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AUTHOR(S):

Dinh C. Nguyen, CST-4	John G. Plato, AOT-1
Robert H. Austin, AOT-17	Steven J. Russell, AOT-17
K. C. Dominic Chan, AOT-17	Richard L. Sheffield, AOT-17
Donald W. Feldman, AOT-17	Boyd A. Sherwood, AOT-17
John C. Goldstein, X-1	Floyd E. Sigler, AOT-17
Stephen M. Gierman, AOT-17	Carl A. Timmer, AOT-8
John M. Kinross-Wright, AOT-9	Michael E. Weber, CST-4
Steven H. Kong, AOT-17	Christopher Ziomek, AOT-5

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RECENT PROGRESS OF THE LOS ALAMOS ADVANCED FREE ELECTRON LASER

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R. L. Sheffield, B. A. Sherwood, F. E. Sigler, C. A. Timmer, M. E. Weber and C. Ziomek.
Los Alamos National Laboratory
Los Alamos, NM 87545

Abstract

Many industrial and research applications can benefit from the availability of a compact, user-friendly, broadly tunable and high average power free electron laser (FEL). Over the past four years, the Los Alamos Advanced FEL has been built with these design goals. The key to a compact FEL is the integration of advanced beam technologies such as a high-brightness photoinjector, a high-gradient compact linac, and permanent magnet beamline components. These technologies enable us to shrink the FEL size yet maintain its high average power capability. The Advanced FEL has been in operation in the near ir (4-6 μm) since early 1993. Recent results of the Advanced FEL lasing at saturation and upgrades to improve its average power are presented.

1. Introduction

In many industrial and research applications, a tunable laser with output power more than 100 watts is highly desirable. Free electron lasers (FEL) based on rf linac are characterized with broad tunability (from ir to uv),¹⁻³ high efficiency (up to 4.5% at 10 μm)⁴ and high average power (kW in burst modes).⁵ These devices also exhibit pulse structures that are unique - macropulses consisting of picosecond

micropulses repeating every few nanoseconds. These pulse structures can be beneficial especially for high average power applications. However, thus far the use of FEL has been hindered by its size, cost and complexity, not to mention the need for shielding from radiation produced by high energy electron beams. For an FEL to be usable by industry standards, it must be compact, user-friendly and easy to maintain. Over the past four years, the Los Alamos Advanced FEL has been built with these considerations. The key to compactness and reliability is the integration of advanced beam technologies that have been developed in the last ten years. The Advanced FEL has been in operation since early 1993 in the spectral region between 4.5 and 6 μm , limited by the bandwidth of multilayer dielectric optics.⁶ With metal mirrors, the Advanced FEL can be tuned from 4 to 12 μm with the existing 1-cm period wiggler. A broader tuning range between 3 and 20 μm can be achieved by lasing at fundamental and harmonic frequencies with a high-field 2-cm period wiggler. Operation at shorter wavelengths is possible with a higher beam energy and/or a mm-period microwiggler. For instance, with a 4-mm period microwiggler and 25-MeV electrons, the Advanced FEL can achieve 850-nm lasing, a wavelength that is useful for applications such as space power beaming. In this paper, the Advanced FEL overall design, various subsystems and their performance will be presented together with the recent results of lasing at saturation. Future upgrades to improve the Advanced FEL average power capability will also be discussed.

2. Advanced FEL Design

For compactness and reliability, the Advanced FEL is designed around a low-energy (less than 25 MeV) electron beam coupled into a short-period (0.2 - 2 cm) wiggler to produce radiation ranging from the visible to mid-ir (0.4 - 20 μm). The initial design uses a 1-cm wiggler

period, so lasing is limited to wavelengths longer than $3.7\text{ }\mu\text{m}$. Although infrared operation does not require an exceptionally good beam emittance, the low emittance (less than $10\text{ }\pi\text{-mm-mrad}$) is useful because the beam can be transported through very small magnet gaps (less than 3 mm). The small magnet gap is especially important for short wavelengths because as the wiggler period shrinks, the gap must also be reduced to obtain high enough magnetic field in order to produce adequate gain. The Advanced FEL design integrates a high-brightness photoinjector to produce electron beams with the requisite emittance. With the use of a relatively low energy electron beam from a single high-gradient accelerator, the Advanced FEL is small enough to fit in a typical laboratory (Fig. 1). The electron beamline and the FEL resonator are mounted on a $6' \times 10'$ vertical optical table. Table I summarizes the Advanced FEL electron beam components: the linac, electron beam, and wiggler. The optics and FEL performance are summarized in Table II. The performance of specific subsystems is described below.

