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AUTHOR(S): John C. Goldstein, X-1

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Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

High Power Free-Electron Laser Concepts and Problems*

John C. Goldstein

Group X-1, MS - F645, Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

Free-electron lasers (FELs) have long been thought to offer the potential of high average power operation. That potential exists because of several unique properties of FELs, such as the removal of "waste heat" at the velocity of light, the "laser medium" (the electron beam) is impervious to damage by very high optical intensitites, and the technology of generating very high average power relativistic electron beams. In particular, if one can build a laser with a power extraction efficiency η which is driven by an electron beam of average power P_{EB}, one expects a laser output power of $P_L = \eta\, P_{EB}$. One approach to FEL devices with large values of η (in excess of 10%) is to use a "tapered" (or nonuniform) wiggler. This approach was followed at several laboratories during the FEL development program for the Strategic Defense Initiative (SDI) project. In this paper, we review some concepts and technical requirements for high-power tapered-wiggler FELs driven by radio-frequency linear accelerators (rf-linacs) which were developed during the SDI project. Contributions from three quite different technologies - rf-accelerators, optics, and magnets - are needed to construct and operate an FEL oscillator. The particular requirements on these technologies for a high-power FEL were far beyond the state of the art in those areas when the SDI project started, so significant advances had to be made before a working device could be constructed. Many of those requirements were not clearly understood when the project started, but were developed during the course of the experimental and theoretical research for the project. This information can be useful in planning future high-power FEL projects.

1. Introduction

An optical-wavelength (as distinct from microwave, or millimeter wavelength) free-electron laser oscillator [1,2], as shown schematically in Fig. 1, consists of a source of relativistic electrons (shown in the figure as a radio-frequency linear accelerator, rf-linac), an optical resonator, and a static, periodic magnetic field which is coaxial with the resonator. Electron storage rings and electrostatic generators (Van de Graafs) have also been used as electron sources. The magnetic field is often generated by an array of permanent magnets, as shown in the figure, but recent requirements for high-field, short-period undulators have led to pulsed electromagnetic devices [3,4]. Relativistic electrons from the source are magnetically guided onto the axis of the device where they acquire a small-amplitude transverse velocity component which oscillates in direction as the beam traverses the undulator magnet. This oscillating, transverse velocity of the beam constitutes a transverse current which can couple directly with the transverse fields of electromagnetic waves contained in the optical resonator, thus allowing energy transfer between the beam electrons and the electromagnetic waves. The interaction between the beam and the optical field is maximized if the optical wavelength, λ, the amplitude and period of the static, plane-polarized magnetic field, B_w and λ_w, and the relativistic factor $\gamma = E / mc^2$ of the beam electrons satisfy a particular relation known as the free-electron laser resonance condition:

$$\lambda = (\lambda_w / n)\,(1.0 + 0.5\, a_w^2) / (2\, \gamma^2) \tag{1}$$

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In this formula, n is the harmonic number ($n \geq 1$ is a positive, odd integer) and $a_w = (e\, B_w\, \lambda_w) / (2\, \pi\, m\, c^2)$ is the dimensionless vector potential of the undulator's magnetic field ($a_w \approx 1$ for most FELs).

The device works as follows: a short ($\sim 10^{-11}$ s) pulse of electrons generated by an rf-linac enters the undulator and amplifies an optical pulse, of similar duration, as both pulses traverse the interaction region (undulator). After the interaction, the electron pulse is magnetically guided out of the resonator and discarded in a beam dump, while the optical pulse is partially reflected by the outcoupler, propagates back to the other mirror where it is totally reflected, and returns to the entrance of the undulator where it encounters a fresh electron pulse from the linac. The process continues until a steady state is reached in which the gain of the optical pulse equals the round-trip loss in the optical resonator. A free-electron laser has a gain function which qualitatively resembles that of a conventional atomic or molecular laser: at low optical intensities the gain is independent of the optical intensity (small-signal gain), while at high intensities the gain decreases monotonically with increasing intensity. The first electron pulse emits incoherent synchrotron radiation during its passage through the undulator; successive electron pulses amplify this initial optical pulse. Note that the length of the optical resonator, L_s, must be adjusted such the the round-trip time of light in the resonator is equal to an integral number, m ($m \geq 1$), of time intervals between successive electron pulses, τ_e; that is, $m\tau_e \approx 2\, L_s / c$. Otherwise, the optical pulse will not overlap an electron pulse during its passage through the undulator: there will be no gain, and the light will decay away at a rate given by the round-trip resonator loss. Note also that the FEL physics (small-signal gain, saturated peak optical power, etc.) depends upon the properties of the electron beam micropulse; high average power is achieved by injecting micropulses from the linac at a very high rate.

In the following sections, it will become apparent that there are three different critical technologies needed for an FEL oscillator: (1) accelerator technology, including (i) high-brightness electron injectors, (ii) beam-brightness-preserving linacs, (iii) beamline and transport magnetic optics, (iv) electron beam diagnostics, and (v) computerized control systems; (2) wiggler magnet technology, including (i) high field strengths (~ 1 T), and (ii) very small fractional wiggler field errors (~ 0.1%); and, (3) optics and optical technology, including (i) optical elements which do not damage at very high optical power levels, (ii) high efficiency resonators (large value of outcoupling fraction divided by the total loss per round trip), (iii) dispersive elements (eg, diffraction gratings) to suppress sidebands in the optical spectrum, (iv) stable alignment, and (v) optical beam diagnostics. In Section 2, we review elements of the "tapered" wiggler concept for high extraction efficiency and its early experimental confirmation. The bulk of the paper reviews ideas for high-power FEL oscillators, and other concepts, developed primarily by researchers at Los Alamos National Laboratory, Boeing Aerospace, Spectra Technology, Inc., and the Rocketdyne Division of Rockwell Corporation during the SDI project. In Section 3, we review results of FEL oscillator experiments and technology developments, including optics and the photocathode injector for high-brightness electron beams. In the next section, Section 4, energy recovery for increased system efficiency is discussed, and in Section5 we present oscillator-amplifier concepts for high power. Finally, in the last section, Section 6, we summarize our results and present some conclusions.

