MATTER IN EXTREME CONDITIONS INSTRUMENT

CONCEPTUAL DESIGN REPORT

SLAC-R-934
October 16, 2009

Stanford National Accelerator Laboratory
Lawrence Livermore National Laboratory
PSRI/Science and Technology Facilities Council

Work supported in part by US Department of Energy contract DE-AC02-76SF00515

Author Institutions

SLAC National Accelerator Laboratory
2575 Sand Hill Road
Menlo Park, California 94025

Lawrence Livermore National Laboratory
L-251
P. O. Box 808
Livermore, CA 94551

Photon Science Research Institute
Science and Technology Facilities Council
Rutherford Appleton Laboratory
Harwell Science and Innovation Campus
Didcot OX11 0QX
United Kingdom

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LIST OF AUTHORS AND CONTRIBUTORS

R. F. Boyce, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
R. M. Boyce, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
G. Haller, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
J. B. Hastings, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
G. Hays, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
H. J. Lee, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
R. W. Lee, *Lawrence Livermore National Laboratory, Livermore, CA, USA*
B. Nagler, *PSRI / STFC, Rutherford Appleton Laboratory, United Kingdom*
M. Scharfenstein, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
D. Marsh, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*
W.E. White, *SLAC National Accelerator Laboratory, Menlo Park, CA, USA*

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LIST OF ACRONYMS

ALARA	As Low As Reasonably Achievable	ESRF	European Synchrotron Radiation Facility
AMO	Atomic, Molecular and Optical Science Instrument	FAC	Facility Advisory Committee
ANSI	American National Standards Institute	FEH	Far Experimental Hall
ARRA	American Recovery and Reinvestment Act	FDI	Fourier Domain Interferometry
APS	Advanced Photon Source	FEE	Front End Enclosure
ANL	Argonne National Laboratory	FEL	Free Electron Laser
AWG	Arbitrary Waveform Generator	FES	Fusion Energy Sciences
BPM	Beam Position Monitor	FOV	Field of View
BCS	Beam Containment System	FY	Fiscal Year
Be	Beryllium	FWHM	Full Width Half Maximum
BES	Basic Energy Sciences	GP	Guiding Principles
BSOIC	Beam Shut Off Ion Chamber	H1-H6	LCLS Experimental Hutches
CA	Channel Access	HED	High Energy Density
CBC	California Building Code	HEDS	High Energy Density Science
CC	Control Camera	HOMS	Hard X-ray Offset Mirror System
CCD	Charge Coupled Device	IH	Industrial Hygienist
CD	Critical Decision	IOC	Input/Output Controllers
CDR	Conceptual Design Report	IPM	Intensity Position Monitor
CF	Core Functions	IR	Infrared
CH	Cross Hair	ISMS	Integrated Safety Management System
CPA	Chirped-pulse Amplification	KDP	Potassium Dihydrogen Phosphate (Doubling Crystal)
CW	Continuous Wave	LANL	Los Alamos National Laboratory
CXI	Coherent X-ray Imaging Instrument	LBNL	Lawrence Berkeley National Laboratory
DAC	Detector Advisory Committee	LCA	Laser-Controlled Area
DAQ	Data Acquisition	LCLS	Linac Coherent Light Source
DOE	Department of Energy	LCW	Low Conductivity Water
DOF	Degree of Freedom	LINAC	Linear Accelerator
EDF	Electron Distribution Function	LLNL	Lawrence Livermore National Laboratory
EEIP	Electrical Equipment Inspection Program	LOI	Letter of Intent
EOS	Equation of State	LOTO	Lock Out and Tag Out
EPICS	Experimental Physics and Industrial Control System	LSS	Laser Safety System
ES&H	Environment, Safety, and Health	LPL	Long Pulse Laser

LUSI	LCLS Ultrafast Science Instruments	Si	Silicon
LVDT	Linear Variable Differential Transformers	SiC	Silicon Carbide
M&O	Management and Operating	SOP	Streaked Optical Pyrometry
MD	Molecular Dynamics	SOP	Standard Operating Procedure
MEC	Matter in Extreme Conditions	SLAC	SLAC National Accelerator Laboratory
MIE	Major Item of Equipment	SPL	Short Pulse Laser
MOPA	Master-Oscillator Power Amplifier	SXR	Soft X-Ray Materials Science Instrument
MPA	Multi-Pass Amplifier		
MSDS	Material Safety Data Sheet	TCP/IP	Transmission Control Protocol/Internet Protocol
NEC	National Electrical Code		
NEH	Near Experimental Hall	TS	Thomson Scattering
OPA	Optical Parametric Amplifier	TPC	Total Project Cost
OPI	OPerator Interface	UCLA	University of California at Los Angeles
OSHA	Occupancy Safety and Health Administration	UL	Underwriters Laboratory
PCW	Processed Cooling Water	UTR	University Technical Representative
PHAR	Preliminary Hazards Analysis Report	VESDA	Very Early Smoke Detection Alarm
PM	Power Meter	VISAR	Velocity Interferometer System for Any Reflector
PMCS	Project Management Control System	WBS	Work Breakdown Structure
PPE	Personnel Protective Equipment	WDM	Warm Dense Matter
PPEP	Preliminary Project Execution Plan	WSHP	Worker Safety and Health Program
PPS	Personnel Protection System	XFEL	X-ray Free Electron Laser
QA	Quality Assurance	XCS	X-ray Correlation Spectrometry Instrument
QIP	Quality Implementation Procedure		
RA	Recovery Act	XPP	X-ray Pump Probe Instrument
RCA	Radiological Controlled Area	XRS	X-ray Spectrometer
RCRA	Resource, Conservation and Recovery Act	XRSC	X-ray Streak Camera
RF	Radio Frequency	XRT	X-ray Tunnel
SAC	Scientific Advisory Committee	XUV	Extreme Ultra Violet

1- EXECUTIVE SUMMARY

1.1. INTRODUCTION

The SLAC National Accelerator Laboratory (SLAC), in collaboration with Argonne National Laboratory (ANL), Lawrence Livermore National Laboratory (LLNL), and the University of California at Los Angeles (UCLA), is constructing a Free-Electron Laser (FEL) research facility. The FEL has already met its performance goals in the wavelength range 1.5 nm - 0.15 nm. This facility, the Linac Coherent Light Source (LCLS), utilizes the SLAC 2-Mile Linear Accelerator (linac) and will produce sub-picosecond pulses of short wavelength X-rays with very high peak brightness and almost complete transverse coherence.

The final one-third of the SLAC linac is used as the source of electrons for the LCLS. The high energy electrons are transported across the SLAC Research Yard, into a tunnel which houses a long undulator. In passing through the undulator, the electrons are bunched by the force of their own synchrotron radiation and produce an intense, monochromatic, spatially coherent beam of X-rays. By varying the electron energy, the FEL X-ray wavelength is tunable from 1.5 nm to 0.15 nm. The LCLS includes two experimental halls as well as X-ray optics and infrastructure necessary to create a facility that can be developed for research in a variety of disciplines such as atomic physics, materials science, plasma physics and biosciences.

This Conceptual Design Report, the authors believe, confirms the feasibility of designing and constructing an X-ray instrument in order to exploit the unique scientific capability of LCLS by creating extreme conditions and study the behavior of plasma under those controlled conditions. This instrument will address the Office of Science, Fusion Energy Sciences, mission objective related to study of Plasma and Warm Dense Matter as described in the report titled LCLS, the First Experiments, prepared by the LCLS Scientific Advisory Committee (SAC) in September 2000.

The technical objective of the LCLS Matter in Extreme Conditions (MEC) Instrument project is to design, build, and install at the LCLS an X-ray instrument that will complement the initial instrument suite included in the LCLS construction and the LUSI Major Item of Equipment (MIE) Instruments. As the science programs advance and new technological challenges appear, instrumentation must be developed and ready to conquer these new opportunities. The MEC concept has been developed in close consultation with the scientific community through a series of workshops team meetings and focused reviews. In particular, the MEC instrument has been identified as meeting one of the most urgent needs of the scientific community based on the advice of the LCLS Scientific Advisory Committee (SAC) in response to an open call for letters of intent (LOI) from the breadth of the scientific community.

The primary purpose of the MEC instrument is to create High Energy Density (HED) matter and measure its physical properties. There are three primary elements of the MEC instrument:

- A) Optical laser drivers that will create HED states by irradiation in several ways and provide diagnostics capability;
- B) The LCLS x-ray free electron laser, which will provide the unique capability to create, probe and selectively pump HED states; and,
- C) A suite of diagnostic devices required to observe the evolution of the HED state.

These elements when combined in the MEC instrument meet the “Mission Need” as defined in CD-0. For the purposes of the description we separate the types of experiments to be performed into three categories:

1) **High pressure:** Here we are interested in the generation of high pressure using the optical lasers to irradiate a surface that ablates and drives a pressure wave into a sample, similar to a piston. The pressures that can be reached exceed 1 Mbar and the properties of interest are for example, the reflectivity, conductivity, opacity as well as the changes driven by the pressure wave on, e.g., condensed matter structure. These phenomena will be studied by means of diffraction measurements, measurements of the pressure wave characteristics, in situ probing by x-ray scattering of various types all time resolved. The necessary diagnostics will be discussed below.

2) **Warm Dense Matter:** The study of Warm Dense Matter (WDM) is concerned with a broad region of the temperature-density-pressure phase space where the matter is neither well described by condensed matter theory nor by the theory applicable to weakly coupled plasmas. It is in the transition regime where matter is heated to and above the melt, progresses to disorder and finally becomes a plasma. The creation of the warm dense matter can be achieved with both the x-ray FEL or with optical lasers. The diagnostic complement will include visible, XUV and x-ray spectrometers, as well as scattering techniques.

3) **High Energy Density Matter:** The study of hot dense matter created by, e.g., optical lasers has been a fertile field of research since the advent of lasers with sufficient energy to heat matter substantially. The scientific interest arises from the fact that one creates matter that has numerous highly charged ion states. Coupling between the atoms/ions and the plasma modify their internal states. Independent of the method of creation (direct irradiation with the x-ray FEL, low intensity optical lasers, high intensity optical lasers or with particle beams created by the optical lasers), unique states of matter that correspond to states found in inertial confinement fusion and astrophysical objects will be created. The primary diagnostics will be Compton scattering and spectroscopy. The spectroscopy can be simple or x-ray FEL pumped emission studies.

Further, there are two aspects of using the X-ray FEL to study non-solid matter interactions that fall into the high energy density matter regime. The first is built on two unique properties of the intense x-ray source: the ability to photoionize gas and create an electron distribution function (EDF) with sharp energy distribution defined by ionization stages, and the small value

of the ponderomotive potential compared to optical lasers at the same intensity. Second, one can study non-linear optical mixing of short and long pulse optical lasers in dense plasmas to create coherent structure. The short pulse x-ray FEL will provide unique information on perturbed densities.

1.2. PROJECT DESCRIPTION

The MEC project plans to build an X-ray instrument over a period of four fiscal years (4Q FY2009 -2Q FY2013). The instrument will be optimized for hard x-ray studies of matter in extreme conditions prepared either by the LCLS beam or by high power optical lasers and probed by the LCLS beam. This instrument will complement the instruments in place or under construction at LCLS, which are directed towards atomic physics, laser pumped ultrafast atomic scale dynamics, nanoscale dynamics in condensed systems and coherent diffraction imaging of nanoscale objects including nanocrystal, large macromolecules and non-reproducible bio-complexes. The scope of the MEC Instrument project includes an x-ray beam transport, optics and diagnostics, laser systems, target chamber and diagnostics are described in Chapter 3 of this Conceptual Design Report (CDR).

1.3. PERFORMANCE CHARACTERISTICS

The LCLS will be an X-ray source with unprecedented brightness and peak power. It will provide pulses of X-rays with duration of about 100 fs or less, in a wavelength range from 1.5 nm to 0.15 nm. In average brightness it will exceed existing storage ring-based sources. In peak brightness, it will surpass existing sources by a factor of 10^9 to 10^{10} . The performance characteristics of the MEC instrument, shown in Table 1-1 will be commensurate with these unique source characteristics.

Table 1-1 Essential Parameters for MEC Instrument.

