curvature see in (c). Some of the curvature is cancelled by the \( T_{566} \) of BC2, but the tail of the bunch (right side) is over-compressed (see 6 GeV \( \delta z \) plot of Fig. 7.2-2) leading to the large spike in the \( z \)-distribution of Fig. 7.2-3 (upper right). Finally, the longitudinal wakefield of L3 flattens most of the coherent energy spread into the core distribution of Fig. 7.2-3 (lower right). This is a critical cancellation which provides the narrow energy spread and depends on the strength of the longitudinal wakefield in L3, the rf phase of L2, and the bunch length in L2.

Calculations of the longitudinal wakefield for the micro-bunch in L3 are believed to be accurate to \( \sim 10\% \) (see Section 7.8). In order to allow for this potential error in the magnitude of the wakefield, the compression systems require a range over which it may be tuned. To demonstrate the tuning range required, a simulation was also run where the wakefield in L3 was arbitrarily scaled up by a factor of 1.5 and the BC2 \( R_{56} \) and L2 rf phase were re-tuned. For this extreme case, the bunch length and energy spread at the end of L3 are still recoverable to the conditions of Fig. 7.2-3. The re-tuning produces an increase of the L2 rf phase (29° \( \rightarrow \) 34°: farther off crest) and decreased BC2 \( R_{56} \) (35.5 mm \( \rightarrow \) 28.2 mm: a weaker chicane). Note, this is a desirable condition since a higher bunch charge will also increase the L3 wakefield, but the BC2 chicane bends are then reduced in strength. A weakened chicane matches a higher bunch charge, and the effects of coherent synchrotron radiation in BC2 are then, for small changes, nearly independent of charge.

Resistive Wall Wakefields

In addition to geometric longitudinal wakefields, the micro-bunch in L3 and beyond experiences a longitudinal resistive wall wakefield which also introduces a coherent energy spread along the bunch. For the linac and transport lines leading up to the undulator, this is a small effect and is described in detail in Section 7.8. The rms relative energy spread induced by the resistive wall effect in the accelerator and the transport lines prior to the undulator is expected to be \( \sim 0.02\% \) (see Fig. 7.8-6). The associated transverse wakefields are insignificant.
Figure 7.2-2. Axial (left column) and energy (center column) distributions and longitudinal phase space (right column) after gun at 10 MeV (top row), after DL1 at 150 MeV (2nd row), after BC1 at 280 MeV (3rd row), after BC2 at 6 GeV (4th row), and at the undulator at 15 GeV (bottom row). All effects discussed are included except for resistive wall wakefields (bunch head at left).
Figure 7.2-3. Longitudinal phase space (lower right), axial (upper left) and energy (upper right) distributions and bunch induced voltage (lower left) at undulator input (15 GeV). After cutting 15% of the charge with high energy tails (see Fig. 7.2-2), the final rms bunch length is 18 μm and the rms energy spread is 0.035% in this ±0.15% energy window. Geometric wakefields, $T_{56}$, rf-curvature, and synchrotron radiation of all bends are included (bunch head at left).

Figure 7.2-4. Longitudinal phase space at (a) start of BC1, (b) end of BC1, (c) start of BC2 and (d) end of BC2. End of linac is shown in Fig. 7.2-3. Parameters are those of Table 7.2-1 with $N = 6.3 \times 10^9$ and geometric wakefields and $T_{56}$ included (bunch head at left).
7.2.4 Beam Jitter Sensitivities

Although it has been optimized, the two-stage compressor is still quite sensitive to beam phase and bunch population jitter. **Fig. 7.2-5** shows the peak current \( I \approx 1/\sigma_z \) variation versus relative bunch population, \( \Delta N/N_0 \), and timing (phase), \( \tau \), jitter at the injector. **Table 7.2-3** lists tolerances for rf phases, chicane bend power supplies and energy jitter for L1, L2, BC1 and BC2. Each tolerance corresponds to a 10% rms bunch length variation. These tolerances represent jitter that is too fast to be corrected with feedback.

![Figure 7.2-5.](image)

**Figure 7.2-5.** Relative peak undulator current, \( I/I_0 \), and FWHM relative energy spread versus bunch population jitter, \( \Delta N/N_0 \), and timing jitter, \( \tau \), at injector \( (N_0 = 6.3\times10^9, I_0 \approx 3.5 \text{ kA}, \sigma_0 = 18 \mu\text{m}) \). Geometric wakefields, \( T_{566} \) and rf-curvature are all included.

The pulse-to-pulse rf phase tolerances per linac are quite tight. However, the common mode phase tolerance for the entire system is an order of magnitude looser. The gun timing jitter tolerance of 0.8 psec rms has been optimized assuming a gaussian axial distribution at the gun cut at \( \pm 2\sigma \) (see top of **Fig. 7.2-2**). When new compression parameters are set up for a uniform gun distribution, however, the best timing jitter tolerances found are more than a factor of two tighter than for the gaussian case.
Individual tolerances to provide <10% bunch length (or peak current) jitter. Timing jitter with a gaussian distribution is assumed for the quadratic $\tau$ sensitivity where a mean bunch length increase of 7% is also produced. All other sensitivities are linear. The L1 rf phase tolerance increases to 0.64° when the beam energy at BC1 is held constant (e.g., using a feedback system).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>rms Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 rf phase</td>
<td>$\varphi_{\text{rf}1}$</td>
<td>deg</td>
<td>0.14</td>
</tr>
<tr>
<td>L2 rf phase</td>
<td>$\varphi_{\text{rf}2}$</td>
<td>deg</td>
<td>0.13</td>
</tr>
<tr>
<td>L1, L2, L3 common rf phase</td>
<td>$\varphi_{\text{rf}1} = \varphi_{\text{rf}2} = \varphi_{\text{rf}3}$</td>
<td>deg</td>
<td>0.8</td>
</tr>
<tr>
<td>BC1 chicane bend supply</td>
<td>$\Delta B_{1}/B_1$</td>
<td>%</td>
<td>0.24</td>
</tr>
<tr>
<td>BC2 1st chicane supply</td>
<td>$\Delta B_{21}/B_{21}$</td>
<td>%</td>
<td>0.70</td>
</tr>
<tr>
<td>BC2 2nd chicane supply</td>
<td>$\Delta B_{22}/B_{22}$</td>
<td>%</td>
<td>4.80</td>
</tr>
<tr>
<td>L1 final energy jitter</td>
<td>$\Delta E_1/E_1$</td>
<td>%</td>
<td>0.28</td>
</tr>
<tr>
<td>L2 final energy jitter</td>
<td>$\Delta E_2/E_2$</td>
<td>%</td>
<td>0.52</td>
</tr>
<tr>
<td>Gun timing jitter</td>
<td>$\tau$</td>
<td>psec</td>
<td>0.80</td>
</tr>
<tr>
<td>Initial bunch population jitter</td>
<td>$\Delta N/N$</td>
<td>%</td>
<td>2.9</td>
</tr>
</tbody>
</table>

### 7.2.5 Energy Management and Overhead

Each linac section must operate with several spare klystrons to accommodate their inevitable failure rate (except L1, which operates on just one klystron). Table 7.2-4 lists, for each LCLS linac section, the total number of klystrons potentially available, $N_K$, the number of klystrons held in reserve, $N_R$, the maximum rf phase anticipated (a worst case estimate to include a tuning range), $|\varphi|_{\text{max}}$, the average energy gain per klystron, $\langle \Delta E \rangle_K$, the beam loading energy loss, $\Delta E_B$, and the resulting maximum energy achievable, $E_{\text{max}}$, (assuming an injection energy, $E_i$).

| Linac | $N_K$ | $N_R$ | $|\varphi|_{\text{max}}$ | $\langle \Delta E \rangle_K$ | $\Delta E_B$ | $E_i$ | $E_{\text{max}}$ |
|-------|-------|-------|--------------------------|-----------------------------|--------------|------|-----------------|
|       | deg   | MeV   | MeV                      | GeV                        | GeV          |      |                 |
| L1    | 1     | 0     | 45                       | 192                        | $\Delta E_B$ | 0.15 | 0.285           |
| L2    | 34    | 4     | 34                       | 230                        | 30           | 0.28 | 5.97            |
| L3    | 45    | 5     | 0                        | 228                        | 63           | 6.00 | 15.1            |
The maximum energy achievable per linac is calculated using

\[ E_{\text{max}} = E_i + (N_K - N_R)(\Delta E)_K \cos \varphi_{\text{max}} - \Delta E_B, \]  

(7.2.8)

where the beam loading is based on a bunch population of \(6.3 \times 10^9\), LCLS bunch lengths, and a nominal rf accelerating gradient of 19.3 MV/m. For the average energy gain calculation, all existing linac structure lengths are used allowing for the required shortening of two 3 meter L1 sections and the removal of both the 20-5A section and the three 3 meter sections for BC1. Note, the rf phases used here are larger than nominal to provide some tuning range, and still a reasonable 12% of available klystrons are held in reserve.

These calculations include the necessary modifications of the existing SLAC linac (BC1 and BC2 insertions) which will eliminate four klystrons. This will nullify 910 MeV of unloaded energy gain. Other accelerating structure modifications and removals (DL1 insertion, L1 quadrupole additions and L2 wire scanners) will forego another 150 MeV for a total loss of 1.06 GeV of unloaded energy gain (with respect to the pre-LCLS linac). For future non-LCLS linac operation this energy is not easily recovered; however, the maximum energy available is still within \(~1\) GeV of the pre-LCLS linac maximum energy of \(~50\) GeV.

7.3 Transverse Linac Beam Dynamics

The LCLS accelerator is composed of four separate S-band linac sections (L0, L1, L2, and L3) each of which require individual lattice designs in order to best minimize transverse emittance dilution due to transverse wakefields and momentum dispersion, both of which are generated through component misalignments. Each section has its own particular beam parameters which motivate the optical design of that linac. For example, a large beam energy spread and short bunch length suggest weak focusing with large quadrupole spacing. Table 7.3-1 summarizes the four linacs and their various beam parameters. The final energy of L3 is also variable from 5 to 17 GeV through appropriate phasing and rf power. The rf phase angles of the various linacs as well as motivations for the length of each linac section are discussed in the section on bunch compression and longitudinal dynamics.

<table>
<thead>
<tr>
<th>Beam Parameter</th>
<th>Unit</th>
<th>L0</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial energy</td>
<td>GeV</td>
<td>0.007</td>
<td>0.150</td>
<td>0.280</td>
<td>6.0</td>
</tr>
<tr>
<td>Final energy</td>
<td>GeV</td>
<td></td>
<td>0.150</td>
<td>0.280</td>
<td>6.0</td>
</tr>
<tr>
<td>Active linac length</td>
<td>m</td>
<td>12</td>
<td>9</td>
<td>420</td>
<td>523</td>
</tr>
<tr>
<td>rf phase (crest at 0)</td>
<td>deg</td>
<td>variable</td>
<td>40</td>
<td>29</td>
<td>0</td>
</tr>
<tr>
<td>Initial rms energy spread</td>
<td>%</td>
<td>0.2</td>
<td>0.2</td>
<td>2.3</td>
<td>1.1</td>
</tr>
<tr>
<td>Final rms energy spread</td>
<td>%</td>
<td>0.2</td>
<td>2.3</td>
<td>1.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>mm</td>
<td>1.0</td>
<td>1.0</td>
<td>0.39</td>
<td>0.020</td>
</tr>
</tbody>
</table>
7.3.1 The L0 Linac

A description of the L0 linac is given in Chapter 6. L0 provides the initial acceleration and transverse emittance compensation from the rf gun. It is a new beamline constructed parallel to the existing SLAC linac in sector-20 displaced approximately 1 meter horizontally. It is composed of four 3 meter acceleration sections that need no quadrupole magnets. It is a space charge dominated system. Following L0 is an adjustable matching section and a transverse emittance diagnostic section, ED0 (see Section 7.7.1 and Fig. 7.6-1). The first dog leg, DL1 (see Section 7.6.1), then bends the beam onto the main SLAC linac axis and into the L1 linac section at the 20-5A location. The existing 3 meter rf-section there is removed to provide space for DL1 injection.

7.3.2 The L1 Linac

L1 initiates the compression process by accelerating off crest, thereby generating the necessary energy-\(\varepsilon\) correlation so the first chicane, BC1, will compress the bunch. L1 is composed of three existing 3 meter linac structures 20-5B, 20-5C, and 20-5D (20-5A is removed in order to inject). Because of the large rf phase angle and the long bunch, the rms energy spread in L1 rapidly increases from 0.2 to 2.3%. Therefore, both dispersion and transverse wakefields are potential emittance dilution mechanisms. At this energy, however, space charge forces are insignificant.

To choose the best focusing lattice for L1, several lattice designs have been simulated using LIAR [4]. This computer program calculates the transverse emittance dilution along a linac and includes both longitudinal and transverse wakefields, random quadrupole, BPM, and rf-structure misalignments and the dispersion these generate. It also provides various steering algorithms. Three different quadrupole spacing schemes were simulated where the betatron phase advance per cell was varied from 15° to 90° in 15° steps for each spacing scheme (18 total lattices simulated).

The three L1 lattice types are as follows:

1. Cut off ~18 cm from the ends of first two 3 m rf-sections so that one quadrupole-BPM-steering pair set is inserted between sections. The quadrupole spacing is then 3 m.

2. Same as 1 above, but also add two “wrap-around” quadrupoles (QWs) per 3 m section. (A “wrap-around” quadrupole is a large bore magnet that is installed around the outside of the rf-structure.) In this case, no further BPMs or steering coils can be added at the QWs. The quadrupole spacing is 1 m.

3. Same as 2 above, but with four rather than two QWs (maximum physical density allowed on one 3 m section). The quadrupole spacing is 0.6 m.

The simulations use 300\(\mu\)m rms random quadrupole, BPM, and rf-structure transverse misalignments (with gaussian distributions). These are pessimistic conditions in order to
optimize the lattice. The same 10 seeds were then run for each lattice and one-to-one steering was applied at each BPM. In all cases, BPMs and steering-coils are only placed between rf-sections—where they will actually fit. The results of these simulations are listed in Table 7.3-2.

Because there can be no BPMs at the new QWs, the increased quadrupole density and weaker focusing does not significantly improve emittance dilution. The results are similar enough to adapt the simplest lattice (type-1) which requires no QWs. In fact, beam-based alignment techniques in the SLAC linac are presently used to align quadrupoles and BPMs to ~100 µm rms [5]. Fig. 7.3-1 shows horizontal emittance growth versus phase advance/cell with and without transverse wake effects for lattice type-1. Error bars are the error on the mean over the 10 seeds. Beta-functions and beamline layout are shown in Fig. 7.3-2 for the type-1 lattice at the chosen 75°/cell.

Included in Fig. 7.3-2 and following L1 is the BC1 bunch compressor chicane (see Section 7.5). BC1 is followed by a second four-wire transverse emittance diagnostic section (ED1, see Section 7.7.1), which is included in order to measure and correct the inevitable dispersion errors of the BC1 chicane.

<table>
<thead>
<tr>
<th>Simulation Results</th>
<th>Unit</th>
<th>Lattice Type-1</th>
<th>Lattice Type-2</th>
<th>Lattice Type-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle \Delta \epsilon_x / \epsilon_0 \rangle \pm \text{rms}$</td>
<td>%</td>
<td>8.4 ± 2.6</td>
<td>5.6 ± 2.3</td>
<td>4.4 ± 1.4</td>
</tr>
<tr>
<td>$\langle \Delta \epsilon_y / \epsilon_0 \rangle \pm \text{rms}$</td>
<td>%</td>
<td>3.5 ± 1.1</td>
<td>5.1 ± 2.0</td>
<td>4.5 ± 1.7</td>
</tr>
<tr>
<td>Optimal phase advance/cell</td>
<td>deg</td>
<td>75</td>
<td>15</td>
<td>15</td>
</tr>
</tbody>
</table>

Figure 7.3-1. Horizontal relative emittance growth versus phase advance/cell for L1 type-1 lattice over 10 seeds (solid: wakes-ON, dash: wakes-OFF). Quadrupole, BPM, and rf-structure misalignments of 300 µm rms were used as well as one-to-one steering. Vertical emittance behavior is similar.
The energy spread is large (1-2%) over the entire 430 meter length of L2, and the bunch is only partially compressed making L2 the most problematic linac section with respect to emittance dilution. The L2 linac begins at the 20-7A location and ends at 24-8D. The lattice choice for L2 was made, as in the case of L1, using the computer code LIAR and varying the phase advance per cell and the quadrupole spacing. Several spacing schemes were tested including (1) the existing 12-meter spacing, (2) a 6 meter spacing over the full L2 length, and (3) a 6 meter spacing for the first 60 meters followed by a 12 meter spacing. Although the shorter quadrupole spacing in the first 60 meters reduced the wakefield induced emittance growth by approximately a factor of two, the reduction was not large enough compared with the increased scale (cost) of modifications required. Furthermore, well tested and very effective emittance correction techniques are also possible and are described below.

Using LIAR to study emittance correction schemes, it was found that even though the L2 emittance growth can easily reach 100%, localized trajectory bumps can be used to restore the emittance to just 5-10% dilution. Fig. 7.3-3 shows the emittance dilution, without corrections applied, versus phase advance per cell for the existing 12-meter quadrupole spacing over the length of L2. The minimum emittance growth occurs near 70°/cell (more clearly when the vertical emittance is included), yet the growth, for these misalignments, is still nearly 100% in each plane if no further correction is attempted. Fig. 7.3-4 shows the beta functions through the L2 linac at 70° per cell and a 12 meter quadrupole spacing. Four wire scanners are indicated at the end of L2 as small circles on the schematic. These are used to measure the L2 output emittance as the correction bumps are empirically optimized. This trajectory-based emittance correction scheme is similar to that used in the SLAC linac for SLC operations [6].
Simulations of trajectory-based emittance corrections are performed using LIAR. Betatron oscillations ("bumps"), which are ~300 meters long and of 100-300 \( \mu m \) peak amplitude, are used to empirically minimize the measured emittance in both planes. Beam position and angle, per plane, are varied near the beginning of L2 (end of sector-20) to optimize emittances at the end of L2. Oscillations are terminated with an orbit controlling feedback system near the end of L2 (end of sector-23).

**Figure 7.3-3.** Horizontal relative emittance growth versus phase advance/cell for L2 and 12-meter quadrupole spacing over 10 seeds (solid: wakes ON, dash: wakes OFF). Quadrupole, BPM, and rf-structure misalignments of 300 \( \mu m \) rms were used as well as one-to-one steering (no bumps applied). Vertical emittance growth (not shown) is similar, resulting in a minimum near 70' /cell.

**Figure 7.3-4.** Beta-functions along L2 at 70' /cell phase advance and 12-meter quadrupole spacing. Small circles on bottom schematic are wire scanners for emittance measurement after L2 (L2-ED).
Figure 7.3-5 shows the emittance all along L2 both before and after correction oscillations are applied. The emittance curves shown are the average of 100 random seeds with 300 \( \mu \text{m} \) rf-structure and 150 \( \mu \text{m} \) rms quadrupole and BPM transverse misalignments after one-to-one steering is applied. Beam-based techniques have produced \( \sim 100 \mu \text{m} \) rms BPM and quadrupole alignment. A typical oscillation is shown at the bottom of the Fig. 7.3-5. Fig. 7.3-6 shows a histogram of horizontal and vertical emittance growth at the end of L2 over 100 seeds with and without emittance bump corrections applied. The mean value of the corrected emittance over these 100 seeds is reduced from \( \sim 100\% \) to \(< 10\% \) in each plane.

No new magnets are needed in L2. The existing quadrupoles are used at their present locations. One new low current (25 A) bulk power supply per sector is installed in order to achieve rms regulation tolerances of \(< 0.5\% \) (not easily achieved with the existing 200 A bulk supply per sector). In addition, the existing booster power supplies (one per quadrupole) will be used to adjust the focusing within a sector.

Quadrupole roll and absolute gradient error tolerances are loose at \(< 0.5^\circ \) and of \( 2\% \) rms, respectively (\( \Delta \epsilon / \epsilon_0 \approx 2\% \)). Tolerances on field harmonics (e.g., dodecapole) in the quadrupoles are extremely loose.

![Graph showing emittance along L2 before and after bumps applied.](image)

**Figure 7.3-5.** Emittance along L2 before (top-solid) and after (top-dash) bumps applied. Emittance curves are an average over 100 seeds with 300 \( \mu \text{m} \) rf-structure and 150 \( \mu \text{m} \) rms quadrupole and BPM misalignments after 1-to-1 steering. The bottom plot shows a typical oscillation (dash-dot).
The L3 linac begins at 25-4A and ends at the end of sector-30. Eleven 3 meter sections from 25-1A to 25-3D are removed to install the long BC2 bunch compressor chicanes (25-1C does not exist). The short bunch of 20 μm in L3 effectively eliminates transverse wakefields as an emittance dilution mechanism, and the rms energy spread shrinks from 1.1% down to <0.1% due to the strong longitudinal wakefield of the short bunch. In this case the dominant emittance dilution mechanism is due to momentum dispersion generated by quadrupole and BPM misalignments. This suggests a weak focusing. LIAR simulations were run for L3 using the existing SLAC linac 12 meter quadrupole spacing but varying the phase advance per cell over the set 20°, 30°, 40°, 60° and 90°. Fig. 7.3-7 shows the horizontal relative emittance growth versus phase advance per cell for L3 with and without transverse wakefield effects.

This clearly demonstrates the weak transverse wakefield due to the extremely short bunch in L3. Large quadrupole, BPM, and rf-structure misalignments of 300 μm rms were used as well as a one-to-one steering algorithm and the nominal undulator energy of 15 GeV.
A phase advance per cell of 30° is chosen for L3 since it is near the minimum emittance dilution and also optimizes the phase advance separation of the existing sector-28 wire scanners for the best $x$ and $y$ emittance resolution. The first and last wires will be relocated to set each wire-to-wire separation at 1.5 cells, or 45° (see Section 7.7.1). Beta-functions and beamline layout are shown in Fig. 7.3-8 for 30°/cell.

**Figure 7.3-7.** Horizontal relative emittance growth versus phase advance/cell for L3 and 12-meter quadrupole spacing over 10 seeds (solid: wakes ON, dash: wakes OFF). Quadrupole, BPM, and rf-structure misalignments of 300 μm rms were used as well as one-to-one steering (no bumps applied). Vertical emittance growth (not shown) is similar. The phase chosen is 30°/cell.

**Figure 7.3-8.** Beta-functions along L3 at a phase advance of 30°/cell. Four existing sector-28 wire scanners are indicated on the schematic (L3-ED: first and last relocated for optimum emittance resolution).
7.4 Design of the Second Bunch Compressor

The second bunch compressor (BC2) is discussed here before the first compressor (BC1) because the beam dynamics through it are more complex than in BC1. BC2 is a pair of magnetic chicanes designed to introduce the energy dependence of a particle’s path length ($\Delta z = R_{56} \delta E/E_0$) needed to compress a 400 $\mu$m bunch to 20 $\mu$m. Many designs were considered, but the simplicity of a four-dipole magnetic chicane is attractive because it (1) introduces no net beamline bend angle, (2) generates no chromaticity or high order dispersion (rectangular bends), since it contains no quadrupole magnets, and (3) allows simple tuning of the momentum compaction, $R_{56}$, with a single power supply.

The high energy and short bunch demand a chicane design where synchrotron radiation generated within the bends does not significantly dilute the emittance. Furthermore, energy independent space charge forces within the dipoles [7] need to be insignificant and the chicane length should be minimized so that the number of removed linac accelerating sections is small. An optimized parameter set has been chosen with a 6 GeV double chicane motivated by synchrotron radiation effects and linac longitudinal beam dynamics simulations. This system will replace the 11 existing 3 meter rf-sections in sector-25 at 25-1, 25-2 and 25-3 (25-1C does not exist).

7.4.1 Overview and Parameters

The chicane design is set by the need to reduce transverse emittance dilution due to coherent synchrotron radiation (CSR) in the bends, which is most pronounced for short bunches. Since the energy spread generated by CSR is coherent along the bunch, its effect on the transverse emittance can be compensated by introducing a double chicane and optical symmetry to cancel the longitudinal-to-transverse coupling [8]. The symmetry is formed by two consecutive chicanes of unequal strength with four quadrupole magnets between them to establish a $-I$ horizontal transfer matrix between chicane centers (as well as between paired chicane bends). The compensation may be optimized empirically by varying chicane strengths while holding the sum of the squares of the two chicane bend angles constant (maintains compression). The compensation is described below. Fig. 7.4-1 is a schematic of a bunched beam traversing the double chicane compressor. The design also minimizes emittance dilution due to incoherent synchrotron radiation (ISR). The parameters in Table 7.4-1 describe the final BC2 design.

Motivations and quantitative arguments for the choices of these parameters are described in the following sections. Results of longitudinal beam dynamics simulations have been used to set the incoming BC2 bunch length at ~400 $\mu$m rms. The bunch length after BC2 is adjustable using the $R_{56}$ of BC2 and the rf phase of L2. A nominal rms final bunch length of 20 $\mu$m is used throughout the following descriptions (unless otherwise noted). In order to allow non-LCLS linac operation, and to ease dipole field quality tolerances (see Section 7.4.7), the center two dipoles per chicane will be placed on remotely moveable horizontal stages. With the dipoles switched off, the two BC2 (and the BC1) chicanes can...
then be straightened out. The maximum horizontal beamline excursion at each chicane center is equal to the maximum dispersion, $\eta_{\text{max}}$, listed in the table.

![Diagram of beam in the double chicane bunch compressor]

**Figure 7.4-1.** Schematic of beam in the double chicane bunch compressor.

**Table 7.4-1.** Parameters of 2nd bunch compressor double chicane, BC2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$</td>
<td>GeV</td>
<td>6.0</td>
</tr>
<tr>
<td>Initial rms bunch length</td>
<td>$\sigma_{z_1}$</td>
<td>$\mu$m</td>
<td>390</td>
</tr>
<tr>
<td>Final rms bunch length</td>
<td>$\sigma_{z_f}$</td>
<td>$\mu$m</td>
<td>20</td>
</tr>
<tr>
<td>Rms incoming relative energy spread (at 6 GeV)</td>
<td>$\sigma_\delta$</td>
<td>%</td>
<td>1.07</td>
</tr>
<tr>
<td>Net momentum compaction</td>
<td>$R_{56}$</td>
<td>mm</td>
<td>35.5</td>
</tr>
<tr>
<td>Net second order momentum compaction</td>
<td>$T_{566}$</td>
<td>mm</td>
<td>−53.3</td>
</tr>
<tr>
<td>Total system length</td>
<td>$L_{\text{total}}$</td>
<td>m</td>
<td>34.7</td>
</tr>
<tr>
<td>Physical length of each dipole magnet</td>
<td>$L_B$</td>
<td>m</td>
<td>1.500</td>
</tr>
<tr>
<td>Drift between first two and last two dipoles (per chicane)</td>
<td>$\Delta L$</td>
<td>m</td>
<td>3.350</td>
</tr>
<tr>
<td>Drift between center two dipoles</td>
<td>$\Delta L_c$</td>
<td>m</td>
<td>0.500</td>
</tr>
<tr>
<td>Bend angle for each of 1st four dipoles</td>
<td>$</td>
<td>\theta_{B1}</td>
<td>$</td>
</tr>
<tr>
<td>Bend angle for each of last four dipoles</td>
<td>$</td>
<td>\theta_{B2}</td>
<td>$</td>
</tr>
<tr>
<td>Magnetic field for each of 1st four dipoles</td>
<td>$</td>
<td>B_1</td>
<td>$</td>
</tr>
<tr>
<td>Magnetic field for each of last four dipoles</td>
<td>$</td>
<td>B_2</td>
<td>$</td>
</tr>
<tr>
<td>Maximum dispersion in chicane-1 center</td>
<td>$\eta_{1-\text{max}}$</td>
<td>m</td>
<td>0.290</td>
</tr>
<tr>
<td>Maximum dispersion in chicane-2 center</td>
<td>$\eta_{2-\text{max}}$</td>
<td>m</td>
<td>0.110</td>
</tr>
<tr>
<td>Emittance dilution due to ISR</td>
<td>$\Delta \varepsilon_{\text{ISR}}/\varepsilon_0$</td>
<td>%</td>
<td>1.4</td>
</tr>
<tr>
<td>Emittance dilution due to CSR (no shielding)</td>
<td>$\Delta \varepsilon_{\text{CSR}}/\varepsilon_0$</td>
<td>%</td>
<td>−5</td>
</tr>
<tr>
<td>rms ISR relative energy spread (at 6 GeV)</td>
<td>$\sigma_{\delta_{\text{ISR}}}$</td>
<td>$10^{-4}$</td>
<td>0.1</td>
</tr>
<tr>
<td>rms CSR relative energy spread (at 6 GeV)</td>
<td>$\sigma_{\delta_{\text{CSR}}}$</td>
<td>$10^{-4}$</td>
<td>−2.4</td>
</tr>
<tr>
<td>Linac 3 rf phase delay per unit $R_{56}$ change</td>
<td>$d\varphi/dR_{56}$</td>
<td>deg/mm</td>
<td>1.72</td>
</tr>
</tbody>
</table>
Figure 7.4-2 shows the dispersion and beta functions through the BC2 chicanes. Dipole magnets with names used in the text are shown at the bottom of the figure. The plot and other calculations are made for a net $R_{56}$ of 35.5 mm ($R_{56-1} = 31.0$ mm, $R_{56-2} = 4.5$ mm).

The momentum compaction ($R_{56}$) of two consecutive chicanes made up of rectangular bend magnets is positive (bunch head at $z > 0$) and is the sum of $R_{56}$ values of each single chicane. For ultra-relativistic electrons and small bend angles, the net $R_{56}$ of the double chicane is given in Eq. 7.4.1 where the symbol definitions are taken from Table 7.4-1.

$$R_{56} = \frac{\partial \delta}{\partial \delta} = 2\left(\theta_{B1}^2 + \theta_{B2}^2\right)\left(\Delta L + \frac{2}{3}L_B\right). \quad (7.4.1)$$

Free parameters are bend lengths, angles, and drift lengths. The required $R_{56}$ is determined from the desired end-of-linac bunch length and energy spread, and the rf phase of L2, which is chosen through longitudinal dynamics simulations as described in Section 7.2.3. The second order momentum compaction ($T_{566}$) of a rectangular bend chicane (no quadrupole magnets) is $T_{566} = -3R_{56}/2$ [9]. From Eq. 7.4.1 the ratio of the two bend angles is clearly adjustable while maintaining the necessary total $R_{56}$. This provides an empirical correction “knob” for the minimization of transverse emittance effects from CSR (as described below in Section 7.4.4).

A beam delay must also be accounted for in the rf phase of L3 as the beam path length increases through a four-dipole chicane with bend angles $\theta_B$. 

![Figure 7.4-2](image-url)
For the double chicane, the approximation at right of Eq. 7.4.2 is accurate to within 0.1° S-band phase over the full \( R_{56} \) range of 0 to 50 mm. The L3 rf phase needs to be delayed, with respect to the chicane-off phase, by \[ \frac{\theta_B}{dR_{56}} \approx \frac{\pi}{\lambda} \approx 1.72°/\text{mm} \] (or 61.1° with the nominal \( R_{56} \) value for BC2).

\[
\Delta \phi = \frac{2 \pi \Delta \theta}{\lambda} = \frac{4 \pi}{\lambda} \left[ 2 L_B \left( 1 - \frac{\theta_B}{\sin \theta_B} \right) + \Delta L \left( 1 - \frac{1}{\cos \theta_B} \right) \right] = \frac{\pi R_{56}}{\lambda}
\] (7.4.2)

### 7.4.3 Incoherent Synchrotron Radiation (ISR)

Transverse emittance dilution will occur if significant energy spread is generated anywhere in the chicane. Synchrotron radiation within the dipoles generates energy spread, which breaks the linear achromaticity of the chicane and therefore dilutes the horizontal emittance. Using a typical symmetric beta function through a single chicane with its maximum, \( \beta_{\text{max}} \), at start and end of the chicane and its minimum, \( \beta_{\text{min}} \), in the middle (see Fig. 7.4-2), and using symbols defined in Table 7.4-1, then

\[
\beta_{\text{max}} = 2 \beta_{\text{min}} = 4 L_B + 2 \Delta L + \Delta \gamma_c.
\] (7.4.3)

The additive ISR emittance dilution [10] can then be approximated \((\Delta \varepsilon / \varepsilon_0 < 1)\) by

\[
\Delta \gamma_{\text{ISR}} = (8 \times 10^{-8} \text{ m}^2 \cdot \text{GeV}^{-6}) \cdot E^6 \left( \theta_B^{5} + \theta_B^{5} \right) \frac{4 \Delta L + 6 L_B + \Delta \gamma_c}{2L_B^2}.
\] (7.4.4)

The parameters of Table 7.4-1 are chosen such that the relative ISR emittance growth is 1.4%. This is entirely determined by the first chicane since \( \theta_{B2} < \theta_{B1} \). This incoherent energy spread is generated through a random process and therefore cannot be corrected.

### 7.4.4 Coherent Synchrotron Radiation (CSR)

**Unshielded Radiation**

For very short bunches, coherent synchrotron radiation can dilute the horizontal emittance by similarly generating energy spread in the dipoles. In this case, however, the energy spread is correlated along the bunch and not a random process. For an rms bunch length \( \sigma_z \), dipole length \( L_B \), bend radius \( R (=L_B/\theta_B) \) and \( N \) electrons per bunch, the CSR-induced relative rms energy spread per dipole for a gaussian bunch under steady-state conditions, is [11]

\[
\sigma_\delta = (0.22) \frac{N_r L_B}{\gamma R^{2/3} \sigma_z^{4/3}},
\] (7.4.5)
where \( r_e \) is the classical electron radius and \( \gamma \) is the Lorentz energy factor. This is valid for a dipole magnet where metallic vacuum chamber radiation shielding is not significant (i.e., for a full vertical vacuum chamber height \( h \) which satisfies [12] \( h >> (\pi \sigma_e \sqrt{\gamma})^{2/3} \equiv h_e \). (7.4.6)

Since the bunch length shortens through the chicane, the energy spread induced at each dipole increases, with the final dipole generating the most significant energy spread (the bunch length is virtually constant in the first and last dipoles—see Fig. 7.4-4). The rms horizontal emittance after a single chicane can be written as

\[
\Delta x = \int R_{16}(s) \frac{d\delta}{ds} \, ds, \quad \Delta x' = \int R_{26}(s) \frac{d\delta}{ds} \, ds, \\
e^2 = e_0^2 + e_0 \left[ \beta (\Delta x^2) + 2 \alpha (\Delta x \Delta x') + (1 + \alpha^2) (\Delta x^2) / \beta \right] + (\Delta x^2) (\Delta x')^2 / 2 - (\Delta x \Delta x')^2 - (\Delta x \Delta x')^2 \quad (7.4.7)
\]

Here \( R_{16}(s) \) and \( R_{26}(s) \) are the standard transfer matrix elements from point \( s \) to end of chicane, \( \beta (= \beta_{\text{max}}) \) and \( \alpha \) are the nominal Twiss parameters at the end of the chicane, and \( e_0 \) and \( \epsilon \) are the initial and final rms horizontal emittances. The change in centroid coordinates, \( \Delta x \) and \( \Delta x' \), pertain to a single longitudinal bunch slice. Their second moments (e.g., \( \langle \Delta x^2 \rangle \)) are ensemble averages over the entire bunch, and \( \zeta \) is the Courant-Snyder invariant (see Eq. 7.7.1). In unshielded, steady-state conditions, where \( \langle \Delta x^2 \rangle \langle \Delta x'^2 \rangle = \langle (\Delta x \Delta x')^2 \rangle \), the relative emittance growth for just the last bend of a single chicane, using Eq. 7.4.5 and Eq. 7.4.7 and a constant gaussian bunch length, is

\[
\frac{\epsilon}{e_0} = \sqrt{1 + \frac{(0.22)^2}{36} \frac{r_e^2 N^2}{\gamma e N \beta} \left( \frac{\theta^5 L_B}{\sigma_c^4} \right)^{2/3} \left[ L_B^2 \left( 1 + \alpha^2 \right) + \frac{9 \beta^2}{2} + 6 \alpha \beta L_B \right]}, \quad (7.4.8)
\]

with \( e_N \) (\( \equiv \gamma e_0 \)) introduced to represent the initial normalized (invariant) emittance.

For a single chicane with parameters of the first chicane in Table 7.4-1 and the full 20 \( \mu \)m final compression occurring in that one chicane, the CSR emittance growth of Eq. 7.4.8 is ~70%. The chicane could be made twice as long but the emittance dilution is still too large. To arrive at the final double chicane design, a single chicane is chosen based on a ~2% ISR emittance growth, and then a second identical chicane is added with reduced bend angles and separating optics to approximately cancel the net CSR emittance increase.

The cancellation can be understood by imagining an electron which looses energy inside the \( n \)th dipole (\( n = 1, 4 \)) of chicane-1. In this steady-state model, the energy loss depends only on the axial position of the electron within the bunch. Fig. 7.4-3 (solid curve) shows
this wakefield voltage (energy variation) along the bunch. The calculation was made using a computer program [13] which calculates the CSR steady-state wakefields in bends, including radiation shielding effects, for a gaussian bunch.

Due to the energy loss, the electron receives an additional horizontal kick, with respect to an on-energy electron, in the \( n \)th bend. This same electron, with its unchanged relative axial position, will again lose energy in the \( n \)th bend of chicane-2, but due to the \( -I \) matrix between paired bend, the shorter bunch in chicane-2, and the arrangement of the relative strengths of the two chicanes, the net horizontal kick at the end of the system is zero. This assumes the electron does not shift axially with respect to the remainder of the bunch as would occur in the case of over-compression (>90° phase space rotation) or a non-linear phase space transformation. In order to estimate the effect over the entire system, a computer program is used to generate the steady-state CSR energy spread of Eq. 7.4.5 in each 1/10th slice of each dipole magnet. The horizontal position and angle of the particles are mapped to the end of the second chicane. The bunch is allowed to linearly compress along the way from 390 \( \mu \)m to 20 \( \mu \)m. The relative emittance increase, CSR energy spread, bunch length, and horizontal dispersion function are plotted in Fig. 7.4-4.

This steady-state calculation ignores field transients, and the CSR forces are assumed to vanish between bends. The net emittance increase is 0.3%. More thorough calculations of the CSR-induced emittance dilution have been made using the DESY “WAKE” code [14] (see below, “Calculations with a Transient Model”) which result in an emittance growth of 3–5%.
Shielded Radiation

If a small vertical vacuum chamber height, \( h \), is used in the bends which does not satisfy Eq. 7.4.6, the CSR induced energy spread may be reduced. Fig. 7.4-3 shows the coherent radiation wakefield voltage for a 30 µm bunch through a bend with \( R = 19.4 \) m both with and without radiation shielding. Here the vacuum chamber is modeled as parallel plates.

![Graph showing CSR induced energy spread](image)

Figure 7.4-4. CSR emittance increase (solid-bottom), energy spread (dash-bottom), bunch length (dash-top) and dispersion function (solid-top) across double chicane at 6 GeV for \( N = 6.3 \times 10^9 \) e⁻/bunch and a final bunch length of 20 µm. The final emittance increase has been optimized to 0.3% by setting the \( R_{56} \) values of the first and second chicanes to 31.0 mm and 4.5 mm, respectively.

![Graph showing CSR induced rms energy spread](image)

Figure 7.4-5 shows the CSR induced rms energy spread of a 30 µm gaussian bunch through a bend versus the vertical vacuum chamber height, \( h \), normalized to critical height, \( h_c \), defined in Eq. 7.4.6. The plot shows bends with \( R = 16.8 \) m (corresponding to \( h_c = 5.3 \) mm) and \( R = 33.6 \) m (corresponding to \( h_c = 6.7 \) mm). Other parameters are \( \theta_B = 30 \) mrad, \( E = 7 \) GeV, and \( N = 6.3 \times 10^9 \) e⁻/bunch. For large vertical gaps, \( h/h_c \gg 1 \), radiation shielding is insignificant and an asymptotic value is reached which is in fair agreement with Eq. 7.4.5.

At \( h/h_c < 0.4 \), the energy spread becomes insignificant.

Shielding is, however, not practical for BC2 since a full vacuum chamber height of <3 mm would be required to significantly shield the short bunch. This presents an aperture restriction and may also generate geometric and/or resistive wakefields comparable to the CSR effects being shielded.

In the case of the double chicane cancellation, significant shielding should also be avoided because it alters the shape of the CSR wakefield function from bend to bend (see Fig. 7.4-3). Shielding reduces the wakefield amplitude but compromises the cancellation.
scheme. Total cancellation will only occur for a wakefield with constant shape from bend to bend. A linearly under-compressed bunch is ideal for the cancellation process. Although the final LCLS bunch is slightly under-compressed, it is not precisely a linear process (see Fig. 7.2-2) and some loss of cancellation is expected.

![Graph showing CSR-induced rms energy spread per bend versus vertical vacuum chamber height](image)

**Figure 7.4-5.** CSR-induced rms energy spread per bend versus vertical vacuum chamber height, $h$, normalized to critical height, $h_c$. Curves for both $R=16.8$ m, $h_c=5.3$ mm (dash) and $R=33.6$ m, $h_c=6.7$ mm (solid) are shown. Horizontal lines nearest asymptotic values are from Eq. 7.4.5.

The $R_{56}$ of the BC2 chicanes is also intended to be adjustable to allow for correction of the longitudinal phase space of the linac output beam and to provide control of the final bunch length. A tuning range of 20 to 50 mm should easily allow for uncertainties in the longitudinal wakefields of the 20 $\mu$m bunch. **Fig. 7.4-6** shows the variation of several parameters over a large $R_{56}$ range. The end-of-system CSR emittance increase, “CSR$_{end}$,” has been minimized (steady-state) at the operational point ($R_{56} = 35.5$ mm). It is not plotted beyond this point since the bunch begins to over-compress at $R_{56} \approx 37$ mm and destroys the cancellation. The scan was made keeping the ratio of the two bend angles constant (~2.6) which is not precisely the optimal CSR cancellation ratio for different $R_{56}$ values.

**Transverse Forces**

A transverse force or “centripetal force” is described by Derbenev and Shiltsev [15] which originates from radiation of trailing particles and depends on the local charge density along the bunch. The maximum force takes place at the center of the bunch and its effect on
transverse emittance is estimated in the reference. This estimate predicts an emittance growth of $\ll 1\%$ for the worst case (last dipole of chicane-2 where bunch is shortest).

![Figure 7.4-6](image.png)

**Figure 7.4-6.** For the BC2 double chicane, the variation of (a) CSR and ISR emittance increase, (b) final bunch length, (c) dipole magnetic fields, and (d) horizontal dispersion in chicane centers, all as a function of the net $R_{56}$ at 6 GeV ($\theta_1/\theta_2=2.6$). The label “CSR$_{\text{max}}$” indicates emittance between chicanes, whereas “CSR$_{\text{end}}$” indicates emittance increase at BC2 system end (no shielding).

**Calculations with a Transient Model**

More complete calculations of the CSR effects on the bunch through BC2 have been made using a computer code written at DESY [16]. The code is a time domain treatment that includes the field transients at entrance and exit of the bends, the $x$-$z$ correlation in the beam at high dispersion points, the space charge forces, and longitudinal as well as transverse forces. The bunch is composed of $N$ (=301) 5 $\mu$m sub-bunches each with a 30 $\mu$m vertical extent, and the double chicane, including the –I quadrupoles, is split into 100 beamline segments. **Fig. 7.4-7** shows the dispersion function and the CSR relative energy spread calculated using both the steady-state [$\sigma_{E_0}/E_0$] model and this transient model [$\sigma_{E}/E_0$].

The total rms CSR energy spread generated to the end of BC2 (end of last dipole) using the transient model is $2.5\times10^{-4}$ while the steady-state model predicts a lower value of $1.6\times10^{-4}$. Furthermore, in the transient model, energy spread is generated between the bends as well as in the bends, whereas the steady-state model only provides for energy spread generation within the bends. Clearly, the emittance growth should be evaluated using the more complete, transient model, so that the contributions from these “drift” sections are included in the emittance dilution estimates. In addition, the CSR wakefield function is not
of constant shape in this model, and the non-linear aspects of the compression process are included (e.g., $T_{566}$). This provides a more realistic evaluation of the transverse emittance growth.

![Image of plot](image_url)

**Figure 7.4-7.** The dispersion function (dash-dot) and the CSR rms energy spread generated in the BC2 double chicane using the transient (dash) and the steady-state (solid) models.

**Fig. 7.4-8** shows the transverse phase space, with and without CSR effects, 1 meter downstream of the last BC2 bend. The points on the plot show the centroid position of each of the 301 longitudinal slices. In this calculation, the axial bunch distribution prior to BC2 is gaussian.

The nominal beam (without CSR effects) is represented as a large-solid ellipse. With CSR effects, each longitudinal slice (301) has this same phase space ellipse but displaced according to its centroid position (points). The equivalent ellipse of the slice centroids, including their different charges, is shown as a small-solid ellipse. The area of this small ellipse is the rms emittance produced by CSR for a zero-emittance input beam (the additive component—$\Delta \varepsilon$ in **Eq. 7.4.7**). The final equivalent ellipse produced by combining the nominal beam and the slice centroids is shown as the large-dashed ellipse. The transverse distribution functions are, in general, no longer gaussian, but they can be described by the second moments of their distributions. In this representation the emittance which is calculated is the **<em>rms</em>** value. Here the relative rms emittance dilution is 14% for an initial rms emittance of 1 mm-mrad.

This 14% emittance growth can be further improved by choosing optimal input beta functions through BC2. The minimal emittance impact is obtained by setting the nominal beta and alpha functions (large-solid ellipse of **Fig. 7.4-8**) to those of the CSR-generated beam (small-solid ellipse)—see **Eq. 7.4.7** with $\zeta = 1$. In this case the beta functions through the BC2 become somewhat asymmetric, but not unreasonably so, and the emittance dilution drops to 6%. A further reduction can be realized by removing the linear component of the
$\langle xz \rangle$ and $\langle x'z \rangle$ correlation. This is possible since energy, $\delta$, and $z$ are also linearly related, and therefore a small spatial and angular “dispersion” adjustment can be used to reduce the emittance growth to just 3.5%.

![Figure 7.4-8](image)

**Figure 7.4-8.** Transverse (bending plane) phase space after BC2. The various ellipses are: nominal beam (large-solid), additive CSR beam (small-solid), and total beam after CSR effects and 14% emittance growth (large-dashed). Points are the centroid positions of the longitudinal slices.

Calculations with a uniform bunch distribution (rather than a gaussian) produce similar results: 20% emittance dilution without optimal beta, 5% with optimal beta, and 3% with dispersion correction and optimal beta functions. Calculations have yet to be done which include the precise bunch distribution of Fig. 7.2-2 (plot of row-3, column-1).

### 7.4.5 Resistive Wall Longitudinal Wakefields in the Bends

Longitudinal resistive wall wakefields in the BC2 vacuum chambers also induce energy spread which may dilute the emittance. The rms relative energy spread generated in a cylindrical vacuum chamber of length $L$, radius $a$, and conductivity $\sigma$ is (see section 7.8.5)

$$\sigma_{\delta RW} = (0.22) \frac{e^2 c N L}{\pi^2 a E \sigma_{\delta z}^{3/2}} \frac{Z_0}{\sigma},$$

(7.4.9)

where $Z_0 (=377 \ \Omega)$ is the free space impedance. Note, Eq. 7.4.9 is for a long, gaussian bunch—see Section 7.8.5. For parameters of Table 7.4-1 using aluminum ($\sigma = 3.6 \times 10^7 \ \Omega^{-1}m^{-1}$) and $a = 15 \ \text{mm}$ through the final bend, where the bunch length is $20 \ \mu\text{m}$, the rms energy spread is $\approx 4 \times 10^{-6}$ which is more than an order of magnitude smaller than the CSR.
energy spread generated in this final bend. Stainless steel, on the other hand, will generate five times this value and should be avoided. The other bends generate much less energy spread.

7.4.6 Beam Size, Aperture and Field Quality

From the parameters in Table 7.4-1 ($\eta_{\text{max}}$ and $\sigma_\delta$), the horizontal rms beam size in the center of the first and second BC2 chicanes is 3.1 mm and 1.1 mm, respectively. This sets tight tolerances on the field quality of the center two dipoles (per chicane) since higher order field harmonics may generate anomalous dispersion which can dilute the horizontal emittance. In addition, the horizontal displacement of the beam within the center dipoles is dependent on the $R_{56}$ value chosen. For an $R_{56}$ tuning range of 20 to 50 mm for chicane-1, the horizontal dipole aperture required for the center two bends is 300 mm. This is a large aperture dipole with tight field quality tolerances over most of the aperture. To relax this tolerance, and also for operational convenience, the center two dipoles are mounted on remotely movable stages to physically move the magnets as the bend angles are varied (asynchronous control is adequate). This locks the horizontal beam position with respect to the dipole aperture so that good field quality is only needed over an aperture of ~30 mm. It also allows the chicanes to be straightened out for non-LCLS operations (dipoles off). For convenience, the second chicane is an identical copy of the first, which is nominally operated at smaller bend angles. In addition, small correction quadrupoles are included in chicane-1 to provide linear horizontal dispersion correction to compensate for errors (Section 7.4.7). Field quality tolerances for the four dipoles of chicane-1 are listed in Table 7.4-2. The tolerances on the center pair of dipoles are tight but achievable, especially in consideration of the empirical corrections built into the system.

| Magnet   | Quantity | Roll Angle | $|b_1/b_0|$ | $|b_2/b_0|$ | $|b_4/b_0|$ |
|----------|----------|------------|------------|------------|------------|
| B21 & B24| 2        | 1.7        | 0.28       | 30.        | >100       |
| B22 & B23| 2        | 2.2        | 0.016      | 0.08       | 0.5        |

Quadrupole field components ($b_1/b_0$) larger than these tolerances are correctable while sextupole ($b_2/b_0$) and decapole ($b_4/b_0$) components, without specialized correction magnets, are not. Magnet roll errors generate anomalous vertical dispersion, which may be corrected with vertical steering or the later addition of small correction skew quadrupoles if necessary.

7.4.7 Tuning and Correction

Dispersion errors (typically in the horizontal plane) will be generated by small quadrupole field components in the center two dipoles of the chicanes (see Table 7.4-2). A
pair of small correction quadrupoles can be included (e.g., in chicane-1) with the first quadrupole (CQ21) placed near the end of B21 at $\eta_x \approx 66$ mm, $\beta_x \approx 9$ m, and the second (CQ22) just upstream of B24 (same $\eta_x$ and $\beta_x$). Two orthogonal linear combinations of these quadrupoles can then be used to correct up to 400% emittance dilution due to dispersion errors. Since the dispersive beam size at these quadrupoles is $\eta_x \sigma_{\delta} \approx 700 \mu$m and the betatron beam size is much smaller at $(\beta_x \epsilon_{x,y})^{1/2} \approx 30 \mu$m, these quadrupoles have little effect on the final beta functions. The specifications for these correction quadrupoles are given in Table 7.4-3 and their locations are shown in Fig. 7.4-2.

**Table 7.4-3.** Dispersion correction quadrupoles for BC2 chicane-1 for horizontal emittance correction of up to 400% (with 1% step size control).

<table>
<thead>
<tr>
<th>Maximum Pole-Tip Field</th>
<th>Quantity</th>
<th>Step Size</th>
<th>Pole Radius</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>kG</td>
<td>2</td>
<td>0.06</td>
<td>50</td>
<td>0.1</td>
</tr>
</tbody>
</table>

The four main dipoles of each chicane will be powered in series by one power supply so that field regulation tolerances can be loosened (see Table 7.2-3). The two chicane supplies are then used in two separate non-linear combinations to orthogonally control the net $R_{56}$ and the CSR emittance compensation. Trim coils should be included in each BC2 main dipole for compensation of magnet-to-magnet construction errors in the dipole field strengths. This will also allow some horizontal steering. In addition, vertical dipole correctors (2 per chicane) will be included to facilitate vertical steering.

### 7.5 Design of the First Bunch Compressor

#### 7.5.1 Overview and Parameters

Like the second compressor, the first bunch compressor (BC1) is also an adjustable magnetic chicane. It performs an initial bunch compression from 1 mm to ~400 $\mu$m. The longer bunch and lower energy allow for a much shorter and simpler design than BC2, and the complexity of a double chicane is not required. The tools developed for the design of BC2 were used to choose a 2.8-meter long chicane for BC1 as outlined below in Table 7.5-1. The dispersion and beta functions through the BC1 chicane are shown in Fig. 7.5-1.

Emittance growth and energy spread through BC1 due to incoherent synchrotron radiation are completely negligible. Emittance growth due to CSR is 5% using the transient model (see Section 7.4.4) and 2% using the steady-state model. If the dipole vacuum chambers are 12 mm in height, the shielding effect reduces the emittance growth to <2%.

The rf phase delay in L2 introduced by the BC1 chicane is given by the approximation at right of Eq. 7.4.2, which is accurate to within 0.2° S-band phase over the full $R_{56}$ range of 0 to 35 mm. The L2 rf phase is delayed by $d\varphi/dR_{56} = \pi/\lambda \approx 1.72\degree/mm$ (or 46.4° with the nominal $R_{56}$).
Table 7.5-1. Parameters of BC1, the first bunch compressor chicane.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$</td>
<td>GeV</td>
<td>0.280</td>
</tr>
<tr>
<td>Initial rms bunch length</td>
<td>$\sigma_z$</td>
<td>mm</td>
<td>1.0</td>
</tr>
<tr>
<td>Final rms bunch length</td>
<td>$\sigma_z$</td>
<td>mm</td>
<td>0.39</td>
</tr>
<tr>
<td>rms energy spread throughout chicane (at 280 MeV)</td>
<td>$\sigma_\delta$</td>
<td>%</td>
<td>2.3</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$R_{56}$</td>
<td>mm</td>
<td>27.0</td>
</tr>
<tr>
<td>Second order momentum compaction</td>
<td>$T_{566}$</td>
<td>mm</td>
<td>–40.5</td>
</tr>
<tr>
<td>Total chicane length</td>
<td>$L_{\text{total}}$</td>
<td>m</td>
<td>2.80</td>
</tr>
<tr>
<td>Length of each of four dipole magnets</td>
<td>$L_B$</td>
<td>m</td>
<td>0.20</td>
</tr>
<tr>
<td>Drift between first two and last two dipoles</td>
<td>$\Delta L$</td>
<td>m</td>
<td>0.75</td>
</tr>
<tr>
<td>Drift between center two dipoles</td>
<td>$\Delta L_c$</td>
<td>m</td>
<td>0.50</td>
</tr>
<tr>
<td>Bend angle of each dipole</td>
<td>$</td>
<td>\theta_0</td>
<td>$</td>
</tr>
<tr>
<td>Magnetic field of each dipole</td>
<td>$</td>
<td>B</td>
<td>$</td>
</tr>
<tr>
<td>Maximum dispersion (in chicane center)</td>
<td>$\eta_{\text{max}}$</td>
<td>m</td>
<td>0.117</td>
</tr>
<tr>
<td>Emittance dilution due to CSR (no shielding)</td>
<td>$\Delta \varepsilon_{\text{CSR}}/\epsilon_0$</td>
<td>%</td>
<td>2</td>
</tr>
<tr>
<td>rms CSR relative energy spread (at 280 MeV)</td>
<td>$\sigma_{\delta,\text{CSR}}$</td>
<td>$10^{-4}$</td>
<td>1.6</td>
</tr>
<tr>
<td>rf phase delay per unit $R_{56}$ change</td>
<td>$d\phi/dR_{56}$</td>
<td>deg/mm</td>
<td>1.72</td>
</tr>
</tbody>
</table>

7.5.2 Beam Size, Aperture, and Field Quality

From the parameters in Table 7.5-1 ($\eta_{\text{max}}$ and $\sigma_\delta$), the horizontal rms beam size in the center of the BC1 chicane is 2.7 mm. A reasonable $R_{56}$ tuning range for BC1 is 20 to 35 mm. As in the case of BC2, the displacement of the center two dipoles is remotely controlled to vary the $R_{56}$. This also allows the chicane to be straightened out for non-LCLS operations (dipoles off).

Field quality tolerances for the four dipoles are listed in Table 7.5-2. Quadrupole field components ($b_1/b_0$) are correctable, while sextupole ($b_2/b_0$) and decapole ($b_4/b_0$) components, without specialized correction magnets, are not. Magnet roll errors generate anomalous vertical dispersion which may be correctable with vertical steering or with the possible later inclusion of small correction skew quadrupoles if necessary. Field quality tolerances on the center pair of dipoles are tight but achievable, especially in consideration of the empirical corrections built into the system (Section 7.5.3).
Dispersion errors (typically horizontal) are generated by quadrupole field components in the center dipoles of BC1 (Table 7.5-2). As in BC2, a pair of small correction quadrupoles are included with the first one (CQ11) placed near the end of B11 at $\eta_x \approx 10$ mm, $\beta_x \approx 2.6$ m, and the second (CQ12) just upstream of B4 (same $\eta_x$ and $\beta_x$). Two orthogonal linear combinations of these quadrupoles can then be used to correct up to 400% emittance dilution due to dispersion errors. Since the dispersive beam size at these quadrupoles is $\eta_x \sigma_\delta \approx 230 \mu$m and the betatron beam size is much smaller at $(\beta_x \epsilon_{x,y})^{1/2} \approx 70 \mu$m, these quadrupoles have little effect on beta functions. The specifications for these two correction quadrupoles are given in Table 7.5-3 and their locations are shown in Fig. 7.5-1.

### Table 7.5-2
Dipole magnet tolerances for BC1. Field harmonics are evaluated on a 10 mm radius and each entry individually corresponds to a 2% emittance dilution.

| Magnet Name | Quantity | Roll Angle | $|b_1/b_0|$ | $|b_2/b_0|$ | $|b_4/b_0|$ |
|-------------|----------|------------|------------|------------|------------|
| B11 & B14   | 2        | 3.7        | 0.5        | 10.        | >100       |
| B12 & B13   | 2        | 4.8        | 0.04       | 0.1        | 0.3        |

### Table 7.5-3
Dispersion correction quadrupoles for BC1 for horizontal emittance correction of up to 400% (2% step size control).

<table>
<thead>
<tr>
<th>Maximum Pole-Tip Field</th>
<th>Quantity</th>
<th>Step Size</th>
<th>Pole Radius</th>
<th>Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>kG</td>
<td>2</td>
<td>0.08</td>
<td>50</td>
<td>0.1</td>
</tr>
</tbody>
</table>
The dipoles are powered in series with a single main power supply so that regulation tolerances can be loosened (Table 7.2-3). Trim coils will also be included in each BC1 main dipole so that compensation can be made for magnet-to-magnet construction variations in the dipole field strength. This will also allow some horizontal steering. In addition, vertical dipole correctors will be included to allow vertical steering.

### 7.6 Beam Transport Lines

This section discusses the two beam transport lines. The first is a low-energy dog leg (DL1) used to transport the electrons from the injector into the main linac. The second is the high-energy dog leg (DL2) used for L3 to undulator transport and energy and energy spread analysis. The DL2 beamline also horizontally displaces the undulator axis from that of the main linac in order to protect the undulator from potential beam halo and dark current.

#### 7.6.1 Low-Energy Dog Leg

The function of the low-energy dog leg (DL1) is to transport the 150 MeV electron beam from the new injector linac (L0) into the existing linac. While it is possible to design the dog leg as a first bunch compression stage, this necessitates a large incoming correlated energy spread of 1–2%, and the chromaticity of the quadrupole magnets within the dog leg, required for a linear achromat, generate large second order dispersion which needs sextupole compensation. Due to this, and also the need for $R_{56}$ tuning (not natural in a dog leg), DL1 is designed as a simple transport line. Its design requirements are:

- Provides a horizontal beamline inflection of ~1 meter over a few meters distance
- Should not alter the bunch length (i.e., should be isochronous)
- Should introduce no significant transverse emittance dilution

The inflection may also be made in the vertical plane or a rolled plane. However, there is no strong motivation to do so. A simple system that satisfies these conditions is composed of two dipole magnets of opposite strength separated by a $+I$ optical transformer (seven quadrupoles) to produce a linear achromat. The dipoles are rectangular bends.

The momentum compaction, $R_{56}$, of such a system, for ultra-relativistic electrons and small angles, is

$$ R_{56} = -\frac{1}{3} \theta_B^2 L_B , $$

(7.6.1)

where $\theta_B$ and $L_B$ are the bend angle and length of each dipole, respectively. A 4 meter long beamline with 14° bends provides the ~1 meter inflection, and 20 cm long dipoles produce an $R_{56}$ of −4 mm. Therefore, an extreme electron which is off energy by 1% will move axially by just 40 $\mu$m, which is small compared to the 1 mm rms bunch length. The effect of the second order momentum compaction, $T_{566}$, is even less. Note, the incoming relative rms
energy spread from L0 is actually <0.2%. The system is therefore, for all practical purposes, isochronous.

Parameters

The main parameters of DL1 are summarized in Table 7.6-1. The dispersion and beta functions along the 150 MeV emittance diagnostic section (ED0) and DL1 are shown in Fig. 7.6-1. The choice of seven quadrupoles between DL1 dipoles, rather than fewer, was made to facilitate beam matching into and out of the system. Space charge effects on bunch length, energy spread, and emittance are negligible [17] at 150 MeV through the full length of transport from the end of L0 to the final bend of DL1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E$</td>
<td>MeV</td>
<td>150</td>
</tr>
<tr>
<td>Total horizontal inflection</td>
<td>$\Delta x$</td>
<td>m</td>
<td>1.0</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>$\sigma_z$</td>
<td>mm</td>
<td>1.0</td>
</tr>
<tr>
<td>rms energy spread throughout dog leg</td>
<td>$\sigma_\delta$</td>
<td>%</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>$R_{56}$</td>
<td>mm</td>
<td>-4.0</td>
</tr>
<tr>
<td>Second order momentum compaction</td>
<td>$T_{566}$</td>
<td>mm</td>
<td>-260</td>
</tr>
<tr>
<td>Total length (including dipoles)</td>
<td>$L_{\text{total}}$</td>
<td>m</td>
<td>4.34</td>
</tr>
<tr>
<td>Length of each of two dipole magnets</td>
<td>$L_B$</td>
<td>m</td>
<td>0.20</td>
</tr>
<tr>
<td>Bend angle of each dipole</td>
<td>$\theta_B$</td>
<td>deg</td>
<td>14</td>
</tr>
<tr>
<td>Magnetic field of each dipole</td>
<td>$</td>
<td>B</td>
<td>$</td>
</tr>
<tr>
<td>Maximum horizontal dispersion</td>
<td>$</td>
<td>\eta_{\text{max}}</td>
<td>$</td>
</tr>
<tr>
<td>Chromatic emittance dilution</td>
<td>$\Delta e/\epsilon_0$</td>
<td>%</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

Figures 7.6-1. Dispersion and beta functions along the 150 MeV emittance diagnostic section (ED0) and low energy dog leg (DL1). Wire scanners are small circles on the schematic at bottom.
Beam Size, Aperture, and Field Quality

The horizontal beam size in DL1 reaches a peak value of ~400 µm with the vertical size at ~150 µm. A 25 mm full aperture is, therefore, completely adequate. The large dispersion in the DL1 quadrupoles and the strong bends set fairly tight tolerances on field quality and gradient errors. Tables 7.6-2 and 7.6-3 list dipole and quadrupole magnet tolerances in DL1.

