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RECENT PROGRESS OF THE COMPACT AFEL AT LOS ALAMOS *

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Abstract

The Advanced Free Electron Laser (AFEL) is a compact, infrared, rf-linac FEL that uses a high-brightness photoinjector and a short-period permanent-magnet wiggler. Lasing at saturation with and without sidebands has been achieved over the 4-6 μm region with a nominally 15-MeV electron beam energy and a 1-cm-period, 24-period wiggler. Sideband-free FEL operation was optimized with respect to outcoupling by tuning off the reflectivity curve of the multilayer dielectric mirrors. Sideband operation was achieved using copper mirrors with a 1.1% outcoupling hole. The measured macropulse energy with ~1300 micropulses was approximately 50 mJ per 1 nC of beam, corresponding to an output efficiency of 0.25% and a maximum extraction efficiency of 1.4%.

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1. Introduction

Since 1988, a number of photoinjector-driven FELs have been built and a few others are under construction [1-5]. Although much has been learned about the characteristics of a photocathode electron gun [6-8], there remain many opportunities in the application of a high-current, low-emittance beam to free-electron lasers. For example, the use of a low-emittance electron beam should allow operation at short wavelengths with a relatively low electron beam energy by lasing at harmonic frequencies. This concept has been demonstrated by O'Shea et al. in 1993 [9] in an experiment where they generated 370-nm UV with a 41-MeV electron beam. A second possibility with the low-emittance beam is the use of a short-period microwiggler to reduce the beam energy requirement, and thus the size and cost of an FEL. A third possibility is to use the high peak currents available from the photoinjector to drive a wiggler with very few periods but with enough gain to lase reliably at saturation. The advantage of using a wiggler with few periods is that the resulting FEL efficiency which is typically less than $1/2N_w$ —where N_w is the number of periods—can be of the order of a few percent if N_w is a small number. The latter two possibilities have recently been realized on the compact Advanced FEL at Los Alamos. Since 1993, the AFEL has lased reliably at 4-6 μm with a 1-cm-period wiggler and a nominal beam energy of 15 MeV. The wiggler has only 24 periods, making it the shortest wiggler ever used in an FEL. Using such a short wiggler requires a high peak current to achieve adequate gain and a low-loss resonator to reach saturation reliably. The AFEL photoinjector routinely generates peak currents of ~ 100 A or higher. With a 100-A, 5- π -mm-mrad electron beam, we predicted a small-signal gain of $\sim 23\%$ using a simple FEL code called FEL-CAD [10]. By varying the outcoupling, we expected to achieve optimum FEL performance. With 15 MeV and 1% extraction efficiency at saturation, the AFEL should be able to extract 150 μJ per nC of beam into each micropulse inside the resonator. In this paper, we present recent experimental results on the Advanced FEL at different outcoupling and compare them with predictions. We show the presence of sidebands and their impact on the FEL performance.

2. System descriptions

Details of the AFEL design have been described elsewhere [11]. The AFEL

present operating parameters are summarized in Table I. Since the initial lasing experiments, we have made the following changes to the system:

2.1 Photoinjector/Linac

We have switched from CsK₂Sb to the more rugged and high-quantum-efficiency Cs₂Te photocathodes. The latter typically have a quantum efficiency greater than 10% at 263 nm and a 1/e lifetime more than 100 hours of operation. A single Cs₂Te cathode can be used for several weeks before it needs to be replaced. Details on Cs₂Te photocathode performance are described in this proceeding [12]. Because Cs₂Te requires UV irradiation, the Nd:YLF drive laser has been frequency-quadrupled to obtain 263-nm light. The linac had exhibited multipactoring that negatively impacted its performance during the initial lasing experiments. The linac was washed with water to remove excess surface cesium and rebaked. Since then, multipactoring has not been observed again.