2.1 Linac and photoinjector

The linac is a standing wave, $\pi/2$ mode, on-axis-coupled structure consisting of 10.5 cells with a single rf feed (Fig. 2). It is powered by an L-band (1300 MHz) klystron rated at 30 MW peak power, $30\text{ }\mu\text{s}$ macropulse and 100 kW average power. The flat portion of the rf macropulse is presently limited to $18\text{ }\mu\text{s}$ by the pulse forming network. The linac is capable of 20 MeV acceleration at room temperature. With extensive surface conditioning and LN2 cryogenic operation to reduce copper resistive loss, the linac can potentially achieve 25 MeV. At 15 MeV, the peak rf power lost to copper is 5 MW. The beam power is 7.5 MW for 0.5 A average current corresponding to 4.6 nC of charge per micropulse at 108 MHz micropulse frequency or 2.3 nC at 216 MHz.

Assuming 20% control margin (2.5 MW above 12.5 MW), the linac efficiency of converting rf power into beam power is 50%. Although the rf macropulse is 18 μ s long, due to cavity fill time, the electrons are turned on during the last 15 μ s of the rf pulse when the cavity field is flat. Within the current pulse, the FEL takes 2-3 μ s to reach steady-state (Fig. 3). Thus, the actual linac efficiency after these corrections is 40%.

The source of high-current electron pulses is a photoinjector located at the first half-cell of the linac. High peak currents are achieved by gating electron emission in synchrony with the accelerating rf field. This is accomplished by irradiating the photocathode with a solid-state laser modelocked in synchrony with the rf but at a subharmonic frequency. Solenoidal emittance compensation in the photoinjector leads to an exceptionally low emittance and thus very high beam brightness.⁹ The photoinjector front-end consists of a drive laser and a high quantum efficiency CsK₂Sb photocathode. The drive laser starts with a Nd:YLF oscillator modelocked at 108.33 MHz (12th subharmonic of rf). A transverse Pockel cell switches out variable-length, programmable macropulses to be amplified in a double-pass amplifier. Frequency doubling in an LBO crystal converts 50% of the 1.05 μ m ir light to 527-nm green light. The shape of the input pulse is programmed to produce a flat-topped macropulse in the second harmonic. A typical 15- μ s macropulse consists of 1,600 micropulses, each approximately 10 ps long. Due to space charge repulsion, the electron pulse width can be larger than 10 ps depending on the beam energy, the charge density and the drive laser phase with respect to the rf. For 15 MeV beams, an illuminated area of 0.4 cm² and a micropulse charge of 3 nC, the calculated electron pulse width is 15 ps. Fig. 3 depicts the macropulse and micropulse structures of the rf, drive laser, electron beam and the FEL output.

The multialkali photocathodes exhibit a typical quantum efficiency

(Q.E.) of 1 - 5% when they are first fabricated. Due to poisoning during the transfer process, their Q.E. is reduced to 0.5 - 1% in the linac. A typical cathode useful lifetime - defined as their ability to produce more than 2 nC of charge with 5 μ J or less of drive laser micropulse energy corresponding to a Q.E. of 0.1% - is on the average 24 hours of operation. To extend beam time, the photocathodes are prepared in a batch of six, called a 6-pack, in a separate preparation chamber. The 6-pack is then transported under vacuum to the accelerator via an actuator/insertion mechanism. In this way, a good 6-pack can provide up to 3 weeks of beam time. New, more rugged photocathode materials are being studied and these will be used in a new future.

2.3 rf System

The rf system is composed of the aforementioned klystron station and a new state-of-the-art low-level rf control system. The control system stabilizes the amplitude and phase of the cavity accelerating field. It employs an analog feedback loop as well as an adaptive digital feed-forward correction loop. The feedback loop corrects against non-repetitive errors due to random fluctuations caused by variations in beam loading and klystron beam voltage levels. The feedforward corrects repetitive errors such as ripples in the klystron voltage caused by the pulse forming network and beam loading transients in the linac cavity. Detailed description of the low-level control system can be found elsewhere.¹¹ With the existing klystron, the low-level rf can achieve a field amplitude stability of $\pm 0.25\%$ and a phase stability of $\pm 0.33^\circ$ against large parameter excursions. A new high-power klystron is presently under construction to complement the low-level rf control system. With this new klystron station, we expect a stability of $\pm 0.05\%$ in amplitude and $\pm 0.1^\circ$ in phase.