	Parameter	Capable of Achieving	CD-4 Parameters
WBS 1.2 X-ray Transport System	Energy range	4 keV-20 keV	by calculation
	Energy resolution	0.1%	by calculation
WBS 1.3 Laser Systems	Short Pulse Laser	800nm -150 mJ	>100 mJ
	Long Pulse Laser	>50 J at 527 nm	>25 J at 527 or 532 nm
WBS 1.4 Target Diagnostics	XUV spectrometer	$\Delta E/E \sim 2 \times 10^{-3}$	by calculation
	Thomson scattering spectrometer	$\Delta E/E \sim 3 \times 10^{-3}$	by calculation
WBS 1.5 Controls & Data Acquisition	Rate of display of instrument control and data acquisition parameters.	Up to 5 Hz	>1 Hz
	Detector data rate	Up to 120 Hz pulse rate.	>30 Hz
	Pico-second Timing System	less than 20 ps jitter	<50 ps
WBS 1.6 Hutch Facilities	Provide facilities for instrument control room	Control operations on mezzanine	Control room ready for commissioning

1.4. COST AND SCHEDULE

The Total Project Cost is estimated to be in the range \$19 million - \$23 million. A four-year construction schedule beginning in 4Q FY2009 is proposed.

1.5. ACQUISITION STRATEGY

The lead contractor for acquisition of the MEC project will be Stanford University, which operates SLAC under contract with the U.S. Department of Energy

2- PROJECT OVERVIEW

2.1. INTRODUCTION

The Matter in Extreme Conditions instrument will combine high energy and/or high peak power laser systems with the LCLS x-ray beam to create and probe states of matter inaccessible under static conditions. The lasers will have the ability to create warm dense matter, hot dense matter and have the ability to drive shocks and create pressures approaching 1 Mbar. The LCLS FEL beam provides a unique probe to study these states of matter via spectroscopy, Thomson scattering, imaging and diffraction. In addition the LCLS can be used to create these states of matter in ways not possible with optical lasers.

2.1.1. Scientific Opportunities

2.1.1.1. High Pressure

These experiments in their fullest will address a wide variety of topics in high-pressure research including shocks [1], equations of state [2], shock induced chemical reactions [3], disorder (diffuse scattering) [4], strength/kinetic issues [5], dislocation dynamics [6], coupling to large scale molecular dynamics (MD) [7], high strain rate phenomena [8] and shear modulus under compression [9] (phonon dispersion curves).

Figure 2-1 A generic high pressure experiment. The X-ray detector to measure the Debye-Scherrer rings is described by Kalantar, see reference [10]

The generic high pressure experiment shown in Figure 2-1 has a long pulse laser focused on to a target, to a spot size of 100 to 400 μm after having its wavefront smoothed with phase plates.

Typical targets vary in thickness between 10 and 1000 μm . The laser impinges on the sample and causes ablation that drives a pressure wave into the target. The synchronization of the LCLS with the optical laser must be a fraction of the transit time for the high-pressure wave, caused by the optical laser at the front surface to reach the rear surface. Thus, for example, in the thinnest 10 μm samples the synchronization required will be $\geq 100\text{ps}$. In the prototype experiment illustrated in Figure 2-1, the sample is polycrystalline and the probe is the LCLS. In other cases the sample could be a single crystal and then the probe must have a larger divergence than the LCLS. The irradiated side of the sample will be monitored by a 2-D CCD system to confirm the focal spot on the sample. The rear of the target is diagnosed by the VISAR [11] system, which measures the surface motion, the surface reflectivity and the rear surface temperature [12]. These diagnostics are complemented by the XUV spectrometer that measures the fluorescence induced by the LCLS. The target diffracts the LCLS beam and the diffraction pattern is recorded by a large solid angle detector in order to accurately cover the Debye-Sherrer rings [10].

2.1.1.2. Warm Dense Matter

Figure 2-2 The experimental setup shows the optical short pulse driving laser (SPL) from the top left, frequency doubled to 2ω , in green. The 1ω beam (red) is used to measure the expansion of the surface using Fourier Domain Interferometry (FDI). The SPL intensity would vary from 10^{13} to $>10^{17}$ W/cm^2 with a <100 fs FWHM pulse length. The SPL is incident on a foil of thickness 5 nm to $1\mu\text{m}$, dependent on composition. The incident energy, reflected energy, transmitted energy, and the scattered energy are measured to determine the absorbed energy. The dashed square represents the component in the chamber. The LCLS, which is synchronized with the SPL and overlaps the SPL focal spot, scattering in the forward and back direction is measured by Thomson Scattering spectrometers.

The study of warm dense matter requires the generation of a sample that is *uniformly* heated to temperatures near and above melt. The method of production can vary from the direct irradiation of a sample by the LCLS or a short pulse laser for thin (0.1nm to 100nm) samples, the irradiation of thicker samples by the LCLS or a long pulse laser on inertially confined samples, or the interaction of ion or electron beams produced by short pulse laser focused to high intensity ($>10^{16}$ W/cm²). In Figure 2-2 a schematic of the arrangement is shown wherein the energy is deposited by a short pulse laser that is frequency doubled to 2ω and probed by part of the short pulse laser that is split off at its fundamental frequency, ω , and used in the Fourier Domain Interferometry (FDI) method [13]. The energy deposited is measured by recording the incident (E_{in}), reflected (E_{out}), transmitted (E_{trans}), and scattered ($E_{scatter}$) 2ω signal. The FDI arrangement measures the motion of the critical density surface on time scales consistent with the pulse length (~ 35 fs) in two polarizations. This provides, as does a VISAR, information on the surface dynamics with time resolution on the order of the short pulse laser pulse duration, but does not probe the information about the bulk. To provide a measure of the conditions within the bulk of the sample one employs the LCLS as a probe to scatter from the warm dense matter determining the temperatures, densities, and ionization state. In the diagram the Thomson scattering (TS) [14] is measured in the forward (TS_{forward}) and back (TS_{back}) direction to obtain information about the collective and single particle nature of the electrons within the sample.

2.1.1.3. High Energy Density Matter

The creation of hot dense matter requires long and/or short pulse lasers to irradiate solid or near solid density material at moderate optical laser intensities (10^{12} to 10^{16} W/cm²). The generic experiment is shown in Figure 2-3 where a solid sample is irradiated by a long pulse laser to create a high energy density (HED) plasma, which has ablated from the surface, and a heat conduction wave that moves into the matter both along, and transverse to, the optical laser beam axis. The plasma plume formed in front of the sample varies in density from near solid ($\rho \sim 0.5\rho_0$) to dilute plasma ($\rho \sim 10^{-4}\rho_0$). To diagnose the plasma temperature and density one uses a variety of diagnostics, including optical Thomson scattering, interferometry, and x-ray spectroscopy.

Figure 2-3 The schematic of the high energy density matter experiment.

The sample alignment is critical: the long pulse laser (LPL) will be aligned to the 10 μm spot in which a microdot of some element, e.g. Al, is embedded. The LPL will be focused and a plasma plume is created that contains the Al. The plasma is measured for temperature and density using the short pulse laser (SPL) to perform optical Thomson scattering recorded on a visible spectrometer. Further, 2-D quasi-monochromatic imaging is used to verify the emission lines of the Al ion species of interest. A survey x-ray spectrometer measures the characteristic emission. With the plasma quantified, the LCLS, which is tuned to a selected energy, irradiates the sample causing excitation on the time scale of the pulse duration and the system relaxation will be tracked by observing the time-dependent changes of the emission with an x-ray streak camera. The time scale for the relaxation is dictated by the plasma condition and will vary from a few ps at near solid density to 100s of ps at low density.

Finally, by changing the sample from a solid to a gas one can study, with the same configuration, the production of plasmas with unique electron distributions.

2.1.2. Summary Project Description

In its vision of the future from 2003, “Facilities for the Future of Science: A Twenty-Year Outlook,” the DOE Office of Science placed the LCLS tied for third in near term priorities, and the highest priority for the Basic Energy Sciences (BES) division. The LCLS will be a scientific user facility for the application of XFEL radiation to experimental science. It will bring a completely new dimension to the use of X-rays to study matter through its unique properties never before available. X-rays from synchrotron light sources are currently used to study static atomic structures, but the synchrotron light sources cannot produce ultrashort pulses, so they cannot resolve the ultrafast motions of atoms during dynamical events such as chemical reactions. The LCLS represents a revolutionary advance within the photon science world, since it offers the X-ray spectrum associated with synchrotron light sources, and the ultra-short, ultra-intense pulses required to study dynamics on the nanoscale. The extraordinary peak brightness of the LCLS X-ray pulse will also be invaluable for creating and probing matter in extreme conditions, and for coherent diffraction imaging of nano-objects, such as small clusters of molecules and possibly individual single molecules.

The LCLS Scientific Advisory Committee (SAC) has recommended experiments in five scientific disciplines or thrust areas for the initial operation of the LCLS. These disciplines cover a variety of scientific areas: atomic physics, high energy density science, chemistry, biology and materials science.

The instrument for atomic physics is included in the LCLS project proper. The LUSI MIE covers the areas of chemistry, biology and materials science. One area, high energy density science, is unique for the Matter in Extreme Conditions Instrument. The MEC instrument project provides the sample environments, specialized target diagnostics, the optical drive lasers, and the data acquisition and controls required to address the scientific opportunities described above. In general, the design of MEC is an extension of common HED high power laser facilities combined with the other LCLS experimental instruments. The details of the instrument are described in Chapter 3.

2.1.3. Project Scope

The scope of the Matter in Extreme Conditions Instrument (MEC) project is to design, build, and install a hard X-ray instrument that will exploit the unique scientific capability of the LCLS for high energy density science. As the LCLS science programs advance and new technological challenges appear, instrumentation needs to be developed to meet these new opportunities. The MEC instrument concepts are being developed in close consultation with the scientific community through a series of workshops, conferences and focused review committees. In particular, the MEC project has been identified as meeting some of the most urgent needs of the scientific community by supplementing the capabilities of the initial LCLS instrument suite based on the advice of the LCLS Science Advisory Committee.

The Matter in Extreme Conditions instrument will combine high energy and/or high peak power laser systems with the LCLS x-ray beam to create and probe states of matter inaccessible under static conditions. The lasers will have the ability to create warm dense matter, hot dense matter and have the ability to create pressures approaching 1 Mbar. The LCLS beam provides a unique probe to study these states of matter via spectroscopy, Thomson scattering, imaging and diffraction. In addition, the LCLS can be used to create these states of matter in ways not possible with optical lasers.

The instrument design will emphasize versatility. These experiments require the union of three experimental capacities: 1) the generation and delivery of x-ray and laser pulses to the sample, 2) the preparation of the excited state in the sample, and 3) the detection of the x-ray probe signals in conjunction with ‘standard’ optical diagnostics. To maximize the range of phenomena that can be accessed, it will be necessary to provide short pulse high peak power laser beams and high energy long pulse laser beams that will, depending on the application, have specific laser pulse energies, frequencies, and temporal profiles. The x-ray diagnostic capability of the LCLS in conjunction with these lasers will be the unique aspect of the MEC instrument for HEDS. MEC will provide the LCLS x-ray beam conditioning optics, the LCLS x-ray beam diagnostics, the laser systems, a versatile target chamber, target diagnostics with an emphasis on x-ray diagnostic tools and the experimental controls and data acquisition systems.

Large high-energy laser facilities dedicated to the study of extreme states of matter exist worldwide since this is such a broad field of research. However, the MEC instrument at LCLS is unique, as no existing facility can combine the laser systems with the LCLS, a unique x-ray source with unprecedented peak brightness. This will be the only instrument capable of mapping out the complexities associated with the nature of these highly excited states of matter on the appropriate time scales.

2.2. GOALS AND MISSION

2.2.1. Design Goals

In general, the MEC instrumentation must:

- Fill a scientific need identified by the community, as demonstrated by strong support from a substantial group of potential users;
- Perform better than other existing instrumentation intended for its class of science;
- Be compatible with the characteristics of the LCLS facility, including safety conditions, source performance and physical constraints imposed by other instruments and the existing physical plant.

The principal technical performance parameters that must be met by this instrumentation are specified in the MEC Preliminary Project Execution Plan (PEP) and are given in Table 1-1, Essential Parameters for MEC Instrument. Compatibility with the LCLS facility characteristics has been assessed by the LCLS organization, and scientific oversight is provided by the LCLS SAC. Technical advice comes from the LCLS Facilities Advisory Committee (FAC). The LCLS, LUSI and MEC also receive additional advice on detector choices and developments as required from an external LCLS Detector Advisory Committee (DAC).