2. The Tapered Wiggler Concept

2.1 The potential for high power operation

The FEL generically has several properties which make it a candidate for a high power laser: (1) The interaction of the electrons with the optical field in the interaction region (the wiggler magnet) degrades the beam quality - primarily by increasing the energy spread. This "waste heat" is removed from the system at the fastest possible speed, that is, essentially at the velocity of light. Other lasers must rely on heat conduction in a solid host material, or gas flow, to remove the waste heat: such processes proceed at rates which are very much slower than the velocity of light. Also, an equally important quality of all FELs is that the laser medium, that is, the electron beam, is impervious to damage by the very high optical intensities which are needed in a high-power FEL. This is not true of other laser media where, for example, self-focusing of intense light in a solid host can damage the laser medium, or photoionization processes in some gas laser systems can reduce the density of active atoms. Finally, if the technology of rf-linacs were sufficiently advanced that very powerful electron beams could be built, then, if one could build an FEL with a power extraction efficiency η, one would expect that the resulting laser power P_L would be approximately related to the electron beam power P_{EB} by a relation like $P_L \approx \eta\, P_{EB}$. The concept of a tapered wiggler was invented to allow for large extraction efficiencies, that is, $\eta \geq 10\%$.

Equation (1) (with $n = 1$, which henceforth will be assumed in the rest of this paper) suggests that electrons cannot lose much energy during their interaction with an optical field of wavelength λ in a wiggler with a magnetic field characterized by a given value of a_w or they will cease to satisfy the resonance condition. In order to avoid such a loss of resonance, we rewrite Eqn. (1) as

$$\gamma_r(z) = [(\lambda_w(z) / 2\,\lambda)\ (1 + 0.5\ a_w^2(z))]^{1/2} \tag{2}$$

where $\gamma = \gamma_r(z)$ is the position-dependent energy of an electron. In order to maintain resonance, it is necessary that either the wiggler period, $\lambda_w = \lambda_w(z)$, or the wiggler dimensionless vector potential, $a_w = a_w(z)$, or both, be also position dependent. This is the fundamental idea of a "tapered", or nonuniform, wiggler: that is, a wiggler with nonconstant period and/or magnetic field amplitude which will maintain the FEL resonance condition as the electron loses energy [5,6,7].

The advent of the tapered wiggler concept was a turning point in the development of FELs for high power. Theoretical studies [1,2,7] showed that FELs with uniform, or untapered, wigglers could be expected to achieve extraction efficiencies at optical wavelengths of about $\eta \sim (1 / 2\,N_w) \sim 1\%$, where $N_w = L_w / \lambda_w$ is the number of periods of the wiggler. The reason for $N_w \sim 50$ was to have sufficient small-signal gain to overcome the optical cavity losses, assuming "reasonable" peak electron beam currents (~ 100 A). Of course, if very large currents, ~ 1000A, were available, then $N_w \sim 5$ would be possible and $\eta \sim 10\%$ might be possible. But, such large currents were thought not to be possible with rf-linacs. Hence, the concept embodied by Eqn. (2) suddenly opened up the possibility of $\eta \sim 10\%$ or more with "reasonable" beam and magnet parameters.

2.2 Electron dynamics in a tapered-wiggler FEL

The dynamics of electrons in a tapered wiggler are illustrated by calculated results [8] shown in Figs. (2a) and (2b). Theory [1,2,7] shows that electrons obey pendulum equations in energy (γ) and phase (ψ) variables, where $\psi(z)$ is the relative phase between the transverse velocity $v_\perp(z)$ of an electron at position z and the phase of the optical electric field $E(z)$ at that same position. That this phase is important can be seen by recalling that an electron will gain or lose energy via $d\gamma / dz \sim v_\perp(z) \bullet E(z) \sim v_{\perp 0}\, E_0 \cos(k_w z + kz - \omega t + \phi)$. Fig. (2a) shows a representation of an electron beam with a finite initial energy spread (γ is plotted along the vertical axis, and ψ is plotted over a $2\,\pi$ range along the horizontal axis) and random (on an optical wavelength scale) initial axial positions. The solid curve is the separatrix (or "bucket"): particles initially within this curve are trapped and decelerated as the curve is lowered in γ, as shown in Fig. (2b) which shows the particle distribution at the end of the wiggler. It can be seen from Fig. (2b) that particles which lie initially outside the separatrix remain approximately at their initial energy, while the trapped, or captured, fraction is decelerated (the deceleration of the bucket is determined by the variation of the wiggler period and field amplitude, that is, the design of the tapered wiggler) although some particles are lost from the bucket during its deceleration ("leakage"). Hence, the extraction efficiency is roughly the product of the capture fraction, the leakage loss, and the bucket deceleration.

Note that the final electron energy distribution in Fig. (2b) is characterized by two peaks: one near the initial energy from the untrapped electrons, and one near the final energy of the bucket where the trapped electrons reside. Amplifier experiments were designed and performed at several laboratories to verify the theory. In Figs. (3a) and (3b) are shown results from the Los Alamos experiments [9] in which a carbon dioxide laser optical pulse with a wavelength of about 10 microns was injected into a tapered wiggler along with a single pulse of ~ 20 MeV electrons from an rf-linac. Fig. (3a) shows that the characteristic double-peaked energy distribution was observed experimentally, and Fig. (3b) shows the measured extraction efficiency as a function of input optical power. Both measurements agree well with theoretical calculations. Similiar results were obtained at Boeing [10]. Several years later, very large extraction efficiencies in excess of 30% were observed at microwave frequencies with an induction linac electron source at Lawrence Livermore National Laboratory [11].

