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INITIAL PERFORMANCE OF LOS ALAMOS ADVANCED
FREE ELECTRON LASER

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Paper Mo1-3

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Abstract

The Los Alamos compact Advanced FEL has lased at 4.7 and 5.2 μm with a 1-cm period wiggler and a high-brightness electron beam at 16.8 and 15.8 MeV, respectively. The measured electron beam normalized emittance is $1.7 \pi \cdot \text{mm} \cdot \text{mrad}$ at a peak current of 100 A, corresponding to a beam brightness greater than $2 \times 10^{12} \text{ A/m}^2\text{rad}^2$. Initial results indicate that the AFEL small signal gain is $\sim 8\%$ at 0.3 nC (30 A peak). The maximum output energy is 7 mJ over a 2- μs macropulse. The AFEL performance can be significantly enhanced by improvements in the rf and drive laser stability.

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1. Introduction

In many industrial applications, a compact tunable laser that puts out more than 100 watts is highly desirable. FELs are inherently tunable, high average power devices but thus far their applications in industry have been hindered by their size, cost and complexity. For an FEL to be usable by industry standard, 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 such as a high-brightness photoinjector, a high-gradient linac, and a permanent magnet beamline.^{1,2} These technologies enable us to shrink the FEL size yet maintain its high average power capability. The AFEL has been operating in the near-ir ($\sim 5 \mu\text{m}$) since early 1993. For more details on the AFEL design, the readers are referred to earlier papers.¹⁻³ In this paper, a description of the AFEL subsystems and their performance, the initial laser results, existing problems and future upgrades to improve the FEL performance will be presented.

2. AFEL Subsystems

Table I summarizes the characteristics and performance of the three main components of the AFEL: the electron beam, wiggler and optics. A schematic of the Advanced FEL is shown in Fig. 1. The performance of the specific subsystems is described below.

2.1 Linac

The source of high-current electron pulses is a photoinjector which forms the first half-cell of a high-gradient rf linac. The klystron-powered linac consists of 10.5 cells with a single rf feed. The 1300-MHz klystron is capable of generating up to 15 MW peak power. The linac is 1.2 m long and capable of producing a maximum electron beam energy of 20 MeV. It is specifically designed to produce a high-brightness electron beam via emittance compensation with a solenoid around the photoinjector.⁴ For minimum beam emittance, a second bucking coil is used to zero the magnetic field on the cathode. The bucking coil field must be set to within a few gauss of the correct value. After a year of operation, the linac regularly exhibited multipactoring that occurred

strongly at high solenoid fields. Multipactoring could be eliminated by increasing the bucking coil field beyond the correct value, at the expense of a larger beam emittance.

2.2 Photoinjector

The photoinjector front-end consists of a drive laser and a high Q.E. CsK₂Sb photocathode. The drive laser is made up of a Nd:YLF oscillator modelocked at 108.33 MHz (12th subharmonic of rf) and a double-pass amplifier. A Pockel cell switches out variable-length macropulses to be frequency doubled in a temperature-tuned 90° phase-matched LBO crystal with an efficiency of ~50%. A typical 6-μs macropulse carries ~650 micropulses, each approximately 7-ps in duration and 10 μJ in energy. The amount of charge per micropulse generated at a known Q.E. and laser pulse energy E_p is given by

$$q \text{ (nC)} = 10 \times \frac{E_p(\mu\text{J}) \times \text{Q.E.}(\%) }{h\nu(\text{eV})}$$

At 527-nm, the photon energy $h\nu$ is 2.3 eV, so a micropulse with 10 μJ in energy is capable of generating 4.3 nC even with a Q.E. of 0.1%. Due to its susceptibility to poisoning, CsK₂Sb requires an ultrahigh vacuum, typically in the low 10⁻⁹ torr. Rf glow discharge, high temperature bakes and high power rf conditioning have been used to condition the linac. The photocathodes are prepared in batches of six cathodes in a separate chamber and transported under vacuum to the accelerator via an actuator/insertion mechanism. A typical CsK₂Sb photocathode Q.E. starts out at 1-5% and then decays to less than 0.5% during storage, mainly due to outgassing of the actuators when they are moved. During the first half-hour of operation, the photocathode Q.E. rises, perhaps because of activation by oxygen, but then it steadily falls until it reaches 0.01%. Dependent on the cathodes and how they are made, this happens about 8 to 24 hours of operation after the initial rise. Thus a good batch of six cathodes can provide up to 3 weeks of beam time.