2.3. ALTERNATIVE ANALYSIS

The purpose of an alternatives analysis is to choose the most efficient, cost effective path to the desired goal; the design, construction and installation of state-of-the-art instrumentation at the LCLS facility. Evaluation of alternatives may be made in terms of the three components of a project baseline: technical performance, cost and schedule. The most compelling argument for the construction of the MEC instrument is the existence of the LCLS itself and the staff and infrastructure at SLAC. There are no technically comparable existing instruments in the U.S. that could be moved to LCLS, and so there is no alternative but to build new ones. The MEC instrumentation will be optimized to match the characteristics of the LCLS source and to take advantage of the fact that the LCLS facility will be the world's first X-ray free electron laser as it begins early operation in 2009. Therefore, no alternative locations for the instrument were considered.

2.3.1. Cost

The SLAC site is the best choice among alternative sites for the design and construction of the MEC instrumentation due to the close proximity of the LCLS site and the critical interactions between the MEC, LUSI and LCLS staffs on a daily basis. Thus any alternative choice of site will incur significant additional costs associated with the interactions needed to integrate the MEC instrument into the LCLS experimental facilities.

2.3.2. Schedule

Early access to the extraordinary capabilities of the LCLS is extremely important in terms of the scientific opportunities that the facility will offer. In order to utilize the LCLS as rapidly as possible, and to minimize interruptions to ongoing experimental operations, the installation of the instrumentation will be staged over a two-year period beginning in FY2011. Studies to examine the possibility of accelerating this schedule are ongoing.

2.3.3. Technical

The MEC instrument is being developed in ways similar to the other LCLS instruments and laser based HED facilities worldwide. However, throughout the life of the project technological advances will be explored and refinements in design concepts made in order to provide the best state-of-the-art instruments.

2.4. PROJECT SCHEDULE

Major milestones for this project schedule are listed in Table 2-1 below.

Table 2-1 Major Project Schedule Milestones.

Milestones	Estimated Dates
CD-0 Mission Need	Approved: May 2009
CD-1 Cost Range Approval	March 2010
CD-2 Performance Baseline Approval	December 2010
CD-3 Fabrication Start Approval	December 2010
CD-4 Start of Operations Approval	March 2013

2.5. COST ESTIMATE

The current estimated total project cost (TPC) range is \$19 million - \$23 million (note the \$23 million would increase the contingency from ~29% to ~49% at the conceptual stage), which is portrayed in Table 2-2 below. It is based on a four-year (4Q FY2010- 2Q FY2013) construction schedule and is consistent with the funding profile displayed in Table 2-3. A separate budget request will be submitted prior to CD-3 approval for authorization to place long-lead procurements for lasers, diagnostics and x-ray optical components.

Table 2-2 Preliminary Estimate by WBS Elements for the MEC Project.

WBS	Description	Estimate (\$M)
1.1	Project Management	1.2
1.2	X-ray transport system	3.7
1.3	Laser systems	5.3
1.4	Target diagnostics	1.8
1.5	Controls & Data Acquisition	2.7
1.6	Hutch Facilities	0.3
	Contingency	4.4
2.0	Other Project Costs	0.5
MEC Total Project Costs		19.9

2.6. FUNDING REQUIREMENTS

The project is fully funded in year one as indicated in Table 2-3 for the four year construction period beginning in 4Q FY2009.

Table 2-3 Projected Funding Profile for the MEC Project.

MEC Project RA Funding Profile	FY 2009	Total
TEC (WBS 1.0)	19.473	19.473
OPC (WBS 2.0)	0.500	0.50
Annual Total	19.973	19.973

2.7. RISK ASSESSMENTS AND STRATEGIES

All instrumentation in the MEC project is being developed in ways similar to other LCLS instruments for which there are either as built costs or detailed estimates. The size of the risk is based on an assessment of how much the costs might shift due to refinements in design concepts and improvements in technology. Throughout the life of the project, technological advances will be explored in order to provide the best state-of-the-art instruments. At this time the MEC project is considered a low-risk investment since the preliminary parameter requirements proposed by the Science Team are considered achievable within current technical capabilities.

2.7.1. Technical Risks

2.7.1.1. Performance of Transport system

The critical X-ray optics within MEC are the focusing elements. Focusing is provided by MEC for the three experimental conditions. For the larger focal spot sizes, commercial beryllium lens technology has been chosen. This technology has been implemented at many hard X-ray synchrotron beamlines, and is particularly appropriate for the MEC application due to the fact that beryllium is one of the few materials that can transmit the high peak power of the LCLS beam without damage. This focusing option thus has minimal risk.

2.7.1.2. Performance of Target Diagnostics

The initial suite of target diagnostics is a combination of diagnostics used at large laser facilities for HEDS. Their designs have undergone optimization based on years of experience. Thus the risks associated with the optical diagnostics in the suite are minimal. In general for the MEC instrument the LCLS replaces ‘laser driven x-ray sources’ that are part of the large laser based HEDS facilities. The unique capabilities of the LCLS will lead to qualitative improvements to the x-ray diagnostics. The technical risk for these diagnostics is thus only the possibility that the MEC conceptual designs are satisfactory but not optimized to use the unique LCLS characteristics in their designs. It must be kept in mind, however, that cost and schedule risks are made low by use of existing systems as a basis for MEC conceptual design.

2.7.1.3. Performance of Laser Systems

The laser systems are all commercial. The system requirements are well defined for both and both short and long pulse laser. Systems that meet these requirements are operational at many sites worldwide. Thus the technical risks for these systems are minimal.

2.7.2. Schedule Risks

The schedule risk for most multi-year projects is the uncertainty in out year funding. For MEC the project is fully funded in year 1 so that this risk does not exist. The designs are based to a large extent on existing equipment; therefore the uncertainty in schedule for the design phase is also small.

2.7.3. Cost Risks

The cost estimate is judged to be of low risk in terms of completing the project within the budget range. The x-ray transport system, target chamber, target diagnostics and laser systems design and components are either commercial or similar to those already developed for other laser based HED facilities or already used in the LCLS instruments: x-ray pump-probe, x-ray correlation spectroscopy and coherent x-ray imaging.

No risks are foreseen in providing funding. The project has been funded at the low range through the ARRA program.

2.8. STAKEHOLDER INPUT

The initial choice of LCLS instrument suite was carried out by the LCLS SAC, in response to a general call for input from the community followed by consideration of compatibility with the LCLS facility. For the selection the SAC was charged to identify instruments that would support the greatest scientific benefit to the U.S. research community and to the DOE mission. The concept for the MEC instrument was developed in collaboration with the MEC Instrument Team led by Dr. R. W. Lee as Team Leader and Dr. P. Heimann as co-Team Leader.

Throughout the planning process for the MEC instrument, every effort has been made to maintain and promote communication with the agencies responsible for science policy in the US,

the prospective LCLS user community, and the management of SLAC. A workshop held in April 2009, attended by nearly 100 scientists from academia and national laboratories focused on the needs of the broad high energy density science community. The Office of Fusion Energy Sciences (FES) has reviewed and approved the “Mission Need” for a dedicated instrument at LCLS for the study of high energy density science.

The SLAC Directorate has been actively involved in planning the integration of LCLS operations and science with the rest of the SLAC Scientific Program. The SLAC Science Policy Committee, an advisory body to the President of Stanford University, has received regular updates on LCLS activities and planning.

2.9. PROCUREMENT STRATEGY

The MEC Project will be executed by SLAC for DOE under the existing Management and Operating (M&O) Contract (DE-ACO2-76SF00515). SLAC will acquire all the required services and purchases based on a competitively solicited best-value fixed price contracts.

Integrated engineering design for the MEC instrument will be carried out primarily by SLAC scientific and technical staff. However, where particular expertise resides in another laboratory, contractual or other arrangements will be made with that laboratory for the particular scope of work best done there. This arrangement will ensure that the instruments are appropriately integrated into the LCLS facility and meet LCLS ES&H and maintenance standards.

For each piece of equipment, specifications will be developed for its major procurements to define the performance and delivery requirements. Major procurements will typically include optical components, lasers and detectors. MEC may also require specialized optical components. Test and acceptance procedures for equipment will be defined in the individual procurement specifications for each item based on the needs of the specific instrument and on manufacturer’s recommendations.

In coordination with SLAC Procurement, MEC project is developing an Advance Procurement Plan which details all the steps and timelines required for the planned acquisitions including the reviews, decision points, and responsible individuals.

2.10. OVERALL LAYOUT

The overall layout of the LCLS/MEC experimental area is shown schematically in Figure 2-4 including the Near Experimental Hall (NEH), the X-ray transport tunnel, and the Far Experimental Hall (FEH).

2.11. SUMMARY

In summary, this Conceptual Design Report (CDR) describes the design of a state-of-the-art instrument that will exploit the unique scientific capability of the LCLS facility. The instrument will be optimized for hard x-ray studies of matter in extreme conditions prepared either by the LCLS beam or by high power optical lasers and probed by the LCLS beam.

Figure 2-4 Overall layout of the LCLS Experimental Facilities including MEC

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3- MEC INSTRUMENT

Since the late 1960's HEDS research has moved continuously toward higher density and higher temperature regimes. The advent of laser-produced plasmas and laser-based plasma diagnostics has fueled interest in the formation of plasmas at densities nearing solid density. There are two distinct areas of HEDS where the new generation of X-ray light sources can play a critical role in moving these fields substantially forward. The first is in the area of warm dense matter research, where the LCLS will provide tremendous improvement over the current state of the field. The second is in the area of hot dense matter probing techniques where the role of the LCLS, which is in this regard essentially an x-ray laser, will provide substantive improvements.

First, LCLS provides a major advance on any X-ray source capability that has existed before, whether we are interested in creating warm dense matter, performing Thomson scattering, or probing a dense plasma[1][2][3]. The key to the advance is the tunable, narrow band x-ray source with very short pulse duration. Since the individual bunch photon intensity is the essential quantity for all the HEDS research, the comparison of the LCLS to current synchrotron sources is best summarized by comparing peak spectral brightness, where one finds a 10 order of magnitude enhancement in capability. For HEDS the high repetition rate of other sources, e.g., APS or ESRF, is not useful; in all experiments the sample is destroyed on each exposure, thus requiring a single photon pulse to either heat, scatter, or probe matter that is transient.

Second, measurement of a Thomson scattering signal in the solid density hot or warm dense matter regime requires an x-ray probe. The LCLS meets this requirement, with temporal duration, short compared to the evolution of the system but long enough to probe the plasma collective modes. The nominal 100 fs pulse duration of the LCLS will make it possible to probe HED samples and determine the in situ temperatures, densities, and collective behavior.

Third, the spectroscopic probing of high energy density matter requires a short-pulse high-energy source. To be useful as a spectroscopic probe, one needs a spectrally tunable source for which the number of photons per mode must be on the order of unity. *Photons per mode* is a measure of the probe's ability to dominate a radiative transition to provide observable signal. The high peak brightness of the LCLS will provide this capability.

3.1. OVERALL LAYOUT

The MEC instrument is simple in concept: it will utilize either the LCLS beam and/or one or more optical lasers focused onto the target to create matter in extreme conditions. The MEC will include a suite of optical and x-ray diagnostics to fully characterize those states. Figure 3-1 shows a schematic diagram of a typical MEC experiment. The figure shows the main components: the drive beams to excite the matter and a suite of diagnostics arranged around the sample to diagnose the sample. The sample and the associated diagnostics are located within a large target

chamber that can accommodate both the optics for the optical drive beams along with the diagnostic suite.

Figure 3-1 Schematic of an MEC experiment

Figure 3-2 Layout of Hutch 6

class laser system and a short pulse (30-50 fs) 150 mJ class system. The x-ray optics includes focusing using refractive lenses as well as slits and diagnostics.

Finally, Figure 3-3 is a block diagram of the MEC components from the x-ray deflecting mirror located at the upstream end of the x-ray transport tunnel through to the target chamber. In the text that follows the individual components are discussed. Table 3-1 describes the purpose and specifications for the major components shown schematically.

Figure 3-3 MEC components from X-ray deflecting mirror to the target chamber.