3. High Power FEL Oscillators with Tapered Wigglers

3.1 Linac stability and beamline considerations

After the basic concept of the tapered wiggler for high extraction efficiency was verified by amplifier experiments, work started on oscillator development. Fig. (4) shows a schematic of the layout of the linac and the optical resonator in the initial Los Alamos experiments. The first experiments used a uniform wiggler, and the results were presented in a series of papers in the IEEE Journal of Quantum Electronics special issue on free-electron lasers (July, 1985). Here we only briefly discuss one aspect of those results as presented in reference [12]. The initial optical output of the LANL oscillator was characterized by a very ragged curve of light intensity versus time in the macropulse [12]. The origin of the optical fluctuations was eventually understood in terms of accelerator field fluctuations from noise in the microwave klystron power sources and the dispersive character of the beamline which transported the electrons from the linac into the optical resonator. Accelerator field fluctuations caused small fluctuations of the mean energy of each micropulse, which, through a nonisochronous magnetic bend, caused jitter in the arrival time of those pulses at the entrance to the wiggler. Since the optical pulse arrived at the wiggler entrance at a time interval determined by the length of the resonator, the jitter in the arrival times of the electron micropulses caused a jitter in their overlap with the optical pulse on successive passes. Thus, on some passes there was no gain because of poor overlap, while on other passes the gain and overlap were good. This result generically points up the need for a very stable linac and a very carefully designed beamline.

3.2 Wakefields

Tapered-wiggler FEL oscillator experiments [13] were undertaken after the completion of the oscillator experiments which used a uniform wiggler. Theory and simulations suggested that the small-signal gain of the tapered wiggler (the same wiggler that had been used in the amplifier experiments several years earlier) was smaller that that of the uniform wiggler, so the linac was modified to produce micropulses of much higher peak current prior to the start of experiments with the tapered wiggler. Initial experiments with the "improved" linac showed almost no performance gain relative to the earlier experiments. Detailed studies revealed that increasing the micropulse peak current also led to increases in the energy spread and the transverse emittance which in effect cancelled the benefits to the FEL of higher peak current. Once again [13], part of the decrease in beam quality was due to beamline design: in this case, the higher peak current caused significant interactions with the beam vacuum pipe (wakefields) which led to large increases in the beam's longitudinal energy spread. Wakefields in beamline bending magnets, together with misalignments, caused significant increases in emittance. Since all high-power tapered-wiggler FELs typically require very high peak micropulse currents, the Los Alamos results underline the need for very careful beamline, and linac, designs to minimize the effects of wakefields.

3.3 Importance of good electron beam quality

Good electron beam quality (that is, small values of the fractional energy spread $\Delta\gamma/\gamma$ and the transverse emittance ε_{rms}) is crucial for a tapered-wiggler FEL for several related reasons [14]. A tapered wiggler for high efficiency usually requires a large taper. For the same peak current, the larger the taper of the wiggler, the smaller will be the initial small-signal gain, but the higher will be the operating optical intensity where the design extraction efficiency is reached. Theory shows that the small-signal gain of a uniform wiggler is maximal if the fractional energy spread of the electron beam, $\Delta\gamma/\gamma$, is related to the number of periods of the wiggler, $N_w = L_w/\lambda_w$, by

$$\Delta\gamma/\gamma \leq 1/(4N_w) \tag{3}$$

Otherwise, from Eqn. (1), electrons of different energies would be resonant with different optical wavelengths, that is, the gain would be reduced by inhomogeneous broadening. This condition is somewhat relaxed in a tapered wiggler because of the inherent broadening due to a spectrum of λ_w and/or a_w values. Nonetheless, a small energy spread is needed to maximize the small-signal gain of a tapered wigler. The transverse emittance affects the small-signal gain in two ways: it acts like an effective energy spread because a beam with a finite emittance has electrons with a distribution of axial velocities, and the resonance condition, Eqn. (1), really involves that quantity rather than an electron's absolute energy; and, the spot size of the electron beam in the wiggler is directly proportional to the transverse emittance. If the optical mode size is smaller than the electron beam size, not all of the electrons will contribute to the interaction. The typical requirement for transverse emittance is $\varepsilon_{rms} \leq \lambda/4\pi$. Therefore, maximal small-signal gain requires a small energy spread and transverse emittance.

The gain in an FEL decreases with increasing optical intensity much as in an atomic laser. The steady-state intensity is determined when the saturated gain equals the round-trip optical resonator loss. Hence, if the initial gain just slightly exceeds the losses, the steady-state intensity will be relatively low. To achieve high values of the steady-state intensity requires large values of the initial gain (more precisely, the ratio of the initial gain to the round-trip loss). Furthermore, the "design" intensity for a tapered wiggler FEL, that is, the optical intensity at which the design extraction efficiency is reached, increases with the taper. If the electron beam quality is not good, high saturated intensities will not be reached. Finally, even if high intensities are reached, the electron distribution should fit into the bucket (see Fig. (2); the bucket height is proportional to $(E\,\lambda)^{1/2}$ where E is the optical field amplitude) or only a small fraction of the beam will be trapped and decelerated in the wiggler. Again, this requires a small energy spread and a small transverse emittance.

3.4 The photocathode injector

The beam quality issue is one reason why it was not easy to build a high-power tapered-wiggler FEL during the SDI program: it is not enough to have a linac which operates at high average power (this in itself is usually a nontrivial engineering achievement), but there are very tight constraints upon the quality of the beam from the linac. A whole new linac design procedure had to be evolved to meet the beam quality requirements simultaneously with the power requirements. An essential development was the photocathode injector which was invented by Fraser and Sheffield [15]. This device, in which a short laser pulse incident upon a photosensitive material causes the emission of a short pulse of electrons, has made possible an order of magnitude reduction in the transverse emittance of an intense beam. The photosensitive material is placed on the wall of the first accelerator cavity so that the electrons which are emitted from the surface are quickly accelerated to relativistic velocities where they are less susceptible to perturbations which lead to emittance and energy spread increases. Since the quality of the electron beam decreases as it passes through the linac and beamline, it is vital to start with the brightest possible beam initially. Although several FEL linacs with photocathode injectors have been operated successfully, only the one at Boeing has operated at a 25% duty factor (see paper 2376-20 of these proceedings) which is suitable for high-average-power rf-linac operation.