2.4 Beamline and Beam Optics

The beamline consists of three bends. The first bend allows the drive laser to illuminate the cathode; the second bend is used to bring the electron beam into the optical axis; and the third bend steers the electron beam into a beam dump. The first two bends are made achromatic by a singlet that refocuses the beam in the dispersion plane. For compactness and reliability, all focusing quadrupoles and bending dipoles are made out of permanent magnets. Detailed designs of the variable-field permanent magnet quadrupoles and dipoles have been reported.¹⁰ The use of permanent magnet components offers two advantages: a) once the electron beam is aligned through the wiggler, lasing can be reproduced every day with only minor adjustments of the beam optics, and b) the permanent magnet optics do not need power or cooling, thus simplifying the design.

To transport the beam through the beamline around the bends and through a small 2.8-mm id wiggler tube, we relied on TRACE3D to set the quadrupoles to approximately the correct values. The beam profiles were then measured using optical transition radiation (OTR) screens and matched to those calculated by TRACE3D by adjusting the quadrupole field. Wall current beam-position monitors (BPM) were used to monitor beam transport through the center of the beamline and also to measure relative beam current. The BPM performance has been reported elsewhere.¹² The BPM beam current was used to ensure 100% beam transmission through the 2.8-mm id wiggler tube.

2.5 Electron beam

The electron beam transverse emittance was measured by performing the well-known “quad scan” in which the beam spot size at a screen at a known distance from the focusing quadrupole was measured as a function of the quadrupole field. For each quadrupole setting, an OTR image of

the beam was snapped, box-averaged and analyzed. A nonlinear least square fit was performed on the spot size versus field, with ϵ (emittance), α , and β Twiss parameters as the fitting coefficients. The measured and predicted (PARMELA) spot sizes are plotted against quadrupole field in Fig. 4a. Due to the low beam emittance ($\epsilon_n = 1.3 \pm 0.7 \pi \cdot \text{mm} \cdot \text{mr}$ at 1 nC), extraordinary care was taken to ensure the minimum spot size was not dominated by the resolution of the optics. In Fig. 4b, the rms emittance is plotted against micropulse charge.

The electron beam energy was measured with the first magnetic dipole using beam position monitors before and after the first bend to determine the beam centroid position. The error in energy measurement is ± 0.05 MeV or 0.3%. A high resolution energy spectrometer after the third bend was used to measure beam energy spread and fluctuation. A typical energy spread, integrated over the 12- μs macropulse and thus including energy slew, is 0.5%. The actual micropulse energy spread has not been measured but it is expected to be much less than 0.5%.

2.6 Wiggler

For oscillation in the 4 - 10 μm region, a 24-cm untapered linear wiggler with 1-cm periods is used. Each period consists of two pairs of samarium cobalt magnets arranged with the magnetization oriented along the beam axis as shown in Fig. 5. The wiggler parameter a_w is related to the peak on-axis field by

$$a_w = \frac{e \cdot \lambda_w B_0}{2\sqrt{2} \pi m c}$$

With a 3-mm gap between the magnets, the measured peak on-axis field is 0.42 T, yielding an rms wiggler parameter a_w of 0.274. Prior to assembly on the beamline, the wiggler was tested via the taut wire

technique.¹² After the wiggler was mounted on the optical table, the area around the wiggler was found to have a constant field of ~ 4 gauss, presumably caused by the surrounding permanent magnet dipoles. A small correction electromagnet was used to cancel out this residual magnetic field.

2.7 Resonator optics

The Advanced FEL optical resonator consists of two concave mirrors mounted in vacuum with the wiggler at the center of the resonator (Fig. 6). The 1.3836-m mirror separation and 0.70-m radius of curvature give a resonator parameter ($g = 1 - L/R$) of -0.9766 and a Rayleigh range of 7.5 cm (about one-third of wiggler length). At $6\text{ }\mu\text{m}$, the calculated lowest order mode size is $378\text{ }\mu\text{m}$ at the center of the wiggler and $753\text{ }\mu\text{m}$ at the end of the 26.3 cm-long wiggler tube. The tube id of 2.8 mm introduces an estimated loss of 0.2% for the lowest order transverse mode. However, this vignetting loss can be substantially larger if hole coupling is used, and is comparable to the outcoupling.¹³

