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Integrated Numerical Modeling of Free-Electron Laser Oscillators*

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ABSTRACT

The nonideal characteristics of the electron beam have largely determined the performance of all free-electron laser (FEL) oscillators that have operated up to the present time. A realistic quantitative theoretical assessment of FEL oscillator performance must therefore include a viable representation of the electron beam's characteristics, as well as the properties of the wiggler magnet and the optical resonator. This paper presents results of integrated numerical modeling of the Los Alamos FEL oscillator, using as input to the 3-d FEL simulation code FELEX, a numerically-generated electron pulse obtained from the accelerator code PARAMELA as a solution of a full model of the Los Alamos accelerator system (electron gun, accelerator cavities, and beam transport line).

1. Introduction

The effects of the quality of the electron beam upon the performance of a free-electron laser have been investigated experimentally [1], [2], and theoretically [3]-[10]. The quality of an electron beam is related to the peak current I , the fractional energy spread $\Delta\gamma/\gamma_0$ about a mean energy γ_0 , and the normalized transverse emittance ϵ_n [11]. Other electron-beam properties are also significant in determining the performance of an FEL, e.g. the temporal pulse width. All of these characteristics are moments of the underlying phase-space distribution of the beam. Most theoretical treatments of FEL performance have used I , $\Delta\gamma/\gamma_0$, and ϵ_n as measures of the quality of the beam although it is possible to have different phase-space distributions which have the same $\Delta\gamma/\gamma_0$ and ϵ_n . There have been some theoretical studies that use the phase-space distribution itself to characterize the electron beam [8], [12].

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Experimentally, it is often quite difficult to measure the characteristics of the electron-beam used in an FEL experiment. In particular, rf-linacs produce picosecond electron micropulses whose properties are very difficult to measure in a time-resolved manner: usually time-integrated (over many micropulses) measurements are made of $\Delta\gamma/\gamma_0$ and ϵ_n (but single micropulse measurements of $\Delta\gamma/\gamma_0$ have been made in [13]). Although the electron energy spectrum can be measured, from which $\Delta\gamma/\gamma_0$ can be deduced, there have not, to our knowledge, been serious attempts to measure the full electron-beam phase-space distribution for any operating FEL.

Extensive numerical simulation methods have been independently developed to model rf-linear accelerators and free-electron lasers. By integrated numerical modeling we mean the use of a numerically-generated electron-beam micropulse in an FEL simulation code. The electron micropulse is the result of a numerical simulation of the accelerator/beam transport system. The performance of the Los Alamos 10 μm FEL oscillator is largely determined by the properties of the electron beam because the mirrors and the wiggler magnet have very nearly ideal properties. Since the beam properties are very difficult to measure, in part due to the very short duration (10 ps) of a micropulse, it is convenient to use the sophisticated linac modeling capabilities at Los Alamos to simulate the accelerator/beam transport system and to numerically generate and propagate an electron pulse up to the wiggler entrance. That pulse is then used in FEL calculations to predict the performance of the laser. If this self-consistent calculational procedure produces results in agreement with measurements, one may also have some confidence that the same design procedure can be relied upon to yield accurate theoretical laser performance data for other accelerator/FEL systems.

This paper presents the results of integrated numerical simulations of the 10 μm Los Alamos FEL oscillator. Results are presented for four different wiggler magnets, each one excited by three different electron beams. The four wigglers which have been used in the FEL oscillator are a 1-m untapered wiggler, a 1-m wiggler approximately linearly tapered in wavelength, a 1-m parabolically-tapered wiggler, and a prebuncher with the parabolically-tapered wiggler. Three different electron beams are used to excite each wiggler: a numerically generated pulse from simulations of the present accelerator/transport system, a pulse from numerical simulations of a photocathode injector rf-linac system, and a Gaussian electron pulse whose properties coincide with experimental measurements. The FEL calculations are done in 3-D with finite optical and electron pulses and a resonator with apertures at locations which correspond to the present experimental arrangement.

2. Accelerator Simulations

The accelerator/beam transport system has been modeled using the PARMELA code. PARMELA is a particle code that computes the motion of electrons through an rf-linac and the associated magnetic optics beam transport channel. It is fully 3-D and it includes the effects of longitudinal wakefields in the accelerator and the beamline as well as external steering and focusing magnets. To simulate the performance of the present Los Alamos accelerator system, a schematic of which is shown in Fig. 1, the following components were included in the numerical model: the electron gun, a subharmonic buncher, a buncher at the fundamental frequency, two accelerator tanks, eight solenoid magnets, two quadrupole triplets, and one quad doublet. The parameters were chosen to maximize the peak current, and to minimize the transverse emittance, of the current micropulse delivered to the entrance of the wiggler magnet. Details of this accelerator system have previously been described

[14] (but note that one subharmonic buncher has been removed from the device described in [14]).