Table 7.6-2. Dipole magnet tolerances for DL1. Field harmonics are evaluated on a 10 mm radius and each entry individually corresponds to a 2% emittance dilution.

| Magnet     | Quantity | Roll Angle | \(|b_1/b_0|\) | \(|b_2/b_0|\) | \(|b_4/b_0|\) |
|------------|----------|------------|----------------|----------------|----------------|
| Name       | mrad     | %          | %              | %              | %              |
| B01 and B02| 2        | 17         | 0.068          | 2.25           | >100           |

Table 7.6-3. Quadrupole magnet tolerances for DL1. Field harmonics are evaluated on a 10 mm radius and each entry individually corresponds to a 2% emittance dilution.

| Magnet     | Quantity | Roll Angle | \(|\Delta b_1/b_1|\) | \(|b_2/b_1|\) | \(|b_4/b_1|\) |
|------------|----------|------------|---------------------|----------------|----------------|
| Name       | mrad     | %          | %                   | %              | %              |
| QL01-07    | 7        | 3          | 0.2                 | 3              | >100           |

The most challenging of these tolerances are the quadrupole content in the bends, \(|b_1/b_0|\), and the absolute gradient errors of the quadrupoles, \(|\Delta b_1/b_1|\). Although six of the seven quadrupoles will be powered in series, their gradients may differ slightly due to construction errors. The tolerance of <0.2% is difficult to achieve. The effect on the beam, however, is the generation of linear dispersion. This can easily be tuned out empirically by including two small correction quadrupoles in the DL1 design. Failure to meet the tolerances on the quadrupole content in the bends results in a beta function mismatch (since the dispersion is so small in the bends). This mismatch can be compensated with matching quadrupoles in front of the DL1. Quadrupole alignment tolerances are ~400 µm and do not present a significant challenge, and dipole field errors (not listed) are correctable with steering coils.

Tuning and Correction

The dominant error which will likely arise in DL1 is anomalous linear dispersion which will dilute the horizontal emittance. Quadrupole field strength errors are the most likely cause. Two small correction quadrupoles on separate power supplies separated by ~90° of betatron phase advance will be used in appropriate linear combinations to generate orthogonal dispersion correction knobs. The emittance can be measured in the diagnostic section following BC1 (BC1 can be switched off if necessary) and will be minimized with the orthogonal knobs sequentially.
7.6.2 High-Energy Dog Leg

The requirements for beam transport to the LCLS undulator are fairly simple. The transport line must:

- Include bends to introduce precise energy and energy spread measurement capability without generating significant CSR or other transverse emittance dilution effects.
- Include precise transverse emittance diagnostics for final verification/tuning prior to undulator.
- Provide adjustable undulator-input matching for the various beam energies desired.
- Not alter the bunch length (must be isochronous).
- Make use of existing FFTB tunnel and components wherever possible, as long as the design or performance of the transport line is not compromised.

Energy and energy spread diagnostics are built into a four dipole horizontal inflector beamline (DL2) where the first bend is located just inside the beginning of the existing Final Focus Test Beam (FFTB) housing. Primarily to meet the small energy spread measurement capability, a doublet of Chasman-Green [18] type cells is used. A cell consists of a dipole pair sandwiching a quadrupole triplet. The horizontal dispersion function in the center of each cell reaches a maximum, while the horizontal beta function converges towards a minimum. A horizontal wire scanner here is capable of measuring an rms energy spread of 0.02% at 15 GeV with a nominal betatron beam size contribution of only 5% (see Section 7.7.3).

The Chasman-Green type cells are also advantageous since they introduce very little path length energy dependence and generate minimal transverse emittance dilution due to incoherent synchrotron radiation. The net system forms a 4-dipole dog leg (DL2) which displaces the beamline horizontally by 0.9 m. The net momentum compaction for the 4-dipole system, similar to DL1, is given by

$$ R_{56} = -\frac{2}{3} \theta_B^2 L_B. $$ (7.6.2)

Bends of $\theta_B = 1.3^\circ$ and $L_B = 2.62$ m produce a net momentum compaction of $R_{56}$ of $-0.9$ mm which is, for a worst case energy spread of ~0.1%, isochronous ($<1 \mu$m axial position shift per 0.1% energy deviation). The emittance dilution due to incoherent synchrotron radiation at 15 GeV is insignificant ($<0.1\%$).

In order to include a high resolution relative energy spectrometer which is insensitive to incoming linac orbit jitter, the centers of the Chasman-Green cells are separated by a unity optical transformer (+I). The signals from two BPMs, one placed at the maximum dispersion point in each cell, are subtracted to eliminate all incoming orbit jitter and enhance the
relative energy signal (the dispersion is of opposite sign in the two cells—see Fig. 7.6-2). With a BPM resolution of 5 \( \mu \text{m} \), the resolution of the relative energy measurement per pulse should be \(<2 \times 10^{-5}\).

**Parameters**

The main parameters of DL2 are summarized in Table 7.6-4. The beta-functions and dispersion are shown in Fig. 7.6-2. The energy spread measuring wire scanner is indicated at \( S \approx 1295 \text{ m} \).

**Table 7.6-4.** Parameters of high energy dog leg (DL2) beamline.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>( E )</td>
<td>GeV</td>
<td>15</td>
</tr>
<tr>
<td>Total horizontal beamline inflection</td>
<td>( \Delta x )</td>
<td>m</td>
<td>0.9</td>
</tr>
<tr>
<td>rms bunch length throughout dog leg</td>
<td>( \sigma_z )</td>
<td>( \mu \text{m} )</td>
<td>20</td>
</tr>
<tr>
<td>rms energy spread throughout dog leg</td>
<td>( \sigma_\delta )</td>
<td>%</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Momentum compaction</td>
<td>( R_{56} )</td>
<td>mm</td>
<td>–0.9</td>
</tr>
<tr>
<td>Second order momentum compaction</td>
<td>( T_{566} )</td>
<td>mm</td>
<td>–61</td>
</tr>
<tr>
<td>Total dog leg length (inc. dipoles)</td>
<td>( L_{\text{total}} )</td>
<td>m</td>
<td>32.7</td>
</tr>
<tr>
<td>Length of each of four dipole magnets</td>
<td>( L_B )</td>
<td>m</td>
<td>2.62</td>
</tr>
<tr>
<td>Bend angle of each dipole</td>
<td>( \theta_B )</td>
<td>deg</td>
<td>1.3</td>
</tr>
<tr>
<td>Magnetic field of each dipole</td>
<td>(</td>
<td>B</td>
<td>)</td>
</tr>
<tr>
<td>Maximum dispersion</td>
<td>(</td>
<td>\eta</td>
<td>_{\text{max}} )</td>
</tr>
<tr>
<td>Emittance dilution due to ISR</td>
<td>( \Delta \epsilon_{\text{ISR}}/\epsilon_0 )</td>
<td>%</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>Emittance dilution due to CSR (no shielding)</td>
<td>( \Delta \epsilon_{\text{CSR}}/\epsilon_0 )</td>
<td>%</td>
<td>1</td>
</tr>
<tr>
<td>rms ISR relative energy spread</td>
<td>( \sigma_{\delta_{\text{ISR}}} )</td>
<td>( 10^{-4} )</td>
<td>0.15</td>
</tr>
<tr>
<td>rms CSR relative energy spread</td>
<td>( \sigma_{\delta_{\text{CSR}}} )</td>
<td>( 10^{-4} )</td>
<td>1.60</td>
</tr>
</tbody>
</table>

**Figure 7.6-2.** Beta and dispersion functions through the DL2/ED2 beamline and up to the undulator entrance. The 4-dipole dog leg (DL2) and the final diagnostic section (ED2) are both included. Wire scanners are indicated by small circles on the schematic at bottom.
Beam Size, Aperture, and Field Quality

The horizontal beam size in DL2 reaches a peak value of \( \sim 200 \, \mu m \) (for a worst case coherent energy spread of 0.1\%) with the vertical size at \( \sim 30 \, \mu m \). A 25 mm full aperture is, therefore, completely adequate. The large dispersion in the DL2 quadrupoles sets fairly tight tolerances on field quality and gradient errors. Tables 7.6-5 and 7.6-6 list dipole and quadrupole magnet tolerances in DL2.

**Table 7.6-5.** Dipole magnet tolerances for DL2. Field harmonics are evaluated on a 10 mm radius and each entry individually corresponds to a 2% emittance dilution.

| Magnet | Quantity | Roll Angle | \( |b_1/b_0| \) | \( |b_2/b_0| \) | \( |b_4/b_0| \) |
|--------|----------|------------|----------------|----------------|----------------|
| Name   | mrad     | %          | %              | %              | %              |
| B31-34 | 4        | 18         | 0.38           | 35             | >100           |

**Table 7.6-6.** Quadrupole magnet tolerances for DL2. Field harmonics are evaluated on a 10 mm radius and each entry individually corresponds to a 2% emittance dilution.

| Magnet | Quantity | Roll Angle | \( |\Delta b_1/b_1| \) | \( |b_2/b_1| \) | \( |b_5/b_1| \) |
|--------|----------|------------|----------------|----------------|----------------|
| Name   | mrad     | %          | %              | %              | %              |
| QL31-33, QL37-39 | 6    | 2.7        | 0.5            | 10             | >100           |
| QL34-36 | 3    | 16         | 0.7            | 50             | >100           |

The most challenging of these tolerances are the absolute gradient errors of the six QL31-33, QL37-39 quadrupoles, \( |\Delta b_1/b_1| \). Although these six magnets will be powered in series, their gradients may differ slightly due to construction errors. The tolerance of <0.5\% is not trivially achievable. The effect on the beam, however, is the generation of linear dispersion. This can easily be tuned out empirically by including two small correction quadrupoles in the DL2 design. Quadrupole alignment tolerances are \( \sim 500 \, \mu m \) and do not present a significant challenge, and dipole field errors (not listed) are correctable with steering coils.

**Tuning and Correction**

The dominant error which will likely arise in DL2 is anomalous linear dispersion which will dilute the horizontal emittance. Quadrupole field strength errors are the most likely cause. Two small correction quadrupoles on separate power supplies separated by \( \sim 90^\circ \) of betatron phase advance will be used in appropriate linear combinations to generate orthogonal dispersion correction knobs. The emittance can be measured in the ED2 diagnostic section following DL2 and will be minimized with the orthogonal knobs sequentially.

**Coherent Radiation**

Since the bunch length is constant over DL2, the symmetry, as in the case of the BC2 double chicane, also cancels the \( \sim 20\% \) CSR horizontal emittance dilution which arises
between bend pairs ($\sigma_z = 20 \mu m$). The emittance growth is calculated using both the transient model computer code (see Section 7.4.4) and the steady-state approximation. The transient calculation results in an emittance growth of 1%, whereas the steady state is 0.1%. The CSR rms energy spread induced is fairly large at $1.6 \times 10^{-4}$, but the allowable coherent energy spread FEL chirp tolerance is nearly an order of magnitude larger ($1 \times 10^{-3}$). Fig. 7.6-3 shows the “steady state” (ss) and the transient modeled energy spread along with the horizontal emittance growth (steady state) due to CSR through the DL2 beamline for a 20 $\mu m$ bunch.

![Figure 7.6-3](image)

**Figure 7.6-3.** The induced rms energy spread (“steady-state”: solid, “transient”: dash) and horizontal emittance growth (dots) due to CSR along the DL2 high energy dog leg for a 20 $\mu m$ rms gaussian bunch. The horizontal dispersion function (dash-dot) and DL2 beamline schematic are also shown.

### 7.7 Instrumentation, Diagnostics, and Feedback

Critical to the preservation of the transverse emittance and the generation of a low-energy spread micro-bunch are the precise measurement techniques and correction schemes used to initially commission and maintain the machine. The LCLS accelerator has many phase space diagnostics and correction schemes built into the design. In most cases the relevant beamline is specifically designed to enhance the performance of these critical diagnostics.

#### 7.7.1 Transverse Emittance Diagnostics

There are six different transverse emittance diagnostic stations distributed along the LCLS accelerator of which five are new installations (the existing sector-28 station [19] will be slightly modified). In four of these cases the emittance measurement is accomplished with four consecutive wire scanners placed along the beamline with appropriate phase advance between scanners to optimize resolution. (Only three scanners are necessary with four used
to improve resolution and provide redundancy.) This also allows non-invasive emittance measurements to be made during normal machine operation. To save space, the emittance measurement following BC2 consists of a single wire scanner placed at a beam waist ($\alpha_{x,y} = 0$) and upstream quadrupole magnets are used to vary the beam size at the scanner. The emittance measurement stations and their parameters are summarized below in Table 7.7-1.

<table>
<thead>
<tr>
<th>Location</th>
<th>Station Name</th>
<th>Energy (GeV)</th>
<th>$\sigma_x$ ($\mu$m)</th>
<th>$\sigma_y$ ($\mu$m)</th>
<th>No. of Scanners</th>
<th>Existing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Following L0</td>
<td>ED0</td>
<td>0.150</td>
<td>67</td>
<td>67</td>
<td>4</td>
<td>No</td>
</tr>
<tr>
<td>Following BC1</td>
<td>ED1</td>
<td>0.280</td>
<td>52</td>
<td>52</td>
<td>4</td>
<td>No</td>
</tr>
<tr>
<td>At the end of Linac 2</td>
<td>L2-ED</td>
<td>5.5-6.0</td>
<td>28-63</td>
<td>32-65</td>
<td>4</td>
<td>No</td>
</tr>
<tr>
<td>Following BC2</td>
<td>BC2-ED</td>
<td>6.0</td>
<td>49</td>
<td>48</td>
<td>1</td>
<td>No</td>
</tr>
<tr>
<td>Sector-28 in Linac 3</td>
<td>L3-ED</td>
<td>9.9-11.7</td>
<td>42-58</td>
<td>42-58</td>
<td>4</td>
<td>Yes</td>
</tr>
<tr>
<td>Prior to undulator</td>
<td>ED2</td>
<td>15.0</td>
<td>30</td>
<td>30</td>
<td>4</td>
<td>No</td>
</tr>
</tbody>
</table>

The energy range of a diagnostic station listed in Table 7.7-1 (e.g., L2-ED) indicates the scanners are separated by accelerator sections. A range of beam sizes in the table represents the minimum and maximum over the four scanners. The ED0, ED1 and ED2 stations listed in Table 7.7-1 are dedicated, non-accelerating emittance diagnostic stations designed to produce identical beam sizes in $x$ and $y$ at all scanners; the betatron phase advance between wires is set to the optimal value for a four-scanner station (45°). These three sections are shown schematically in Figs. 7.6-1 (ED0), 7.3-2 (ED1), and 7.6-2 (ED2) with small circles indicating wire scanner locations on the beamline schematics. The scanners are separated by quadrupole doublets, with an upstream matching section. For four scanners, this 45° separation minimizes emittance resolution sensitivity to incoming beta function errors. Fig. 7.7-1 shows the emittance measurement resolution for the four wire systems of ED0, ED1 or ED2 (solid) versus the phase of an incoming beta-mismatch with a large amplitude of $\zeta = 1.5$, as defined in Eq. 7.7.1. The subscripted parameters represent the ideal matched beam and the non-subscripted parameters are the perturbed beam.

$$\zeta = \frac{1}{2} (\beta_0 \gamma - 2\alpha_0 \alpha + \gamma_0 \beta) \geq 1 \quad (7.7.1)$$

For comparison, the same resolution sensitivity to mismatch phase is plotted (dash) for the existing linac sector-28 four-wire system of the SLC. A modified SLC system is also shown (dots)—(see L3-ED description below). The single scanner relative beam size resolution used here is 5%. The average emittance measurement resolution (for $\zeta = 1.5$) for an optimally designed system (6.7%) is nearly a factor of 2 better than that (11%) of a system.
where wire scanners are a latter addition to an existing optical design (as in the case of the sector-28 system). The resolution at the worst case phase is nearly three times better. The equal beam sizes at each scanner in both $x$ and $y$ may also help reduce systematic errors of the measurement and simplify the measurement interpretation (i.e., beam is matched when all wires show equal beam size).

![Graph](image)

**Figure 7.7-1.** Emittance resolution versus beta-mismatch phase for a $\zeta = 1.5$ and beam size resolution of 5%. Resolution is shown for the EDO/ED1/ED2 sections (solid), the existing SLC sector-28 system (dash) and a modified sector-28 for SLC (dots). Lines are the average resolution.

**ED0 Emittance Station**

The ED0 station (see schematic of Fig. 7.6-1) is used to confirm and optimize the emittance of the injector system. It is a resolution optimized four-wire system as shown in Fig. 7.7-1, which is minimally sensitive to incoming beta-function errors. For the nominal emittance of 1 mm-mrad at 150 MeV, the rms beam size is identically $67 \mu m$ at each wire in both planes.

**ED1 Emittance Station**

The ED1 station (Fig. 7.3-2) is placed directly after BC1. It is crucial for the measurement and empirical correction of dispersion errors generated in BC1. The BC1 chicane can also be completely switched off to help isolate the different errors of BC1, L1, and DL1. Like ED0, ED1 is a dedicated emittance measurement section. At 280 MeV a $52 \mu m$ beam size exists at each wire in both planes.

**L2-ED Emittance Station**

The L2 linac is the most sensitive to orbit variation (note large growth in Fig. 7.3-3) and therefore can be expected to require frequent, perhaps daily, emittance optimization. The L2-ED station is placed at the end of L2 (Fig. 7.3-4). It is a space-constrained, four-scanner
station with non-optimal phase advance and an expected emittance resolution of ~10%. This section will be used primarily to empirically minimize the wakefield emittance dilution of L2.

BC2-ED Emittance Station

The BC2-ED station is a single wire (“WS26” in Fig. 7.4-2) included to provide some separation of BC2 dilution effects from those of the first half of L3. The quadrupoles used to measure the emittance are, however, upstream of BC2 and therefore may not provide the most ideal measurement since the beta functions will vary through BC2 as the measurement progresses (see Eq. 7.4.7). The L3-ED (sector-28) scanners may also be used to monitor BC2 dilution effects.

L3-ED Emittance Station

The L3-ED station (Fig. 7.3-8) is composed of four existing sector-28 wire scanners. The linac optics, however, change somewhat in this area for LCLS operation and therefore a small modification to the existing scanner locations is called for. The first sector-28 scanner will be moved upstream by one cell (24 meters) and the last scanner will be moved downstream by one cell. The LCLS optics then provides nearly 45° per plane between scanners. In fact, the statistical resolution for the SLC optical configuration is also marginally improved (Fig. 7.7-1: dots). The rms beam sizes are not identical at each wire; however, the phase advance between scanners provides optimal statistical measurement resolution. The L3-ED station will be used primarily to guide BC2 dispersion and CSR corrections. Emittance dilution occurring within L3 (see Fig. 7.3-7) is expected to be very small due to the short bunch there.

ED2 Emittance Station

A final emittance measurement section (Fig. 7.6-2) is included just upstream of the undulator entrance. This section will be used to make precise adjustments to the final horizontal and vertical beta functions (using quadrupoles QM33-36 of Fig. 7.6-2) and to confirm and optimize the final emittance immediately before the undulator. This emittance measurement section is also necessary to diagnose potential emittance dilution arising in DL2 through dispersion errors or CSR. Like ED0 and ED1, ED2 is a dedicated emittance measurement section, but with a 30 µm beam size at each wire in both planes at 15 GeV.

7.7.2 Bunch Length Diagnostics

The beam current delivered to the LCLS undulator is a critical parameter. It is determined by both the charge accelerated and the final bunch length achieved by the two bunch compressors. To optimize the compression, the bunch length needs to be measured before and after BC1 and BC2. In addition, once the bunch compressors are set up, a bunch length feedback system will be advantageous in the stabilization of the compressors. These feedback systems have not yet been designed.
The bunch lengths of interest are approximately 1000, 400, and 20 \( \mu \)m rms (10, 4, and 0.2 psec full width, respectively). Measuring 10 psec accurately using a streak camera is straightforward. The 4 psec measurement is more challenging but still feasible. Direct measurement of the 0.2 psec bunch is problematic. Bunch length monitors [20] designed to use coherent synchrotron radiation (CSR) have demonstrated fast, non-invasive measurements in the LCLS regime. They, however, provide a relative bunch length measurement. Absolute bunch length requires an understanding of the frequency spectrum of the radiation, the various component attenuation functions, and the CSR process.

For the LCLS accelerator, CSR detectors are used as the basic bunch length monitors, and their outputs are calibrated using a streak camera for the 10 and 4 psec ranges and using a “zero-phasing technique” [21] for the 0.2 psec range. The zero-phasing technique employs an rf system at a zero-crossing angle to generate a correlated energy spread. The transverse beam size can then be measured in a dispersive region to extract the bunch length. In the LCLS, the L3 linac is used as the rf system. The measurement is invasive and performed infrequently to calibrate or cross-check the CSR detectors. The micro-bunch is transported to the energy spread measuring wire scanner in DL2 with a +90° L3 rf phase (zero crossing producing no acceleration in L3). The measurement is then repeated at a –90° rf phase. The bunch length is then given by the average of the two energy spread values.

\[
\sigma_z \approx \frac{\lambda}{4\pi} \frac{E_i}{E_f - E_i} \left( \sigma_{(-90)} + \sigma_{(+90)} \right)
\]  

(7.7.2)

Here \( \lambda \) is the rf wavelength (105 mm), \( E_i \) is the L3 injection energy (6 GeV), \( E_f \) is the L3 final energy obtained when the L3 rf phase is at crest (15 GeV), and \( \sigma_{\pm90°} \) are the two energy spread measurements at +90° and –90°.

Results of a measurement using this method are simulated in Fig. 7.7-2, including wakefields, and demonstrate that it can be used to measure the absolute bunch length with an accuracy of a few percent. A 55 \( \mu \)m FWHM bunch length generates FWHM energy spread values of 0.31% (–90°) and 0.67% (+90°) which, when used in Eq. 7.7.2, reproduce the 55 \( \mu \)m bunch length to within 1 \( \mu \)m. Statistical resolution is dependent on the wire scanner used and should be 5–10%. The horizontal FWHM beam size at the DL2 energy spread wire associated with these conditions is ~1 mm. The less invasive CSR monitor is then directly calibrated.
The energy spread measurement in DL1 is made with a single wire scanner located between the two dipoles of DL1 at the point where the horizontal dispersion function reaches a value of $\eta_x = -126$ mm with a horizontal beta function of $\beta_x = 3.7$ m (see “WS05” of Fig. 7.6-1). For the nominal emittance and nominal energy spread of $\sigma_\delta \approx 0.2\%$ at 150 MeV, the betatron beam size is 113 $\mu$m, but the dispersive size is 252 $\mu$m. This produces a systematic energy spread measurement error of 10% (see Eq. 7.7.3). The statistical error depends on the wire scanner and should be 5–10%.

$$\frac{\sqrt{\eta_x^2 \sigma_\delta^2 + \epsilon_x \beta_x}}{\eta_x \sigma_\delta} - 1 \leq 10\% \quad (7.7.3)$$

The energy spread measurement in BC1 is made with a single wire scanner located in the center of the chicane at a point where the horizontal dispersion function is $\eta_x = 117$ mm and the horizontal beta function converges towards a minimum of $\beta_x = 1.4$ m (see “WS11” of Fig. 7.5-1). For the nominal emittance and nominal energy spread of $\sigma_\delta = 2.3\%$ at 280 MeV,
the betatron beam size is $50 \mu m$, but the dispersive size is $2700 \mu m$. This produces no systematic error in the energy spread measurement.

**BC2 Energy Spread Diagnostics**

The energy spread measurement in BC2 is also made with a single wire scanner located in the center of the first chicane at a point where the horizontal dispersion function is $\eta_x = 290$ mm and the beta function converges towards a minimum of $\beta_x = 6.5$ m (see “WS25” of Fig. 7.4-2). For the nominal emittance and nominal energy spread of $\sigma_\delta = 1.1\%$ at 6 GeV, the betatron beam size is $24 \mu m$, but the dispersive size is $3200 \mu m$. As in the case of BC1, this produces no systematic error in the energy spread measurement.

**DL2 Energy Spread Diagnostics**

The energy spread measurement in DL2 is made with a single wire scanner located where the dispersion function is $\eta_x = 178$ mm and the beta function converges towards a minimum of $\beta_x = 4$ m (see first wire scanner of Fig. 7.6-2). For the nominal emittance and a rms energy spread of $\sigma_\delta = 0.02\%$, the betatron beam size is $12 \mu m$, but the dispersive size is a measurable $36 \mu m$. The total beam size is then $38 \mu m$, and a horizontal wire scanner produces an energy spread measurement accuracy of $5\%$ at 15 GeV.

**7.7.4 Orbit and Energy Monitors and Feedback Systems**

**Orbit Feedback Systems**

Orbit feedback systems will be placed at the entrance of the L2 linac, the L3 linac and at the undulator entrance. As at the SLC [22], these systems will each be composed of ~10 $x$ and $y$ BPMs preceded by a set of two horizontal and two vertical fast dipole corrector magnets controlled by a microprocessor based cascaded feedback system. The cascade algorithm isolates each feedback system such that the systems do not all respond to the same orbit change.

In order to control transverse orbit variations to better than $1/10$ of the beam size, the BPM resolutions for the three systems described above need to be $50 \mu m$, $20 \mu m$ and $10 \mu m$, respectively (decreasing with increasing energy). Orbit variations which occur at frequencies below $\sim10$ Hz will be stabilized. Faster variations cannot be damped significantly and will need to be identified at the source. Additional orbit control systems (e.g., in the L0 linac) are addressed in Chapter 6 or not yet identified.

Transverse vibrations of quadrupole magnets will generate orbit variations which, if fast enough, will not be damped by feedback systems. Tolerance calculations in L2 (strongest quadrupole gradients) indicate that uncorrelated random vibrations of all 35 L2 quadrupoles at the level of $400$ nm rms will generate orbit centroid fluctuations in the undulator which are $6\%$ of the beam size there ($6\%$ of $30 \mu m$). Measurements in the SLC indicate that existing linac magnet vibrations are <250 nm [23] with the highest frequency content at 59 Hz and
10 Hz driven by cooling water. These observed vibrations are small enough to limit undulator orbit centroid jitter to well below the goal of 20% of its nominal beam size.

**Energy Feedback Systems**

Energy feedback systems will be placed at each bending system (DL1, BC1, BC2, and DL2). A single BPM or group of BPMs placed at a high dispersion point will be used to determine energy variations, and upstream rf phases will be used to stabilize the energy. A group of klystron phases will be used to control the energy while maintaining the correlated energy spread such that compression variations are not induced. Similar systems have been successfully tested at SLC [24].

The DL1 Energy Feedback System consists of at least 3 BPMs—one placed inside QL01, another in QL07, and a third near QL04 (see Fig. 7.6-1). With this simple system, energy variations can be distinguished from betatron oscillations, and the large dispersion at the QL01 and QL07 BPMs (195 mm) produces a relative energy resolution of $\delta < 1 \times 10^{-4}$ with 20 $\mu$m resolution BPMs.

The BC1 Energy Feedback System consists of 3 BPMs—one placed at the center of the chicane and at least two more beyond the chicane in the ED1 diagnostic section (see Fig. 7.3-2). The large dispersion (117 mm) at the chicane center should produce a relative energy resolution of $\delta < 2 \times 10^{-4}$ with a 20 $\mu$m resolution BPM.

The BC2 Energy Feedback System consists of 2 BPMs—one placed at the center of each BC2 chicane. Since the $2 \times 2$ transfer matrix between chicane centers is $-I$ (see Fig. 7.4-1) summing these two $x$ BPM readings will exactly cancel any betatron oscillation signal leaving only an energy variation signal. The large nominal dispersion in the two chicanes (290 mm and 110 mm, respectively) should produce a relative energy resolution of $\delta \approx 7 \times 10^{-5}$ with two 20 $\mu$m resolution BPMs.

The DL2 Energy Feedback System consists of 2 BPMs—one placed at QL32 and another at QL38 (see Fig. 7.6-2). Since the $2 \times 2$ transfer matrix between these quadrupoles is $+I$, differencing these two $x$ BPM readings will cancel any betatron signal leaving only the energy signal. The large nominal dispersion in the two quadrupoles (200 mm) should produce a relative energy resolution of $\delta \approx 7 \times 10^{-5}$ with two 20 $\mu$m resolution BPMs.

In all cases above, the energy resolution exceeds that necessary for the compression system tolerances (see Table 7.2-3).

**7.8 The Wake Functions for the SLAC Linac**

**7.8.1 Introduction**

Obtaining wake functions for the SLAC linac structure that are sufficiently accurate to be used in beam dynamics studies for bunches as short as 20 $\mu$m (rms) is not an easy task. It requires an accurate knowledge of the impedance of the structure over a large frequency range, which is difficult to obtain both by means of frequency domain and time domain
calculations. Direct time-domain integration, using a computer program such as the MAFIA module T2 [25], needs a very large mesh and hence prohibitive amounts of computer time. Even then, errors will tend to accumulate in the results. The approach actually employed, uses a frequency-domain calculation applied to a simplified model of the linac structure, an approach which also has its difficulties. The wake functions obtained are the wake fields excited by a point charge, as a function of distance behind that charge. By performing a convolution over the bunch, the wake fields left by a bunch of arbitrary shape can be obtained.

A SLAC structure is 3 m long; it consists of 84 cells. It is a constant gradient structure, and both the cavity radius and the iris radius gradually become smaller (the change in iris radius is 0.5%/cell) along the length of each structure. In our calculations each SLAC constant gradient structure is broken into five pieces. Each piece is represented by a periodic model with an average iris radius, and the rounded iris profiles are replaced by rectangular ones. The wake fields for the five models are obtained and then averaged to obtain wake functions to represent an entire structure. Questions as to the accuracy and applicability of the calculated wake functions concern primarily:

- The accuracy of the periodic calculations themselves
- Transient effects and effects at the ends of a structure
- The fact that the irises vary in the real structure
- The effects of resistivity/roughness of the iris surface

### 7.8.2 The Calculated Wakefields for the SLAC Linac

The wakefields for the SLAC linac structure were first calculated many years ago [26]. The methods and results presented here are essentially the same, though there are some changes in the details (see, for details, where these methods are applied to the NLC X-band structure [27] and the SBLC S-band structure [28]). To obtain the wake fields for each of the representative periodic models, several hundred mode frequencies and loss factors are obtained using computer programs that employ mode-matching techniques. The accuracy of these calculations is not easy to assess. The density of modes obtained is one consistency check, and good agreement is found.

The high-frequency contribution to the impedances is obtained employing the so-called “Sessler-Vainsteyn optical resonator model” [29,30]. It is a simple model that combines the Poynting flux at the iris due to the beam with the diffraction due to light at the edges of a periodic array of circular mirrors. It yields the expected high-frequency dependence of the impedance; e.g., the real part of the longitudinal impedance varies with frequency as $\omega^{-3/2}$.

Fig. 7.8-1 shows the real part of the longitudinal impedance, averaged over frequency bins, for the geometry of cell 45 ($a$ in the plot is the iris radius). The dashed curve is the Sessler-Vainsteyn prediction. At the higher frequencies the agreement is seen to be quite good. As a dipole example, the real part of the longitudinal dipole impedance, averaged over frequency
bins, for the geometry of cell 45 is plotted in Fig. 7.8-2, with the dashed curve again giving the Sessler-Vainsteyn prediction. There appears to be a 15% systematic difference between the two results at high frequencies, probably due to the approximate nature of the Sessler-Vainsteyn model. The agreement, however, is acceptable for our requirements.

The longitudinal wakefield of the 5 representative cells—cells 1, 23, 45, 65, and 84—is given in Fig. 7.8-3, and the average (with the end cells weighted by one half), representing the whole structure, is given by the dashes. One important consistency check is that for each model structure, the longitudinal wakefield at the origin must satisfy

$$W_0(0) = \frac{Z_0 c}{\pi a^2}, \quad (7.8.1)$$

with $Z_0 = 377 \, \Omega$ and $a$ the iris radius. In all cases the computed values are low, but in no case by more than 4%. Similarly, the transverse wakefield of the representative cells is given in Fig. 7.8-4, and the average, again representing the whole structure, is given by the dashes. The transverse wakefield of the representative cells must satisfy Eq. 7.8.2 [26]. In all cases the agreement is within 1-2%.

$$W_z(0) = \frac{2 Z_0 c}{\pi a^3} \quad (7.8.2)$$

### 7.8.3 Discussion

The calculated wakefields are asymptotic wakefields in that they apply only after the beam has traversed a critical number of cells $N_{\text{crit}}$. For a gaussian bunch, for the total loss obtained using only the asymptotic wake functions to be within a few percent of the loss when transient effects are also included, requires that

$$N_{\text{crit}} = \frac{\alpha a^2}{p \sigma_z} \quad (7.8.3)$$

with $\alpha \geq 0.5$, $p$ the structure cell length, and $\sigma_z$ the bunch length. The transient region is largest for short bunches. In the LCLS the bunch is shortest after the second bunch compressor where $\sigma_z \approx 20 \, \mu m$. Taking, in addition, $a = 1 \, \text{cm}$ and $p = 3.5 \, \text{cm}$, that $N_{\text{crit}} \approx 70$, which represents about 80% of the length of one structure or 0.4% of the length of the third linac. In most of the SLAC linac the 3-m structures are combined in groups of four, with nearly no extra space in between them; the groups of four are separated by about 20 cm of beam tube, and every 100 m there is an extra 4 m of beam tube. With this arrangement, after the end of the structures, the wakefields generated by the beam do not have a chance to return to their initial conditions, except partially at the 3% of the structures that follow the 4 m gaps. Therefore, using the asymptotic wakefields to represent the entire SLAC linac, and ignoring the transient effects, should result in very little error even for a 20 $\mu m$ bunch.
Figure 7.8-1. The real part of the longitudinal impedance, averaged over frequency bins, for the geometry of cell 45. The Sessler-Vainsteyn prediction is given by the dashed curve.

Figure 7.8-2. The real part of the longitudinal dipole impedance, averaged over frequency bins, for the geometry of cell 45. The Sessler-Vainsteyn prediction is given by the dashed curve.
There are four other effects that can be important for short bunches: (1) The so-called “catch-up distance” effect: If the head of the beam generates a wakefield at a certain position in the linac, due to causality the tail does not feel the effect until a distance \( \sim 0.5 \alpha^2/\sigma_z \), which in this case is 2.5 m, later. Since this is a small fraction of the 516 meters of accelerating structure after the second compressor, this effect should not be important. (2) For \( \sigma_z \leq \alpha/\gamma \), which in this case is 0.3 µm, the impedance drops dramatically. Since the minimum bunch length is 20 µm, this effect should also not be important for the LCLS.
(3) The effect of the resistivity of the iris surface is shown, in the following section, not to be a significant effect for the LCLS accelerator. (4) The effect of the roughness of the iris surface will be discussed in Section 7.8-6.

Finally, it should be noted that the above estimates all assume that the bunch is gaussian, which it is not. The real bunch shape is rather rectangular with spikes, which have a rms length on the order of a few microns, at the tail of the distribution. The Fourier transform of such a bunch shape reaches to higher frequencies than the gaussian approximation, and therefore the short bunch effects will become somewhat more pronounced than estimated above. However, even with this consideration, the calculated wake functions will accurately represent the wakefield effects in the linac for the LCLS project.

### 7.8.4 Confirmations

There have been confirmations, both theoretical and by measurement, of the calculated SLAC wake functions and, more recently, of the similarly calculated wake functions for the NLC and the DESY-SBLC linac. All the comparisons, however, have been done for bunch lengths significantly larger than the 20 µm of interest here. As to theoretical comparisons, the calculated SLAC wake functions have been confirmed, for gaussian bunches down to \( \sigma_z = 0.5 \) mm, using the time domain program TBCI [32]. A time domain program exists that seems to be able to obtain accurate results for short bunches in accelerating structures [33]. For the case of a 100 µm bunch in the NLC structure, the results of this program, as well as those of a frequency domain program [34], agree with our frequency domain results to within 7%.

As to confirmation by measurement, in the SLC linac the total wakefield-induced energy loss [35] and more recently the wakefield-induced voltage of a bunch [36] have been shown to agree quite well, for bunch lengths down to 0.5 mm. Also, in the ASSET test facility, the short range transverse wakefield of a 0.5 mm bunch in the NLC structure has been measured, and the results agree quite well with the calculated results [37].

### 7.8.5 Resistive Wall Wakefields

In addition to geometric wakefields, the micro-bunch in L3 and beyond experiences a longitudinal resistive wall (RW) wakefield which may also introduce a coherent energy spread along the bunch [38]. For a bunch with gaussian axial distribution which is much longer then the characteristic length, \( s_0 \),

\[
\sigma_{\delta RW}^2 = \left( \frac{2a^2}{Z_\sigma} \right)^{1/3}
\]

the rms relative energy spread, \( \sigma_{\delta RW} \), induced in a smooth cylindrical chamber of radius, \( a \), and conductivity, \( \sigma \), is
\[ \sigma_{\delta}\text{kw} = (0.22) \frac{e^2 c N L}{\pi^2 a E \sigma_z^{3/2}} \sqrt[3]{\frac{Z_0}{\sigma}}. \] (7.8.5)

The 172 3-meter copper accelerating structures that make up most of the length of L3 are each composed of 84 cavities. A model of three such cavities is shown in Fig. 7.8-5.

![Figure 7.8-5](image)

**Figure 7.8-5.** Model of the geometry of three cavities (of 84) of one SLAC 3-meter accelerating section. The dimensions used are: \( a = 11.6 \text{ mm}, \ b = 41.3 \text{ mm}, \ d = 35.0 \text{ mm}, \) and \( g = 29.2 \text{ mm}. \) The iris radius, \( a, \) actually decreases from 13.1 to 9.1 mm along the section. The mean is used here.

The large radius \( (b) \) segments of the structures are not “seen” by the bunch and therefore contribute nothing. For copper \( (\sigma = 5.9 \times 10^7 \Omega^{-1} \text{m}^{-1}) \) and \( N = 6.3 \times 10^9 \text{ e– per bunch, the RW relative rms energy spread at } \gamma mc^2 = 15 \text{ GeV is 0.01%. Note, this is for a gaussian bunch which is long compared to } s_0 (\text{Eq. 7.8.4}). \) To more accurately estimate the RW energy spread generated along the entire beamline from BC2 exit to undulator entrance, including non-accelerating sections, the beamline is broken into three discrete sections of significantly small radius (Table 7.8-1). The remaining sections (~120 m) have much larger radii (40–400 mm) and are ignored here.

<table>
<thead>
<tr>
<th>Beamline Section</th>
<th>Material</th>
<th>Conductivity</th>
<th>Radius</th>
<th>Length</th>
<th>( s_0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac 3 rf-structures (iris ( a) )</td>
<td>Copper</td>
<td>5.9\times10^7</td>
<td>11.6</td>
<td>87</td>
<td>23</td>
</tr>
<tr>
<td>Linac 3 non-accelerating chambers</td>
<td>Stainless Steel</td>
<td>0.14\times10^7</td>
<td>12.7</td>
<td>60</td>
<td>85</td>
</tr>
<tr>
<td>Linac-to-undulator beamline</td>
<td>Aluminum</td>
<td>3.6\times10^7</td>
<td>12.7</td>
<td>100</td>
<td>29</td>
</tr>
</tbody>
</table>

The 60 meters of 1-inch diameter stainless steel are distributed along Linac 3 as quadrupole/BPM chambers, and other short non-accelerating sections including 12 meters beyond sector-30 in the beam switchyard. The aluminum sections will be new chambers that
follow the large radius beam switchyard sections and make up the chamber for the DL2 section. For all of these sections, the bunch (20 µm) is shorter than the characteristic length $s_0$. The RW energy spread of the short-bunch ($\sigma_z/s_0<~1$) is calculated using the Green’s function wakefield [39],

$$E_z(s) = -\frac{4qcZ_0}{\pi a^2} \left( \frac{1}{3} e^{-s/s_0} \cos \frac{3s}{s_0} - \frac{\sqrt{2}}{\pi} \int_0^\infty dx \frac{x^2 e^{-x^2/s_0}}{x^6 + 8} \right), \quad (7.8.6)$$

of a short bunch which is convoluted with the bunch distribution of Fig. 7.2-3. This estimate ignores the frequency dependence of the conductivity. The results for each of the three sections of Table 7.8-1 are shown in Fig. 7.8-6. For this bunch distribution (shown on arbitrary vertical scale as solid curve in the figure), the total rms RW energy spread generated by all three sections is $2.5 \times 10^{-4}$ (with respect to the mean), which is a factor of 4 below the chirp tolerance ($\sim 1 \times 10^{-3}$). If the linear component of the energy spread is removed ($\sim 0.5^\circ$ rf phase increase in L2), this is reduced to $1.7 \times 10^{-4}$.

![Figure 7.8-6](image.png)

**Figure 7.8-6.** Resistive wall wakefield of a 1 nC bunch after convolution with the axial distribution (solid, arbitrary vertical scale) of Fig. 7.2-3. The energy spread at 15 GeV is generated by the beamline sections described in Table 7.8-1. The total RW rms relative energy spread (with respect to mean) is $2.5 \times 10^{-4}$ which can be reduced to $1.7 \times 10^{-4}$ when the linear component is removed.

### 7.8.6 The Impedance Due to the Roughness of the Iris Surface

The wakefields due to the surface roughness of a tube have been recently estimated [40]. The energy spread generated by the longitudinal wakefield is correlated along the bunch and is much more critical in the undulator with its small tube radius. The effect as it pertains to
the accelerator is briefly described here. A more thorough discussion is taken up in Section 8.7.

The effect of roughness is important primarily after the second bunch compressor, where the beam is shortest. From causality it is seen that the wakefield effect experienced by the beam in the accelerator structure can only be due to the 12 mm radius irises. The length of accelerating structure after the second compression is ~520 m; the fraction of the period that is the iris length is 0.167; therefore, the effective length for this calculation is 86 m. For a 1 nC, 20 $\mu$m rms gaussian bunch and a surface roughness of 0.15 $\mu$m [41] we find a correlated rms energy spread of $\sigma_\delta = 0.06\%$ at 14.3 GeV. However, the bunch distribution is closer to uniform than gaussian (see Fig. 7.2-3). This reduces the rms energy spread to a tolerable ~0.02%. The transverse wakefields generated by the rough surface are negligible (see also Section 8.7).

7.9 Summary of Dilution Effects

7.9.1 Transverse Emittance Dilution

The overwhelming majority of emittance dilution mechanisms occurring in the accelerator produce an immediate ‘correlated’ emittance growth such that the mean transverse position of each bunch slice is altered, but the local electron density remains nearly unaltered; the projected emittance is changed but the slice emittance is not. The degree of preservation of this correlation through the entire accelerator has not, at this time, been studied in sufficient detail to predict its full impact on FEL performance. Whether the emittance is correlated or not has different implications for the brightness and the saturation length. A correlated emittance growth effects the brightness whereas an increase in the slice emittance effects both brightness and saturation length. Detailed multi-particle tracking studies are needed to quantify this issue.

Simulations of transverse emittance dilution throughout the various accelerator sections have been presented in the preceding sections. A summary is presented here of the accelerator ‘emittance budget’. Included in this budget are estimates of the emittance measurement resolution and correction capabilities of each system. For example, if the emittance after BC1 is increased through the generation of anomalous momentum dispersion, then the ED1 wire scanners are used to measure the emittance so that it can be empirically minimized using the CQ11 and CQ12 quadrupole pair in BC1. The correction is ultimately limited by the measurement resolution which is conservatively assumed (from SLC experience) to be $\Delta e / e_0 \approx 10\%$. If the emittance is measured 5 times in each minimization scan the final resolution should be ~$(10\%)/\sqrt{5} \approx 4\%$. This represents the approximate minimum emittance dilution achievable after optimization, assuming full correction is possible. Table 7.9-1 lists the emittance budget based on these estimates and other uncorrectable dilution components.
Table 7.9-1. Accelerator emittance budget based on the dominant dilution mechanisms of each section. The final sum is given as a range of 20-48% depending on how the various dilutions add; quadratically or linearly (worst case).

<table>
<thead>
<tr>
<th>Beamline section</th>
<th>$\Delta\varepsilon^\theta_0$ [%]</th>
<th>Component Errors</th>
<th>Dilution Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>ED0/DL1</td>
<td>4</td>
<td>Quadrupole gradient errors</td>
<td>Dispersion</td>
</tr>
<tr>
<td>L1</td>
<td>4</td>
<td>Quad., BPM and rf-structure misalignments</td>
<td>Wakefields and dispersion</td>
</tr>
<tr>
<td>BC1</td>
<td>6</td>
<td>Quad. misalignments and dipole field errors</td>
<td>CSR and dispersion</td>
</tr>
<tr>
<td>L2</td>
<td>15</td>
<td>Quad., BPM and rf-structure misalignments</td>
<td>Wakefields</td>
</tr>
<tr>
<td>BC2</td>
<td>8</td>
<td>Quad. misalignments and dipole field errors</td>
<td>CSR, ISR and dispersion</td>
</tr>
<tr>
<td>L3</td>
<td>4</td>
<td>Quad. and BPM misalignments</td>
<td>Dispersion</td>
</tr>
<tr>
<td>DL2/ED2</td>
<td>4</td>
<td>Quad. gradient and dipole field errors</td>
<td>Dispersion</td>
</tr>
<tr>
<td><strong>Quadratic/linear sum</strong></td>
<td><strong>20/48</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7.9.2 Final Energy Spread

As in the case of the transverse emittance dilution, mechanisms which increase the final electron beam energy spread affect, dominantly, the mean energy of each bunch slice, whereas the energy spread within the slice is nearly unaffected. This produces a chirp in the resonant frequency of the FEL. **Table 7.9-2** summarizes the various components of the final rms relative energy spread at the undulator entrance. The incoherent spread refers to the slice energy spread while the coherent refers to the energy spread projected over the entire bunch (correlated).

Table 7.9-2. Estimates of the various incremental components of the final rms relative energy spread at the undulator entrance. Each entry is normalized to 14.3 GeV. The total is given as a range of 0.4-0.9×10⁻³ depending on how the various effects add; quadratically or linearly (worst case).

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>$\Delta\sigma_\theta$ incoherent [10⁻³]</th>
<th>$\Delta\sigma_\theta$ coherent [10⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic incoherent spread</td>
<td>0.060</td>
<td>—</td>
</tr>
<tr>
<td>ISR of BC2</td>
<td>0.004</td>
<td>—</td>
</tr>
<tr>
<td>ISR of DL2</td>
<td>0.015</td>
<td>—</td>
</tr>
<tr>
<td>Uncompensated geometric wake</td>
<td>—</td>
<td>&lt;0.2</td>
</tr>
<tr>
<td>CSR of BC1</td>
<td>—</td>
<td>0.003</td>
</tr>
<tr>
<td>CSR of BC2</td>
<td>—</td>
<td>0.120</td>
</tr>
<tr>
<td>CSR of DL2</td>
<td>—</td>
<td>0.150</td>
</tr>
<tr>
<td>L3/DL2 resistive-wall total</td>
<td>—</td>
<td>0.240</td>
</tr>
<tr>
<td>Roughness wakefield in L3/DL2</td>
<td>—</td>
<td>~0.250</td>
</tr>
<tr>
<td><strong>Total quadratic/linear sum</strong></td>
<td><strong>0.06</strong></td>
<td><strong>0.4/0.9</strong></td>
</tr>
</tbody>
</table>
7.10 References


2. The simulation was performed using the computer code “LITRACK” written by K.L. Bane.

3. Dian Yeremian, private communication.


13. The computer code was written by R. Warnock at SLAC.


34 K. Yokoya, private communication.


41 D. Walz, private communication.
**8 Undulator**

**TECHNICAL SYNOPSIS**

After reviewing several possible magnet designs, a planar Halbach hybrid type was adopted, with a period of 30 mm and a fixed 6 mm magnetic gap. The focusing of the electron beam is obtained with a FODO separated function lattice, with permanent quadrupoles placed between segments of the undulator. Each segment contains 64 periods and is 1.92 m long. The poles are made of vanadium permendur, and the magnets that drive them will be made of NdFeB. The separation between sections is 23.5 cm long. This free space will house the focusing quadrupoles, beam position monitors and vacuum ports. The quadrupoles are used to correct the beam trajectory by moving them transversely and thus are also used in beam based alignment. The electron beam trajectory is required to be straight to within 5 \( \mu \text{m} \) over a field gain length (11.7 m) to achieve adequate overlap of the electron and photon beams. It is shown that this specification, although presently beyond state-of-the-art mechanically, can be achieved with beam-based techniques. A suspended wire and mechanical actuator feedback will be used to maintain alignment at the micron level. A small amount of tapering is required to compensate for the energy loss due to the emission of radiation and resistive wall wakefields.

Each undulator section is supported by a girder. A pier supports the ends of two girders, and the magnets and components located between the girders. Beam Position Monitors (BPMs) are the primary system for measuring the transverse electron position in the undulator. The BPMs must have the ability to detect relative changes in position of 1 \( \mu \text{m} \) at the operating charge of 1 nC. After a review of several BPM technologies, it was decided that a microwave cavity type detector can provide sub-micron resolution and micron level absolute accuracy, and this is the non-intercepting monitor choice for the LCLS. In addition to non-intercepting microwave cavity BPMs, beam intercepting wires will be positioned between undulator segments. Carbon wires will be used for emittance measurements and to measure simultaneously the electron and photon beams’ position and size.

Because of the small chamber radius, wakefield effects have to be taken into account in the design. The resistive wall effects can be made small by plating the stainless steel chamber with copper. Roughness of the inside pipe surface may cause a momentum spread increase and interfere with the lasing FEL dynamics if greater than about 100 nm. With some R&D effort, this smoothness is achievable.
8.1 Overview

8.1.1 Introduction

In a single pass FEL operating in the SASE regime, exponential gain of the coherent radiation intensity is predicted by theory and power saturation is achieved in about ten gain lengths. An FEL operating at saturation will have a more stable radiation output, a feature considered essential by the experimental users of the LCLS. The task of the undulator design is to achieve saturation in a real device in a length not significantly larger than an ideal undulator.

A planar Halbach hybrid undulator with fifty-two segments has been chosen. Each segment is 1.92 m long and is separated from its neighbors by a gap of 23.5 cm for focusing, trajectory control, beam position and vacuum components. This gives a total undulator length of 112 m. Section 8.2 outlines the undulator magnetic field optimization. Section 8.3.1 describes the mechanical design of the undulator. Stray radiation–bremsstrahlung and the direct electron beam hits–can damage the undulator by catastrophic single strike effects and by changing the magnetization of the permanent magnet material over longer periods of time. The effects of radiation demagnetization have been shown to be mitigated by thermally stabilizing the magnetic material. Protection of the undulator from errors in the incoming beam trajectory can be met by standard beam collimator designs and is described in Section 8.3.2. The undulator vacuum system is fairly straightforward and is described in Section 8.4. To ensure overlap of the radiation field with the electron beam traversing the undulator, an alignment tolerance of 5 µm over a gain length (11.7 m) is required. Mechanical survey cannot meet this requirement. A beam based alignment system that will be used to achieve this tolerance is described in Section 8.5.2. After the initial undulator setup a measurement and feedback system will be needed to maintain the beam trajectory. The BPM system for measuring the trajectory is described in the Section 8.6. In order to allow and correct for ground motions—vibrations, tides, diurnal thermal effects etc.—the undulator magnets will incorporate a Wire Position Monitor (WPM) system. This system is also described in Section 8.6. In addition, Section 8.6 describes the carbon wire position and emittance diagnostic and the combined electron/photon position diagnostic. To achieve the high undulator fields needed for the LCLS FEL, the pole tip gap is set to 6 mm. The small bore of the beam pipe needed to fit into this gap necessitates careful consideration of resistive wall wakefields and the effects of surface roughness. These effects are extensively discussed in Section 8.7. Finally Section 8.8 considers the effects of ions generated by the electron beam passing through the undulator vacuum.

8.1.2 Undulator Design Summary

Introduction

The LCLS undulator is made of a permanent-magnet hybrid array with 30 mm period and 6 mm gap. It is designed to take a 233 fsec (fwhm), 1 nC pulse of electrons at 4.5–
14.3 GeV and microbunch the pulse with 15–1.5 Å period, and to cause the microbunches to radiate coherently at 15–1.5 Å. A device that will achieve these performance goals with a magnet length that is not excessively greater than the 94 m saturation length of an ideal undulator has been designed.

The design includes the undulator proper, the termination of the undulator at separations between segments, and quadrupole magnets, which are used for focusing, trajectory corrections and beam-based alignment. It also requires the measurement of the fields of fabricated components, and the design of shimming strategies to achieve desired tolerances.

Design Concept History

Several undulator options were studied and a plane polarizing design that uses hybrid permanent magnet technology was chosen. Optical klystron style dispersive sections in the undulator allow the energy-modulated bunch to become spatially modulated, but this approach is ruled out because of the LCLS energy spread. (See Chapter 5.)

Superconducting DC and warm-pulsed bifilar helical electromagnetic undulators were considered, but were thought to be costly, complicated, difficult to hold to mechanical tolerances and to provide with steering corrections. Access to the beampipe completely surrounded by undulator would be impaired. The technological complications of going to a superconducting magnet design and the resultant R&D required argue against that approach.

Besides the bifilar helix, there are permanent magnet helical undulator concepts, both with permanent magnets only (twistor designs) and with hybrid structures. These do not offer short periods like the electromagnet devices, and are as costly and complex as the plane polarizing devices. A pure permanent magnet plane polarizing undulator would work for the LCLS, but it would have a longer period than a hybrid device because the field is weaker for a given gap. Also, errors are harder to control in the pure permanent magnet design. Such a design might have the advantage that steering and focusing fields could be superimposed by electromagnets surrounding the undulator. As a result of the above considerations, a hybrid permanent magnet design was chosen.

The Undulator

The undulator is a standard Halbach hybrid design [1]. The undulator will have 1.92 m, 64 period segments, with a ferromagnetic field clamp at the end of each segment. The poles will be vanadium permendur, and the magnets that drive them will be NdFeB. The NdFeB will be heat treated after it is magnetized at temperatures as high as 125°C in order to stabilize the material against radiation damage. It will also be exposed to demagnetizing fields, which also stabilizes the material by demagnetizing marginal domains. In the mechanical design, each pole will have one single block of magnet material attached to it, and it will also receive flux from the neighboring poles’ magnets, through a small longitudinal gap that is imposed in the design to prevent mechanical stackup. The mechanical design is described in Section 8.3.
Ultra-smooth beampipe with 0.25 in OD (6.35 mm) is already commercially available. If manufacturing of a 6 mm ultra-smooth beampipe proves to be costly, the 6.35 mm diameter pipe can be drawn into an oval to fit the 6 mm gap. (Wakefields are not significantly affected by such a modification.)

Each end of the girder will be supported by a pier, and a separation of 23.5 cm will be allowed between undulator segments, to allow the electrons to fall behind the photon beam by one photon wavelength. The separation will be used for diagnostics, and for focusing corrector magnets. The undulator sections can be mounted on high precision movers, if it is necessary to control their positions using feedback.

The separation between two sections of the FEL undulator is given by the condition that, as the electron and the photon waves travel the distance $z_{sep}$, the phase between the two waves advances by $\Delta \phi = 2\pi$. A time $t$ is required for the electron to travel the distance $z$ and $\Delta \phi$ is given by:

$$\Delta \phi = 2\pi = k z_{sep} - \omega t = k z_{sep} - \omega \int^z_a \frac{dz}{v_z(z)}$$

In the separation, where the velocity of the electron, $v_z$, is constant:

$$t = z / c \beta_z \approx z(1 - 1/2 \gamma^2) / c$$

so that:

$$2\pi = k z_{sep} [1 - (1 - 1/2 \gamma^2)] = \pi z_{sep} / \lambda_u \gamma^2$$

and $z_{sep}$ will be given by:

$$z_{sep} = 2 \gamma^2 \lambda_u = 2 \gamma^2 \frac{\lambda_u (1 + K^2 / 2)}{2 \gamma^2} = \lambda_u (1 + K^2 / 2)$$

In the LCLS case, $z_{sep} = 23.76$ cm for $K = 3.71$, and undulator period $\lambda_u = 30$ mm. $z_{sep}$ is independent of $\lambda_u$, the radiation wavelength, and independent of electron energy. The electron’s velocity $v_z$ is not constant in the undulator or at the end of the undulator, so a more exact separation must be calculated numerically. The termination of the magnetic field should be done with a ferromagnetic field clamp in a manner that causes the least loss of resonant wiggles (see Section 8.2.2).

As the electron beam travels down the undulator, it loses energy to radiation ($\delta E \approx -0.16\%$ at 14.3 GeV), and wakefields ($\delta E \approx -0.1\%$ at 14.3 GeV). Beampipe roughness causes energy spread of the order of 0.05% rms over the core of the electron bunch. This effect is not as well understood as the first two. Because of the loss of electron energy, the
electrons move outside the potential well established by the radiation field. To offset these effects, it is necessary to taper the undulator. A purely mechanical gap taper for $\delta E \approx -0.3\%$ would require a gap increase of about $15 \, \mu m$ over 100 m. Magnetic tapering is discussed in Section 8.2.1.

Two other types of tapering can be used. One is fixed (to account for $\delta E \approx -0.3\%$) to offset the radiation and resistive wall effects that are considered well understood. The second is variable (up to $\delta E \approx -0.15\%$) to allow some realtime adjustability for wakefield effects that are less well understood.

The variable taper is achieved by recalling that the magnetic field strength varies as $\cosh(2\pi x/\lambda_u)$ across the gap. If the beam is off-center horizontally, it experiences a greater magnetic field strength than when it is on-center. Therefore a taper can be achieved by moving modules of the undulator so that the beam is off-center at the beginning and on-center at the end. A displacement of 136 $\mu m$ is required to achieve $\delta E \approx -0.15\%$ at 14.3 GeV.

**Strong Focusing**

Simulations of the LCLS show that strong focusing must be added to the undulator lattice to maintain a small beam diameter; natural focusing would give a beta function length of about 70 m; optimal focusing occurs with a beta function of less than 20 m. The LCLS design energy ranges from 4.5 to 14.3 GeV. Optimum focusing at all energies can be obtained by focusing with variable permanent magnet quadrupoles or electromagnetic quadrupoles. As was shown in Chapter 5, this flexibility is not required, since the optimum beta function at 14.3 GeV, is not far off the optimum for 4.5 GeV. For this reason, permanent magnet quadrupoles are used.

Segment separations allow for a separated function FODO lattice. See Fig. 8.1-1. The smallest beta-function (6 m) is at 4.5 GeV. This implies that the FODO cell length needs to be less than 6 m (see Chapter 5). The LCLS design nominally adopts a 1.92 m (64 periods) undulator segment length with a BPM and corrector in each separation between segments. Simulations show that this spacing meets the requirements for beam-based alignment.

![Figure 8.1-1](image.png)

**Figure 8.1-1.** A schematic side view of the undulator structure, showing the FODO lattice with separations between 1.92 m undulator sections for diagnostics, focusing correctors, and vacuum ports. The undulator magnets are mounted on aluminum girders whose temperature is stabilized.

The quadrupole magnets serve two other functions. They are used in the initial alignment to establish a straight-line trajectory. They will be moved mechanically on vertical and
horizontal slides to correct the trajectory to approximate a straight line. See Section 8.3 for a more detailed description. They are also used as run time correctors; they will be moved transversely to offset small trajectory errors that are detected by the BPM systems. See Section 8.5 for details.

To be less vulnerable to electronic drifts in the BPM signals, it is preferable to place the BPMs on the undulator girders, so that their positions are tracked and corrected by the WPM system (see Section 8.6.4). They would still move on x-y stages, but now relative to a non-drifting frame of reference.

The quadrupole focusing magnets are made using permanent magnets. Assuming a field gradient of 50 T/m over a length of 10 cm, a 200 μm motion would result in a 40 μm deflection at a BPM that is 2 m downstream. In addition to errors caused by the non-zero field integrals of the undulators, errors caused by the earth’s field need also to be corrected. A 1 G environmental field would cause a 14.3 GeV beam to deflect by 8 μm every 2 m. The quadrupole correction system can control this easily.

The fields inside a Halbach “orange slice” pure permanent magnet quadrupole (see Fig. 8.1-2) are given to leading order by [1]:

$$B^*(z) = B_x - iB_y = B_0 e^{i\phi} = \frac{MB_i}{\pi} \frac{z(r_2 - r_1)}{\eta r_2} \cos^2 \left[ \frac{\pi}{M} \right] \sin \left[ \frac{2\pi}{M} \right]$$

(8.1.5)

where $z = x + iy = re^{i\theta}$, $M$ is the number of “orange slices”, $r_1$ is the radius of the bore, and $r_2$ is the outer radius. In the case where $M = 4$:

$$B_0 = \frac{2Br (r_2 - r_1)}{\pi}$$

(8.1.6)

The field gradient will therefore be:

$$\frac{dB_0}{dr} = \frac{2Br (r_2 - r_1)}{\pi \eta r_2}$$

(8.1.7)

Figure 8.1-2. Cross-sectional views of Halbach (left) and Panofsky (right) pure permanent magnet quadrupole focusing corrector magnets. The arrows show the direction of magnetization in blocks of permanent magnet material.
A gradient of 50 T/m is far below the maximum achievable with a pure permanent magnet design and a simple quadrupole design with four trapezoidal pole pieces of NdFeB 2.7 cm outer radius and a 1 cm bore will suffice. See Fig. 8.1-2. The LCLS is insensitive to higher harmonics of the magnetic field.

**Undulator Tolerances**

For large scales, such as the length of an undulator segment, the principle that governs the tolerances is that the emitted radiation meets the resonance condition, so that it can create coherent electron bunching. Errors that cause off-resonance radiation should be no larger than the resonance width defined by the energy spread of the electron beam, which is 0.02% at 14.3 GeV, and 0.068% at 4.5 GeV. For small scales, such as the length of one period of the undulator, simulations show that random magnetic field errors are tolerable up to \( \Delta B_{max}/B_{max} < 0.1\% \), beyond which there is a degradation of the FEL gain according to FRED-3D. See Chapter 5 for details. This tolerance corresponds to a local period error of 35 \( \mu m \), or a local gap error of 7 \( \mu m \). These tight tolerances can be met with standard machining and assembly and magnetic shimming techniques. See Fig. 8.1-3.

**Figure 8.1-3.** Left: Top view of undulator, showing shims on poles and small gaps between pole assemblies. Shims may also be applied to the gap side faces of the NdFeB. Right: End view of undulator, showing NdFeB overlapping vanadium permendur pole pieces. The field of the undulator is horizontal, so that the radiation is vertically polarized.

It is possible to order magnets with \( \Delta B/B_{rms} < 0.5\% \), and an angular error of 0.5° from the nominal easy axis, but 1.0%, 1° magnets are much less costly. For pure permanent magnet devices, computerized sorting techniques can reduce undulator field errors by a factor of about 5 over those in a randomly assembled undulator. The same reduction factor is expected with a hybrid structure [2]. Since magnetic sorting and shimming will be used to get to 0.1% \( \Delta B/B_{rms} \) the looser tolerances are probably acceptable. See Section 8.2.1 for details.

**Undulator Construction**

The undulator pole assembly comprises vanadium permendur poles with an NdFeB magnet closely attached to one face, as shown in Fig. 8.1-3. The NdFeB magnet opposite the other face will be separated from the pole by a small gap, in order to prevent mechanical stackup error. This is not ideal magnetically, as it can lead to some direct fields from the NdFeB reaching the gap. But by keeping the separation to 50 \( \mu m \), these fields are small.
Even with precision machining, sorting of magnets, tight specifications, and precise assembly, measurable field errors are expected. A standard Hall probe can, in principle, be used to measure fields in the Tesla range with 20 \( \mu \)T (0.2 Gauss) resolution [3]. Each pole will be shimmed to minimize the trajectory and photon resonance errors. A coordinate measuring machine with 0.8 mm absolute positioning accuracy over a volume of 1.2 m x 1 m x 0.6 m [4] is available and has been fitted with a temperature-compensated Hall probe (calibration drift = 80 ppm/K). This will enable the magnetic field to be characterized precisely.

The effect of placing small shims on the ends of the pole pieces away from the gap, which lowers the field in the gap by a few Gauss, has been modeled. Magnets with 1\% (125 Gauss) individual magnetization errors can be sorted to lower the effective undulator field errors to 0.2\% (25 Gauss). These errors are well within the range of the shimming strategy. A desirable feature of the shimming strategy is that the effect is local to one pole, with little fanout. Thin ferromagnetic shims may also be placed on the gapside faces of the NdFeB magnets to control phase errors.