Two sets of optics have been used in the Advanced FEL resonator. The first set of mirrors are diamond-turned gold evaporated copper mirrors. These mirrors have an averaged reflectivity of better than 99% over the mid-ir region. However, due to the concave surfaces, the diamond-turned grooves introduce an additional scattering loss of $\sim 3\%$. Thus, the resonator round-trip loss with two mirrors before out-coupling is $\sim 8\%$. Out-coupling in metal mirrors is provided by a hole drilled in the center of the mirrors. For a hole with radius a that is small compared to the empty cavity mode size w at the mirrors, the fraction of light out-coupled is $\sim 2(a^2/w^2)$. Although metal mirrors provide broad spectral coverage, there are two problems associated with hole-coupling. First, diffraction caused by the presence of the out-coupling hole modifies the

empty cavity mode in such a way that the vignetting loss at the wiggler ends increases. The vignetting loss increases as one tries to out-couple more by increasing the hole size, and so the ratio of out-coupling to total loss is relatively constant.¹³ Second, for small out-coupling holes, alignment is difficult because the alignment HeNe beam cannot be injected through the out-coupling hole and matched into the resonator mode.

The second set of optics is ZnSe/ThF₄ multilayer dielectric (MLD) on ZnSe substrates. Two different MLD coatings with 99.5% and 99.0% reflectivity at 4.5-5.5 μm have been used. The transmission of each mirror, estimated to be 0.5% and 1% respectively over the 4.5-5.5 μm region, provides the out-coupling. Higher out-coupling is possible by tuning the FEL wavelength to either side of the coating reflectivity curve. The advantages of using dielectric mirrors are the low resonator loss (the round-trip cavity loss was equal to $1-R_1R_2$) and the ability to inject the alignment HeNe laser beam with a matched size through one of the mirrors. However, the MLD coatings are easily damaged - in the forms of mm-size pits and cracks - by the high intracavity power. The coating damage limits the intracavity power averaged over the macropulse to less than 400 kW (1.2 MW/cm² on the mirrors) and precludes sideband operation which would lead to much higher extraction efficiencies.

2.8 Resonator length setting

The correct resonator length is defined as the one that gives maximum overlap between the optical and electron micropulses, and it is approximately given by

$$L_c = \frac{n \cdot c}{2 \cdot f}$$

where n: number of micropulses in the resonator at any given time, c:

speed of light, and f : micropulse repetition rate. In the Advanced FEL the resonator length was set by both mechanical and optical means. Since the resonator length is only 1.38 m, it is possible to set a temperature-compensated ruler parallel to the optics axis and measure the cavity length, provided the exact dimensions of the mechanical mounts are known. This method yields a measurement uncertainty of $\pm 50 \mu\text{m}$. By injecting the drive laser beam into the Advanced FEL cavity and measuring the multiple pulses reflected off the mirrors with a streak camera, in theory one can set the cavity length so that all the reflected pulses are overlapped. In practice, due to the drive laser pulsewidth of 7 ps, the cavity length must be detuned $\pm 2 \text{ mm}$ or more in order to accurately measure the delay time between successive pulses. To find zero detuning, we did a linear least-square fit of the delay time versus cavity length and found the zero-crossing at $-170 \mu\text{m}$ (Fig. 7). The uncertainties in measuring the delay times at large detunings limit the accuracy of this method to within $\pm 150 \mu\text{m}$. These results illustrate that for a short cavity, it is more accurate to set the cavity length by mechanical means.

2.9 FEL optical diagnostics

The FEL output was characterized with various optical diagnostics. A sensitive HgCdTe was used to measure the spontaneous emission and the coherent emission from bunched electron beam. To obtain macropulse buildup and ringdown times, a Molelectron pyroelectric detector with ns response time was used. Macropulse energy was measured, sometimes at both ends of the FEL if the outcoupling was bidirectional, via a Molelectron and a Gentech energy meter. The FEL spectral characteristics were measured via a spectrum analyzer with a pyroelectric array at the exit focal plane.