Figs. 2-7 show various properties of the numerically-generated electron micropulse. Fig. 2 shows the current vs. position (the origin of the longitudinal coordinate Z is at the electron gun). The FWHM is 11.8 ps, and the total charge is about 2 nC. Fig. 3 shows the number distribution of electron energies for the pulse, Fig. 4 shows the variation of the mean energy vs. position within the micropulse, and Fig. 5 shows the variation of the rms value of the energy vs. position. Figs. 6 and 7 show the variation of the normalized transverse emittance in the X direction and the Y direction, respectively, vs. position. All of the wigglers are plane-polarized with the XZ plane being the plane of the electrons' wobble motion and the YZ plane being the plane of the betatron motion. For brevity, we shall refer to this electron pulse as EB1 below.

Simulations were also performed for the Los Alamos accelerator system with a photocathode injector. The numerical model included the injector, two accelerator tanks, and various associated magnets. This pulse was numerically propagated only through the accelerator but not through the rest of the beamline up to the wiggler. In the FEL calculations, it was represented as a pulse with a Gaussian phase-space distribution having a peak current I of 500 A, a normalized transverse emittance ϵ_n of 25π mm-mrad, a fractional energy spread $\Delta\gamma/\gamma_0$ of 0.5%, and a FWHM of 10 ps. We shall refer to this electron pulse as EB2 below.

FEL calculations were done with a third electron pulse which was taken to be Gaussian with the following properties: $I = 300$ A, $\epsilon_n = 170 \pi$ mm-mrad, $\Delta\gamma/\gamma_0 = 1.3\%$, FWHM = 10 ps. These properties correspond to experimental data for the best pulses produced by this accelerator system. We shall refer to

this pulse as EB3. The mean energy of all three pulses was about 21 MeV at the entrance to the wiggler.

3. FEL Calculations

All the FEL calculations were done with the FEL simulation code FELEX [15], [16]. The calculations are 3-D with finite optical and electron pulses. The optical cavity length L_c was chosen to correspond to exact synchronism, i.e. $2 L_c/c = T_e$ where T_e is the time interval between successive electron pulses from the linac. The optical resonator consisted of two copper mirrors about 7-m apart. The total round-trip optical intensity loss due to these mirrors was 3%, with an additional 1% loss added by the vignetting effects of many apertures along the optical axis. These apertures were located and sized according to measurements made in the actual resonator of the Los Alamos FEL oscillator and corresponded to various devices needed to guide and analyze the electron beam. The finite transverse dimensions of the wiggler magnet were of course also included as effective apertures within the resonator. The Rayleigh range was taken to be 43 cm with the optical waist located 7.8 cm upstream of the center of the wiggler (which was also at the geometrical center of the resonator).

Although the calculations are fully 3-D, including such transverse effects as the optical mode shape, diffraction, finite transverse emittance and radial electron density profile for the electron beam, etc., computer resources limited the number of optical wavefronts to a small number which could not represent the modulation which arises from the sideband instability. Optical pulse shape modifications due to the shape of the electron pulse were resolved, but no sidebands were generated due to the coarse zoning. Hence, the results hold as if an ideal optical filter were inserted into the optical

resonator to suppress sidebands without otherwise distorting the optical pulse.

Table I gives more details of the designs of the four wiggler magnets treated in the calculations. Wiggler W4 is a type of optical klystron designed to operate at high intensity to enhance the capture fraction of the main wiggler [17]. The deceleration efficiency $\Delta\gamma_R/\gamma_R$ is the energy extracted if all electrons would be coincident with the synchronous particle.

4. Results

Table II gives the results of the FEL simulations for the small-signal regime. All numbers are intensity gain in percent. Two numbers are given for each entry: the first represents the gain calculated by propagating once through the wiggler the lowest-order empty-cavity Gaussian mode (specified by the optical wavelength, the Rayleigh range 43 cm, and the waist position 7.8 cm upstream of the center of the wiggler). Other than specifying the initial mode, no other aspect of the optical resonator is used. The second number (in parenthesis) represents the multiple-pass small-signal gain which includes the vignetting effects of apertures and the finite mirror reflectivities. For large single-pass gain values, substantial mode distortion occurs: this distortion leads to large vignetting losses which is why the multipass gain values are usually substantially smaller than the single pass values. The quoted results have been maximized with respect to the carrier wavelength of the optical pulse.

