RECENT EXPERIMENTS WITH THE FREE-ELECTRON LASER AT LOS ALAMOS*

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Abstract

Improvements in the operational characteristics of the Los Alamos free-electron laser have produced experimental results in reasonable agreement with theory and simulation. The results of these experiments will be described.

Introduction

A great deal of effort over the past several years has gone into improving a number of system parameters in the Los Alamos free-electron laser (FEL). The amplitude and timing fluctuations in injector gun pulses and rf power have been reduced by about an order of magnitude; nonlinear optical effects in cavity mirrors have been eliminated with the use of copper mirrors; wakefields, which produced transverse and longitudinal emittance growth at high peak currents, have been eliminated or reduced. These improvements have enabled us to carry out a series of experiments[1-4] in the past year that demonstrated laser performance in gratifying agreement with both qualitative theory and numerical simulations. Each of the following sections briefly describes a set of experiments that demonstrates a significant aspect of free-electron laser operation. The first group involves a uniform wiggler, the second, several tapered wigglers. A description of these wigglers, the accelerator, and optical system can be found in our earlier publications.

Lasing with Uniform Wigglers

Sideband Suppression

Before the recent improvements in the system, we had observed gains as high as 40% in the 1-m uniform wiggler. In recent experiments, we have seen gains as high as 250% at peak currents of ~300-400 A. These gain values are in rough agreement with simulations.[5] The characteristics of the laser now change in a reproducible and predictable way with changes in the length of the cavity resonator. Figure 1 shows a typical experimental detuning curve. One-

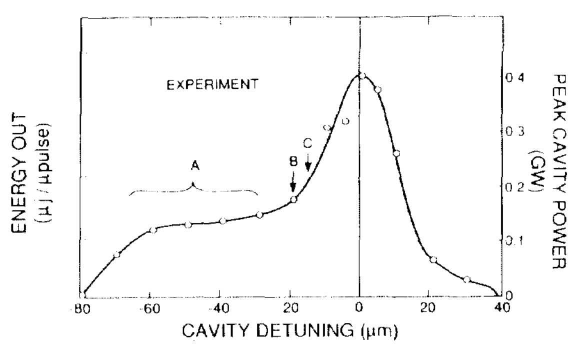

Fig. 1. Experimental in-cavity optical power vs cavity-length detuning.

dimensional pulse calculations for the same conditions yield similar results. A, B, and C indicate the region and points where the spectra are as shown in Fig. 2 a-c. In region A, the spectrum is consistent with the transform limit of our 10-ps electron pulse (Fig. 2a). At B (Fig. 2b), sidebands begin to develop, and at C the spectrum develops into a pattern called the spiking mode (Fig. 2c).[6] This pattern implies a strong

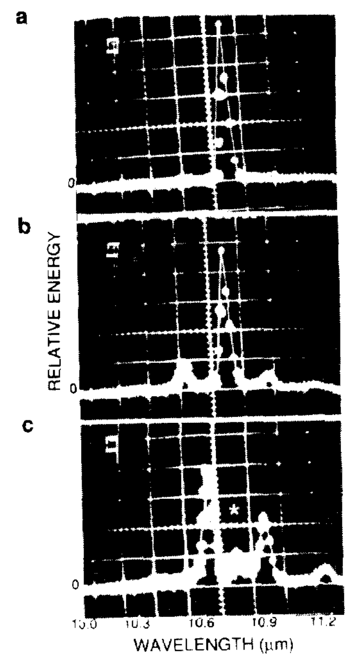

Fig. 2. Experimental spectrum showing (a) narrow spectral shape for large detuning near A; (b) weak sidebands for moderate detuning near B; (c) multiple, evenly spaced sidebands near C.

modulation of the optical pulse, with peak powers 5 times the average, that is, 10-50 GW. The same behavior has been shown in simulations.[5] At larger detuning, the spikes become sharper, narrower, and chaotic, also in agreement with calculations.[5] The spectrum extends over a wavelength range of ~10%, and estimated peak powers exceed 100 GW.