3. Laser results

3.1 General characteristics

With the exception of a long break during the summer of 1993 to fix the linac multipactoring problem, the Advanced FEL has been lasing regularly since April 1993. It typically takes 45 to 60 minutes to match the electron beam to obtain lasing after the drive laser is warmed up and aligned on the photocathode, an operation that takes approximately 30-45 minutes. Thus on the average, the Advanced FEL can be in operation after 90 minutes. The startup procedure involves matching the electron beam on the OTR screens, followed by maximizing the spontaneous emission signal on a slow but sensitive HgCdTe detector. This is done by small amounts of electron beam steering and mirror tip/tilt adjustments. Dependent upon the room temperature, the cavity length may have to be readjusted to achieve coherent emission from bunched electron beams. The coherent bunched beam emission is characterized by its strong dependence on current (signal proportional to N_e^2). Small current fluctuations due to phase modulation during the macropulse cause the bunched beam emission to exhibit large amplitude fluctuations. The bunched electron emission intensity is between two to three orders of magnitude above spontaneous emission. At this point, laser oscillation can be achieved by optimizing the cavity length, the mirror tip/tilts and the electron beam matching. The optimization procedure is repeated at finer scales to achieve lasing at saturation. The macropulse shape is detected by a fast Molectron pyroelectric detector (Fig. 8a). Note the famous "rocky mountain" effect on the FEL macropulse. This is caused by a small phase jitter of the rf system with respect to master oscillator even with feedback and feedforward stabilization. This rf phase jitter, less than 1 ps, slightly modulates the overlap between the optical and electron pulses, causing the latter to go in and out of synchrony periodically. Additionally, the drive

laser exhibits a long-term phase drift of a few ps per hour due to thermally induced changes. This phase drift causes a change in the micropulse current, increases the energy spread and thus reduces the FEL gain. A small adjustment of the rf phase usually brings back optimum oscillation. Additionally, drifts in the cavity length due to thermal expansion of the optical table necessitate occasional adjustments of the cavity length.

3.2 Extraction efficiency

From the user's standpoint, the extraction efficiency is defined as FEL output power divided by electron beam power. However, from the FEL physics point of view, the extraction efficiency is the amount of energy extracted from the electron beam into the intracavity power. The two efficiencies are related to each other by the following expression.

$$\eta_{\text{out}} = \eta_{\text{in}} \frac{\Gamma}{\alpha_{\text{total}}}$$

where Γ the out-coupling fraction and α_{total} is the total cavity loss.

The highest macropulse energy ever observed at a beam energy of 15 MeV and a peak current of 200 A was 240 mJ after correction for loss in transport optics. The beam power in each micropulse was 3 GW. The mirrors used in this experiment were a 1% hole-coupled gold-evaporated mirror with 4% additional loss and an MLD mirror that has an out-coupling of 7% at 5.8 μm . The measured ring-down is 75 ± 10 ns corresponding to a total cavity loss of $12 \pm 2\%$ (Fig. 8b). The maximum output energy recorded was 25 mJ at the 1% out-coupling mirror of the resonator through a CaF_2 window. The top energy meter recorded 175 mJ through a CaF_2 window, two Cu mirrors and a CaF_2 lens. The total output energy after correcting for reflection loss was 240 mJ. Ignoring

the ends of the macropulse, there are approximately 1200 micropulses in 11- μ s saturated portion of the macropulse (Fig. 8a). The energy in each micropulse was thus 200 μ J. The estimated peak optical power was 20 MW corresponding to an efficiency of converting electron beam power into light of 0.7%. For the above set of numbers, Γ is 8% while the α is 12%. Therefore, the intracavity extraction efficiency is estimated to be 1%, one-half of the theoretical limit without sideband of 2% ($1/2N$). To get wall-plug efficiency, one must multiply the efficiency of e-beam-to-light conversion by the efficiencies of the linac ($\sim 40\%$) and the klystron ($\sim 50\%$). Thus, the 0.7% conversion efficiency gives a wall-plug efficiency of 0.14%.

The electron energy loss can be observed readily on an electron energy spectrometer (Fig. 9). Note the distinct energy distribution at lower energy corresponding to the electrons trapped in the ponderomotive potential, i.e. the bucket. The ability of forming a well-defined electron energy distribution in an untapered wiggler has been observed recently and is attributed to the use of high-quality beams from a photoinjector.