3.5 Compound wigglers

The highest extraction efficiency in the Los Alamos tapered-wiggler FEL oscillator experiments was achieved with a parabolically-tapered (in $k_w = 2\,\pi\,/\,\lambda_w$) main wiggler preceded by a short prebuncher [16, 17]. The basic idea is similar to that of the optical klystron [1,2] except that the prebuncher is designed to enhance the high-power performance of the FEL rather than its small-signal gain. Figure (5) shows that the wiggler consists of a short (~ two periods) untapered prebuncher followed by the main tapered wiggler. The prebuncher modulates the electron velocities which, after evolution in the drift distance between the two wigglers, cause the beam to be bunched when it arrives at the main wiggler [16]: the prebunching increases the capture fraction into the bucket of the tapered section significantly. These experiments produced a maximum measured extraction efficiency of $\eta \approx 4.4\%$ [17].

3.6 Optical resonators for FEL oscillators

The optical resonators used in essentially all early FEL oscillator experiments were conventional two mirror designs in which the outcoupling occurred through the partially transmitting mirrors [13,18]. These resonators provided very good optical mode quality [18] due in part to their long and narrow geometry. However, an FEL has several characteristics which complicate the optical design, particularly when high-power operation is desired. FEL oscillators which are designed for wavelength tunability obviously require wide reflectivity bandwidth mirrors. Most high-power applications do not require large wavelength tunability but emphasize operation at a single wavelength, a considerable simplification for the optical design. However, a tapered-wiggler FEL typically needs to operate at high intracavity optical micropulse power levels, thus making possible damage to optical components a primary concern. Indeed, damage from very high peak powers was commonly observed in the earliest experiments [13]. Note that a high-average-power device would also need to protect its optical components against thermal distortions or damage due to absorption: actively cooled elements were extensively studied to handle relatively slow heat flow problems.

To reduce the loading of optical elements without making resonator dimensions impossibly large, ring resonators with large magnifications and some grazing angle-of-incidence reflectors were studied. A prototype device of this sort was installed and tested at the Boeing FEL [19]: Fig. (6) shows a schematic of the entire FEL device, while Fig. (7) shows details of the ring resonator itself (~ 60 m long).

A tapered-wiggler FEL oscillator usually requires another kind of optical element to operate at maximum extraction efficiency: the dynamics of electrons interacting with the optical field at high power levels leads to the generation of sidebands, or additional spectral components, in the optical spectrum [1,2,7,13,17,20]. The presence of these spectral components reduces the extraction efficiency in a tapered-wiggler FEL by increasing the "leakage" from the bucket. Sidebands must be eliminated in order for a tapered-wiggler device to achieve its design extraction efficiency. This is typically done by a dispersive optical element which introduces additional loss at the expected sideband wavelengths. One interesting sideband supression device which was extensively studied theoretically [21] is a grating rhomb, that is, a pair of diffraction gratings separated by a fixed distance. The Boeing resonator was designed to be fitted with such a device, although no FEL experiments were performed with that device in place.

Besides difficulties in the optical design and fabrication of a sideband supression element itself, such elements usually have a lower threshold for damage in high-power optical fields than other elements of the resonator. Hence, they can have a significant impact the overall resonator design for a high-power FEL. It is believed that optical damage would ultimately limit the power level that an FEL oscillator could attain. Other system designs, as discussed in Section 5, are needed for still higher power operation.

4. Energy Recovery for Higher Efficiency

4.1 Generalities

Since usually only a small fraction of the energy of an electron beam is converted into light, even in a tapered-wiggler high-extraction efficiency FEL oscillator, why not devise a system to either reuse the spent electrons (which would have to be reaccelerated but not from zero energy) or capture their energy for use in the linac? Such thoughts have long been considered for use in FELs. It is not very practable to reuse the spent electrons in part because their phase-space density has been reduced by the FEL interaction. Electron storage ring FELs do just that, but a ring typically cannot accept a beam with a very broad energy spread as would come from a tapered wiggler operating at high power. The phase-space density of the beam can be increased in storage rings by the combination of acceleration and synchrotron damping, but the time scale for such processes is usually much slower than that of the beam disruption by the FEL interaction. Rather, it is preferable to start with fresh electrons, but perhaps devise a way to convert the energy of the spent beam into rf which can then be used in the linac. Such schemes would be effective only if most of the rf energy injected into the linac goes into the beam and not into ohmic losses in the copper walls of the accelerator cavities. Hence, energy recovery might work well with a superconducting linac and in fact has been demonstrated in one already [22]. Besides increased overall electrical efficiency, if the spent electron beam is decelerated to a few MeV, the beam dump design and its associated radiation shielding may be greatly simplified.

4.2 The Los Alamos experiment

An energy recovery experiment was successfully performed at Los Alamos [17] in which the spent beam was decelerated in a separate structure which was rf-coupled to the accelerator as shown in Fig. (8). This was chosen for experimental flexibility, but "same cell" recovery, in which the spent beam is injected into the linac at a decelerating phase of the rf field, was done in [22] and is proposed for the Novosibirsk microtron (see paper 2376-13 of these proceedings). Accelerator stability is an issue with recovery schemes: two instabilities were observed in the Los Alamos experiments, both due to loss of spent electrons in the transport beamline. If low energy electrons were lost (deliberately by use of a scraper plate), the energy recovered in the decelerator would drop, the rf coupled to the accelerator would drop causing a drop in the accelerating fields which would produce lower energy new electrons, which in turn would be lost, etc. This resulted in a steady state of zero current. However, if high energy electrons were lost, an oscillating instability was observed because as the high energy electrons are lost, less energy is recovered, and the accelerating field in the linac is reduced so new electrons of lower energy are made. Those low energy electrons are not lost, thus increasing the recovered current which leads to the production of higher energy new electrons, etc. Most recovery schemes significantly complicate the linac operation, and a careful analysis is needed to determine whether dealing with those complications (and stability questions) remains worthwhile in view of the increase in overall system energy efficiency.