2.2 rf station

A feed-forward/feed-back system has been implemented on the rf station to correct for both systematic and random fluctuations in the amplitude and phase of the cavity accelerating field. It employs an analog feed-back loop as well as an adaptive digital feed-forward correction loop. The feed-back loop corrects against non-repetitive errors caused by random fluctuations in beam loading and klystron beam voltage levels. The feed-forward loop corrects repetitive errors such as ripples in the klystron voltage caused by the pulse forming network and beam loading transients in the linac cavity. With the existing klystron station, the low-level rf can achieve a field amplitude stability of $\pm 0.3\%$ and a phase stability of $\pm 0.5^\circ$ against large parameter excursions at beam current of 1-2 nC/micropulse.

2.3 Optical diagnostics

A sensitive HgCdTe detector is used to measure the spontaneous emission, or with suitable attenuation, the buildup of spontaneous emission into oscillation. A Molelectron P500 pyroelectric detector with sub-ns response time is used to measure the macropulse length and ring-down. The macropulse energy is measured with either a Molelectron J50 and a Gentec ED-200 pyroelectric energy detectors right after the FEL beam exits the CaF₂ window. All energy measurements are quoted after

correction for the ~8% Fresnel reflection loss from the CaF_2 window. The FEL spectral characteristics are measured via an Optical Engineering spectrum analyzer equipped with a 75-grooves/mm grating and a Molelectron pyroelectric array at the exit focal plane.

3. Recent results

3.1 *Lasing at saturation*

To avoid transients that occurred in the first few microseconds of the rf pulse, the electron beam was turned on during the last 15 μs of the rf pulse when the cavity field amplitude and phase were sufficiently flat (Fig. 1a and 1b). The first μs of the electron beam was ramped—the drive laser Pockel cell had a ramp to avoid ringing—and it took another 2-4 μs for the FEL to reach saturation, giving a saturated FEL macropulse of ~11 μs in duration (Fig. 1c). At 108.33 MHz, there are approximately 1300 micropulses in each macropulse.

3.2 *Optimum outcoupling*

The optics used in this experiment consisted of a copper mirror as a total reflector and a ZnSe/ThF_4 multilayer dielectric (MLD) outcoupler. The copper total reflector had a reflectivity of 99% and thus introduced a round-trip loss of 1%. The MLD coatings had a reflectivity of 99.0% at $4.5 \rightarrow 5.5 \mu\text{m}$. Its transmission of 1% provided the out-coupling. By tuning the FEL wavelength to the long wavelength edge of the reflectivity curve, we could increase the outcoupling of the MLD mirror. The measured total cavity loss and outcoupling are plotted versus wavelength in Fig. 2. The difference between the two remains relatively constant at 3-4% and is attributed to the combined loss due to mirror absorption and vignetting of the optical mode. For wavelengths longer than 6 μ , the MLD reflectivity curve dropped sharply with increasing wavelength and small wavelength fluctuations caused large variations in outcoupling, resulting in very unstable lasing. Furthermore, atmospheric water absorption at 6-7 μ significantly reduced the FEL energy incident on the energy meter and prevented accurate pulse energy measurements.

Streak camera measurements of the electron pulses at 15 MeV and 3-mm beam radius on the photocathode yielded an approximately linear relationship between the electron pulsewidth and charge, $\tau_{\text{fwhm}} = 5.63 \text{ ps} + (6.46 \text{ ps/nC}) Q$. The beam current thus followed a function that asymptotically approached 155 A. Since

the peak current was relatively constant at ~ 100 A over the range 1-1.7 nC, the small-signal gain should be relatively constant. For comparison, the observed macropulse energies in different measurements were normalized to the micropulse charge.

In Fig. 3, the predicted and observed macropulse energies per nC of beam are plotted vs. wavelength. Although there is a trend of increasing output energies with increasing wavelength, the measured energies do not follow predictions. The best performance was at 6% outcoupling where the observed macropulse energy per nC of charge was 54 mJ, corresponding to a micropulse energy of 42 μ J per nC at 15 MeV. From these numbers and a resonator efficiency of 66.7%, we estimated an output efficiency of 0.28% and an extraction efficiency of 0.42%. At output energies less than 40 mJ/macropulse, there is good agreement between measurements and predictions. As the output energies increase, the discrepancy between predictions and measurements also increases, independent of wavelength (Fig. 3). This behavior can be explained by a nonlinear absorption that has been observed previously in ZnSe optics at 10 μ [13]. The nonlinear absorption seemed to occur in the ZnSe substrate and had an intensity threshold of about 5 MW/cm² in the substrate, i.e. not intracavity. This and optical damage at high intracavity power severely limit the utility of MLD mirrors for high power FELs.