Table III gives the calculated high intensity saturated gain results. As noted above, the saturated gains were about 4%, 3% from the assumed mirror losses and an additional about 1% from vignetting losses. Two numbers are given for each entry: the first is the extraction efficiency in percent from

the electron beam. The second number (in parenthesis) of each pair represents the peak optical power of the optical micropulse inside the optical resonator.

5. Discussion and Conclusions

The calculations reported here represent the results of the most complete numerical model of accelerator/FEL performance to date for the Los Alamos 10 μm FEL oscillator. The FEL results do not include the effects of sidebands or cavity length detuning, as noted above. Otherwise, the FEL calculations are fully 3-D for both the optical and electron beam micropulses.

The FEL calculations were carried out using a precise representation of the optical resonator in use at present in the Los Alamos FEL oscillator. However, it is difficult to compare the results of the calculations with experimental data for several reasons. First, electron beam EB2 has not been generated experimentally at all. Although EB1 should be the best representation of the actual beam used in experiments, it is a single optimum beam and different experiments may have been run under different accelerator conditions. The results for EB3 are for comparison with those for EB1 using beam parameters that are the best measured. Experimentally, small-signal gain data have not been accurately measured due to initial accelerator transients present during the low-intensity part of the macropulse [18]. The calculated results at high intensity cannot be directly compared with data because the experiments used no sideband suppression with the copper mirror resonator, and absolute values (such as zero) of the cavity length detuning cannot be determined. Also, measurements with W4 [19] used a different prebuncher than was assumed for the calculations. The best measurements for W1 and W2 give extraction efficiencies of 1.3% and 1.7%.

It is clear that every effort should be made to generate EB2: this would lead to large predicted improvements in FEL performance. Optical power levels

might become so high that a new resonator will be needed to avoid optical damage.

It will be relatively easy to extend the FEL calculations to include nonzero cavity length detuning. Since high-efficiency performance will also include sideband suppression, more quantitative comparisons with experimental data should be possible in the future.

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Figure Captions

Figure 1: Schematic of rf-linac/beam transport system for the Los Alamos FEL oscillator.

Figure 2: Current vs. position from PARMELA at the wiggler entrance.

Figure 3: Number distribution of electron energies for PARMELA pulse.

Figure 4: Mean energy vs. position for PARMELA pulse.

Figure 5: RMS value of electron energy vs. position within PARMELA pulse.

Figure 6: Normalized $\hat{x}$ -direction transverse emittance vs. position for PARMELA pulse.

Figure 7: Normalized $\hat{y}$ -direction transverse emittance vs. position for PARMELA pulse.

Table I: Wiggler Magnet Properties

<u>Wiggler</u>	<u>Description</u>
W1	1-m uniform, $\Delta\gamma_R/\gamma_R = 0$, $\lambda_w = 2.73$ cm $B_w = 0.3$ T
W2	1-m linearly tapered in λ_w , $\Delta\gamma_R/\gamma_R = 7.35\%$
W3	1-m parabolically tapered in λ_w , $\Delta\gamma_R/\gamma_R = 16\%$
W4	Wiggler W3 preceded by a prebuncher located 31.5 cm upstream. The prebuncher consisted of two periods of uniform wiggler with $\lambda_w = 3$ cm and $B_w = 0.2$ T.

Table II: Single-Pass (Multiple-Pass) Small Signal Gain Results

Electron Beam	Wiggler Magnets			
	W1	W2	W3	W4
EB1	119(106)	16(10.4)	9.5(5.3)	12.3(8.5)
EB2	15,070(2200)	2309(200)	606(60)	761(80)
EB3	200(180)	35.8(27.7)	19.8(14.6)	23(19)

Table III: Saturated Gain Results for the Extraction
Efficiency in Percent (Peak Intracavity Power in GW)

Electron Beam	Wiggler Magnets			
	W1	W2	W3	W4
EB1	0.65(1.4)	2.1(5.0)	2.2(5.7)	3.0(7.1)
EB2	1.8(7.3)	5.0(19)	9.1(33)	9.8(36)
EB3	1.3(2.8)	3.6(7.7)	5.7(13)	8.0(21)

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Figure 1: Schematic of rf-linac/beam transport system for the Los Alamos FEL oscillator.

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