5. MOPA Systems for Higher Powers

As was mentioned at the end of section 3.6, it is presently believed that optical damage is the factor which ultimately limits the power level for which an FEL oscillator can be designed. If still higher powers are desired, MOPA (Master Oscillator Power Amplifier) systems seem to be possible. Damage problems are avoided by placing beam director optics a very long distance from the end of the FEL amplifier in order to allow natural diffraction to expand the optical beam size to such a large value that damage does not occur. Such systems, with separate rf-linacs driving the oscillator and the amplifier, were considered for the SDI program but were thought to be too expensive (the Lawrence Livermore National Laboratory / TRW program planned to use a conventional laser oscillator and an induction-linac-driven FEL amplifier for the SDI project). A less expensive alternative, the SAMOPA (Single Accelerator MOPA), has also been proposed [23]. A low power demonstration experiment was actually performed at Stanford University [24] to show feasibility of this idea. A version of such a system, designed to produce 100 kW at a wavelength of 10 microns, is shown in Fig. (9): this was the last system extensively studied theoretically before the end of the SDI program [25].

6. Summary and Conclusions

The operating power levels for an FEL to fulfil the power beaming mission are comparable to those which were under consideration during the SDI project. Thus, the experience, knowledge and understanding gained during that project should be applicable to the present deliberations. We have reviewed a few of the ideas which came out of one particular approach to a high-power FEL during the SDI project, namely rf-linac-driven high-extraction-efficiency FELs which were designed around tapered wigglers. One realization which came from that program was that a high-power FEL design has a very large number of tightly linked components. A convenient way to optimize the design of such a complicated device is to devise a computer code which has simple (often analytic) representations of all of the relevant information about accelerators, FEL performance, optics, prime power sources, etc. Such an engineering code, the FEL physical process code, is discussed by L. E. Thode in paper 2376-15 of these proceedings.

The tapered-wiggler approach to high-extraction-efficiency high-power FELs driven by rf-linacs has many technical requirements, such as the generation, acceleration, and transport of very bright electron beams; and, innovative optical resonator designs which contain sideband-supression elements and can withstand the harsh environment of very high optical fluxes without sustaining damage. MOPA or SAMOPA systems are promising concepts for power levels which cannot be attained in FEL oscillators.

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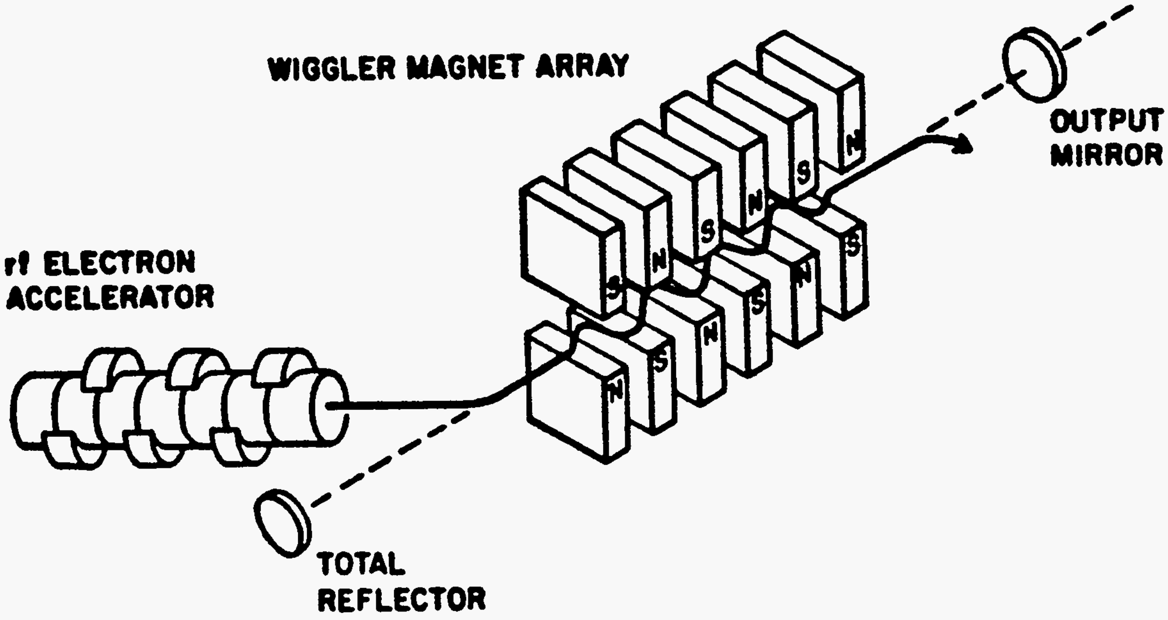

Figure 1: Free-electron laser oscillator schematic.

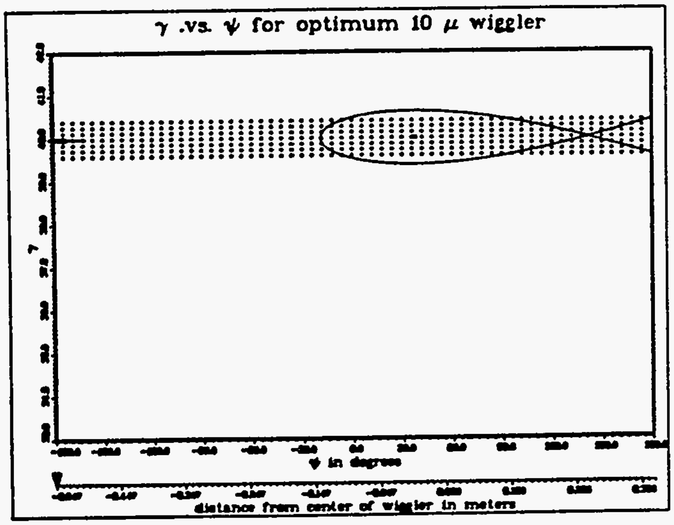

Figure 2a: Electron phase space at the tapered wiggler entrance.