Table 3-1 MEC Components

Item	Purpose	Specification
HOMS Mirror System	Deflect the LCLS beam from the central path into hutch 6	90% reflectivity up to 24.8 keV Resistant to beam damage Accept 4σ of the beam at 8 keV
B4C Collimator	Provide hardware protection at separation of MEC beam pipe	Withstand FEL beam power & collimate extreme rays
Slits/Apertures	Beam definition, Beam halo cleaning	1 μm accuracy 1 μm repeatability Resistant to beam damage
Attenuators	Provide variable attenuation for alignment	Variable, up to 10^6 reduction
Pulse Picker	Match the LCLS pulse rate to the drive laser systems/target diagnostics	Select a single pulse and any pulse rate below the nominal LCLS 120 hz rate.
Profile-Intensity Monitor	Alignment of x-ray optical components	Profile: 10mm FOV, 5 μm Intensity: 10^3 dynamic range
Intensity Position Monitor	Pulse by pulse measurement of beam flux and position	Position: resolution 20 μm Flux: 0.1% resolution
Harmonic Rejection Mirror	Attenuate the FEL higher harmonics	10^4 reduction of third harmonic
Be Focusing Lens System	Focus the LCLS beam either as a pump or probe	Focal spot size of < 3 microns over the energy range 4-25 keV
Target Chamber	Provide a vacuum environment for the final drive laser optics, sample and target diagnostics	Base pressure < 1×10^{-5} torr
Laser Systems	Provide drive beams and/or laser beams for diagnostics	Short pulse: 150 mJ at 800 nm Long pulse: 100J at 527 nm
Target Diagnostics	Provide detectors for the experiment	Fourier Domain Interferometer VISAR X-ray and XUV spectrometers X-ray and visible photodiodes

3.2. X-RAY TRANSPORT SYSTEM

The x-ray transport system includes all the components to deliver the x-ray beam to the target chamber center. X-ray beam parameters such as the beam size, pulse energy, position, arrival time and wavelength are critical for MEC experiments. These parameters must be either well defined or measured on a pulse-by-pulse basis to ensure experimental success. The X-ray optics and diagnostics described below will be used to tailor these parameters to meet the requirements for each MEC experiment.

3.2.1. X-ray Deflection Mirror system

The x-ray beam that is delivered to the MEC instrument passes through both of the upstream far experimental hall hutches (Hutch 4 and Hutch 5). In order to provide space for these instruments the MEC beam needs to be offset. There is a choice of x-ray optics to accomplish this, either a large offset monochromator or an x-ray mirror. Since MEC requires the full LCLS pulse energy only an x-ray mirror will work. X-ray mirrors covering the energy range up to the third harmonic of the LCLS are already in use in the front end enclosure (FEE). These hard x-ray offset mirrors (HOMS) use SiC coated Si mirrors and reflect to 25 keV with high efficiency. MEC will use this mirror system design in detail. The reflectivity of the mirror for our choice of grazing angle, 1.375 mrad, is shown in Figure 3-4. The mirror has greater than 90% reflectivity over the energy range, 2-25 keV spanned by the MEC experiment.

Figure 3-4 SiC reflectivity versus photon energy for the following: 1.375 mrad grazing angle, SiC density 0.9 of bulk, thickness 50 nm, layer and substrate roughness 0.5 nm [4]

The optical design and the mechanical design [5] for the mirror positioning will be identical to that for the HOMS mirrors in the FEE. The pointing stability will be less than 10% of the beam size and a thermal enclosure to stabilize the temperature to better than 0.03° C. Figure 3-5 shows the assembly of the mirror system as designed for the HOMS application. The mirror system is fully retractable from the beam allowing x-rays to pass to H4 or H5 through the use of a translation stage. Vacuum pressure in the mirror chamber will be $\sim 10^{-9}$ torr by using differentially pumped regions both up and down beam of the mirror system.

Figure 3-5 HOMS mirror assembly to be used for the MEC deflection mirror

3.2.2. Slit Systems

Precision slit systems are required to define the spatial region of the sample that is being probed by the X-ray beam and to remove parasitic scatter. This device is a critical beamline component due to the relatively large shot-to-shot spatial fluctuations of the LCLS FEL. Spatial fluctuations of the X-ray beam on the sample can be problematic impeding the measurement of spatial dependences of the sample being studied. The transverse coherence of the FEL radiation must be considered in the design of the slit system. In particular, parasitic scattering from the slit blade itself can be significant when a coherent beam is apertured. A cylindrical slit blade design has been implemented to reduce the background scatter from the slit blades.

The x-ray beam dimension will thus be tailored for the MEC instrument with a variable aperture. This will be achieved with the use of two horizontally opposed and two vertically opposed translating blades. Two different slit types are required that differ only in the material of the blade:

- (1) Low Z slits with a light material for the blade selected to withstand the full LCLS beam.
- (2) High Z slits with a heavy material blade selected to fully absorb the beam over the 4-25 keV range but not capable of withstanding the full LCLS beam.

Under some circumstances, a Low Z slit will be mounted directly upstream of a High Z slit so that the Low Z slit can withstand the full LCLS beam and protect the High Z slit from damage. The MEC will use the designs in detail that have been developed for the LUSI instruments [6]. The overall design is shown in Figure 3-6.

To minimize parasitic scattering from the slits, very smooth edges must be realized. A proven solution is the use of cylindrical surfaces since this geometry helps to control the direction of parasitic scatter. The slit blades shall be cylindrical with a 1.5 mm radius to avoid large reflective surfaces that would produce unwanted parasitic scatter. The details of the slits are given in Table 3-2 Slit Blade Materials, Geometry and Surface Finish Requirements.

Table 3-2 Slit Blade Materials, Geometry and Surface Finish Requirements.

Blade Names	Material	Blade Radius	Surface Roughness Goal (maximum)
Low Z blade	Silicon Nitride <i>Si₃N₄</i>	1.5 mm	0.025 μm (0.5 μm)
High Z blade	Tantalum 90/ Tungsten 10 <i>Ta90W10</i>	1.5 mm	0.025 μm (0.5 μm)

Figure 3-6 LUSI single and double slit systems

3.2.3. Harmonic Rejection Mirror System

The LCLS beam contains not only the fundamental but also higher harmonics. The third harmonic for example may be as large as 1% of the fundamental. For most MEC experiments this is not a difficulty; however in those cases where harmonic purity is important the MEC instrument will have available a harmonic rejection mirror system. The concept is simple: by choosing the grazing angle of total reflecting x-ray mirrors such that the fundamental reflects and the higher harmonics don't one can reduce the third harmonic content by a factor of more than 10^4 with a pair of mirrors arranged as shown schematically in Figure 3-7. The mirrors are single crystal Si which has high reflectivity, high damage threshold and excellent surface and figure

quality. MEC will use the LUSI design for this system [7] Figure 3-8 is a 3-d drawing of one of the mirror pair.

Figure 3-7 Schematic of the harmonic rejection mirror pair.

Figure 3-8 Drawing of LUSI design for one of the harmonic rejection mirror pair.

3.2.4. Be Lens Focusing System Refractive Lens Systems

The index of refraction of hard X-rays in materials differs from unity. Thus, it is possible to focus X-rays using an appropriately shaped lens in much the same way as a visible wavelength lens. In general, a stack of lenses is required to focus the beam at manageable focal lengths since the index of refraction ($1-\delta$) only slightly differs from unity (δ typically on the order of 10^{-4}). The lenses are manufactured from beryllium to minimize the X-ray attenuation through the lens as well as maximize the damage threshold of the lens. High purity beryllium with a very good surface finish must be used to minimize degradation of the coherent phase front of the FEL beam. Figure 3-9 is a schematic of both a single lens and a multi-lens stack.

The primary advantage of the refractive lens system is that the beam is not deviated from the unfocused trajectory when the optic is inserted, as well as the ease of alignment. The two major disadvantages of refractive lenses are the chromaticity of the optic and transmission loss. The

index of refraction of hard X-rays varies with wavelength and thus for a single lens system different wavelengths will have different focal properties (focal length, spot size). The transmission loss will generally be less than 50% but this will depend upon the number of lenses required. As with all the x-ray optics and diagnostics the MEC will utilize the LUSI design [8]. Figure 3-10 shows the vacuum housing and the lens holder details. The design has the ability to choose any one of three lens combinations without breaking vacuum. This, in combination with a z-translation (along the beam direction), will accommodate the chromatic effects of the refractive lens keeping the focus at the target chamber center.

The MEC lens system will provide a 500 nm FWHM beam size over the photon energy range 4.0-24.8 keV. The system will also have ± 20 cm of travel to permit the use of an expanded beam downstream of the waist. For a Gaussian beam this travel will give a 30 μm FWHM.

Figure 3-9 Schematic of a single parabolic refractive lens (top) and a compound stack of lenses (bottom).

Figure 3-10 LUSI Be lens system

3.2.5. Profile-Intensity Monitor

The profile intensity monitor that will be implemented in the MEC instrument is the same as that designed for LUSI [9]. The 3-d drawing of the LUSI system is shown in Figure 3-11. In order to minimize the space allocated to this diagnostic the LUSI design incorporates both the intensity and the profile monitor in a single component. Since both monitors are 'destructive' there is no loss in functionality by this approach.

The intensity monitor device consists of an X-ray diode and associated electronics. The requirements for the X-ray diode are low noise, large dynamic range up to 10^4 , and integrating rather than counting mode.

A position diagnostic that can capture a direct image of the X-ray beam position and profile is required for assisting the alignment of optical components. The assembly is composed of a fluorescent screen, a mirror for visible wavelength light, a vacuum actuator and an optical imaging. A cerium-doped yttrium aluminum garnet (YAG:Ce) crystal has been chosen as the scintillating element of the profile monitor. There is both a wide field of view (12mm with 50 μm spatial resolution) and a narrow field of view (1mm with 4 μm spatial resolution) capability.

Figure 3-11 LUSI Profile-Intensity Monitor

3.2.6. Intensity Position Monitor

Pulse-to-pulse fluctuations of the X-ray pulse intensity are about 10% or less in saturated operation. Fluctuations in the third harmonic can be considerably larger. Thus, a single-shot transmissive intensity monitor is required for signal normalization. This capability is important for the alignment of X-ray optics and is paramount for experiments that are detecting induced changes in the X-ray scattering due to external influences.

A non-destructive hard X-ray intensity monitor will be constructed based on the detection of in-elastically scattered X-ray photons from a thin foil. Calculations suggest that 0.2% of incident photons are in-elastically scattered by a 100 μm thick piece of beryllium. As much as 30% of the scattered photons can be collected by an X-ray diode placed a few millimeters upstream of the foil. When used in the direct LCLS beam (10^{12} photons/per pulse), this equates to 10^9 photons incident upon the X-ray diode. The shot noise for this amount of photons is 3×10^{-5} . Thus, an intensity measurement with a precision of 10^{-3} should be achievable with appropriate designs for the X-ray diode and readout electronics.

The intensity monitor can also serve as a beam position monitor (BPM) with the use of a quadrant X-ray diode array. Calibration of the BPM is performed by precisely translating the

diode array by known distances while monitoring the signals in the diode array. A schematic of the hard X-ray intensity monitor is displayed in Figure 3-12 where a fraction of the X-ray beam, incident from right to left, is backscattered from a foil target onto a quadrant diode array. Figure 3-13 is the LUSI detailed design. MEC has adopted this design [10].

Figure 3-12 Intensity-position monitor schematic.

Figure 3-13 LUSI intensity-position monitor.

3.2.7. Pulse Picker-Attenuator System

In some instances it may be required to attenuate the X-ray intensity to prevent either sample or detector damage due to the extremely high peak power of the FEL radiation. Variable attenuation can be achieved by inserting a combination of foils into the beam path. The foil material must be able to withstand the LCLS beam without damage and lead to only minimal distortion of the wavefront of the LCLS beam. The LUSI attenuator system utilizes Si single crystals and provides a 10^6 factor in attenuation with an incremental attenuation of 4-steps-per decade at a photon wavelength of $1.5 \text{ \AA}$.

Again to save precious space the LUSI design also incorporates a 'pulse picker' in the attenuator vacuum enclosure. The 3-d drawing of the design is shown in Figure 3-14. The pulse picker can select a single LCLS pulse which will be a common mode for MEC since the long pulse drive laser runs at 1 shot approximately every 4 minutes. In addition the pulse picker can run at repetition rates between the single pulse mode and the full LCLS repletion rate of 120 hz. Again for MEC the short pulse laser system has the capability to run up to 10 hz and here the pulse picker will operate to match that. MEC will use the LUSI design [11].

Figure 3-14 LUSI Attenuator-pulse picker assembly.

3.3. LASER SYSTEMS

Two laser systems will be constructed for the MEC instrument: a short-pulse high-intensity Ti:sapphire laser and a high-energy, multi-beamed Nd:glass laser. The short-pulse laser (fs-laser) will have a peak intensity of ≤ 5 TW operating at 10 Hz and 800 nm. The long pulse laser (ns-laser) will have two outputs, each making ≤ 25 J per pulse at 527 nm. Each laser will be constructed from commercially available components; however final assembly, alignment, and maintenance will be performed by LCLS Laser Group. Both systems will be located inside the MEC hutch. Also custom designed optical assemblies will transport both lasers to the target chamber.

Figure 3-15 Layout of MEC laser table. The short pulse laser is positioned left of the target chamber, and the long pulse laser is on the right.