2.3 Beamline & beam diagnostics

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 FEL optical axis; and the third bend steers it into a beam dump (Fig. 1). The first two bends are made achromatic by the use of a singlet to refocus the beam in the dispersion plane. For compactness and reliability, all variable-field focusing quadrupoles and bending dipoles are made out of permanent magnets. Detailed designs of the permanent magnet quadrupoles and dipoles can be found elsewhere.⁵ The integrated quadrupole fields are variable between -0.262 T and +2.15 T, with a resolution of 3 G. The field is reproducible to less than 1 G. The dipole fields are variable between 0.07 T and 0.3 T, with a resolution of 2.3 mG. The magnetic fields of the three dipoles are within 5% of one another. There is a small amount of backlash (~20 G) in one of the dipoles, but overall the dipole and quadrupole fields are highly reproducible.

A toroid is used as a calibrated current monitor. Wall current beam-position monitors (BPM) are strategically located to ensure beam transport through the center of the beamline. The BPM performance has been evaluated and reported elsewhere.⁶ Emittance measurements on the AFEL electron beams are described in more details by Sheffield *et al.*⁷ Beam energy is measured with a combination of the first dipole and BPM, while energy spreads are measured with a spectrometer screen at the third bend.

2.4 Wiggler

The first lasing experiments were performed on a 24-period permanent magnet wiggler with 1-cm periods. Each period consists of two pairs of samarium cobalt magnets arranged to enhance the third harmonic operation. At a gap of 3 mm, the maximum on-axis field is 0.415 T, giving an rms wiggler parameter a_w of 0.274.

2.5 Optics & optical diagnostics

The FEL optical resonator consists of two near-concentric mirrors mounted in vacuum with pressure equalizing bellows. The mirror radius of curvature is 0.7 m (Fig. 2). Gold-coated copper mirrors with hole coupling have been used unsuccessfully. These mirrors have an average reflectivity of 98.5% over the 4-6 μ region. Outcoupling is provided by a hole drilled in the center of one 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 outcoupled is $\sim 2(a^2/w^2)$. Although metal mirrors

provide broad spectral coverage, there are two problems associated with hole-coupling. First, diffraction alters the cavity mode causing vignetting loss at the wiggler ends to be higher than predicted. Second, alignment is difficult and cannot be done when an electron beam is on.

The metal mirrors were replaced with ZnSe/ThF₄ multilayer dielectric mirrors. The MLD coatings had 99.5% reflectivity at 4.5-5.5 μm . The transmission of each mirror was used as outcoupling. Thus, when lasing occurred, two laser beams came out of the FEL resonator, one directed toward an ir detector (such as a HgCdTe or a fast Cu-doped Ge detector) and the other to a pyroelectric joule meter. The mirrors spacing and tip/tilts were adjusted remotely via piezoelectric micrometers.

3. Experimental results

3.1 Electron beam characterization

The electron beam transverse emittance was measured by performing the well-known “quad scan” in which the beam spot size at a screen a known distance from the focusing quadrupole is measured as a function of the quadrupole field. Typically, for each quadrupole setting, an OTR image of the beam was snapped, box-averaged and analyzed with a commercial image analysis software. A nonlinear least square fit was performed on the spot size versus quad 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. 3a. 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. The agreement between measured and predicted emittance is good for 1 and 2 nC but the measured emittance at 3 nC deviates from PARMELA prediction (Fig. 3b). Further experiments are required to resolve this discrepancy. The measured energy spread integrated over the 6- μs macropulse is 1%.