As described above, changing the cavity length by ~30 μm forces the FEL to operate in a single, transform-limited line. The theory explaining such sideband suppression is described in Ref. 7 and is consistent with our observations. Detuning is an elegant way to eliminate sidebands because it requires no additional apparatus. For a uniform wiggler, detuning causes a loss of efficiency. This result, however, is intrinsic to sideband suppression in uniform wigglers because the modulation of the optical pulse by the sidebands is the direct cause of the enhancement in efficiency at zero detuning. In contrast, for tapered wigglers, sidebands reduce efficiency, and detuning has been a completely satisfactory sideband suppression technique for all of those wiggler configurations that we have tested.

The most obvious disadvantage of cavity-length detuning for sideband suppression is that the wavelength is not constrained to a fixed value but changes with beam energy and cavity power. A suppression technique that selects a fixed frequency would be of use. We have experimentally examined one such technique: the use of a diffraction grating ruled on one of the cavity mirrors. The mirror is a spherical grating operated in a Littrow configuration; that is, the desired light, diffracted into the first order, is returned upon itself. Light at the sideband wavelengths is diffracted to the side; it does not interact with the electron beam and is not amplified. Using a grating with a pitch of six lines/mm, we were able to produce transform-limited line widths at cavity powers in excess of 100 MW and simultaneously couple light out of the cavity in an adjacent grating order. The efficiencies observed with a grating were consistent with cavity detuning results; that is, the same efficiency was observed whether the sidebands were suppressed by an active device or by cavity detuning.

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Harmonics Generated by Spontaneous Emission

The axial motion of the electrons in the wiggler field contains oscillating components at twice the frequency of the fundamental, transverse motion. The axial motion and its interaction with the transverse motion produces spontaneous emission at all harmonics of the fundamental frequency. We have made a number of measurements of light output at the 2nd, 3rd, and 5th harmonic wavelengths. Harmonics higher than these were too weak to be seen. Measurements were made over a range of micropulse charge. Some spatial symmetry measurements of the modes were obtained, and the effects of cavity feedback on the 3rd and 5th harmonics were measured.

With no appreciable feedback at the harmonic wavelengths, that is, low reflectivity of the mirrors at these wavelengths, the intensities of the 2nd and 3rd harmonics were found to be $\sim 10^{-5}$ of the fundamental; the 5th was $\sim 10^{-7}$. This is in reasonable agreement with harmonic measurements made at Stanford.[8] When feedback was introduced at the harmonic frequency (either by using copper mirrors or dielectric mirrors with high reflectivity at the harmonic frequency), the 3rd harmonic increased to $\sim 10^{-4}$ of the fundamental. We tentatively interpret the large effect of feedback on the spontaneous emission to the following model: The spontaneous emission produced in each successive pass of the coherent fundamental light is coherently related to that of previous passes (over the lifetime of light in the cavity at the harmonic frequency). Because the added light is coherent, the field amplitudes rather than intensities add. If the phase angle between the fields on successive passes is small, this addition produces a large enhancement over what would be expected from simple incoherent trapping of the light in the cavity. We have not yet done a theoretical analysis or numerical simulation that shows that the phase relationship of the harmonic light on successive passes is such as to produce this enhancement.

Measurements of the spatial distribution of the output showed the expected behavior: that is, a single lobe for the fundamental, two for the 2nd harmonic, and three for the 3rd harmonic. We were unable to determine whether the multiple lobes were axially symmetric, that is, doughnut shaped.

Harmonic Lasing

Lasing has previously been observed on the third harmonic by one[9] or two[10] groups at Stanford. We have now been able to lase on the 3rd harmonic of the 10- to 11-µm fundamental by increasing the gain at the harmonic and increasing the cavity losses at the fundamental. The gain at the harmonic was increased by decreasing the wiggler gap from 8.8 to 5.8 mm, thus increasing the wiggler A value from ~0.7 to ~1. A set of various diameter apertures could be inserted into the cavity to increase the losses for the fundamental. With the use of apertures, lasing could be observed on both the fundamental and the 3rd harmonic. The efficiency of the 3rd harmonic lasing is approximately one-third that of the fundamental.