3.3.1. Femtosecond Laser System

The design of the femtosecond laser will be based upon the technique of chirped-pulse amplification (CPA)[19], and will use the master-oscillator power amplifier (MOPA) architecture. It will be composed primarily of commercially available laser systems. Pulse generation will begin with a mode-locked Ti:sapphire oscillator. It will operate at 68 MHz, producing 20 fs pulses at 800 nm. In order to synchronize the fs-laser to the FEL, the oscillator pulse rate frequency will be slaved to the 8th sub-harmonic (476 MHz) of the S-band linac RF signal. The 476 MHz is distributed to the hutch by the LBNL optical fiber timing system. By design this system should measure sub-100 fs of timing jitter between the FEL and optical laser systems.

Figure 3-16 Optical schematic of the femtosecond laser system. Power meters are labeled as PM, and cameras are labeled C1.

Amplification will be performed in two stages: the first will be in a commercial kilohertz regenerative amplifier, and the second will be in a custom built multi-pass amplifier (MPA). The commercial regenerative amplifier will include the pulse stretcher, pump laser, regenerative amplifier, and a kilohertz pulse compressor for energies ≤ 10 mJ. The kHz compressor could also be configured to generate both synchronous and asynchronous probe beams for various experiments. The regen, which is pumped by a frequency doubled Nd:YLF laser, will produce ≥ 6 mJ amplified pulses at 800 nm. A Pockels cell and polarizer will be incorporated between the regen and the kHz compressor to serve as a pulse picker and cleaner. Selected pulses from the Pockels cell will be sent to seed the second stage MPA, and will have an increased pre-pulse contrast ratio of $10^6:1$.

Final amplification will be in the MPA, which will be designed and constructed by the LCLS laser group. It will be configured as a 4-pass, bow-tie amplifier, and will be pumped by a 1.2 J, 10 Hz, frequency doubled Nd:YAG laser. The commercial pump laser will be pre-optimized by the manufacturer to have a super-Gaussian spatial profile to improve gain uniformity in the MPA Ti:sapphire crystal. With 20% extraction efficiency, the MPA should amplify the pulses to greater than 200 mJ before compression.

After amplification, the pulse will be resized and sent to the high-energy pulse compressor. The compressor and beam transport to the target chamber will be in vacuum to prevent self-phase modulation from propagation through air. The high-energy compressor will be a two grating design, and will compress the pulse back down to < 40 fs. The vacuum chamber will be large enough to accommodate large aperture gratings for a possible future high-energy upgrade.

The compressor will also be motorized to vary the pulse width, and to adjust the beam alignment into the target chamber.

The fs-laser system will also have a full suite of diagnostics and controls available through the EPICS interface. Users will be able to remotely monitor and control all critical components of the laser including: mode-locking and RF-locking of the oscillator, energy measurements, beam pointing and centering, pulse width adjustment, plus beam alignment and focal position within the target chamber. A SLAC designed feedback control loop will be used at the output of the MPA to stabilize the slow drift (>1 sec) beam pointing, and maintain the alignment into the vacuum pulse compressor. In addition pulse energy, along with spatial and temporal profiles will be saved on a per pulse basis into the LCLS data stream.

3.3.2. Nanosecond Laser System

The long pulse laser will be a custom Nd:glass laser, and will also be based upon MOPA architecture. It will consist of a commercial front-end laser seeding a bifurcated Nd:glass amplifier chain. The output will have two temporally synchronized, 25-Joule pulses at 527 nm. Because the amplifier has multiple outputs, the laser can be configured to fire at several different shot rates with multiple beam configurations. Users will be able to fire 25 Joules every 5 minutes or 50 Joules every 10 minutes. The glass heads will be procured from a commercial vendor; but design, assembly, and alignment of the laser and its diagnostics will be done by the LCLS Laser Group.

Figure 3-17 Optical schematic of the ns-laser system. The laser has two arms, each capable of generating ≤ 25 Joules at 527 nm (< 50 J total) to the target chamber.

The front-end will consist of a single longitudinal mode Nd:YLF laser. The laser has a CW fiber oscillator that is fed into a pulse shaper. The shaper is driven by an arbitrary waveform generator (AWG), which enables the front-end to have both a variable pulse width and temporal shape. After the AWG, the pulse is amplified to >100 mJ at 10 Hz for all pulse widths by a multistage Nd:YLF amplifier. Users will be able to select pulse widths between 2 to 20 ns with a variety of different shapes. A feedback control loop will also be used to stabilize the slow drift (>1 sec) beam pointing of the front-end into the amplifier chain.

Next the output pulse from the front-end laser will illuminate a serrated aperture, and then be spatially filtered to truncate the Gaussian wings and produce a parabolic spatial profile. A parabolic beam is required to maximize the energy extraction and to compensate the radial gain profile of the large aperture rod amplifiers. The radial gain variance in the rod amplifiers will gain shape the parabolic spatial profile of the seed and generate a flattop, super-Gaussian at the amplifier output. The beam will then be image relayed to a pair of single pass, 25 mm diameter Nd:glass rod amplifiers that are arranged with birefringence compensation. Next a 50/50 beam splitter separates the output of 25 mm rods into two beams. Each is then image relayed to a final pair of 50 mm diameter rod amplifiers. The rods are also single passed and arranged with birefringence compensation. The output of each 50mm rod pair will be ≤ 50 J at 1053 nm, and frequency doubled to ≤ 25 J at 527 nm.

After frequency conversion, the output of both amplifiers will be combined on a single large aperture mirror, and then transported together to the target chamber. Both beams will be temporally synchronized to <100 ps. The transport line will incorporate nitrogen purged beam tubes and a vacuum image relay telescope to relay the plane of the doubling crystals to the target chamber. The transport will also have motorized mirror mounts and insertable cross hair assemblies to assist with alignment of the beams into the chamber. Inside the chamber the pulses can be spatially multiplexed to several configurations: two beams co-propagating with the x-rays, two beams co- and counter-propagating with the x-rays, or one or more beams off axis of the x-rays. Also phase plates can be used to generate smooth intermediate field spatial profiles.

Finally the controls network will monitor and record full set of diagnostics for the ns-laser system. Each amplifier chain will have its energy, temporal, and spatial profiles saved to the LCLS data stream on a shot by shot basis. The final focusing optics in the target chamber will be on a 5-axis positioner to provide full adjustment and alignment of the beams. Additionally there will be an equivalent-plane imaging camera to show the focused beams at the target interaction region.

Figure 3-18 Schematic of the ns-laser optical transport to the target chamber. The two laser pulses will be combined onto one mirror, and then transported to the target chamber together through a single beam pipe.

3.4. TARGET DIAGNOSTICS

The target diagnostics system is comprised of two major subsystems: a target vacuum chamber and target diagnostics.

3.4.1. Target Chamber

The target chamber will need to accommodate multiple types of targets, the relay optics for the two MEC laser systems, and the experimental geometries as described in section 3.1. The MEC chamber design will follow that of the LANL Trident vacuum chamber [12] which has 8 symmetrical ports and is nearly 2.5 meters in diameter (see Figure 3-19). This type of chamber is sufficiently spacious to contain the optics required for both the long and short pulse laser beams, the target stage and the required experimental diagnostics. These components will be mounted on an optical breadboard inside the chamber that is mechanically isolated from the chamber itself to eliminate the vacuum loading effects. Vacuum pressure will be in the 10^{-6} torr region. The target chamber position will be fixed in the hutch and the chamber will include a target stage providing 6 degrees of freedom, X, Y, Z, pitch, yaw and roll for target alignment. If required, users can bring their own target chambers and install it downstream of the main target chamber in the MEC hutch. Space has been reserved to accommodate a 1-meter diameter chamber in this location.

Figure 3-19 Design of the Trident experimental vacuum chamber at Los Alamos National Laboratory.

3.4.2. Target Diagnostics

The MEC target diagnostics provide several measurement capabilities in various experimental geometries. The different sub-instruments described below are compatible with each other so that simultaneous data acquisition of any or all the diagnostics is possible. All the data acquisition is integrated into the main data subsystem of the MEC instrument (see section 3.5). Every diagnostic component is required to be either in vacuum or have an appropriate vacuum interface. The main MEC target diagnostic sub-instruments are described below.

3.4.2.1. The Fourier Domain Interferometry (FDI)

The primary purpose of the FDI diagnostic is to measure the phase and amplitude of the reflection of a femtosecond laser from the target (See Figure 2-2) [13]. The phase information is extracted, by interfering two time-delayed pulses in a spectrograph. The difference in phase between the pulses (one typically before the incidence of a pump or heater beam and one after), provides information on the different mechanisms that can cause the phase changes such as: plasma expansion (including Doppler shift), surface movement and deformation, and density changes. The interferograms are spectrally resolved leading to high accuracy, and time delays up to picoseconds can be experimentally set and scanned. In this way, a FDI provides information on the energy deposition and the internal temperature of the sample.

A FDI is a very versatile instrument. Using chirped probe pulses, the FDI can be reconfigured to determine surface motion, deformation and reflectivity versus time in a single shot. The different components of the FDI are:

- A) A femtosecond optical probe pulse that is synchronized with the drive beam within 10fs.
- B) A Michelson interferometer with a variable delay between the two arms.
- C) A spectrograph, in which the temporally separated pulses interfere on a CCD, giving the frequency resolved reflectivity and phase profile of the target.

3.4.2.2. Spectrometers for Thomson scattering, Emission, and XUV spectroscopy

Spectrometers are important diagnostic tools required for x-ray Thompson scattering [14], emission spectroscopy [15], and XUV spectroscopy [16]. The MEC instrument will provide both X-ray crystal spectrometers and XUV grating based spectrometers coupled to x-ray CCD camera. Both crystal and grating spectrometers will be installed inside MEC experimental chamber and will be configurable in order to meet experimental needs.

The housing of the X-ray spectrometer shall be designed to accommodate different crystals and detectors according to the required energy range and resolution. Figure 3-20 shows a conceptual design using a focusing curved crystal coupled to an x-ray detector.

The XUV spectrometers, based on either a toroidal grating or flat field grating with a focussing collection optic will have a high collecting efficiency and a energy range of about 20 eV tunable from 5 eV to 120 eV, depending on the experimental requirements.

Figure 3-20 Design sketch of one of the spectrometers with curved crystal

3.4.2.3. Velocity Interferometer System for Any Reflector (VISAR) and Streaked Optical Pyrometry (SOP)

A VISAR system measures the surface velocity and reflectivity of a target versus time. It is a crucial diagnostic in shock wave and high pressure experiments. It is used to determine shock breakout times and shock velocity, allowing for the determination of the Equation of State (EOS) of matter under extremely high pressure [17]. In a VISAR, a 10-50 ns laser pulse is reflected off the back of the high-pressure target, and sent through a Michelson interferometer with different delays in each arm. The resulting fringes are streaked in time. The position of the fringes is determined by the phase difference of the beams coming from the two arms of the interferometer, which, due to their delay difference, are directly related to the velocity of the target surface. Two VISARs are required to resolve the 2π phase ambiguity when a jump in velocity occurs during the passing of a shock front. The system envisioned for the MEC instrument will be a line VISAR. The line VISAR images the target onto the slits of the streak cameras, allowing for a

velocity profile in one spatial dimension and time to be measured. As a VISAR allows for the velocity measurement over tens of ns, it is complementary to the FDI.

The VISAR system is combined with a SOP. In this diagnostic, the self emission of the (hot and high pressure) target is spectrally resolved and streaked, which allows one to determine the temperature change versus time of the target. Both diagnostics are co-located (Figure 3-21), and image the same part of the target on the same timescale.

Figure 3-21 The VISAR Diagnostic System schematic showing the Streaked Optical Pyrometer (SOP), the Alignment station, the two interferometers and the two optical streak cameras.

3.4.2.4. Diode detector

X-ray and optical diode detectors will be extensively used for a variety of purposes with a capability of readout rates that match the machine repetition rate of 120 Hz. They can be used in transmission and reflection geometries [15]. X-ray photodiodes that provide a linear response will be used to measure the incident x-ray flux. Optical diode detectors such as silicon photodiodes and avalanche photodiodes provide high quantum efficiency between 400 and 1000 nm. Thus these devices can be used at low photon intensities as diagnostics for the laser sample interaction.