The phase shake tolerance is given by \( \Delta \phi < \sigma_\gamma / (\gamma \sqrt{5} \rho) \) [5], where \( \rho = 0.00047 \) is the 1-FEL parameter for the LCLS at 14.3 GeV. Thus, a phase shake tolerance of 14.4°, which is easy to meet, is likely to make phase shimming unnecessary. Also, field shimming of poles with thin strip shims may be labor intensive, so a tuning screw approach, that is more labor efficient, will be developed.

Detailed design of the undulator has been carried out using the AMPERES 3-D magnet modeling code [6]. These simulations show us that the vanadium permendur poles should be 25–30 mm wide (parallel to gap) 5 mm thick, and 30 mm tall (normal to gap). The NdFeB should be 35–40 mm wide, 10 mm thick (longitudinally), and 35 mm tall. It might be possible to reduce these dimensions somewhat if significant economies could be achieved.

Each segment of the undulator will have to have careful termination of the field, with the goal of keeping as many undulations of the trajectory on resonance as possible. A field clamp will control the fields of the undulator in the separation between segments. A preliminary design for this termination is given in Section 8.2.2.

Mechanical, Thermal, and Geophysical Engineering

The LCLS undulator will be placed in the existing FFTB facility at SLAC. The first third of the tunnel for the undulator is underground; the last two-thirds are in an above ground heavily shielded concrete structure. The substrate throughout is a continuous slab of miocene sandstone. In the range below 100 Hz, there is cultural and ocean-generated vibration, but at the top of existing sand/epoxy composite FFTB piers, the measured amplitude of these vibrations is less than 50 nm.

Diurnal thermal movements of the tunnel outside the hillside can be as much as 100 \( \mu \)m/day, but they can be reduced by isolating the tunnel with trenches cut into the substrate alongside it. The slow diffusive ground motion can separate points 100 m apart by
about 100 $\mu$m/year [7]. These measurements indicate that the feedback system needs to have a dynamic range of some fraction of a millimeter. Presently the tunnel air temperature is stable to about 1 K. This air temperature stability is sufficient as the undulator structure will be stabilized with flowing water whose temperature is controlled to 0.2 K.

8.2 Undulator Magnetic Design

8.2.1 Design of Undulator Segments

Basic Considerations

Simulation results (Chapter 5) indicate that satisfactory performance of the LCLS can be obtained when the rms magnetic field error is 0.1% or less over the entire undulator. Hybrid undulators utilize REC (rare earth-cobalt) permanent magnet blocks to excite the ferromagnetic (typically Vanadium-Permendur) poles (Fig. 8.2-1). The magnetic properties of these REC blocks can be well described by “charge-sheet-equivalent-magnet” (CSEM) theory.

Figure 8.2-1. Hybrid undulator construction top view, showing Vanadium-Permendur poles and CSEM blocks with magnetization vectors.

The CSEM blocks produced by conventional manufacturing techniques contain errors in both remanent field strength ($B_{rem}$) and orientation direction. The blocks are magnetized so that the primary component (M1) provides the flux feeding into the poles, but minor (transverse) components (M2, M3) will also be present. For large block populations, the distribution of errors in remanent field and orientation can be kept fairly tight (Figs. 8.2-2 and Fig. 8.2-3). Spreads of 1% in remanent field and 1° in magnetization orientation can be obtained fairly routinely. The allowable tolerances on the block distribution are determined by (at least) two factors. One is the requirement on the field error as seen by the beam. The other is the balance between sorting and shimming. Using a set of blocks with a relatively small spread in errors (e.g., 1.0% / 1.0° or 0.5% / 0.5°), the designer can rely upon sorting to achieve most of the error reduction in the on-axis field. However, if a set of blocks with a larger spread of errors (e.g., 1.5% / 1.5° or 2.0% / 2.0°) is used, then sorting by itself will not be able to reduce the errors to a tolerable level. In that case, ferromagnetic shims must be carefully placed to shunt flux away from the beam axis and, hence, to reduce the field error.
This process is usually iterative, and is very labor-intensive. For a very long device, it may be less expensive to purchase better blocks than to purchase more hours of labor.

![Distribution of magnetization components in a simulated block population.](image1)

**Figure 8.2-2.** Distribution of magnetization components in a simulated block population.

![Distribution of transverse magnetization components in the block distribution.](image2)

**Figure 8.2-3.** Distribution of transverse magnetization components in the block distribution.

**Correcting Local Field Errors**

The CSEM blocks possess magnetization errors as described above, which lead to errors in the field seen by the electron beam. Deviations in the magnitude of the primary component (M1) yield pole-to-pole excitation errors, while minor components of the magnetization (M2, M3) can be seen by the beam as normal and skew multipole fields [8]. Thus, the primary magnetization components (M1) are only seen indirectly by the beam since that flux must pass through the poles, while the minor components (M2, M3) constitute field errors that are
seen directly. It is the net effect of several blocks that produce the field seen by the beam at any given point along the axis.

Thus, the main strategy for reducing error is to arrange the blocks in a configuration that minimizes the net rms field error that arises from local, random field components. Techniques have been used in the past which reduce the rms error to the 0.1% level for a pure permanent magnet insertion device [2]. These techniques use a simulated annealing or threshold acceptance method, which combines a Monte Carlo search algorithm with a well-defined acceptance criterion to evaluate possible configurations of blocks to minimize a given “energy” or “cost” function. These methods aggressively seek out a “global” minimum for the cost function instead of merely finding the “local” minimum. The particular cost function is constructed so that a particular objective goal can be attained. In the case of the LCLS, this goal would be to reduce the rms field error to acceptable levels.

Initial Sorting Model and Results

The physical model is shown in Fig. 8.2-4. Each pole pair assembly is excited by four CSEM blocks. Only the fundamental magnetization component (M1) of each block contributes to the pole excitation. This is reasonable given the small variances in the magnet population. In addition the error in pole excitation is assumed directly proportional to the error in the individual block’s magnetization. Finally, the error in the on-axis field is also assumed directly proportional to the pole excitation errors. Thus, in this model, the errors in the fundamental magnetization component directly drive the field errors observed between the poles.

![Diagram](image)

**Figure 8.2-4.** Pole pair assembly. Errors in fundamental magnetization component (M1) of each CSEM block, pole excitation, and on-axis field are shown.

The errors in the transverse magnetization components (M2, M3) of the blocks can also be added to the sorting algorithm. In this way, performance in sorting pole excitation errors can be traded off with sorting skew and normal field components generated directly from the
permanent magnet blocks themselves. This is done by constructing two independent cost functions and combining them linearly.

This model neglects higher order contributions to the field error. These other contributions arise from a variety of sources—differential permeability effects in the poles, transverse magnetization components contributing to pole excitation, exact 3-D distribution of the magnetic field, etc. A better sorting model would try to include these effects. However, the current model should give a reasonable initial solution to magnet block placement. Higher order errors as well as errors in the final mechanical assembly will always be present, and will be corrected by shimming.

To construct the pole pair excitation error cost function, the following definitions are made:

\[ \varepsilon_i^\pm = (M1)_i^\pm - \langle M \rangle \]  

(8.2.1)

is the error in the magnetization for an individual block (+ -) bordering the \(i^{th}\) pole pair, where \(\langle M \rangle\) is the average magnetization for the entire block population,

\[ \delta_i^+ = \varepsilon_i^+ + \varepsilon_{i+1}^+ \]  

(8.2.2)

is the error in the excitation of the \(i^{th}\) upper (+) or lower (-) pole, and

\[ \sigma_i = \delta_i^+ + \delta_i^- \]  

(8.2.3)

is the relative error in the on-axis field.

The construction of the direct field error cost function is similar. It is observed that there is no fundamental magnetization in the transverse directions of the ideal device, so that the entire transverse magnetization components (\(M2\) and \(M3\)) are errors. The net error in a given transverse component is simply the sum of magnetization components of the upper and lower blocks, normalized by the average magnetization of the blocks.

The total cost function used in the sorting process is the total variance of the on-axis field error, including a weighting factor \((\alpha)\),

\[ \text{Total Cost} = [\alpha \sum (\sigma_i * \sigma_i) + (1 - \alpha) \sum (\mu_i * \mu_i)] \]  

(8.2.4)

where the summations are over the total number \((N)\) of block or pole pairs in the sort, and

\[ \text{Total Cost} = [\alpha \sum (\sigma_i * \sigma_i / N) + \sum (\mu_i * \mu_i / N)] / (\alpha + 1) \]  

(8.2.5)

is the measure of the relative direct field error at the \(i^{th}\) block pair.
A weighting factor \((0 < \alpha < 1)\) can be used to balance the relative contribution between pole excitation and direct field error effects to the final cost function. For example, by placing a larger emphasis upon the direct field error cost function \((\alpha < 1/2)\), these effects can be reduced while somewhat enhancing the pole excitation errors. Without any other information, however, the most straightforward method is to assume equal contributions from both cost function components \((\alpha = 1/2)\).

For this calculation the total magnet population is comprised of 2000 blocks, which can be used to feed \(N = 1000\) pole pairs or 500 periods. Thus, sorting is done for a length (15 m), which is somewhat longer than a gain length (11.7 m). Such a long section of the device is sorted all at once in order to improve the resulting rms error in the field. The extra blocks are utilized to form a “bull pen.” These blocks are then excluded from the final device, or re-used in other segments of the device. This technique improves the final quality of the device without incurring significant additional material costs.

In this case, the sorting is done with a block population possessing a nearly uniform distribution in remanent field strength \(B_{\text{rem}} = <M>\) with average value of 1.25T, a uniform distribution in azimuthal angle, and a Gaussian distribution in inclination angle (see Fig. 8.2-2 and Fig. 8.2-3).

The total cost function is calculated during the sorting process. Fig. 8.2-5 and Fig. 8.2-6 show the individual cost function values for each pole or block pair. Summing these values, the net variance in the error components is calculated. From this, the relevant rms relative errors averaged over the entire gain length as well as individual pole and block pair errors can be derived.

![Figure 8.2-5](image-url)

Figure 8.2-5. Pole pair excitation error cost function \((\sigma_i \times \sigma_j)\) versus pole pair position \((i)\), before (triangles) and after (asterisks) sorting, for \(N = 1000\) and \(<M> = 1.25\)T.
The net rms relative error in the pole pair excitation before sorting is approximately 0.66%. After sorting, that figure drops to 0.075%. The net rms relative direct field error before sorting is approximately 1.4%, dropping to 0.11% after sorting. Using a different weighting factor ($\alpha = 1/4$) equalizes both sets of errors to 0.1% after sorting.

If instead of a magnet population that had a 1.0% spread in magnetization strength and a 1.0° spread in inclination angle, a set with spreads in strength and orientation of 1.5% and 1.5° respectively had been used, then after sorting the relative pole excitation error would be approximately 0.12% and the relative direct field error would be approximately 0.16%. Even after readjusting the weighting factor to balance these values (approximately 0.14%), the design specifications would be not met. Extensive additional shimming would then be necessary.

Looking at the individual values of the two components of the total cost function the magnitude of the local error can be calculated. After sorting the maximum value of the cost function for the pole pairs (Fig. 8.2-2) is seen to be approximately $8 \times 10^{-6}$, corresponding to a 35 G error in excitation between upper and lower poles. The maximum value of the direct field cost function (Fig. 8.2-3) is approximately $1 \times 10^{-5}$ after sorting, corresponding to a 40 G error in the transverse field components between upper and lower blocks.

The actual results will be even better because the large number of magnets needed by the LCLS can be binned into groups with smaller variances. Binning will be done according to magnetization strength. The ideal bin might be 1024 magnets, corresponding to four modules. This arrangement improves the variance of the pool from which the sorting is done, with the consequent improvement in the sort result. The undulator will be built with a small mechanical adjustment of the gap, so that the mean field amplitude can be corrected, thus taking out the difference between the bins. The total range of gap variation would be on the

![Figure 8.2-6. Direct field error cost function ($\mu_i \ast \mu_j$) versus block pair position ($i$), before (triangles) and after (asterisks) sorting, for $N = 1000$ and $\langle M \rangle = 1.25T$.](image-url)
order of 10s of microns. This will be combined with tapering, which is needed to keep the electron beam on-resonance, as explained in Section 8.1.2. Instead of keeping the mean field amplitude constant, it would be graded linearly; each module being 0.3%/52 = 0.0057% weaker than the previous one. The tapering will be done by forcing the mean of the sort to be different from the mean of the randomly arranged magnets. This works, but only a small difference can be achieved before the error magnitude increases excessively. The total range of gaps required for tapering is about 50 µm.

Use of Shims to Correct Field Errors

As a final correction to the fields, ferromagnetic shims may also be employed. These can be used to “neutralize” field strengths of the order of several Gauss. The exact placement of the shims depends upon the type of error. Pole excitation can be decreased slightly by placing the shim on the exterior surface of the pole piece. Transverse magnetization errors in the blocks can be decreased by placing shims on the surface of the individual block.

For the magnitude of the errors described above, shimming may be entirely unnecessary because the required field tolerances can be attained by sorting through a population of magnet blocks with tight tolerances. Sorting can reduce the initial rms error by an order of magnitude and the design specifications can be obtained. Relaxing the tolerances on the magnets will result in larger errors that may then need correction. However, the process of field measurement, fabricating and placing shims, field re-measurement, etc., is extremely labor- and time-intensive. It may be more desirable to eliminate much of that effort by using a block population with tighter tolerances from the start.

8.2.2 End Design of Undulator Segments

The end design concept is based on a normalized pole scalar potential distribution that provides a maximum number of regular periods while avoiding unacceptable end steering effects. The normalized scalar potentials of the poles in the uniform interior of the wiggler are +1, -1, +1, -1, etc. A desirable truncation scheme is \ldots +1, -1, +1, -1, +1/2, 0. This distribution provides rapid termination and no net end steering effect.

Abrupt termination of a hybrid (permanent magnet material and steel poles) results in relatively little net integrated steering field but has the disadvantage of a skewed scalar potential distribution in the last several poles of the structure and thus a reduction in the performance of the device.

By altering the quantities of the permanent magnet (P.M.) material between the last few poles of the device, it is possible to approach the desired scalar potential distribution previously described. A 3-D boundary element code was used to model a hybrid end structure. A 2-D cross-section of the upper half of this structure is shown in Fig. 8.2-7.

An additional section of P.M. material along with a shunt plate is shown to the right of pole 0 in Fig. 8.2-7. This provides an independent excitation parameter to control the steering excitation of pole 0. This shunt plate is sufficiently thick so that it is in an...
unsaturated condition and acts as a field clamp that reduces the fringe fields extending beyond the end of the structure to the right. Beyond the shunt plate to the right as shown also in Fig. 8.2-7 are two magnetically detached shield plates which further reduce the fringe fields of the structure. Preliminary 3-D calculations show less than 10 G fields at 2 cm beyond the center of pole 0.

**Figure 8.2-7.** Cross-section of end structure with reduced P.M. material between poles 0 and 1 and increased material at pole 2.

The midplane field results are shown in the graph of Fig. 8.2-8. This graph includes the $B_y$ field on the midplane of the device and the first and second integrals of the field, which give the beam steering and trajectories. This preliminary design shows: (1) good peak-to-peak uniformity leading up to the last pole of the device, and (2) small steering first integral and rapid termination of the fields beyond the steering pole. By adjusting the P.M. quantities in the structure, the net first integral can be brought arbitrarily close to zero to eliminate the end steering.

**Figure 8.2-8.** Graph of $B_y$ with first and second integrals of $B_y$ which give the steering field and normalized beam trajectory. The horizontal axis is z (cm).
8.3 Undulator Mechanical Design

8.3.1 Mechanical and Thermal Design

Introduction

The 100 m long undulator is made up of 52 nominally 2.16 m sections. Each 2.16 m section consists of 1.92 meters of permanent magnets and monitors (BPMs and WPMs) supported by a girder. The remaining 0.235 m located between adjacent girders contains a focusing corrector magnet and miscellaneous non-magnet components. A pier supports the end of each girder and the magnet and components located between the girders. Fig. 8.3-1 shows the layout of the components.

![Diagram of undulator components](image)

**Figure 8.3-1.** Layout of girders and undulator components - basic 1.92 m section.

Physics considerations for successful operation dictates that the maximum position deviation of the undulator segments relative to each other not exceed 100 $\mu$m horizontally and 500 $\mu$m vertically. The ability to perform real time global alignment of the girders and the absence of real time control of the sub-components of each girder section translates to a condition where most of the 100/500 $\mu$m stability tolerance can be allocated to the girder assemblies. After subtracting for global alignment tolerances, the remaining tolerance must be budgeted between machining tolerances, magnet assembly tolerances, and alignment tolerances within a girder.

There are 64 periods per girder. The period is 30 mm with a tolerance of 35 $\mu$m. The horizontal pole gap is 6 mm with a tolerance of 7 $\mu$m. The gap between poles and magnets...
should be a minimum. In the girder design, the effects of heat loads, vibration, and ground motion are considered. Each of these will be covered in detail in this section.

The focusing corrector located between adjacent girders is a 120 mm long permanent magnet. These magnets must be aligned horizontally and vertically (perpendicular to the beam axis) within 100 $\mu$m. The positioning of these magnets is not critical with respect to axial position and angular alignment. The alignment of the sub-modules on the girder and the global alignment of the girders are described in Chapter 12.

**Piers**

The piers are monolithic structures with center-to-center spacings of 2.16 m. The ends of each girder are supported by adjacent piers. The piers will also support components located between the girders. The height of the piers will be determined by the elevation of the electron beam above the floor and the dimensions of the individual components making up the magnet support system. The result will be a pier on the order 1 m high.

The capability of motors to adjust the position of the girders (in five degrees of freedom) in real time permits corrections to be made for dimensional changes in the piers due to thermal conditions and positional changes due to geophysical motions. Currently the plan does not call for motor control in the z-axis, but if necessary, it can be implemented. The ability to correct for slow (on the order of hours, days or longer) changes in the dimensions and position of the piers up to 1 mm eliminates the need for high global stability of the girders.

Concrete piers have several advantages. The most obvious is that they are the least costly. Aside from the cost of the raw material, the use of concrete permits *in-situ* fabrication and eliminates one step associated with other alternatives; the concrete “pots” itself into the hole made in the sandstone ground structure.

Often associated with concrete are large values for shrinkage and swelling. In the case of the undulator, the initial shrinkage and the slow changes that take place over days, weeks or longer are not important. The total magnitude can be accommodated by the girder movers is the only relevant factor.

Although there are many factors affecting the behavior of concrete (e.g., mix ratio, water ratio, curing conditions) the following shrinkage and strain information is typical of a broad range of conditions. Shrinkage decreases rapidly with time. Based on total shrinkage at 20 years:

- 14–34% of the shrinkage occurs in 2 weeks
- 40–80% of the shrinkage occurs in 3 months
- 66–85% of the shrinkage occurs in 1 year

A typical number for strain at 1 month is 40 $\mu$m/m and at 5 years 100 $\mu$m/m (these values are linear strains). Thus between 1 month and 5 years the strain is 60 $\mu$m/m. Assuming the
Concrete shrinks 75% of its total lifetime value before alignment begins at 1 year, the strain becomes 25 \( \mu \text{m/m} \) between 1 and 5 years.

Shrinking and swelling due to changes in humidity should be very small after initial curing. Moisture would only be an issue if the concrete were stored “in water,” in which case significant swelling would be experienced over even 1 month. However, this is not the case.

Concrete also exhibits a change in strength over time. Considering the exceptionally low loads, and that concrete attains 70% of its strength within 28 days and 90% of its strength within 3 months, the issue of strength is irrelevant. The bottom line is that concrete appears to be an acceptable material for construction of the piers.

An alternative to concrete is Anorad Corporation’s Anocast\textsuperscript{®}, which is a sand-epoxy composite used for the FFTB piers. According to the manufacturer, this polymer/granite sand composite exhibits excellent vibration damping, structural rigidity, and thermal stability. However, their comparisons are with metal structures used in machine tool design. It is not clear whether there is actually an advantage over concrete piers in the undulator design. Table 8.3-1 compares useful properties of concrete and Anocast\textsuperscript{®}.

### Table 8.3-1. Properties of Concrete and Anocast\textsuperscript{®}.

<table>
<thead>
<tr>
<th>Property</th>
<th>Concrete\textsuperscript{(a)}</th>
<th>Anocast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (lb/in(^3))</td>
<td>0.09</td>
<td>0.084</td>
</tr>
<tr>
<td>Modulus of Elasticity (psi ( \times 10^{-6} ))</td>
<td>2.5–4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>—</td>
<td>0.24</td>
</tr>
<tr>
<td>Tensile Strength (psi)</td>
<td>—</td>
<td>4,200</td>
</tr>
<tr>
<td>Compressive Strength (psi)</td>
<td>1,000–10,000</td>
<td>17,000</td>
</tr>
<tr>
<td>Shear Strength (psi)</td>
<td>200–2,000</td>
<td>3,000</td>
</tr>
<tr>
<td>Coefficient of Thermal Expansion (x ( 10^6/\text{F} ))</td>
<td>6.0–8.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Thermal Conductivity (BTU/hr-ft-F)</td>
<td>0.54–0.70</td>
<td>1.08</td>
</tr>
<tr>
<td>Heat Capacity (BTU/lbm-F)</td>
<td>0.20</td>
<td>0.27</td>
</tr>
</tbody>
</table>

\textsuperscript{(a)} Properties vary with mix ratios, age and moisture.

A negative aspect to Anocast\textsuperscript{®} is its relative high overall cost—material, fabrication, shipping (it is factory fabricated), and installation. Because Anocast\textsuperscript{®} piers would be factory-fabricated, they require potting into the hole in the sandstone ground structure.

Due to the low aspect ratio of the piers (length to width on the order of two to four), deformation of the pier due to vibration is not an issue. Analysis has shown that the amplitude of vibration of the girders is very small even when no damping is associated with the pier. Therefore damping is not a critical factor in the choice of pier material. The
The coefficient of thermal expansion is basically the same for both concrete and Anocast®. Therefore, thermal expansion does not appear to be a factor in choosing one material over the other. The strength of Anocast® is clearly greater than concrete, but the total loading on the piers is very low and is therefore not a factor in choosing one material over the other.

The advantage of Anocast® is that its properties are more uniformly controlled and known than concrete, and SLAC has had positive experience with it and less satisfactory experiences with concrete for support structures. However, the modest tolerances associated with the piers combined with the lack of definitive reasons for the use of Anocast® make concrete the most likely candidate. Therefore, the baseline design calls for concrete piers unless mitigating factors are discovered, e.g., the cost of Anocast® piers can be greatly reduced by recycling the 38 Anocast® piers that will be removed from FFTB facility.

The design of the pier is the same, and dimensional changes will occur as a result of diurnal temperature cycles of the ground and air inside the tunnel regardless of whether concrete or Anocast® is chosen. The diurnal changes in temperature are slow, and induced motions of the girders can be corrected by the girder control motors, provided that the motions are less than the range of the control system. In the system envisioned, the control motor-mechanisms will have a range of 1 mm.

To eliminate the diurnal temperature cycles associated with the ground, it is only necessary for the piers to extend 1–2 feet below the concrete floor [9]. Given that the piers should be set into the sandstone ground structure, the piers will extend on the order of 2 feet below the floor level or more as required to reach the sandstone. The piers will be isolated from the concrete floor.

If the total height of a pier is 1.5 m and the coefficient of thermal expansion is $7.0 \times 10^{-6} \degree F$ (this is equivalent to $7.0 \, \mu m/m/\degree F$), the thermal expansion (or contraction) of a pier length for a 5°F change in temperature is $52 \, \mu m$. This magnitude is small relative to the capability of the motors to make corrections to the position of the girders. At the same time, temperature stabilization of the tunnel environment to within 5°F is a reasonable requirement.

**Motors**

Motors will be coupled to the girders using a system of cams as outlined in “Precision Magnet Movers for the Final Focus Test Beam” [10]. This system has been shown to be capable of providing sub-micron resolution and stability. Step size and gearing can be adjusted to obtain a resolution commensurate with the positioning tolerances required while minimizing the time per move.

The magnets will be mounted on five eccentric cams (see Fig. 8.3-2), which are driven by stepping motors and harmonic drive gear reduction units. The stepping motors have 200 steps/turn, the harmonic drives 100:1 gear ratios, and the cam an eccentricity of 1 mm, for a net resolution of 10 steps/$\mu m$. Rotation of the five cams controls pitch, yaw, roll, x, and y motion. A kinematic algorithm is used to control the motors. All five motors have to move...
to correct an error in any of these degrees of freedom. These stepping motors are energized only when they are to be moved, so as not to create unwanted heat. Each motor dissipates about 10 W in motion. If, on average, one motor is running at a time, only this 10 W has to be removed from the system.

![End view of the undulator magnet and mover showing three of the cams on one end of the girder (there are two on the other end) and the wire position monitors (upper left and right). The beampipe is 6 mm OD stainless steel tube.](image)

**Figure 8.3-2.**

Girder

The strongback for each 1.92 meter section of magnets will be a hollow, square tube girder with nominal dimensions of 8 x 8 x 0.375 inches. **Figure 8.3-3** shows the cross section. Each girder will be supported kinematically as described in the preceding section. Deformation of the girder resulting from thermal effects can not be corrected by any means. Therefore the temperature of the girder must be maintained within a tolerance range sufficiently narrow to preclude such deformation. A worse case estimate of the effects of thermal distortion indicates that 30 \( \mu \)m stability can be obtained with \( \pm 0.5 \)°F temperature control of the girder. This is coarse control even compared with off-the-shelf technology.

Temperature control of the girder can be obtained by two methods:

- The tunnel's environment is maintained within the necessary tolerance and the net flow of heat to and from the girder is nulled by forced convective heat transfer.
- The girders are manufactured with water cooling tubes and the net flow of heat to and from the girder is nulled by conductive heat transfer.

There are two strong reasons for the use of water-cooling to stabilize the temperature of the girders. Conductive heat transfer has a much stronger effect than convective heat transfer, and the accurate control of water temperature is much simpler and less costly than the control of air temperature. Therefore, each girder will be designed with four (possibly eight) water-cooling tubes running its length. The water in these tubes is set to the desired operating temperature (near ambient temperature) of the girder and acts as a sink for heat loads.
Three alternatives for fabrication of the girders were considered:

- Single extruded girder with integral cooling tubes
- Four extruded plates with integral cooling tubes that are bolted together
- Four cast plates with machined cooling tubes that are bolted together

Other alternatives include soldered or brazed cooling tubes, or the use of high thermal conductivity pastes. These were eliminated because they either limited the choice of materials, because they exhibited poorer thermal conduction, or because of their complexity.

The optimum material for the girder is non-magnetic and one that has a maximum ratio of coefficient of thermal conduction to coefficient of thermal expansion. Table 8.3-2 lists several commercially available materials.

<table>
<thead>
<tr>
<th>Material</th>
<th>$k$ (btu/hr-ft$^2$°F)</th>
<th>$\alpha$ (1/°F) ($\times 10^6$)</th>
<th>$k/\alpha$ (btu/hr-ft$^2$°F) ($\times 10^6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper (OFC)</td>
<td>226</td>
<td>9.8</td>
<td>23.1</td>
</tr>
<tr>
<td>Bronze (90% Cu-10% Zn)</td>
<td>109</td>
<td>10.2</td>
<td>10.7</td>
</tr>
<tr>
<td>Aluminum (1100)</td>
<td>128</td>
<td>13.1</td>
<td>9.8</td>
</tr>
</tbody>
</table>

The LCLS design uses aluminum. The lower density for aluminum helps reduce the amplitude of vibration. The fact that the ratio of $k/\alpha$ is not optimized for aluminum has been shown not to affect the distortion of the girder beyond acceptable limits.

Cast aluminum tooling plate material (e.g., MIC-6, Alca Plus, and K-100S) is designed to provide excellent dimensional stability. The negatives to the use of this material include the cost of machining cooling channels and the potentially negative effects of bolting plates together. Stresses are generated during bolting, and bolted connections have poor shear characteristics. Also, the heat transfer in an $xy$-section of a girder is limited by the thermal contact resistance at the connections when individual plates make up the girder.
The use of extruded plates with integral cooling tubes eliminates the need for machining cooling channels. However, the negatives associated with bolting them together still remain. A single extruded girder with integral cooling tubes is the preferred alternative from the standpoint of simplicity and optimum heat transfer. However, the extrusion process does have the potential to induce internal stresses that may lead to dimensional instability. This potential problem can be eliminated by well-designed post-extrusion heat treatment. In the extreme case, the extrusions can be heat treated to their annealed condition, in which case there are little if any residual stresses. For annealed aluminum (e.g., T1100) the tensile strength is 13,000 psi, and the yield strength is 5,000 psi, which are more than adequate, given the low stresses (240 psi max) that will be encountered. Therefore, the baseline design includes extruded aluminum girders with integral cooling tubes. Initial straightness of a girder is not critical because the magnets will be aligned relative to each other, not relative to the girder.

The error budget allows $10 \, \mu m$ for machining, $20 \, \mu m$ for assembly, and $45 \, \mu m$ for thermal distortion, for a sum in quadratures of $50 \, \mu m$ rms. This conforms favorably with the global position tolerance for the undulator which is $100 \, \mu m$ horizontally and $500 \, \mu m$ vertically.

Three mechanisms are known that can potentially affect distortion of the girder. The following three mechanisms are treated more fully below:

- Heat loads resulting in differential thermal expansion of the girder
- Vibration of the girder
- Dimensional instability of the girder

**Thermal Considerations**

Heat sources in the tunnel may transfer heat to or from the girder. The design of the support mechanism for the girder, in which conduction is limited by line contact, precludes conduction as one of the transfer mechanisms for this heat. Heat is conducted along the $z$-axis strut, but this can be controlled by the choice of dimensions and materials, or by attaching the strut close to a cooling tube. This leaves convection and radiation as the two mechanisms of heat transfer between the tunnel and the girder.

Counteracting the heat transfer between the tunnel and the girder is the heat transfer between the cooling water and the girder. The high thermal conductivity of aluminum combined with the large heat capacity for cooling water provides an excellent temperature controlling mechanism. The limiting factor on this mechanism is the thermal contact resistance between the water and the wall of the cooling tube. Regardless, this mechanism dominates all other heat transfer mechanisms of concern.

Because vibration is another mechanism by which the girder can distort, it is important that the flow of water within the cooling tubes not be a source of excitation. If necessary, this
can be accomplished by limiting the Reynolds number to avoid both transition and turbulent flow, i.e., the flow is laminar.

**Vibration of the Girder**

A finite element model was used to determine the effect of ground motion on the vibration of the girder. In this model the magnets were assumed to be assembled into sub-modules and the sub-modules mounted to the girder. The weight of the sub-modules (base plates and magnets) was accounted for by increasing the density of the top of the girder proportionally. The model included an end cap on each open end of the girder. This is necessary in order to obtain bending-like first and second modes. Without the end caps, the square tube has lower frequency modes associated with skewing (parallelogram-like motion) which are undesirable. The first and second modes are first-order bending modes at 49 and 60 Hz. The next lowest mode is a twist mode at 118 Hz. The girder can be tuned to shift the 60 Hz mode, if desired.

A dynamic random response analysis was run using: (1) a power spectral density (PSD) input of $1.038 \times 10^{-9} \text{g}^2/\text{Hz}$, from 0.1 to 100 Hz as the input simultaneously in the transverse and vertical directions (based on SLAC data); (2) the first four modes; and (3) a damping coefficient of 2%. The rms or apparent displacement for a point at the center of the top edge of the girder relative to the girder supports is $1.7 \times 10^{-6} \mu \text{m}$. Clearly, vibration will not be a problem.

Another positive effect of small vibration amplitude is that the transfer of energy due to water flow in the turbulent regime will probably cause little additional vibration. If true, then the cooling water in the girder can flow in the turbulent regime thereby decreasing the thermal resistance and increasing the heat transfer dramatically.

**Dimensional Stability**

The last and most difficult mechanism that may affect distortion of a girder is dimensional stability. Marschall and Maringer [11] describe the causes of dimensional instabilities that can affect precision hardware. The problem at hand is less difficult than the problems described in the literature because the girders will not experience oscillating loads or large changes in temperature, and stresses will always be small. There cannot be any change in loading of the girders after alignment because that, in itself, would change the shape of the girder. The requirement of accurate temperature control should eliminate stress relieving due to thermal cycling. The maximum stress in the girders has been calculated at 1.66 N/mm$^2$ (240 psi), excluding local stresses at the points of support, for a girder supported at its ends. This is very low. The corresponding maximum deflection in the girder is 86 $\mu \text{m}$ (0.0034 inch).

Microcreep can potentially cause distortion of the girders at low stress levels over long periods of time. This effect can involve both short-range (on a molecular level) and long-range (usually associated with fabrication processes) internal stresses. The key to controlling
microcreep is the removal of internal stresses from the system prior to final alignment and removal of factors that cause stress relaxation after alignment. Appropriate heat treatment as a final step in the processing of the girder is very important to minimize internal stresses. The avoidance of thermal cycling and mechanical exercising helps prevent stress relaxation.

Quantitative measures of stability are obtained from experiment. There does appear, however, to be a stress below which significant microcreep will not occur over substantial time periods. At 30°C (85°F) for 356-T6 aluminum that stress is on the order of 5,000 psi and for 6061-T6 aluminum it is on the order of 6,000 psi. These values are more than an order of magnitude greater than the maximum stress expected in the girders. The most conservative approach, short of an experiment to verify the dimensional stability of the material used (including the manufacturing processes), is to use the desired material in the annealed condition that will have minimal internal stresses.

**Magnet Support**

There are 64 periods per girder. Each half-period consists of two magnet/pole units, and each unit consists of one NdFeB permanent magnet and one vanadium permendur pole. The baseline design has the magnets assembled into sub-modules of 8 periods or 16 half-periods. There are two reasons for choosing 8 periods per sub-module versus 16 periods, the next larger integral division of 64. There is no active cooling of the base plates for the sub-modules, and keeping the dimensions of the sub-modules small translates to less deformation of the base plates by temperature gradients. Also, the tolerances of the fabrication processes are a function of the size of the parts. Doubling the size of the sub-module causes an unwanted increase in the fabrication tolerance.

The bases for the sub-modules are made from aluminum tooling plate with machined index features. **Fig. 8.3-4** shows the following features of the base:

- **Lands**—The lands fulfill two purposes. Each pair, such as “left land #1” and “left land #2”, form the vertical support for each pole. The profile of the top surfaces of all lands will have a tolerance of 5 μm. The tops of these lands form the secondary datum for each magnet/pole unit. The rear faces of each pair of lands provide two of the three datum points of the primary datum (the third datum point will be discussed later). The magnet of each magnet/pole unit will index on these rear faces. The absolute position of the rear faces will have a tolerance of 13 μm, which translates to a tolerance on the period of 13 μm (± 6.5 μm).

- **Gap spacer**—The gap spacer sets the spacing between left and right poles, and controls the transverse offset. It is the tertiary datum. The tolerance on the width of the gap spacer is 7 μm, and the tolerance on the transverse offset is 13 μm. A temporary mechanism will be used to apply a force to the outside edge of the pole, thereby insuring that it is butted against the gap spacer.
- Vertical clamping screw hole—The base incorporates clearance holes for vertical clamping screws. These holes will align with tapped holes in the poles. The screws create the reaction force to counter the moment couple caused by the attraction of left and right magnet/pole units. These holes are purposely placed outboard as far as possible relative to the undulators centerline to maximize their effectiveness and minimize their effect on the magnetic field.

- Magnet glue holes—One or more holes (three shown in Fig. 8.3-4) penetrate the thickness of the base plates under each magnet. These holes are used to inject glue into the gap between the base plates and the magnets. Machined “dams” may be incorporated to facilitate proper glue distribution.

- Kinematic features—Not shown in Fig. 8.3-4 are the machined features required to kinematically mount the sub-modules to the girders.

- Alignment features—Not shown in Fig. 8.3-4 are the machined features that may be required to mount alignment hardware.

![Diagram of base plate with vertical supports and top spacer blocks attached.](image)

**Figure 8.3-4.** Base for the sub-modules.

**Fig. 8.3-5** shows a sub-module base plate with the vertical supports and top spacer blocks attached. The top spacer blocks have axial locating tabs spaced identical to the axial spacing of the lands on the base plates. These tabs form the third datum point of the primary datum.
The design allows sufficient space adjacent to the final position of the magnet/pole units to permit the units to be slid into position from the side. The units finally come to rest on and against the lands, against the tabs of the top spacer blocks, and against the gap spacer. In their final position there is a small gap between each magnet and the top spacer block. Holes through the top spacer block provide access for injecting glue into the gap between each magnet and the top spacer block.

Initially the top spacer blocks must be aligned relative to the lands on the base plate and consequently to each other. This alignment may be accomplished with a coordinate measuring machine (CMM). Fig. 8.3-6 shows a sub-module with a half-period (left and right magnet/pole units) installed. The temporary mechanisms used to force the pole against the gap spacer are not shown.

Fig. 8.3-7 shows a complete sub-module without kinematic mounting and alignment features. The current design calls for the use of both screws and glue to secure the magnet/pole units. Both are used because screws are superior in tension or compression, and glue is superior in shear. A detailed study of the assembly process will determine the final choice of technologies.
Figure 8.3-6. Sub-module with a half-period (left and right magnet/pole units) installed.

Figure 8.3-7. Complete sub-module without kinematic mounting and alignment features.
Following is a list of some of the salient features of the conceptual design:

- Each pole is aligned to its corresponding magnet using a jig. In this process, strong magnetic forces hold the pole and the magnet together. The arrangement of the magnet/pole units in the final configuration will cause these forces to be nulled. Therefore, glue is used to form a fillet bond between the pole and magnet of each unit. The gap between the magnet and pole is zero.

- During the installation of the first left and right magnet/pole units, an axial force is applied to insure that each unit is indexed correctly against its primary datum. When a subsequent magnet/pole unit is installed, strong magnetic forces pull it toward the adjacent magnet/pole unit. The resultant of this magnetic force lies within the triangle of the three primary datum points, thus creating a stable configuration during assembly.

- CNC control during the machining processes insures that the half-period length is maintained without build-up along the length of the sub-module.

- The axial gap between adjacent magnet/pole units is determined by the accuracy to which the magnets and pole thickness are ground, and the accuracy to which the primary datum points are located. A gap of 50 ±25 μm is reasonable to expect.

- The vertical gap between two poles is controlled at the bottom by the dimension of the gap spacer. The gap at the top is also a function of the perpendicularity of the inside edge of the pole to the bottom edge of the pole, which sits on the secondary datum. Corrections for this error can be made by “magnetic” shimming.

- While the vertical clamping screw provides restraint against the moment couple that wants to rotate the magnet/pole units around the gap spacer, the glue acts as the axial restraint mechanism. The glue is a positive mechanism for this restraint, unlike the vertical clamping screws that generate frictional forces. The glue eliminates the concern that the magnet/pole units may be accidentally knocked out of alignment.

- The assembly of the magnet/pole units into the sub-module does not require the use of a CMM, although it may be used to verify the correct assembly and to inspect the magnetic field.

- BPMs are attached to the downstream end of each girder.

- WPMs are attached to both ends of each girder.
Conclusions

No show stoppers were identified with respect to the mechanical and thermal design of the LCLS undulator. The tolerances for alignment of the magnets into sub-modules is within the limits of precision machining. The level of stability that is required can be met with careful attention to the temperature control and material processing in conjunction with active alignment of the girders. The LCLS design satisfies all these requirements.

8.3.2 Electron Beam Collimation and Vacuum Chamber Design

This section analyzes the vacuum chamber and magnetic material with regard to the need for protection from accidental electron beam losses and discusses the vacuum chamber surface roughness limits.

Beam Parameters Used in These Calculations

It is of vital importance to fully understand the consequences of primary electron beam exposure to the undulator. Of greatest concern is the behavior of the permanent magnet material and that of the undulator vacuum chamber. The following electron beam parameters (at injection into the undulator) and geometric dimensions were used in the analysis:

- **Beam Energy** \( E_0 = 5–15 \text{ GeV} \), with 14.3 GeV being the most desirable
- **Bunch Charge** \( Q = 1 \text{ nC} \) (with the desire to increase to 2 nC in the future)
  \[ N = 0.625 \times 10^{10} e/\text{bunch} \]
- **Repetition Rate** Pulse Repetition Rate, PRR \( \leq 120 \text{ Hz} \)
- **Average Power** \( P_{av} \leq 1.8 \text{ kW} \)
- **Beam Size** \( \sigma \sim 32 \text{ µm} \)
- **Magnet Gap** \( g = 6.0 \text{ mm} \)
- **Vacuum Chamber** OD = 6.0 mm
  \[ \text{ID} = 5.0 \text{ mm} \equiv 0.97 \text{ inch} \]
  \[ \therefore \text{Wall thickness} \ t = 0.50 \text{ mm} \equiv 0.020 \text{ inch} \]

Permanent Magnet Material

The material used for this analysis is neodymium-iron-boron (NdFeB) (2-14-1) with the following material properties:

- **Modulus of Elasticity** \( E = 1.5 \times 10^{11} \text{ N/m}^2 \equiv 21.74 \times 10^6 \text{ psi} \)
- **Poisson Ratio** \( \nu = 0.3 \)
- **Tensile Strength** \( \sigma_{UT} = 80 \text{ N/mm}^2 \equiv 11,600 \text{ psi} \)
- **Coefficient of Thermal Expansion**
  \[ \alpha_{\parallel} = 3.4 \times 10^{-6}/\text{°C} \]
  \[ \alpha_{\perp} = -4.8 \times 10^{-6}/\text{°C} \]
  \[ \therefore E \alpha_{\parallel} = 74 \text{ psi/°C}; E \alpha_{\perp} = 104 \text{ psi/°C} \]
- **Specific Gravity** \( \rho = 7.4 \text{ to } 7.5 \text{ g/cm}^3 \)
- **Specific Heat** \( c = 0.11 \text{ cal/(g°C)} \equiv 0.46 \text{ Ws/(g°C)} \)
Based on composition values and atomic weights of the constituents, the radiation length, atomic number, and material critical energy of the material are: \(X_o = 11.54 \text{ g/cm}^2; X_o/\rho \sim 1.55 \text{ cm}; \ Z \sim 29; \ \varepsilon_o \sim 17.3 \text{ MeV}\). The minimum ionization loss is \(\text{dE/dx} = \varepsilon_o/X_o \sim 1.5 \text{ MeV/(g/cm}^2)\). Note: these values very closely match those of copper.

For a square hit up front with no shower multiplicity (i.e., \(\Pi(e^-) = 1\)), the normalized power deposition is \(P' \sim 1.35 \text{ W/cm}\). For the highest envisioned incident beam energy of 17 GeV, shower maximum of the electromagnetic cascade occurs at a depth of \(T_{\text{max}} \sim 6 X_o \equiv 9.2 \text{ cm}\), and the maximum shower multiplicity is \(\Pi_{\text{max}}^{(e^-)} \sim 120\) (from Rossi, High Energy Particles). Consequently, the maximum normalized power deposition is \(P'_{\text{max}} = P\Pi_{\text{max}}^{(e^-)} \sim 160 \text{ W/cm}\).

First, the exposure at the undulator entrance where the assumed Gaussian distributed beam has a predicted transverse size of \(\sigma = 32 \mu \text{m}\) is estimated. Assuming a uniform particle distribution inside \(0 < r < \sigma\), a heat source term after folding in a double-convoluted Gaussian is defined as \(S = CP'/A_b \sim 16.5 \times 10^3 \text{ W/cm}^3\), where \(C \sim 0.4\) to reflect the double convoluted Gaussian, and \(A_b = \sigma^2 \pi \sim 16.5 \times 10^3 \text{ W/cm}^3\). For a specific heat capacity of \(\rho_c = 3.43 \text{ Ws/(cm}^3\text{C)}\), the temperature rise per pulse (RF-bunch) for pulse repetition rate (PRR) = 120 Hz is

\[
\Delta T = \frac{S}{P\rho_c\text{PRR}} = 40^\circ \text{C/pulse}. \tag{8.3.1}
\]

The consequential thermal stresses are proportional to the product of the coefficient of thermal expansion \(\alpha\) and the modulus of elasticity \(E\):

\[
\sigma_{th} \propto E\alpha\Delta T. \tag{8.3.2}
\]

Numerically \(\sigma_{th}\) is \(\sim 4100 \text{ psi} \sim 0.35 \sigma_{UT}\) for a fully restrained body. Since this is near a surface, actual stresses are somewhat lower. This should not present any structural challenge to the magnetic material, even for repeated exposures. At \(T_{\text{max}}\), the effective transverse beam size increases to \(\sigma_{eff} \sim 220 \mu \text{m}\) (from Monte Carlo simulations for copper and scaling). Using \(\Pi_{\text{max}}^{(e^-)} = 120\), the heat source term is \(S \sim 40 \text{ kW/cm}^3\), and the resulting single pulse temperature rise is \(\Delta T \sim 100^\circ \text{C/pulse}\).

Somewhat higher temperatures are actually observed short of \(T_{\text{max}}\), at a depth of \(\sim 3.5\) to \(4 X_o\) for \(E_o = 15 \text{ GeV}\), since the increase in the transverse shower has not yet caught up with the rapidly increasing shower multiplicity. At \(4 X_o\), \(\sigma_{eff} \sim 130 \mu \text{m}\) and \(\Pi^{(e^-)}\) is \(\approx 83\). The resulting effective heat source term is \(S_4 X_o \sim 82 \text{ kW/cm}^3\), the temperature rise per pulse is

\[
\Delta T \sim 200^\circ \text{C/pulse}, \tag{8.3.3}
\]

and the consequential thermal stress rise is of the order of \(\sigma_{th} \sim 21,000 \text{ psi} \sim 1.8 \sigma_{UT}\).
The permanent magnet material must therefore be protected from direct hits by the electron beam. The material is a powder-metallurgical product and is quite brittle, i.e., has very low ductility, and exposure to one pulse might fracture it. Independent of structural concerns, temperature changes of this magnitude would cause permanent changes in the remanent magnetic field which are not acceptable.

Since the magnetic material has atomic properties very similar to copper, neither copper nor materials with similar or higher atomic number are suitable as primary collimator materials. The primary material must be protected by a low-Z material like titanium.

Undulator Vacuum Chamber

There are two distinctly different beam exposure scenarios for the undulator vacuum chamber. The first is direct e⁻-beam exposure at the entrance to the undulator with the momentum vector approximately parallel to the undulator and vacuum chamber axis (this assumes that no collimator is in place). The second exposure scenario results from excessive beam deflection inside the undulator resulting in the beam impinging at shallow angles onto the vacuum chamber. Selection of an appropriate material for the vacuum chamber creates tradeoffs between physics performance, survival during direct primary beam exposure, and ease of manufacture, and thus economics. Physics performance dictates a chamber material of low electrical resistivity, at least on the inside surface to keep the resistive wall wake function at acceptable levels. Materials like copper and aluminum are good choices.

Long term survival against direct hits by the e⁻-beam requires a low-Z material with good strength and endurance characteristics. Titanium and some of its alloys, as well as some aluminum alloys, are good choices. Since the undulator and its vacuum chamber are ~100 m long, the chamber needs to be built in segments (anticipated modular length ~2.16 m) and joined by vacuum flanges and bellows. All of the materials mentioned above are technically feasible to use, but they also present fabrication, installation, and economic challenges. Copper, aluminum, titanium, and stainless steel were evaluated for possible use as vacuum chamber material. Stainless steel is the final choice, and an analysis of its performance for the two exposure criteria is presented below. Cost effective manufacturing, ease of installation, and maintenance for ultra-high vacuum make stainless steel a first choice, but at the expense of high electrical resistivity. This handicap can be compensated by surface coating with a low resistivity material.

Beam Strikes at the Entrance to the Vacuum Chamber

Using the minimum ionization loss and no shower multiplicity ($\Pi^{(e^-)} = 1$), the power deposition at normal incidence to the chamber is

$$P' = (-\rho \frac{dE}{dx}) N \times 1.6 \times 10^{-19} \text{ PRR} = 11.6 \times 10^6 \times 0.625 \times 10^{10} \times 1.6 \times 10^{-19} \times 120 = 1.4 \text{ W/cm}$$

using $\frac{dE}{dx}$ for iron to approximate stainless steel.
Next, again assuming a Gaussian beam intensity distribution with $\sigma \sim 32 \text{ \mu m}$, and also assuming a uniform intensity in the radial interval $0 < r \leq \sigma$, the heat source term becomes $S \sim 17 \text{ kW/cm}^3$. The temperature rise per single rf-bunch follows as $\Delta T = 17 \times 10^3/(4 \times 120) \sim 35^\circ\text{C}$. The resulting thermal stresses are $\sigma_{th} \sim 12,500 \text{ psi}$ for a fully restrained body. Thin-walled tubing and beam exposure near the surface (inside or outside) will remove some of these restraints and thereby reduce the magnitude of these stresses at the expense of increased elastic strain. The endurance limit for the type of stainless steel used for vacuum chamber tubing (300 Series) is $\sigma_{\text{End}} \sim 38,000 \text{ psi}$, and there would be no problem for this level of beam exposure. Even the yield strength of $\sigma_y \sim 30,000 \text{ psi}$ is significantly above the exposure stress, and no plastic, permanent deformations would occur.

**Beam Strikes Inside the Undulator**

Once inside the undulator, the electron beam can experience additional deflections. Based on alignment considerations for both the undulator and the quadrupoles, it is desirable to have a dynamic range of $\pm 500 \text{ \mu m}$ at each magnet mover. For an assumed maximum quadrupole gradient of 45 T/m and an effective magnetic length of $l_{\text{eff}} = 12 \text{ cm}$, the maximum kick angle becomes $50 \text{ \mu rad}$. The present design value of the center-to-center module length is 2.16 cm. The deflection at the end of one modular section is therefore 108 $\text{\mu m}$. The vacuum chamber inside diameter is 5.0 mm. It can readily be shown that six consecutive maximum kicks will amount to a deflection of $\sim 2.3 \text{ mm}$ and the beam could strike the following module vacuum chamber wall with a maximum angle of $\theta \sim 300 \text{ \mu rad}$ (see Fig. 8.3-8). The shortest longitudinal distance, $l$, over which the $2\sigma$ core of the incident Gaussian distribution could strike the vacuum chamber is then $l = 2\sigma\theta = 21.3 \text{ cm} \equiv 13 X_o$ for stainless steel with 1 $X_o \sim 1.66 \text{ cm}$. Similarly, the shortest distance of the momentum vector traversing the vacuum chamber wall is $l = \nu\theta = 167 \text{ cm} \equiv 100 X_o$. This means that every conceivable $e^-$ energy envisioned for the undulator reaches the peak of the electromagnetic cascade inside the vacuum chamber wall, and also, with the exception of particles scattered out of the wall in the transverse direction, the chamber wall is almost a complete absorber of the cascade. Examining the region of shower maximum where the normalized power deposition varies little ($dP/dT \sim 0$) and using the longitudinal interval of $T_{\text{max}} \pm 1 X_o \equiv 4.5 \text{ to } 6.5 X_o \equiv 3.3 \text{ cm}$, Monte Carlo simulations using the EGS code, show that $\sim 0.23 P_{av}$ is absorbed in this region. The volume element defined by $2\sigma$ and $\pm 1 X_o$ is a “skewed” ellipsoid, and after folding in a double convoluted Gaussian, the expected power deposition is $P_{4.5-6.5X_o} \sim 0.23 \text{ CP}_{av} = 0.23 \times 0.4 \times 1.8 \times 103 \sim 165 \text{ W}$. Let $\Delta\sigma$ be the average transverse increase in $\sigma$ at the depth location of the ellipsoid; then the two axes are $(l + 2\Delta\sigma \sim l \sim 21.5 \text{ cm})$ and $(2\sigma + 2\Delta\sigma \sim 0.27 \text{ cm})$. The effective volume of the ellipsoid is then $V = A_{\text{eff}} h \sim [(l + 2\Delta\sigma) (2\sigma + 2\Delta\sigma) \pi/4] 2X_o \sim [21.5 \times 0.27\pi/4] 2 \times 1.66 \times 300 \times 10^{-6} \sim 4.54 \times 10^{-3} \text{ cm}^3$.

Before arriving at a heat source term $S$, allowance has to be made for transverse leakage of shower particles out of the chamber wall. Monte Carlo calculations of a beam impinging in the center of a thin-walled stainless steel tube of similar wall thickness (1.27 mm) with the

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momentum vector parallel to the tube axis have been made. These resulted in volumetric power deposition values approximately a factor of 3.5 lower than those found for a semi-infinite medium of the same material ($E_0$ was 50 GeV and $\sigma = 100 \mu m$ for the tube and 200 $\mu m$ for the semi-infinite medium). Then $P_{4.5-6.5X_0} \sim 40$ W. The heat source term for assumed uniformly distributed heat sources is then

$$S_{\text{eff}} = P_{\text{eff}} / V \sim 9\text{KW/cm}^3$$

and the temperature rise per pulse for stainless steel with $\rho c = 4 \text{ Ws/(cm}^3\text{°C})$ is

$$\Delta T_{\text{pulse}} = S_{\text{eff}} / (\rho c PRR) = 20 \text{°C}.$$  

![Diagram](image)

Figure 8.3-8. Model of accidental exposure of vacuum chamber to electron beam.

The consequential thermal stress spike in a fully restrained body would be about $\sigma_{th} \sim 6600$ psi. Since a thin-walled tube is not very restrained, actual stresses would be even lower. Both pulse temperature rise and thermal stress are very modest; and one could comfortably manage even 2nC per pulse.

Next the steady state conditions when the beam is accidentally “parked” on the chamber for a long time are evaluated. The effective power is converted into a heat load per unit length based on the distance of impingement, $l_i$. Then $P'_{\text{eff}} = P_{\text{eff}} / l_i = 40/21.5 \sim 2\text{W/cm}$. Assume a hypothetical heat sink at $\pi = 180$° from the line source. Then the azimuthal conduction heat flux in the tube is $q'_c = P'_{\text{eff}} / 2t = 2/(2\times0.050) \sim 20 \text{ W/cm}^2$. Ignoring natural convection and thermal radiation losses for the moment, the maximum temperature difference over $\pi$, i.e., $\delta = r\pi = 0.864$ cm and for a thermal conductivity of $k = 0.165 \text{ W/(cm}^2\text{°C/cm})$ is $\Delta T = q'_c \delta / k = 20 \times 0.864 / 0.165 \sim 105$ °C. This difference is modest, and to first approximation, a uniform temperature can be assumed for heat rejection by thermal radiation over the entire surface of the longitudinal section of chamber under consideration.
The radiation heat flux is then \( q_r^* = P_{\text{eff}} / \pi d = 2/(0.06\pi) \approx 1.06 \text{W/cm}^2 \). For stainless steel tubing, thermal emissivity is \( \varepsilon = 0.1 \) of black body. Solving the Stefan-Boltzmann equation for black body radiation to an ambient temperature \( T_a \approx 300 \text{ K} \equiv 27^\circ \text{C} \) for the surface temperature of the tubing, then \( T_\delta = (q_r^* / \varepsilon \sigma + T_a^{\frac{1}{4}})^{1/4} = 1345\text{K} = 1072^\circ \text{C} \).

Even if one factored in a small reduction due to the contribution of natural convection, steady state temperatures of this magnitude are too high for the stainless steel chamber and they are disastrous for the adjacent permanent magnet material. Such an errant beam condition must be detected in a reasonable time, and beam delivery to the undulator temporarily interrupted.

In addition to stainless steel, three other potential magnet vacuum chamber materials were analyzed. Aluminum was found to comfortably withstand the consequences of single rf-bunch hits; but for continuous exposure to a 1.8 kW beam, the steady state temperature exceeds the melting point. OFE copper was found to be able to take individual bunch hits but was marginal for repeated exposure at the same location; i.e., single bunch thermal stresses were modestly above the endurance limit. Continuous beam exposure resulted in steady state temperatures near the melting point, and this material is not suitable for a vacuum chamber. Early detection of errant beam would remove this handicap for both copper and aluminum. A proposed ceramic (Al₂O₃) vacuum chamber concept has also been analyzed. Single pulse temperature and stress rises were modest, and the steady state temperature was well within the capability of this material. When compared to stainless steel, neither of these materials were cost effective; and the ceramic presented additional engineering challenges.

In summary, the proposed stainless steel vacuum chamber can comfortably accept missteered beam pulses inside the undulator and will not suffer any damage for \( \sigma \geq 32 \ \mu\text{m} \) and \( P_{\text{av}} = 1.8 \text{ kW} \). However, a continuous beam exposure must be detected and beam delivery terminated before significant temperature increases in the chamber and adjacent magnetic material occur.

Adjustable Collimators to Protect Undulator and Vacuum Chamber

The analysis of various collimator concepts resulted in selection of a jaw design with multiple materials. For many reasons, such as fabrication, water-cooling, compactness, etc., it is still highly desirable to use copper as the primary power absorber material. For fully annealed OFE copper to withstand the exposure to a very large number of pulses, the cyclic thermal stresses should not exceed \(-5000 \) to \( 6000 \) psi. Working backwards, the effective transverse beam size for an assumed Gaussian distributed beam should be \( \sigma \geq 50 \ \mu\text{m} \) at the beam entrance face of a copper collimator jaw where \( \Pi^{(e^-)} = 1 \). But the transverse beam size at that location is \( \sigma \approx 38 \ \mu\text{m} \). To guarantee long term survival of the copper, the transverse beam size must be increased. Using a spoiler of a lower Z material with appropriate mechanical properties is a simple and passive method of achieving this goal. In the past a titanium alloy (Ti-6 Al-4V) has been successfully used for this purpose. Modeling with the Monte Carlo code EGS resulted in a minimum spoiler thickness of \( ~0.3 \ X_o \).
However, after this thickness, $\Pi^{(e^-)}>1$, which increases the minimum beam size for the copper block. Moreover, the region of the highest power density and therefore temperature rise for the beam energies of interest and for copper is at a depth of $\sim 3X_o$. Since there is significant shower multiplicity to that depth without a commensurate transverse spread of the beam, the minimum size of the beam needs to increase to $\sigma \sim 160 \mu m$ at the front face of the jaw. A spoiler of thickness $\sim 1X_o (= 3.77 \text{ cm})$ will do the job. The shower multiplicity in the titanium alloy at that depth is $\Pi^{(e^-)} \sim 45$ and $\sigma_{eff} \sim 310 \mu m$. Then the heat source term becomes $S_{3X_o} \sim 9 \text{ kW/cm}^3$, $\Delta T_{pulse} \sim 22^\circ C$, and $\sigma_{th} \sim 6200 \text{ psi} \sim \sigma_{End}$. This is acceptable for long term operation. The spoiler thickness can be increased even more, but it would be at the expense of more power deposition in the titanium jaw, which has poor thermal conductivity. The Ti-slab can be mechanically attached directly to the entrance face of the copper block.

The steady state power deposition in $1X_o$ of Ti is $P \sim 6 \text{ W}$ and can be conducted into the copper. The copper block needs to be water-cooled. To completely attenuate and absorb a 17 GeV cascade shower, a total jaw length of $\sim 30X_o$ is recommended. However, most of the power has been absorbed after $\sim 15X_o$, and one could switch to a higher Z material at that depth and keep the assembly compact. The recommendation is to have a jaw composed of $1X_o \equiv 3.77 \text{ cm Ti-6Al-4V}$ followed by $14X_o \text{ Cu } \equiv 20.23 \text{ cm}$ and completed with $15X_o \text{ W } \equiv 5.16 \text{ cm}$ for a total length of $30X_o \equiv 27.2 \text{ cm } \equiv 10.7 \text{ inch}$. Here W stands for preferably W-26 Re or a free-machining tungsten composite with good ductility. The transverse size should be of the order of $8 \text{ cm } \times \text{ 8 cm}$. Only the copper section of the jaw would be water-cooled. A flow rate of $\sim 0.5 \text{ to } 1 \text{ gpm}$ is recommended. Such jaws could be mounted to standard SLAC collimator designs with only minor modifications.

**Fixed Aperture Protection Collimators**

Since the undulator represents such a large investment and is the centerpiece of the whole LCLS, it is prudent to back up the adjustable collimators with an additional fixed aperture protection collimator just ahead of the entrance to the undulator. Such a collimator could be made of copper or even tungsten (if space were at a premium), would not have to be water-cooled, and would be a sacrificial device since exposure to primary beam would be an accidental occurrence. The aperture of the collimator would need to be less than the inside diameter of the vacuum chamber (ID = 4.57 mm), and its length should be 25 to 30 $X_o$ ($\sim 36 \text{ to } 44 \text{ cm}$) with sufficient transverse size to shadow all of the undulator structure. Its presence would also reduce exposure of the undulator to scattered radiation from the many possible sources in the e-beam transport system.

Additional fixed aperture collimators need to be placed in the transport system at strategic locations for equipment protection reasons. They should be patterned after the FFTB protection collimator design and either can be copper if $\sigma \gtrsim 50 \mu m$ or must have a titanium (like Ti-6Al-4V) insert in locations where $\sigma < 50 \mu m$. 
Vacuum Chamber Surface Roughness

Recent computer modeling by K. Bane, et al., (ref. [51], Chapter 7, and Section 8.7.5) gave indications that the surface roughness on the inside of the undulator vacuum chamber may have deleterious effects on beam quality. Two effects, namely the geometric wall wakefield and the resistive wall wakefield, can negatively influence beam performance. The 6 mm OD × 5 mm ID stainless steel tubing needs to have a small surface roughness. Various roughness-reducing procedures have been investigated. The semiconductor industry has an ongoing need for ultra pure gas systems, and much R&D effort was invested in recent years to satisfy these demands. Present state-of-the-art technology identified fully austenitic stainless steel Type 316-L with very stringent chemical composition limits as a successful starting material. It is extruded into seamless tubing with special high quality dies, to great straightness, and under very clean conditions. The tubing is then cleaned and electropolished in lengths up to 6 m ≡ 20 ft. Tubing with a surface roughness of $R_a \sim 125$ nm (rms) is readily available off the shelf and for modest cost. Flat surfaces are electropolished to $R_a \sim 50$ nm, and such a value might also be achievable inside a tube with more R&D effort. Another quantity in surface roughness evaluation is the total peak-to-valley depth of roughness, $R_t$ or $R_{max}$, which varies from 4 to 12 times the $R_a$ value.

Since stainless steel has a high electrical resistivity, it increases the resistive wall wake. To reduce this effect, the plan is to deposit a thin layer of copper (> skindepth) onto the electropolished surface with a very thin nickel substrate for better adhesion. Electropolishing is then repeated on the copper surface. Early estimates indicate that the combination of electropolishing and copper surface deposition will result in surfaces inside the undulator vacuum chamber that should not materially degrade the electron beam.

8.4 Undulator Vacuum System

8.4.1 System Requirements and Description

The vacuum system for the undulator must have the following attributes to provide a good environment for the electron and photon beams:

- The vacuum system components must provide low impedance to avoid producing beam instabilities and minimize higher-order mode heating.
- Adequate pumping must be provided to maintain a low beamline pressure ($<10^{-7}$ Torr average).
- The beamline must provide an adequate aperture for the electron and photon beams.

The LCLS beampipe is a 6 mm outside diameter, 0.5 mm thick wall stainless steel (type 316-L) tube. The interior surface of the tube will be plated with approximately 0.01 mm of OFE copper to minimize Ohmic heating from the image current induced by the electron beam. The beampipe is constructed in segments that are 2.16 m long and which correspond
to the undulator magnet segments. The beampipe segments are constructed from type 316-L stainless steel to minimize the magnetization of the heat-affected zone at the welds. After welding, each beampipe section will be annealed to completely de-magnetize the welds. Vacuum processing of the vacuum tubes section will consist of baking at 800°C for a minimum of 4 hours.

Between undulator segments there are 23.5 cm gaps where vacuum pumping, beam steering, and diagnostic components are located. The undulator segments with the 23.5 cm gaps are repeated over the 112 m long device. A typical segment gap is shown in Fig. 8.4-1.