3.3 Small-signal gain and cavity length detuning

Theoretically, the small-signal gain can be measured by looking at the buildup of optical power as it gets out of spontaneous emission with a fast and sensitive detector. There are two problems with such measurements: first, it is very difficult to determine where in the buildup curve corresponds to the small signal regime, and second, any transients in the rf, the linac and the electron beam will interfere with the measurement. For the purpose of estimating the small-signal gain, the cavity length can be detuned and the net gain is estimated from the FWHM of the detuning curve as given by the following expression:

$$\delta = \frac{N_w g_{ss} \lambda}{4}$$

where δ is the FWHM of the detuning curve, N_w number of wiggler periods and λ the wavelength of light. The Advanced FEL relative output power at 1.3 nC (usable current = 100 A) is plotted versus cavity length detuning in Fig. 10. The measured detuning length is 5.5 μm . For $N_w = 24$, $\lambda = 5.8 \mu\text{m}$, the estimated net gain is 17%. The measured resonator ring-down for this experiment yields a loss of 4%. Thus, the small-signal gain is ~21%. For a micropulse charge of 1 nC at a beam emittance of 5 $\pi\cdot\text{mm}\cdot\text{mrad}$, 3-D FELEX simulation predicts a small signal gain of 28.4%. Although the detuning curve is a crude method for estimating small-signal gain, it does give an approximate value that can be used to optimize the free-electron laser. In the future, the small-signal gain will be measured via other techniques.

3.4 Average power consideration

At the macropulse repetition rate of 10 pps, the highest measured macropulse energy was 150 mJ. Thus, the Advanced FEL has achieved a true average power of 1.5 W. In order to increase this average power, a number of strategies will have to be implemented. These strategies are listed in Table II. First, the drive laser will be upgraded to an all diode-pumped system that can operate at 100 pps. The new rf station is being tested to operate at 30 MW peak power, 30- μs macropulse and 50 kW of average rf power. If we can achieve the design-point linac efficiency of 40%, we will have 20 kW of average electron beam power. To obtain a 1-kW of light, the wiggler efficiency must be 5% or higher. Extraction efficiencies approaching 5% has been achieved by using a tapered wiggler with a prebuncher.⁴ New tapered wigglers with prebunchers are being designed to achieve efficiencies as high as 10%. For an untapered

wiggler, efficiency can be increased by operating the FEL with sidebands.⁵ Simulation using 3-D FELEX predicts that with sidebands, the Advanced FEL efficiency can be as high as 4%. The problem with sideband operation is the mirror damage caused by the high intracavity optical intensity. New resonator optics are being designed to handle the GW intracavity peak power. The high intracavity powers are also necessary for getting high extraction efficiencies from a tapered wiggler, especially with a prebuncher. In a near future, the upgrades listed in Table II will conceivably allow us to achieve average powers greater than 100 W. In burst modes, i.e. operating for a few seconds, average powers of the order of 1 kW appear feasible.

4. Summary

The compact Advanced FEL has achieved lasing at saturation with improved performance in the spectral region of 4-6 μm . All components of the Advanced FEL have operated according to the design points. The high-gradient linac has produced very low-emittance electron beams at energy up to 18 MeV. The state-of-the-art beamline consisting of permanent magnet components reduces the startup time and significantly increases the system reproducibility. The low-level rf control system has dramatically increased the FEL performance. The Advanced FEL is almost at the point where it can be operated by a single operator. The highest macropulse energy ever observed is 200 mJ and the highest true average power achieved is 1.5 W. Optical damage in dielectric mirrors has limited the intracavity power to less than 500 MW. Polished Cu mirrors are being tested for high average power demonstrations. A number of strategies to increase this average power to possibly 100 W are being implemented. The results will be reported in a near future.

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Figure Captions

1. The compact Advanced FEL is built around a low-energy high-gradient electron accelerator, an all-permanent magnet beamline and a short-period permanent magnet wiggler.
2. The high-gradient linac is capable of up to 25 MeV beam energy.
3. Temporal structures of the drive laser, rf, electron beam and FEL output showing both macropulses and micropulses.
4. a) The "quad-scan" technique yields beam emittance and Twiss parameters for use in TRACE3D calculations. b) Measured emittance as a function of micropulse charge at 13 MeV.
5. The wiggler for mid-ir operation is made out of SmCo₅ permanent magnets. The periods are 1 cm long, each consisting of 2 opposing magnets arranged as shown.
6. The near concentric resonator yields the tightest waist in the middle of the wiggler. Even so, at 6 μm , the calculated optical mode (378 μm) is much larger than the focused electron beam ($\sim 150 \mu\text{m}$).
7. Setting the cavity length with the drive laser and a streak camera. The inset shows the expanded scale near the origin. Zero is defined as the cavity length as measured by mechanical means.
8. The optical power as a function of time, measured with a pyroelectric detector. Top trace 2 $\mu\text{s}/\text{div}$: FEL oscillation occurred over a 11- μs macropulse. Bottom trace 50 ns/div: the cavity ringdown of 70 ns corresponds to a 13% round-trip loss.
9. Energy spectrometer shows the uncaptured electron at 16 MeV and trapped electron peaked at 15.8 MeV.
10. The Advanced FEL cavity length detuning curve for 1.3 nC (100 A usable current) yields a small signal gain of 21%, consistent with the predicted value of 28.4% at 100 A.