3.4.2.5. X-ray pinhole camera

A pinhole camera combined with proper band-pass filters such as thin beryllium or aluminum foil is a simple detector for imaging the spatial distribution of warm dense matter or high energy density matter [18]. The camera consists of a light-tight enclosure with a pinhole collimator, or an aperture, see Figure 3-22. It will be used in conjunction with an x-ray framing camera and CCD for temporally resolved images (50-200 ps). In addition, time-integrated images of the dense plasmas can be recorded with x-ray pinhole cameras used in conjunction with a CCD detector. In general a small pinhole results in good image resolution. However, a small diameter often causes diffraction effects that affect the image quality. To achieve optimum

resolution of the detected image, the required diameter of the hole d can be determined by $d=1.9(\lambda f)^{1/2}$. The parameter λ and f are the photon wavelength and focal length, that is, the distance from the pinhole to a detector.

Figure 3-22 A schematic of the geometry for a pinhole detector.

3.4.2.6. User provided diagnostics.

The MEC instrument will allow users to field their own specialized equipment and diagnostics. The large Trident chamber with 8 ports pointing towards the interaction point allows for great flexibility in this regards, and should accommodate the specific demands of most users. Alternatively, users can bring their own chamber, complete with diagnostics, which can be placed downstream of the Trident chamber. These diagnostics will be integrated into the MEC control system as needed.

3.5. CONTROLS AND DATA SYSTEMS

3.5.1. System Overview and Scope

An important objective is to take advantage of the effort invested in the controls and data systems for the previous instruments (AMO, SXR, CXI, XCS, XPP) either in design, being installed, or already commissioned at LCLS. A single standardized architectural framework for controls, data acquisition, and data management systems is used at LCLS. The specific needs of individual instruments are addressed on this common framework. Figure 3-23 shows a simplified system diagram. Some of the MEC equipment to be controlled and read out are grouped into vacuum (gauges, pumps, valves), motion (motors, encoders, LVDT, solenoids), viewing (slow cameras), diagnostics (signal processing and digitization), low and high voltage power supplies and detectors. Racks, trays, cabling are part of the system to be installed.

The control software frame-work is EPICS (Experimental Physics and Industrial Control System), used in the entire LCLS project.

The data acquisition system controls, acquires, and processes data at up to 120-Hz, real-time, from detectors and cameras. For MEC a maximum of 30 Hz acquisition rate is required. Program and data servers and network switches connect the individual clients.

Figure 3-23. Schematic Diagram of Controls/Data Acquisition System.

The scope for the control and data system is to design, implement, purchase and install mostly rack based controllers and data-acquisition components, including cables to the beam line and chambers. Software and user interface screens specific to MEC will be written and tested. Control and user work-stations for the control room will be provided.

3.5.2. System Overview

3.5.2.1. Controls

The MEC control subsystem will consist of three major components: the slow control component, the shot-by-shot real-time operation component, and the fast timing component. The slow control component will perform e.g. vacuum, motion, and viewing control. In addition control of the Hutch 6 laser system will be realized, which entails mainly vision and motion control and readback..

The shot-by-shot real-time operation component will embed pulse characterization information with experimental data acquired with the MEC cameras on a per pulse basis. This requirement stems from the intrinsic wavelength, intensity, timing, positional, and directional jitters in the FEL pulses. The frame-work for the shot-by-shot communication has already been implemented for an existing experiment and will be copied for MEC.

The fast timing with a timing resolution of the order of 100 fsec is also required by MEC. It will be based on hardware and software already in use at LCLS. A copy of the fast-timing laser receiver will be purchased and integrated.

MEC will be interfaced to several common systems in place at LCLS, such as machine protection system, hutch protection system, machine timing and triggering, laser safety system, although MEC will need to purchase the necessary instrument-specific components, and install and commission them.

All activities that are “slow”, supervisory, and not timing critical are handled within the EPICS control system. In general EPICS is satisfactory for communication among entities and control of functions that are not timing sensitive (e.g. requiring response times of the order of a few microseconds) and not deterministic (due to the use of TCP/IP communications protocol among EPICS supervisory computers and input/output controllers).

The EPICS platform uses Client/Server techniques to provide communication among various control entities. Most servers, called Input/Output Controllers (IOCs), perform real-world I/O and local control tasks, and make information about their states available to their clients via the Channel Access (CA) network protocol, which is designed for medium bandwidth, quasi real-time network applications. The hardware architecture of EPICS is distributed such that each IOC or OPI (OPERator Interface) can communicate with all the others, providing flexibility and scalability to system implementation. MEC will connect to LCLS EPICS server located in the Near Experimental Hall (NEH) server room. Fiber optics connections from the server room to Hutch 6 are already in place.

For MEC the following components must be controlled in the LCLS X-ray Tunnel: Vacuum (valves, ion-pumps, gauges) for the beam-pipe, motion for deflecting mirrors and pop-in profile monitors. In Hutch 4 and Hutch 5, vacuum ion pumps and gauges must be controlled and read out to support Hutch 6 operation. In Hutch 6, EPICS IOCs will control and read out vacuum, motion, viewing, and diode readout conditioning and digitization.

3.5.2.2. Data Subsystem

Figure 3-24 shows a block diagram of the data system components. Control of the experiment is via the Level 0 (L0) work stations. The control and acquisition of data from front-end detectors is via the Level 1 (L1) data acquisition components which can be either waveform sampling devices, fast cameras, or silicon detectors. At that stage the data is merged with the accelerator time stamps received via the accelerator timing system. Subsequently the shot-to-shot real-time data from the other sections of the accelerator or photon area devices are merged and forwarded to the Level 2 (L2) processing farm where online processing and real-time data rendering to enable user monitoring is performed. The data-cache provides for several days of data storage. Data is also forwarded to the computing center (not shown in figure) for offline tape storage.

Figure 3-24. Component Level Block Diagram of Data Subsystem.

The MEC data-acquisition hardware for the camera control and readout will need to be integrated into the LCLS system which requires some software effort. The software for L1, L2, and L3 services has already been developed and will need to be commissioned for the MEC data path. Server and processing farm hardware in the NEH server room will be used, network fiber connections between the server room and Hutch 6 are already in place.

In principle, it will possible to control the MEC experiment from any supervisory computer on the SLAC site, subject to appropriate access security limitations. However it is expected that the experiment will be controlled, and the slow and fast data is displayed, by workers located close to Hutch 6. The control and data rendering work-stations are located in the Hutch 6 control area. Several control and user work-stations will be set up adjacent to the hutch.

3.6. REFERENCES

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4- ENVIRONMENT, SAFETY & HEALTH

4.1. INTRODUCTION

The SLAC National Accelerator Laboratory (SLAC) Worker Safety and Health Program is designed to meet Title 10 of the Code of Federal Regulations, Part 851 (10 CFR 851). The regulation requires all Department of Energy (DOE) sites to establish a worker protection program that will reduce or prevent the potential for injuries, illnesses, and accidental losses by providing workers with a safe and healthful workplace. The SLAC program describes the Worker Safety and Health Program (WSHP) that has been developed at SLAC, a DOE site, to comply with 10 CFR 851.

In addition to the above mentioned WSHP, it is SLAC's policy and objective to integrate safety and environmental protection into its management and work practices at all levels, so that its mission is accomplished while protecting the worker, the public, and the environment. To achieve this objective, SLAC has developed and implemented an Integrated Safety Management System plan (ISMS), required by DOE P450.4, Safety Management System Policy. Fundamental to the ISMS process is the application of Guiding Principals (GPs) and Core Functions (CFs). GPs are a series of best management practices or “basic philosophy” that ensure start-to-finish management of ES&H issues. CFs provide the necessary structure that describes the scope of work, identifies and analyzes the hazard, develops and implements hazard controls, allows work to be performed within the controls, and uses feedback from the work performed to improve the safety system. Responsibility for achieving and maintaining excellence in this system rests with line management, who implement the SLAC ES&H policy with the personnel under their supervision.

Existing and mature programs at SLAC will be used to ensure that all aspects of the design, installation, and testing phases of the project are properly managed. The MEC project will be presented to the SLAC Safety Overview Committee, which coordinates and assigns safety reviews for new projects or facility modifications to other citizen committees, which have knowledge or skills in a specific area. The hazards for MEC may require reviews from such committees as: Radiation Safety Committee, Electrical Safety Committee, Earthquake Safety Committee, Laser Safety Committee and the Fire Protection Safety Committee. The MEC Instrument project will design, build, and install one instrument to be used in conjunction with the Linac Coherent Light Source (LCLS). After installation of the MEC, LCLS operations will conduct an Instrument Readiness Review prior to its operation. The instrument will comply with and operate within the bounds of the approved LCLS Accelerator Safety Envelope.

At SLAC, the MEC project will not generate any hazards that have not already been defined and addressed within the WSHP and will not present any significant challenges from the ES&H perspective. All aspects of the project will conform to WSHP and ISMS. The MEC has developed a Preliminary Hazards Analysis (PHAR) which indicates that no previously unidentified safety hazards were found in the development of the PHAR beyond the hazards addressed in the LCLS Safety Assessment Document, and the results of the hazards analysis were consistent with those of the LCLS analysis that resulted in a low hazard facility determination following the criteria defined in DOE-O 420.2B Safety of Accelerator Facilities.

Appendix A identifies the potential hazards, causes, and mitigating controls that the MEC project may encounter as identified in the PHAR.

4.2. IONIZING RADIATION

The design and operation of all radiation-producing facilities at SLAC are governed by the ALARA (as low as reasonably achievable) policy. SLAC has always maintained radiation dose limits below the maximum allowed by regulation.

4.2.1. Radiation Shielding

Shielding for MEC will conform to the Radiation Safety Systems Technical Basis Document, Chapter 1 Radiological Guidelines for Shielding and Barriers (SLAC-I-720-0A05Z-002). Under normal operation the design criterion will be (i) 1 rem/yr at 30 cm from the shield surface, assuming a 2000 hr working year and an occupancy factor of 1. In addition MEC will have non-radiological workers (Users); additional shielding may be required to maintain their annual effective dose equivalent below 0.1 rem/yr taking exposure duration and occupancy factors into account. SLAC internal design criteria also requires that under a system failure (ii) the total effective dose equivalent shall not exceed 3 rem for a broad beam and 12 rem for a narrow beam, and that under an accident scenario that requires human intervention to turn off the beam (iii) the maximum dose equivalent shall not exceed 25 rem averaged over a 1 hour period for broad beam exposure or 100 rem averaged over 1 hour for narrow beam exposure.

An analysis of the present shielding indicates that potential beam losses from the LCLS during operation could produce high radiation doses. Local shielding, in some cases movable, will be used to mitigate these hazards to acceptable values. Defining the type and amount of local shielding is dependent on the final configuration of the LCLS for the experimental halls and experimenter hutches. Installation of radiation loss monitors at the hutches for diagnostic capabilities may be used to determine where beam losses are taking place. Adding this monitoring package in addition to the Beam Containment System (BCS) will further help maintain dose levels below those limits allowed at SLAC.

The MEC laser system (especially the short pulse beam) has the capability of generating ionizing radiation when focused onto solid samples (e.g. Au) at best focus, and as such poses a radiation safety hazard. The target chamber and hutch will be appropriately shielded and interlocked to mitigate such hazard for users and operators.

4.2.2. Personnel Protection System

The personnel protection system (PPS) consists of electrical interlocks and mechanical barriers whose primary functions are to prevent entry of personnel into a beamline enclosure when prompt radiation and electrical hazards are operating, and to turn off the beam, RF, and electrical hazards when a security violation is detected. Other functions that it must also accomplish are: (i) provide interlocks for the orderly searching of an area before beam is turned on, (ii) allow for various access states, such as No Access, Controlled Access or Permitted Access, (iii) have emergency shut-off capabilities, and (iv) control the electrical hazards in beam housing areas. As installation of the MEC instrument will not require a significant change to the present shielding footprint, the PPS will undergo only necessary upgrades and enhancements to address the instruments. These upgrades include: additional status and control interfaces to accommodate new power supplies, access control modules for the injector and experimental areas, logic upgrades, and interlocks with beam stoppers, Beam Shut Off Ion Chambers (BSOICs), and those burn-through monitors that are controlled through the PPS. The PPS will remain largely the same in terms of its design, function, and configuration as other PPS to installations used at SLAC and LCLS, and all additions will conform to the Radiation Safety Systems Technical Basis Document, Chapter 2 Personnel Protection Systems (SLAC-I-720-0A05Z-002).