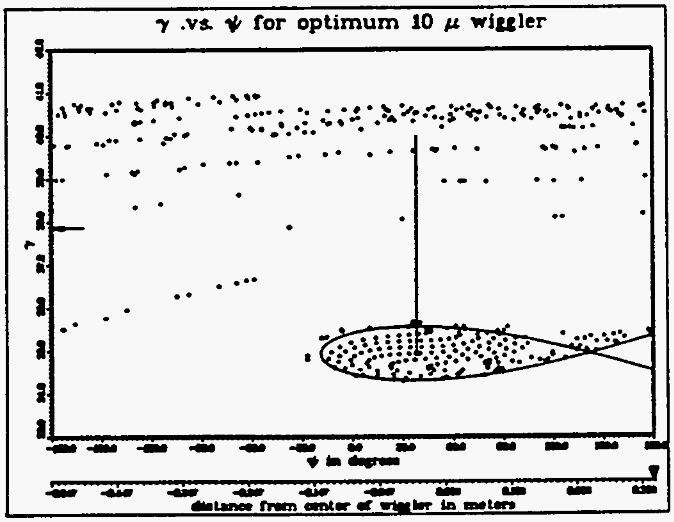

Figure 2b: Electron phase space at the tapered wiggler exit.

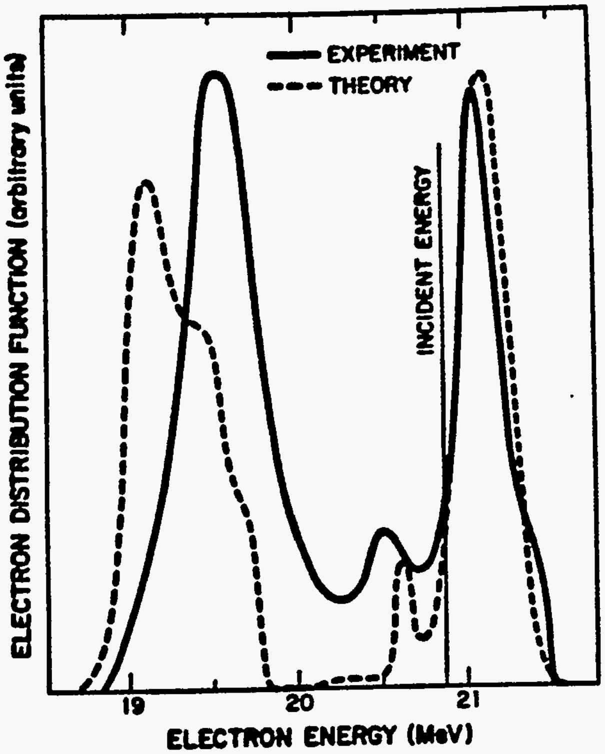

Figure 3a: Measured electron distribution after tapered wiggler interaction [9].

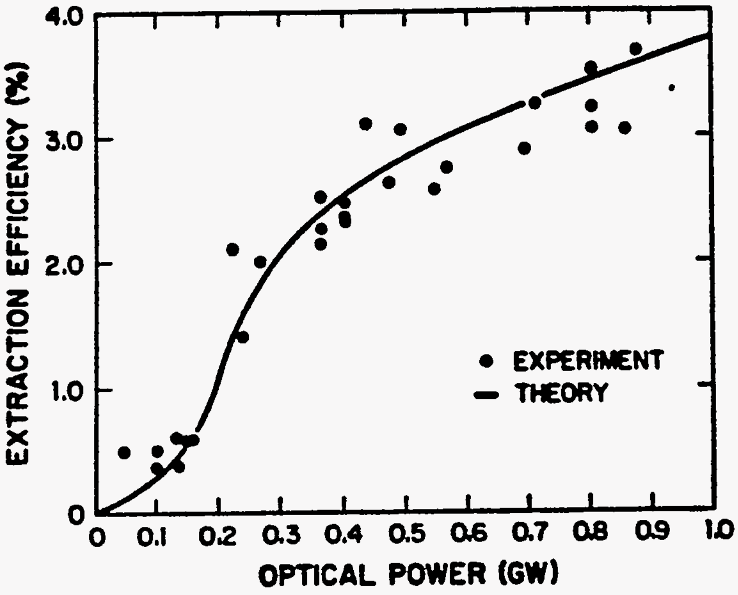

Figure 3b: Measured extraction vs optical power [9].