3.2 Electron beam matching

The high-brightness electron beam was transported through a brightness-preserving beamline.⁵ Care was taken to minimize emittance growth in the first two bends. In general, the beam is considered acceptable if its measured emittance after the first two bends is less than 5

π ·mm·mrad. Beam matching into the bends and the wiggler was accomplished by comparing the observed beam spots on the OTR screens with Trace3D and PARMELA predictions. Within small errors, the quadrupole fields for the first 2 doublets and the singlet in the achromatic bends agree well with Trace3D. The actual quadrupole fields for the 3rd doublet (after the 2nd bend) are approximately 20% higher than Trace3D values. Experimentally, although 100% electron transmission through the wiggler was regularly achieved at low charges (0.5 nC or less), at higher charges, we had difficulties matching into the wiggler. This happened because the bucking coil could not be set to zero out the solenoid field right at the cathode. Instead, the bucking coil was artificially increased to get rid of multipactoring. The readers are referred to Ref. 7 for further details on the AFEL multipactoring and how to eliminate it.

3.3 Cavity length setting

The correct cavity length was set by both mechanical and optical means. Since the cavity 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 that one knows the exact dimensions of the mechanical mounts. This method yields a measurement uncertainty of ± 50 μ m. By injecting the drive laser beam into the FEL cavity (with metal mirrors), and measuring the multiple pulses reflected off the mirrors with a streak camera, in theory one can set the FEL cavity length so that all the reflected pulses are overlapped and that would be the correct cavity length. In practice, due to the drive laser pulsewidth of 7 ps, the FEL cavity length must be detuned 2 mm or more in order to accurately measure the delay time between successive pulses. A linear least-square fit of delay time versus cavity length yield zero-crossing position at -170 (Fig. 4). The uncertainties in measuring the delay times at large detunings limit the accuracy of this method to within ± 150 μ m. These results illustrate that for a short cavity length, it may be more accurate to measure the cavity length mechanically.

3.4 Laser results

Shortly after we replaced the metal mirrors with MLD mirrors, the AFEL lased on April 13, 1993 at a mechanical cavity length setting of -30 μ m (140 μ m from the optical cavity length setting). The electron beam

energy for the first laser experiment was 15.8 MeV and the measured FEL wavelength was 5.2 μm . The initial laser was chaotic and hard to maintain. There were two obvious causes of instability. First, the rf system was running without feedback stabilization, and consequently its phase with respect to the master oscillator exhibited a slew of $\sim 18^\circ$ during the macropulse. Secondly, the drive laser had a long-term phase drift due to thermally induced changes in its cavity length. Subsequently, we attempted to stabilize the rf via a feed-forward circuit and the FEL performed much better in terms of laser startup and reproducibility. On April 16, 1993, the electron beam energy was changed to 16.8 MeV and the FEL lased at 4.7 μm at a threshold current of 20 A. Oscillation occurred mostly at the end of the macropulse where the rf phase slew was at a minimum (Fig. 5). The maximum output energy recorded was 3.5 mJ at one end of the FEL resonator. Since the mirrors had equal reflectivity (and thus equal outcoupling), we deduced a total output energy of 7 mJ.

3.5 Cavity length detuning curve

The AFEL relative output power is plotted versus cavity length detuning in Fig. 6. For the purpose of finding the FWHM of the detuning curve, the data was fit to two halves of Gaussian curves, with the positive half having a smaller $1/e$ width than the negative half. The points at 0 and $+0.5 \mu\text{m}$ detuning are slightly saturated. The small-signal 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. For $\delta = 2.4 \mu\text{m}$, the estimated small-signal gain is 8%, in reasonable agreement with 3-D FELEX prediction (Table II).

4. Summary and Conclusion

The Los Alamos compact Advanced FEL has lased at 4.7 and 5.2 μm with a 1-cm period wiggler and a high-brightness electron beam at 16.8 and 15.8 MeV, respectively. The measured electron beam normalized

emittance is $1.3 \pi \cdot \text{mm} \cdot \text{mrad}$ at a peak current of 100 A, corresponding to a beam brightness greater than $2 \times 10^{12} \text{ A/m}^2\text{rad}^2$. Initial results indicate that the AFEL small signal gain at 0.3 nC (30 A peak) is 8%, in reasonable agreement with 3-D FELEX simulations (28.4% at 1 nC). The maximum output energy is 7 mJ over a 2- μs macropulse. Table III summarizes the initial laser results of the Advanced FEL.

