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Numerical Simulation Studies of the Design and Performance of the AFEL for High Average Power Operation*

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The AFEL (Advanced Free-Electron Laser) at Los Alamos [1 - 7] is a compact free-electron laser oscillator which utilizes a very high-brightness electron beam generated by a high gradient linac whose source of electrons is a photocathode injector. This device has been operating, with 15 - 17 MeV electrons, at optical wavelengths in the 4.5 - 6.0 μm range, since April of 1993 with a one-centimeter-period, permanent-magnet wiggler which is 24 periods long. The linac produces about 12 μs macropulses at a normal repetition rate of one Hz, while the micropulse repetition rate within a macropulse is 108.33 Mhz which is consistent with the optical cavity length of about 138.5 cm. A program is now underway to upgrade the subsystems of this laser in order to allow it to produce long-time-average optical output powers in the range of 0.1 to 1.0 kW. In this communication, we briefly indicate the details of the equipment upgrades, describe a new high-extraction-efficiency wiggler, and present the results of numerical simulation studies of the proposed design.

The accelerator has been designed from the onset for high average power operation, so no major changes are needed other than the addition of a new beam dump. The linac structure was designed to minimize dipole modes and, therefore, to increase the threshold current for cumulative beam-breakup instabilities. Also, the structure has good electrical efficiency despite having been designed primarily to preserve the brightness of the electron beam. The rf-system will be upgraded by installing a new modulator for the 30 MW peak-power klystron. This will allow longer macropulses and a higher macropulse repetition rate (~ 100 Hz). The rf-system will be capable of 50 kW average power operation. The Nd:YLF photocathode drive laser will be converted to a diode-pumped system which will allow operation at a micropulse repetition frequency of 216 Mhz, a macropulse duration of about 30 μs , and a macropulse repetition rate of 100 Hz. As is true with the present laser, the upgraded laser will operate at the fourth harmonic, $\lambda \sim 0.25 \mu\text{m}$, and will illuminate a Cs_2Te photocathode. Increased drive laser energy per micropulse will allow for greater electron micropulse charge.

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The proposed high-extraction-efficiency wiggler design is shown in the figures. Figure 1 shows the variation of the wiggler wavelength (λ , solid line, left side scale) and wavenumber ($k = 2\pi/\lambda$, dashed line, right side scale) versus axial location. Figure 2 shows the variation of the peak wiggler field amplitude b_0 (solid line, left side scale) and associated dimensionless vector potential $a_w (= e b_0 \lambda / (2\pi m c^2))$, dashed line, right side scale). The device consists of a short prebuncher wiggler, a drift distance (blank space in the figures), and a wiggler in which the wiggler wavenumber varies quadratically with axial location. The taper is 25%, which corresponds to a fractional deceleration of the bucket by almost 13%. The drift distance is filled by a dispersive magnetic field generated by four dipoles with a remotely-variable gap. The dispersive section is needed to reduce the overall length of the wiggler assembly, which otherwise would severely truncate the short Rayleigh range optical mode, while allowing for an optimum drift length for bunching to occur.

Simulations were performed with the following electron beam and optical resonator parameters: for the beam, kinetic energy 16.5 MeV ($\gamma = 33.29$), peak current $I = 200$ A (2 nC in a 10 ps FWHM Gaussian), "90%" normalized transverse emittance 10π mm-mr, and fractional energy spread FWHM $\Delta\gamma/\gamma = 0.5\%$; for the resonator, length 138.36 cm, Rayleigh range 8.587 cm, optical wavelength $5.4\ \mu\text{m}$, empty cavity focal point 0.4 cm upstream of the center of the tapered wiggler, mirror clear aperture radii of 1 cm, and reflectance of copper equal to 0.99.

The results of the simulations pointed up various features of the proposed design. 1-D, single-pass, single-wavefront calculations showed a reasonable small-signal gain of 53%. At an input to the prebuncher of 0.9 GW, the gain was 25.6% with an extraction efficiency $\eta = 6.8\%$, while at 2.5 GW input the gain dropped to 12.9% and $\eta = 9.6\%$. Hence, the wiggler operates at high efficiency only for internal power levels of several GW, and to reach those power levels requires cavity losses below 13%. The present resonator probably cannot tolerate more than about 1 GW before micropulse damage occurs on the downstream mirror on which the mode area is about $1/7\ \text{cm}^2$. Finite-pulse, multiple-pass 1-D results show that sidebands develop: at steady-state, an internal power of about 0.37 GW is reached, with $\eta = 3.5\%$, with 18.5% cavity loss, while reducing the loss to 12% increases the extraction to only $\eta = 3.75\%$. Hence, sidebands must be eliminated for efficient wiggler operation, but addition of such elements (a grating rhomb, or a Littrow grating on one of the mirrors) adds cavity loss and lowers the threshold for optical damage on those elements.

3-D single-wavefront, single-pass calculations show that, for 0.9 GW input, the gain (20.3%) and extraction efficiency ($\eta = 5.4\%$) are reduced by 20% only if the transverse emittance is doubled, or the energy spread is quadrupled. 3-D single-wavefront, multiple-pass simulations show that a hole in the upstream mirror for outcoupling causes significant diffraction loss in the empty cav-

ity: 13.5% for a 0.12 cm diameter hole (7% outcoupling), and 19.5% for a 0.1453 cm diameter hole (11% outcoupling). These losses increase for the loaded cavity: including a reflection loss of 1% for each mirror, and using the smaller outcoupling hole, a net small-signal gain of 17%, and a gross gain of 47%, was found, thus implying a total cavity loss of 20.4%. At large signal, a steady state was found with a net gain of 19.1% at 1.3 GW, implying a cavity loss of 16%.

These results show that the present resonator might be usable up to ~ 100 watts output, although the mirrors would have to be cooled to avoid thermal distortion. For greater power levels, side-band suppression is needed along with a longer resonator to reduce loading of the optical elements: either a ring resonator, or a "folded" resonator could be used. Further work is needed to complete the resonator design and evaluate the resulting FEL performance.

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Figure Captions:

Figure 1: Wiggler wavelength (λ , solid line, left side scale) and wavenumber ($k = 2\pi/\lambda$, dashed line, right side scale) versus axial location.

Figure 2: Peak wiggler field amplitude b_0 (solid line, left side scale) and associated dimensionless vector potential a_w (dashed line, right side scale) versus axial location.

wiggler λ and k

Figure 1

wiggler b_0 and a_w

Figure 2