![Figure 8.4-1. Undulator segment gap with vacuum and magnet components.](image)

Between each undulator segment, there is an RF shielded bellows module. The purpose of the bellows is to provide flexibility for ease of installation of adjacent segments of the beampipe and to account for any minor length changes due to temperature fluctuations. A cross-section of the LCLS bellows module is shown in Fig. 8.4-2. Since space is tight, vacuum pumping of the beampipe is accomplished within the bellows module. A 2 liter/sec noble diode ion pump is mounted on one of the bellows end flanges. Pumping occurs through ten 1-mm diameter holes in the beampipe. Conductance losses through the module decreases the actual pumping speed to approximately 1 liter/sec.

The sliding RF fingers within the bellows are fabricated from a thin wall type 316-L stainless steel tube. The ends of the tube have 0.15 mm slits, which allow the tube to flex radially and provide spring force to maintain contact with the adjacent tubes. The tube slits are plated with 0.01 mm thick silver. The contacting surfaces of the adjacent tubes are plated with 0.01 mm thick rhodium. The combination of the relatively soft silver and the hard rhodium provide a sliding surface with both good lubricity and good electrical conductivity.

The flanges in the vacuum system are raised face type using a “VAT” style seal. The VAT seal is a commercially available, silver-plated, soft copper gasket. The gasket has a raised bead around the inside diameter of the beam tube, which is crushed between the flanges. The raised bead acts as both the vacuum seal and the RF seal across the flanged joint.
In general, accelerator beampipes are conductance limited. In the case of the undulator vacuum system, this problem is extreme. It turns out that the amount of pumping at 2.16 m intervals has little effect on the average system pressure. This can be demonstrated with a simple calculation. Assuming a constant gasload along the length of the beampipe and considering the symmetry of the vacuum system, the average beampipe pressure is calculated analytically using the following equation:

\[
P_{av} = \left( q \frac{pL}{C} \left( \frac{C}{S} + \frac{1}{3} \right) \right)
\]

where

- \( P_{av} \), average pressure, Torr
- \( q \), H\(_2\) gasload = 1 \times 10^{-11}\) Torr-liter/sec-sq cm
- \( p \), perimeter = \( \pi \) (0.5 cm) = 1.57 cm
- \( L \), half-length of cell = 108 cm
- \( C \), beampipe conductance = 0.0269 liter/sec
- \( S \), pumping speed

Assuming a pumping speed of 1 liter/sec, the average pressure is 2.27 \times 10^{-8} Torr. If the pumping speed is increased to 10 liter/sec, the average pressure decreases to 2.11 \times 10^{-8} Torr (only a 7.6% improvement). From this, it can be seen that minimizing the gasload has a much greater effect on beampipe pressure than does pumping speed. The gasload within the

Figure 8.4-2. Bellows module cross-section.

8.4.2 Gas Load and Vacuum Pressure
undulator vacuum system comes from two processes, thermal desorption and photo-desorption. Thermal desorption is common to all types of vacuum systems; it is the heat-stimulated release of gas constituents adsorbed on the walls of the system. Photo-desorption is the outgassing that occurs due to synchrotron radiation hitting the walls of the beampipe and desorbing gas molecules. Good thermal desorption data exists for UHV processed copper plated stainless steel from the PEP-II project \[12,13\]. Typically, \( q_t = 5 \times 10^{13} \) Torr-liter/sec-sq cm (@ T = 20°C) after a 800°C bake for 4 hours. Since the undulator vacuum system is expected to operate at 20°C, this value will be used.

Photodesorption is a little harder to estimate. The undulator produces 90 GW of total power. A worst case estimate would be that 100 GW hits the walls of the vacuum system. Converting power to photon flux:

\[
N_\gamma = \frac{P_{SR} t f (6.242 \times 10^{15} keV / J)}{E_{\text{photon}}}
\]  

(8.4.2)

where

- \( N_\gamma \): photon flux = photons/sec
- \( P_{SR} \): synchrotron radiation power = 100 x 10^7 Watts
- \( t \): pulse length = 100 x 10^{-15} sec
- \( f \): pulse frequency = 120 sec^{-1}
- \( E_{\text{photon}} \): average photon energy = 200 keV/photon

\( N_\gamma \) for the undulator is 3.74 x 10^{13} photons/sec. The distribution of the photon flux is assumed to increase linearly along the length of the vacuum system as shown in Fig. 8.4-3.

![Figure 8.4-3. Undulator photon flux profile.](image-url)
The photo-desorption gasload is calculated as follows:

\[ q_p = N \gamma \eta \left(2.83 \times 10^{-20}\text{Torr} - 1/\text{molecule}\right) \]  

(8.4.3)

where \( q_p \), photo-desorption gasload = Torr-liter/sec 
\( \eta \), photo-desorption rate = molecules/photon

Photo-desorption of copper and stainless steel beam tubes were investigated in the past. Brookhaven National Laboratory conducted studies for the PEP-II Project, determining the values of \( \eta \) with respect to flux [14]. The photon flux for the undulator vacuum system is in fact quite low, so, realistically, photon scrubbing will not occur during the lifetime of the machine. From the Brookhaven results, it has been determined that an \( \eta = 5 \times 10^{-3} \) molecules/photon is appropriate for design purposes. Using this value, the photo-desorption profile is calculated and is shown along with the calculated thermal desorption profile in Fig. 8.4-4.

Using the desorption profiles, a vacuum pressure profile for the 100 m long undulator vacuum system is calculated using VACCALC [15], a pipeline pressure computer code. The entire undulator beampipe is modeled using discrete pipeline segments. Each segment is defined by its length (m), conductance (liters/sec), gasload (nTorr-liter/sec), and pumping speed (liter/sec). All values for conductance, gasload and pumping speed are calculated for “hydrogen.” Fig. 8.4-5 shows the pressure profile along the length of the undulator vacuum system, with its average pressure being 1.06 \( \times 10^{-9} \) Torr (1 nTorr). This is well below the design requirement of \( 10^{-7} \) Torr.

![Figure 8.4-4. Undulator thermal and photo-desorption profiles.](image-url)
As described above, 100 GW of synchrotron radiation power strikes the walls of the beampipe. However, the pulse length of the photons is $100 \times 10^{-15}$ sec and the frequency of the pulse is 120 Hz. Therefore, the total power absorbed by the entire 112 m of beampipe is 1.2 Watts. With such a low level of incident power, there is no need to actively cool the vacuum chamber.

8.4.3 Thermal Considerations

As described above, 100 GW of synchrotron radiation power strikes the walls of the beampipe. However, the pulse length of the photons is $100 \times 10^{-15}$ sec and the frequency of the pulse is 120 Hz. Therefore, the total power absorbed by the entire 112 m of beampipe is 1.2 Watts. With such a low level of incident power, there is no need to actively cool the vacuum chamber.

8.5 Alignment and Trajectory Control

8.5.1 Introduction

FEL simulations show that transverse displacement as well as phase slippage between the electron and radiation beams have to be kept small and to very high tolerances (see Section 5.7). While the radiation beam, once generated coaxially with the electron beam path, will propagate in a straight line, the path of the electron beam can be changed by magnetic fields. The strongest magnetic field component acting on the beam is the undulator field itself. The ideal undulator field will cause the beam path to undergo undulation with very small amplitudes that average to zero over one 3 cm long undulator period, thus keeping the electron beam on a straight line.

Deviations from the ideal field will cause the average beam position to move away from a straight line onto a random walk trajectory. These deviations or field errors can only partially be corrected by field shimming techniques. Another contribution to random walk can come from transverse misalignment of the focusing quadrupoles. While undulator field errors will cause random walk mostly in one plane, quadrupole misalignment will produce a wander in two planes.

Random walk trajectories need to be controlled by correcting the beam path using electron beam position monitors from which the trajectory’s deviation from a straight line can
be obtained. While state-of-the-art electron beam position monitors offer excellent position resolution, their absolute position information is comparatively poor. A level of absolute alignment would be required that is beyond what present technology can do.

Beam-based alignment with variable electron energy offers a solution to this problem. Without putting very tight tolerances on absolute physical BPM alignment, the technique provides information about BPM position and BPM gain errors that can be used to correct the readings so that the electron beam trajectory deviation from a straight line can be measured down to a few microns. See Section 8.5.2.

The beam-based alignment procedure will be used infrequently to provide and update BPM calibration data. Continuous beam trajectory correction will be applied based on the calibration data. The methods considered include point-to-point steering with high spatial frequency components or a method (based on the linear algebra “Singular Value Decomposition” or SVD technique) that allows limiting the spatial frequency components and the maximum kick angles. All methods include trajectory measurements in one or more shots and trajectory correction in subsequent shots.

The point-to-point technique effectively uses one corrector (i.e., permanent quadrupole position) at a time to steer the beam to the calibrated center of the next position monitor. In the LCLS, correctors (movable quadrupoles) and monitors will be positioned next to each other. In the presence of large calibration errors, small spacings between subsequent correctors can lead to large kick angles that will eventually increase FEL saturation length.

For practical reasons, the spacing between monitor/corrector stations is much larger than an undulator pole or period. While the kicks produced by quadrupole misalignments can be eliminated, the random walk amplitude between two stations can only be minimized to some degree. The residual amplitude will depend on the field error amplitude, the monitor/corrector station separation and, to some extent, the steering algorithm.

Section 8.5.2 describes the initial trajectory control using undulator beam-based alignment. Section 8.5.3 describes trajectory control based on the Singular Value Decomposition (SVD) technique.

8.5.2 Undulator Beam Based Alignment

The electron trajectory within the LCLS undulator needs to be straight to a high degree of accuracy so that the undulator radiation overlaps efficiently within each gain length of the undulator. This condition requires a trajectory straightness of ~5 \( \mu \text{m} \) over a 10-meter length of undulator. This level is very difficult to achieve with tunnel component survey alignment techniques. For this reason, an empirical beam-based alignment technique that uses beam position monitor (BPM) readings as a function of large, deliberate variations in the electron energy has been developed. The measurements are analyzed and then converted to (1) quadrupole magnet transverse position corrections, (2) BPM offset corrections, and (3) adjustments of the incoming beam position and angle at the undulator entrance (initial
launch conditions). The alignment procedure is repeated 2–3 times in succession for the initial machine startup, and then reapplied only once per few weeks or months as necessary. Between these infrequent applications a simple steering technique will be used for daily trajectory control, and a fast feedback system will maintain the trajectory down to a time scale of seconds. This section discusses primarily the alignment procedure that is applied during the initial machine commissioning.

Introduction

The readback of the $i\text{th}$ BPM, which measures the centroid of the transverse position of the electron bunch at location $s_i$ along the beamline, can be written as

$$m_i = \sum_{j=1}^{i} \theta_j C_{ij} - b_i,$$

(8.5.1)

where $\theta_j$ is the kick angle at point $j$ ($j<i$) due to a transversely misaligned quadrupole magnet or dipole field error upstream of BPM-$i$, $C_{ij}$ is the transfer coefficient which maps a beam angle at point $j$ to a position at point $i$, and $b_i$ is the readback offset (mechanical and/or electrical) of the $i\text{th}$ BPM. The initial launch conditions are ignored for now (more on this below). This is described graphically in Fig. 8.5-1.

![Figure 8.5-1](image)

**Figure 8.5-1.** Schematic of an electron trajectory for the nominal beam energy ($\Delta E = 0$) and for a much lower energy ($\Delta E < 0$). The undulator induced oscillations of the central trajectory are not shown.

The kick angles in the figure are represented as dipoles; however, they are completely equivalent to either quadrupole magnets with transverse displacements or to field errors of the undulator dipoles or both. The quadrupole focusing within the undulator is not explicitly shown in the figure, but is represented mathematically in the transfer coefficient, $C_{ij}$.

Since the kick angles, $\theta_j$, are inversely proportional to beam momentum, $p$, whereas the BPM offsets, $b_i$, are independent of momentum, then variations of the beam energy (momentum) can be used to measure both parameters simultaneously. This is demonstrated by substituting a dipole field error, $\Delta B_j$, (equivalent to a quadrupole misalignment) for $\theta_j$ and explicitly showing the momentum dependence of Eq. 8.5.1.
Here \( l \) is the dipole length, \( e \) is the electron charge (the subscript \( k \) on momentum and BPM readback is introduced to indicate different values of beam momentum). The transfer coefficients, \( C_{ij}(p_k) \), in general also include a momentum dependence, except in the case of no quadrupole focusing. As a simple example, this no-quadrupole case is graphically represented in \textbf{Fig. 8.5-2} as a linear dependence of \( m_i \) on \( 1/p \) plus an offset, \( b_i \). The measurement then reduces to a line-fit where the slope is equal to the summation term in \textbf{Eq. 8.5.2} and the offset is equal to \( -b_i \). The general case, including quadrupole focusing, is similar but does not appear as the simple line-fit shown.

\[
m_{ik} = \frac{1}{p_k} \sum_{j=1}^{i} e\Delta B_j C_{ij}(p_k) - b_i . \tag{8.5.2}
\]

The solutions are obtained more effectively in a linear fit using all BPMs and energies simultaneously. A matrix expression for this linear system is given in \textbf{Eq. 8.5.3}. Here the elements \( P_{ij}(k) \equiv eC_{ij}p_k \) are the scaled momentum dependent transfer coefficients which map the \( j \)th field error to the \( i \)th BPM. \( N \) BPMs, \( N \) kicks, and two different momenta \((k = 1, 2)\) are also indicated.

\[
\begin{align*}
\begin{bmatrix}
m_{11} & m_{21} & \vdots & \vdots & \vdots & \vdots \\
m_{21} & m_{22} & \vdots & \vdots & \vdots & \vdots \\
m_{N1} & m_{N2} & \vdots & \vdots & \vdots & \vdots \\
m_{N1} & m_{N2} & \vdots & \vdots & \vdots & \vdots \\
m_{N1} & m_{N2} & \vdots & \vdots & \vdots & \vdots \\
m_{N1} & m_{N2} & \vdots & \vdots & \vdots & \vdots \\
\end{bmatrix}
\begin{bmatrix}
P_{11}(1) & \cdots & \cdots & \cdots & \cdots & \cdots \\
P_{21}(1) & P_{22}(1) & \cdots & \cdots & \cdots & \cdots \\
P_{N1}(1) & \cdots & \cdots & \cdots & \cdots & \cdots \\
P_{N2}(1) & \cdots & \cdots & \cdots & \cdots & \cdots \\
P_{N1}(2) & \cdots & \cdots & \cdots & \cdots & \cdots \\
P_{N2}(2) & \cdots & \cdots & \cdots & \cdots & \cdots \\
\end{bmatrix}
\begin{bmatrix}
b_1 \\
b_2 \\
b_N \\
\Delta B_1 \ell \\
\Delta B_2 \ell \\
\Delta B_N \ell
\end{bmatrix}
\end{align*}
\tag{8.5.3}
\]
There is a large number of dipoles along the undulator (~6600) and therefore too many to determine. Because of this, the fact that the simulated BPM readbacks contain contributions from the dipole field errors is ignored and the BPM data is fit to quadrupole magnet misalignments and BPM offsets only. Therefore, any BPM readback sensitivity to energy change will be identified as upstream quadrupole offsets, and the determined quadrupole misalignments (in the bend plane) will necessarily be biased in order to best cancel the net dipole error (real localized dipole errors plus quadrupole misalignment). The quality of this cancellation is examined in the simulation section described below. The non-bend plane has no dipoles, and therefore the determined quadrupole positions will not be biased (unless dipole roll errors or other stray magnetic fields exist). This is a significant advantage for the energy scan technique where all bend fields, without explicit knowledge of their source, are approximately canceled by biasing the final quadrupole positions to remove trajectory sensitivity to energy variations.

To write Eq. 8.5.3 explicitly in terms of quadrupole misalignments, \( \Delta B_{jl} \) is replaced by the quadrupole magnet misalignment, \( \Delta x_j \), and \( P_{ij}(k) \) by

\[
P_{ij}(k) \rightarrow [1 - Q_{11}^j(k)]R_{11}^{ji}(k) - Q_{21}^j(k)R_{12}^{ji}(k),
\]

where \( Q_{11}^j(k) \) and \( Q_{21}^j(k) \) are the thick-lens transfer matrix elements across the \( j \)th quadrupole magnet evaluated at the \( k \)th momentum, and \( R_{11}^{ji}(k) \) and \( R_{12}^{ji}(k) (=C_{ij}) \) are the position-to-position and angle-to-position, respectively, transfer matrix elements from the exit of the \( j \)th quadrupole to the \( i \)th BPM and are also evaluated at the \( k \)th momentum. Note, a thin lens quadrupole of pole-tip field \( B \), radius \( r \), and length \( l \) has a focal length \( f = rp/Bl \). The right side of Eq. 8.5.4 reduces to \(-C_{ij}(k)/f\), where the minus sign indicates that a horizontally focusing quadrupole (\( 1/f < 0 \)) which is displaced in the positive direction (\( \Delta x > 0 \)) will kick the beam in the positive direction.

In practice, the linear system of Eq. 8.5.3 is solved by imposing “soft-constraints” on the solutions to stabilize the system. The inclusion of the soft-constraints is equivalent to including the additional known information that the quadrupole and BPM offsets are zero to within ~1 mm. The constraints are not hard limits but rather weight the normalized residual fit error (\( \chi^2 \)) such that the solutions do not wander out to large values over long distances [16]. Eq. 8.5.5 shows the standard least-squares minimization where additional “soft-constraints” are included for the BPM and the quadrupole offsets (last two terms).

\[
\chi^2 = \sum_{i,k} \left( \frac{1}{\sigma_{m_i}} \left( m_{ik} - \left[ \sum_{j=1}^{N} P_{ij}(k)\Delta x_j - b_{i} \right] \right) \right)^2 + \sum_{i=1}^{N} \left( \frac{\Delta x_i}{\sigma_{x_i}} \right)^2 + \sum_{i=1}^{N} \left( \frac{b_{i}}{\sigma_{b_{i}}} \right)^2
\]

(8.5.5)

The BPM and quadrupole offsets are weighted by their respective soft-constraints, \( \sigma_{x} \) and \( \sigma_{b} \) (=1 mm in the simulations to follow). The solutions are then found in the standard way where the gradient of \( \chi^2 \) with respect to the solutions is set to zero.
By ignoring the initial launch conditions of the beam at the entrance to the undulator in Eq. 8.5.3 the reference line for the determined BPM and quadrupole misalignments (\(b_i\) and \(\Delta x_j\)) is defined as the incoming position and angle of the beam. When Eq. 8.5.3 has been solved, \(N\) values of \(b\) and \(\Delta x\) are available. A best line fit (initial position and angle) from these data is used to adjust the launch conditions (with steering dipoles prior to the undulator) so that the quadrupole and BPM offset corrections will not systematically follow these initial erroneous launch conditions. On the next application of the procedure, the launch conditions should be much closer to the axis defined by the initial BPM and quadrupole positions (the initial tunnel survey).

The advantage of scanning the beam energy, compared with scanning quadrupole field strengths, is that the energy scanned BPM data are sensitive to all bending fields whether due to quadrupole misalignments, undulator dipole errors or other stray fields such as the earth’s field. By using these field-sensitive data, the solutions obtained provide the best minimization of all bending by biasing the quadrupole positions slightly offset with respect to the beam centroid. The net effect is to produce minimal erroneous bending within the undulator. Given dipole errors and other stray fields, this produces a much straighter trajectory than is obtainable by varying quadrupole field strengths, which is also inconvenient for permanent magnet quadrupoles.

**Simulation Results**

Simulations have been run for the entire beam-based alignment algorithm, from initial rough steering through final precision alignment. The simulations use 48 quadrupoles and 48 BPMs, where quadrupoles are separated by 2.16 m (center-to-center) and have a field gradient of 48 T/m and length of 12 cm. One BPM is located at the upstream face of each quadrupole. A conservative set of statistical and systematic errors is included in the simulations as summarized in Table 8.5-1. The sensitivities of the final results to the input errors are studied in the next section.

The “correlated” BPM and quadrupole offsets (misalignments) define a random walk path where the expectation value of the square of the misalignment, \(\langle x^2 \rangle\), is related linearly to its distance, \(L\), from the undulator entrance [17]. This treatment approximates the long undulator survey “wander” error arising over 100 meters. In this case, an rms of 100 \(\mu m\) per 10 meter length, or \(\sim 300 \mu m\) over 100 meters is used. The BPMs and quadrupoles both follow the same random walk plus an additional 50 \(\mu m\) rms “uncorrelated” component (applied to both BPMs and quadrupoles separately). Two adjacent elements are therefore misaligned with respect to each other by \(\sqrt{2} \times 50 \mu m = 70 \mu m\) rms. Over longer distances the relative misalignment increases.

The “calibration error” in the table implies that the BPMs (magnet movers) are mis-scaled so that an actual displacement of 1 mm will read back as (move by) 1.1 mm. The “mover reproducibility” provides a random digitization error such that the final position of the mover achieves its desired position plus a uniformly distributed random component of up
to ±1 µm. The “incoming trajectory bias” is a static beam launch error which is 10 times that of the rms beam size in both position and angle (10 × 30 µm and 10 × 1.7 µrad). The “incoming orbit jitter” is a randomly varying launch position and angle error that occurs during the energy-scan data acquisition. The simulation shown here includes no orbit jitter, but in fact the results are insensitive up to a 10% rms launch jitter. The jitter can actually be reduced even further in practice, to a level of a few percent, by acquiring ~100 orbits and using the 8–10 pre-undulator BPMs to select only those orbits which produce a constant mean trajectory launch. The undulator alignment procedure for initial machine startup is shown in Table 8.5-2.

Table 8.5-1. Parameters used in simulation of beam-based alignment procedure. All random errors have Gaussian distributions except the magnet mover reproducibility, which is uniformly distributed.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
<th>Unit</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPM rms resolution</td>
<td>1</td>
<td>µm</td>
<td>net resolution—not necessarily single pulse</td>
</tr>
<tr>
<td>BPM offsets (uncorrelated)</td>
<td>50</td>
<td>µm</td>
<td>rms BPM-to-BPM survey and/or electrical offsets</td>
</tr>
<tr>
<td>BPM offsets (correlated)</td>
<td>300</td>
<td>µm</td>
<td>rms BPM “random walk” over length of undulator</td>
</tr>
<tr>
<td>BPM mean calibration error</td>
<td>10</td>
<td>%</td>
<td>mean calibration error of all BPMs</td>
</tr>
<tr>
<td>BPM rms calibration error</td>
<td>3</td>
<td>%</td>
<td>rms calibration error spread over BPMs</td>
</tr>
<tr>
<td>Quadrupole offsets (uncorrelated)</td>
<td>50</td>
<td>µm</td>
<td>rms quad-to-quad transverse alignment survey errors</td>
</tr>
<tr>
<td>Quadrupole offsets (correlated)</td>
<td>300</td>
<td>µm</td>
<td>rms quad “random walk” over length of undulator</td>
</tr>
<tr>
<td>Quadrupole mean gradient error</td>
<td>0.3</td>
<td>%</td>
<td>mean gradient error for all quadrupoles</td>
</tr>
<tr>
<td>Quadrupole rms gradient error</td>
<td>0.3</td>
<td>%</td>
<td>rms gradient error spread over quadrupoles</td>
</tr>
<tr>
<td>Undulator dipole error</td>
<td>0.1</td>
<td>%</td>
<td>rms dipole field errors over all poles</td>
</tr>
<tr>
<td>Mover mean calibration error</td>
<td>5</td>
<td>%</td>
<td>mean calibration error of all magnet movers</td>
</tr>
<tr>
<td>Mover rms calibration error</td>
<td>3</td>
<td>%</td>
<td>rms calibration error spread over magnet movers</td>
</tr>
<tr>
<td>Mover reproducibility</td>
<td>±1</td>
<td>µm</td>
<td>digitization—mover attains setting to within ±1 µm</td>
</tr>
<tr>
<td>Incoming trajectory static bias</td>
<td>10</td>
<td></td>
<td>initial orbit position and angle in beam size units</td>
</tr>
<tr>
<td>Incoming orbit jitter</td>
<td>0-0.1</td>
<td></td>
<td>rms of initial orbit variation in beam size units</td>
</tr>
</tbody>
</table>

The initial step is to reduce the field strength of the 2nd bunch compressor chicane bends so as to increase the bunch length in the undulator to ~150 µm. This will alleviate transverse resistive wall wakefields as a source of systematic error which may otherwise be quite strong when large trajectory excursions occur during the alignment procedure. The transverse
geometric wakefields increase with a longer bunch, but are still weak with a 150 µm bunch length.

**Figure 8.5-3** shows the specific quadrupole and BPM misalignments used in the simulation with respect to a line defined by the pre-undulator beamline axis (as are all figures in this section unless otherwise noted). Both the correlated and uncorrelated misalignment components are included (see **Table 8.5-1**).

The resultant, un-steered horizontal and vertical beam trajectory through the undulator is shown in **Fig. 8.5-4** (prior to step-1). The true orbit is shown (as in the plots to follow) every 12.5 cm along the undulator (every 8th dipole of 6624). The BPM readbacks (diamonds) are, in practice, the only known quantities at this point. The first correction (step-1) is to adjust the launch based on the first 10 BPMs in the undulator which are used in a best fit to an incoming betatron oscillation (see dashed line in first 20 meters of **Fig. 8.5-4**). **Table 8.5-3** shows the initial launch conditions for this simulation both before and after the step-1 correction.

**Table 8.5-2.**  Beam-based undulator alignment procedure. Beam energy is 14.3 GeV unless otherwise noted.

<table>
<thead>
<tr>
<th>Step #</th>
<th>Description</th>
<th>time/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Adjust the 2nd bunch compressor chicane for a ~150 µm electron bunch length to minimize transverse wakefields in the undulator</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>Adjust the launch using best position and angle fit to 1st 10 BPMs</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>Apply weighted steering to reduce (not zero) both the absolute BPM readings (∆50 µm) and the applied mover changes (∆50 µm)</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>Save ~100 sets of BPM readings for each of 5, 10, and 14.3 GeV beam energies while scaling upstream magnets to new energy each time</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Run BPM data through analysis program to determine BPM and quadrupole offsets (select from data sets to minimize orbit jitter)</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>Adjust launch position and angle to remove determined linear component of BPM and quadrupole offsets</td>
<td>0.1</td>
</tr>
<tr>
<td>6</td>
<td>Set quadrupole movers to new positions and correct BPM offsets</td>
<td>0.1</td>
</tr>
<tr>
<td>7</td>
<td>Steer offset-corrected BPM readings to approximately zero using a minimum number of magnet movers</td>
<td>0.2</td>
</tr>
<tr>
<td>8</td>
<td>Repeat steps 3-7 until peak BPM readings at 4.5 GeV are &lt;50 µm</td>
<td>3.5/ iteration</td>
</tr>
</tbody>
</table>

The launch conditions are significantly reduced in this case, which reduces the trajectory amplitude and, given systematic errors such as BPM calibration and quadrupole field gradient errors, improves the speed of convergence of the algorithm. A complete correction is not possible since the BPMs used in the launch fit include offsets and resolution errors,
and the misaligned quadrupoles between the BPMs kick the trajectory off of a free betatron oscillation. Note that the quality of this correction is dependent on the specific set of misalignments (random seed). The random seed shown here is fairly typical. The quality of this correction impacts only the number of iterations necessary.

Figure 8.5-3. Quadrupole (crosses) and BPM (diamonds) misalignments used in the simulation with respect to the line defined by the pre-undulator beamline coordinates.

Figure 8.5-4. True beam trajectory (solid) through the undulator including incoming trajectory bias of ~300 µm and ~17 µrad. Also shown are BPM readbacks (diamonds), quadrupole positions (crosses), and the fitted initial launch using the readbacks of the first 10 BPMs (dash—first 20 meters only).
Table 8.5-3. Initial launch conditions at undulator entrance before and after step-1 launch correction.

<table>
<thead>
<tr>
<th>Launch Parameter</th>
<th>Before Step-1</th>
<th>After Step-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle x \rangle$</td>
<td>320 μm</td>
<td>73 μm</td>
</tr>
<tr>
<td>$\langle x' \rangle$</td>
<td>16.0 μrad</td>
<td>5.4 μrad</td>
</tr>
<tr>
<td>$\langle y \rangle$</td>
<td>283 μm</td>
<td>13 μm</td>
</tr>
<tr>
<td>$\langle y' \rangle$</td>
<td>18.0 μrad</td>
<td>4.9 μrad</td>
</tr>
</tbody>
</table>

Step 2 involves a weighted steering procedure using the undulator quadrupole magnet movers. The absolute readings of the BPMs are minimized with respect to a 50 μm weighting and the magnet mover changes are simultaneously minimized with respect to a 50 μm weighting. Without this weighting the magnet movers can move more than 1 mm in order to exactly zero each BPM reading which, due to the large BPM offsets, is an unnecessary steering accuracy at this early stage. With the weighting included, the movers change by ~50 μm which is sufficient to correct the large trajectory deviations of Fig. 8.5-4. Fig. 8.5-5 shows the trajectory after the Step 2 weighted steering is applied.

![Figure 8.5-5](image)

Figure 8.5-5. True beam trajectory (solid) at 14.3 GeV after application of Step 2 weighted steering. The BPM readbacks (diamonds) and the applied magnet mover changes have been minimized with respect to a 50 μm weighting. The post-steering absolute quadrupole positions (crosses) are also shown.

These 14.3 GeV BPM data are saved and the energy is then lowered to 10 GeV by switching off klystrons in the last part of the linac. The fields of the magnets upstream of the undulator are scaled to the new energy, and any beam position differences upstream of the undulator, with respect to the 14.3 GeV orbit, are manually corrected until the launch position at 10 GeV is within ±3 μm of that at 14.3 GeV. Note that any beam angle difference at the undulator entrance will not be detectable with the BPMs upstream of the undulator.
However, this angle will eventually be properly incorporated into a correction of the transverse position of the first undulator quadrupole. Fig. 8.5-6 shows the trajectory at 10 GeV while Fig. 8.5-7 shows the trajectory at 4.5 GeV. No changes are made to the undulator components during the energy scan. Only the pre-undulator trajectory is adjusted, if necessary, to maintain a constant beam position.

Since the fields of the magnets upstream of the undulator will be scaled to the lower energies, the beta functions at the undulator entrance will be constant during the procedure. In addition, the undulator focusing is accomplished with permanent magnet quadrupoles. Therefore a betatron-mismatch, with respect to the energy dependent periodic beta functions of the undulator FODO lattice, will propagate through the undulator at the lower beam energies. In the worst case (4.5 GeV) the beam size will beat at twice the betatron frequency reaching a peak rms size of ~80 µm as compared to the 50 µm beam size of the 4.5 GeV periodic beta functions. This worst case beat in beam size should have no significant effect on the alignment procedure.

With the 5, 10, and 14.3 GeV BPM readback data saved, the analysis program is run which calculates BPM offsets and quadrupole magnet positions with respect to the Step 1 corrected incoming beam position and angle. Fig. 8.5-8 shows the calculated quadrupole offsets as well as the true offsets (used in the simulation). The fine structure of the calculated offsets agree well with the true offsets. The values differ, however, by a straight line, which is due to both (1) the Step 1 corrected launch bias and (2) the correlated component of the BPM and quadrupole offset errors. The best line fitted to the calculated BPM and the quadrupole offsets is also shown. The slope and offset of the best line fit is used to readjust the initial launch position and angle at the undulator entrance.
Figure 8.5-7. True beam trajectory (solid) at 4.5 GeV. BPM readbacks (diamonds) and quadrupole positions (crosses) are also shown. These BPM readings are saved for analysis.

Figure 8.5-8. True (solid) and calculated (dash) quadrupole positions. The best line fit to the calculated BPM and quadrupole offsets is also overlaid. The BPM offsets are similar but not shown.

Figure 8.5-9 shows the new electron trajectory after the launch conditions, the quadrupole magnet movers and the BPM offsets are corrected. The BPM offsets and the mover corrections applied are the differences between the best line fit of Fig. 8.5-8 and the data shown (dashed line connecting error bars). In addition, a final steering using a minimum number of magnet movers, is applied to remove any remaining betatron oscillation. At each
stage the real magnet mover limitations (calibration errors and reproducibility errors) and BPM errors (calibration and resolution) are incorporated.

The linear component which remains in the Fig. 8.5-9 trajectory is due to the correlated quadrupole and BPM offsets (random walk of initial tunnel survey). Since these offsets are due dominantly to the difference between the line defined by the linac beamline axis and the slightly different line established by the undulator beamline, the alignment procedure inevitably launches the electrons straight down the undulator vacuum chamber which presumably follows these correlated tunnel survey errors. The true trajectory shown in Fig. 8.5-9 is then actually the most desired trajectory where a slight change in beam position and angle at the undulator entrance is used to launch the electron beam down the center of the undulator. The tiny dispersion generated by this slight position and angle change is completely negligible, especially in consideration of the <0.02 % rms relative energy spread.

Figure 8.5-10 shows the same data as in Fig. 8.5-9 except that the linear component of the true orbit has been removed in order to show more clearly the straightness of the trajectory. Fig. 8.5-11 shows this linear-corrected view of the final trajectories after a second iteration of Steps 3-7 is applied. The rms of the electron trajectory over the length of the undulator with respect to a straight line achieves a value of ~3 µm. Finally, Fig. 8.5-12 shows the final quadrupole magnet mover settings after the two iterations have been completed. The final alignment correction requires magnet mover settings with an rms value of ~100 µm.

![Image](image-url)
Figure 8.5-10. True beam trajectory (solid) at 14.3 GeV, with linear component removed, after one iteration of Steps 1-7. BPM readbacks (diamonds) and quadrupole positions (crosses) are also shown. The quadrupole positions are shown in the same linear-corrected coordinates of the true orbit. The true beam trajectories with respect to a straight line over the undulator length (for this first pass correction) has rms values of $x_{\text{rms}} = 7.9 \mu m$, $y_{\text{rms}} = 11.7 \mu m$ and peak values of $x_{\text{pk}} = 18 \mu m$, $y_{\text{pk}} = 36 \mu m$.

Figure 8.5-11. True beam trajectory (solid) at 14.3 GeV, with linear component removed, after two iterations of Steps 3-7. BPM readbacks (diamonds) and quadrupole positions (crosses) are also shown. Quadrupole positions are shown in the same linear-corrected coordinates of the true orbit. The true beam trajectories with respect to a straight line over the undulator length has rms values of $x_{\text{rms}} = 3.1 \mu m$, $y_{\text{rms}} = 2.9 \mu m$ and peak values of $x_{\text{pk}} = 6.8 \mu m$, $y_{\text{pk}} = 6.6 \mu m$. 
Sensitivities

The sensitivities of the final rms trajectory straightness to the simulation input errors are summarized in Table 8.5-4. A new simulation is run using the input errors listed in Table 8.5-1 except that for each run a different error is doubled. The first row summarizes the simulation shown in detail above, and every following row represents a new simulation where the noted error has been doubled with respect to Table 8.3-1.

Table 8.5-4. Sensitivities of the final rms trajectory straightness (in \( \mu m \)) to the simulation input errors. All errors are those of Table 8.3-1 unless noted at left in which case that error has been doubled. The random seed used is unchanged for purposes of comparison.

<table>
<thead>
<tr>
<th>Input Error Varied</th>
<th>1st Iteration [( \mu m )]</th>
<th>2nd Iteration [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( x_{\text{rms}} )</td>
<td>( y_{\text{rms}} )</td>
</tr>
<tr>
<td>All errors of Table 8.1-1</td>
<td>7.9</td>
<td>11.7</td>
</tr>
<tr>
<td>2 ( \mu m ) BPM resolution</td>
<td>8.8</td>
<td>9.3</td>
</tr>
<tr>
<td>0.2 % rms dipole errors</td>
<td>8.8</td>
<td>9.3</td>
</tr>
<tr>
<td>100 ( \mu m ) uncorrelated BPM &amp; quadrupole offsets</td>
<td>12.3</td>
<td>18.8</td>
</tr>
<tr>
<td>0.6 % quadrupole gradient errors (mean &amp; rms)</td>
<td>8.5</td>
<td>15.1</td>
</tr>
<tr>
<td>Mover reproducibility error ( \pm 2 \mu m )</td>
<td>8.3</td>
<td>12.7</td>
</tr>
<tr>
<td>Incoming trajectory bias ( \approx 20 \times ) (rms beam size)</td>
<td>8.2</td>
<td>13.0</td>
</tr>
<tr>
<td>Rms incoming orbit jitter ( \approx 0.1 \times ) (rms beam size)</td>
<td>8.4</td>
<td>11.5</td>
</tr>
</tbody>
</table>
All errors are returned to original values for each new run except for the noted error. As the table shows, two iterations of the alignment procedure renders the algorithm fairly insensitive to the precise beamline errors. A third iteration (not shown) will, in most cases, reduce the rms trajectory to <3 \( \mu \text{m} \) in both planes. This is certainly true for the case of 100 \( \mu \text{m} \) BPM and quadrupole misalignments.

**Summary**

A final electron trajectory of 3 \( \mu \text{m} \) rms with respect to a straight line over the length of the LCLS undulator is achievable using energy scanned beam-based alignment. Therefore, prior to the alignment procedure, BPM and quadrupole uncorrelated misalignments of 100 \( \mu \text{m} \) rms plus 300 \( \mu \text{m} \) rms correlated misalignments are tolerable for the LCLS undulator. Effects such as BPM and magnet mover calibration errors, quadrupole field gradient errors, and dipole field errors are included in a detailed simulation that demonstrates this level can be achieved with high confidence. Only one random seed is presented here as an example. However, many seeds have also been run with similar success. In some cases a third iteration is necessary in order to achieve the 3 \( \mu \text{m} \) rms. However, the second iteration still achieves 5–6 \( \mu \text{m} \) rms, which is nearly adequate. An estimated time of 8–12 hrs is required to accomplish the alignment. The procedure will likely be required every 1–3 months.

### 8.5.3 The Singular Value Decomposition (SVD) Technique

**Description**

The primary task of the trajectory control system is to provide run-time correction of the beam position as it wanders from the aligned trajectory described in Section 8.5.2. The simulations here determines the optimum spacing of BPMs and correctors for LCLS conditions, based on an assumed magnitude of field error that causes trajectory error. The result is that a BPM and a corrector every 2 m gives acceptable trajectory control, which is the same interval required for initial alignment. Depending on the actual field errors, the results can be scaled linearly. Based on the 2 Gauss field error figure, the dipole kick is

\[
\theta = \left| \frac{B dl}{B_p} \right| = \frac{2G - m}{5 \times 10^5 G - m} = 4 \, \mu\text{rad}
\]

for a meter of undulator.

In the computer simulation, random dipole kicks of 2 \( \mu \text{rad} \) rms every 0.5 m are used to perturb the electron beam trajectory. The random kick distribution is truncated at 3 \( \sigma \). All calculations are performed in a single plane. No fast pulse-to-pulse studies were made.

Computer simulations of the trajectory control system are based on first-order particle transport calculations. Initially, a beamline file is specified containing quadrupoles, dipole kick locations, and BPM locations. Undulator field perturbations are neglected. The quadrupoles are modeled as thick lens devices with no fringe fields. For 360° phase advance...
over 100 m, the quadrupole field gradient is 50 T/m. The dipole kicks produced by undulator field errors are modeled as impulses located every 0.5 m. BPMs are also located every 0.5 m. BPMs located at the movable quadrupoles are used in the singular value decomposition correction algorithm, while the remaining BPMs are used as “virtual” BPMs to monitor the simulated trajectory deviations between the active BPMs.

Beam dynamics is modeled by calculating linear response matrices from the model. The response matrix for the dipole kicks is simply an array of response values, i.e., the amount of orbit displacement created by the kick at the BPM location and normalized by the kick’s amplitude. This matrix connects quadrupole displacement to trajectory displacements at BPMs. For both the dipole kicks and quadrupole displacements only BPMs downstream of the active element have non-zero entries.

The trajectory correction, described here, calculation borrows a technique known as “singular value decomposition” from linear algebra. This technique is analogous to calculating normal modes of a system using eigenvalue/eigenvector analysis of simultaneous linear equations. The system of equations in this case is Δx = R Δxq, where the “constraints” Δx are the column vector of trajectory deviations as measured at the BPMs. The “variables” Δxq are a column vector of quadrupole motions needed to produce the dipole kicks to correct the beam position. The response matrix, R, connects each quadrupole motion to the trajectory motion detected at each BPM. R can either be calculated (as done for the simulations presented here) or measured directly on the LCLS undulator.

Given a set of measured trajectory perturbations Δx, the response matrix R must be inverted to calculate the quadrupole displacements, Δxq. The method of choice for the matrix inversion is SVD. SVD decomposes the matrix operator R much like Fourier series analysis decomposes a function: the trajectory perturbation Δx is numerically decomposed into a set of eigenorbits (Δx = Σ Δxi). Each eigenorbit has a corresponding corrector pattern, Δθi, so that Δxi = RΔθi.

The power of the SVD is that each component, or eigenorbit, has an associated singular value or eigenvalue with index i. Large amplitude singular values tend to be associated with “smooth,” long wavelength trajectory perturbations, whereas small singular values represent short wavelength perturbations. By eliminating components of the trajectory perturbation with small singular values, short wavelength perturbations (noise) can be eliminated. In effect, one can low pass filter the noise from the signal by eliminating signal components with small singular values. This procedure smoothes the orbit correction by eliminating large dipole kicks from the correction pattern. The net effect is to reduce peak correction strengths and trajectory angles that would otherwise be introduced by electronic noise on the BPMs.

Using the SVD algorithm, the LCLS trajectory simulations proceed as follows:

1. Generate random numbers for dipole kicks.
2. Calculate trajectory perturbation.
3. Add random noise to BPM readback values.
4. Calculate quadrupole motions to correct trajectory.
5. Discrete quantization of quadrupole motions.
6. Calculate corrected orbit.
7. Accumulate statistics.

Simulation results are based on statistical analysis of many sets of random dipole kicks to perturb the electron beam trajectory. One thousand random machines were used for these results. The pertinent simulation parameters used for the LCLS are:

- Dipole kicks: $2 \mu\text{rad}$ rms, $3 \sigma$ truncation
- BPM noise: $2 \mu\text{m}$ rms, $3 \sigma$ truncation
- Quadrupole position setting errors: +/-0.125nm (discrete quantization)

Simulation Results

Figure 8.5-13 shows an example of a single random electron beam trajectory through the undulator transport line, including BPM noise. The trajectory executes random drift-kick-drift-kick motion through the beamline. Because of the weak focusing effect from the FODO structure, the rms trajectory displacement, calculated for many machine seeds, does not proceed as, $\sqrt{N}$ with $N$ the number of dipole kicks.

Figure 8.5-14 shows the standard deviation over many random seeds of corrected beam trajectories with BPMs and quadrupole movers placed after every 1.92 m section of undulator (2.155 m on center). The BPMs are located at the null points in the standard deviation plots. It is clear from the plot that the trajectory control at the BPMs is down to the noise level ($2 \mu\text{m}$ rms in this case). The rms quadrupole displacements required to correct the beam trajectory are on the order of 27 $\mu\text{m}$. For this example, all of the singular values were used to correct the orbit. The effect of eliminating singular values (eigenvalues) from the correction algorithm is demonstrated below.

Figure 8.5-14 also shows the standard deviation of the corrected electron beam trajectory when all quadrupole movers are used, but only half the BPMs (4.31 m on center). In this case, the peak rms trajectory displacement reaches 3.5 $\mu\text{m}$ between BPMs, and the rms quadrupole motions required to correct the orbit are about 20 $\mu\text{m}$. For both cases (BPM at 2 m, BPM at 4 m) the quantized quadrupole motion of 250 nm does not cause a problem. If the undulator field errors are increased from the 2 Gauss value cited above, the peaks of the rms trajectory displacements scale linearly. For instance, in the case with BPMs every 4 m the peak rms trajectory displacements are 3, 6, 9, and 12 $\mu\text{m}$ for field errors of 2, 4, 6, and 8 G, respectively.
Figure 8.5-13. Example of a single random electron beam trajectory through the undulator transport line, including BPM noise.

Figure 8.5-14. Standard deviation over many random seeds of corrected beam trajectories with BPMs and quadrupole movers placed after every 2 m (smaller amplitude curve) and 4 m (larger amplitude curve). The threshold is due to a random BPM detection error of 2 µm rms that is build into the simulation.

Figure 8.5-15 shows a plot of the average of the rms trajectory displacements, taken over the length of the 100 m undulator, for 1000 machine seeds as a function of the number of singular values used for the trajectory correction. In this case, BPMs were used every 2 m. By reducing the number of singular values, noise introduced by the BPMs is effectively filtered out. Also indicated in this plot is the average of the rms corrector strengths, taken over the length of the 100 m undulator, as a function of the number of singular values used by the trajectory correction algorithm. Note that even as the number of singular values is reduced, the statistical deviation of the electron beam orbit from the central axis remains...
roughly constant until only about half of the singular values are used. At the same time, the
rms quadrupole displacements decrease by about 20%. Although the displacement of the
electron beam trajectory at the BPMs is slightly relaxed, large deviations occur between
BPMs as the number of singular values is reduced.

![Plot of the average of the rms trajectory displacements, taken over the length of
the 100 m undulator, for 1000 machine seeds as a function of the number of
singular values used for the trajectory correction.](image)

Figure 8.5-15. Plot of the average of the rms trajectory displacements, taken over the length of
the 100 m undulator, for 1000 machine seeds as a function of the number of
singular values used for the trajectory correction.

Summary

The method of singular value decomposition (SVD) of the corrector-to-BPM response
matrix for trajectory control in the LCLS looks satisfactory. The SVD control algorithm is
presently used for trajectory control on many storage rings and on various sections of the
SLC linac. The trajectory control algorithm is easy to implement from a control system
interface point of view. Another redeeming feature of SVD is the robustness of the solution
as the number of singular values is reduced: the control algorithm can be used as a software
filter to reduce the effects of noise. Weighting of individual BPMs and correctors is also
possible. It should be noted that the success of the trajectory control depends on the
quadrupole mover and BPMs being located near each other. If the movers and BPMs are
“interlaced” (every 2 m for instance), then large trajectory excursions and trajectory angles
can occur.

8.6 Beam Diagnostics

8.6.1 rf Cavity BPMs

The Beam Position Monitor (BPM) system is the primary system for measuring the
transverse position of the electron beam in the LCLS. The instrument must provide these
measurements with exceptional accuracy through every phase of FEL operation:
commissioning, problem resolution, user operation, and facility improvement. The BPM
system is used to maintain co-linearity of the electron and photon beams, within 5 \( \mu \text{m} \) rms over any 10 m length with 14.3 GeV electrons. However, the absolute accuracy of the BPM system is not the basis of the alignment system. The initial survey errors of BPM detectors are held to better than 50 \( \mu \text{m} \). So as to contribute little to the total position error, the accuracy of individual BPMs was specified, with respect to their external fiducials, at less than 25 \( \mu \text{m} \). This includes all error factors: mechanical, electronic, and electronic drift. Each BPM must have the ability to detect relative changes in position of 1.0 \( \mu \text{m} \) at the nominal operating charge of 1 nC bunches.

These requirements placed on the BPM system are stringent, but within the forefront of position measurement technology. The structure of the electron beam is 1 nC bunches, nominally rectangularly distributed along the direction of travel (\( z \)-axis), with FWHM\(_z\) = 70 \( \mu \text{m} \). The bunch repetition rate is 120 Hz. Each BPM station shall provide single shot position measurements on any bunch in both x and y planes, and a beam intensity measurement. The requirements of the LCLS BPM system are shown in Table 8.6-1.

<table>
<thead>
<tr>
<th>Operational Mode</th>
<th>Single shot, any bunch, x &amp; y planes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position accuracy (with respect to local external fiducials)</td>
<td>( \Delta &lt; 25 \mu \text{m} )</td>
</tr>
<tr>
<td>Position resolution</td>
<td>( \delta &lt; 1.0 \mu \text{m} / 1 \text{nC} ) (10 ( \mu \text{m} / 0.1 \text{nC} ))</td>
</tr>
<tr>
<td>Current accuracy</td>
<td>2% (0.05 nC - 2.5 nC)</td>
</tr>
<tr>
<td>Current resolution</td>
<td>0.1%</td>
</tr>
<tr>
<td>Data collection/ local memory number of points</td>
<td>( 10^5 ) point FIFO memory with acquisition enable</td>
</tr>
</tbody>
</table>

Review of BPM Technology

Several BPM technologies, including both intercepting and non-intercepting methods, were evaluated against the LCLS requirements. The expected performance of Non-Intercepting BPM technologies is summarized in Table 8.6-2. Four of the technologies (U) don’t meet the LCLS design specifications, while two do (D).

Intercepting monitors were also considered because of the high absolute accuracy that a mechanical drive/hard stop assembly can provide. Intercepting monitors would be inserted infrequently, to obtain an absolute position calibration. The offsets of the non-intercepting monitors would then be measured and applied as corrections in the database. The intercepting monitors which were considered for the LCLS are shown in Table 8.6-3.
Table 8.6-2. Evaluation of BPM technologies for LCLS (non-intercepting).

<table>
<thead>
<tr>
<th>Device Parameters</th>
<th>Device Parameters</th>
<th>Accuracy of Center</th>
<th>Estimated Resolution</th>
<th>Operating Frequency</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall Current Monitor (U)</td>
<td>z = 6 mm, R_B = 2 Ω</td>
<td>Moderate</td>
<td>0.2 μm/nC</td>
<td>&gt; 1 GHz</td>
<td>Ferrite saturation.</td>
</tr>
<tr>
<td>Stripline (U)</td>
<td>z = 9 mm, Z_0 = 40 Ω, g = 0.125</td>
<td>Moderate (~ 50 μm)</td>
<td>0.25 μm/nC</td>
<td>~ 2–5 GHz</td>
<td>Strips on ceramic cylinder</td>
</tr>
<tr>
<td>Microwave Aperture (U)</td>
<td>3.0 x 1.5 mm slot to waveguide.</td>
<td>Good</td>
<td>0.1 μm/nC Unproved</td>
<td>&gt; 50 GHz</td>
<td>Operates above chamber cutoff. HOM errors.</td>
</tr>
<tr>
<td>Cavity (U)</td>
<td>φ_ID = 7.0 mm z = 2.8 mm</td>
<td>Good</td>
<td>1 μm/nC</td>
<td>~ 32 GHz</td>
<td>f₀ near chamber cutoff. Low Q</td>
</tr>
<tr>
<td>Stripline (D)</td>
<td>z = 40 mm, Z_0 = 50 Ω</td>
<td>Moderate (~ 50 μm)</td>
<td>0.25 μm/nC</td>
<td>~ 0.5–2 GHz</td>
<td>Good technical maturity</td>
</tr>
<tr>
<td>Cavity (D)</td>
<td>φ_ID = 60 mm z = 5.0 mm</td>
<td>Excellent (~ 5 μm)</td>
<td>5 GHz</td>
<td>~ 5 GHz</td>
<td>Robust design, TM₀₁₀ mode.</td>
</tr>
</tbody>
</table>

Table 8.6-3. Evaluation of BPM technologies for LCLS (intercepting).

<table>
<thead>
<tr>
<th>Device Parameters</th>
<th>Device Parameters</th>
<th>Resolution</th>
<th>Operating Regime</th>
<th>Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluorescent screen (YAG, CsI)</td>
<td>Doped crystal</td>
<td>~ 1 μm</td>
<td>Unproven. Suffers from saturation.</td>
<td>Superposed photon and e⁻ beams.</td>
</tr>
<tr>
<td>Transition radiation Conducting foil</td>
<td>Fair. Optics change in radiation.</td>
<td>Unproved</td>
<td>~ 30 μm</td>
<td>Competing undulator radiation</td>
</tr>
<tr>
<td>Wire scanner 7 - 20 μm carbon wire</td>
<td>Good (~ 10 μm)</td>
<td>5–10 μm</td>
<td>Bremsstrahlung 22–39 MeV</td>
<td>Proven technology.</td>
</tr>
</tbody>
</table>

Evaluation of BPM Options for the LCLS

The BPM design approach for the LCLS may incorporate both intercepting and non-intercepting monitors, if a single variety cannot meet every requirement. The monitors will be located within the 23.5 cm long drift spaces between sections of the undulator. The regions within the undulator considerably restrict the BPM mechanics that can be built, and present other complications. For example, in the case of the Wall Current Monitor (WCM), its ferrite cannot be allowed inside the undulator. For any of the monitors, vacuum feedthroughs within the undulator can only be accommodated with difficulty. Monitors such as the aperture monitor or multi-aperture monitor [18], which operate on Bethe hole
radiation, must have small apertures, and as such are strongly influenced by higher order modes. The cavity monitor within the undulator, with beam pipe apertures nearly the size of the resonator end plates, would have low Q. In addition, the relative compactness of any of these “within undulator” structures raises the operating frequency, contributing to signal cable losses and higher component costs. These factors argue in favor of locating BPM structures in the drift spaces.

BPM structures in the drift regions offer superior performance with fewer design restrictions. Of those investigated, three monitor types meet or nearly meet the LCLS requirements: The cavity structure [19,20,21] can be built to meet the design requirements. An absolute accuracy of ~ 5 \( \mu \)m results from the natural symmetry which is achieved in a circularly machined component. The stripline design [22] also meets many of the requirements, while approaching the accuracy requirement. A four-electrode stripline within the undulator has been studied extensively. Wire scanners could be used in a few locations to check the accuracy of center of the non-intercepting monitors.

**LCLS Stripline BPM**

An LCLS stripline detector, consisting of four longitudinal strips, 8 mm long and 2 mm wide, plated to a 10 mm long ceramic section of beam tube, was designed to fit within the undulator. The strips may be plated to either the inner or outer surfaces of the ceramic. In the latter case, the electromagnetic fields of the beam readily penetrate the ceramic, producing signal current on the strips. Position sensitivity occurs because of the non-symmetrical image current distribution on the strips. Each of the two strip configurations offers particular advantages. For the internally plated strips, less ceramic is exposed to the beam, diminishing the possibility that static charges accumulate on the insulator. (In either configuration, the ceramic is lightly coated with ~ 0.5 M\( \Omega \)/square resistive material to drain the charge). The externally plated strips have the considerable advantage that feedthrough connections are not required, reducing cost, complexity, and potential vacuum leaks. If feedthroughs are used, they would be simple wires, fired into the “green” ceramic tube.

The strip characteristic impedance \( (Z_0) \) must be well controlled to minimize accuracy of center error. The strip impedance is entirely governed by the transverse geometry of the strip and its associated ground, a shield that occupies a larger radial space than the beam tube alone. Optimal performance is obtained when the strip length is \( \lambda/4 \) at the selected processing frequency, the chosen frequency to be a strong beam current component. In the LCLS, the spectrum of beam current is constant from DC to ~ 2 THz; not an optimizable parameter. The stripline frequency response is broad and low Q. An operating frequency of 2.4 GHz is desirable, because convolution of the detector and long haul cable response is peaked, and very low cost communication components are available at 2.4 GHz.

The stripline detector, as with every detector under consideration for the LCLS, produces very high peak voltages. In the stripline design, the high voltage problem has been addressed. First, the plating geometry of the upstream end can be designed to be dispersive at the higher
frequencies. Second, a shunt capacitor of 0.2 pF is added, to pass the high frequency currents through the strip. The downstream end is shorted to the beamtube. These modifications to the standard stripline would not affect the desired instrumentation signals. The peak voltages are reduced from 9.6 kV to 0.7 kV.

The “within undulator” stripline detector would be difficult to fabricate. With limited radial space, the ceramic vacuum barrier is 0.5 mm thick, and the ceramic-to-metal joints are likely to be weak. The device is small, not especially robust, and accuracy of center is only fair. However, the signal power is strong, and the technology is well known. A stripline design external to the undulator would be sufficiently robust and would have moderately good accuracy (~ 50 µm) of center.

LCLS Microwave Cavity BPM

The LCLS Microwave Cavity BPM detector is a circularly symmetric microwave cavity, which can provide sub-micron resolution and micron level absolute accuracy. It is the non-intercepting monitor of choice for the LCLS. The cavity is a circular cylindrical resonator, excited by the passing electron beam pulses, which “rings down” in a set of characteristic frequencies. The frequencies are precisely determined by the cavity dimensions. A first order performance estimate can be obtained by considering a metal pillbox of radius \( a \) and length \( d \). Attached beam pipe tubes of radius \( b \), with their axes in the \( z \)-axis, concentrically enter each flat end plate. The pillbox model is shown in Fig. 8.6-1.

![Pillbox cavity BPM model](image)

**Figure 8.6-1.** Pillbox cavity BPM model.
An electron beam moving on or parallel to the $z$-axis excites TM modes in the cavity. TE modes are only excited if a transverse component of current exists. For general TM fields, the components $E_r$, $E_\phi$, $E_z$, $H_r$, and $H_\phi$ are non-zero, but the cavity modes may be readily visualized from the expression for $E_z$ alone.

\[
E_z = E_\omega J_n \left( \frac{P_{nl}}{a} r \right) \left( \frac{\sin(n\phi)}{\cos(n\phi)} \right) \cos\left( \frac{q\pi}{d} z \right) e^{i\omega t} \tag{8.6.1}
\]

\[
H_\phi = -i \frac{\omega}{\omega_\eta} E_\omega J_n' \left( \frac{P_{nl}}{a} r \right) \left( \frac{\sin(n\phi)}{\cos(n\phi)} \right) \cos\left( \frac{q\pi}{d} z \right) e^{i\omega t}
\]

Fields which will exist in the cavity for a specified beam excitation may be expressed by an orthogonal expansion of these functions. The index $n$ specifies the order of the Bessel function and the number of field reversals around the cavity circumference. Index $l$ specifies the number of field reversals radially, while index $q$ specifies the number of field reversals longitudinally. The mode of interest for beam position measurement is the dipole or TM$_{110}$ mode, which is excited only when beam is off axis. This mode has zero field reversals radially and longitudinally, and one reversal circumferentially. Two polarizations of the TM$_{110}$ mode may exist in the simple pillbox cavity. For single plane position measurements, only one polarization is coupled out.

Signal power is coupled from the dipole mode using precisely fabricated probes. The probe geometry must be controlled to $\sim$10 $\mu$m tolerances, suggesting magnetic probes may be selected over electric probes, as magnetic probes are grounded at one end. The radial location of the probes is an area for study, as at least three options exist. One option is to locate the probes for maximum coupling to the TM$_{110}$ field. A second option is the radial position where the dipole mode is strongest relative to competing modes. A third option involves consideration of critical coupling to the cavity. A BPM station suitable for use in the LCLS, shown with separate position and intensity cavities, is depicted in Fig. 8.6-2.

Using the pillbox cavity approximation, it is possible to calculate a transfer function for signal power output as a function of beam displacement. For a bunch containing $N$ charges, the peak power, $P_{110}$ coupled from the resonant cavity for a displacement $\delta x$, is given by:

\[
P_{110} = (\delta x)^2 (eN)^2 \left( \frac{cP_{11}}{a} \right)^2 \frac{\eta dp_{11}}{4\pi a^3 Q_L J_0^2(p_{11})} \tag{8.6.2}
\]

where $\eta = (\mu/e)^{1/2}$, $Q_L$ is the cavity loaded quality factor, and $p_{11}$ is the first root of the Bessel function $J_1$. The transfer function may be simply expressed by:

\[
\frac{P_{110}}{\mu W} = K \left( \frac{\delta x}{\mu m} \right)^2 \tag{8.6.3}
\]
Various investigators [23,24] have measured or calculated the coefficient $K$, reporting values between 4.0 and 7.0. Measurements made by Shintake [21] in the FFTB indicate the coefficient to be $\sim 4$, resulting in a calculated position resolution of 5 nm.

The accuracy to which the BPM cavity is machined limits the precision of the electrical center. Using diamond turning on ultra-precision lathes, mechanical tolerances of a few microns can be achieved. However, even a perfectly machined cavity is limited in accuracy because of the presence of a symmetrical excitation of the cavity [25]. The desired TM$_{110}$ mode is not the dominant cavity mode, and must compete with two lower frequency modes. The TE$_{111}$ mode exists at a lower frequency, but only if $d/a > 2$. This situation is readily prevented. The remaining lower mode is the TM$_{010}$, which is excited with beam on or off axis. This dominant mode is significantly stronger than the dipole mode. This loss of precision is the primary research issue which must be addressed for a cavity monitor, and at least two techniques [26] are known—symmetry discrimination and frequency discrimination. The former involves canceling the large amplitude TM$_{010}$ signal, which is present on all output ports of the cavity, using a hybrid junction. This “common mode” cancellation, taken alone, is not expected to be sufficient to provide the required suppression. Frequency discrimination using narrow-band receiver techniques will also be used. This method is fundamentally limited, however, by the fact that the cavity is shock excited by a single bunch. The cavity responds producing the strong dominant (TM$_{010}$) mode, which contains finite spectral density at the signal (TM$_{110}$) frequency, at which the receiver is
tuned. This phenomenon can be improved but not eliminated by increasing the \( Q \) of the cavity [21].

Schnell [25] has estimated the required rejection of the beam-induced common mode signal. To obtain a position resolution of \( \delta x \) from a circular cylindrical cavity of radius \( a \), the rejection factor must exceed the ratio of the power in the two modes. The ratio is given by:

\[
\left( \frac{P_{110}}{P_{010}} \right) \approx 10.9 \left( \frac{\delta x}{a} \right)^2
\]  

(8.6.4)

The level of common mode rejection (frequency discrimination) provided by the cavity is given by:

\[
CMRR_f = Q_{110} \left( 1 - \frac{\omega_{010}^2}{\omega_{110}^2} \right)
\]  

(8.6.5)

where \( Q_{110} \) is the loaded cavity quality factor in the dipole mode, and \( \omega_{110}/\omega_{010} = 1.6 \) is the ratio of the mode frequencies. The rejection available from symmetry discrimination is a function of imperfections in the cavity and hybrid junction fabrication, with the junction believed to dominate. Because of the small fractional bandwidth, advantage can be taken of tuning. This second factor is conservatively taken to be \( CMRR_s = 0.02 \).

**Parameters of the LCLS BPM Cavity**

A cavity operating frequency of 6 GHz is under consideration for the LCLS BPM. This is well below the beam tube cutoff (35.1 GHz) frequency, therefore reducing corruption by beam higher order modes. The selected frequency is not so low as to make the cavity very large, where machining tolerances proportional to radius would dominate. This operating frequency is independent of the SLAC accelerating frequency and its harmonics. There is no advantage to operating there, but the decided disadvantage of man-made electromagnetic interference. At 6 GHz, the radius of the position cavity is 28.5 mm, and the power ratio \( P_{110}/P_{010} = 79 \) dB. Taking \( Q_{110} = 2000 \), then \( CMRR_f = 62 \) dB, and with \( CMRR_s = 34 \) dB, the total rejection is adequate. While position resolution improves with operating frequency, the price to performance ratio of microwave components at 6 GHz (C-band) is favorable [21], generally increasing with increasing frequency. Consideration of other operating frequencies between 6 GHz and 25 GHz is an appropriate R&D effort.

The parameters and performance of the microwave cavity BPM are summarized in Table 8.6-4.

**Microwave Cavity Beam Impedance**

The microwave BPM cavities remove real signal power from the passing bunch, and as such are a small, but not insignificant, source of beam impedance. The impedance of a single cavity has been estimated using analytical and numerical methods. Because the bunches are
very short (σ/α < .018), the diffraction model [27,28,29] of the high-frequency impedance of a cavity is used. According to the model, the longitudinal impedance varies as ω^1/2, and the transverse impedance as ω^3/2. The loss factors, k, for a single cavity are calculated by integrating the impedances over the bunch spectrum, and are shown in Table 8.6-5. The BPMs make a noticeable contribution to the machine’s total longitudinal loss.