The measured gain was small due to the low currents used in the initial experiments. At higher currents, the beam could not be matched into the wiggler due to multipactoring in the linac. Since the multipactoring has been solved,⁷ it is expected that with better beam matching, the FEL small signal gain can be increased to the full value of 38% at 1 nC as predicted by 3-D FELEX. The AFEL performance can also be significantly enhanced by improvements in the rf and drive laser stability. By fixing the rf phase slew that causes a variation in electron beam energy, we expect the FEL will reach saturation more quickly and lase over the entire 6- μs macropulse. Ongoing efforts are concentrated on upgrading the rf and drive laser systems for high-average power operation.

5. References

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Figure 1

Figure 2

Figure 3

Figure 4

Figure Captions

1. Schematic of the Advanced FEL. The beamline and FEL resonator optics are mounted on a 6' x 10' vertical optical table. The klystron and drive laser are not shown in this figure.
2. The compact AFEL resonator is a near-concentric resonator with an optical beam waist of 335 μm in the middle of the wiggler. The calculated spot size for the electron beam (inner envelope) is between 100 and 150 μm in radius.
3. a) Measuring emittance via the "quad scan" technique. This set of data is for a micropulse charge of 1 nC. b) Plots of emittance vs. charge show the linear dependence (predicted) and unexplained emittance growth at high charges (observed).
4. Setting the cavity length with the drive laser and a streak camera. The inset shows the expanded scale near the origin. The optical method yields a zero-crossing cavity length (as measured mechanically) of -170 μm . The FEL has lased at cavity lengths between -50 and -30 μm .
5. The optical power as a function of time, as measured with a HgCdTe detector, indicated that FEL oscillation occurred over a 2- μs portion of the macropulse. This is due to the rf phase slew that causes a shift in electron beam energy even though the transmitted current is flat.
6. The FEL cavity length detuning curve yields a small signal gain of 8%, in agreement with values predicted by 3-D FELEX.

Figure 5

Figure 6

Table I
AFEL Parameters

Electron Beam		
Micropulse charge	q	0.1 - 3 nC
Micropulse width	τ	10 ps nominal
Peak current	I	10 - 300 A
Micropulse frequency	f	108.33 MHz
Beam energy	E	16.8 MeV ($\gamma = 33.9$)
Normalized emittance (rms)	ϵ_n	$1.3 \pi \cdot \text{mm} \cdot \text{mrad}$ at 1 nC
Energy spread	$\Delta\gamma/\gamma$	1% (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
Optical		
Cavity length	L_c	138.36 cm
Mirror radius of curvature	R_c	70 cm
Rayleigh range	z_R	7.5 cm ($\sim L_w/3$)
Beam radius at waist	w_0	.3355 mm
Beam radius at wiggler end	w	.6765 mm
Wiggler clear aperture	$2a$	2.8 mm
Round-trip vignetting loss	$4 \cdot \exp(-2a^2/w^2)$	0.08 %
Reflectivity ^a	R	99.5%
Round-trip cavity loss ^a	L	~1.1%

^a With Multilayer Dielectric Mirrors only

Table II
FELEX Simulation of AFEL Small-signal Gains vs Emittance

Micropulse charge	q	1 nC
Beam energy	E	15.5 MeV
Wavelength	λ	5.5 μm
Energy spread	$\Delta\gamma/\gamma$	1% (FWHM)
<hr/>		
Small-signal Gain		
<hr/>		
$\epsilon_n = 2.5 \pi \cdot \text{mm} \cdot \text{mrad}$	$5 \pi \cdot \text{mm} \cdot \text{mrad}$	$10 \pi \cdot \text{mm} \cdot \text{mrad}$
37.7%	28.4%	18.6%
<hr/>		

Table III
Summary of Initial Laser Results

Wavelength	λ	4.7 μm
Small-signal gain (at 0.3 nC)	g_{ss}	8%
Cavity length detuning curve	δ	2.4 μm
Macropulse energy	E_{mp}	7 mJ
Macropulse length	$\Delta\tau$	2 μs
Average micropulse energy	$E_{\mu p}$	30 μJ
Optical power	P	3 MW
Beam power	P_e	500 MW
Efficiency	$\eta=P/P_e$	0.6%

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