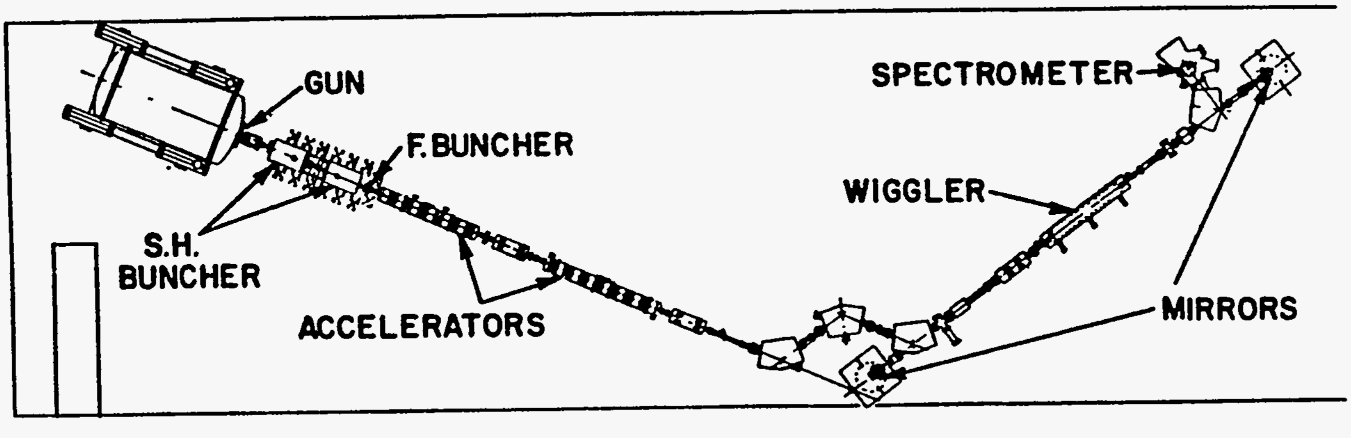

Figure 4: Linac and optical resonator layout for Los Alamos experiments.

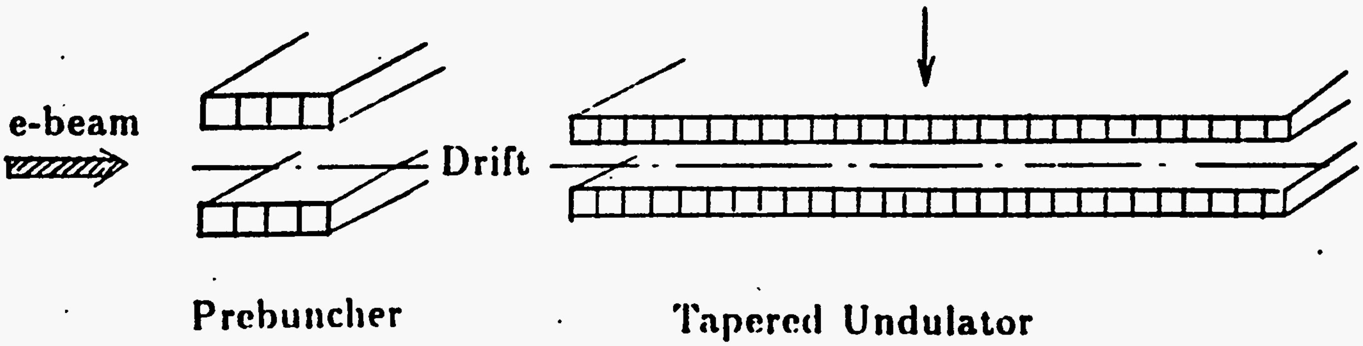

Figure 5: Compound wiggler schematic.

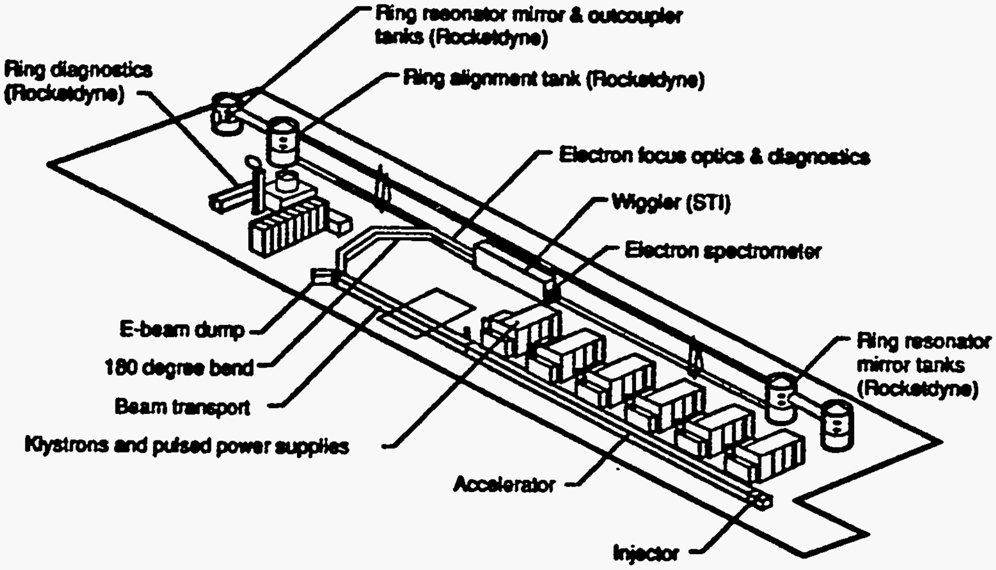

Figure 6: Boeing FEL schematic.

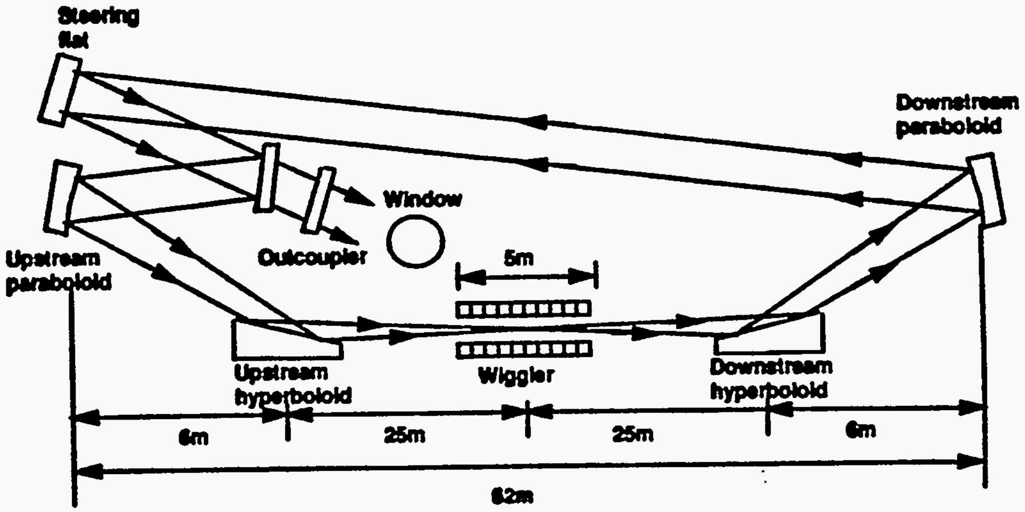

Figure 7: Ring resonator at Boeing FEL.