Table 8.6-4. Parameters and performance of microwave cavity BPM.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cavity radius</td>
<td>a = 28.5 mm</td>
</tr>
<tr>
<td>Cavity height</td>
<td>d = 5 mm</td>
</tr>
<tr>
<td>Beam pipe radius (inner)</td>
<td>b = 2.5 mm</td>
</tr>
<tr>
<td>Frequency TM_{110}</td>
<td>6 GHz</td>
</tr>
<tr>
<td>(R/Q) TM_{110}</td>
<td>8.4 Ω</td>
</tr>
<tr>
<td>Shunt impedance (R_{SH}) TM_{010}</td>
<td>27.5 kΩ</td>
</tr>
<tr>
<td>V_{out} into 50 Ω TM_{110}</td>
<td>15 μV/nm/nC</td>
</tr>
<tr>
<td>Absolute position accuracy (Δx)</td>
<td>~ 10 μm</td>
</tr>
<tr>
<td>Position resolution (δx)</td>
<td>&lt; 1 μm</td>
</tr>
<tr>
<td>Peak electric field σ_z = 20 μm</td>
<td>7.7 MV/m</td>
</tr>
<tr>
<td>q = InC r σ_z = 40 μm</td>
<td>5.3 MV/m</td>
</tr>
</tbody>
</table>

Table 8.6-5. Cavity BPM beam impedances and wakefields.

<table>
<thead>
<tr>
<th>Impedance</th>
<th>Wakefield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal loss factor k_x(σ)</td>
<td>37.1 V/pC</td>
</tr>
<tr>
<td>Transverse loss factor k(σ)</td>
<td>342 V/pC/m</td>
</tr>
<tr>
<td>Longitudinal loss factor k_y(σ) TM_{110} (only)</td>
<td>0.6 V/pC</td>
</tr>
<tr>
<td>Longitudinal impedance (f=50 GHz)</td>
<td>(14.8 + i 14.8) Ω</td>
</tr>
<tr>
<td>Energy spread σ_e</td>
<td>0.0255%</td>
</tr>
<tr>
<td>Emittance Growth Δε/ε</td>
<td>0.00242</td>
</tr>
</tbody>
</table>

The numerical simulation code MAFIA was used to confirm the loss factors and to calculate the wakefields. The energy spread and emittance growth were calculated with the equations in this section, using the parameter values listed at the bottom of Table 8.6-5. The number of cavities N_{cav} is taken as 104, allowing for two cavities in each of 52 locations. This assumes one two-plane position sensitive cavity at each location, with a similar intensity cavity. The intensity cavities produce a significant additional impedance, each cavity producing far more signal power (~ 4 W) than required. A lower impedance source of
the intensity signals is possible, consisting of a slot-coupled pickup, with more than one symmetrically placed slot, coupled by a single vacuum feedthrough. Its signal must then be filtered using an external cavity, which does not interact with the beam.

**Microwave Cavity Signal Processing**

The BPM signal processor produces digital position and intensity information by demodulating the signals produced by the two cavities. Each measurement plane requires two output ports. The number of outputs from each cavity would be the subject of study, which would consider the dominant mode issue and possible mode suppression methods, against the value of obtaining both planes from a single cavity. The output ports may be either waveguide or coaxial line. Waveguide coupling to the cavity is accomplished by machined rectangular slots in the cavity circumference, the shorter edge parallel to the beam direction. The waveguides are actually machined from the same metal block as the cavity, and form a “Magic-Tee,” which rejects the dominant (3.7 GHz) common mode. The waveguide approach preserves absolute accuracy because the entire structure is machined to micron level tolerances. Coaxial line coupling is better suited to a low frequency cavity, but allows more degrees of freedom, and higher mechanical tolerance accumulations. By connecting the coaxial lines to machined pins, which are held in place by precision ceramic bushings, excellent tolerances can also be achieved. In the proposed design, opposing coaxial outputs feed the difference arms of a hybrid coupler. This difference output is transmitted by low-loss coaxial cable to the electronics area, a maximum of 70 m away.

The difference signal is a tone burst at 6 GHz, of amplitude $6 \mu V/nm/nC$ (rms), with an e-folding time of 30 ns. This duration can be extended somewhat by weakening the cavity coupling, noting that the cavity is the highest $Q$ device in the system. The signal is filtered to attenuate the strong mode at 3.7 GHz, and attenuated as necessary by a binary controlled attenuator. Small signals suffer only residual attenuation and are amplified. The amplifier is protected by a passive diode limiter. Attached to the position cavity, the intensity or “reference” cavity, operating at 6 GHz in the monopole mode, provides the phase reference signal. The phase reference signal is proportional to beam intensity and is provided as an output. The position and reference signals are filtered to reject power in all undesired modes, and then mixed to a suitable Intermediate Frequency (IF) using a Local Oscillator (LO). For a small fractional bandwidth, the IF should be several times the information bandwidth. A particularly poor choice for the LO would be 4.85 GHz, since the strong 3.7 GHz mode becomes the image, translated directly into an 1150 MHz IF. An IF in the range 500 MHz is preferable, with an LO at 6.5 GHz.

The LO is synthesized using a signal from the reference cavity and an independent oscillator. This added step causes the IF operating frequency to equal that of the independent oscillator and be essentially constant. The oscillator is itself synthesized from a stable crystal oscillator using a Direct Digital Synthesizer (DDS) and Phase-Locked Loop (PLL) multiplier. Such a solution provides broad frequency coverage for *in situ* frequency response testing, calibration in the presence of beam, and low phase noise. In the absence of beam, the
reference cavity signal will be provided by a crystal oscillator, which is injection locked to the beam frequency when beam is present. **Fig. 8.6-3** shows a block diagram of the detection scheme.

![BPM analog signal processing scheme](image)

**Figure 8.6-3.** BPM analog signal processing scheme.

Calibration circuitry provides the capability to inject the same or different frequencies into the position and intensity inputs. The connections are made near the receiver inputs with directional couplers. The calibration procedure can be completed while beam is present by operating at a frequency offset. The calibration sources can also be un-powered to avoid isolation problems. Finally, the raw cavity signals can be monitored at the directional couplers. These are designed with sufficient isolation not to affect the normal diagnostic operation.

Because the position and reference signals are (approximately) the impulse responses of two different filters, the detected difference will contain a phase precession. To circumvent the problem, In-Phase and Quadrature (I&Q) detection is applied. Using I&Q, phase synchronization is not required, and the system is immune to phase delay changes in cables and components. The low frequency information on each I and Q line is captured by a Track-and-Hold amplifier, and is digitized with 12-bit precision. A computer then calculates the position using the two numbers. Many of the sources of amplitude and phase error can be measured, updated, and compensated after digitization. This approach follows a modern trend [30] in signal processing toward error compensation in software, rather than extensive adjustment of the analog electronics to zero out these errors.

### 8.6.2 Carbon Wire BPMs

**Beam Position Measurement**

To test the alignment of the electron beam in the undulator, fine wires can be used as electron beam targets. They would be positioned between undulator segments, would be used as needed, perhaps daily, and must not interfere with the beam when not in use. The optimum number of stations for alignment may be affected by their use also as emittance diagnostics.
Wire scanners are standard tools of accelerator instrumentation. In cases where beam heating is severe, the wire of choice is made of carbon. At the final focus in SLD and at the FFTB, carbon filaments seem to withstand the heating of spots of 2 $\mu m \times 2 \mu m$ (rms width x rms width) for $10^{10}$ electrons per pulse. Thus a round spot of 31 $\mu m$ would not be a threat. There is even more experience with tungsten wires. It is estimated that they should withstand beams up to 15% of the intensity limit of carbon, so the LCLS beam is well within the range of tungsten. A degree of caution should be exercised, because heavily used tungsten wires have shown susceptibility to failure in 120 Hz operation. This is associated with arcing at their support points. Although a solution is not yet in hand, trials of alternative support designs are being made. Alternative materials, for example silicon carbide, are also being tested.

Various techniques have been used to detect a signal from the beam overlap with the wire. The most robust and successful is detection of the Bremsstrahlung gamma rays. Their 1/e spectrum is emitted in a cone of half angle about $1/\gamma$ ($\gamma$ is the Lorentz factor). In some cases a better signal is obtained from the Bremsstrahlung electrons well below beam energy. This, of course, requires that they are forced out of the beam pipe by a magnetic field. In either case, beam line components can make it difficult to access the raw signal, and sometimes only the tail of an electromagnetic shower can be used. With the tungsten radiation length less than 2% of that of carbon, its Bremsstrahlung signal is much stronger, while a different type of signal also becomes accessible. This is the yield of delta rays, of about 1 MeV and at right angles to the beam, that is used in numerous places at SLC and FFTB. Although it requires a thin window in the vacuum pipe, it can be used when the straight-ahead Bremsstrahlung signal is not available. From a carbon fiber, however, this process is normally too weak to be useful.

Finally, secondary emission (of electrons of 1 eV and above) has been used with carbon and other materials. Because of the large rf noise accompanying the beam, the charge signal is collected in a shaping amplifier with a shaping time of several microseconds, giving time for the bipolar rf noise to die away. Several systematic effects have been encountered. For the short SLC pulses, the electric dipole induced at the surface of the wire has the effect of suppressing secondary emission from an electron beam (and enhancing it from a positron beam). The higher energy electrons, often called $\delta$-rays, are still ejected. A further problem was encountered at the SLC final focus, but never resolved. When the spot width decreased below roughly 5 $\mu m$ rms, for $5 \times 10^6$ per pulse, the signal became unstable and unrepeatable. However, the technique evidently is applicable within the LCLS parameters.

Since a tungsten wire could be thinner than a carbon filament while still maintaining a larger signal for beam measurement, one could expect to use a 7.5 or 10 $\mu m$ diameter wire as against the available 34 $\mu m$ for carbon. Fibers are normally mounted spanning the prongs of a fork. Common fork materials are Macor, alumina, or aluminum. In the former cases the surfaces are rendered slightly conducting to bleed away any charge buildup. A typical wire span is in the range of 2 cm. Somewhat shorter lengths, more suitable to LCLS, are probably
safe: for carbon fibers, one must be careful to avoid relative movement or vibration on the prongs beyond the 1% fiber strain limit.

The beam will be multiply scattered by the filament. Whatever fraction is intercepted, say 25%, would have an rms scattering angle of about 12 $\mu$rad from a 34 $\mu$m carbon fiber. For a 10 $\mu$m tungsten wire these numbers would become 7% at 55 $\mu$rad. The mean fractional energy lost through Bremsstrahlung by the part of the beam penetrating the carbon would be $3 \times 10^{-5}$, or $2 \times 10^{-3}$ for tungsten.

In operation, a Gaussian curve would be fitted to the pulse-by-pulse signals from a scan. From SLC experience, the uncertainty on the location of the center of the fit would be in the range of 2% of the width, or better than a micron. However, a careful evaluation of the quoted SLC error bars has not been done. The most serious issue affecting accuracy will certainly be the systematics of the exact location of the target wires, and for this reason tungsten is favored. The center of the thinner wire can be located more accurately, approximately as the ratio of the diameters.

Since the wires are difficult to see even under good conditions, it is assumed that they will not be surveyed directly in the vacuum tank. Instead, after attaching them, the lab work would include measuring their positions relative to a fiducial on the holder structure, but outside the vacuum. This probably has to be done optically, since touching the wires is generally counter-productive. An accuracy of about 2 $\mu$m would be budgeted for this work, and it would be a challenge for the 34 $\mu$m carbon material. Repeatability at this level has, however, been achieved for thinner wires. It is clear that the process of fiducialization would have to be built into the design from the beginning. The external fiducial would have to be surveyed relative to the beam-line monument system, probably relying on Invar or fused silica spacers, and optical systems.

The mechanisms to move the forks on or off the beam line would have a total motion of one or two cm. Stages that accomplish this in 1 $\mu$m or 5 $\mu$m steps are readily obtained. (Steps of 5 $\mu$m would be fine enough for spot sizes down to 10 $\mu$m rms.) SLAC usually has a redundant direct read-back of the position using an LVDT. This is hardly an absolute location measurement, but can give an accurate offset relative to a stop. If an absolute readback is necessary, grating-based optical encoders can be used. The design will be dominated by systematic concerns. For instance, between two materials, a typical difference in expansion coefficients might be $10^{-5}$ per °C. For a mechanism length of 30 cm and a 1°C temperature excursion, the differential motion would be 3 $\mu$m. A smooth beam pipe aperture for FEL operation could be mounted on the same mechanism as the wire-fork. This would increase the length of motion of the linear stages by perhaps two centimeters.

In summary, the most difficult problems facing a thin-wire-based technique for beam alignment are the same problems as face all techniques. Surveying and aligning the position monitors within <5 $\mu$m relative to a straight line, and maintaining long term dimensional stability, will require careful engineering.
Beam Emittance Measurements

Carbon wire scanners can be used to measure the horizontal and vertical emittance of the electron beam; these could be the same systems as the carbon wire BPMs or the combined photon/electron diagnostics. Wire scanners near the end of the undulator will permit observation and correction of emittance dilution (e.g., that caused by wakefields) generated within the undulator. The wires measure the transverse beam size, which is used to calculate the emittance, if there are at least three independent measurements of the beam size per plane and these three are separated by an appropriate betatron phase advance. An array of wire scanners placed toward the end of the undulator will provide precision, redundancy, and energy adaptability in undulator emittance measurements.

For an emittance measurement, a minimum of three measurements per plane are required because of the three independent parameters (ε, β, α) necessary to describe the second central moments of the electron beam phase space per plane (〈x^2〉, 〈y^2〉, 〈xy〉). To transform these beam size measurements into phase space parameters requires that they span the space adequately. This condition is optimally set when the wire-to-wire separation is πN in betatron phase advance, where N is the number of wire scanners. For the minimum, N = 3, the optimal separation is 60°. To provide redundancy in the measurement (for increased precision and backup for failed wires), N = 4 and an optimal separation of 45° are used. The configuration described here is for one plane. The other plane should be similarly configured.

With permanent magnet focusing, the betatron phase advance per cell, Δψ, of the undulator lattice is energy dependent. At 5 GeV it is Δψ ≈ 45°. This is nearly ideal for four wires when one wire is placed at each of the last four cells (4.32 m or every other quadrupole) with the last wire at the end of the undulator. Fig. 8.6-4 shows the locations of the wires and their various groupings for 5, 10, and 15 (or 14.3) GeV beams. The 5 GeV grouping of wires is indicated as wires 5A, 5B, 5C and 5D. At 15 GeV Δψ ≈ 13° and a wire every three cells provides 3Δψ ≈ 40°. For this case, the last two wires, 5D=15D and 5A=15C, already exist from the 5 GeV case. By adding one wire at 6 (15B) and one at 9 cells (15A) upstream of the last wire, the 15 GeV case is also fully covered. At 10 GeV Δψ ≈ 21°), or other intermediate energies, using the last three wires (10A, 10B and 10C) located for 15 GeV provides 3Δψ ≈ 63°, which is nearly ideal for N = 3. Redundancy is included by using any of the other two 5 GeV wires (5B and/or 5C) 21° away, when necessary. This 6-wire array then covers all energies adequately. The other transverse plane may be covered by adding another set of 6 scanners slipped by one-half cell upstream, or by designing each scanner to measure both planes. In the latter case the beam size is smaller for one plane than the other, especially at 5 GeV (by a factor of 1.45). For alignment purposes about five more wires per plane are added every 3 cells (13 m) extending from near the undulator entrance toward these emittance wires.
8.6.3 The Combined Electron and Photon Beam Diagnostic

The trajectory control techniques described in Section 8.5.2 assume that the FEL photon beam will overlap with the LCLS electron beam if the electron beam forms a straight line. A technique to verify the electron and photon beams overlap directly is also desirable. This technique is described here.

The proposal is to insert a 10–30 µm wire, probably carbon, into the beampipe. When it is struck by the electron beam, bremsstrahlung will be generated, which can be detected at the end of the undulator. When it is struck by the photon beam, photons will be diffracted at a large angle by the polycrystalline wire, and can be detected using a PIN diode or similar solid state detector. Powder diffraction from a polycrystalline carbon wire can be used to select a narrow bandwidth of photon energy or the FEL fundamental energy, 8.3 keV (1.5 Å), can be chosen. The carbon wire would have to be mounted on a movable x-y stage, and there would have to be wires in both horizontal and vertical orientations. This apparatus can be used to measure the electron and photon beam sizes, to verify overlap of electron and photon beams and for rough beam alignment. One carbon wire monitor every 10 m, or about one per gain length is sufficient for LCLS needs (see Section 8.6.2).

If this apparatus were to be used for rough beam alignment, the procedure would be as follows. It is presumed that a beam of spontaneous radiation is launched in a straight line from the first segment of the undulator. The task would then be to steer the electron beam at a point downstream so that it overlaps this first photon beam. This could be done by observing the electron and photon beams in separate positions, finding the sensitivity of the electron beam to steering, and calculating the best steering for overlap. The process would then be repeated for the next monitor downstream.

The spontaneous radiation at the 1.5 Å fundamental has a characteristic transverse size given by $\sigma_{\text{rad}} = \sqrt{\sigma_x^2 + \sigma_y^2} L$, reflecting the electron beam size (31 µm rms radius) plus the photon beam divergence. At a distance $L = 10$ m, this size is 38 µm, and at 100 m it is 70 µm. The FEL beam divergence is smaller, only 0.74 µrad at the end of the undulator, so its beam size is dominated by the electron beam size. On axis, the FEL power is expected to be greater than the spontaneous power only after about 7 gain lengths. Sweeping a 20–30 µm
carbon wire (rms effective size = radius/2) through the beam should provide the ability to find the beam centroid to 5 µm resolution, as required.

A 20–30 µm carbon wire can withstand millions of impacts from a 1 nC, 14.3 GeV, 280 fsec electron beam, as demonstrated in the SLC and FFTB experiments. Also, the spontaneous radiation and FEL radiation absorption is low enough in carbon that the radiation does not hurt the wire. A 20 µm carbon wire would absorb a peak power of about 0.3 MW from the spontaneous radiation and about 40 MW peak from the laser (assuming the wire is just at the end of the undulator). Thus the spontaneous radiation gives a negligible effect compared to the laser. Now 40 MW corresponds to about 10 µJ per pulse, or 0.02 eV per carbon atom per pulse, or equivalently an instantaneous temperature rise of about 200°C for the carbon atoms in the beam.

Bremsstrahlung gamma rays are emitted in a fairly flat energy spectrum from 0 MeV up to the energy of the electron beam. The average energy of the degraded electrons will be approximately 1.1 MeV less than 14.3 GeV. The radiation length in carbon is 27 cm at that energy, and 20 µm of carbon would generate far more bremsstrahlung than a column of gas 100 m long at 10⁻⁶ Torr. The ideal way to detect gamma rays is to use one radiation length of lead, followed by quartz. In one radiation length of lead (5 mm) the gamma produces pairs of electrons and positrons, which generate visible Čerenkov photons as they traverse the quartz. They are detected by a photomultiplier tube. The radiation length in silicon is 9.6 cm, so one would use 10–20 cm of quartz. See Fig. 8.6-5.

![Figure 8.6-5](image)

Figure 8.6-5. The combined photon and electron beam position monitor system. The x-ray detector could be a solid state photodiode; the bremsstrahlung detector is a radiation length of lead that converts bremsstrahlung into electron positron pairs, followed by a block of silica in which the pairs emit Čerenkov radiation that is detected by a photomultiplier tube.

The x-ray diffraction pattern from a bundle of 7 µm carbon wires has been examined. This is essentially a powder diffraction experiment and diffraction peaks will be seen if the wire has some crystallinity. A peak is seen at an angle of about 26°—with a FWHM of about 5°. This large width is due to the partially amorphous nature of the carbon wire used.

The position of the FEL and spontaneous undulator fundamental beam can be detected by observing powder diffraction from the carbon wire. Though the wire is not completely
crystalline or powder-like, the x-ray diffraction tests at SSRL have shown that these wires have enough of a graphite-like polycrystalline character to give an easily observable powder pattern. It is expected that heating in the electron and x-ray beams would increase the crystallinity of a wire.

The strongest graphite powder reflection of 1.5 Å radiation occurs at a 25.8° scattering angle. A limited-aperture detector set at this angle would signal when the carbon wire intercepts and scatters the undulator fundamental radiation (near the beginning of the undulator) or the FEL radiation (farther down the undulator where the FEL intensity is dominant). If operation at a different FEL wavelength is desired, it would be necessary to move the powder diffraction detector to a different angle. Practical constraints on this angle would probably limit the utility of this beam-location technique to wavelengths shorter than 6 Å. The optimal detector would be a small silicon avalanche diode, which could be moved inside a wedge-shaped vacuum chamber annex to set the scattering angle.

8.6.4 Wire Position Monitors

The LCLS proposes to detect and correct diurnal, thermal, and ground motions with a system that was successfully implemented on the FFTB [31]. Two wires will be suspended inside hollow chambers that run the length of the undulator. The chambers are fixed to the undulator magnets; one end of the wire runs over a pulley and is tensioned by a fixed hanging weight. The exact shape of the curve described by the wire is not a catenary, but is distorted by imperfections in the wire at the micron level. However, a wire suspended this way is very stable. Using optical LED and split photodiode position sensors, the WPM system is capable of resolving changes in the position of the wire with submicron resolution.

8.7 Wakefield Effects in the Undulator

8.7.1 Introduction

When the electron beam moves through the undulator it will excite longitudinal and transverse wakefields due to the resistance and the discontinuities in the beam tube wall. Let us assume that the wall geometry is cylindrically symmetric. Then the longitudinal (monopole) wakefield will generate an energy loss and an increase in energy spread independent of the beam orbit, and the transverse (dipole) wakefield will generate an emittance growth that does depend on the orbit. It is, however, important to recognize that the forces due to the wakefields are correlated with longitudinal position. Assuming the bunch is composed of many slices at different longitudinal positions, the wakefields affect only the centroid values of the slices—i.e., the average energy and the average position of the slices in, respectively, the longitudinal and the transverse case. The distributions of the slices about their centroids are not affected.

The critical issues concerning the electron beam with respect to wakefield effects in the undulator are:
• The absolute value of the maximum relative energy deviation of a bunch “slice” (slippage length: ~0.5 μm) with respect to the mean of the whole bunch generated over the length of the undulator at 14.3 GeV should be less than ~0.1%. This tolerance is derived from GINGER simulations.

• The dilution of the “projected” emittance (emittance projected over the entire bunch) should not exceed ~10%.

• The mean energy loss over the undulator, including radiation losses, will determine the necessary taper of the magnetic fields of the undulator dipoles.

Since undulator wakefields have very little effect on the “slice” energy spread and the “slice” emittance, these tolerances are not considered here.

In this report the longitudinal and transverse wakefield effects on the LCLS beam during its time in the undulator are estimated to see how well these conditions are satisfied. Note that the beam dynamics and wakefield concepts that are presented are thoroughly discussed, with equations in [28].

### 8.7.2 Wakefield Induced Beam Degradation

In the longitudinal case the wake function for a Gaussian bunch, from which the average wake (also known as the loss factor) \( \langle W_z \rangle \) and the rms deviation of the wake with respect to the mean, \( (W_z)_{rms} \) (the units are V/C/m) are derived, is first obtained. Then the wakefield induced energy loss is given by

\[
\langle \delta \rangle = \frac{e^2 NL \langle W_z \rangle}{E},
\]

with \( N \) the number of particles in the bunch, \( L \) the length of travel, and \( E \) the beam energy. The rms energy spread, with respect to the mean, becomes

\[
\sigma_\delta = \frac{e^2 NL (W_z)_{rms}}{E}.
\]

In the transverse case the average of the transverse wakefield of a Gaussian bunch \( \langle W_z \rangle \) (here in units of V/C/m²) is first obtained. The focusing lattice in the undulator is a FODO type with a phase advance of 13’/cell at 14.3 GeV, and therefore a smooth focusing analysis is appropriate. First, to study the effect of injection jitter, the wake function is applied to obtain the projected emittance growth due to a betatron oscillation in the undulator. The offset at the end of the undulator, averaged over the bunch, can be written as

\[
\langle x \rangle = x_0 e^{iL/\beta} (1 - i \nu)
\]
with $x_0$ the initial offset, $\beta$ the beta function, and $\nu$ the strength parameter (as long as it is small). The strength parameter is given by

$$
\nu = \frac{e^2 N L \langle W_x \rangle \beta}{2E}.
$$

(8.7.4)

The relative emittance growth, if it is small, is then given by

$$
\frac{\Delta \varepsilon}{\varepsilon} = \frac{x_0^2 \gamma}{2\varepsilon \beta}.
$$

(8.7.5)

with $\gamma$ the energy factor and $\varepsilon_N$ the normalized emittance. If the beam tube wall is not perfectly straight and aligned then even if the beam does not undergo betatron oscillations the projected emittance can grow. However, unlike in the case of injection jitter, since this error is a static error some correction can usually be performed to reduce the effect. The misalignment errors are divided into two types, those that are uncorrelated to each other and those that are correlated. In the former category suppose the wakefield generating object is composed of $M_p$ equal, randomly misaligned pieces. Then the emittance growth will again be approximately given by Eq. 8.7.5, but with $x_0$ replaced by the rms misalignment of the pieces divided by the factor $M_p^{1/2}$. For correlated errors, the largest effect, for a given misalignment amplitude, is when the misalignment varies as $\cos(z/\beta)$, and the results are the same as given in Eq. 8.7.5, but with $x_0$ representing the misalignment amplitude. If the oscillation frequency of the misalignments differs from the betatron wave number by $\Delta k$ then the effect on emittance decreases according to $\text{sinc}^2(\Delta k L)$.

The above effects are due to a resonance term in the equation of motion. But there is normally also a bounded, non-resonance term. For example, consider the case where the beam’s trajectory follows the magnetic focusing axis in the undulator, but this axis is not aligned with the axis of the impedance generating objects. In this case the projected emittance of the beam will grow and then again decrease within the undulator. Even though the final emittance growth in the LCLS undulator due to this effect is small, there may be a tolerance for bunch emittance growth anywhere within the undulator. In such a case this effect will set a tolerance for the alignment of the wakefield generating axis with respect to the magnetic axis. For this example, the maximum emittance growth is given by Eq. 8.7.5, with $x_0$ the distance between the two axes and with $\nu = 2e^2 N \langle W_x \rangle \beta^2/E$.

In the calculations below, the following bunch and machine properties are considered: total charge of 1 nC, rms bunch length $\sigma_z = 20 \mu m$, normalized emittance $\varepsilon_N = 1.0$ mm-mrad (the undiluted emittance is used for a conservative estimate), and energy $E = 14.3$ GeV. The length of the undulator is $L = 112$ m and the average focusing beta function is $\beta = 18$ m. Note that in reality the bunch shape is not Gaussian, and to obtain a more accurate result one would need to use the real bunch shape in the calculations. The results given in this report should serve as reasonable estimates. The generators of wakefields considered are the wall
resistance of the beam tube, the flange gaps, the pumping slots, and the bellows. The effect of the beam position monitors (BPM's) is discussed in Section 8.5. Finally, the effects of wall surface roughness are considered.

8.7.3 The Resistive Wall Wakefields

The beam tube inside the undulator is made of stainless steel or stainless steel plated with copper. It is of circular cross-section and has a radius of $a = 2.5$ mm. The normal formulas for the resistive wall wakefields are valid only if $\frac{z}{s_0} > 1$, with the characteristic distance

$$s_0 = \left(\frac{2a^2}{Z_0 \sigma}\right)^{\frac{1}{3}},$$

(8.7.6)

where $Z_0 = 377 \, \Omega$ and $\sigma$ is the conductivity of the metal. For stainless steel (SS) $\sigma = 1.7 \times 10^6 \, \Omega^{-1} \cdot m^{-1}$, for copper (Cu) it is $60 \times 10^6 \, \Omega^{-1} \cdot m^{-1}$. Therefore, for the beam tube with SS $s_0 = 27 \, \mu m$, with Cu $s_0 = 8 \, \mu m$. Thus, in either case, since $\sigma_z \approx 20 \, \mu m$, the normal formulas should be valid. The average of the longitudinal wakefield of a Gaussian bunch is given by

$$\langle W_z \rangle \approx \frac{\Gamma(3/4)}{4\sqrt{2\pi^2}} \frac{c}{a \sigma_z^{3/2}} \left(\frac{Z_0}{\sigma}\right)^{1/2}, \quad \sigma_z/s_0 > 1$$

(8.7.7)

with $\Gamma(3/4) \approx 1.23$, and the rms is given by $(W_z)_{rms} = (1.02)\langle W_z \rangle$. Combined with Eq. 8.7.1 this gives $\langle \delta \rangle = 0.34\%$ for stainless steel and 0.06\% for copper, and similar results for the induced rms energy spread. The effects of the more realistic, non-Gaussian bunch distribution, and also the general case for $\sigma_z/s_0 < 1$, are discussed in Section 8.7.6. Here the resistive-wall loss and spread are both smaller than that of the Gaussian case examined above.

For the transverse case

$$\langle W_x \rangle \approx \frac{\Gamma(1/4)}{2\sqrt{2\pi^2}} \frac{c}{a^3 \sigma_z^{1/2}} \left(\frac{Z_0}{\sigma}\right)^{1/2}, \quad \sigma_z/s_0 > 1$$

(8.7.8)

with $\Gamma(1/4) \approx 3.63$. Combined with Eq. 8.7.4 it is seen that $\nu$ is 0.58 and 0.10 for the SS and Cu cases, respectively. For an extreme 100 $\mu m$ oscillation (e.g. random pulse-to-pulse jitter which is not correctable) the emittance growth is 260\% for SS and 8\% in the case of Cu.

As to the effects of static errors, it is noted first that the beam tube is composed of 52 equal pieces. With uncorrelated, random misalignments with an rms of 100 $\mu m$, the emittance growth will be a factor of 52 less than given above. Or, conversely, the misalignment tolerance for 10\% emittance growth, assuming copper is used, is 800 $\mu m$. For
a correlated, cosine variation of misalignments of amplitude 100 $\mu$m the emittance growth is approximated by the above jitter results multiplied by $\text{sinc}^2(\phi k L)$, where $\phi k$ is the deviation from the betatron wave number of the wall oscillation wave number. Finally, if the static emittance growth has to be kept to less than 10% anywhere within the undulator, the axis of the beam tube must be aligned to the axis of the quads to within 200 $\mu$m in the case of copper.

8.7.4 The Effect of Flange Gaps, Pumping Slots, and Bellows

The flange gaps are small cavities with a gap of $g = 0.25$ mm; over every 2 m section there are 4, or a total of $M = 208$ objects in the entire undulator. For the flange gaps, since $\sigma_z/a << 1$, the diffraction wakefield model applies [29]:

$$\langle W_z \rangle \approx \frac{\Gamma(1/4)}{4\pi^{5/2}} \frac{Z_\phi c M}{a L} \sqrt{\frac{g}{\sigma_z}}, \quad \sigma_z/a << 1$$

(8.7.9)

with $\Gamma(1/4) \approx 3.63$, and $(W_z)_{\text{rms}} \approx (0.40)\langle W_z \rangle$ gives the average effect of all the flange gaps. In the transverse case

$$\langle W_x \rangle \approx (4.63) \frac{Z_\phi c M}{\pi^2 a^2 L} \sqrt{g \sigma_x}, \quad \sigma_x/a << 1.$$  

(8.7.10)

Substituting for the parameters of the flange gaps, $\langle \phi \rangle = 0.012\%$ and $\sigma_\phi = 0.005\%$, the emittance growth due to a 100 $\mu$m oscillation is very small, 0.08%.

The pumping slots consist of ten, longitudinally arranged ovals in each 2 m section, or a total of $M = 520$ slots. For each slot the width $w = 1$ mm and length $g = 5$ mm. Usually in accelerators pumping slots are inductive. In the LCLS case, however, since $\pi \sigma_z$ is small compared to the slot width, energy will radiate into the slot. The diffraction formulas of the previous paragraph, multiplied by an azimuthal filling factor $w/2\pi a (=0.064)$, can be used to estimate the wakefields. The results are that $\langle \phi \rangle = 0.008\%$, $\sigma_\phi = 0.004\%$, and the emittance growth due to a 100 $\mu$m oscillation is 0.04%. There is one bellows in every 2 m section, giving a total of 52. The bellows are shielded, so that the wake effects should be negligible, and will be taken to be zero.

The results of the above calculations, as well as the effects of the 52 BPMs (see Section 8.5), are summarized in Table 8.7-1. Note that a stainless steel surface (top row) is clearly not acceptable. It is further noted that, with copper, the resistive wall wakefield still dominates the impedance, though in this case, the rms energy spread is nearly a factor of two below the maximum tolerable deviation per slice. Finally, another effect that will add to these values is that of incoherent synchrotron radiation within in the undulator which will produce a relative energy loss of 0.16% for a 14.3 GeV electron beam. Combining this with the loss factors (Cu) of Table 8.7-1 results in a total loss of ~0.3% which is approximately the undulator field taper required. These results are for a gaussian bunch distribution.
effects of the non-gaussian distribution are examined in Section 8.7.6 where the fraction of the beam meets the required conditions described in the introduction is determined.

Table 8.7-1. The total longitudinal and transverse wakefield effects, for a gaussian axial distribution, due to the various types of objects in the LCLS undulator. Given are the average energy loss, $\langle \delta \rangle$, the rms energy spread, $\sigma_\epsilon$, and the relative correlated emittance growth, $\Delta \epsilon \epsilon_\gamma$, of a 100 $\mu$m betatron oscillation.

<table>
<thead>
<tr>
<th>Type of Objects</th>
<th>$\langle \delta \rangle$/%</th>
<th>$\sigma_\epsilon$/%</th>
<th>$\Delta \epsilon \epsilon_\gamma$/%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive Wall (SS)</td>
<td>0.340</td>
<td>0.350</td>
<td>260</td>
</tr>
<tr>
<td>Resistive Wall (Cu)</td>
<td>0.060</td>
<td>0.060</td>
<td>8</td>
</tr>
<tr>
<td>Flange Gaps</td>
<td>0.012</td>
<td>0.005</td>
<td>0.08</td>
</tr>
<tr>
<td>Pumping Slots</td>
<td>0.008</td>
<td>0.004</td>
<td>0.04</td>
</tr>
<tr>
<td>BPMs</td>
<td>0.027</td>
<td>0.010</td>
<td>0.39</td>
</tr>
</tbody>
</table>

8.7.5 The Effect of Wall Surface Roughness

In a recent paper the impedance due to a rough metallic surface is estimated [32]. The calculation procedure was to find first the low frequency impedance (the inductance) of a small bump on a smooth beam pipe surface, and then to use averaging to obtain the effect of a random distribution of bumps. Some of these results are reproduced here.

At low frequencies the longitudinal impedance of a small perturbation on the wall of a cylindrical tube is inductive and can be written as

$$Z_l(\omega) = -i \omega L = -i \frac{\omega}{c} Z_0 \frac{r^3}{6\pi^2 a^2} f$$

(8.7.11)

with $\omega$ the frequency, $r$ the size of the perturbation, $a$ the beam pipe radius, and $L$ the effective inductance; $f$ is a form factor which equals 1 when the perturbation is a small, shallow hole of radius $r$ [33]. The impedance of various shapes of perturbations was investigated numerically. Some results are reproduced in Table 8.7-2. (Note that the definition of $f$ used here is slightly different from that used in [32].) Given are the inductance $L$ of: (1) a hemisphere with radius $r$, (2) a half cube with width $w$ and length $l$ both equal, and height $h = w/2$, (3) a post with $w = l = h/\sqrt{8}$, rotated by 45°, (4) a wedge with base dimensions $w = l$ and height $h = w/2$, and (5) a cube with $w = l = h$. The absolute dimensions were chosen so that all have base area $\pi r^2$, with $r = 0.5$ mm. Also given is the form factor $f$ when comparing to a shallow hole of radius $r = 0.5$ mm. The longitudinal and transverse profiles of the objects are sketched below the table.

It is noted that the impedance of a bump is much larger than that of an equivalent-sized hole. Also, from the first 4 examples in Table 8.7-2, it is seen that for objects that are of similar size, the form factor $f$ can vary by a large factor, in this case by a factor three to four. The fifth example demonstrates a roughly quadratic dependence on height. In the report it is
also shown that when two cubes are longitudinally aligned, if they are separated by a distance \( > h \) then the effect is about twice the single cube result.

### Table 8.7-2.

Results for 5 selected objects, whose longitudinal and transverse profiles are sketched below. All have base areas \( \pi r^2 \), with \( r = 0.5 \text{ mm} \). Given is the inductance \( L \), and the form factor \( f \) when comparing to a shallow hole with radius \( r = 0.5 \text{ mm} \).

<table>
<thead>
<tr>
<th>Case</th>
<th>( L/\text{[pH]} )</th>
<th>( f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemisphere (analytical)</td>
<td>0.13</td>
<td>4.7</td>
</tr>
<tr>
<td>Half Cube</td>
<td>0.33</td>
<td>12.1</td>
</tr>
<tr>
<td>Rotated Post</td>
<td>0.08</td>
<td>2.9</td>
</tr>
<tr>
<td>Wedge</td>
<td>0.15</td>
<td>5.3</td>
</tr>
<tr>
<td>Cube</td>
<td>1.41</td>
<td>50.8</td>
</tr>
</tbody>
</table>

Without knowing the microstructure at the beam tube surface, an accurate estimate of the roughness impedance cannot be obtained. To obtain a rough estimate, however, let us assume that the tube is covered by a random set of bumps. In the longitudinal case (not treated in [32]) the shape of the induced voltage is given by the derivative of the bunch shape. Therefore, the average energy loss is near zero. The wakefield rms for a gaussian bunch, according to this model, is

\[
(W_z)_{\text{rms}} = \frac{Z_0 c}{3^{7/4} \sqrt{2\pi} 5^{5/2}} \frac{rf\alpha}{a\sigma_z^2}, \quad (8.7.12)
\]

with \( r \) the typical size of the bumps, \( f \) a form factor, and \( \alpha \) the surface filling factor of the bumps. In Eq. 8.7.12 it is assumed that the average base area of a bump is \( \pi r^2 \).

In the transverse case, the shape of the wakefield is the same as the shape of the bunch. For a gaussian bunch the average wake becomes

\[
\langle W_x \rangle = \frac{Z_0 c}{3\pi 5^{5/2}} \frac{rf\alpha}{a^3 \sigma_z}. \quad (8.7.13)
\]

Let us assume that typically the form factor \( f = 5 \) and the surface filling factor \( \alpha = 0.5 \). Then to keep the rms energy spread \( \sigma_\delta < 0.05\% \) implies that the allowable bump size \( r < 40 \text{ nm} \). Or transversely to keep the emittance growth due to a 100 \( \mu \text{m} \) oscillation to less than 10\%
requires that the bump size \( r < 100 \text{ nm} \). These required levels of smoothness would be difficult to achieve.

The microstructure of a metallic surface depends on the manufacturing and machining method used to create the surface. With state-of-the-art manufacturing methods the necessary tolerance can be achieved. For example (see Section 8.2.6), using a die to extrude a stainless steel tube, a variation on the order of 75 nm can be achieved. This surface roughness can be improved upon by electro-polishing. This process is followed by deposition of a 1 \( \mu \text{m} \) layer of copper, which may result in an even smoother surface. A model of the final product a surface with 150 nm wide, smooth bumps, with an elliptical longitudinal profile, with semi-minor axis (the depth) of 75 nm and semi-major (longitudinal) axis of 200 nm is used. On top of these bumps there are many smaller bumps with a typical size that may be significantly smaller than 40 nm. The effect of both types of bumps to give \( \sigma_z < 0.05% \) and, for a 100 \( \mu \text{m} \) oscillation, \( \Delta z/E_0 \approx 2% \) is estimated. Clearly these estimates are only approximate. More study is needed both in the questions of what the undulator tube surface actually might look like and, more fundamentally, the correctness of the rough surface impedance model. Trying to answer these questions is an ongoing research project.

### 8.7.6 The Effects of the Expected Bunch Shape

The fact that the bunch shape is not gaussian will affect the above results, primarily in the longitudinal case. The actual bunch distribution, except at the head and the tail, is rather constant. Therefore, the longitudinal effect, since it depends on the derivative of the distribution, will be very small over the core of the bunch but very large at the head and the tail. **Fig. 8.7-1** shows the roughness wakefield and the resistive wall wakefield (for the general case without the limit: \( \sigma_z/E_0 > 1 \)) generated by 1 nC over the length of the 112 meter undulator. The axial bunch distribution used here, \( f(z) \), from **Fig. 7.2-3**, is also overlaid on an arbitrary scale. The chamber surface is copper and the roughness amplitude is \( r = 100 \text{ nm} \). Other parameters of **Eq. 8.7.12** are \( \alpha = 0.5, a = 2.5 \text{ mm}, f = 5 \) and \( E = 14.3 \text{ GeV} \). The fraction of the electron beam with an energy change of less than \( \pm 0.1\% \), with respect to the mean, over the length of the undulator, is 55\%. According to GINGER simulations, if the energy of a bunch slice deviates by more than 0.1\% from the synchronous energy over the length of the undulator, the saturation length starts to increase. The mean energy loss is \( \langle \delta \rangle \approx -0.016\% \) and the rms spread, with respect to the mean, is \( \sigma_\delta \approx 0.034\% \). This may be improved by further flattening the axial distribution through optimization of the compression parameters, and/or by advanced beam pipe surface preparation techniques, both of which are continuing research efforts.

### 8.7.7 Conclusion

Using copper-plated stainless steel for the LCLS undulator beam tube will meet the tolerance limits both in increased correlated energy spread and in projected emittance growth. The implications of slice energy deviation and projected emittance increase are twofold. One effect is a decrease in beam brightness, which with the numbers discussed in
the previous sections, will be small in the LCLS (see also Section 10.1, where this point is discussed in more detail). The other issue that was investigated is the effect of a slice energy deviation on the FEL dynamics (see Section 8.7.6). The consequence of this effect is that 55% of the beam is within tolerance of 0.1%, as shown in Fig. 8.7-1. Thus 45% of the beam may experience a lengthening of the saturation length. Note that this conclusion is highly dependent on the precise model of the surface roughness wakefield and on the longitudinal bunch charge distribution.

![Graph showing f(x) and the total wakefield](image)

**Figure 8.7-1.** Roughness (DASH), resistive wall (DOTDASH) and total (SOLID) wakefield generated within the 112-meter LCLS undulator for the non-gaussian bunch distribution, f(x). A copper surface and a roughness of 100 nm is assumed. Just 55% of the electrons are altered in energy by less than ±0.1% (DOTTED). The bunch head is at left here.

### 8.8 Ion Effects

In this section the number of ions generated during a bunch passage in the 100 m long undulator of the LCLS x-ray FEL is calculated, emittance dilution caused by these ions is discussed, and the acceptable vacuum pressure is estimated.

#### 8.8.1 Introduction

This section investigates ion production by the beam and by the synchrotron-radiation photons during a bunch passage in the LCLS undulator [34], and three different mechanisms of emittance dilution induced by these ions. The acceptable vacuum pressure for FEL operation is estimated from the calculated emittance growth.

#### 8.8.2 Ionization Processes

There are three conceivable mechanisms by which ions can be created:
1. Collisional ionization by the beam.

A typical ionization cross section for a GeV electron beam and carbon monoxide or nitrogen gas is of the order of 2 Mbarn (the ionization cross section for hydrogen molecules would be approximately 10 times smaller). The 2-Mbarn cross section translates into an ion line density of about

\[ \lambda_{\text{ion}} [m^{-1}] = 5N_b p [\text{nTorr}] \]  

(8.8.1)

at the end of the bunch, or 320 ions per meter for a pressure of 10 nTorr and \( N_b = 6.3 \times 10^9 \) electrons per bunch.

2. Ionization by incoherent synchrotron radiation.

The ionization cross section of 8-keV photons for typical elements is about 100 barn [35]. Even though the number of photons at 1.5 Å is three orders of magnitude higher than the number of electrons, this cross section is so much smaller than the collisional-ionization cross section that the photoionization at Angstrom wavelengths can be neglected in comparison.

In addition to the photons emitted at the first (and higher) FEL harmonic wavelengths, a broad spontaneous photon spectrum extends to much lower energies, where the photoionization cross section is considerably higher. Below about 100 eV the photoionization cross section becomes comparable to, and may even exceed by up to a factor of 5, the cross section for collisional ionization.

From Figure 6 in Ref. [34], illustrating the spontaneous photon spectrum, and from Fig. 8.8-1, showing its low-energy part, it is estimated that, at the end of the undulator, there are about \( 6 \times 10^{10} \) photons per bunch with energies below 1 keV, and fewer than \( 5 \times 10^9 \) photons whose energy is below 100 eV. Thus, the number of low-energetic photons is about equal to the number of electrons in the bunch. With an rms opening angle of 10-20 \( \mu \)rad for the spontaneous radiation (and an even wider opening angle at low photon energies), the photoionization processes occur on average far away from the beam orbit. Therefore, considering the small number of low-energy photons, the ions are assumed to be produced by photo-ionization form a diffuse halo, whose effect on the beam is negligible compared with that of the much denser ion cloud produced by collisional ionization inside the beam.

3. Tunneling ionization in the coherent laser field.

Up to frequencies of the order

\[ \omega_k = ceE / \sqrt{2m_e c^2 I} \]  

(8.8.2)
the tunnel effect is determined simply by the instantaneous value of the electric field [36,37]. In Eq. 8.8.2, the parameter \( E \) is the electric field, \( m_e \) the electron mass, and \( I \) the ionization potential. The peak electric field of the laser pulse can be roughly estimated from the equation

\[
\hat{E} \approx \left( \frac{2N_f h \nu}{(2\pi)^{3/2} \varepsilon_0 m_e \sigma_x \sigma_y \sigma_z} \right)^{1/2}
\]  (8.8.3)

and is found to be about 85 GV/m. Somewhat arbitrarily using \( I \approx 20 \) eV, the threshold frequency is \( \omega_t \approx 10^{16} \) s\(^{-1}\), which is very low compared to the FEL frequency \( \omega \approx 10^{19} \) s\(^{-1}\). This means that the standard formula for static tunneling ionization does not apply here. To determine if the coherence of the FEL X-rays is important, the photon density is calculated as

\[
n_{\gamma} \approx \frac{N_f}{(2\pi)^{3/2} \sigma_x \sigma_y \sigma_z} = 7.2 \times 10^{24} \text{ m}^{-3},
\]  (8.8.4)

which implies that in a sphere with a radius equal to the Bohr radius \( a_0 \) (\( a_0 \approx 0.5 \) Å) on average there are only \( 1.2 \times 10^6 \) photons at any given time during the pulse. It is thus legitimate to consider the photons as incoherent [38], in which case, as seen under point 2, their contribution to the ionization is insignificant.

![Figure 8.8-1.](image-url) Number of photons per 0.03 % frequency interval and per bunch passage at the end of the LCLS undulator; the spontaneous flux increases linearly along the undulator.
8.8.3 Emittance Dilution

Ions could dilute the bunch emittance in various ways: first, the ions induce a tune shift across the bunch which could lead to filamentation and to an effective increase in the transverse emittance; second, the electrons or, third, the ions generated by the bunch head can excite the bunch tail and cause a beam break-up instability.

Pessimistically assuming that all electrons originating in the ionization process are dispersed and lost before the end of the bunch (using this assumption, which is not fulfilled for the LCLS, the actual tune shift will be overestimated), one can estimate the ion-induced shift in betatron phase advance between head and tail of the bunch at the end of the undulator:

$$\Delta \psi_{x,y} \approx \frac{\beta_{x,y} \lambda_{ion} L_u}{\gamma \sigma_{x,y} (\sigma_x + \sigma_y)}$$  \hspace{1cm} (8.8.5)

Using an ion line density $\lambda_{ion}$, as expected for collisional ionization, Eq. 8.8.1, the phase shift is $\Delta \psi_{x,y} \approx 4 \times 10^{-6}$ rad for 1 nTorr and $4 \times 10^{-4}$ rad for 100 nTorr. Significant emittance growth due to filamentation would be expected only for an average pressure exceeding 100 µTorr, for which the phase shift approaches 1 rad.

Since, different from the situation in most other accelerators, the bunch length in the LCLS is shorter than the transverse beam size, the electrons do not escape from the bunch during its passage, but the electrons generated by the head will still affect the trailing particles. The resulting emittance growth can be estimated from a first-order perturbation expansion, in analogy to the treatment in [39]:

$$\Delta \varepsilon_y = \frac{\pi^2 N_b \lambda_{ion} \beta_y \gamma \sigma_y 5^2 \beta_y}{24 \sqrt{2} \pi \sigma_y^3 (\sigma_x + \sigma_y)^3}$$  \hspace{1cm} (8.8.6)

where $\hat{y}$ describes the amplitude of an initial vertical perturbation of the form $y_b^0(s,z) = \hat{y} \cos(\omega z + \theta) \sinh(\omega z + \theta)$ with $\omega = \sqrt{4 N_b \sigma_x / 3 \sqrt{2 \pi \sigma_x \sigma_y (\sigma_x + \sigma_y)}}^{1/2}$, where $s$ is the longitudinal position along the beam line, and $z$ denotes the longitudinal position of a particle with respect to the bunch center. Inserting numbers, $\omega \sigma \approx 0.3$. Exactly the same expression with the subindices $x$ and $y$ interchanged applies to the horizontal case, and, by symmetry, it yields the same emittance growth. Inserting numbers and assuming an ion density as in Eq. 8.8.1, Eq. 8.8.6 is rewritten as

$$A(\varepsilon_y)[m] \approx 4 \times 10^{-19} \left(\frac{\hat{y}}{\sigma_y}\right)^2 \left(p [\text{nTorr}] \right)^2.$$  \hspace{1cm} (8.8.7)
For a huge perturbation, \( \hat{y} = 10 \sigma_y \), one finds that the emittance growth becomes significant when the pressure approaches \( 10^{-4} \) Torr, which is almost five orders of magnitude higher than the anticipated operating pressure.

In principle, not only the electrons but also the ions themselves could drive an instability, even though the ions do not move during the beam passage. This could happen when the bunch is tilted and the ions generated by the head are offset with respect to the tail. Especially important is the case when the ion force drives the beam tail in resonance with the betatron motion. As an example, due to the acceleration in the SLAC linac, the beams in the SLC arcs usually exhibit a significant energy spread that is correlated with the longitudinal position along the bunch. At locations with vertical dispersion, the beam is tilted vertically with respect to the forward direction. Since the vertical dispersion in each achromat of the arc propagates exactly like a betatron oscillation, ions generated by the head then drive the tail in resonance. This effect, in fact, sets the tolerance on the acceptable arc vacuum pressure [40]. In the case of the LCLS, effects of this type are unlikely to be important because the horizontal design dispersion in the undulator is small. The peak dispersion is only about \( \bar{\eta}_x = \theta_x \lambda_0 / \pi = 1.26 \mu m \) so that any perturbation involving energy variation and dispersion will be very small compared with the transverse beam size. \( \theta_x = 132 \mu rad \) is the maximum deflection angle during the wiggle motion.

### 8.8.4 Conclusion

In this section, the number of ions generated during a bunch passage in the LCLS undulator and their effect on the beam emittance is established. The ionization of the residual gas due to the coherent x-rays and, from the viewpoint of beam dynamics, also the ionization due to the lower-energetic spontaneous photons were found to be insignificant compared with the collisional ionization by the beam. There is not a tight tolerance on the vacuum pressure in the LCLS undulator. Even a pressure as high as 1 \( \mu \)Torr would still appear to be perfectly acceptable.

### 8.9 References

3. Group 3 Technology Ltd. model DTM 130 Teslameter.
6. Integrated Engineering Software Inc., Winnipeg, Canada

Eckhart and Drake, “Analysis of Heat and Mass Transfer”


This misalignment component was suggested by Chris Adolphsen.


38 P. Chen, private communication (1997).


9 Undulator-to-Experimental Area

**Technical Synopsis**

The primary function of the undulator-to-experimental area is to deflect the electron beam away from the radiation exiting the undulator, dump it, and then pass the radiation on through a high-vacuum system of spectral-angular filters and beam lines. The electron beam is then dumped. The radiation is passed on through a system of spectral-angular filters whose function is to transport either the spontaneous or coherent photons to the experimental end station and suppress, as much as possible, the transmission of the bremsstrahlung component and any secondary noise generated by it. After the beam has exited the undulator, an absorption cell intercepts the radiation; its purpose is to attenuate the power to levels manageable with conventional optics and to provide a continuous transition to power densities at which meaningful research on the interaction of LCLS-type pulses with matter can proceed. The coherent FEL radiation will be separated from the spontaneous radiation by the absorption cell, by spectral and angular filters made of mirrors or crystals, and by horizontally/vertically tunable x-ray slits. The bremsstrahlung radiation, a concern for both personnel safety and experimental noise, will be intercepted by a mirror or a crystal, while the thermal neutrons created by this interaction will be stopped by a lead/polyethylene shield wall.

The spectral range of the coherent FEL line (820 eV–8200 eV in the fundamental and up to about 25 keV in the 3rd harmonic) requires the use of both crystal and specular optics to transmit and process the radiation for experimental applications.

The absorption cell is used to vary the output power of the radiation. Alternatively, a long beam line (780 m long) could be built to reduce the beam’s power density without diluting its brightness. One of its major advantages would be that the reduced power density would allow conventional optics to be installed in hutches far downstream from the undulator exit and employed to control the output power density in a continuous fashion. The Experimental Hall will consist, initially, of one crystal and one mirror beamline.

### 9.1 Transport System

The radiation emanating from the undulator may be broadly classified into three categories: (1) the coherent spectral lines (the FEL fundamental and its harmonics); (2) the ordinary spontaneous undulator spectrum; and (3) a very broad bremsstrahlung and secondary-particle spectrum consisting of gamma rays, neutrons, muons, and other particles with energies bounded by the operating energy of the LCLS (4.5–14.3 GeV). All three types
of radiation emerge more or less co-terminously with the high-energy electron bunch that drives their production. The primary function of the undulator-to-experimental area beamline is to deflect the electron beam away from the (predominantly neutral) radiation into a beam dump, and then pass the radiation on through a system of spectral-angular filters whose function is to transport either the spontaneous or coherent undulator photons to the experimental end stations while suppressing, as much as possible, the transmission of the bremsstrahlung component and any secondary noise generated by it.

Apart from their role in performing these general functions, a number of the details of the LCLS optical system and components shown in Fig. 9.1-1 are also determined by the necessity of handling the unprecedented peak power densities of the coherent light. The basic components (shown schematized in Fig. 9.1-2), as well as their functions and layout, can be assessed from this perspective.

The LCLS will generate coherent radiation in the fundamental over the range of 820 eV–8.2 keV. This necessitates the unobstructed transport of the radiation (i.e., with no normal-incidence barriers or windows) from the undulator exit out to the experimental instrumentation and samples. Furthermore, since the net power absorbed by a number of the components that intersect the LCLS x-rays at extreme grazing incidence is very sensitive to surface contamination, all such vacuum-sensitive components must be bracketed by differential pumping sections featuring large isolation ratios. The goal of the design is to maintain, on the average, Ultra High Vacuum (UHV) environments (i.e., <10^{-9} Torr) in the bracketed regions. The most critical optical element is the absorption cell. Its primary purpose is basically twofold: (1) to attenuate the LCLS power to levels manageable by ordinary optics, and (2) to provide a continuous transition to power densities at which meaningful research on the interaction of LCLS-type pulses with matter can proceed. Indeed, the cell itself constitutes an appropriate physical system for performing initial studies of this type. An alternative means for controlling the power density, a long beam line, has also been considered, and a brief account of some of the details is given in Section 9.3.2.

An important option for various experimental applications is the possibility of separating, or suppressing, the spontaneous radiation with respect to the coherent line spectrum. In the layout of Fig. 9.1-2, spectral-angular filtering function is performed by: (1) the absorption cell itself, (2) the take-off mirrors or crystals, and (3) by the horizontally/vertically tunable x-ray slits. In particular, the first slit-pair has been located just upstream of the absorption cell, allowing the suppression of the long-wavelength part of the spontaneous spectrum. This is expected to enhance the control of scattering experiments performed in the absorption cell, as well as to provide an upstream half of a long collimator whose downstream part consists of a similar set of slits at the entrance to the experimental area. In this regard, both the slits and the absorption cell can be considered as high-pass spectral filters. In particular, if the absorption cell is very effective at the LCLS fundamental, it can transmit most of (the high-energy part of) the spontaneous spectrum on to the experimental area. The mirrors downstream of the second set of slits provide the
complementary function of low-pass filtering. Since, as is shown below, the spontaneous radiation spectrum can extend out to more than 1 MeV, the mirrors, in conjunction with the absorption cell and the slits, can approximately isolate and deliver selected FEL harmonics to experiments requiring them. In an analogous sense, the crystal take-off optics can be viewed as a spectral-angular bandpass filter, but with a substantially sharper response.

Finally, the primary bremsstrahlung radiation cone and its derivatives, generated by the collimators upstream of the undulator and the undulator vacuum, present a potential concern both for personnel safety and for experimental incursion (via detector and instrumentation noise). In view of its high average spectral energy, bremsstrahlung noise will co-propagate with any undulator radiation until it hits a medium with an adequately short extinction depth. In the system of Fig. 9.1-1, this may be either a mirror or a crystal. The impact will, in general, impulsively excite an intense thermal neutron field that will decay with a time constant on the order of milliseconds. To suppress any possible interference with LCLS experiments operating over similar time intervals, the layout includes a lead/polyethylene shield wall between the crystal and specular take-off optics tanks and the experimental end stations. Since both beam lines pass through this wall at off-axis angles and via small
apertures, the suppression of this source of interference by the wall is expected to be very effective.

9.2 Shielding Enclosures

The space for the undulator and the x-ray transport line is provided by the existing FFTB tunnel enclosure [1]. This structure is sufficiently long and wide to allow installation of the 112 meter long undulator without major facility modifications. The shielding structures, designed to protect against radiation generated by dumping the 50 GeV FFTB beam, consist of: (1) 1.2 m thick concrete tunnel walls and a 1 m thick ceiling; (2) an FFTB dump shield consisting of an 8 m x 8 m concrete and steel bunker surrounding the dump core; and (3) a 22 m long iron muon shield extending past the downstream wall of the FFTB dump enclosure. Under the FFTB experimental protocols, the FFTB tunnel and beam dump facility shielding allows routine operation of 50 GeV beams with \( \sim 10^{10} \) e⁻/pulse, at 10 Hz, or an average power of \( P_{\text{av}} \sim 800 \) W. By special arrangement this can be increased to 30 Hz, or \( P_{\text{av}} \sim 2500 \) W. At the nominal e⁻-beam parameters of <15 GeV and \( P_{\text{av}} \sim 1800 \) W, operation will consequently not present any requirements beyond those already satisfied for FFTB operation. Despite this basic compatibility, modifications to the dump system design to handle the lower (4.5–14.3 GeV) beam energies will be required, and selected initial recalculations of the existing dump and shielding structures for the new parameters have already been performed.
Apart from the revised dump design, the major new shielding structures required for the LCLS are associated with the transport of high-power bremsstrahlung and X-through-γ radiation into the x-ray transport line and on through a vacuum pipe running through the FFTB dump structure and into the contiguous Experimental Hall. The additional structures are: (1) a radiation enclosure for the absorption cell located in the FFTB tunnel; and (2) a shielded experimental hutch located in the Experimental Hall. The primary functions of the added structures are: (1) personnel protection, (2) shielding of experimental detectors from bremsstrahlung-generated radiation, or (3) both.

The absorption cell enclosure is intended to shield the area around the absorption cell from bremsstrahlung-generated noise radiation, enabling detectors to be placed and operated in close proximity to the cell. The performance of the conceptual design, consisting of lead and polyethylene bricks arranged to form a rectangular enclosure (see Fig. 9.1-2), has not, as yet, been rigorously calculated. An optimal configuration for this structure will be developed as part of continuing LCLS R&D.

The hutch in the Experimental Hall will have a construction similar to the hutches employed on the beamlines on SPEAR [2], but probably with somewhat thicker lead shielding. A singular aspect of the hutch design—the shield wall separating the mirror and crystal tanks from the experimental station area—is motivated by the time structure of the electron beam. Due to the sub-picosecond duration of the electron bunches, both the bremsstrahlung and the x-rays will strike the solid mirror or crystal surfaces more-or-less simultaneously with a peak fluence far exceeding that on existing synchrotron storage ring beam lines. For FEL gains substantially below saturation, or otherwise with the absorption cell strongly attenuating the fully saturated output, the incoming bremsstrahlung pulse may contain substantially more energy than the pulse, and the resulting thermal neutron flux that it will generate may interfere with experimental signals picked up immediately following the pulse. The primary function of the shield wall is, consequently, to suppress the transport of thermal neutron flux from the mirror/crystal tank area to the experimental stations.

9.3 Beam Lines and Experimental Stations

9.3.1 Experimental Beam Lines

The spectral range of the coherent line output (820 eV - 8200 eV in the fundamental and up to about 25 keV in the 3rd harmonic) necessitates the use of both crystal and specular optics to transmit and process the radiation for experimental applications. The natural spectral partition is to use crystal optics for wavelengths <3-5 Å and specular or transmissive optics over the complete range (i.e., reflective and refractive optics over the 800 eV–25 keV range and diffractive specular optics for wavelengths >5 Å). This natural emphasis on the two spectral regimes has led to the current minimal allocation of two experimental beam lines to the experimental hutch. Since the use of specular reflective and diffractive optics generally requires operation at extreme grazing incidence with long dispersion lengths in the x-ray range, the specular line has been assigned a length of ~15 m. This should permit the
implementation of sufficiently high resolution monochromators, as well as focusing optics of sufficiently high demagnification. The crystal optics beam line, which will operate with beams deflected at much larger angles to the undulator axis (see Section 10.4.6), is correspondingly shorter.

As described in Section 10.4.5, the angle of incidence on the mirrors in the long beam line will nominally lie in the 0.0001–0.0005 rad range. If at least two reflectors are used, the net angle of deflection away from the undulator axis will lie in the 0.0004–0.002 rad range. At a distance of 15 meters, the corresponding net deflection of the beam from the undulator axis will be in the 6–30 mm range. If additional deflection is required, extra mirror tanks or mirrors can be added to provide additional tandem reflections. Alternatively, should line-of-sight propagation be required, the mirrors and crystal elements in the two tanks can be moved out of the beam's way, providing a direct path to the rear hutch wall.

Apart from the nominal spectral ranges of the two beam lines, it is noted that the longer line provides low pass filtering via its mirrors, which is also a potentially useful function for experiments in the <3–5 Å range (e.g., those requiring harmonic suppression). This condition can be realized by operating the crystal tank in tandem with the mirrors. Clearly, should additional reflections be required, the longer beam line could also be used for this purpose, with the appropriate crystal instrumentation mounted in a suitable location between the crystal tank and the downstream hutch wall. An additional attribute of this line is sufficient space to install additional optics for spatial or temporal processing of the radiation pulses (e.g., beam expanders or beam splitters, delay lines, etc.). Finally, its ~15 m length provides additional flexibility for spectral/angular separation of the spontaneous SR spectrum from the coherent FEL lines and the installation of experimental equipment to utilize this radiation.

9.3.2 The Long Beam Line

The peak power density of the x-ray beam leaving the undulator is many orders of magnitude higher than that currently handled by existing optical methods and technologies. To provide a continuous variation of this parameter from maximum down to conventional values at the experimental stations (which are located at distances of approximately 35 m and 50 m from the undulator exit), the present system design incorporates a gas (or liquid) absorption cell. Alternatively, a “long” beam line could also be used to reduce the beam’s power density by allowing it to spread out over a substantially increased area via natural divergence. A major advantage of this approach is that the reduced power density would allow conventional optics to be installed in hutches far downstream from the undulator exit and employed to either further reduce the power density or to increase it, in a controlled way, to levels corresponding to its diffraction-limited waist.
One way to accomplish this is by extending the x-ray beamline along the linac machine slope beyond the aforementioned two experimental stations. Such a beamline would cross the SLAC Central Research Yard above ground and eventually encounter a hill bordering the SSRL access road at a distance of ~115 m from the FFTB dump. A small diameter tunnel would have to be bored and a short section of the access road elevated. The local topography is such that the beam trajectory would approach the top surface of the hill to within ~8 meters at a distance of ~335 meters from the proposed exit of the undulator. This location can readily accommodate an experimental hutch that would be partially buried in the ground, but would be near an access road and utilities. The tunnel could be extended even farther underneath an adjacent hill and would eventually surface at an ultimate distance of ~780 meters from the end of the undulator. This site is encumbered by access to utilities, but is otherwise very suitable for a research enclosure. Figures 9.3-1 and 9.3-2 display a topographical map and a vertical cross sectional contour along the proposed siting route of the beam’s nominal axis.