4.2.3. Beam Containment System

The Beam Containment System (BCS) prevents accelerated beams from diverging from the desired channel, and detects excessive beam energy or intensity that could cause unacceptable radiation levels. Beam containment is usually accomplished by a combination of passive devices such as collimators, which are designed to absorb errant beams, and active devices such as electronic monitors that shut off the beam when out of tolerance conditions are detected. The present BCS in the Linac consists of passive mechanical devices (such as slits, collimators, magnets, electron beam stoppers, and dumps) and active electronic devices such as average current monitors, burn through monitors, and beam shut off ion chambers. Additionally the LCLS will install photon stoppers, ion chambers, and burn-through monitors for the proposed beamlines. Gas absorption cells are planned to be installed in critical places, for attenuating the beam as needed.

4.2.4. Radiation Safety Training

In accordance with SLAC's Site Access and Identification Badges Policies and Procedures (SLAC-I-720-0A0Z-002-R001), all individuals at SLAC who enter a Radiologically Controlled Area (RCA) or the Accelerator Area must be either properly trained or escorted by a properly trained individual. Levels of training depend on the area to be accessed and in some cases the duration of the individual's stay.).

4.3. ELECTRICAL SAFETY

An experimental facility by nature has subsystems that either produce or use high voltage or high current, either of which can present an electrical hazard to personnel if not managed

properly. The MEC project will operate in a similar mode to other research facilities at SLAC with control and work procedures for electrical subsystems being well documented and understood. Primary mitigation of the hazard will be through de-energization of equipment, placement of barriers and the effective use of Lock Out and Tag Out (LOTO) procedures.

The design, upgrade, installation and operation of electrical equipment will be in compliance with the National Electrical Code, applicable parts of OSHA and SLAC's policy on Electrical Safety as found in ES&H Manual Chapter 8 (Electrical Safety) and 51 (Control of Hazardous Energy). Entry into the experimental facility requires the mitigation of electrical hazards through either the lockout of power supplies or selective use of mechanical barriers, interlocked to further reduce the risk of exposure to electrical shock. Various levels of electrical safety training and LOTO training are provided by SLAC for those personnel who may work on or near potential electrical hazards.

4.4. LASER SAFETY

The MEC hutch will serve as a laser-controlled area (LCA) for several high-energy class IV laser systems. An engineered laser safety system (LSS) with controls and interlocks will enable operation of these lasers as mandated by ANSI Z136.1, *American National Standard for Safe Use of Lasers* and by DOE Rule 10 CFR 851, *Worker Safety and Health Program*. The LSS will be entirely separate and independent from the radiation PPS system.

LCLS will develop, review and approve in cooperation with the SLAC ES&H division a Standard Operation Procedure (SOP) for the safe use of lasers within the MEC hutch. The LSS will then implement the requirements mandated by the SOP and by Chapter 10: Laser Safety of the SLAC ES&H Manual. The LSS enforces the appropriate state of the laser safety shutters and interlocks depending on the mode of operation as specified in SOP. Further it will ensure that laser light is entirely contained within the hutch, and that controlled access is limited only to qualified laser operators.

4.5. EMERGENCY PREPAREDNESS

It has been estimated by the U. S. Geological Survey that the chance of one or more large earthquakes (magnitude 7 or greater) in the San Francisco Bay area in the coming 30 years is about 67 percent. All SLAC personnel are trained in the immediate response to earthquakes and other emergencies via their employee orientation to environment, safety and health.

4.6. SEISMIC SAFETY

SLAC structures are designed and constructed to minimize the effects of a major earthquake to acceptable levels. The MEC components will be installed in the new LCLS facility, whose seismic stability is well documented and deemed acceptable.

4.7. EMERGENCY PLANNING

The design, review, installation and operation of all experimental equipment at SLAC is done in a manner that minimizes the risk of accident or injury to personnel and property in the event of either a natural disaster or emergency situation. SLAC's formal emergency planning system as described in the SLAC Emergency Preparedness Plan (SLAC-I-730-0A14A-001) will help ensure a logical, organized, and efficient site wide response to any emergency. Facility specific procedures, which supplement the SLAC emergency plan, support a timely initial response, further decreasing the probability of personal injury and limiting potential loss or damage to both property and the environment.

4.8. HAZARDOUS MATERIALS

During the installation and operation phases of MEC it is anticipated that a minimum amount of hazardous materials will be used, examples would be paints, epoxies, solvents, oils and lead in the form of shielding, etc. There are no current or anticipated activities at the MEC project that would expose workers to levels of contaminants (dust, odors, and fumes) above acceptable levels.

The SLAC Industrial Hygiene Program detailed in the SLAC ES&H Manual addresses potential hazards to workers from the use of hazardous materials. The program identifies how to evaluate workplace hazards at the earliest stages of the project and implement controls to eliminate or mitigate these hazards to an acceptable level. Site and facility specific procedures are also in place for the safe handling, storing, transporting, inspecting and disposing of hazardous materials. These are contained in the SLAC ES&H Manual Chapters 40 (Hazardous Materials), 22 (Waste Minimization and Pollution Prevention) and 17 (Hazardous Waste).

The UTR or Project Engineer has added responsibilities with respect to the management of hazardous materials. They ensure subcontractor personnel are aware of, and remain in compliance with SLAC's written Hazard Communication Plan, also keeping affected SLAC personnel informed of hazardous material usage and the associated hazards and risks.

4.9. FIRE SAFETY

The probability of a fire during the assembly and installation of MEC instrument is expected to be comparable to other research facilities at SLAC since components are primarily fabricated out of similar, non-flammable materials and combustible materials in general are kept to a minimum. The most "reasonably foreseeable" incident or event with any substantial consequences would be a fire in the insulating material of the electrical cable plant caused by an overload condition. This differs from the maximum credible fire loss, which assumes proper functioning of the smoke detector system and a normal response from the on-site fire department. In this case, losses would be confined to isolated components, and associated cabling. The ES&H Manual Chapter 12, "Fire Safety" (SLAC-I-720-0A29Z-001-R007) address all fire safety issues.

Installation of new cables for the MEC project will meet the current SLAC standards for cable insulation and comply with National Electric Code (NEC) standards concerning cable fire resistance. While this reduces the probability of a fire starting, an aspiration type smoke detection system (VESDA) in the accelerator housing and fire breaks in the cable trays will mitigate fire travel. Support buildings for power supplies, electronic equipment or experimental areas are protected by automatic heat activated wet sprinkler systems and smoke detectors. Fire extinguishers are located in the Experimental Halls for use by trained personnel. The combination of smoke detection systems, sprinklers and on-site fire department (response time ~3 minutes) affords an early warning and timely response to fire or smoke related incidents.

Burn injuries caused by a fire are not expected because in the Experimental Halls personnel are less than 150 ft from an exit. Multiple entry/exit points also helps in keeping property damage to a minimum.

4.10. ENVIRONMENTAL PROTECTION

It is likely that the assembly and installation of the MEC instrument may produce hazardous wastes, such as used solvent from degreasing baths or spent cutting fluids. These are ongoing operations at SLAC, disposal of wastes is routine, and in full compliance with SLAC's policies on the management of hazardous materials and waste minimization. Any hazardous waste would be disposed of in accordance with SLAC procedures and ultimately to a permitted Treatment, Storage and Disposal Facility, under regulations set forth in the Resource, Conservation and Recovery Act (RCRA).

4.11. QUALITY ASSURANCE

Quality assurance (QA) is an integral part of the design, procurement, fabrication, and installation of the MEC Instrument. MEC project management will communicate high expectations and concrete goals for the attainment of quality, and make decisions to ensure that performance objectives for both fabrication and operation are met. Special attention is given to items and services that affect the safety and operational reliability of the MEC.

The MEC Quality Assurance Manager is responsible for development and implementation of the *MEC Quality Implementation Procedure, SLAC-I-050-07010-000*.

The purpose of the MEC Quality Implementation Procedure (QIP) is to detail the quality assurance plan by which the MEC Project will produce an instrument within the technical scope and regulations. This document contains policies for:

- Designing in quality and reliability.
- Promoting early detection of problems to minimize failure costs and impact on schedule.
- Developing appropriate documentation to support construction and operational requirements.

- Establishing methods to identify critical systems and to release these systems based on demonstrated performance.
- Assuring that personnel are trained as needed before performing critical activities, especially those activities that have environment, safety or health consequences.
- Defining the general requirements for design and reviews including environment, safety, and health issues.

This Quality Implementing Procedure (QIP) was prepared to meet the SLAC Office of Assurance Quality Implementing Procedure Requirements, revision in effect on date of approval, and the applicable requirements of DOE Order 414.1C, "Quality Assurance".

4.12. PROCEDURES AND POLICIES REFERENCES

SLAC Worker Health and Safety Program

SLAC-I-720-0A21B-001-R002;

SLAC Safety Management System:

SLAC-I-720-0A00B-001-R004

SLAC Environment, Safety & Health Manual:

<http://www-group.slac.stanford.edu/esh/eshmanual/>

SLAC Radiation Safety Systems Technical Basis Document

SLAC-I-720-0A05Z-002

Specification for Seismic Design of Buildings, Structures, Equipment, and Systems at the Stanford Linear Accelerator Center

SLAC-I-720-0A05Z-002

SLAC Emergency Preparedness Plan

SLAC-I-730-0A14A-001

4.13. HAZARD ANALYSIS

Table 4-1 Hazard Identification and Risk Determination

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
1	Ionizing radiation exposure inside the experimental hut (greater than 1 rem/h) [10CFR835.502]:1 1. Prompt	PPS failure or inadequate search	Level 1 Catastrophic Frequent	<p>Personnel Protection System (PPS). PPS operator training. Periodic testing of PPS. Radiation safety training.</p> <p>Search Procedures, Entry and Exit Procedures, PPS Interlock Checklists Instrument operations procedures</p> <p>Training – LCLS User orientation will warn of the hazards of being in the experiment enclosure and the personnel protective systems in place.</p> <p>Beam Line Authorization, Pre-run Checks, PPS Safety Inspection Checklists</p> <p>Shutter open warning lights</p> <p>PPS door lock and PPS interlock for beam cutoff if enclosure door is open when shutter is open.</p> <p>Ref: SLAC Guidelines for Operations, Radiological Control Manual, SLAC ES&H Manual, Chapter 9 Radiological Safety</p>	Personnel high radiation exposure	Level 20 Negligible Improbable

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
2	Ionizing radiation exposure (greater than 1 rem/hr) outside the hutch enclosure	Failure of shielding, monitoring or interlock systems	Level 1 Catastrophic Frequent	<p>Beam Containment System (BCS)</p> <p>Beam Line Authorization, Pre-run Checks, PPS Safety Inspection Checklists</p> <p>Dosimetry</p> <p>Ref: <i>Radiation Safety Systems, <u>Radiation Safety System Technical Basis Document</u>, SLAC ES&H Manual, Chapter 9 Radiological Safety</i></p>	Personnel radiation exposure.	Level 20 Negligible Improbable
3	Non-ionizing radiation exposure	<p>Laser room connected to experimental hutch</p> <p>Class IV laser in experimental hutch</p>	Level 7 Marginal Frequent	<p>Engineered controls including opaque barriers, laser safety system, beam containment during routine operation</p> <p>PPS equipment: appropriate laser goggles for wavelengths in use.</p> <p>Administrative controls including laser safety training, alignment mode with only trained personnel in hutch</p> <p>Ref: <i>SLAC ES&H Manual, Chapter 10, Laser Safety</i></p>	Personnel injury – eye damage or skin burns	Level 20 Negligible Improbable

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
4	Fire	Cable Plant Combustible material in experimental areas	Level 8 Catastrophic Remote	<p>LCLS Fire Hazards Analysis defined recommended design guidelines to minimize the fire potential on the project.</p> <p>Based on these recommendations the LCLS was classified as an “improved risk” system, meeting the objectives of DOE Order 420.1.</p> <p>Recommendations from this analysis included:</p> <ul style="list-style-type: none"> - VESDA smoke detection system reporting to the Pyrotronics MXL panel. - Fire sprinklers. - Proper selection of cable plant. - Fire breaks in cable trays. - Limiting combustible and flammable material in experiment stations. <p>In addition SLAC has an on-site fire department. Ref: <i>SLAC ES&H Manual, Chapter 12, Fire & Life Safety</i></p>	<p>Loss of technical equipment</p> <p>Partial loss of cable plant</p> <p>Shut down of operations</p> <p>Personnel Injury – burns, smoke inhalation</p> <p>Death or asphyxiation</p>	Level 14 Marginal Remote