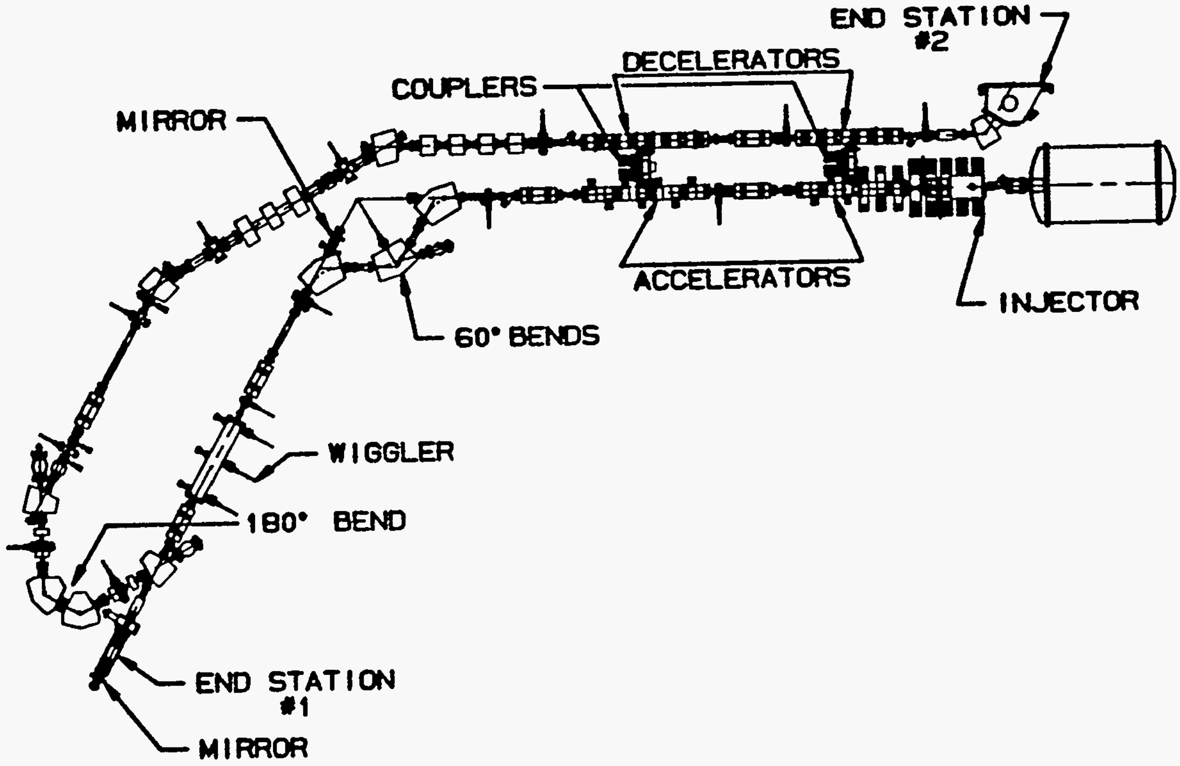

Figure 8: Los Alamos energy recovery experimental layout.

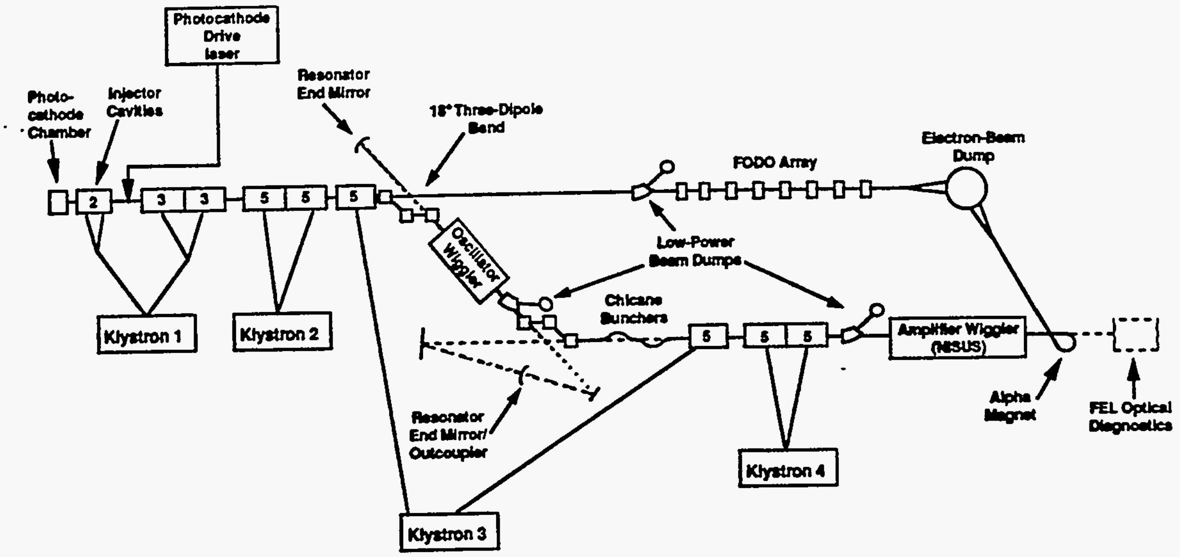

Figure 9: Boeing SAMOPA design [25].