To obtain estimates of cost and effort associated with the above options, a firm specializing in micro tunneling was contacted. Their assessment was that such a tunnel would be a routine construction and that no special challenges are foreseen. Depending on the specific boring equipment used, the minimum diameter of such a tunnel would be either ~3/4 m or ~1.1 m for the two hutch locations, respectively. The difference comes from the different boring methods that would be used. The longer and larger diameter tunnel would be driven using a laser guided boring head, which has great pointing accuracy. Either tunnel would have a liner installed to keep soil and water out. The estimated lapse times to
construct such a tunnel to the two hutch locations would be ~1 month and ~2 months, respectively.

Two other options for the long beam line were at least superficially examined and deemed to be less attractive than the solution presented above. The first one was to build an electron transport system to the undulator that aims the x-ray beam to the SLC Collider Hall (CEH). The required deflection of the electron beam from the linac trajectory over, say, the length of the undulator alone is ~15 m. This would require the FFTB tunnel with all of its conventional facilities and associated buildings to be dismantled and rebuilt. Further, there are four other buildings in the Central Research Yard in the way of the trajectory. Lastly, if no vertical correction was made and the beam was delivered to the CEH on the machine slope, it would emerge out of the west wall at an elevation ~12 m above the floor. This means a building would have to be erected inside the CEH west pit to provide the necessary research space. Another option that was examined was to deflect the beam to the south and up so it would surface in a small valley or depression above the Alpine Road entrance gate to SLAC. This solution requires an even larger horizontal deflection and also a substantial upward deflection with all of the associated beam containment safety issues. Like the trajectory to the CEH, this solution would also require the complete removal of the FFTB tunnel, construction of a new one, and would interfere with several other buildings in the Research Yard.

### 9.3.3 Experimental Stations

The nominal locations of the specular and crystal beam line experimental stations are indicated in plan view in Fig. 9.1-1. Due to the numerous possibilities for the installation of instrumentation optimized for different experimental applications, detailed layouts of the station areas have not, as yet, been attempted. As the experimental program evolves, sites for
various beam-characterization, scattering, and peak power damage experiments will in fact be developed at various other locations in the x-ray optics system (e.g., the absorption cell in the FFTB tunnel). It is likely that the designated experimental areas will need to remain “flexible” in this sense, with each experiment or class of experiments resulting in a different layout of instrumentation, detectors, shielding, and data acquisition protocols.

### 9.4 Experimental Hall

The function of the Experimental Hall is to contain the shielded experimental hutch and to provide access to it from a controlled environment. Related functions include the establishment of climate control to reduce the effect of outside temperature variations on the optical and experimental system components and the provision of utility and communications support for workers. The design laid out in Fig. 9.1-1 was based on securing a hutch space of maximal length without interfering with any of the adjacent buildings in the Research Yard. The dimensions of the hall are 10 m wide x 5.8 m high x 27 m long, providing a total floor space of \( \sim 2700 \text{ m}^2 \). The 10 m width allows for approximately a 2 m wide walkway between the building and hutch walls toward the downstream end of the hall, with a substantially larger floor area located between the hutch and building walls in proximity to the FFTB beam dump. This rather narrow floor area can be used for placement of electronic racks and data acquisition and control computers. Depending on the location of access doors to the hutch, the remaining floor space could be used for preparing samples and queuing of experimental equipment.

In continuing design studies, possibilities for extending the length and width of the Experimental Hall, possibly by removing or merging with adjacent buildings, will be pursued.

### 9.5 References


The coherent output of the LCLS features peak output powers in the 10 GW range, average powers on the order of 1 W, spectral bandwidths on the order of 0.1%, full transverse coherence, and pulse lengths of approximately 300 fs. The peak brightness of the LCLS can attain values in the $10^{33} - 10^{34}$ (ph/s, mm$^2$, mr$^2$, 1%BW) range. A comprehensive set of calculations of the spontaneous spectral flux has been carried out in the far-field approximation. The spectral distributions and peak power densities associated with both the coherent and spontaneous LCLS beams have been calculated and archived for use in optical instrumentation and experimental design. The peak on-axis power density of the spontaneous radiation, approximately $10^{13}$ W/cm$^2$ for 15 GeV operation, is approximately only one hundred times smaller than that of the coherent line, which due to its full transverse coherence can, in principle, be focused (at 1.5 Å) to an approximate limit of $10^{25}$ W/cm$^2$.

The bremsstrahlung flux, generated by scattering off in-vacuum molecules and various upstream collimators and optical elements, is of concern both for personnel safety and the maintenance of a low-noise experimental environment. Detailed modeling of the bremsstrahlung gamma flux entering the experimental area has been carried out. The modeling has determined that this gamma flux is controllable with standard shielding techniques. Time-domain modeling of the conversion of the bremsstrahlung into thermal neutron flux and the associated design optimization of the experimental hutch shield wall and experimental areas will be continued as part of the x-ray optics design effort.

The layout of the initial optical system, dedicated to transporting and processing the above species of radiation, has been designed to satisfy two basic requirements. First, it will provide diagnostic capabilities for analyzing the output in the initial stages of the facility's operation. Second, it will provide a nominal set of spectral-angular filtering capabilities for supporting a flexible range of exploratory experiments. These capabilities include low-resolution high-pass, low-pass, and band-pass filtering, as well as one high-resolution monochromator. The transport system and optical beam lines will utilize windowless in-vacuum transport for the radiation, and specially designed shutters and stoppers for personnel and facility protection.

The primary elements in the x-ray transport and optical beam line systems are: Differential Pumping Sections (DPSs), x-ray slits, an absorption cell, mirrors, and crystals. The establishment of windowless in-vacuum transport, as well as Ultra High Vacuum (UHV) environments for selected beam line optics, will be realized with the DPSs. These components provide up to five orders of magnitude of vacuum isolation by blocking line-of-
sight molecular flow with electron-based ionizing and magnetic-deflection-based trapping mechanisms. Spatial and angular phase-space filtering of the radiation will be provided by two sets of horizontally and vertically oriented slits. Both the slit apertures and angles of incidence will be individually adjustable, allowing operation in either a normal-incidence or grazing-incidence mode.

The absorption cell, designed for variable attenuation of the coherent radiation, will operate by emitting streams of high-pressure xenon, or an alternative gas, onto the radiation axis. Since the present design has been based on calculations valid for weak-field radiation/matter interactions, it is anticipated that more detailed studies of such interactions in the strong-field regime of the LCLS will need to be performed for the development of an optimized design. The mirrors, utilized for low-pass filtering and beam deflection, are designed to operate at extreme grazing incidence to dilute the incoming power density of the reflected light. In order to keep the absorbed energy density below the activation threshold of various damage mechanisms, the mirror surfaces must be polished down to roughness in the 1–2 Å range and kept free of contaminants during operation.

For crystal optics, energy-absorption calculations indicate that very thin, low-Z materials should be used at large angles of incidence in order to minimize the absorbed energy. Alternatively, the incidence angle could be reduced by using asymmetrically cut samples. In either case, diamond, and perhaps beryllium, appear to be optimal choices with regard to weak-field calculations, although here too there is no experimental data and little theoretical knowledge of how they will behave in the parameter regime of the LCLS. In addition to the primary optics, special instruments and components will need to be developed in support of the beam diagnostics and selected scientific experiments. In the first case, for example, calorimeters, spectrometers, and other instruments (e.g., Michelson interferometers) will be required to characterize or profile the phase-space parameters of the LCLS pulses. In the second case, extending or tailoring the source parameters of the coherent light will be necessary. For example, beam splitters and time-delay lines will be required to support time-domain correlation experiments; pulse compressors may be required for the study of ultra-fast phenomena; and microfocusing of the beam to power densities orders of magnitude in excess of those in the raw x-ray beam will be desirable for coherent imaging and nonlinear physics investigations.

10.1 Coherent Radiation

A basic theme underlying the design and development of the x-ray optical system components and instrumentation listed above has been, and remains, the lack of theoretical and experimental knowledge regarding the interaction of the radiation pulses with matter. In view of the fact that the initial designs of critical components such as the mirrors and absorption cell have been predicated on physical data and techniques valid in the weak-field regime, it is anticipated that an intensive theoretical and experimental R&D program for investigating the interaction of LCLS-type radiation pulses with matter will be required to
provide understanding and control of the physical factors necessary for optimal instrumentation and experimental design. Indeed, it is expected that the first use of the x-ray system will be to investigate such interactions using the optical elements and materials initially in place.

The characteristics of the coherent line spectrum of the LCLS operating in the SASE mode have been studied extensively, both theoretically and numerically [1,2,3,4,5,6,7,8,9,10,11,12]. The results are typically condensed into tabulations or graphs of the peak power, brightness, transverse/longitudinal coherence, and the temporal/spectral structure of the output pulses as explicit or implicit functions of the electron beam and undulator parameters. Many if not all, of the cited investigations idealize or restrict the FEL system being studied in various ways. The primary ones include: (1) the representation of beams and interaction regions in spaces of reduced dimension; (2) restriction to the dynamics of the exponential gain process without a comprehensive or realistic model of startup noise; (3) an emphasis on the realistic characteristics of startup noise and their propagation using simplified linearized models of the electron beam and its bunching dynamics; (4) the use of simplified analytical models to represent actual insertion device fields; (5) the use of simplified electron beam phase space and field models; and (6) restriction to selected regimes of the FEL gain process, such as the onset and evolution of saturation. In many instances, analytical treatments are used to provide nominal or initial estimates of selected output parameters, followed ultimately by deferral to computer simulations that are perceived to be more realistic.

For purposes of optical design and the reliable calculation of the propagation of radiation through the optical system, a comprehensive quantitative description of its phase-space parameters is required. This description naturally takes into account the statistical and coherence properties of the radiation field [13], providing a convenient set of parameters whose spatial-angular and spectral-temporal propagation through linear systems can be calculated with the aid of well-known analytical techniques, e.g., the van Cittert-Zernicke [14] and Wiener-Khintchine [15] Fourier-transform relations.

The first-order coherence properties of the LCLS pulses [16] are expressible in terms of the source brightness $B$ [photons/(sec mm$^2$ mr$^2$ 0.1%BW)], and the closely related degeneracy parameter, $\delta$. The brightness, whose propagation through linear systems can also be calculated using well-known analytical formalisms [17], can be defined as the photon energy density in phase space, 

$$B = \frac{N_{\text{phot}} / \sigma_\tau}{(2\pi)^3 \varepsilon_x \varepsilon_y (\sigma_f / f)}.$$  \hspace{1cm} (10.1.1)

Here $N_{\text{phot}}$ is the number of photons, $\sigma_\tau$ is the standard deviation of the pulse’s duration, $\varepsilon_x (= \sigma_x \sigma_y)$ and $\varepsilon_y (= \sigma_x \sigma_y)$ are the total transverse emittances, $\sigma_f$ is the standard deviation of the bandwidth, and $f$ is the mean photon frequency. If the wakefield effects,
discussed in Section 8.7, cause the slices along the bunch to differ in their average transverse location $\epsilon_x$, $\epsilon_y$, and energy spread, $\sigma_f$, should be replaced by the larger values of projected emittance and energy spread. The corresponding degeneracy parameter is defined as the photon number per phase space mode volume,

$$
\delta = \frac{(\lambda/2)^2 N_{\text{phot}}}{(2\pi)^3 \epsilon_x \epsilon_y \sigma_x \sigma_f} = B \left( \frac{\lambda^3}{4c} \right)
$$

(10.1.2)

where $\lambda$ is the mean photon wavelength and $c$ the speed of light. In numerical terms, $\delta = 8.25 \times 10^{-25} (\lambda [\text{Å}])^3 B$. For a fully transversely coherent source, $(2\pi)^3 \epsilon_x \epsilon_y = (\lambda/2)^2$, resulting in the simplified expression $\delta = N_{\text{phot}} / 2\pi \sigma_x \sigma_f$. As stressed by Coisson [18], $\delta$ can be used as an index to assess the probability of collective, or stimulated, photon/electron beam interactions (with the probability approaching 1 for $\delta >> 1$). When expressed as the density of photons in the real-space volume associated with a single phase-space mode, $\delta$ can be contrasted with the particle density of the material the pulse is interacting with to gauge the relative expectation of collective and multi-photon processes.

Using these definitions, the basic radiation parameters of the LCLS can be summarized on the basis of results from the aforementioned theoretical studies and numerical simulations. A graphical representation of the temporal and spectral characteristics of a short interval of an LCLS-type radiation pulse at saturation is shown in Fig. 10.1-1. A simplified analysis of the evolution of SASE from startup noise into lineshapes similar to the ones depicted can be found in the references (e.g., Saldin et al.). Due to its origin in shot noise, the temporal output consists of peaks of random phase and amplitude, with the average peak width corresponding to $\sim 0.05N_u\lambda - 0.1N_u\lambda$, where $N_u$ is the number of undulator periods.

Nominal parameters corresponding to the SLAC LCLS operating at 1.5 Å and 15 Å are listed in Table 10.1-1.
Table 10.1-1. Optical and source parameters of the LCLS. Undulator $K=3.71$. $N_u=3328$ periods. Undulator period $\lambda_u=3$ cm.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength [Å]</td>
<td>1.5</td>
</tr>
<tr>
<td>Norm. emittance $\gamma$ [mm-mrad]</td>
<td>1.5</td>
</tr>
<tr>
<td>Electron energy [GeV]</td>
<td>14.35</td>
</tr>
<tr>
<td>Peak current [A]</td>
<td>3400</td>
</tr>
<tr>
<td>Bunch duration [fs, FWHM]</td>
<td>277</td>
</tr>
<tr>
<td>Peak spontaneous power [GW]</td>
<td>81</td>
</tr>
<tr>
<td>Peak coherent power(^a) [GW]</td>
<td>9</td>
</tr>
<tr>
<td>Average coherent power(^b) [W]</td>
<td>0.31</td>
</tr>
<tr>
<td>Energy/pulse [mJ]</td>
<td>2.5</td>
</tr>
<tr>
<td>Coherent photons/pulse (x10(^{15}))</td>
<td>1.9</td>
</tr>
<tr>
<td>Approximate bandwidth (BW) [%]</td>
<td>0.1</td>
</tr>
<tr>
<td>Peak brightness(^c) (x10(^{22}))</td>
<td>12</td>
</tr>
<tr>
<td>Peak degeneracy parameter [x10(^9)]</td>
<td>3.3</td>
</tr>
<tr>
<td>Average brightness(^c) (x10(^{31}))</td>
<td>40</td>
</tr>
<tr>
<td>Transverse size [µm, FWHM](^d)</td>
<td>78</td>
</tr>
<tr>
<td>Divergence angle [µrad, FWHM](^d)</td>
<td>1</td>
</tr>
<tr>
<td>Spontaneous fundamental opening angle [µrad, FWHM]</td>
<td>4.9</td>
</tr>
<tr>
<td>Spontaneous fundamental transverse size [µm,FWHM]</td>
<td>82</td>
</tr>
<tr>
<td>Peak Power Density [W/mm(^2)](^d) (x10(^{12}))</td>
<td>1.88</td>
</tr>
<tr>
<td>Peak Field [V/m](^d) (x10(^{10}))</td>
<td>3.8</td>
</tr>
</tbody>
</table>

\(^a\) Output fully transversely coherent.
\(^b\) At 120 Hz rep rate.
\(^c\) Photons/s/mm\(^2\)/mrad\(^2\)/0.1%BW.
\(^d\) At exit of undulator.

An important aspect of the temporal structure of the LCLS is that the full pulse is effectively partitioned into a sequence of contiguous, causally non-overlapping intervals of length $L_{slip} = N_u \lambda_u$ (referred to in the FEL literature as “slippage” lengths). In the LCLS pulse at 15 GeV, for example, there are approximately 166 such intervals. Due to the physical independence of each interval, its coherent radiation mode must also be considered fully independent of the others. Under the assumed ideal conditions that each such interval of the LCLS bunch travels and emits along exactly the same axis, is characterized by the same statistics, and has the same mean energy, its mean (peak) brightness and degeneracy parameters will be equal to those of the full pulse. In general, however, there may be a substantial variation of the mean radiation and phase space parameters, as well as of their
higher statistical moments, from interval to interval. This may result in an increased (average) mode volume, or a decreased amount of photon energy per mode. For example, if the longitudinal density profile of the electron bunch is strongly non-uniform, the amount of gain saturation within each interval may vary with the local density. Other possibilities may include changes in the mean electron beam energy (and thereby of the emitted photon energy by twice the relative amount) from interval to interval, as well of the average transverse position and angle. Under these conditions, it becomes critical to distinguish between the two limiting cases where the variation of the statistical moments from interval to interval is: 1) random, or “uncorrelated”; and 2) dependent, or “correlated,” with respect to \( z \).

Each of these limiting cases requires a basically different description of the source characteristics, corresponding to the distinction drawn in the statistical literature between “frequency” versus “time” series [19]. In the random case, the phase space probability distributions of the entire beam can be trivially derived from the corresponding distributions of the individual sub-bunches. The statistical moments of the entire bunch are then obtained by averaging the powers of the parameters in question with the distributions of the whole bunch.

In the second case, while the same procedure can also be formally applied, it also becomes critical to describe the correlation, or functional dependence, of the statistical moments of the individual bunch intervals with respect to \( z \). This can be straightforwardly accomplished by calculating, for example, the autocorrelation of each statistical moment over the entire bunch as a function of \( z \). If the mean energy of each sub-bunch decrease monotonically versus \( z \) (as in the case of the “chirp” induced in the electron bunch by linac wakefields), a knowledge of this dependence can be exploited for designing optics for temporally compressing the LCLS output [20]. More generally, the existence of such “chirps” in the transverse phase space parameters are also of extreme interest, as they can influence the design of instrumentation for experimental applications, as well as the interpretation of experimental results.

A representation of LCLS peak and average brightness contrasted with other quasi-coherent x-ray or SR sources is shown in Fig. 10.1-2. The maximum values (dashed curves) assume homogeneous and smooth temporal and spectral lineshapes, as well as diffraction-limited transverse outputs. Due to the idealized nature of these assumptions, the brightness is displayed as a range in anticipation of realistic factors that could ultimately lessen the maximum value. In addition to the one discussed above, these could include: (1) spectral broadening effects due to non-linearities in the gain process (dilution of \( N_{\text{photon}} \)); (2) actual mode structures more complex than the one evidenced in current analytical theories (increase of phase-space volume); and (3) correlated and uncorrelated energy spreads in the beam greater than those assumed in current simulations (dilution of \( N_{\text{photon}} \)).
Combined coherent and spontaneous output flux of the LCLS based on the parameters listed in Table 10.1-1 is shown in Fig. 10.1-3. Peak and average flux values corresponding to 120-Hz operation of the SLAC linac are marked on the opposing ordinates. The spontaneous curve is normalized to the electron beam γ and a fixed undulator K value of 3.71. For this value the spontaneous spectrum is seen to extend well beyond the 50th harmonic, whereas the expected output of the third coherent harmonic is up to two orders of magnitude weaker than the fundamental. The nominal FWHM opening angle of the i\textsuperscript{th} coherent FEL peak is of the same order of size as the opening angle, θ\textsubscript{ISR}, of the i\textsuperscript{th} spontaneous radiation harmonic,

\[ \theta\textsubscript{ISR} = \left[ 2(1 + K^2/2)/iN_a \right]^{1/2} / \gamma, \]  

and at least a factor \( \sqrt{iN_a} \) smaller than that of the remaining spontaneous background. In view of the fact that the total spontaneous power can match or greatly exceed the total coherent power, it is of interest to rigorously calculate and contrast the power and power density of both. These calculations are described in the following section.
Two observations concerning the full transverse coherence of the FEL spectral line radiation are in order. First, it is (in principle) admissible to consider focusing the beam down to a diffraction-limited waist of the scale of $\lambda$. Although the practical obstacles to attaining this level of focusing are formidable, especially toward the short end of the wavelength scale, a systematic effort starting with the longest wavelengths would prove to be a worthwhile R&D effort. Second, the saturated transverse coherence could activate scattering or threshold damage effects during propagation through non-homogeneous materials by significantly enhancing local electric field amplitudes via the mechanism of near-field diffraction. The investigation of this potentially significant effect is also a subject for continuing numerical and experimental R&D.

10.2 Spontaneous Radiation Calculations

The long transverse LCLS undulator can emit a characteristic synchrotron radiation (SR) spectrum with a total peak (and average) power an order of magnitude or more greater than the coherent line power (see Table 10.1-1). As depicted in Fig. 10.1-2, this radiation, distributed about the forward direction of the coherent FEL line, can contain on-axis harmonics out to the >1 MeV range. Due to its broad spectrum and high power, the spontaneous SR can be either useful or nocuous. In the first case it could be used for novel experiments requiring broadband spontaneous radiation with an ultra-short-pulse time structure, while in the second instance it can interfere with experiments designed to utilize the coherent FEL line. In view of this, the capability of processing and separating, either spectrally or angularly, the spontaneous SR from the FEL line(s) is clearly of critical
importance to the operation and scientific utility of the LCLS. This, in turn, necessitates a quantitative spectral-angular description of the SR spectrum.

In view of the limited available time and other resources, the calculations for the present study were restricted in a number of ways. First, the far-field limit of the general classical expression for the spectral-angular flux distribution, as described elsewhere [21,22], was employed. Although not as general as the more realistic near-field calculations that will eventually need to be performed in support of future experimental applications, the use of the simplified (and thereby substantially more rapid) far-field algorithms has: (1) provided a conservative description of the power density distribution for optical design purposes (i.e., the actual near-field spectra will be spectrally and angularly more diluted [23]), and (2) permitted an initial comprehensive mapping of the LCLS’s spontaneous spectral-angular parameter space. Second, a zero-emittance source with a zero energy spread was assumed. Again, this may be justified for the following reasons: (1) the zero-emittance assumption is approximately realistic in the long-wavelength limit of the LCLS fundamental (at ~800 eV); (2) for the relatively small emittance of the LCLS beam, which is only a factor of four greater than the diffraction-limited emittance at 8.3 keV, longitudinal and transverse phase-space corrections to the peak spectral flux numbers can be easily factored in, using simple analytical expressions [24]; and (3) the calculated peak values represent the maximum attainable flux density, which provides a conservative referent for optical design purposes. Finally, a continuous undulator structure with no field errors was assumed. Again, this resulted in maximal estimates for the spectral flux density, which were of primary relevance to the present design study. In the real-life case, however, the presence of undulator field errors, together with the electron beam’s realistic phase space parameters, can cause substantial deviations of the real spectrum from ideality, particularly at harmonic energies well above the fundamental. To illustrate this, in Fig. 10.2-1 an equivalent-K wiggler spectrum [25] has been superimposed on the ideal integrated spectrum of the LCLS. To first order, the effects of undulator errors and beam emittance will tend to wash out the undulator’s harmonic peaks in the region around and above the wiggler’s critical energy, bringing it into approximate agreement with the high end of the wiggler’s rolloff. With the availability of more realistic modeling calculations, these discrepancies could, to a certain extent, be used to establish information about the undulator’s and electron beam’s departures from ideality [26,27].

In continuing R&D efforts on the LCLS project, the calculations we report here will be extended in a number of ways. First, the unrestricted formalism for the spectral-angular flux density will be used to calculate realistic flux distributions for the fundamental and selected higher harmonics at distances representative of the actual locations of the experimental end stations. Second, the effects of the electron beam’s phase space parameters will be factored into the spontaneous radiation model. Third, provisions will be made for including discontinuous undulator structures with realistic field errors into the source simulations. Fourth, polarization profiles incorporating realistic beam and undulator parameters will be
calculated for the fundamental and lower-order harmonics. Finally, if required, the calculations will be extended to elliptically polarizing field structures.

Most of the present calculations were carried out either on SSRL’s mainframe computer or on the Cray computers at the NERSC facility at LBNL. The data files have been archived at SSRL. In the following sections selected results of these calculations are summarized.

![Graph](image)

**Figure 10.2-1.** Equivalent-K ($K=3.67$) wiggler spectrum superimposed on an angle-integrated spectrum of the LCLS undulator.

### 10.2.1 Spectral-angular Radiation Profiles

The basic far-field geometry employed for a spectral-angular description of the spontaneous SR emitted by the LCLS is shown in Fig. 10.2-2. The target areas are circular or annular regions centered on the axis of the undulator. The dimensions of the regions are given in angular units normalized to the particle beam’s Lorentz contraction factor $\gamma$ and the undulator deflection parameter $K$ via the parameter $\gamma^* = \gamma / (1 + K^2 / 2)^{0.5}$. In these units, the quantity $\gamma^* \theta$ [rad] represents the angular radius of the far-field distribution for arbitrary values of $\gamma$, which is the primary spectral tuning parameter of the LCLS. In particular, the radius $\gamma^* \theta=1$, emphasized by the heavy black circle, represents the contour containing approximately 85% of the emitted spontaneous power. The small solid circular area in the center of Fig. 10.2-2 represents the FWHM angular diameter of the spontaneous SR fundamental. This diameter, which is of the same order of size as the angular diameter of the fundamental FEL line, also contains all the higher spontaneous (odd) SR harmonics. In Fig. 10.2-3 the peak spectral flux integrated over the solid central aperture is plotted versus harmonic number. This spectrum is seen to consist primarily of the odd on-axis harmonics with only a small fraction of the off-axis even harmonic flux appearing at large harmonic number.
values. In Fig. 10.2-4 the peak flux integrated over the central circular area 1 is plotted. As expected, it contains the same, but broadened, on-axis lines as the aperture of the fundamental, but with a much higher content of the off-axis (even) harmonic flux. In Fig. 10.2-5 the peak spectral flux contained in the 10th annular region is plotted, and the sum of the flux integrated over each of the regions of the entire target area is graphed in Fig. 10.2-6. Apart from the sharp low-energy features associated with truncating the integration at $\gamma^*\theta = 2.5$, it is seen to agree closely with the fully integrated spectrum in Fig. 10.1-2.

To obtain a corresponding representation of the azimuthal distribution of the peak spontaneous flux, the target area depicted in Fig. 10.2-7 was employed. Features of the integrated spectra for selected azimuthal/radial angular apertures are plotted in Figs. 10.2-8 through 10.2-13.

A calculation of fundamental interest is the far-field spectrum integrated over the full angular aperture of the undulator’s vacuum duct. We find, for an inner duct diameter of 5 mm and an assumed source point located at the center of the ~100-m long undulator, an angular aperture of $\gamma^*\theta = 0.5$ at ~15 GeV, and $\gamma^*\theta = 0.16$ at ~5 GeV. The corresponding spectra (assuming 100% loss due to absorption or surface-roughness scattering of the light subtended by the duct) are plotted in Fig. 10.2.1-14 and Fig. 10.2.1-15. These rather strongly-filtered distributions are of course strictly valid in the far field, a condition only

Figure 10.2.-2. Far-field radial target geometry for the spontaneous radiation emitted by the LCLS undulator.
poorly approximated by the present geometry of the LCLS (see Fig. 9.1-1). However, in the event of the development of an ultra-long LCLS beam line (see Section 9.3.2) their relative accuracy will be considerably improved. Prior to such a development, realistic distributions spectrally filtered by the undulator’s vacuum duct will need to be computed with a more valid near-field radiation formalism (see Section 10.2).

**Figure 10.2-3.** LCLS spontaneous flux distribution integrated over the FWHM aperture of the fundamental.

**Figure 10.2-4.** Spontaneous LCLS flux distribution integrated over a small aperture near the axis.
Figure 10.2-5.  Spontaneous LCLS flux distribution in a narrow annular region away from the axis.

Figure 10.2-6.  Spontaneous LCLS flux distribution integrated over a large finite aperture.
Figure 10.2-7. Far-field radial/azimuthal target geometry for the spontaneous radiation emitted by the LCLS undulator.

\[ \gamma = \gamma/(1 + \kappa^2/2)^{0.5} \]

\[ \Delta \phi = \pi/20 \]

\[ \phi = 0 \]

\[ D = 2\gamma + \theta = 4.75 \]

\[ D = 2\gamma + \theta = 5 \]

Figure 10.2-8. Spontaneous LCLS flux distribution integrated over \(0.0 < \gamma\theta < 0.5\) and \(0 < \phi < \pi/20\).
Figure 10.2-9. Spontaneous LCLS flux distribution integrated over $0.0<\gamma \theta<0.5$ and $9\pi/20<\phi<\pi/2$.

Figure 10.2-10. Spontaneous LCLS flux distribution integrated over $0.5<\gamma \theta<1$ and $0<\phi<\pi/20$. 
Figure 10.2-11. Spontaneous LCLS flux distribution integrated over over $0.5<\gamma\theta<1$ and $9\pi/20<\phi<\pi/2$.

Figure 10.2-12. Spontaneous LCLS flux distribution integrated over over $1<\gamma\theta<2.5$ and $0<\phi<\pi/20$. 
Figure 10.2-13. Spontaneous LCLS flux distribution integrated over over $1<\gamma \theta <2.5$ and $9\pi/20<\phi<\pi/2$.

Figure 10.2-14. Spontaneous far-field LCLS flux distribution integrated over the angular aperture of the LCLS undulator’s vacuum duct at ~15 GeV.
To estimate the spontaneous power density distribution at a fundamental wavelength of 1.5 Å, the total power contained in each circular or annular region of Fig. 10.2-2 was calculated by integrating the spectrum associated with the region versus harmonic energy. The curve connecting the corresponding values of power is plotted in solid black in Fig. 10.2-16. The integral of this curve is plotted versus $\gamma^*\theta$ as the monotonically increasing dashed line. As can be independently verified with simple analytical approximations [24,28] the asymptotic value of the power density represents the total emitted spontaneous power. The calculations have been done out to the 46th harmonic. The average power density over each region is calculated by dividing the total power in that region by the corresponding circular or annular area. The resulting power density values are connected by the monotonically decreasing curve.

For reference, the peak coherent output power of the LCLS and its output power density at a distance of 10 meters from the undulator exit are marked on the ordinate by arrows in Fig. 10.2-16. Note that the peak spontaneous power density is only two orders of magnitude smaller than the coherent power density. This is explained by the large number of additional odd harmonics that exit along the same axis as the spontaneous fundamental. As noted in Section 10.1, however, the power density in the coherent raw beam represents a lower limit with respect to that attainable by additional focusing. If we assume that focusing down to the theoretical diffraction limit can be attained, the upper limit on the attainable peak power density of the LCLS will lie well in excess of $10^{25}$ W/cm$^2$ as shown in Fig. 10.2-16. Fig. 10.2-17 shows these curves and data points with the additional designation of this critical limiting point.
On the basis of the approximations presented here, the above graphs represent the maximum attainable spontaneous SR power densities that can be expected from the LCLS. These total power density distributions, integrated over all energies, will only be moderately sensitive to the beam’s phase space and undulator error parameters. However, the power densities associated with any particular energy (i.e., when the radiation is viewed through a spectral filter) can be expected to vary more noticeably with departures from source ideality, and may consequently need to be more accurately recalculated for selected instrumentation design studies or experimental applications.
10.3 Bremsstrahlung Calculations

The radiation concerns related to the LCLS project fall into three distinct areas:

- Radiation safety
- Radiation background in experiments
- Machine protection

In each of these areas one or more of the following radiation sources needs to be considered:

- Bremsstrahlung from beam/halo interactions with beamline components
- Gas bremsstrahlung
- Synchrotron radiation
- Neutrons
- Muons
- Induced activity
- Secondary electrons and positron

In this section we are concerned with radiation effects in the areas downstream of the undulator, taking into account any relevant radiation source, located upstream, inside, or downstream of the undulator. Potentially all sources listed above can contribute to the radiation background in experiments. Machine protection mainly concerns possible radiation damage to mirrors and collimators that will intercept the spontaneous synchrotron radiation accompanying the laser beam proper. The radiation safety items include shielding, beam containment system (BCS), and personnel protection system (PPS). Since the LCLS electron beam power will be comparable to that of the FFTB, the existing enclosure and dump shielding as well as PPS and BCS should be adequate without major modifications. New designs of the three safety items are only required for the optics enclosure and experimental hutch downstream of the electron beam dump. The ultimate goal is to have sufficiently accurate estimates of radiation and their effects. Initial modeling of some of the dominant sources has been completed, and the status of the calculations is summarized in the text below. More comprehensive calculations, as described below, will be continued in the future.

10.3.1 Bremsstrahlung from Halo

Forward-directed bremsstrahlung can be produced by the interaction of the electron beam halo with the protection collimators upstream of the undulator, with the undulator, and possibly other beamline components downstream. Using the Monte Carlo transport code FLUKA [29], one particular scenario has been simulated. In this case electrons are assumed to hit the vacuum chamber at a very grazing angle near the undulator exit. The beam line layout was simplified to a cylindrical-slab geometry, as represented schematically (not to scale) in Fig. 10.3-1. Due to its length, the geometry in this figure is broken into two parts,
starting in the top left corner. The front face of the undulator (b) is the origin of longitudinal coordinates describing the position of important components. In these simulations most of the components are symmetrical relative to the beam line axis (shown as a dashed line). The two sets of vertical and horizontal collimators (f) present their plane surfaces to the beam under a very small angle and were therefore simulated in greater detail. The extent of the geometry in the radial direction around the beam pipe is very constrained up to the experimental hutch (o). Particles exceeding this radial limit are killed in order to save computation time, because they have an extremely low probability of reaching one of the three scoring regions (n) in the experimental hutch.

The high electron energy and the long distance between the undulator and the experimental hutch (more than 30 m) require long computing times in order to achieve sufficient statistics. Figure 10.3-2 shows the poor dose score obtained behind a 20-cm thick lead dump at the end of the line after simulating $10^6$ histories, despite very high cutoffs and leading particle biasing.

To improve statistics, importance biasing was implemented setting the relative importances as a function of distance from the source based on the scored energy deposition in the wall of the vacuum chamber (Fig. 10.3-3 and 10.3-4). The new result, corresponding to $5 \times 10^5$ histories, is shown in Fig. 10.3-5. The dose on the front side of the same dump is shown in Fig. 10.3-6.

![Figure 10.3-1. Features of the bremsstrahlung source/propagation model of the LCLS from the undulator to the experimental area.](image)
Figure 10.3-2. Tissue dose as a function of distance from the beam axis at the end of the experimental hutch, behind the electron beam dump. Only leading particle biasing was implemented.

Figure 10.3-3. Energy absorbed per unit length in the vacuum chamber wall as a function of distance from the end of the undulator.
Figure 10.3-4. Relative region importances assigned as a function of distance from the end of the undulator.

Figure 10.3-5. Tissue dose as a function of distance from the beam axis at the end of the experimental hutch, behind the dump. Leading particle biasing, windows and importance biasing were implemented.
In future work, calculations will be extended to include bremsstrahlung from collimators upstream of the undulator.

10.3.2 Gas Bremsstrahlung

Gas bremsstrahlung will arise from beam interactions with the residual gas over a straight portion of the beamline, starting near the end of the dogleg and comprising the undulator. A length of about 130 m was considered. This is indeed a unique situation, since gas bremsstrahlung is normally supposed to be an issue only in the straight sections of electron storage rings. However, while on one hand the 0.1 $\mu$A current of the LCLS electron beam will be about a factor of $10^6$ smaller than that found in storage rings, on the other hand the assumed maximal residual pressure ($10^{-7}$ Torr) will be 100–1000 times larger and the length of the straight section will also be larger by two orders of magnitude. In addition, the electron energy will be approximately two-to-three times that of existing high-energy storage rings (dose from gas bremsstrahlung increases with more than the second power of energy). Based on a number of Monte Carlo simulations, Ferrari et al., [30] proposed an analytical formula to calculate dose rates from gas bremsstrahlung as a function of distance, length of the straight section, air pressure, electron beam current, and electron energy. A simple extrapolation of this formula would give 5 rem/h in the optical enclosure. However, it is not obvious that the formula can be applied to the LCLS situation, i.e., extrapolated to such extreme straight section lengths and energies. A full Monte Carlo simulation is planned in the near future.
10.3.3 Muons

The 15 GeV electron beam terminating in the beam dump will be a non-negligible source of muons. Preliminary estimates of muon dose rates behind the concrete and iron shielding of the FFTB beam dump were done with the MUON89 code written by W.R. Nelson [31]. Approximately 6 m of iron shielding, in addition to the existing FFTB dump shield, would be needed to bring the dose rate in the forward direction to 6 mrem/h, assuming that the beam power is 3 kW. These estimates were confirmed by another simple method described by Sullivan [32]. If the beam is directed, or deflected sufficiently in the downward direction, the narrow maximum of the muon beam might emerge from the FFTB dump shield already underground, in which case its shielding would be a lesser problem.

The MUON89 program, however, was designed for simple assessment of accelerator shielding and is not suited for complex geometries. These could be investigated in the future using the Monte Carlo code MUCARLO [33]. Another possibility is to couple two codes, letting MUON89 or MUCARLO do the muon production and FLUKA the transport.

10.3.4 Future Work: Other Radiation Sources

Besides personnel protection issues in experimental hutchess, transport of synchrotron radiation is of interest for machine protection. A series of collimators will be inserted in the LCLS photon beam line in order to eliminate as much as possible the spontaneous synchrotron radiation from the useful laser beam. To minimize local heating, such collimators will consist of slabs of an approximately cuboid shape tilted at a very grazing angle, and will be coated with a very smooth and thin layer of gold. The energy deposition in such a thin layer must be calculated. However, it will be necessary to implement in FLUKA reflection and refraction properties of low-energy x-rays in addition to the existing normal interactions at the level of a single atom.

To estimate neutron generation in the beam dump and other beamline components, we plan to exploit the recently improved capability of FLUKA to simulate the whole electromagnetic cascade, including photonuclear reactions, in any nucleus at all energies [34]. Accurate assessment of the neutron field, including thermal neutrons, is needed for both personnel protection and experimental background.

Fluence and spectra of secondary electrons and positrons in experimental apparatus can be readily obtained in FLUKA calculations concerning bremsstrahlung and other sources. FLUKA also was used to assess activation of the undulator material and can be used for this purpose in other beamline components.

Finally, the pulsed structure of the LCLS beam will require a study of the time development of each component of the background fields. In principle, FLUKA can be used to carry out such an analysis, but the task is expected to be demanding on staff and computer resources.
10.4 Optical System

The x-ray optics system provides the interface between the LCLS undulator and the experimental stations, and performs a number of critical functions, selected representations of which are schematized in Fig. 10.4-1. This diagram, which depicts those functions that are incorporated in the present design in solid blocks and a number of those that can be added subsequently in dashed outline, provides a convenient basis for a general description of the optical system and its components (see Fig. 10.4-2).

Figure 10.4-1. Functional diagram of the experimental and diagnostic capabilities of the LCLS x-ray optics system.

Figure 10.4-2. Schematic layout of LCLS x-ray optics system components. Drawing not to scale.
A convenient starting point is to take account of the high peak power of the LCLS pulses and the potential damage they can cause. During the course of the design study, this led to the assessment of two alternative ways of mitigating this problem: (1) a long beam line, and (2) an absorption cell. The cell, chosen both for reasons of economy and for the immediate opportunity it will afford for studying the interactions of FEL radiation pulses with matter, will also provide readily controllable attenuation of the intensity from maximum down to levels at which conventional diagnostic and experimental instrumentation, as well as experimental samples, can be safely illuminated. This will enable the systematic study of both the onset and overall extent of high peak power effects, a major initial goal of the LCLS experimental program.

The following capabilities provided by the optical system are in the critical area of spectral-angular filtering. For convenience, they may be classified into low-pass, high-pass, and band-pass categories for the spectrum, and into equivalent aperture filters for the beam’s spatial and angular phase-space parameters. The two slit systems located upstream of the absorption cell and downstream of the FFTB dump are designed to perform both spectral and phase-space filtering functions. Operated together, they constitute a long and ultra-precise collimator with an angular aperture adjustable down to a value of zero. Individually, they can also be used as (spatial) apertures and high-pass spectral filters. One particularly important application of these capabilities will be the separation of the (off-axis) spontaneous spectrum from the coherent line by reflection and absorption, a critical prerequisite for selected scattering experiments (e.g., in the absorption cell). In normal operation, the slits will also pass the high-energy part of the spontaneous radiation, which propagates co-axially with the FEL line. The separation of these two spectra can be accomplished with the basic low-pass filtering component, the mirror. The corresponding (spectral/angular) bandpass filtering function can be provided either by a (natural) crystal located in the crystal tank or by multilayer reflectors in the mirror tank.

Due to the perceived importance of certain scattering and diffraction-based experiments currently performed in the hard x-ray range at SSRL and elsewhere, one high-resolution crystal monochromator, similar to the ones currently employed at SSRL for one of the experimental end stations, will be provided. This will enable experiments of current interest to be extrapolated to the new source parameters and then referenced to the broad base of data and experience available at SSRL.

As indicated in Fig. 10.4-1, no optical means for (1) controlling the polarization, (2) microfocusing, and (3) tailoring of the spatial and temporal parameters of the radiation pulses were included in the present design. These are, however, critical capabilities for important classes of experiments, and their implementation will be pursued in future phases of the LCLS x-ray optics experimental program.

In the initial phase of the LCLS experimental program, perhaps the most critical function of the x-ray optics system will be to provide diagnostic capabilities for the light emitted by the undulator. Due to the availability of the absorption cell, these functions will be able to be
performed with conventional instrumentation. For example, analysis of the radiation spectrum can be carried out by a crystal spectrometer in the <5 Å range and by a reflection-grating spectrometer at longer wavelengths. Calorimetry will be performed by conventional instruments, which can either be purchased and adapted, or designed and fabricated at SLAC. Phase-space diagnostics will be executed with suitable interference-based, spectrophotometric, or spatial/temporal scanning/recording techniques.

In view of the enormous peak powers and electric fields emitted by the undulator, damage to the specular beam line components (the slits and mirrors) is expected to be exacerbated by surface contamination, particularly by adsorbates forming irregular surfaces or otherwise by those inducing a reflectivity drop at the angle and energy of the incoming radiation. Suppression or prevention of these effects will involve maintaining an Ultra High Vacuum (UHV) environment in the slit and mirror chambers, as well as providing capabilities for in situ surface cleaning. A further requirement, in view of the 820–8200 eV range of the LCLS fundamental, is the necessity for line-of-sight optics through to the experimental stations (operation without windows). These requirements, as well as the vacuum isolation of the absorption cell from the optics transport line, will be accomplished by suitably designed Differential Pumping Sections (DPSs).

10.4.1 Differential Pumping Section

The provision for windowless (line-of-sight) radiation transport through the LCLS x-ray optics system will be accomplished with conventionally implemented vacuum pumping at all locations generating non-negligible gas loads and by special Differential Pumping Sections (DPSs) bracketing all the chambers in which Ultra High Vacuum (UHV) environments need to be maintained. The DPS chosen for this task [35] develops a large isolation ratio across its length by effectively suppressing the “straight-through” molecular flux propagating along the axis of its line-of-sight aperture. This flux component, which is usually the limiting factor in the effective conductance of straight-through ducts, is blocked by generating a high-density electron cloud along a section of the duct volume. The electrons, generated, trapped, and accumulated by a structure similar to that of a conventional ion pump, ionize the propagating molecules, allowing them to be deflected and trapped on getters or duct walls by various well-known mechanisms [36]. A drawing of a typical pump structure (omitting the external magnet) is shown in Fig. 10.4-3. The performance of the pump in isolating N2 ambient pressures is shown in Fig. 10.4-4. In continuing the x-ray optics engineering studies, we will optimize the DPS design for adequate pumping of the noble (and other) gases that may be employed in the x-ray transport and optics systems.
Figure 10.4-3. Differential pump chamber and connecting flange geometry.

Figure 10.4-4. Projected differential pump performance curves for N₂ versus aperture diameter. Aperture length 15 cm.
10.4.2 X-ray Slits (Collimators)

At 15 GeV the x-ray beam entering the x-ray optics transport system following the beam dump consists of an intense coherent FEL line with an FWHM angular divergence of ~1 µrad (~9 µrad at 5 GeV) surrounded by a broad spontaneous distribution with an FWHM angular width of ~100 µrad (~310 µrad at 5 GeV). For particular experimental applications, the low energy spontaneous radiation can constitute a noise source and needs to be removed. For other applications, removal of the full off-axis spectrum may be required. These considerations have led to the introduction of the two-slit-pair system shown in Fig. 9.1-2. The first slit-pair is located just upstream of the absorption cell so that low energy spontaneous radiation can be filtered out for scattering experiments located at the cell. The second slit-pair, located ~15 m farther downstream, can also be used as an independent aperture, or combined with the first slit-pair to provide an angular collimator with an extremely small acceptance, providing a broad range of spectral-angular filtering options, including the delivery of quasi-monochromatic beams. As will become clear from the energy-loading calculations presented below, an additional, equally important function of the slits (when operated with suitable ancillary collimators) will be to protect the mirrors from excessive peak power damage stemming from transient beam jitter.

The configuration of each slit-pair is schematized in Fig. 10.4-5. The basic strategy is to control both the minimal aperture of each slit (d_{LV} or d_{RH}), as well as the angles of incidence presented to the off-axis x-rays—\( \tan^{-1}((d_{uv} - d_{dv})/L) \) or \( \tan^{-1}((d_{uh} - d_{dh})/L) \). The basic structure of each slit segment (jaw) consists of a low-Z substrate to minimize bremsstrahlung propagation, coated with a high-Z material to maximize reflectivity at a given incidence angle (which in the present design is assumed to be greater than the critical angle). The nominal materials considered for our initial design studies were Al and Au. For the actual structure we propose to use a modified version of an existing SLC collimator design as presently employed in the SLAC beam switchyard for collimator C-0 and momentum slit SL-2 [37]. The modification will replace the existing jaws, which have curved surfaces, with the geometry of Fig. 10.4-5. The most recent jaw design assumes a 0.5-m long block of Al heat-treated for exceptional dimensional stability. The collimating surface will be lapped flat to a low surface roughness of 50–100 nm (rms). The high-Z material will be deposited onto this surface to a thickness of a few-to-several µm and polished. Although average power deposition will be modest and cooling by thermal radiation appears acceptable, the jaws will nevertheless be water-cooled for optimal dimensional stability during operation. In the existing chamber design, the jaws are remotely adjustable by means of stepper motors and can be differentially adjusted to control \( d_{uv}, d_{dv}, d_{uh}, \) and \( d_{dh} \), as well as the average vertical and horizontal midplanes of the slits. A maximal incidence-angle range of ~0–1.5 mrad is envisaged, and the minimum aperture size will be variable from 0 to >1 cm.
Although the average x-ray beam power deposited into the jaws through the reflecting surfaces is expected to be quite small, the total cross section of the spontaneous radiation at both slit locations will be significantly larger than the upstream slit apertures $d_{uv}$ and $d_{uh}$. This means that not only can one or more of the slits absorb most of the spontaneous x-ray power during operation, but that most of it will impact the jaws’ upstream faces at normal or near-normal incidence. As calculated in Section 10.2, the spontaneous peak power density at normal incidence can attain off-axis values within three orders of magnitude of that of the coherent spectral line, which brings the peak power densities anticipated for the jaws to levels at which little or no experimental data exist. Similar peak power levels in the high-Z reflecting material (assuming ~99% reflectivity) can be expected for scenarios where the LCLS coherent spectral line impacts the jaw surface, whether due to jitter or for other reasons. For illustration, a list of characteristic absorption lengths for five high-through-low-Z materials is shown for selected LCLS harmonic energies in Table 10.4-1. Based on the tabulated values, energy absorption data for a block of tungsten were calculated and are listed in Table 10.4-2. The peak power absorption value, after folding in a double-convoluted Gaussian angular distribution, was found to be $\sim 3 \times 10^{13}$ W/cm$^3$ for the coherent LCLS fundamental. At this level of power loading, the total absorbed energy per pulse is high enough to bring the temperature near to the melting range of tungsten. Should the incidence angle attain substantially larger values (e.g., by the coherent striking one of the slit jaws’ upstream faces), the energy absorption could approach catastrophic values. For this reason, additional protective apertures will be incorporated into the final slit assembly designs.

For the spontaneous harmonics, the total absorbed energy density per pulse is, even in this worst-case limit, small enough to result in relatively safe temperature increases when
averaged over sufficiently long intervals of time. On the other hand, since for both the fundamental and spontaneous radiation the absorbed energy is deposited in a time interval too short for thermalization and diffusion processes to evolve, energy removal may proceed via mechanisms that could induce alternative types of irreversible damage in the jaw materials. Although there is some evidence of survival of mirrors exposed to very high specific power densities from alternative sources, the processes that take place in the temporal and spectral regimes of the LCLS [38] are still very poorly understood and more experimental and theoretical studies will be needed.

Table 10.4-1. Normal-incidence 1/e absorption lengths (in μm) for W, Cu, Ti, Al, and C versus LCLS harmonic photon energy.

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<td>27040</td>
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</tbody>
</table>

<sup>a</sup> fundamental
Table 10.4-2. Energy absorption data for tungsten at 15 GeV. Assumed -0.0015 rad incidence angle (-99% reflectivity for the fundamental; <<100% for the harmonics). FWHM beam waist 80 μm.

<table>
<thead>
<tr>
<th>Harmonic #</th>
<th>Source Photons per Second, per 1% BW (x10(^{-22}))</th>
<th>1/e Absorption Volume [cm(^3)] (x10(^{-8}))</th>
<th>Beam Power [W] (x10(^{-7}))</th>
<th>Absorbed Power Density [W/cm(^3)] (x10(^{-13}))</th>
<th>Absorbed Energy Density(^d) [J/cm(^3)-pulse]</th>
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<td>2400(^b)</td>
<td>1.08</td>
<td>3260</td>
<td>3019</td>
<td>8568</td>
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<td>1(^c)</td>
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<td>0.24</td>
<td>378</td>
<td>10.1</td>
<td>2.67</td>
<td>7.48</td>
</tr>
</tbody>
</table>

a. Coherent fundamental.
b. Per 0.1% BW
c. Spontaneous fundamental.
d. \(\sigma_T = 112\) fs.

10.4.3 Personnel Protection System Beam Stoppers

Two Personnel Protection System (PPS) beam stoppers will be required to allow entry into the experimental hutch while the \(e^-\) beam is being delivered to the undulator and deflected into the dump. The function of these stoppers is to block and absorb any coherent or incoherent \(\gamma\) or \(x\)-radiation from the undulator, as well as bremsstrahlung from anywhere in the beam transport system. These stoppers are patterned after an SLC design used in Sector 10 of the SLAC linac and in the PEP-II extraction lines [39]. The design energy is 15 GeV, and the assumed power for continuous exposure is P\(_{AV}\)\textasciitilde5 kW. The absorbing element in each stopper is a copper/tungsten block assembly with an overall length of
20.32 cm [~22 radiation lengths ($X_0$)]. The beam first encounters the 3.7 $X_0$ long Cu section. The remaining 12.3 $X_0$ are provided by a block of free-machining tungsten (tungsten content $\sim 90\%$, $\rho \sim 17$ g/cm$^3$) which is brazed to the Cu. The shower maximum of the electromagnetic cascade for 12-15 GeV occurs at a depth of 5.5–5.7 $X_0$. A built-in burn-through monitor is located at that z-depth. It consists of a pair of cavities separated by a Cu diaphragm. The first cavity is pressurized with dry N$_2$. Its return line contains a pressure switch with the trip level set to 15 psig. Should excessive beam power be deposited in the stopper block, the diaphragm will perforate, allowing the N$_2$ to escape into the second cavity, which is open to atmospheric conditions on the outside. The pressure switch will interrupt beam delivery within 2–3 linac pulses. The transverse dimensions of the stopper block are 3.16 cm wide x 2.9 cm high. The minimum radial attenuation distances are then, respectively, 3.5 $X_0$ and 3.1 $X_0$ in the Cu section and 7.7 $X_0$ and 7.1 $X_0$ in the free-machining tungsten. This is more than adequate to attenuate the radial shower.

The absorber block can be vertically inserted or removed from the beam channel by means of a remotely controlled air cylinder. The block has a water-cooled heat sink attached to the top surface, which allows continuous and safe dissipation of up to 5 kW of beam power.

A third stopper will be installed which is essentially an ordinary pneumatic valve with no special heat-removal provisions. It is intended for protective insertion when the linac is running in an ultra-low peak or average current mode, for which the average radiation power is on the order of milliwatts or less.

### 10.4.4 Absorption cell

Attenuation of the coherent pulses of the LCLS can be accomplished by passage through a gaseous, solid, or liquid medium. The nominal LCLS design is for a gas cell operated with high pressure puff valves to introduce the absorbing gas into the path of the coherent FEL photons (see Fig. 10.4-6, left). The axial dimensions of the chamber and the number of valve nozzles must be adequate or numerous enough to allow a sufficient thickness of the gas to provide four or more orders of magnitude of attenuation over the full range of the LCLS fundamental energy (820 eV–8.2 keV). The combined axial and transverse dimensions are determined by the requirement of maintaining an average vessel pressure of <0.0075 Torr, corresponding to the Knudsen-through-molecular flow regimes [40]. This pressure, which (for N$_2$) is sufficiently low to be reduced to $< 10^{-6}$ Torr by the differential pumping sections bracketing the chamber [35], will be determined primarily by: (1) the average volume of gas introduced into the chamber per puff, (2) its average pressure, (3) the axial conductance out of the gas cell, (4) the chamber volume, (5) the puff valve repetition rate, and (6) the capacity of the primary pump(s) connected directly to the chamber. A set of valve and vacuum parameters for the absorption cell representing maximal loading conditions is listed in Table 10.4-3. Initial design calculations show that the gas absorption will be able to support
initial operation of the LCLS at 120 Hz. Additional R&D will be required to optimize performance of the pump for alternative gases [36] and nozzle geometries.

Although no comprehensive simulations of the interaction of the LCLS pulses with candidate absorbing media have as yet been undertaken, the operation of the gas cell in the weak-field (linear) regime using xenon as an absorber has been calculated for reference. In Fig. 10.4-7 the absolute attenuation of x-rays through xenon for four given pressure $\times t_g$ [Torr-cm] products is plotted from 800 to 25000 eV. The curves indicate that a 7500 Torr Xe gas jet with $t_g = 1$ cm would provide an attenuation factor of $\sim 10^{-4}$ for an input intensity at which the absorption mechanisms are essentially unimolecular and linear. With suitable design and a sufficiently low pulse repetition rate, the loading of the vacuum system by the required amount of gas should be maintainable at acceptable levels.

![Figure 10.4-6. Schematized gas (left) and liquid (right) nozzle configurations for the LCLS absorption cell.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve Rep Rate [Hz]</td>
<td>120</td>
</tr>
<tr>
<td>Valve Pressure [Torr]</td>
<td>7500</td>
</tr>
<tr>
<td>Particles/Puff</td>
<td>$6.65 \times 10^{17}$</td>
</tr>
<tr>
<td>Chamber Pump Capacity [l/s]</td>
<td>1800</td>
</tr>
<tr>
<td>Gas Load Q [Torr-l/s]</td>
<td>2.25</td>
</tr>
<tr>
<td>Average Pressure [Torr]</td>
<td>$1.25 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Table 10.4-3. Absorption cell valve and vacuum parameters. Valve orifice width 250 $\mu$m; $t_g=1$ cm; gas jet height 1 mm.

An alternative system with a substantially smaller vacuum loading effect could be based on a liquid metal, such as gallium [41,42]. As schematized in Fig. 10.4-6 (right), the surface area of a liquid stream exposed to the vacuum could, with proper reservoir and baffle design,
be kept small even with the use of continuous pumping, while the time-averaged vacuum loading could be further reduced with suitably designed rotating beam shutters. In Fig. 10.4-8 a set of attenuation curves is plotted over the 800–25000 eV range for three values of $t_1$. A jet with a thickness controllable over a range of 0.1–1 mm, could evidently provide effective attenuation over the entire fundamental-through-3rd-harmonic range of the LCLS.

![Graph](image1)

**Figure 10.4-7.** Weak-field attenuation curves for xenon.

![Graph](image2)

**Figure 10.4-8.** Weak-field attenuation curves for gallium.

As a third option, an attenuator system based on movable foils could also be employed [20]. Such a system would be destructive, and would probably need to employ synchronized
shutters bracketing the foil to capture debris and inhibit contamination of the vacuum system. Relatively frequent access to the absorption cell to replace the obliterated absorbing material would also be required.

The absorption cell will be used for initial studies of scattering of the LCLS pulses by absorbing media. The chamber design, predicated on the initial use of xenon, includes ports for line-of-sight fluorescence detection, as well for the introduction of external magnetic and electric fields. Due to its location inside the FFTB tunnel, provisions for a detector shielding enclosure has been included (see Fig. 9.1-2).

A basic question at this point is how the actual LCLS pulses, whose intensity and degeneracy parameters lie well outside the regime of weak-field interactions, will interact with candidate absorbing media. To resolve this question to the degree at which a satisfactory prediction of the absorption cell’s performance vis-a-vis its linear absorption characteristics can be made, a number of physical processes, parameters, and effects must first be theoretically analyzed, understood, and calculated. The primary parameters are the cross sections of the various scattering and energy conversion processes encountered by the radiation (see Fig. 10.4-9). At the field strengths of the LCLS, absorption mechanisms that are ordinarily negligible for weak fields can become activated [43] and grow strong enough to significantly influence the total absorption cross section. Potentially prominent ones include: (1) multi-photon absorption or ionization, and (2) field (tunneling) ionization. A second set of critical parameters includes the time constants associated with the various absorption and scattering processes. Here a distinction is usually drawn between processes taking place at the individual molecular level and those involving collective interactions. Again, the high field strength and degeneracy parameter of the LCLS can complicate a quantitative assessment. For example, if the spatial density of coherent photons is of the order of the absorber’s atomic density, it may be necessary to treat some or all of the ordinarily independent absorption mechanisms as collective phenomena. In view of these and other complexities, the question of how well various gaseous or liquid absorbers will attenuate the LCLS pulses in contrast to weak-field radiation will probably be ultimately answerable only with actual experimental measurements. Notwithstanding this, the curves presented in this section may be regarded, for purposes of coarse estimation, as lower bounds on the actual (unimolecular) absorptivities, primarily due to the activation of additional scattering mechanisms that are inoperable in the weak-field regime.

Regarding the propagation of the pulses through the absorbing medium, in addition to the above-mentioned cross sections, the dynamics and characteristic time constants of the dominant energy-conversion channels in the absorbing medium must be known. In a broad discussion of the physical interactions representative of a gas or liquid absorber, it is useful to refer to six fundamental time constants: (1) $\Delta \tau_{LCLS}$, the temporal interval between LCLS pulses (for 120 Hz operation, $\Delta \tau_{LCLS} = 8.33$ ms); (2) $\tau_{\text{pulse}}$, the FWHM temporal pulse length ($\sim 233$ fs); (3) $\tau_{\text{spike}}$, the FWHM temporal length of the average random spike contained in the full FEL pulse ($\sim 0.25$ fs); (4) $\tau_{\text{EL}}$, the time constant associated with the fastest (electronic)
scattering, absorption, or ionization mechanisms (e.g., resonant scattering, single and multiple photon ionization, tunneling ionization, multiple-photon scattering, etc.); (5) \( \tau_\text{F} \), the characteristic duration of fluorescence processes; and (6) \( \tau_\text{A} \), the time constant of the longest (collective) energy-conversion and thermodynamic processes in the medium (e.g., thermalization, charge neutralization, relaxation back to equilibrium, etc.). In general, the relations \( \tau_\text{spike} < \tau_\text{pulse} < \Delta \tau_\text{LCLS} \) and \( \tau_\text{EL} < \tau_\text{F} < \tau_\text{A} \) will apply. An additional characteristic parameter relevant to operation with a gas or liquid jet, is the flow velocity, which, if high enough, can re-establish a locally neutral and equilibrated absorbing medium by the time of arrival of the subsequent pulse.

![Diagram](image)

**Figure 10.4-9.** Energy-conversion and scattering channels for radiation passing through an absorbing medium.

For an assumed static medium, the propagation of the LCLS pulses through the absorption cell can be represented as in **Fig. 10.4-10.** A fundamental question to be resolved for scientific experiments or pulse metrology utilizing the cell is the effect of its various scattering and absorption processes on the temporal shape and the longitudinal and transverse coherence of the pulses. Although to first order it can be assumed that there will be an unscattered (as well as elastically scattered) fraction of photons [44] that will retain their incoming coherence properties, an accurate quantitative estimate of this fraction may, for various regimes of LCLS parameter space, be difficult to obtain [45]. Additionally, non-linear absorption mechanisms may substantially modulate the photons’ temporal distribution. For example, apart from the non-linearities associated with high fields, those that collectively saturate, or “use up” available electronic transitions can subject the downstream part of the pulse to stronger absorptivities than its upstream end [46]. Finally, if the interval \( \Delta \tau_\text{LCLS} \) becomes too short, the overall model for propagation will acquire additional complexity due to the fact that the medium’s state will bear the imprint of preceding pulses.
10.4.5 Mirrors

From the output parameters listed in Table 10.1-1 it can be estimated that a coherent photon pulse at normal incidence can deposit of the order of 10–100 eV per atom for absorptivities [47] and penetration depths typical of solid state materials in the x-ray range. This level of energy loading, which is high enough to enhance the probability of irreversible lattice damage, can pose a serious problem for optical elements that are expected to handle more than a small number of pulses over their lifetimes.

A natural way of trying to accomplish this is by decreasing the angle of incidence, $\theta_i$, with respect to the optical surface. This will not only dilute the power density inversely with $\theta_i$ but the density of damage sites as well, compounding the effective improvement in the optic’s longevity. Should the required $\theta_i$ prove to be impermissibly small, a configuration of equal-$\theta_i$ multiple reflectors, as shown in Fig. 10.4-11, could be used to increase the total reflection angle, $\theta_T$, to an acceptable value.

![Figure 10.4-11. Tandem-grazing-incidence reflector geometry. $R_m$ is the reflectivity and $\hat{n}_m$ the complex index of refraction of the mth reflector.](image)
To assess the ultimate effectiveness of this approach, it is first necessary to analyze how the distribution of deposited energy varies with $\theta_i$ and the material parameters of the optic in question. Assuming an approximately equal absorption of energy in each reflector in Fig. 10.4-11 ($R_m$=R~1 for all m), a convenient expression for the absorbed energy density in terms of the relevant optical parameters of the photon beam and reflecting medium, is easily derived [20]:

$$\eta_A [eV/\text{atom}] = \frac{P_{\text{peak}} \sqrt{2} \sigma_T}{q} \left[ \frac{\theta_i}{D_w} \right] \left[ 1 - \frac{R}{\delta_p \#} \right]$$

(10.4.1)

Here $P_{\text{peak}}$ is the peak coherent power (Table 10.1-1), $\sigma_T$ is the standard deviation of the temporal pulse length, $q$ is the electronic charge in MKS units, $D_w$ [cm] is the beam diameter at the optic, $\delta_p$[cm] is the 1/e penetration depth of the light into the material in a direction normal to the surface, and # [cm$^{-3}$] is the atomic density of the material. Since it is known from first principles that the probability of lattice disruption will be high when the deposited energy density is on the order of 1 eV/atom, our aim is to determine if parameters for grazing-incidence reflection can be found for which $\eta_a << 1$.