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
5	Electrical	<p>Installation of standard industrial distribution (< 210 V) systems.</p> <p>Contact with energized cables during installation of instrumentation</p>	<p>Level 4 Catastrophic Occasional</p>	<p>Implementation of building and structural codes (CBC)</p> <p>Design standards and Safety Committee review and inspections. New equipment complies with all applicable electrical codes and standards.</p> <p>All equipment used in LCLS installations must be EEIP certified. Certain conventional equipment will be UL listed.</p> <p>Project reviewed by the SLAC electrical safety committee review.</p> <p>Installation of standard industrial distribution systems.</p> <p>LOTO training for all individuals working on exposed electrical systems.</p> <p>Specific LOTO procedure (EEIP) for each power supply.</p> <p>Electrical hot work permits, where applicable.</p> <p>Ref: <i>SLAC ES&H Manual, Chapter 8, Electrical Safety</i></p>	Shock or arc (flash)	<p>Level 14 Marginal Remote</p>
6	Seismic	<p>Falling objects during earthquake</p>	<p>Level 8 Catastrophic Remote</p>	<p>Design standards and Safety Committee review and inspections.</p> <p>Ensure all equipment is adequately secured during design and readiness reviews.</p> <p>Pre-operational inspections for modifications.</p> <p>Ref: <i>Specification for Seismic Design of Building, Structures, Equipment, and Systems. SLAC-I-720-0A24E-001-R002</i></p>	Personnel struck by or pinched between equipment during an earthquake	<p>Level 14 Marginal Remote</p>

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
7	Chemical	<p>Cleaning chemical during installation</p> <p>Possible exposure to chemicals during sample development and experiment set up</p> <p>Health hazard gas leaks</p> <p>Components containing materials of toxic nature (Pb, Be)</p>	<p>Level 4</p> <p>Catastrophic</p> <p>Occasional</p>	<p>Minimize quantities of chemicals used during experiment.</p> <p>Exhaust health hazard gases through building exhaust system</p> <p>Secondary containment system for health hazard gases (i.e. exhausted gas cabinet) with verification of integrity of gas lines before use permitted.</p> <p>SLAC IH monitoring program will periodically assess chemical handling practices.</p> <p>Personnel training</p> <p>MSDS will be available for all chemicals used, and all chemicals will be stored in labeled containers and approved storage lockers. Implementation of building and structural codes</p> <p>Personnel Protective Equipment (PPE), Secondary chemical containment</p> <p>Ref: <i>Chemical Process Hazard Analyses</i>; and <u>SLAC ES&H Manual Ch. 40. Hazardous Materials & Ch. 16 Spills</u></p>	<p>Contact with personnel, spills, material handling</p>	<p>Level 20</p> <p>Negligible</p> <p>Improbable</p>

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
8	Thermal / cryogenic	Use of Cryogenics Vacuum Bakeout	Level 10 Critical Remote	<p>Cryogenics will likely be used during the installation of instrumentation.</p> <p>Cryogenics are likely to be used during the conduct of experiments.</p> <p>Use of proper PPE including gloves and face shields when handling cryogenic liquids.</p> <p>Analyzing the maximum volume of liquid nitrogen that will be allowed in the experimental areas without an oxygen deficiency monitor. The current plan to have oxygen deficiency monitors installed in the experimental halls, unless calculations indicate otherwise.</p> <p>Ref: <u>SLAC ES&H Manual Ch. 36. Cryogenic and Oxygen Deficiency Hazard Safety & Ch.19. Personnel Protective Equipment</u></p>	Personnel cryogenic burn exposures	Level 20 Negligible Improbable
9	Mechanical/Physical	<p>Vacuum & pressure vessels PCW feed & return lines</p> <p>Compressed air and gas lines</p> <p>Hoisting and Rigging</p> <p>Repositioning of experimental hardware – pinch hazards</p>	Level 8 Catastrophic Remote	<p>Engineered systems designed to conservative standards. Training of personnel in hazard recognition and support</p> <p>Housekeeping to minimize trip hazards</p> <p>Ref: <u>SLAC ES&H Manual Ch.41. Hoisting and Rigging</u> Ref: <u>SLAC ES&H Manual Ch.14. Pressure, Vacuum & Cryogenic Systems</u></p>	Personnel injury	Level 20 Negligible Improbable

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
10	Environmental	Spills Discharges to sanitary or storm drains Noise	Level 14 Marginal Remote	Training – Stormwater Awareness Course 298 Hazardous Material Management Core Course 105 Training Secondary containment Minimize of chemicals quantities Management of waste waters from discreet operations (i.e., purging LCW systems, coolant from concrete-saw cutting) IH monitoring Dust management during construction <u>Ref: SLAC ES&H Manual Ch. 17. Hazardous Waste and Ch. 43. Industrial Wastewater</u>	Personnel exposure Release of liquids to drain system	Level 20 Negligible Improbable
11	Magnetic	High magnetic fields will not be present in or at points accessible to individuals assembling or installing MEC equipment.	Level 10 Critical Remote	None required		Level 20 Negligible Improbable

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
12	Oxygen Deficiency	<p>There could be oxygen deficient or confined spaces during instrument assembly or installation within the target chamber.</p> <p>There could be an oxygen deficient environment in an experiment station if a large dewar of nitrogen spilled or ruptured.</p>	Level 12 Catastrophic Improbable	<p>Limit volumes of gasses and liquefied gasses in experimental hall</p> <p>Analyzing the maximum volume of liquid nitrogen that would be allowed in the experimental areas without an oxygen deficiency monitor. The current plan is to have oxygen deficiency monitors installed in the experimental halls, unless calculations indicate otherwise.</p> <p>Equipment/Process review</p> <p>Safe work procedures</p> <p>Standard Operating Procedures for target chamber access for equipment changes</p> <p>Ref: <u>SLAC ES&H Manual Ch. 36. Cryogenic and Oxygen Deficiency Hazard Safety</u></p>	Asphyxiation	Level 20 Negligible Improbable

Item	Hazard	Cause	Unmitigated Risk Level	Prevention/ Mitigation	Potential Impact	Mitigated Risk
13	Vacuum and Pressure	<p>Vacuum systems are part of the instruments.</p> <p>Possible reservoirs of high pressure gasses connected to the vacuum chambers.</p>	Level 10 Critical Remote	<p>SLAC safety reviews, acceptance testing of pressure devices</p> <p>SLAC safety reviews and training, acceptance testing of pressure devices. Safety reviews will evaluate the need for such devices as barriers for impact debris between workers and equipment if highly pressurized equipment is included in the experimental equipment design.</p> <p>The review will also evaluate the of redundant pressure relief devices, like a self-contained burst disk .Limit volumes of gases experimental hall.</p> <p>Vacuum chambers with a potential of being pressurized during an experiment will be fit with low positive pressure burst disks that are compliant with 10CFR851 to prevent them from being over pressurized.</p> <p>Safe work procedures. <u>Ref: SLAC ES&H Manual Ch. 38 Compressed Gas Cylinders & Ch.14 Pressure and Vacuum Vessels</u></p>	Personnel injury	Level 20 Negligible Improbable

5- WBS DICTIONARY

5.1. INTRODUCTION

The Work Breakdown Structure (WBS) is used for defining work packages and developing and tracking the cost and schedule for the project. The work is broken down into tasks, each of which has a manager, costs and schedule, and technical scope.

Each level 2 and 3 element has a System Manager who is responsible for the execution of the project plans for that element. The System Manager is responsible for translating system performance requirements into design choices for the MEC instrument. He/she is also responsible for control of cost and schedule, quality and safety, and documentation. Performance requirements for systems at level 2 and below will be established and advocated by a System Manager. The System Manager advises the MEC Project Management as to whether the systems will meet specifications necessary for the success of the Project. Line responsibility for design choices and execution flows through MEC Management and the System Managers.

The WBS is used to specify change control. The Project Execution Plan specifies the levels of approval required for changes in cost and/or schedule at each level of the WBS.

The WBS is used for cost reporting. The project will report costs and progress to the DOE monthly at level 2 of the WBS. The project management will review costs and progress monthly at level 3. The System Managers will review costs and progress monthly at the lower levels of the WBS.

5.2. LEVEL 3 WORK BREAKDOWN STRUCTURE

The following describes the scope of work for each of the level 3 elements of the WBS. Each element includes design, simulations, documentation, fabrication, testing, and installation, of the equipment. Commissioning of each instrument will be carried out by LCLS Operations.

1. MEC Project

1.1. Project Management. This element includes the general management of the project, establishment and operation of the cost and schedule tracking systems, generation of financial and technical reports, organizing technical and project reviews, and physics activities not covered by the individual systems. Costs related to management of project-wide ES&H issues will be captured in this WBS element.

1.1.1. Project Management. This element will include the management and administrative activities of the project. It will also include the Project Management Controls operation, and the cost of contracted management support.

- 1.1.2. ES&H. This element will capture effort and other costs associated with management of safety related issues in the design and construction phases of the Project.
- 1.1.3. Project Support. This element will include the finance and PMCS support of the project.
- 1.1.3. Technical Support. This element will capture all review activities, quality assurance, and general collaboration.
- 1.2 X-RAY TRANSPORT AND DIAGNOSTICS. This element includes all the design, procurement, and fabrication efforts associated with the FEL photon beamline.
 - 1.2.1. System Design & Integration. In this element are all the management and cost associated with the execution of the design, procurement and fabrication efforts associated with the X-ray transport and target chamber systems.
 - 1.2.2. Vacuum System. This element includes all the design, procurement, and fabrication efforts associated with the vacuum transport pipes.
 - 1.2.3. X-ray Optics & Diagnostics. This element includes all the design, procurement, and fabrication efforts associated with the x-ray diagnostics and optics.
 - 1.2.4. Target Chamber. This element includes all the design, procurement, and fabrication efforts associated with the target chamber and pumping system
 - 1.2.5. Installation. This element includes all the procurement, and installation efforts to install the x-ray transport hardware.
- 1.3 LASER SYSTEMS. This element includes all the design, procurement, and fabrication efforts associated with the MEC Laser System.
 - 1.3.1. System Design & Integration. In this element are all the management and cost associated with the execution of the design, procurement and fabrication efforts associated with the long and short pulse laser systems.
 - 1.3.2. Femtosecond Laser. This element includes all the design, procurement, and fabrication efforts associated with the Femtosecond Laser, transports, and tables.
 - 1.3.3. Nanosecond Laser. This element includes all the design, procurement, and fabrication efforts associated with the Nanosecond Laser, transport, and tables.
 - 1.3.4. Installation. This element includes all procurement, and installation effort associated with installing the laser system.

- 1.4 TARGET DIAGNOSTICS. This element includes all the design, procurement, and fabrication efforts associated with producing the target diagnostics required to support the MEC instrument.
 - 1.4.1. System Design & Integration. In this element are all the management and cost associated with the execution of the design, procurement and fabrication efforts associated with the target diagnostics of the MEC Instrument.
 - 1.4.2. Reserved
 - 1.4.3. Diagnostics, This element includes all the design, procurement, and fabrication efforts associated with the suite of diagnostics for MEC, including target stage, Thomson & Emission spectroscopy, and FDI
 - 1.4.4. Installation. This element includes all the procurement, and installation effort associated with installing the diagnostics in the target chamber in H6.
- 1.5 CONTROLS AND DATA AQUISITION. This element includes all the design, procurement, and fabrication efforts related to control systems associated with the MEC instrument.
 - 1.5.1. System Design & Integration. In this element are all the management and cost associated with the execution of the design, procurement and fabrication efforts associated with the controls and DAQ for the MEC instrument.
 - 1.5.2. Vacuum Controls. This element includes all the design, procurement, and fabrication efforts associated with the vacuum controls for MEC.
 - 1.5.3. Common Services Controls and DAQ. This element includes all the design, procurement, and fabrication efforts associated with
 - 1.5.4. Racks & Cabling. This element includes all the design, procurement, and fabrication efforts associated with the MEC controls racks and cable plant.
 - 1.5.5. Laser Safety and Controls. This element includes all the design, procurement, and fabrication efforts associated with controls for the laser system and development of the laser safety system.
 - 1.5.6. Target Diagnostics Controls. This element includes all the design, procurement, and fabrication efforts associated with controlling the selection of target diagnostics at the end station.
 - 1.5.7. Installation. This element includes all the procurement, and installation effort associated with racks, cable plant, testing and checkouts of the MEC control system
- 1.6 HUTCH FACILITIES
 - 1.6.1. System Design & Integration. In this element are all the management and cost associated with the execution of the design, procurement and fabrication

efforts associated with the MEC hutch and control room to support the instrument.

- 1.6.2. Utilities & Hutch equipment. This element includes all the design, procurement, and fabrication efforts associated with configuring the hutch utilities to service the target chamber and target diagnostics in H6.
- 1.6.3. Control Room. This element includes all the design, procurement, and fabrication efforts associated with development of the H6 control room on the mezzanine above H6.