3.3 Sideband generation:

Sideband generation was achieved by reducing the outcoupling to obtain a larger gain-to-loss ratio. It was most reliably observed using copper mirrors with a small outcoupling hole. The outcoupling hole had a diameter of 0.5 mm; at 5.6 μ , this gave an approximate outcoupling of 1.1%. Sidebands were observed in the spectral output of the AFEL. At negative resonator length detuning, the AFEL output exhibited a narrow spectrum (Fig. 4a). As the resonator length was increased, so did the output power until the resonator length reached what we called zero detuning, at which point, the AFEL power became unstable and exhibited large excursions in amplitude. Concomitantly, its spectrum became chaotic and displayed significant broadening, mostly to the long wavelength side (Fig. 4b). The highest macropulse energy observed with sidebands was 105 mJ for a micropulse charge of 2 nC. Thus, the normalized macropulse energy was about 50 mJ/nC for an 11-ns macropulse. From these values, we estimated a micropulse energy of 38 μ J/nC. At 15.3 MeV, this corresponds to an output extraction efficiency at saturation of 0.25%.

Combined with an outcoupling of 1.1% and a total resonator loss of 6%, the extraction efficiency at saturation is 1.4%.

With strong lasing, the electron energy spectrum exhibited a well-defined electron energy distribution shifted down in energy from the injected electron energy (Fig. 5). From the shift in centroid, we measured an extraction efficiency, integrated over the macropulse, of 1.2%. This value is in reasonably good agreement with the efficiency estimated from the measured macropulse energy.

4. Conclusion

We have demonstrated lasing at saturation over the 4-6 μ spectral region with the compact Advanced FEL. By tuning off the reflectivity curve of the multilayer dielectric mirrors, we have observed improved performance up to an outcoupling of 6%. The best performance without sideband gave a macropulse energy of ~55 mJ/nC corresponding to an output extraction efficiency of 0.28%. Anomalous nonlinear absorption in ZnSe was suspected to cause the low observed efficiency. Beyond 6% (at 6 μ or longer for this set of MLD mirrors), the output power became too unstable to make reliable measurements. By reducing the resonator loss and using copper mirrors, we have also observed sidebands. The measured output and extraction efficiencies with sidebands are 0.25% and 1.4%, respectively. Although sideband operation offered a higher extraction efficiency, it did not give the highest output efficiency due to a lower resonator efficiency—ratio of outcoupling to total loss. At a micropulse charge of 2 nC, the AFEL routinely produces 100 mJ of infrared light in a nominally 11- μ s macropulse. Thus, its average power during the macropulse is about 9 kW. With a macropulse repetition rate of 10 pps, the true average power is about 1 watt. Since there are approximately 1300 micropulses per macropulse, we estimate a micropulse energy of ~80 μ J in nominally 19-ps FWHM, yielding a peak power of about 4 MW. Both the peak power and average power during the macropulse are high enough for many applications. Since the micropulse separation is 9.23 ns, an electro-optic Pockel cell can be used to switch out a single micropulse. The AFEL spectral linewidth without sideband is about 0.5% (0.03 μ FWHM). However, due to rf amplitude fluctuations of $\pm 0.3\%$ —a result of both running the klystron near saturation and fluctuations in beam current—even with feedforward/feedback, the rms wavelength fluctuation from shot to shot is about $\pm 0.6\%$.

In the future, we will implement a new rf system with improved amplitude and phase stability. We will also increase the AFEL average power by going to a higher macropulse repetition rate and a more efficient tapered wiggler. Alternatively, the untapered wiggler can be shortened to have only a few periods to increase the $1/2N_w$ extraction efficiency. We will then need to increase the small-signal gain by increasing either a_w or the electron current or both. The peak current can be increased by bunching the electron beam with a chicane right before the wiggler. On the AFEL, we expect to achieve 1-ps pulsewidth with 1-nC charge, corresponding to 1-kA peak current.