Table I
Advanced FEL Electron Parameters

Linac

Frequency	rf	1300 MHz
Number of Accelerating Cells		10 + 1/2 cells
Accelerating gradients (@ 18 MeV)		
	First 1/2 cell	23 MeV/m
	Cells 2-11	20 MeV/m
Coupling	β	1.77
Measured Q (unloaded)	Q	20,060
Shunt Impedance	Z	40 M Ω /m

Electron Beam

Micropulse charge	q	2 nC
Micropulse width	τ	10 ps nominally
Peak current	I	200 A
Micropulse frequency	f	108.33 MHz
Beam energy	E	15 MeV ($\gamma = 30.4$)
Normalized emittance (rms)	ϵ_n	2.5 $\pi \cdot \text{mm} \cdot \text{mrad}$ at 1 nC
Energy spread	$\Delta\gamma/\gamma$	0.5% (FWHM)

Wiggler

Period	λ_w	1 cm
Length	L_w	24 cm ($N_w = 24$)
Full Gap	2H	0.3 cm
Peak Magnetic Field	B_w	0.415 T
Wiggler parameter (rms)	a_w	0.2738
Betatron Period	λ_β	123.8 cm

Table II
Advanced FEL Optical Parameters

Optics

Cavity length	L_c	138.36 cm
Mirror radius of curvature	R_c	70 cm
Dimensionless resonator factor	g	-.977
Rayleigh range	z_R	7.5 cm ($\sim L_w/3$)
Beam radius at waist	w_o	.378 mm
Beam radius at wiggler end	w	.753 mm
Wiggler clear aperture	$2a$	2.8 mm
Round-trip vignetting loss	$4 \cdot \exp(-2a^2/w^2)$	0.5%
Out-coupling	Θ	8%
Absorption and scattering loss	L	~3.5%
Round-trip cavity loss ^a	Γ	12%

FEL Results

Wavelength	λ	5.8 μm
Small-signal gain (at 0.3 nC)	g_{ss}	21% (at 100 A)
Cavity length detuning curve	δ	5.5 μm
Macropulse energy	E_{mp}	200 mJ (at 200 A)
Macropulse length	$\Delta\tau$	11 μs
Average micropulse energy	$E_{\mu p}$	170 μJ
Optical power	P	17 MW
Beam power	P_e	3 GW
Beam-to-light efficiency	$\eta_{out}=P_{out}/P_e$	0.6%
Extraction efficiency	$\eta_{in}=P_{in}/P_e$	0.9%
Macropulse repetition rate	f_{mp}	10 pps
Macropulse energy @ rep. rate	E_{mp}	150 mJ
True average power	P_{ave}	1.5 W

Table III
High Average Power Upgrades

<u>Strategies</u>	<u>Improvement</u>	<u>Power Enhancement</u>
Diode-pumped Drive Laser	Macropulse rep. rate 10 -> 100 pps	X10
	Micropulse rep. rate 108 -> 216 MHz	X2
New rf Station	Higher Power to handle rep. rates	
	Macropulse length 15 -> 30 μ s	X2
Tapered Wiggler with Prebuncher	Higher Efficiency 1% -> 7%	X7
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Total enhancement		X280
Present average power		1.5 W
Projected average power		420 W

Figure 3

Magnet Arrangement

$$\lambda_w = 1 \text{ cm}$$

$$L_w = 24 \text{ cm (N = 24)}$$

$$B_{\text{peak}} = 0.415 \text{ T}$$

$$a_w (\text{rms}) = 0.2738$$

Streak Camera Output

Grey Level Intensity

Figure 10

DATE

FILMED

6/14/94

END