To establish this, the parameter $R$ needs to be quantitatively investigated as a function of $\theta_i$ and the optical constants of the reflecting material. Following conventional analysis [48], we define the TM and TE reflectivities

$$R_{TM} = \frac{\rho^2 (\sin \theta_i - \rho)^2 + k^2}{\rho^2 (\sin \theta_i + \rho)^2 + k^2}$$

(10.4.2)

and

$$R_{TE} = R_{TM} \frac{\rho^2 (\cos \theta_i \cot \theta_i - \rho)^2 + k^2}{\rho^2 (\cos \theta_i \cot \theta_i + \rho)^2 + k^2}.$$  

(10.4.3)

Here

$$\rho = \sqrt{\frac{1}{2} \left[ \sin^2 \theta_i - 2 \delta + \sqrt{(\sin^2 \theta_i - 2 \delta)^2 + 4k^2} \right]}$$

(10.4.4)

and $\delta$ and $k$ are the decremental components of the complex index of refraction $\hat{n} = 1 - \delta + ik$. For this study, it is convenient to identify the “critical angle” $\theta_{ic}$, the incidence angle for which $\sin \theta_{ic} \equiv \theta_{ic} = (2 \delta)^{1/2}$. At this angle, the use of higher-Z reflecting materials generally improves the reflectivity, since $\delta$ increases with $Z$ and $R_{TE(TM)}$ generally increases for $\theta_i < \theta_{ic}$. At the same time, since there is interest in the smallest feasible incidence angles, there is also interest in the behavior of $R_{TE(TM)}$ for $\theta_i << \theta_{ic}$. Inserting this condition into (Eq 10.4.2) and (Eq. 10.4.3) and expanding, gives [49]
which reveals the dependence of the reflectivity on the ratio $k/\delta$ in this limit. Since this ratio drops rapidly for low-Z materials, for certain values of photon energy and $\theta_i$, the optimum power loading performance may shift from high-Z to low-Z materials [50].

For the present study, the polarization of the incident light has been set to TE under the assumption that it may be less conducive to the initiation of peak-field damage mechanisms than TM. Fig. 10.4-12 shows the reflectivities of three candidate reflecting materials: an Au (high-Z), Ni (medium-Z), and Be (low-Z) in for three representative values of the LCLS’ coherent fundamental and ~3rd harmonic lines (900 eV, 8500 eV, and 30000 eV). The physical constants for the calculations were generated using the recently installed XREFLECTION utility at SSRL [51]. As expected, the 3 db rolloff angle at each energy increases with Z.

Next, denoting the wavelength of the incident radiation by $\lambda$, and taking $\delta_p = \lambda \rho / 4\pi k$, $\eta_A$ (Eq. 10.4.1) is plotted versus $\theta_i$ for the same set of materials and photon energies, in Fig. 10.4-13. The curves clearly exhibit the aforementioned interplay between the atomic number Z, $\theta_i$, and $\tilde{n}$ as a function of photon energy. Thus, while Be is seen to offer superior performance at energies >2.6 keV, its performance at 1 keV is greatly inferior to that of the higher-Z materials. The selection of materials and mirror parameters for the LCLS can proceed on the basis of the information shown in Figs. 10.4-12 and 10.4-13. Selecting, e.g., $\eta_A \leq 0.01$, a criterion suggested by earlier experimental work at SSRL [52], for example, an Au-coated mirror with $\theta_i \sim 0.0001$ for energies <3 keV, and a Be-coated reflector with $\theta_i \sim 0.0005$ for all energies >3 keV may be selected. The general result is that, for acceptable power-loading performance, the optimal Z of the materials utilized for the specular optics (slits, mirrors, diffraction gratings, etc.) on the LCLS beam lines will depend on the spectral regime in which they operate.

The theoretical results arrived at need to be integrated with a number of practical considerations in developing a mirror design. First, due to the high power and peak fields of the LCLS pulses, the issue of surface roughness is of paramount importance. As it is clear from Eq. 10.4.1 and the performance graphs, even a minor degradation of R (which decreases exponentially with the square of rms roughness) can drive $\eta_A$ rapidly to values in excess of 1. Thus, not only does the selected mirror material need to exhibit acceptable power loading performance in the ideal limit, but it must also be polishable down to rms roughnesses in the range of 1-3 Å. Second, the value of $\theta_i$ will define, for a given $D_w$, the required length of the mirror. In this respect the mirror length will be quite sensitive to the actual value of $\eta_A$ at which the mirror is operated. Thus, in order to avoid the use of extremely long mirrors (e.g., >1 m) it will be important to identify and utilize those high-Z materials that exhibit the least amount of damage over time. Finally, for similar reasons, the
use of materials with surfaces least prone to the accumulation of carbon and other material deposits over time will be necessary.

![Graph](image1)

**Figure 10.4-12.** Reflectivity (TE) of candidate LCLS mirror materials versus grazing incidence angle and LCLS energy.

![Graph](image2)

**Figure 10.4-13.** Peak power energy loading of candidate LCLS mirror materials versus (TE) grazing incidence angle and LCLS energy.

An initial configuration developed for the mirrors and mirror chamber (tank) of the LCLS [53] is shown in **Fig. 10.4-14.** The multiple-mirror reflectors are stacked in a vertical bank to allow the appropriate reflector to intercept the beam with a vertical motion. The
mirror width (shown as a nominal 4 cm) allows a large degree of mitigative redundancy against surface damage by repeated vertical displacements. The length $L$ of each facet is determined by the value of $\theta_i$ utilized for its particular reflector. Provisions for UHV pumping and in situ cleaning [54], which may prove to be critical to the practical longevity of the reflectors, are included. For illustrative purposes, a set of nominal mirror dimensions and mirror bank parameters is listed below in Table 10.4-4. Evidently, facet length will be a sensitive parameter for higher-Z reflecting materials, and the initial design parameters of the mirror enclosure may need to be revised, or additional enclosures added, to accommodate multiple reflectors.

![Diagram](image)

**Figure 10.4-14.** LCLS mirror chamber geometry.

<table>
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<tr>
<th>Mirror Material</th>
<th>Energy Range</th>
<th>$m$</th>
<th>$L$ [m]</th>
<th>$\theta_i$ [rad]</th>
<th>$\theta_T$ [rad]</th>
<th>$\eta_A$ (x 10^-4) [eV/atom]</th>
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<td>0.0004</td>
<td>0.0004</td>
<td>6-0.12</td>
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<tr>
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<td>1</td>
<td>0.0001</td>
<td>0.0004</td>
<td>200</td>
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</tbody>
</table>

In view of the importance of specular reflection, fundamental areas of investigation include the theory and modeling of the interaction of ultra-intense, ultra-short x-ray pulses with matter [45]. Such studies, coupled with selected experimental investigations, are needed to shed light on a number of physical effects with the potential of inducing damage. These include radiation field/surface interactions versus surface roughness and surface contaminants; radiation/surface interactions as a function of polarization; photoemissive
surface stresses induced by radiation pulses; and bulk and surface ionization-related damage effects. Regarding the mirror tank and the mirrors, engineering R&D will be required for the ongoing identification and study of alternative mirror materials with optimal properties, the development of adequate in situ cleaning processes for those that are selected, and the fabrication, polishing, and testing of prototypes.

10.4.6 Crystals

In view of the broad-based scientific case developed over the last 4 years for an x-ray FEL [55,56,57,58], the use of crystals and crystal-based instrumentation will undoubtedly prove to be critical to the ultimate productivity of the LCLS. Depending on the unit cell structure of the material and its lattice spacing, a number of candidates can efficiently diffract LCLS radiation in the <3–5 Å wavelength range, for which a broad depth of experience has been acquired at storage ring SR and other facilities over the last 20 years. In recent years in particular, the development of established techniques for crystal-based instrumentation design [59] has been brought to a state of reliable maturity at 3rd and earlier-generation SR facilities [60,61,62]. Singular enhancements in practical crystal performance have been brought about by two relatively recent technological advancements: (1) the development of perfect (mosaic-free) Si and C crystals, and (2) the introduction of cooling techniques that can operate diamond crystals at temperatures at which the sensitivity of lattice distortion to heat loading is drastically minimized [63]. Given the evident promise of crystal technology for LCLS applications, it is important to assess whether or not the unprecedented peak power densities of the LCLS could be expected to inhibit its use.

Assuming a crystal cut to a thickness equal to its extinction depth, \( t_e \) [64], and using a set of simple conservative assumptions to obtain an estimate of power and energy loading. The assumptions are: (1) the angles of incidence of the radiation (with respect to the surface plane) are large enough to enforce negligible reflection; (2) on the average, the diffracted beams travel through approximately the same distance in the material as the 0th order beam; and (3) on average, the absorption depth, \( t_A \), for the diffracted beams is the same as for the incoming beam. Under these conditions, an expression for the energy loading of the crystal material (in eV/atom), analogous to Eq. 10.4-1, is straightforwardly derived:

\[
\eta_A \text{[eV/atom]} \equiv \frac{P_{\text{peak}} \sqrt{2\pi\sigma_\tau}}{q \tau \frac{D_w}{2} \#}.
\]  

(10.4.6)

Table 10.4-5 shows selected physical constants [63] and \( \eta_A \) for various crystal plane orientations for Be, C, and Si. The lower absorbivities of the lower-Z materials result in substantially lower energy loading, in fact down to levels comparable to those that were presumed marginal for the mirror materials in Section 10.4-5. On the other hand, even at 1.5 Å, it is evident that carbon (i.e., diamond), ostensibly the material of choice, is beginning
to experience substantial loading. At wavelengths > 2–3 Å, the corresponding numbers for all three materials would begin to warrant serious concern.

Table 10.4-5. Selected crystal and energy loading parameters under LCLS beam conditions at 1.5 Å. $D_W=100 \mu$m. Assumed crystal thickness - $t_c$.

<table>
<thead>
<tr>
<th>Material</th>
<th>Lattice Spacing $d_H$ [Å]</th>
<th>1st Order Diffraction Angle [°]</th>
<th>Resolution $\Delta \lambda/\lambda$ (x10^-6)</th>
<th>Absorption Depth $t_A$ [µm]</th>
<th>Extinction Depth $t_e$ [µm]</th>
<th>$\eta_A$ [eV/atom]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be (002)</td>
<td>1.7916</td>
<td>24.75</td>
<td>22.8</td>
<td>1200</td>
<td>5</td>
<td>0.014</td>
</tr>
<tr>
<td>Be (110)</td>
<td>1.1428</td>
<td>41.02</td>
<td>7.1</td>
<td>1874</td>
<td>3.3</td>
<td>0.009</td>
</tr>
<tr>
<td>C (111)</td>
<td>2.0593</td>
<td>21.36</td>
<td>52.7</td>
<td>250</td>
<td>2.2</td>
<td>0.069</td>
</tr>
<tr>
<td>C (220)</td>
<td>1.2611</td>
<td>36.49</td>
<td>12.3</td>
<td>408</td>
<td>4.16</td>
<td>0.042</td>
</tr>
<tr>
<td>Si (111)</td>
<td>3.1354</td>
<td>13.84</td>
<td>135</td>
<td>8.7</td>
<td>1.48</td>
<td>2.011</td>
</tr>
<tr>
<td>Si (220)</td>
<td>1.9200</td>
<td>22.99</td>
<td>57.7</td>
<td>14.2</td>
<td>2.12</td>
<td>1.232</td>
</tr>
</tbody>
</table>

In spite of this, the following observations can be made. First, it is determined that the best candidate materials for crystal optics are those of lowest Z, i.e., diamond and, possibly, Be. Second, it is possible to utilize special lattice orientations (using asymmetrically cut crystals) that could further decrease the absorbed power density, albeit at some cost in optical performance. Third, it is in principle possible (albeit expensive) to adapt to overly rapid damage accrual by employing dynamic optics [20], i.e., by displacing the crystal to successively new exposure points following a definite series of pulses. Ultimately, the actual longevity and performance of candidate crystals will of course need to be experimentally determined. An obvious critical parameter is the wavelength at which unacceptable levels (or rates) of irreversible damage appear, and whether this wavelength will seriously limit the possibilities for crystal-based instrumentation at energies at or below 8.5 keV. The further theoretical and numerical investigation of peak power damage effects in crystals, coupled with testing on alternative sources prior to the operation of the LCLS, is a fundamental component of the R&D program.

For completeness, the use of synthetic Bragg reflectors (multilayers) can also be considered as a crystal option for those LCLS applications requiring low-to-moderate spectral/angular resolutions. Although a broad base of experience has been accumulated in developing multilayers for SR applications in the energy range of the LCLS [65,66,67], they are probably inferior—in terms of damage sustainability—to the elemental crystals discussed above. First, at the angles of incidence required for efficient operation, the typical depth presented to the radiation will be similar to or greater than the values of $t_c$ listed in Table 10.4-5. In view of the fact that one of the materials will typically have a moderate-to-high Z, the corresponding energy loading will be substantially more severe than for the homogeneous low-Z crystals. Second, the bonding between the layer materials, as well as
their internal homogeneities are, on the average, substantially poorer than in perfect crystals, leading to the acceleration of damage mechanisms [68]. Finally, the disparity between the bulk and surface properties of the substrate (which would almost certainly need to be a low-Z material such as Be or C) and the multilayer constituents could also be expected to contribute to the activation or exacerbation of irreversible damage processes. Nonetheless, the exposure of multilayers to the LCLS pulses is of inherent interest, and the operation and investigation of multilayers at the LCLS is expected to become a continuing R&D activity.

### 10.5 Beam Line Optical Instrumentation

The beam line optical instrumentation may be classified into two categories: (1) conventional instrumentation, intended for operation in conjunction with the absorption cell; and (2) instruments and components specially designed or developed to handle the peak power density of the coherent light. Each of these may be further subdivided according on the spectral range that is involved (see Section 9.3.1). In category (1), custom-designed or commercially available monochromators, spectrometers, interferometers and calorimeters can be employed, both to perform beam diagnostics and to support initial experiments. The second category of instrumentation, which will be developed as experience with the unprecedented x-ray power densities is acquired, will be designed both for particular experimental applications, as well as to further control and enhance the spectral-angular, temporal, polarization, and coherence properties of the LCLS beam [20]. The design of such components (e.g., monochromators, interferometers, beam splitters, etc.) is expected to present both significant challenges and opportunities. For example, the diffraction-limited transverse source volume of the LCLS should allow the development of simple monochromator configurations in which the beam source serves as the entrance aperture. At the same time, special care may need to be exerted in the use of diffraction gratings in the specular wavelength regime (>3–5 Å). For example, their ordinarily sharp-featured grooves may need to be made smooth to mitigate against high edge-field effects, and the usual transverse orientation of the grooves with respect to the light may need to be switched to a conical diffraction geometry. As another example, the development of microfocusing optics [52,69] aimed at approaching the diffraction-limited waist size is an extremely challenging goal, which if pursued diligently enough, could substantially extend the range of scientific applications at the LCLS. Due to potential damage effects and the extreme brevity of the radiation pulses [70], special techniques such as transverse or longitudinal beam expansion and compression, spectral filtering, or novel elements such as multi-phase or dynamical optics, may need to be developed to attain the desired spectral profiles, resolving powers, and efficiencies. Current and projected R&D activities in this area include: (1) theoretical and computer investigations of short-pulse effects, instrumentation concepts and systems; and (2) demonstration experiments on optical components to investigate limiting effects related to coherence, specular and interfacial scattering, and peak power damage. A number of valid experiments in these areas could be initiated at emerging longer-wavelength FEL or plasma x-ray laser facilities [55,71,72].
10.6 References


**TECHNICAL SYNOPSIS**

The control system for the LCLS consists of three separate systems. (A) The control system currently running the SLAC facility will control and monitor the operation of the photocathode gun and accelerator systems up stream to the undulator. (B) A workstation will control and monitor the operation of the undulator systems. These systems include: (1) Undulator segments and steering magnets alignment and stabilization movers. The motion controls and movers of the undulator segments need to operate over a limited range of +/- 0.5 mm with a resolution of 10 \( \mu \text{m} \). The undulator segments will be mounted on five cam-movers (x, y, roll, pitch, and yaw). The motion controls and movers of the undulator steering correctors need to operate over a limited range of +/-0.5 mm with a position resolution of 1 \( \mu \text{m} \). (2) Wire Position Monitors (WPMs) that monitor the mechanical position of the undulator segments and their mechanically attached beam position monitors. The WPMs are designed to detect position changes with a resolution of 1 \( \mu \text{m} \) over a range of +/- 1 mm. To keep the undulator segments in their proper position requires that the signals from the WPMs will be processed on-line, and then fed back to the segment movers’ stepper motors in the form of the number of steps to move and the direction in which to move. (3) Beam Position Monitors (BPMs) that operate with high stability, low drift, low impedance, and high resolution (1 \( \mu \text{m} \) or better). The beam trajectories measured by the electron BPM signals will be processed on-line, and then fed back to the steering magnets movers. (4) Beam intercepting position monitors. (C) Another workstation will control and monitor the operation of the x-ray optics and the acquisition of data from the detectors. The x-ray optics and experiment controls have two major objectives. One objective is to provide local control of the x-ray optical elements. The x-ray optics includes the take-off mirror(s), the crystal monochromator, collimators, a gas attenuation cell, and possibly filters. The second objective is to provide local control of the experimental stations and the experiment data collection equipment. The equipment includes optical tables, adjustable slits, sample positioners, calorimeters and detectors with their associated high-speed electronics.

Most of the LCLS x-ray experiments require synchronization of the experimental station’s equipment with the electron beam. The electron beam, in turn, is phased to the 476 MHz of the SLAC master clock. Temporal jitter between the RF and the beam is specified to less than 0.5 ps. A timing system is designed to assure that the synchronization between experiment lasers and the FEL x-ray (External Pulse Class of experiments) have jitter better than 1 ps for time delays of +/-1 ns and better than 1 ns for time delays of +/-10 ms.
11.1 Control System

The LCLS operation will be controlled by three separate systems: (1) the photocathode-gun and accelerator controls; (2) the undulator controls; and (3) the x-ray optics and the experimental stations controls.

1. Since part of the SLAC Linac will be used as the LCLS accelerator, the control system currently running the SLAC facility will be used to operate the LCLS systems up stream to the undulator. Systems, such as the RF photocathode gun, the accelerator, the beam steering, as well as access to the FFTB tunnel will be controlled and monitored from the SLAC Main Control Center (MCC). Touch-panel consoles located in the MCC provide the human interface to the machine hardware. For commissioning and maintenance purposes, additional control terminals will be built into the electronics racks in the LCLS support buildings. Control of the systems hardware and the acquisition of data from the sensors and diagnostics instrumentation in the FFTB tunnel will be done by a CAMAC based system that is an extension of the existing SLAC control structure. Some of the LCLS specific diagnostics may be implemented in VME or VXI crates, and integrated into the existing SLC/PEP-II control structure via EPICS. EPICS is presently used at SLAC in subsystems of the PEP-II accelerator (RF system and longitudinal feedback).

2. The undulator will be operated from the LCLS Experimental Hall (see Fig. 11.1-1). A workstation will control and monitor the operation of the undulator systems. These include undulator segments and steering magnets alignment movers, Wire Position Monitors, Beam Position Monitors, and Beam-Intercepting Position Monitors. The undulator controls are described in Section 11.2. Control of the hardware and acquisition of data from the sensors and diagnostics instrumentation will be done by CAMAC and/or VXI-based systems. The workstation will include a PCI-based Interconnect Highway Driver that will be linked through a fiber-optics cable to CAMAC or VXI Interconnect Crate Controllers. The workstation will also be linked to the SLAC network. This link will allow communications with the SLC computer and with other control consoles.

3. Operation of the x-ray optics and experimental stations will be done from the LCLS Experimental Hall (see Fig. 11.1-1). Another workstation will control and monitor the operation of the x-ray optics and the acquisition of data from the detectors. It will control the mirror and crystal monochromator movers, optical tables, adjustable slits, a gas attenuation cell, sample positioners, calorimeters, and detectors. The x-ray optics and experiment controls are described in Section 11.3. Control of the hardware, and acquisition of data from the detectors and diagnostics instrumentation will be done by a CAMAC and/or VXI-based systems. The workstation will include a PCI-based Interconnect Highway Driver that will be linked through a fiber-optics cable to CAMAC or VXI Interconnect Crate Controllers. The workstation will also be linked to the SLAC network. This will allow communications with the SSRL network and with other control consoles.
The Interconnect is specifically designed to facilitate synchronous data acquisition over a distributed area while maintaining the time coherency of the data. It operates over a wide range of sampling rates and throughputs as well as collects data from a number of modular standard I/O chassis including VXI, CAMAC, and VME. The implementation of the Interconnect is based on 125 MHz bit-serial technology and a protocol that provides

Figure 11.1-1. Schematic layout for the LCLS controls.
throughputs up to 10 Mbytes/second. For short distances (up to 5 m) a coaxial cable can be used. For longer distances, or where good isolation is required, a fiber optic link is supported. Fiber optic links up to 2 km between nodes are available. The Interconnect is designed as a single master (host) with up to 126 addressable slave nodes or I/O chassis. Similar configurations using workstations with Alpha CPUs and Grand Interconnect are used by all the SSRL beam lines.

Relevant acronyms are defined in Table 11.1-1.

Table 11.1-1. Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAMAC</td>
<td>Computer Automated Measurement and Control is an IEEE-standard (583). CAMAC is widely used in SLAC (SLC, PEP II, etc.) and other laboratories.</td>
</tr>
<tr>
<td>EPICS</td>
<td>Experimental Physics and Industrial Control System is used and supported by a number of universities and DOE laboratories (ANL, LANL, LBNL, CEBAF, TJNAF, and SLAC). EPICS is a set of software tools and applications developed for the purpose of controlling particle accelerators and large experiments.</td>
</tr>
<tr>
<td>VME</td>
<td>Versa Module Eurocard is an IEEE-standard (1014). VME has become one of the most popular bus standards in use today. It is widely used in industrial, commercial, and military applications.</td>
</tr>
<tr>
<td>VXI</td>
<td>VMEbus eXtension for Instrumentation is an IEEE-standard (1155). VXI has gained broad support from the major instrumentation manufacturers and is becoming a widely accepted standard.</td>
</tr>
</tbody>
</table>

11.2 Undulator Control

11.2.1 Undulator Elements

The LCLS undulator will be comprised of 1.92 m long sections of a 3-cm-period, planar-hybrid-Halbach design. A separation of 23.5 cm between sections of the undulator will accommodate a 12 cm long permanent magnet focusing corrector, an electron Beam Position Monitor (BPM), a beam intercepting position monitor, and vacuum ports. The undulator will include 52 segments supported on piers spaced every 2.16 m. Atop the piers will be mounted movers to align each end of an undulator segment and to align the steering quadrupole magnets. The electron beam position monitors will mechanically be attached, in a fixed manner, to each upstream undulator segment, so that the electrical center of the BPM remains closely aligned to the magnetic center of the undulator segment. The position of the undulator segments, as well as the BPMs attached to them, will be actively stabilized by the Wire Position Monitor (WPM) system. The steering correctors will sit on movers attached to the piers, and the BPM system will actively stabilize their position. The position of the steering correctors will not be monitored by the WPM system, even though the piers may move due to ground motions and temperature changes.
The basic specification for alignment and stabilization is that the beam trajectory must be straight to within 5 μm over the field gain length (≈10 m). Achieving this requires that: (1) The WPMs that monitor the position of the undulator segments and attached BPMs have a resolution of 1 μm; (2) The undulator segments and attached BPMs be aligned and stabilized by motion controls and movers with a position resolution of 10 μm; and (3) The steering correctors be aligned and stabilized by motion controls and movers with a position resolution of 1 μm.

A WPM system will be installed along the undulator. The system will include two parallel stretched wires; one on each side of the undulator, with the WPMs mechanically coupled to the undulator segments. The WPM system will provide information about changes in the position of the undulator elements relative to the position of the two reference wires.

11.2.2 Mover Mechanism

The movers are needed for the initial alignment process of each undulator segment and steering magnet as well as for their mechanical repositioning should the magnets drift beyond acceptable amounts. The motion controls and the movers of the undulator segments (including the mechanically attached BPMs) need to operate over a limited range of ±0.5 mm, with a position resolution of 10 μm. The movers are designed to respond to environmental changes or disturbances that occur over extended periods, but not to those that occur sporadically and last a few seconds or less. The undulator segments will be mounted on five-cam movers (x, y, roll, pitch, and yaw), and each motion will be driven by a stepper motor. The mover design is similar to the movers used in the FFTB and the SLC final focus. These movers have a positional accuracy of ±5 μm and an increment positioning precision of ~0.5 μm under loads of several tons for all 5 degrees of freedom.

The motion controls and the movers of the undulator steering correctors need to operate over a limited range of ±0.5 mm, with a position resolution of 1 μm. The correctors will be mounted on x-y slides with no roll motion.

11.2.3 Stepping Motor Controllers and Position Potentiometers

Stepping motors will drive each camshaft through a “harmonic drive” gearbox. The motors will run in “full step,” and the gearboxes will have a gear ratio of 100:1. This will provide a resolution of 0.1 μm for a full transverse range of ±0.5 mm. The undulator control computer will calculate the number of steps and the direction that each motor needs to take. Stepper Motor Control (SMC) commands will be sent out to the drivers in the form of the number of steps needed and direction to move. Currently the movers controls design is based on a CAMAC system and SLAC SLC-type motor drivers. The final design may use a VXI-based system and commercially available stepper motor drivers. Single turn, high precision rotary potentiometers will be fixed to each cam at the end opposite to the stepping motor. The potentiometers will be used to determine the undulator segment midrange position and
to check that a motor is responding correctly to the number of steps that it has been commanded to move.

11.2.4 The Wire Position Monitor System

The mechanical position of each undulator segment and attached beam position monitor will be monitored by the WPM system. The operation of the WPM system is based on the detection of the position of two parallel stretched wires, one on each side of the undulator. Each wire is suspended inside an evacuated pipe under tension from a weight, and is not coupled or in contact with any part of the undulator. High resolution WPMs will be mechanically coupled to undulator segments, such that a movement of an undulator segment will cause its attached WPMs to move with respect to the two wires. Conceptually, a WPM consists of a U-shaped bracket with a light emitting diode on one side and a split silicon photo-diode on the other side. The split photo-diode outputs will be connected to a differential amplifier. The stretched wire runs between the emitting diode and the split photo-diode, casting a shadow on the split photo-diode. If the WPM is off-axis relative to the wire, the split photo-diode will produce a differential output signal. The signal amplitude depends on the distance of the shadow from the split diode center, and its polarity depends on the split diode that has the greater shadow. When the diode is centered about the wire, the output of the two sides of the split photo-diode is the same and the differential amplifier output is zero. Each WPM is composed of a pair of sensors. One sensor measures the displacement from the wire in the X direction and the other sensor measures the displacement in the Y direction. The WPMs are designed to detect position changes with a resolution of $1 \mu \text{m}$ or better over a range of $\pm 1 \text{ mm}$. Four WPMs will be coupled to each undulator segment to detect the position of the two parallel stretched wires. This will be sufficient to determine changes in the horizontal and vertical positions as well as possible changes in the roll, pitch, and yaw of the magnet’s orientation. A total of 208 WPMs will be required to monitor the position of all the 52 undulator segments and BPMs attached to them.

As mentioned above, the WPM system does not determine the absolute position of the undulator magnets, but rather their relative position. The WPM system detects changes in the alignment of the undulator segments with respect to the wire position. These are changes from the absolute positioning that was established when the alignment was originally established. To fully stabilize the undulator segments may necessitate a system that monitors changes in the position of the stretched wires. To keep the undulator segments and the BPMs in their proper position requires that the signals from the WPMs be processed on-line, and then fed back to the movers’ stepper motors in the form of the number of steps to move and the direction in which to move.

11.2.5 The Beam Position Monitors

The undulator steering magnets, beam position monitors, and carbon wire scanners will be installed in the 23.5 cm gaps between the undulator segments. The BPMs will be attached
mechanically, in a fixed manner, to the undulator segments. The BPMs need to operate with high stability, low drift, low impedance, and high resolution (1 μm or better). The beam trajectories measured by the electron BPM signals will be processed on-line, and then fed back to the steering magnets movers, in the form of the number of steps and direction of motion. Ten carbon wire scanners will be spaced equally along the undulator. The motion controls and movers of the carbon wire scanners need to operate over a range of approximately 1 cm, with a position resolution of 1 μm or better. The repeatability of the motion of the scanners will be monitored by using LVDTs or optical encoders that will be mechanically fixed to the scanner’s motion mechanism.

11.2.6 Control System Layout

A workstation will control and monitor the operation of the undulator systems. The systems include: undulator segments and steering magnets alignment movers; wire position monitors; beam position monitors; beam-intercepting position monitors; and ion pumps (see Fig. 11.2-1). Control of the hardware and acquisition of data from the sensors and diagnostics instrumentation will be done by CAMAC and/or VXI-based systems. The workstation will include a PCI-based Interconnect Highway Driver that will be linked through a fiber-optic cable to CAMAC or VXI crate controllers. The workstation will also be linked to the SLAC network. This link will allow communications with the SLC computer and with other control consoles.

The undulator will be operated from the LCLS Experimental Hall (see Fig. 11.2-2). The BPM and WPM processing electronics (head amplifiers), stepper motor controls, and the control crates will be installed in Building 406.
Figure 11.2-1. Functional layout for the undulator controls.
Figure 11.2-2. Schematic layout for the undulator controls.
11.3 Beam Line Electronics and Controls

11.3.1 X-ray Optics and Experimental Stations

For instrumentation and control purposes, the LCLS x-ray optics system can be divided into three parts: (1) the x-ray transport line, (2) the x-ray beam lines, and (3) the experimental stations.

1. The x-ray transport line carries the x-ray beam from the undulator into the x-ray beam line. The x-ray transport line will be installed inside the FFTB tunnel and will include the following diagnostic equipment: differential pumping sections to isolate the high vacuum systems, horizontal and vertical adjustable collimators (slits), a gas attenuation cell, and calorimeters.

2. The x-ray beam line carries the x-ray beam from the transport line and directs it to the experimental stations. The x-ray beam line will be installed in a hutch (shielded enclosure) and will include a mirror system, a crystal monochromator, differential pumping sections, horizontal and vertical adjustable collimators, and diagnostics instrumentation.

3. The experimental stations will also be installed in the hutch. A shielded partition will separate the beam line optics and the experimental stations. The experimental stations will include adjustable slits, sample positioners, detectors, and vacuum equipment to allow the continuous vacuum transport line to connect to the UHV experimental chamber. Additional equipment will be required for external pulse and time-resolved detection experiments (see Section 11.3-6).

11.3.2 Control System Objectives

The x-ray optics and experiment controls have two major objectives. One objective is to provide local control of the x-ray optical elements. The x-ray optics includes the take-off mirror(s), the crystal monochromator, collimators, a gas attenuation cell, and possibly filters. The second objective is to provide local control of experimental data collection equipment. The equipment includes the detectors and associated high-speed electronics. Timing techniques for a number of different types of possible experiments are described below in Section 11.3-6.

The LCLS x-ray optics and experimental control hardware is designed to be compatible with the SSRL beam lines optics and experimental control systems, including database and protocols. The software and applications programs that have been written for SSRL’s beam lines will be available for use on the LCLS.

11.3.3 Control System Layout

The x-ray optics and experiment control system will control the operation of the various motion controllers and actuators in the x-ray transport line, x-ray beam line, and
experimental stations. A functional layout of the x-ray optics motion and actuator controls is shown in Fig. 11.3-1. The optics and experiment control system will be installed in the LCLS Experimental Hall. A workstation will control and monitor the operation of the x-ray optics and the acquisition of data from the detectors. It will control the operation of the mirror and crystal monochromator movers, optical tables, adjustable slits, a gas attenuation cell, sample positioners, calorimeters, and detectors. Control of the hardware and acquisition of data from the sensors and diagnostics instrumentation will be done by a CAMAC and/or VXI based system(s). The workstation will include a PCI-based Interconnect Highway Driver that will be linked through a fiber-optics cable to CAMAC or VXI interconnect crate controllers (see Fig. 11.3-2).

### 11.3.4 Motion Controls

The x-ray transport line, x-ray beam line, and the experimental stations include systems such as adjustable collimators, mirror optics, crystal optics, and adjustable slits. To operate these systems requires position control and position readback. The design goals, such as positioning accuracy, position encoder linearity and resolution, and processing electronics resolution, differ from mover to mover. They strongly depend on the mechanical design like the motor gear ratio and the position encoder range of travel.

The mechanical position will be measured directly with linear variable differential transformers (LVDTs). LVDTs were chosen for their resolution (essentially determined by the number of bits in the read-out ADC and the LVDT range of travel), their linearity (<0.15%), and their ease of use.

The x-ray optics and experiment control computer will calculate the number of steps and directions that each motor needs to take. Stepper Motor Control (SMC) commands will be sent out to the drivers in a form of the number of steps and direction to move. Currently the movers controls design is based on a CAMAC system and SLAC SLC-type motor drivers. The final design may use a VXI based system and commercially available stepper motor drivers.

### 11.3.5 Photon Beam Stabilization at the Sample

Experiments that require irradiation of a fixed sample point (e.g., diffraction from an individual microstructure) may require the stable positioning of the beam to within a fraction of its diameter. Factors contributing to positional beam jitter or drift at the sample plane might include the following: (1) power supply and other component fluctuations in the gun-to-undulator system, (2) vibration or positional drift in the linac and undulator structures, and (3) vibration or positional drift of the x-ray optics system components. For factors contributing to beam motion that have sufficiently long time constants, detection of jitter or drift and their stabilization may be accomplished with suitable detectors providing feedback to any of the upstream LCLS system elements that govern beam position and attitude.
Figure 11.3-1. Functional layout for the x-ray optics motion and actuators control.
Detection of positional and attitudinal jitter or drift can be accomplished with non-destructive photon beam position monitors of the type used on SPEAR, or with, for example, a beam splitter directing part of the (suitably attenuated) radiation to a position sensitive detector (PSD) array in proximity to the experimental location. The detector signal can be fed back to positional/angular controllers in the mirror or crystal tanks. The control system for accomplishing this will need to be based on algorithms that can correlate the observed beam drift with the required corrective motion(s) or current(s) of the upstream elements. Operation of the full photon beam stabilization system, which will need to be under the control of the experimenter, can be incorporated into the control network schematized in Fig. 11.3-2.

![Diagram](image)

**Figure 11.3-2.** Schematic layout for the x-ray optics and the experimental stations controls.

### 11.3.6 Timing System

Most LCLS x-ray experiments require synchronization of the experimental stations’ equipment with the electron beam. The electron beam, in turn, is phased to the 476 MHz of the SLC master clock. Temporal jitter between the RF and the beam is specified to less than 0.5 ps rms.

To minimize the jitter of the 476 MHz timing pulses at the LCLS experiment stations, the RF signal needs to be derived from the SLC RF system at a location as close as possible to the LCLS Experimental Hall. The timing pulses used currently at the FFTB facility are derived from the linac RF at sector 30 (the end of the linac), optically modulated, and transferred by an optical fiber link to the FFTB building 407B (a distance of ~600 m). There, they are demodulated to electrical pulses. This 476 MHz RF signal is divided in frequency as...
necessary to generate the various triggers. An optical fiber cable is used because it is less sensitive to environmental changes (e.g., temperature changes) than coaxial cables. For the short link between building 407B and the LCLS Experimental Hall (~50 m) a temperature-stabilized heliax coaxial cable should be sufficient.

The following are the timing requirements and techniques for three types of LCLS x-ray experiments: (1) split pulse, (2) external pulse, and (3) time-resolved detection.

1. Split pulse (x-ray probe/probe) experiments are planned for the study of fast correlations in solids, liquids, glasses, phonons, and phase transition dynamics. The technique is based on splitting the LCLS x-ray pulse with a x-ray beam splitter into two parts. One part hits the sample directly and the other hits the sample after an adjustable delay of 0-1 ns (see Fig. 11.3-3(A)). With this technique the time delay is created in the experimental hutch, with high precision. Nevertheless, the activating window for the detectors has to be synchronized with the FEL 120 Hz source and delayed accordingly.

2. External pulse (x-ray or laser pump/x-ray probe) experiments are designed for the study of structures of transient states and relaxation of excitations. This technique utilizes an external optical laser as the pumping source and the FEL x-ray beam pulse as the probe. The required triggering range for the external laser is from -10 ms to +10 ms. This class of experiments requires that the synchronization between the user laser and the FEL x-ray beam have a timing jitter better than 1 ps for time delays of ± 1 ns, and better than 1 ns for time delays of ± 10 ms. (see Fig. 11.3-3(B)).

3. Time-resolved detection experiments are planned for the study of relaxation phenomena. This class of experiments also requires that the synchronization between the user laser and the FEL x-ray beam have a timing jitter of approximately 1 ps for time delays in the 1 ns range (see Fig. 11.3-3(C)).
The operation of the external-pulse (laser pump/x-ray probe) timing system is an important factor in experiments such as those described above. A schematic of the system is shown in Fig. 11.3-4. The requisite wide triggering range is achieved by using a pulse selection stage. The main components of the pulse selection stage are two polarizers, a Pockels cell, an HV pulser, and a pulse delay unit. The pulse delay unit 120 Hz input trigger is synchronized with the laser oscillator (119 MHz). Therefore, the selection of any laser pulse can be done by setting the pulse delay unit’s digital delay. The laser oscillator produces very narrow light pulses (~10 fs) every ~8 ns. To select a given laser pulse requires that it pass the Pockels cell while the cell is pulsed by the high voltage pulser. A pulse width of 6 ns assures that only one laser pulse is selected at a time. The fine synchronization between the x-rays and the user laser is achieved by the delay stage. The delay stage consists of a prism that is installed on a stepper motor controlled translation stage and two mirrors. The position of the prism determines the light travel time through the delay stage. A translation stage with a linear motion of ~33 cm and resolution of 1 µm provides a total delay of 2 ns.
All the components of the LCLS except for the x-ray beam line and the experimental stations, are either already in operation or will be built and installed in the SLAC Linac and the FFTB tunnel. The linac and FFTB tunnel are already protected by the SLAC-wide Personnel Protection System (PPS).
The radiation protection system in place in the FFTB includes the following: (1) shielding, (2) Beam Containment System (BCS), and (3) PPS.

1. The radiation protection system is designed to shield personnel working inside the FFTB tunnel from radiation which could be generated by other beams in the switch yard, and to protect personnel outside the FFTB enclosure from potential radiation generated during the LCLS operation.

2. The BCS prevents the accelerated beams from diverging from the desired channel, and exceeding levels of energy and intensity that may cause excessive radiation in occupied area. The FFTB BCS already in place consists of the following: (1) devices which limit the incoming average beam power to 2.4 kW (current monitors I3, I4, and I5); (2) devices which limit normal beam loss so that the radiation level outside the tunnel shielding is less than 1 mrem/hr (current monitors I6 and I7 and long ion chambers); (3) protection collimators which ensure that errant beams do not escape containment; and (4) ion chambers and water flow switches which protect collimators, stoppers and dumps. The beam power on the D2 dump is limited to 15 kW and is protected by ion chambers IC104A and IC104B. The beam stoppers ST60 and ST61 are protected by ion chambers IC65 and IC66. The FFTB BCS will be modified and used for the LCLS (see Fig. 11.4-1).

3. The PPS already in place in the FFTB tunnel is designed to protect personnel from radiation and electrical hazards. The function of the system is to prevent unauthorized access into the tunnel where there is the potential for beam and/or electrical hazards. It is also designed to prevent the radiation dose or dose rate from exceeding the radiation design criteria inside the tunnel when access is permitted, or outside the tunnel during the LCLS operation.

The FFTB PPS is composed of beam stoppers, an entry module, a search/reset system, and emergency buttons. The system is controlled from the SLAC Main Control Center (MCC). It allows beam stoppers to be opened only after the tunnel has been searched and...
secured and is in the No Access state. Access to the tunnel is permitted by the PPS only if all the beam stoppers (D2, ST60, and ST61) are closed.

Radiation safety inside the tunnel is insured by the following: beam dump D2 and beam stoppers ST60 and ST61; a Burn Through Monitor (BTM) installed up stream of the muon shielding; and several Beam Shut-Off Ion Chambers (BSOICs) installed down stream of the muon shielding inside the tunnel. This system prevents the beam from striking the muon shield and shuts the beam off if radiation levels inside the tunnel exceed the allowed limit. An additional BTM is installed behind the FFTB dump, and several BSOICs are installed outside the tunnel to monitor the radiation levels outside the FFTB shielding.

The x-ray beam line and the two experiment stations will be installed in a shielded hutch. The hutch will be designed to contain all radiation background so that the dose rates outside the hutch are acceptable when photons from the FEL are inside the hutch. Access to the hutch will be controlled by a Hutch Protection System (HPS) modeled after existing SSRL hutches. The key parts of the HPS are the access door, photon stoppers, and search/reset system. The HPS allows either physical access or permission to direct beam into the hutch. It contains the logic circuits that govern the sequence of access operations based on the status of the stoppers. It also captures or releases the hutch door keys, acknowledges completion of a search, and keys the experiment enclosure on-line or off-line.

The LCLS HPS will control the operation of four photon stoppers. The system will allow the photon stoppers to be opened (go on-line) only if the hutch has been searched and secured, and the hutch door key is captured in the HPS panel. Access to the hutch is permitted only if all photon stoppers are closed. Stoppers MM1, IS1, and IS2 will be installed inside the FFTB tunnel, and stopper MM2 will be installed in the hutch. Stoppers MM1, IS1, and IS2 are designed to protect personnel from radiation generated by the FEL. The MM2 stopper is designed to protect personnel from scattered radiation generated from the interaction of the electron beam on the main dump (see Fig. 11.4-1). Table 11.4-1 lists possible PPS violations and system responses.

<table>
<thead>
<tr>
<th>Table 11.4-1. PPS violation and response.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. FFTB tunnel security fault</td>
</tr>
<tr>
<td>2. Inside tunnel BSOICs trip</td>
</tr>
<tr>
<td>3. Outside tunnel BSOICs trip</td>
</tr>
<tr>
<td>4. HPS security fault</td>
</tr>
</tbody>
</table>
Figure 11.4-1. Schematic layout of the Personnel Protection System.
11.5 Machine Protection

A Machine Protection System (MPS) is designed to protect the LCLS components. The three primary functions of the MPS are to protect: (1) the integrity of the vacuum system; (2) the proper cooling of the water cooled components; and (3) the LCLS components from damage resulting from errant steering of the electron beam.

1. The MPS will control and monitor the operation of vacuum components such as differential pumping sections, ion gauges, ion pumps, and isolation valves.

2. The MPS will monitor temperature sensors and water flow switches that insure that the magnets, collimators, stoppers, x-ray mirror, and monochromator crystals are sufficiently cooled.

3. Ionization chambers and long ion chambers capable of detecting average radiation are currently installed in the FFTB tunnel. If the average rate of beam loss is found to be sufficient to threaten machine components, the beam repetition rate is automatically reduced. In addition, a pulse-to-pulse comparator system measures the beam current. The operation of the pulse-to-pulse comparator is based on measuring the beam current in two locations. The signal from a toroid at the beam's final destination (beam dump) is compared with that from a toroid at the beginning of the area being protected. If the comparison on a pulse-to-pulse basis shows a beam loss greater than some specified amount the beam is automatically turned off.

The LCLS MPS will consist of two separate systems. One system will protect the LCLS components up stream to the undulator and the second system will protect the components of the undulator, the transport line, the x-ray beam line, and the experimental stations. The first system will be operated from the SLAC MCC, and the second system will be operated from the LCLS Experimental Hall. The two control systems will be interfaced to provide vacuum and thermal interlocks to protect the LCLS accelerator and the x-ray beam line from the following: (1) accidental exposure to atmospheric pressure; and (2) accidental interruption of the Low Conductivity Water (LCW) to water-cooled components. Status signals such as vacuum and LCW faults as well as permits to open or close isolation valves will be shared by both systems.

The existing FFTB MPS control panels are installed in building 406. These controls will be modified to protect the LCLS components in the tunnel. The undulator-to-experimental stations MPS control panels will be installed in the Experimental Hall. This system will include a Programmable Logic Controller (PLC) and control panels. A typical PLC consists of processor (CPU) and Input/Output (I/O) modules. Most of SSRL beam lines’ MPS use PLCs. The undulator-to-experimental stations component layout is given in Fig. 11.5-1.
Figure 11.5-1. Undulator-to-experimental stations component layout.


12 Alignment

**TECHNICAL SYNOPSIS**

This section describes the procedures and methods used to position the LCLS components with their required accuracy. The network design philosophy is based on a 3-D design, now widely used in high precision metrology. The network consists of 3 parts: the linac, undulator, and transport line/experimental area networks. Since the linac exists already, the linac network does not need to support construction survey and alignment, but rather will only provide tie-points during the linac straightening (smoothing) procedure. The undulator network’s geometry is dictated by the tunnel and machine layout. The geometry should permit observation of each target point from at least three different stations. A triplet of monuments is placed in the tunnel cross section. The Transport Line/Experimental Area Network will be constructed and established like the undulator network, with the only difference that each cross section will have only two monuments.

The alignment coordinate system will be a Cartesian right handed system, with the origin placed where the present SLC origin is (Linac Station 100). The instrumentation for the network observation will be a laser tracker/Total Station combination. The laser tracker will be used for position, and the total station for angle accuracy.

The alignment tolerances in the linac and transfer line tunnels are achievable with established techniques. The undulator requirements are somewhat tighter. The trajectory in the undulator is determined by a string of quadrupoles, supported by magnet movers. For the beam-based algorithm to converge, 100 µm initial placement accuracy is required. Laser tracker measurements supported by hydrostatic level observations will provide the required positional accuracy. The positional stability of the undulator will be monitored using a hydrostatic level system in the vertical dimension and a stretched wire based system in the horizontal dimension.
12.1 Surveying Reference Frame

Horizontal position differences between the projection of points on the geoid\(^1\) or a best fitting local ellipsoid and those on a local tangential plane are not significant for a project of the size the LCLS. Hence, it is not necessary to project original observations like angles and distances into the local planar system to arrive at planar rectangular coordinates [1].

In the vertical plane, however, the curvature of the earth needs to be considered (see Fig. 12.1-1). Since leveling is done with respect to gravity, the reference surface is the geoid. Because of the relatively small area of the LCLS project, one can substitute the non-parametric geoid with a locally best fitting sphere or spheroid. Table 12.1-1 shows the projection differences between a tangential plane, a sphere, and an ellipsoid as a function of the distance from the coordinate system’s origin. Notice that for distances as short as 20 m the deviation between plane and sphere is already 0.03 mm (see Table 12.1-1).

![Figure 12.1-1. Effect of earth curvature.](image)

<table>
<thead>
<tr>
<th>Distance, R, [m]</th>
<th>Sphere, H(_S), [m]</th>
<th>Spheroid, H(_E), [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.00003</td>
<td>0.00003</td>
</tr>
<tr>
<td>50</td>
<td>0.00020</td>
<td>0.00016</td>
</tr>
<tr>
<td>100</td>
<td>0.00078</td>
<td>0.00063</td>
</tr>
<tr>
<td>1000</td>
<td>0.07846</td>
<td>0.06257</td>
</tr>
</tbody>
</table>

---

1 The Geoid is the reference surface described by gravity; it is the equipotential surface at mean sea level that is everywhere normal to the gravity vector. Although it is a more regular figure than the earth’s surface, it is still irregular due to local mass anomalies that cause departures of up to 150 m from the reference ellipsoid. As a result, the geoid is nonsymmetric and its mathematical description nonparametric, rendering it unsuitable as a reference surface for calculations. It is, however, the surface on which most survey measurements are made, as the majority of survey instruments are set up with respect to gravity.

The reference ellipsoid is the regular figure that most closely approximates the shape of the earth, and is therefore widely used in astronomy and geodesy to model the earth. Being a regular mathematical figure, it is the surface on which calculations can be made.
12.1.1 Network Design Philosophy

The global alignment tolerance, the relatively weak links between machine sections, and advances in surveying make it possible to forego the traditional design of a two-tiered network hierarchy covering the whole machine. Instead, each machine section can be considered independent, only connected by tunnel networks. A two-tiered approach will only become necessary if a remote experiment is added to the project and at that time needs to be connected to the undulator. Omitting a primary network not only removes many constraints for component placement, since fewer lines-of-sight need to be maintained, but also presents a significant reduction in alignment costs.

Traditionally, forced centered\(^2\) “2 + 1 - D” triangulation and trilateration techniques\(^3\) were used to measure the tunnel networks. However, a 3-D “free stationing\(^4\)” approach does not require forced-centered instrument set-ups, thus eliminating the need for set-up hardware and their systematic error contributions. Removable heavy-duty metal tripods, translation stages, CERN sockets, and optical plummets are not needed (see Fig. 12.1-2). The network design still must consider other systematic error effects, especially lateral refraction.\(^5\) Another important consideration is the target reference system. Its design becomes less difficult with free stationing since there are only targets and not instruments. Accordingly, a 3-D design will be used, which is now quite common in high precision metrology. This approach is centered on a 1.5 inch\(^6\) sphere. Different targets can be incorporated into the sphere in such a way that the position of the target is invariant to any rotation of the sphere. At SLAC, designs have been developed to incorporate theodolite targets (see Fig. 12.1-3), photogrammetric reflective targets, as well as glass and air corner cubes (see Fig. 12.1-4) into the sphere. Receptacles for the spheres, which are usually referred to as “nests” or

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\(^2\) Forced centering refers to a specific instrument mount. This type of mounting system, whether vendor specific or independent, allows the exchange of instruments on a station without losing the measurement point, i.e., all instruments are by mechanical “force” set up in exactly the same position. However, experience has shown that even the best of these forced centering systems has a \(\sigma\) of about 50-100 \(\mu\)m. Unfortunately, the forced-centering system contributed error is not random. Since a whole set of measurements is usually completed from a slightly offset position, this error behaves mostly systematically. No efficient method is known to determine the offset vector. These errors, vertical refraction, and lateral refraction are the biggest contributors to the systematic error budget in surveying engineering.

\(^3\) 2 + 1 - D refers to the fact that because of mechanical problems in the forced-centering hardware, three-dimensional networks were usually split into separate horizontal (2-D) and vertical (1-D) networks. Both networks were established, measured and analyzed separately.

\(^4\) Rather than setting up the instrument over a known point, the instrument’s position is flexible and chosen only following considerations of geometry, line of sight, and convenience. To determine the instrument position, at least three points, whose coordinates are already known or are part of a network solution, need to be included in the measurements.

\(^5\) Lateral refraction is caused by horizontal stationary temperature gradients. In a tunnel environment, the tunnel wall is often warmer than the air. This creates vertical stable temperature layers with gradients of only a few hundredth of a degree Celsius per meter. If one runs a traverse close to a tunnel wall on one side only, the systematic accumulation of the effect can be significant; e.g., during the construction of the channel tunnel, a control measurement using gyro theodolites revealed that after about 4 km they had already veered about 0.5 m off the design trajectory.

\(^6\) The diameter of the 1.5 in. sphere is equivalent to 3.81 cm.
“cups,” have been designed to accommodate different functions. TJNAF has a very suitable design for nests to be grouted into the floor, and designs are available at SLAC for cups tack-welded onto magnets, for mounting cups on wall brackets and for a “centered” removable mounting placed into tooling ball bushings (see Fig. 12.1-5).

Figure 12.1-2. Forced centered set-up at SLAC.

Figure 12.1-3. Sphere mounted theodolite target.
The LCLS network consists of three parts: the linac network, the undulator network, and the transport line/experimental area network.

**Linac Network**

The linac network serves a different purpose than the other networks. Since the linac already exists, the linac network does not need to support construction survey and alignment, but rather will only provide local tie-points during the linac straightening (smoothing) procedure.

**Undulator Network**

The undulator network’s overall geometry is dictated by the tunnel geometry, machine layout and the fact that the free stationing method requires a greater number of reference points. The geometry should also permit observing each target point from at least three different stations. The reference points can be of two different hierarchical classes. The
second order points, or tie points, mainly serve to connect the orientation of free stationed instruments. In addition the first order points provide the geometric reference during machine installation; they are the equivalent of traditional traverse points or monuments. The following sketch (Fig. 12.1-6) shows a typical section of the layout. A triplet of monuments is placed in the tunnel cross section at the position of each corrector magnet. One monument will be placed close to the corrector magnet on the floor, the second one mounted at instrument height to the aisle wall, and the third monument mounted to the back wall also at instrument height.

![Undulator network layout.](image)

Transport Line/Experimental Area Network

Initially, the project will only include an experimental area directly down-stream of the undulator. This network will be constructed and established similar to the undulator network, the only difference being that each cross section will have only two monuments. These monuments will be mounted to the walls at instrument height.

12.1.3 Alignment Coordinate System

The alignment coordinate system will be a Cartesian right-handed system. The origin is placed at the linac Station 100 (in analogy to the SLC coordinate system). There will be no monument at the origin; it is purely a virtual point. The Y-axis assumes the direction of the gravity vector at the origin but with opposite sign. The Z-axis is in the direction of the linac, and the X-axis is perpendicular to both the Y and Z-axes. The signs are defined by the right-handed rule (see Fig. 12.1-7).
12.1.4 Network Survey

The most efficient instrumentation for the network observations will be a “laser tracker”/“total station” combination (Fig. 12.1-8). The two state-of-the-art SMX4000/4500 laser trackers, and in addition a new total station optimized for industrial metrology, the Leica TDA5000 (Fig. 12.1-9) are available at SLAC. While the total station is superior in angular accuracy to a laser tracker, it is significantly less accurate in distance measurements. Consequently, the laser tracker will be used for distance accuracy and the total station for angle accuracy.

The laser tracker will be placed close to the intersection of the diagonals of each reference point quadrilateral (see Fig. 12.1-10). From there, four points in a forward direction and four points in backward direction will be measured. The measurement procedure will include three sets of direction measurements to the same eight points in both front and reverse positions plus one set of distances in both positions. To strengthen the determination, the total station will be used to measure additional direction sets. It will be set up at two additional stations at the Z-position of the intersection of the quadrilateral diagonals and laterally shifted by about 0.5 m in both directions. From these stations, direction sets to six points, each downstream and upstream, will be measured. All reference points will also be observed with a standard high precision double-run level procedure. A Zeiss DiNi11 digital level in combination with 2 m invar rods is recommended. To further strengthen the elevation determination, all points will also be observed with the portable HL5
hydrostatic level. First simulations show absolute station standard deviations of less than 80 μm.

Figure 12.1-8. SMX laser tracker.

Figure 12.1-9. Leica TDA5000 total station.
To reduce the data from the measurements as described above, special software is required. This type of analysis software is based on the photogrammetric bundle approach. Since a photogrammetric sensor is arbitrarily oriented in space, not only its translational parameters but also its rotational orientation parameters must be treated as unknowns and become part of the solution. With traditional trilateration/triangulation-based analysis software, however, pitch and roll are supposed to be oriented to gravity, and yaw is expressed as a function of translations. Additionally, the traditional software assumes that the instrument is centered on a point to which sufficient measurements have been taken. This analysis approach does not work well with free stationing, and does not work at all with present generation laser trackers, since they cannot be oriented directly to gravity.

To reduce errors stemming from transcription of data, the data-flow should be automated. The suggested instruments support direct connection to field computers. The fully automated data-flow should extend from field computers through data analysis to data storage.

Measurements with any type of instrument will be guided by software based on rigid procedures running on field data logging computers. The data logging software will also pre-analyze the measurements, and will try to determine and flag possible outliers before the measurement set-up is broken down. This method combined with an automated data-flow will greatly reduce errors and improve measurement consistency and reliability.

12.2 Lay-out Description Reference Frame

12.2.1 Lattice Coordinate System

The LCLS lattice is designed in a right-handed beam following coordinate system, where the positive y-axis is perpendicular to the design plane, the z-axis is pointing in the beam
direction and perpendicular to the y-axis, and the x-axis is perpendicular to both the y and z-axes.

### 12.2.2 Tolerance Lists

The relative positioning tolerances $\sigma_x$, $\sigma_y$, $\sigma_z$ of the undulator segments, BPMs, and quadrupoles are listed in Table 12.2-1. The undulator is oriented such that the x-axis is in the direction of the magnetic field.

#### Table 12.2-1. LCLS positioning tolerances.

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_x$</th>
<th>$\sigma_y$</th>
<th>$\sigma_z$</th>
<th>$\sigma_x/z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative alignment between segments</td>
<td>100</td>
<td>500</td>
<td>1</td>
<td>n/a</td>
</tr>
<tr>
<td>Global straightness of undulator</td>
<td>300</td>
<td>500</td>
<td>2</td>
<td>100/10</td>
</tr>
<tr>
<td>Linac straightness</td>
<td>n/a</td>
<td>n/a</td>
<td>n/a</td>
<td>150/15</td>
</tr>
<tr>
<td>Quadrupole ab initio</td>
<td>100</td>
<td>100</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>

### 12.2.3 Relationship between Coordinate Systems

The relationship between the surveying and lattice coordinate systems is given by the building design and machine layout parameters. The result is a transformation matrix (rotations and translations).

### 12.3 Fiducializing Magnets

The correct fiducialization of magnets is as important as their correct alignment since an error in either task will affect the particles’ trajectory and cannot be distinguished from each other. Fiducialization can be accomplished either through opto-mechanical and opto-electrical measurements or by using fixtures, which refer to a magnet’s reference features. Detailed descriptions can be found in the literature [2].

The most demanding task is the quadrupole positioning. With a total error budget of 100 $\mu$m, the fiducialization should be done to about 25 $\mu$m to accommodate a 90 $\mu$m alignment error. The quadrupoles will have tooling plates attached which reference fiducials to the magnets’ axes. To find the magnetic axes, the preferred method is the vibrating wire method. A Coordinate Measurement Machine (CMM) will be used to relate the wire position to the fiducials.

The undulator fiducialization will be carried out on a CMM from physical measurements and verified using Hall probes mounted to the CMM probe head.
12.4 Absolute Positioning

Common to all parts of the machine, free-stationed laser trackers, oriented to at least four neighboring points, are used for the absolute positioning measurements. The tracking capabilities of these instruments will significantly facilitate the control of any alignment operation (moving components into position).

12.4.1 Undulator Absolute Positioning

Undulator Anchor Hole Layout Survey

During the anchor layout survey, the anchor hole positions for the girder supports are marked on the piers. Fabricating a standard template including all anchor holes at one girder end, thus significantly reducing the number of individual layout pointings, will be needed. A total station from one free-stationed position can locate and position the template with only two pointings. Before the holes are marked, the location of the template should be checked from a second station. In the sequences of work, the last station can then serve for the $n+1$ girder as its first station. Specialized software is required to improve the efficiency and reliability of this task.

Pre-alignment of Girder Supports and Magnet Movers

The undulator girders will be supported by motorized adjustment systems sitting directly on top of concrete piers. The motorized adjustment systems are based on the Bowden camshaft design. Two individually controlled camshaft pairs and two single camshafts provide 5 degrees of freedom per girder. The cam shaft design does not compromise the rigidity of the supports and, consequently, does not show a resonance in an undesirable frequency range. This mover system comes in two horizontal slices. The bottom piece consists of a mounting plate, which holds the shafts and stepping motors. The top part is integrated into the girder by mounting the kinematic cams to the girder. The girder is held onto the shafts by gravity or, if necessary, loaded by springs.

To accommodate easy installation, the bottom parts of the movers, set to mid range, have to be aligned relative to each other. The required relative position tolerance of these, however, is fairly loose, since the two axes cams are only paired with a single axis cam. On the other hand, to retain as much magnet mover range as possible, the bottom part of the magnet movers should be within 0.5 mm of their nominal positions.

To facilitate placing a pedestal such that its top is within 0.5 mm of its nominal position, a widely used method can be used. Here, the base plate of the bottom part of a mover is mounted to the pier by four standoff screws, which are grouted/epoxied into the concrete. The vertical/horizontal pre-alignment of the base plate is accomplished by the following sequence of steps. (1) After the four bolts are epoxied into the concrete, a nut with a washer on top is screwed onto each bolt. These nuts are set to their nominal heights by a simple level operation. (2) Next the base plate is set on the nuts, and a set of washers and nuts is then
screwed on the bolts to fasten it down. However, the top nuts remain only hand tight at this point. (3) Next, the elevation and tilts of the base plate are set by adjusting the position of the lower nuts, and subsequently checked with a level with respect to local benchmarks. (4) Then a total station with a “free station Bundle” software package is used to determine the horizontal offset and to simultaneously double-check the vertical offset of the base plate from its nominal position. (5) Finally, the base plate is moved into horizontal alignment using a clamp-on adjustment fixture (push–push screw arrangement), and the nuts are tightened to the prescribed torque. To vibrationally stiffen the set-up, the space between the pier and the base plate should be filled with non-shrinking grout after the alignment has been confirmed.

Once the pedestal is positioned, the bottom part of its magnet mover is mounted and aligned following the same procedures as described in the previous paragraph.

**Absolute Quadrupole Positioning**

After the lower part of the magnet mover assembly is mounted and aligned, the components can be installed. Since the magnet mover parts have a defined geometrical relationship to the magnetic axes of the quadrupoles and undulator segments, the installation will place these components to within 0.5 mm. In preparation for the relative alignment, the position of the quadrupoles will be mapped and adjusted using a laser tracker in reference to adjacent network points. Absolute position accuracy relative to the network points of about 100 µm can be achieved.

**Quality Control Survey**

Once the above set is completed, the components will be mapped. If the positional residuals exceed the tolerance, a second iteration can be “jump started” by using the quality control map to quantify the position corrections, which need to be applied. If a second iteration be necessary, a new quality control survey is required after completion of the alignment process.

**12.4.2 Transport Line and Experimental Area Absolute Positioning**

The absolute positioning of these components will follow the same procedures as described above.

**12.5 Relative Alignment**

**12.5.1 Relative Undulator Alignment**

**Introduction**

The trajectory is determined by a string of quadrupoles and BPMs. The quadrupoles are supported by magnet movers and can be moved to permit beam-based alignment. For the beam-based alignment algorithm to converge, a 100 µm ab initio placement is required.
Taking fiducialization errors into account, these magnets need to be aligned to 90 $\mu$m. The BPMs, taking fiducialization and acquisition error into account, need to be aligned to 80 $\mu$m.

**Relative Quadrupole Positioning**

The absolute position alignment of the quadrupoles is refined by repeating the same process with the important difference, however, that measurements to a quadrupole are taken with respect to its neighbors and not to the network points. Consequently, systematic errors stemming from the network are not propagated into the relative quadrupole positioning.

For vertical positioning, measurements using the portable hydrostatic level Pellissier H5<sup>10</sup> will give elevation differences to better tan 10 $\mu$m.

The standard deviation of uncorrelated quadrupole positions will be better than 80 $\mu$m in the horizontal dimension and better than 50 $\mu$m in the vertical dimension.

**Undulator Alignment**

After the quadrupoles are aligned and their positions are refined with beam-based alignment, they define the undulators’ trajectory. The undulator segments can now be accurately positioned using the same triangulation/trilateration and hydrostatic leveling based method as were used for the quadrupole alignment.

**12.5.2 Linac Smoothing**

**Purpose of Linac Smoothing**

To generate an optimal beam for injection into the undulator, the present local straightness of the linac is not sufficient. To achieve the desired beam parameters, the straightness quality needs to be mapped, and, where necessary, mechanically adjusted. In particular, the straightness of individual linac structures, the straightness alignment of structures on a girder, and of the relative alignment of the sections on either side of a quadrupole with respect to each other and with respect to all needed to be mapped. See Fig. 12.5-2, Fig 12.5-3, and Fig. 12.5-4.

![Map Internal Straightness of Individual Accelerator Structures](image)

**Figure 12.5-2.** Straightness of individual accelerator structures.
Linac Straightness Measurement Procedure

Because of the required resolution, reliability and the large amount of work (about 1 km of beam line), the task is best performed with a system that does not require an operator to point and adjust micrometers. It also should allow on-line data logging. A laser system developed by Hamar [3] will be used. The instrument generates two laser light planes by bouncing a laser beam off rotating mirrors. The two light planes are truly perpendicular to each other. The flatness or wobble-induced error of each light plane is specified as 5 µrad, which is well below the straightness specification at maximum distance. The light source would be set up about the middle between two quadrupoles, offset horizontally and vertically such that the light planes clear all beam line components. This set-up versus a set-up at an endpoint reduces the length of the line-of-sight to about 5 m, thus greatly lessening the effects of potential refraction and air turbulence on the light beam. After bucking in the light planes both horizontally and vertically to two points on the measured object, intermediate offsets, for example, between the accelerator structure and the light planes, are measured with a photo-sensitive-detector (PSD) attached to an offset arm. The detector is linked to an interface box by a cable, which can be as long as 15 m. The interface box provides a serial link to a data logger. To measure the offsets, the offset arm is held against the accelerator structure sequentially in both planes. To determine the perpendicular offset, the alignment technician will arc the arm. While the arm is being arced, the light position is continuously read out and stored. Software will then determine the perpendicular offset by finding the
smallest read-out value. Since the PSD measurement range is limited to about 8 mm, the arm will be adjustable in length. To avoid errors due to the adjustability, the adjustment length will be monitored by an electronic dial gauge, which also reports its reading to the data logging software. The total straightness measurement error budget is expected to be below 75 $\mu$m.