References

- [1] M. Curtin et al., Nucl. Instr. and Meth. **A296** (1990) 127.
- [2] P.G. O'Shea et al., Nucl. Instr. and Meth. **A318** (1992) 52.
- [3] S. Joly et al., Nucl. Instr. and Meth. **A331** (1993) 199.
- [4] D.C. Nguyen et al., Nucl. Instr. and Meth. **A341** (1994) 29.
- [5] I.S. Lehrman et al., Nucl. Instr. and Meth. **A341** (1994) ABS 31.
- [6] B.E. Carlsten and R.L. Sheffield, Proc. Linear Accelerator Conf., Williamsburg, VA 1988, p.365.
- [7] C. Travier, Nucl. Instr. and Meth. **A304** (1991) 285 and references therein.
- [8] R.L. Sheffield et al., Nucl. Instr. and Meth. **A318** (1992) 282.
- [9] P.G. O'Shea et al., Nucl. Instr. and Meth. **A341** (1994) 7.
- [10] D. C. Nguyen et al., This proceeding, paper Mo3-25.
- [11] K.C.D. Chan et al., Nucl. Instr. and Meth. **A318** (1992) 148.
- [12] S. Kong et al., This proceeding, paper Mo3-20.
- [13] J.E. Sollid et al., Proc. LASER'88, Lake Tahoe, CA (1988) LA-UR 89-560.

Figure Captions

1. a) rf macropulse with feed-forward/feed-back control; b) electron beam current; and c) pyroelectric detector signal.
2. Multilayer dielectric mirror output coupling (solid) and total resonator loss (open) are plotted versus wavelength. The resonator dissipative loss, loss other than outcoupling, remains relatively constant at ~3%-4%.
3. Predicted (open) and observed (solid) macropulse energy as functions of wavelength. The squares represent a slightly different gain or resonator loss.
4. AFEL spectral characteristics (a) without sidebands; and (b) with sidebands.
5. Electron energy spectrum with lasing. The decelerated electrons form a well-defined distribution centered at 2% fractional energy loss.

Table I

Accelerator & rf

Frequency	1300 MHz
Number of Accelerating Cells	10 + 1/2 cells
Accelerating gradient (1st cell)	19 MV/m
Accelerating gradient (others)	16 MV/m
Beam Energy	15 MeV
Macropulse length	20 μ s
Amplitude stability	$\pm 0.3\%$
Phase stability	$\pm 0.5^\circ$

Electron Beam

Micropulse charge	q	1.7 nC
Micropulse width	τ	17 ps
Peak current	I_{peak}	100 A
Micropulse frequency	f	108 MHz
Beam energy	E	14→17 MeV
Normalized emittance (rms)	ϵ_n	5 π -mm-mr
Energy spread	$\Delta\gamma/\gamma$	0.25%
Pulse-to-pulse energy fluctuation		$\pm 0.3\%$

Wiggler (untapered)

Period	λ_w	1 cm
Length	L_w	24 cm
Gap	2H	3 mm
Peak Magnetic Field	B_w	0.404 T
Wiggler parameter (rms)	a_w	0.266

Resonator

Resonator length	L	1.3836 m
Mirror radius of curvature	R	0.7 m
Rayleigh range	z_R	13 cm
Wavelength range	λ	4→6 μ
Outcoupling (ZnSe/ThF4)	Γ	1-6% (variable)
Outcoupling (hole-coupling)	Γ	1.1%

FEL Performance

Energy per macropulse	E_{macro}	100 mJ
Macropulse length	t_{macro}	11 μs
Power during macropulse	P_{macro}	9 kW
Macropulse repetition rate	f_{macro}	10 pps
Energy per micropulse	E_{micro}	80 μJ
Micropulse length	t_{micro}	19 ps
Micropulse peak power	P_{micro}	4 MW
Micropulse repetition rate	f_{micro}	108 MHz
Extraction efficiency	η	1.4%