The relative alignment of a linac quadrupole in relation to its adjacent accelerator sections will be determined analogously. However, since these quadrupoles are not fiducialized and also do not have any precision reference surfaces, the offset will be measured to their BPMs instead. Each BPM has a cylindrical body, which is inserted between the poles with a very close fit, and protrudes from the poles on either side of the magnet. The BPM is expected to reference the magnet’s axis to about 100 $\mu$m. The adjustment range of the offset arm will be sufficiently dimensioned to allow the same arm to measure both BPMs and accelerator structure offsets.

12.5.3 Relative Alignment of Transport Line and Experimental Area Components

The position tolerances of these components will be achieved during the absolute alignment step. A relative alignment is not required.

12.6 Undulator Monitoring System

In the vertical dimension, a hydrostatic leveling system cloned after ESRF’s HLS will accurately monitor relative and global vertical position changes. Four sensors per girder are required. To eliminate temperature effects on the hydrostatic leveling results, any vertical deviations from a plane of the water runs must be avoided. This condition is guaranteed using the “half-filled” pipe approach. Assuming four sensors per girder, a total of about 88 sensors will be required.

Since there is no natural absolute reference in the horizontal plane, some kind of artificial local reference needs to be created as is done by stretched wires. Two wires, one on either side of the undulator sections/magnets will provide the straight-line reference. Inductive sensors will provide wire position information. The system is modeled after the Panofsky wire system used in the original installation of SLAC’s A beam. Test measurements have shown sub-micron resolution and better than 10 $\mu$m stability.

12.7 References

1. R. Ruland, Magnet Support and Alignment, in H. Winick, Editor, Synchrotron Radiation Sources–A Primer, pp. 274 - 304.
3. Hamar Lasersystems, Model L-723 Triple Scan® Laser with Model A-517 Scan Target.
13 Radiation Issues

**Technical Synopsis**

The radiation concerns related to the LCLS fall into three distinct areas: radiation safety, radiation background in experiments, and machine protection. This chapter covers these concerns in the region downstream of the undulator, since the linac will be taken care of by the existing system. The effect of gas scattering on the residual gas of the undulator was computed, and no degradation of the undulator is expected from this source of radiation. The photon deposition due to spontaneous emission in the undulator was calculated and does not cause a problem. The effectiveness of the undulator protection collimators was found to be very good. The emission due to gas bremsstrahlung was estimated with an analytical formula. Computational estimates of the muon dose rates behind the concrete and iron shielding have been made. All these studies indicate that the radiation is quite manageable. The dose rates due to induced activity were calculated and with the expected low level of beam loss in the undulator, the activation of the unit, and the resulting personnel exposure, are expected to be very low.

### 13.1 Radiation Concerns Downstream of the Undulator

Radiation concerns downstream of the undulator have been extensively discussed in Section 10.3, Bremsstrahlung Calculations.

### 13.2 Radiation Issues in the Undulator

#### 13.2.1 Introduction

The 100 m long undulator will be located partly underground in the tunnel of the SLAC linac, and partly in a less heavily shielded enclosure which is presently occupied by the Final Focus Test Beam experiment (FFTB). While the linac and the Beam Switchyard are shielded with more than 12 m of concrete and earth, the FFTB enclosure shield is only 1.2 m thick laterally, and 1 m thick on the roof. However, since the LCLS electron beam power will be comparable to that of the FFTB, the existing shielding should be adequate. As far as the undulator section of the LCLS project is concerned, the existing Personnel Protection System (PPS) and Beam Containment System (BCS) can be used with little modification. The radiation issues that need to be studied relate therefore more to machine protection, such as
radiation damage to the permanent magnets, than to radiation safety. Assessment of potential radiation sources and relevant effects are described in the following sections.

13.2.2 Beam Scattering on the Residual Gas

The beam pipe inside the undulator will be very long (100 m) and will have a very small diameter (5 mm). Therefore, beam electrons scattered by the residual gas, although in a very forward direction, have a good chance to hit the vacuum chamber wall and could in principle contribute to the dose absorbed by the permanent magnets. The usual condensed history transport implemented in most electron-photon Monte Carlo codes could not be applied to this problem. Therefore, the single scattering algorithm [1] of the Monte Carlo radiation transport code FLUKA [2] was activated in these calculations. Cylindrical-slab geometry was assumed in order to achieve better statistics.

Similar to the more familiar problem of gas bremsstrahlung [3], the low density of the residual gas (at a pressure of 10^{-6} Torr) does not allow a direct simulation. Therefore, calculations were performed at higher gas pressures and the results were extrapolated to the actual gas density. The interaction of beam particles with gas was initiated more than 100 m up stream of the start of the undulator.

Since the energy deposited in the undulator by the scattered particles is not uniformly distributed throughout the unit, the appropriate choice of scoring bin is important. In each simulation, the dose was scored for different bin sizes. Results show no dependence on the choice of the bin size along the incident beam axis, but a strong dependence on the radial bin size, due to the large dose gradient. The results also show that for radial bin sizes of less than 0.01 cm a plateau is reached. Thus, a correcting factor depending on bin size was established. For a bin size of 1 cm, the correction factor is more than 20. However, most of the simulations were performed with a bin radial size of 0.2 cm, corresponding to a correction factor of 2.7. Figure 13.2-1 shows the deposited dose at 10^{-3} Torr for the 2 mm thick shell (radial bin) closest to the beam axis along 60 m of the undulator length with an upper limit of 2.5 x 10^{15} Gy (2.5 x 10^{13} rad) per incident electron. At 10^{-6} Torr, the dose rate is reduced by a factor 1000, but when corrected for the bin size it reaches 7 x 10^{18} Gy (7 x 10^{16} rad) per incident electron. Assuming a bunch intensity of 1 nC per pulse, 120 Hz, 9 months of operation per year, and an “up-time” of 80%, the estimated dose to the innermost shell of the LCLS undulator is less than 10^2 Gy (10^4 rad) per year.

At this radiation level no degradation of the undulator is expected from scattering of the beam off the residual gas in the beam pipe.

13.2.3 Spontaneous Radiation

Spontaneous synchrotron radiation will be emitted in a cone with a larger angle than the laser beam, and its total power will be of the same order. Its angular and energy distribution is rather complex. A source user code was written for FLUKA to sample photons from
energy-angle distributions. The total number of low energy photons in a cone of half-aperture 85 $\mu$rad is $3 \times 10^{24}$ per second (peak value).

![Graph](image1.png)

**Figure 13.2-1.** Dose along the undulator from scattering of a 15 GeV electron from air at $10^{-3}$ Torr.

To simplify the problem, the source was assumed to be pointlike (a conservative assumption) and located at the entrance of an undulator 100 m long. **Figure 13.2-2** shows the spectrum of photons scored as they hit the wall of the vacuum chamber.

![Graph](image2.png)

**Figure 13.2-2.** Spontaneous emission synchrotron radiation: scored spectrum of photons hitting the vacuum chamber wall inside the undulator. The peaks correspond to different harmonics.
Variance reduction techniques (splitting) were used for photon transport, due to the strong attenuation of low energy photons in iron. The dose scored in a very thin superficial layer of the undulator material is shown in Fig. 13.2-3 as a function of distance along the undulator. Figure 13.2-4 shows the radial attenuation.

The maximum estimated dose per year, taking into account a duty factor of $1.2 \times 10^{11}$ (120 Hz, pulse duration $10^{-13}$ seconds), was $2 \times 10^3$ Gy ($2 \times 10^5$ rad). Averaging over a radial layer 1 cm thick, one would obtain a dose 10 times lower.

---

**Figure 13.2-3.** Longitudinal dose distribution due to spontaneous synchrotron radiation in a layer 0.1 mm thick inside the undulator.

**Figure 13.2-4.** Radial dose distribution due to spontaneous synchrotron radiation inside the undulator.
13.2.4 Bremsstrahlung from Halo on Collimators

To protect the undulator from strikes by a mis-steered primary beam and from continuous radiation deposition generated by particles in the beam halo, Protection Collimators (PC) need to be deployed up stream of the undulator. FLUKA was also used to study the effectiveness of the collimators. In the simulations, a 15 GeV electron beam was assumed to strike a 10 cm long cylindrical collimator, located 100 cm up stream of the LCLS undulator. The inner diameter of the collimator was taken to be 1 mm. The vacuum chamber was assumed to be made of aluminum. Normal incidence and incidence at a grazing angle were considered.

Normal Incidence

In the simulation, the beam was assumed to be incident on the collimator, 1.5 mm from the center, parallel to the axis of symmetry (Fig. 13.2-5a). The results show that if the PC is made of 10 cm of aluminum most of the energy (87%) will escape from the collimator and get deposited in the undulator. The aluminum collimator absorbs only 7% of the initial beam energy. Figure 13.2-6 shows the beam deposition profile along the length of the undulator for 1 cm radial bins.

![Diagram of beam deposition profile along the length of the undulator](image)

Figure 13.2-5. Cylindrical-slab geometry assumed in the FLUKA simulations.
When corrected for the bin size effect, the dose rate deposited in the innermost shell of the undulator from such a scenario will reach $2.2 \times 10^{-9}$ Gy ($2.2 \times 10^{-7}$ rad) per incident electron.

When the collimator is assumed to be made of high-Z material, the electromagnetic shower fully develops in the collimator, which thus protects the undulator from continuous deposition of energy due to particles in the beam halo. **Fig. 13.2-7** shows the energy deposition profile in a 10 cm long tungsten collimator. In this scenario 99% of the energy of the incident beam is absorbed in the PC. It should be pointed out that tungsten would not withstand strikes with the direct beam; therefore, a combination of low-Z material acting as a spoiler followed by a high-Z absorber may be needed for an efficient protection collimator.

![Graph](image)

**Figure 13.2-6.** Dose along the undulator for a 15 GeV beam normally incident on an aluminum collimator 10 cm long.

**Grazing Angle Incidence**

In the simulation, the beam was assumed to strike the inside of the tungsten collimator, 1 cm from the front face, at an angle of incidence of 10 mrad (**Fig. 13.2-5b**). The results show that the undulator would receive 51% of the initial beam energy. When a similar collimator is added 80 cm down stream of the first PC (20 cm up stream of the undulator) the second unit absorbs part of the energy escaping from the first PC. The energy deposited in the undulator for the same scenario would reduce from 51% to 26%. **Figure 13.2-8** shows the radiation deposited in the first 10 cm length of the undulator where the largest radiation deposition is expected in the two cases of one and two collimators.
Figure 13.2-7. Dose profile inside the tungsten collimator for a normally incident 15 GeV electron beam.

Figure 13.2-8. Energy deposition in the first 100 cm of the undulator, for a 15 GeV electron incident at a grazing angle (10 μrad) on a tungsten collimator. The beam is assumed to strike the first collimator at 1 cm from its front face. One and two collimator cases are shown.

In another calculation the beam was assumed to strike the inside of the first tungsten collimator, 9 cm from the front face (Fig. 13.2-5c). Results show that the undulator receives 77% of the energy in the beam. Addition of a second PC would reduce the deposited energy to 28%. The dose per electron deposited in the undulator for the one and two collimator
cases when beam strikes 9 cm from the front face of the first collimator is shown in Fig. 13.2-9. When corrected for the bin size effect, the largest dose deposited in the undulator is $6.2 \times 10^{-8}$ and $6.2 \times 10^{-11}$ Gy per incident electron for the one and two collimator simulations, respectively.

![Graph showing dose per incident electron vs distance along the undulator](image)

**Figure 13.2-9.** Same situation as in Fig. 13.2-8, but with beams striking 9 cm from the front face of the first collimator.

### 13.2.5 Induced Activity

The main concern about induced activity is the potential exposure to personnel working on the undulator after it has been in service for a period of time. Calculations based on methods developed by H. DeStaebler [4] and on Swanson’s tabulations [5] express the rate of radionuclide production in terms of saturation activity $A_s$, i.e., the activity of a target that has been steadily irradiated for a time long compared with the half-life of the produced radionuclides at the instant that the irradiation has stopped. For these calculations, the permanent magnets were assumed to be made of natural iron and natural cobalt, 50% each. To calculate the exposure rate, $A_s$ is multiplied by $\gamma$, the specific gamma ray constant which gives the exposure rate in air at a fixed distance (1 m) per unit of activity (Ci).

Natural iron is comprised of $^{54}\text{Fe}$, $^{56}\text{Fe}$, $^{57}\text{Fe}$, $^{58}\text{Fe}$ isotopes. Reactions ($\gamma,n$) ($\gamma,2n$) ($\gamma,np$) ($\gamma,p$) ($\gamma$,spallation) were considered. The product radionuclides that contribute the largest fraction of the dose are Mn isotopes. Natural cobalt is 100% $^{59}\text{Co}$, and the reactions ($\gamma,n$)$^{58}\text{Co}$, ($\gamma,2n$)$^{57}\text{Co}$ were considered. Reactions ($\gamma,p$), ($\gamma,pn$), ($\gamma,p2n$) ($\gamma,p4n$) all lead to stable iron isotopes, and ($\gamma,p3n$) leads to Fe with a 5.9 keV x-ray which would be self shielded in the target.
The total exposure rate from an activated magnet immediately after shut-down is conservatively estimated to be 5 mR hr$^{-1}$ W$^{-1}$ at 1 m. The exposure is dominated by a 0.8 MeV gamma from $^{58}$Co with a half-life of 71 days. Monte Carlo simulations of Armstrong et al. [6] on a free electron laser wiggler result in exposure rates of 3–3.5 mR/hr for an average beam loss of 1 W/m compared to 5 mR hr$^{-1}$ W$^{-1}$ calculated above.

Personnel exposure from radioactive components in the beam line is of concern mainly around beam dumps, targets, or collimators where the entire beam or a large fraction of the beam is dissipated continuously. At the dose rates calculated above, and with the expected low level of beam losses in the undulator, the activation of the unit and resulting personnel exposure are expected to be very low.

### 13.3 References


## Parameter Tables

### 1. Beam Tracking

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<td>[%]</td>
<td>[mm mrad]</td>
<td>[%]</td>
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<td>[nC]</td>
<td>[mm]</td>
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*Relative to the initial emittance.
*Beam Halo will not contribute to FEL process.
## 2. Parameter Summary

### Injector Beamline

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<tr>
<th>Parameter</th>
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<td>Energy at gun</td>
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<tr>
<td>Energy at end of dogleg</td>
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<td>Normal transverse rms emittance</td>
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### Linac

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<tr>
<td>Energy at second compressor</td>
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<td>Energy after linac</td>
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<td>Norm. transverse rms emittance after linac</td>
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### Undulator

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### X-ray Optics

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<td>rms bunch length $\tau_B$</td>
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<td>Average $\beta$-function</td>
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### Units

- $\pi$ mm mrad
- $10^{12}$ Photons/pulse
- $10^{24}$ Photons/s
- $10^{13}$ Photons/s/mm²/mrad²/1%
- $10^{22}$ Photons/s/mm²/mrad²/1%
3. **Gun Laser**

**Oscillator**
- CW mode-locked Ti:sapphire

**Oscillator pump**
- frequency-doubled CW Nd:YAG laser
- pumped by several diode lasers

**Amplifier**
- Ti:sapphire

**Amplifier pump**
- frequency-doubled, flash-lamp-pumped,
- Q-switched (about 1 ns), Nd:YAG or YLF

**Output wavelength**
- 780 nm

**Operating wavelength**
- 260 nm (3rd harmonic)

**Pulse repetition rate**
- 120 Hz

**Number of micropulses**
- 1

**Micropulse energy on cathode (note b)**
- >500 µJ (maximum)

**Micropulse radius on cathode (note c, d)**
- 0.9 mm HWHM

**Micropulse risetime (note e)**
- 1.0 ps

**Micropulse length (note c, f, g)**
- 10 ps FWHM

**Longitudinal micropulse form**
- various

**Longitudinal homogeneity on cathode**
- 10 % pk-pk

**Transverse micropulse form**
- uniform

**Transverse homogeneity on cathode**
- 10 % pk-pk

**Pulse-to-pulse energy jitter**
- ≤1 % (rms)

**Pulse-to-pulse phase stability (note h)**
- ≤0.5 ps (rms)

**Spot diameter jitter at cathode**
- 1 % pk-pk

**Pointing stability**
- < 1 % pk-pk of spot radius

(a) Definitions and clarifications: The term "rms" after units indicates a 1-σ value; both the terms
"FWHM" (full-width at half maximum) and "HWHM" (half-width at half-maximum) are used.

The laser produces "pulses" and the gun produces "bunches."

(b) The design will be for 18 µJ of IR energy, resulting in at least 500 µJ available at the cathode.

For a QE of 10⁻⁵, 500 µJ of excitation light at 260 nm at the cathode will produce 1 nC of charge.

(c) If σₓ = A σₓ, A = 0.2, where A is the aspect ratio.

(d) For a uniform, round, transverse cross section, the FWHM = σ (rms) * 6/(2π)¹/².

Thus a 0.9 mm HWHM section has a radius whose rms sigma is 0.75 mm.

(e) A risetime of 1 ps (10-90%) is sufficient for pulse shaping requirements, but the system will be
designed for 0.5 ps.

(f) Since δp/p = 1/2 (κ₂ σ₂) for an electron bunch near the crest of the rf, the momentum spread is
σ∼0.17% due to rf alone.

(g) For a flat-top longitudinal cross section, the FWHM = σ (rms) * 8/(2π)¹/². Thus a 10 ps FWHM
pulse has an rms sigma of 3 ps.

(h) Present simulations in the linac indicate that a timing jitter in the electron beam of 1 (2) ps
rms will lead to a 20 (40) % emittance growth because of non-linearities in the resulting
bunch-length growth. A stability of 2 ps rms has been achieved in laser-electron
collisions for SLAC experiment E-144.
4. **Injector - rf Photocathode Gun**

<table>
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<td>metal (Cu or possibly Mg)</td>
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<tr>
<td>Active diameter of cathode</td>
<td>12 mm</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>$1 \times 10^{-5}$ at 260 nm</td>
</tr>
<tr>
<td>Nominal extraction field</td>
<td>140 MV/m</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>1.0 nC</td>
</tr>
<tr>
<td>Longitudinal pulse form</td>
<td>truncated gaussian</td>
</tr>
<tr>
<td>Bunch length</td>
<td>3.5 mm FWHM</td>
</tr>
<tr>
<td>Bunch length</td>
<td>11.6 ps FWHM</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>1.00 mm</td>
</tr>
<tr>
<td>rms bunch length</td>
<td>3.3 ps</td>
</tr>
<tr>
<td>Peak current (note i)</td>
<td>87 A</td>
</tr>
<tr>
<td>rf frequency</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>rf pulse duration</td>
<td>3 - 4 µs</td>
</tr>
<tr>
<td>Peak rf power</td>
<td>15 MW</td>
</tr>
<tr>
<td>Number of cells</td>
<td>1.6</td>
</tr>
<tr>
<td>Beam energy at exit</td>
<td>7 MeV</td>
</tr>
<tr>
<td>Energy spread at exit of gun (note j)</td>
<td>1.5 % correlated</td>
</tr>
<tr>
<td>Length (note j)</td>
<td>0.168 m</td>
</tr>
</tbody>
</table>

(i) Assumes a laser pulse temporal profile is flat top. If Gaussian, then

$I_{pk}=Q\left[\frac{1}{2\pi\sigma_z}\right]$, or in the case about 130 A.

(j) The beam energy is quoted for 130 MV/m extraction field and initial phase of 54° with respect to the crest of the rf.
5. **Injector - Accelerator**

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>14 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

- Initial electron energy: 7 MeV
- Initial rms bunch length: 1 mm
- Initial charge: 1 nC
- Initial peak current: 87 A

**Electron Beam Parameters at Exit**

- Final electron energy: 150 MeV
- Final normalized emittance: 1 $\pi$ mm mrad
- Final rms bunch length: 1 mm
- Final charge (beam core): 1 nC
- Final peak current: 87 A

**Electron Beam Optics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focusing structure</td>
<td>solenoids</td>
</tr>
<tr>
<td>Minimum horizontal $\beta$-function</td>
<td>1 m</td>
</tr>
<tr>
<td>Maximum horizontal $\beta$-function</td>
<td>10 m</td>
</tr>
<tr>
<td>Minimum vertical $\beta$-function</td>
<td>1 m</td>
</tr>
<tr>
<td>Maximum vertical $\beta$-function</td>
<td>10 m</td>
</tr>
<tr>
<td>Maximum dispersion function</td>
<td>0 m</td>
</tr>
<tr>
<td>Minimum beam-stay-clear radius</td>
<td>1 mm</td>
</tr>
<tr>
<td>Maximum beam-stay-clear radius</td>
<td>7 mm</td>
</tr>
</tbody>
</table>

**Linac Parameters**

- Number of linac sections: 4
- rf-phase at exit: 0 degrees
- rf-phase jitter: 0.5 degrees
6. Injector - Dogleg

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dogleg type</td>
<td>2 dipole dogleg</td>
</tr>
<tr>
<td>R56</td>
<td>-4 mm</td>
</tr>
<tr>
<td>Transverse offset</td>
<td>1.0 m</td>
</tr>
<tr>
<td>Total length</td>
<td>12 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>150 MeV</td>
</tr>
<tr>
<td>Initial normalized emittance</td>
<td>$1 \pi$ mm mrad</td>
</tr>
<tr>
<td>Initial total energy spread</td>
<td>0.20 %</td>
</tr>
<tr>
<td>Initial slice energy spread</td>
<td>0.01 %</td>
</tr>
<tr>
<td>Initial rms bunch length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Initial charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>87 A</td>
</tr>
<tr>
<td>Location after cathode</td>
<td>14.2 m</td>
</tr>
</tbody>
</table>

**Electron Beam Quality Reduction**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity loss</td>
<td>0.00 %</td>
</tr>
<tr>
<td>Mean emittance growth $\Delta \varepsilon / \varepsilon_{\text{entrance}}$</td>
<td>4.0 %</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Exit**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>150 MeV</td>
</tr>
<tr>
<td>Final normalized emittance</td>
<td>$1.04 \pi$ mm mrad</td>
</tr>
<tr>
<td>Final total energy spread</td>
<td>0.20 %</td>
</tr>
<tr>
<td>Final slice energy spread</td>
<td>0.01 %</td>
</tr>
<tr>
<td>Final rms bunch length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Final charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Final peak current</td>
<td>87 A</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>5900 A</td>
</tr>
</tbody>
</table>

**Electron Beam Optics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum horizontal $\beta$-function</td>
<td>2 m</td>
</tr>
<tr>
<td>Maximum horizontal $\beta$-function</td>
<td>30 m</td>
</tr>
<tr>
<td>Minimum vertical $\beta$-function</td>
<td>2 m</td>
</tr>
<tr>
<td>Maximum vertical $\beta$-function</td>
<td>20 m</td>
</tr>
<tr>
<td>Maximum dispersion function</td>
<td>0.2 m</td>
</tr>
</tbody>
</table>
6. Injector - Dogleg (continued)

### Quadrupole Magnets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of quadrupoles</td>
<td>20</td>
</tr>
<tr>
<td>Maximum focusing gradient</td>
<td>8.7 T/m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.15 m</td>
</tr>
</tbody>
</table>

### Dipole Magnets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dipoles</td>
<td>2</td>
</tr>
<tr>
<td>Maximum deflection angle</td>
<td>14 degrees</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.2 m, each</td>
</tr>
</tbody>
</table>

### Electron Beam Diagnostics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wire scanners</td>
<td>5</td>
</tr>
<tr>
<td>Number of x,y BPM pairs</td>
<td>20</td>
</tr>
</tbody>
</table>

### Vacuum System

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal vacuum chamber ID</td>
<td>24 mm</td>
</tr>
<tr>
<td>Vertical vacuum chamber ID</td>
<td>24 mm</td>
</tr>
</tbody>
</table>
## 7. General Linac Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>rf frequency</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Acceleration gradient</td>
<td>19 MV/m</td>
</tr>
<tr>
<td>Active length of section</td>
<td>3 m</td>
</tr>
<tr>
<td>Q</td>
<td>13000 - 14000</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>53 - 60 MΩ/m</td>
</tr>
<tr>
<td>Iris diameter</td>
<td>26.2 - 19.1 mm</td>
</tr>
<tr>
<td>Klystron type</td>
<td>5045</td>
</tr>
<tr>
<td>Peak rf power</td>
<td>60 MW, 130 MW SLED</td>
</tr>
<tr>
<td>Mean rf power</td>
<td>45 kW</td>
</tr>
</tbody>
</table>
8. Linac-1

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>12.375 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

- Initial electron energy: 150 MeV
- Initial normalized emittance: 1.04 π mm mrad
- Initial total energy spread: 0.20 %
- Initial slice energy spread: 0.01 %
- Initial rms bunch length: 1 mm
- Initial charge: 1 nC
- Initial peak current: 87 A
- Longitudinal brightness: 5900 A
- Location after cathode: 26.2 m

**Electron Beam Quality Reduction**

- Intensity loss: 0 %
- Mean emittance growth $\frac{\Delta \varepsilon}{\varepsilon_{\text{entrance}}}$: 3.8 %

**Electron Beam Parameters at Exit**

- Final electron energy: 280 MeV
- Final normalized emittance: 1.08 π mm mrad
- Final total energy spread: 2.30 %
- Final slice energy spread: 0.005 %
- Final rms bunch length: 1 mm
- Final charge: 1 nC
- Final Peak current: 87 A
- Longitudinal brightness: 5900 A
- Focusing structure: FODO
- Mean cell length: 6 m
- Minimum horizontal $\beta$-function: 3 m/rad
- Maximum horizontal $\beta$-function: 10 m/rad
- Minimum vertical $\beta$-function: 3 m/rad
- Maximum vertical $\beta$-function: 10 m/rad
- Maximum dispersion function: 0 m
- Phase advance per cell: 75 degrees
- Beam-stay-clear radius: 11.6 mm
8. Linac-1 (continued)

**Quadrupole Magnets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of quadrupoles</td>
<td>2</td>
</tr>
<tr>
<td>Maximum focusing gradient</td>
<td>3.1 T/m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.1 m</td>
</tr>
</tbody>
</table>

**Linac Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of linac sections</td>
<td>3</td>
</tr>
<tr>
<td>rf phase</td>
<td>-40 degrees</td>
</tr>
<tr>
<td>rf-Phase jitter tolerance</td>
<td>0.1 degrees</td>
</tr>
<tr>
<td>rms pulse to pulse energy variation tolerance</td>
<td>0.06 %</td>
</tr>
</tbody>
</table>
9.  Bunch Compressor-1

General Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor type</td>
<td>4 dipole chicane</td>
</tr>
<tr>
<td>R56</td>
<td>27 mm</td>
</tr>
<tr>
<td>Transverse offset</td>
<td>117 mm</td>
</tr>
<tr>
<td>Total length</td>
<td>2.8 m</td>
</tr>
</tbody>
</table>

Electron Beam Parameters at Entrance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>280 MeV</td>
</tr>
<tr>
<td>Initial normalized emittance</td>
<td>1.08 π mm mrad</td>
</tr>
<tr>
<td>Initial total energy spread</td>
<td>2.3 %</td>
</tr>
<tr>
<td>Initial slice energy spread</td>
<td>0.005 %</td>
</tr>
<tr>
<td>Initial rms bunch length</td>
<td>1 mm</td>
</tr>
<tr>
<td>Initial charge</td>
<td>1 nC</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>87 A</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>5900 A</td>
</tr>
<tr>
<td>Location after cathode</td>
<td>38.5 m</td>
</tr>
</tbody>
</table>

Electron Beam Quality Reduction

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity loss</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Mean emittance growth Δε/ε_{Entrance}</td>
<td>5.6 %</td>
</tr>
</tbody>
</table>

Electron Beam Parameters at Exit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>280 MeV</td>
</tr>
<tr>
<td>Final normalized emittance</td>
<td>1.14 π mm mrad</td>
</tr>
<tr>
<td>Final total energy spread</td>
<td>2.3 %</td>
</tr>
<tr>
<td>Final slice energy spread</td>
<td>0.013 %</td>
</tr>
<tr>
<td>Final rms bunch length</td>
<td>0.39 mm</td>
</tr>
<tr>
<td>Final charge</td>
<td>0.995 nC</td>
</tr>
<tr>
<td>Final peak current</td>
<td>220 A</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>5851 A</td>
</tr>
</tbody>
</table>

Electron Beam Optics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum horizontal β-function</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Maximum horizontal β-function</td>
<td>2.8 m</td>
</tr>
<tr>
<td>Minimum vertical β-function</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Maximum vertical β-function</td>
<td>2.6 m</td>
</tr>
<tr>
<td>Maximum dispersion function</td>
<td>0.117 m</td>
</tr>
<tr>
<td>Beam-stay-clear radius</td>
<td>&gt;30 mm</td>
</tr>
</tbody>
</table>
9. Bunch Compressor-1 (continued)

**Dipole Magnets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dipoles</td>
<td>4</td>
</tr>
<tr>
<td>Maximum deflection angle</td>
<td>7.1 degrees</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.2 m</td>
</tr>
</tbody>
</table>

**Electron Beam Diagnostics**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wire scanners</td>
<td>1</td>
</tr>
<tr>
<td>Number of x,y BPM pairs</td>
<td>1</td>
</tr>
</tbody>
</table>

**Vacuum System**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal vacuum chamber ID</td>
<td>60 mm</td>
</tr>
<tr>
<td>Vertical vacuum chamber ID</td>
<td>20 mm</td>
</tr>
<tr>
<td>Mean longitudinal brightness growth</td>
<td>2 %</td>
</tr>
</tbody>
</table>
10. Linac-2

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>430 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial electron energy</td>
<td>280 MeV</td>
</tr>
<tr>
<td>Initial normalized emittance</td>
<td>1.14 π mm mrad</td>
</tr>
<tr>
<td>Initial total energy spread</td>
<td>2.3 %</td>
</tr>
<tr>
<td>Initial slice energy spread</td>
<td>0.013 %</td>
</tr>
<tr>
<td>Initial rms bunch length</td>
<td>0.39 mm</td>
</tr>
<tr>
<td>Initial charge</td>
<td>0.995 nC</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>220 A</td>
</tr>
<tr>
<td>Location after cathode</td>
<td>41 m</td>
</tr>
</tbody>
</table>

**Electron Beam Quality Reduction**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity loss</td>
<td>0.0 %</td>
</tr>
<tr>
<td>Mean emittance growth Δε/ε&lt;sub&gt;entrance&lt;/sub&gt;</td>
<td>13.2 %</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Exit**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final electron energy</td>
<td>6 GeV</td>
</tr>
<tr>
<td>Final normalized emittance</td>
<td>1.29 π mm mrad</td>
</tr>
<tr>
<td>Final total energy spread</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Final slice energy spread</td>
<td>0.0006 %</td>
</tr>
<tr>
<td>Final rms bunch length</td>
<td>0.39 mm</td>
</tr>
<tr>
<td>Final charge</td>
<td>0.995 nC</td>
</tr>
<tr>
<td>Final peak current</td>
<td>220 A</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>5800 A</td>
</tr>
</tbody>
</table>

**Electron Beam Optics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focusing structure</td>
<td>FODO</td>
</tr>
<tr>
<td>Mean cell length</td>
<td>25 m</td>
</tr>
<tr>
<td>Minimum horizontal β-function</td>
<td>10 m</td>
</tr>
<tr>
<td>Maximum horizontal β-function</td>
<td>47 m</td>
</tr>
<tr>
<td>Minimum vertical β-function</td>
<td>10 m</td>
</tr>
<tr>
<td>Maximum vertical β-function</td>
<td>44 m</td>
</tr>
<tr>
<td>Maximum dispersion function</td>
<td>0 m</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>70 degrees</td>
</tr>
<tr>
<td>Beam-stay-clear radius</td>
<td>11.6 mm</td>
</tr>
</tbody>
</table>
10. Linac-2 (continued)

**Quadrupole Magnets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of quadrupoles</td>
<td>35</td>
</tr>
<tr>
<td>Maximum focusing gradient</td>
<td>17.5  T/m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.1   m</td>
</tr>
</tbody>
</table>

**Linac Parameters**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of linac sections</td>
<td>133</td>
</tr>
<tr>
<td>rf-compression phase</td>
<td>-29 degrees</td>
</tr>
<tr>
<td>rms rf-phase jitter tolerance</td>
<td>1 degrees</td>
</tr>
<tr>
<td>rms pulse to pulse energy variation</td>
<td>0.15 %</td>
</tr>
</tbody>
</table>
11. Bunch Compressor-2

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor type</td>
<td>double 4 dipole chicane</td>
</tr>
<tr>
<td>R56</td>
<td>36 mm</td>
</tr>
<tr>
<td>Transverse offset</td>
<td>0.29 m</td>
</tr>
<tr>
<td>Total length</td>
<td>35 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>6.0 GeV</td>
</tr>
<tr>
<td>Initial normalized emittance</td>
<td>1.29 π mm mrad</td>
</tr>
<tr>
<td>Initial total energy spread</td>
<td>1.0 %</td>
</tr>
<tr>
<td>Initial slice energy spread</td>
<td>0.0006 %</td>
</tr>
<tr>
<td>Initial rms bunch length</td>
<td>0.39 mm</td>
</tr>
<tr>
<td>Initial charge</td>
<td>0.995 nC</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>220 A</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>5800 A</td>
</tr>
<tr>
<td>Location after cathode</td>
<td>471 m</td>
</tr>
</tbody>
</table>

**Electron Beam Quality Reduction**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity loss</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Mean emittance growth Δε/ε&lt;sub&gt;entrance&lt;/sub&gt;</td>
<td>6.2 %</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Exit**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>6.0 GeV</td>
</tr>
<tr>
<td>Final normalized emittance</td>
<td>1.37 π mm mrad</td>
</tr>
<tr>
<td>Final total energy spread</td>
<td>1.01 %</td>
</tr>
<tr>
<td>Final slice energy spread</td>
<td>0.012 %</td>
</tr>
<tr>
<td>Final rms bunch length&lt;sup&gt;*&lt;/sup&gt;</td>
<td>0.020 mm</td>
</tr>
<tr>
<td>Final charge</td>
<td>0.990 nC</td>
</tr>
<tr>
<td>Final peak current</td>
<td>3560 A</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>5765 A</td>
</tr>
</tbody>
</table>

**Electron Beam Optics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum horizontal β-function</td>
<td>17 m</td>
</tr>
<tr>
<td>Maximum horizontal β-function</td>
<td>35 m</td>
</tr>
<tr>
<td>Minimum vertical β-function</td>
<td>17 m</td>
</tr>
<tr>
<td>Maximum vertical β-function</td>
<td>35 m</td>
</tr>
<tr>
<td>Maximum dispersion function</td>
<td>0.29 m</td>
</tr>
</tbody>
</table>

<sup>*</sup>Starts to get difficult to quantify due to increasing non-linearities of correlations.
11. Bunch Compressor-2 (continued)

**Dipole Magnets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of dipoles</td>
<td>8</td>
</tr>
<tr>
<td>Maximum deflection angle</td>
<td>3.4/1.3 degrees</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>1.5 m</td>
</tr>
</tbody>
</table>

**Electron Beam Diagnostics**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wire scanners</td>
<td>2</td>
</tr>
<tr>
<td>Number of x,y BPM pairs</td>
<td>10</td>
</tr>
</tbody>
</table>

**Vacuum System**

<table>
<thead>
<tr>
<th>Description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal vacuum chamber ID</td>
<td>80 mm</td>
</tr>
<tr>
<td>Vertical vacuum chamber ID</td>
<td>30 mm</td>
</tr>
<tr>
<td>Mean longitudinal brightness growth</td>
<td>5 %</td>
</tr>
</tbody>
</table>
12. Linac-3

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>587.5 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

- Initial electron energy: 6.0 GeV
- Initial normalized emittance: 1.37 π mm mrad
- Initial total energy spread: 1.0 %
- Initial slice energy spread: 0.012 %
- rms bunch length: 0.020 mm
- Initial charge: 0.990 nC
- Peak current: 3560 A
- Longitudinal brightness: 5800 A
- Location after cathode: 506.0 m

**Electron Beam Quality Reduction**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensity loss</td>
<td>0 %</td>
</tr>
<tr>
<td>Mean emittance growth $\Delta \varepsilon / \varepsilon_{\text{entrance}}$</td>
<td>2.9 %</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Exit**

- Final electron energy: 14.35 GeV
- Final normalized emittance: 1.41 π mm mrad
- Final total energy spread: 0.10 %
- Final slice energy spread: 0.005 %
- Final rms bunch length: 0.020 mm
- Final charge: 0.990 nC
- Final peak current: 3560 A
- Longitudinal brightness: 5700 A

**Electron Beam Optics**

- Focusing structure: FODO
- Mean cell length: 25 m
- Minimum horizontal $\beta$-function: 32 m
- Maximum horizontal $\beta$-function: 68 m
- Minimum vertical $\beta$-function: 33 m
- Maximum vertical $\beta$-function: 72 m
- Maximum dispersion function: 0 m
- Phase advance per cell: 30 degrees
- Beam-stay-clear radius: 11.6 mm
12. Linac-3 (continued)

<table>
<thead>
<tr>
<th>Quadrupole Magnets</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of quadrupoles</td>
<td>46</td>
</tr>
<tr>
<td>Maximum focusing gradient</td>
<td>18.7  T/m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.1   m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Linac Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of linac sections</td>
<td>188</td>
</tr>
<tr>
<td>rf-compression phase</td>
<td>0     degrees</td>
</tr>
<tr>
<td>rms rf-phase jitter (typical)</td>
<td>2     degrees</td>
</tr>
<tr>
<td>rms bunch to bunch energy variation (typical)</td>
<td>0.05  %</td>
</tr>
</tbody>
</table>
13. Linac to Undulator Transport

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>68 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

- Electron energy: 14.35 GeV
- Initial normalized emittance: $1.41 \, \text{π mm mrad}$
- Initial total energy spread: 0.10 %
- Initial slice energy spread: 0.005 %
- Initial rms bunch length: 0.020 mm
- Initial charge: 0.99 nC
- Initial peak current: 3560 A
- Longitudinal brightness: 5800 A
- Location after cathode: 1093.5 m

**Electron Beam Quality Reduction**

- Intensity loss: 0.0 %
- Mean emittance growth: $2.8 \%$ of entrance

*Halo will not contribute to FEL process.

**Electron Beam Parameters at Exit**

- Electron energy: 14.35 GeV
- Final normalized emittance: $1.45 \, \text{π mm mrad}$
- Final total energy spread: 0.10 %
- Final slice energy spread: 0.006 %
- Final rms bunch length: 0.020 mm
- Final charge: 0.990 nC, Beam Core
- Final peak current: 5600 A
- Longitudinal brightness: 5765 A

**Electron Beam Optics**

- Minimum horizontal $\beta$-function: 4 m
- Maximum horizontal $\beta$-function: 39 m
- Minimum vertical $\beta$-function: 2 m
- Maximum vertical $\beta$-function: 23 m
- Maximum dispersion function: 200 mm
- Beam-stay-clear radius: 12 mm
13. Linac to Undulator Transport (continued)

**Quadrupole Magnets**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of quadrupoles</td>
<td>21</td>
</tr>
<tr>
<td>Maximum focusing gradient</td>
<td>78 T/m</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>0.46 m</td>
</tr>
</tbody>
</table>

**Dogleg Characteristics**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>R56</td>
<td>-0.9 mm</td>
</tr>
<tr>
<td>T566</td>
<td>-61 mm</td>
</tr>
<tr>
<td>Dogleg type</td>
<td>4 dipole dogleg</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>4</td>
</tr>
<tr>
<td>Maximum deflection angle</td>
<td>1.3 degrees</td>
</tr>
<tr>
<td>Magnetic length</td>
<td>2.62 m</td>
</tr>
<tr>
<td>Transverse</td>
<td>90 cm</td>
</tr>
</tbody>
</table>

**Diagnostics**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of wire stations for ε</td>
<td>1 - 4</td>
</tr>
<tr>
<td>Number of wire stations for Δp/p</td>
<td>1</td>
</tr>
<tr>
<td>Number of x,y BPM pairs</td>
<td>21</td>
</tr>
</tbody>
</table>

**Collimator**

<table>
<thead>
<tr>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of collimators</td>
<td>4</td>
</tr>
<tr>
<td>Collimator bore</td>
<td>1.2 mm</td>
</tr>
</tbody>
</table>
14. Undulator

**Undulator Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length, including separations</td>
<td>111.825 m</td>
</tr>
<tr>
<td>Undulator magnet length</td>
<td>99.84 m</td>
</tr>
<tr>
<td>Start location after cathode</td>
<td>1161 m</td>
</tr>
<tr>
<td>Undulator type</td>
<td>planar hybrid undulator</td>
</tr>
<tr>
<td>Magnet material</td>
<td>NdFeB</td>
</tr>
<tr>
<td>Permeable material</td>
<td>Va Permendur</td>
</tr>
<tr>
<td>undulator period $\lambda_u$</td>
<td>30 mm</td>
</tr>
<tr>
<td>Full gap g</td>
<td>6 mm</td>
</tr>
<tr>
<td>Undulator field $B_{\text{max}}$</td>
<td>1.32 T</td>
</tr>
<tr>
<td>Undulator parameter $K$</td>
<td>3.71</td>
</tr>
<tr>
<td>$a_u$ (K /N²)</td>
<td>2.62</td>
</tr>
<tr>
<td>Number of periods per segment</td>
<td>64</td>
</tr>
<tr>
<td>Number of segments</td>
<td>52</td>
</tr>
<tr>
<td>Separation between segments</td>
<td>0.235 m</td>
</tr>
<tr>
<td>Segment magnet length</td>
<td>1.92 m</td>
</tr>
<tr>
<td>Number of periods $N_u$</td>
<td>3328</td>
</tr>
<tr>
<td>Wiggle plane</td>
<td>vertical</td>
</tr>
</tbody>
</table>

**Electron Beam Optics**

<table>
<thead>
<tr>
<th>Property</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focusing method</td>
<td>separated function</td>
</tr>
<tr>
<td>Focusing scheme</td>
<td>FODO</td>
</tr>
<tr>
<td>Quadrupole length</td>
<td>12 cm</td>
</tr>
<tr>
<td>Quadrupole type</td>
<td>permanet magnet</td>
</tr>
<tr>
<td>Cell length</td>
<td>4.32 m</td>
</tr>
<tr>
<td>Quadrupole gradient</td>
<td>45.5 T/m</td>
</tr>
</tbody>
</table>
## 14. Undulator (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>4.54 14.35 GeV</td>
</tr>
<tr>
<td>Average $\beta$-function</td>
<td>6.1 18.0 m/rad</td>
</tr>
<tr>
<td>Maximum $\beta$-function (Initial $\beta_x$)</td>
<td>8.4 20.1 m/rad</td>
</tr>
<tr>
<td>Minimum $\beta$-function (Initial $\beta_y$)</td>
<td>3.8 15.9 m/rad</td>
</tr>
<tr>
<td>Beta-function modulation</td>
<td>76 23 %</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>45 13 degrees</td>
</tr>
</tbody>
</table>

**Electron Trajectory Correction**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trajectory correction scheme</td>
<td>quadrupole displacement</td>
</tr>
<tr>
<td>Center distance between steering quads</td>
<td>2.16 m</td>
</tr>
<tr>
<td>Number of steering quads</td>
<td>52</td>
</tr>
<tr>
<td>Maximum transverse quad displacement (In horizontal and vertical plane)</td>
<td>500 µm</td>
</tr>
<tr>
<td>Maximum trajectory slope angle</td>
<td>180.3 57.0 µrad</td>
</tr>
<tr>
<td>Number of beam position correctors</td>
<td>52</td>
</tr>
<tr>
<td>Number of carbon wire stations</td>
<td>10</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>4.54 14.35 GeV</td>
</tr>
<tr>
<td>Normalized emittance</td>
<td>2.00 1.50 π mm mrad</td>
</tr>
<tr>
<td>Correlated (rms) energy spread</td>
<td>0.10 0.10 %</td>
</tr>
<tr>
<td>Uncorrelated (rms) energy spread</td>
<td>0.014 0.006 %</td>
</tr>
<tr>
<td>rms bunch length $L_B$</td>
<td>20 20 µm</td>
</tr>
<tr>
<td>FWHM bunch length $L_{B,FWHM}$</td>
<td>233 233 fs</td>
</tr>
<tr>
<td>Pulse charge</td>
<td>0.95 0.95 nC</td>
</tr>
<tr>
<td>Peak current</td>
<td>3400 3400 A</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>226 226 A</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters inside the Undulator**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron beam radius (rms)</td>
<td>37 31 µm</td>
</tr>
<tr>
<td>Electron beam divergence (rms)</td>
<td>6.1 1.7 µrad</td>
</tr>
<tr>
<td>Maximum undulation angle</td>
<td>418 132 µrad</td>
</tr>
<tr>
<td>Maximum pk-pk undulation amplitude</td>
<td>4.0 1.3 µm</td>
</tr>
<tr>
<td>Maximum disp. function for ideal undulator</td>
<td>4.0 1.3 µm</td>
</tr>
</tbody>
</table>
14. Undulator (continued)

**Vacuum System**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum chamber height OD</td>
<td>6 mm</td>
</tr>
<tr>
<td>Vacuum chamber wall thickness</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Vacuum chamber material</td>
<td>copper plated stainless steel</td>
</tr>
<tr>
<td>Bunch frequency $\omega = \frac{2\pi c}{L_B}$</td>
<td>$6.8 \times 10^{12}$ s$^{-1}$</td>
</tr>
<tr>
<td>Skin depth</td>
<td>64 nm</td>
</tr>
<tr>
<td>Maximum inner surface roughness</td>
<td>100 nm</td>
</tr>
<tr>
<td>Beam pipe straightness</td>
<td>200 $\mu$m / m</td>
</tr>
<tr>
<td>Vacuum pressure</td>
<td>$&lt; 10^{-7}$ mbar</td>
</tr>
<tr>
<td>Expected Radiation Dose per Year</td>
<td>4 kGy*</td>
</tr>
<tr>
<td>Rad. to damage mag. face $\Delta B/B_r = 1%$</td>
<td>100 kGy*</td>
</tr>
</tbody>
</table>

* 1 Gy - 1 J/kg = 100 rad

**Miscellaneous**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel Temperature Stability</td>
<td>1 K</td>
</tr>
<tr>
<td>Und. Water Systems Temp. Stability</td>
<td>0.1 K</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>4.54 14.35 GeV</td>
</tr>
</tbody>
</table>

**Static Electron Beam Tolerances at Entrance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>0.05 0.05 %</td>
</tr>
<tr>
<td>Peak current</td>
<td>20 20 %</td>
</tr>
<tr>
<td>Maximum correlated rms energy spread</td>
<td>0.1 0.1 %</td>
</tr>
<tr>
<td>Maximum uncorrelated rms energy spread</td>
<td>0.07 0.02 %</td>
</tr>
<tr>
<td>Horizontal and vertical $\beta$ matching</td>
<td>2 2 %</td>
</tr>
<tr>
<td>Maximum horizontal and vertical $\eta$</td>
<td>0.188 0.500 m</td>
</tr>
<tr>
<td>Maximum horizontal and vertical $\eta'$</td>
<td>0.031 0.028</td>
</tr>
<tr>
<td>Maximum slice emittance</td>
<td>2.0 1.5 $\pi$ mm mrad</td>
</tr>
<tr>
<td>Maximum projected emittance</td>
<td>2.5 2.0 $\pi$ mm mrad</td>
</tr>
<tr>
<td>Maximum beam position displacement</td>
<td>36.9 31.0 $\mu$m</td>
</tr>
<tr>
<td>Maximum beam angle</td>
<td>6.1 1.7 $\mu$rad</td>
</tr>
</tbody>
</table>

**Pulse-to-Pulse Electron Beam Tolerances at Entrance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>0.05 0.05 %</td>
</tr>
<tr>
<td>Peak current</td>
<td>20 20 %</td>
</tr>
<tr>
<td>Maximum correlated rms energy spread</td>
<td>0.1 0.1 %</td>
</tr>
<tr>
<td>Maximum uncorrelated rms energy spread</td>
<td>0.07 0.02 %</td>
</tr>
<tr>
<td>Pulse-to-pulse positional stability (rms)</td>
<td>7.4 6.2 $\mu$m</td>
</tr>
<tr>
<td>Pulse-to-pulse angular stability (rms)</td>
<td>1.2 0.3 $\mu$rad</td>
</tr>
</tbody>
</table>
### 14. Undulator (continued)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength $\lambda_r$</td>
<td>15 1.5 Å</td>
</tr>
<tr>
<td>Electron energy $E$</td>
<td>4.54 14.35 GeV</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>8879 28077</td>
</tr>
<tr>
<td>Normalized electron beam emittance $\varepsilon_n$</td>
<td>2.00 1.50 π mm mrad</td>
</tr>
<tr>
<td>Initial charge</td>
<td>0.95 0.95 nC</td>
</tr>
<tr>
<td>Longitudinal pulse form</td>
<td>flat-top</td>
</tr>
<tr>
<td>Transverse pulse form</td>
<td>gaussian</td>
</tr>
<tr>
<td>rms bunch length $L_B$</td>
<td>20 20 μm</td>
</tr>
<tr>
<td>$\tau_B$</td>
<td>67 67 fs</td>
</tr>
<tr>
<td>FWHM bunch length $L_{B,FWHM}$</td>
<td>70 70 μm</td>
</tr>
<tr>
<td>$\tau_{B,FWHM}$</td>
<td>233 233 fs</td>
</tr>
<tr>
<td>Peak current</td>
<td>3400 3400 A</td>
</tr>
<tr>
<td>Uncorrelated rms $\Delta p/p$</td>
<td>0.068 0.021 %</td>
</tr>
<tr>
<td>Correlated $\Delta p/p$</td>
<td>0.2 0.1 %</td>
</tr>
<tr>
<td>Longitudinal brightness: $I_{pk}/(2\pi)^{1/2}\sigma_{\gamma}$</td>
<td>226 226 A</td>
</tr>
<tr>
<td>Cooperation length $L_c$</td>
<td>182 51 nm</td>
</tr>
<tr>
<td>$2\pi L_c$</td>
<td>1145 322 nm</td>
</tr>
<tr>
<td>Slippage length $L_{slip}$</td>
<td>4992 499.2 nm</td>
</tr>
<tr>
<td>FEL parameter $\rho$</td>
<td>13 4.7 $10^{-4}$</td>
</tr>
<tr>
<td>Rayleigh length $z_R$</td>
<td>5.7 40 m</td>
</tr>
<tr>
<td>Power gain length $L_{\xi}$</td>
<td>1.8 5.8 m</td>
</tr>
<tr>
<td>Field gain length $L_{\eta}$</td>
<td>3.7 11.7 m</td>
</tr>
<tr>
<td>Peak saturation power $P_{sat}$</td>
<td>11 9 GW</td>
</tr>
<tr>
<td>Saturation length $L_{sat}$</td>
<td>32.2 94.2 m</td>
</tr>
<tr>
<td>$L_{sat}$</td>
<td>~48 ~100 m</td>
</tr>
<tr>
<td>$L_{u}$</td>
<td>100 100 m</td>
</tr>
<tr>
<td>Energy of first harmonic</td>
<td>0.82 8.2 keV</td>
</tr>
</tbody>
</table>
## 15. FEL

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength $\lambda_r$</td>
<td>15 1.5 Å</td>
</tr>
<tr>
<td>Electron energy $E$</td>
<td>4.54 14.35 GeV</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>8879 28077</td>
</tr>
<tr>
<td>Normalized electron beam emittance $\varepsilon_n$</td>
<td>2.00 1.50 $\pi$ mm mrad</td>
</tr>
<tr>
<td>Initial charge</td>
<td>0.95 0.95 nC</td>
</tr>
<tr>
<td>Longitudinal pulse form</td>
<td>flat-top flat-top</td>
</tr>
<tr>
<td>Transverse pulse form</td>
<td>gaussian gaussian</td>
</tr>
<tr>
<td>rms bunch length $L_{\text{bl}}$</td>
<td>20 20 µm</td>
</tr>
<tr>
<td>$\tau_B$</td>
<td>67 67 fs</td>
</tr>
<tr>
<td>FWHM bunch length $L_{\text{BL,FWHM}}$</td>
<td>70 70 µm</td>
</tr>
<tr>
<td>$\tau_{\text{BL,FWHM}}$</td>
<td>233 233 fs</td>
</tr>
<tr>
<td>Peak current</td>
<td>3400 3400 A</td>
</tr>
<tr>
<td>Nominal uncorrelated rms energy spread $\Delta p/p$</td>
<td>0.07 0.02 %</td>
</tr>
<tr>
<td>Correlated $\Delta p/p$</td>
<td>0.2 0.1 %</td>
</tr>
<tr>
<td>Longitudinal brightness: $I_p/(2\pi)^{1/2}\sigma_y$</td>
<td>226 226 A</td>
</tr>
<tr>
<td>Cooperation length $L_c$</td>
<td>182 51 nm</td>
</tr>
<tr>
<td>$2\pi L_c$</td>
<td>1145 322 nm</td>
</tr>
<tr>
<td>Slippage length $L_{\text{slip}}$</td>
<td>4992 499.2 nm</td>
</tr>
<tr>
<td>FEL parameter $\rho$</td>
<td>13 4.7 $10^{-4}$</td>
</tr>
<tr>
<td>Rayleigh length $z_R$</td>
<td>5.7 40 m</td>
</tr>
<tr>
<td>Power gain length $L_G$</td>
<td>1.8 5.8 m</td>
</tr>
<tr>
<td>Field gain length $L_E$</td>
<td>3.7 11.7 m</td>
</tr>
<tr>
<td>Peak saturation power $P_{\text{sat}}$</td>
<td>11 9 GW</td>
</tr>
<tr>
<td>Saturation length $L_{\text{sat}}$</td>
<td>32.2 94.2 m</td>
</tr>
<tr>
<td>$L_{\text{sat}}$</td>
<td>~48 100 m</td>
</tr>
<tr>
<td>$L_u$</td>
<td>100 100 m</td>
</tr>
<tr>
<td>Energy of first harmonic</td>
<td>0.82 8.2 keV</td>
</tr>
</tbody>
</table>
## 15. FEL (continued)

### FEL Radiation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average saturation power</td>
<td>0.36</td>
<td>0.31</td>
<td>W</td>
</tr>
<tr>
<td>Energy per pulse</td>
<td>3.0</td>
<td>2.6</td>
<td>mJ</td>
</tr>
<tr>
<td>Number of coherent photons per pulse</td>
<td>22</td>
<td>2.0</td>
<td>$10^{12}$ Photons/pulse</td>
</tr>
<tr>
<td>Peak photon flux</td>
<td>81</td>
<td>7.1</td>
<td>$10^{24}$ Photons/s</td>
</tr>
<tr>
<td>Peak brightness</td>
<td>1.2</td>
<td>12</td>
<td>$10^{12}$ Photons/(s mm$^2$ mr$^2$.1%)</td>
</tr>
<tr>
<td>Average brightness</td>
<td>0.42</td>
<td>4.2</td>
<td>$10^{22}$ Photons/(s mm$^2$ mr$^2$.1%)</td>
</tr>
<tr>
<td>Instantaneous photon energy spread</td>
<td>0.14</td>
<td>0.05</td>
<td>%</td>
</tr>
<tr>
<td>Integrated photon energy spread</td>
<td>0.42</td>
<td>0.21</td>
<td>%</td>
</tr>
<tr>
<td>FEL fund. trans. beam size</td>
<td>37</td>
<td>31</td>
<td>µm</td>
</tr>
<tr>
<td>FEL fund. trans. beam divergence</td>
<td>3.2</td>
<td>0.38</td>
<td>µrad</td>
</tr>
</tbody>
</table>

### Spontaneous Radiation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit 1</th>
<th>Unit 2</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak spontaneous power per pulse</td>
<td>8.1</td>
<td>81</td>
<td>GW</td>
</tr>
<tr>
<td>Average spontaneous power</td>
<td>0.27</td>
<td>2.7</td>
<td>W</td>
</tr>
<tr>
<td>Energy loss from spont. radiation</td>
<td>0.0023</td>
<td>0.023</td>
<td>GeV</td>
</tr>
<tr>
<td>Rel. energy loss from spont. radiation</td>
<td>0.050</td>
<td>0.16</td>
<td>%</td>
</tr>
<tr>
<td>$\Delta E/E$ induced by spont. radiation</td>
<td>&lt; 0.02%</td>
<td>&lt; 0.02%</td>
<td>%</td>
</tr>
<tr>
<td>Spont. fund. trans. beam size</td>
<td>52</td>
<td>33</td>
<td>µm</td>
</tr>
<tr>
<td>Spont. fund. trans. beam divergence</td>
<td>6.2</td>
<td>2.0</td>
<td>µrad</td>
</tr>
</tbody>
</table>
16. Electron Beam Dump

**General Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total length</td>
<td>10 m</td>
</tr>
</tbody>
</table>

**Electron Beam Parameters at Entrance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron energy</td>
<td>14.35 GeV</td>
</tr>
<tr>
<td>Initial normalized emittance</td>
<td>1.50 π mm mrad</td>
</tr>
<tr>
<td>Correlated energy spread</td>
<td>0.10 %</td>
</tr>
<tr>
<td>Uncorrelated energy spread</td>
<td>0.05 %</td>
</tr>
<tr>
<td>Initial rms bunch length</td>
<td>0.024 mm</td>
</tr>
<tr>
<td>Initial charge</td>
<td>0.95 nC</td>
</tr>
<tr>
<td>Initial peak current</td>
<td>3400 A</td>
</tr>
<tr>
<td>Longitudinal emittance</td>
<td>40 MeV mm</td>
</tr>
<tr>
<td>Longitudinal brightness</td>
<td>104 A</td>
</tr>
<tr>
<td>Location after cathode</td>
<td>1273.788 m</td>
</tr>
</tbody>
</table>

**Electron Beam Optics**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum horizontal $\beta$-function</td>
<td>4 m/rad</td>
</tr>
<tr>
<td>Maximum horizontal $\beta$-function</td>
<td>39 m/rad</td>
</tr>
<tr>
<td>Minimum vertical $\beta$-function</td>
<td>23 m/rad</td>
</tr>
<tr>
<td>Maximum vertical $\beta$-function</td>
<td>2 m/rad</td>
</tr>
</tbody>
</table>

**Dipole Magnets**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet type</td>
<td>permanent magnet</td>
</tr>
<tr>
<td>Number of dipoles</td>
<td>6</td>
</tr>
<tr>
<td>Maximum deflection angle</td>
<td>~4.5 degrees</td>
</tr>
</tbody>
</table>
### 17. X-ray Optics

**Radiation Source Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation wavelength $\lambda_r$</td>
<td>15</td>
<td>1.5 Å</td>
</tr>
<tr>
<td>Macropulse rep rate</td>
<td>120</td>
<td>120 Hz</td>
</tr>
<tr>
<td>Number of micropulses/macropulse</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>rms Pulse duration</td>
<td>67</td>
<td>67 fs</td>
</tr>
<tr>
<td>FWHM Pulse duration</td>
<td>232</td>
<td>232 fs</td>
</tr>
<tr>
<td>Peak 1st FEL harmonic power</td>
<td>11</td>
<td>9 $10^9$ W</td>
</tr>
<tr>
<td>Energy/FEL pulse</td>
<td>3.0</td>
<td>2.6 mJ</td>
</tr>
<tr>
<td>Number of photons/FEL pulse</td>
<td>22</td>
<td>2.0 $10^{12}$</td>
</tr>
<tr>
<td>FWHM source size (electron)</td>
<td>93</td>
<td>78 µm</td>
</tr>
<tr>
<td>FWHM source divergence (electron)</td>
<td>15</td>
<td>4.3 µrad</td>
</tr>
<tr>
<td>FWHM FEL mode &amp; mode src. size (photon)</td>
<td>93</td>
<td>78 µm (TEM00)</td>
</tr>
<tr>
<td>FWHM FEL mode &amp; mode src. div. (photon)</td>
<td>8.1</td>
<td>1.0 µrad (TEM00)</td>
</tr>
<tr>
<td>1st harmonic rms FEL Rayleigh waist</td>
<td>37</td>
<td>31 µm</td>
</tr>
<tr>
<td>1st harmonic FEL Rayleigh length</td>
<td>5.7</td>
<td>40 m</td>
</tr>
<tr>
<td>1st harm. homogeneous bandwidth $\sigma$</td>
<td>0.14</td>
<td>0.05 %</td>
</tr>
<tr>
<td>1st harm. inhom. (z-corr.) bandwidth $\Delta$</td>
<td>0.42</td>
<td>0.21 %</td>
</tr>
<tr>
<td>Peak 1st FEL harm. power density (@10m)</td>
<td>7.0</td>
<td>15 $10^{11}$ W/mm²</td>
</tr>
<tr>
<td>Peak 1st FEL harmonic field (@10m)</td>
<td>2.3</td>
<td>3.4 $10^{10}$ V/m</td>
</tr>
<tr>
<td>Peak spontaneous power</td>
<td>8</td>
<td>81 GW</td>
</tr>
<tr>
<td>Time-averaged spontaneous power</td>
<td>0.3</td>
<td>2.7 W</td>
</tr>
<tr>
<td>90% total power bandwidth</td>
<td>~0.006</td>
<td>~0.025 keV</td>
</tr>
<tr>
<td>FWHM spont. source size (photon)</td>
<td>~131</td>
<td>82 µm (far field)</td>
</tr>
<tr>
<td>FWHM spont. source div. (photon)</td>
<td>~15.5</td>
<td>4.9 µrad (far field)</td>
</tr>
</tbody>
</table>
17. X-ray Optics (continued)

**Absorption Cell**

<table>
<thead>
<tr>
<th>Length</th>
<th>DTU*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st differential pumping section</td>
<td>1.1 m</td>
</tr>
<tr>
<td>1st x-ray slit pair</td>
<td>2.7 m</td>
</tr>
<tr>
<td>2nd differential pumping section</td>
<td>1.1 m</td>
</tr>
<tr>
<td>Absorption Cell</td>
<td>1.2 m</td>
</tr>
<tr>
<td>3rd differential pumping section</td>
<td>1.1 m</td>
</tr>
</tbody>
</table>

**Near-FFTB X-ray Optics**

<table>
<thead>
<tr>
<th>Length</th>
<th>DTU*</th>
</tr>
</thead>
<tbody>
<tr>
<td>4th differential pumping section</td>
<td>1.1 m</td>
</tr>
<tr>
<td>2nd x-ray slit pair</td>
<td>2.2 m</td>
</tr>
<tr>
<td>5th differential pumping section</td>
<td>1.1 m</td>
</tr>
<tr>
<td>Mirror tank</td>
<td>0.9 m</td>
</tr>
<tr>
<td>6th differential pumping section</td>
<td>1.1 m</td>
</tr>
<tr>
<td>Crystal tank</td>
<td>0.44 m</td>
</tr>
<tr>
<td>7th differential pumping section</td>
<td>1.1 m</td>
</tr>
</tbody>
</table>

**Specular Optics Beamline**

<table>
<thead>
<tr>
<th>Length</th>
<th>DTU*</th>
</tr>
</thead>
</table>

**Crystal Optics Beamline**

<table>
<thead>
<tr>
<th>Length</th>
<th>DTU*</th>
</tr>
</thead>
</table>

**Long Beam Line X-Ray Optics**

<table>
<thead>
<tr>
<th>Length</th>
<th>DTU*</th>
</tr>
</thead>
<tbody>
<tr>
<td>End station (Option 1)</td>
<td>n/a</td>
</tr>
<tr>
<td>End station (Option 2)</td>
<td>n/a</td>
</tr>
</tbody>
</table>

* Distance to Undulator