Figure 3 shows the measured detuning curves, with no aperture (Fig. 3a) and two successively smaller apertures (Fig. 3 b and c). Lasing at the 3rd harmonic appeared only when apertures were used and with a very narrow cavity-length tuning range. As the aperture was made progressively smaller, the detuning curve for the fundamental shifted to the short cavity side and no longer overlapped the 3rd harmonic detuning curve. This shift was caused by scraping at the apertures. The admixture of higher order transverse modes produces increased phase shifts for a round trip of the light in the cavity, thus increasing the effective length of the cavity.

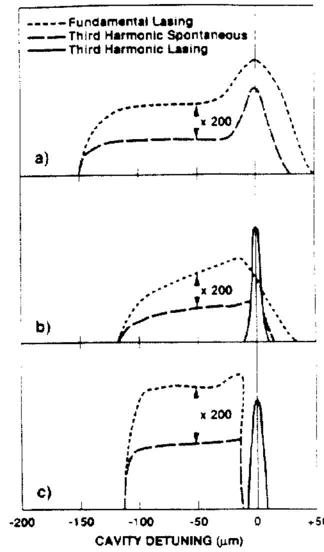

Fig. 3. Measured detuning curves for fundamental and third harmonic with a 5.8-mm-gap wiggler (a, b, and c are successively smaller apertures.)

Lasing with Tapered Wigglers

Wiggler Characteristics

Early FEL experiments at Los Alamos used a permanent magnet Halbach wiggler with an approximately linear 12% wavelength taper. The experiments during the past year have employed this wiggler and another of similar construction, but with a 30% parabolic taper. This parabolic configuration was chosen because it produced adequate small-signal-gain in the initial flat region and also had a large overall taper. Because the taper is continually increasing, we expected that electrons would not stay in resonance throughout the length, so that trapping would not be as nearly complete as with the linearly tapered wiggler.

The tapered wiggler experiments described here also employed a prebuncher, located ahead of the main wiggler, that produces a velocity modulation that enhances the capture of electrons in the main wiggler. Unlike previous prebunchers or optical klystrons,[11,12] the prebuncher employed here was optimized at high optical power[13] to produce maximum extraction efficiency rather than at low power to enhance small signal gain. It was a ~2.5 period wiggler that could be moved to vary the drift space between the prebuncher and wiggler from about 25-40 cm. Calculations[13] indicated that the prebuncher would produce an enhancement of about a factor of 2 in extraction efficiency at high cavity powers, and this was found to be the case. In agreement with simulations,[14] we found that changing the prebuncher-to-wiggler drift distance had large, periodic effects on the wavelength and the efficiency of the laser. The repeat distance, 3.3 cm, was $\sim \lambda_{LASER} \cdot (2\gamma^2)$, as predicted by slippage arguments.

Electron Trapping

Previous experiments showed that the energy spectrum of electrons that traversed a tapered wiggler had a long low-energy tail,[15] but only a slight sign of electrons trapped in a "bucket" of the ponderamotive potential. The absence of a bucket was caused by the growth of the transverse emittance of the electrons in the beam transport line and large energy loss during transit of the wiggler, both caused by wakefield effects. When these problems were eliminated, the results were different. Figure 4, the results of lasing with the prebuncher and 12% wiggler combination, shows the electron energy distribution in a 100-µs macropulse. Figure 4a is the distribution without lasing; Fig. 4b is the distribution when lasing. The electrons show a well-defined group of trapped particles, which are lowered in energy by an amount consistent with the taper of the wiggler. Similar effects are seen in the 30% tapered wiggler. As expected, the electrons tend to spill out of the bucket with this wiggler, particularly when the FEL is lasing weakly. When the cavity power is higher, the buckets are deeper, fewer electrons fall out, and a well-defined peak in the energy spectrum appears at an energy loss consistent with the wiggler taper. The experimental energy spectra for both wigglers are in good qualitative agreement with simple physical models of tapered wigglers. In addition, the spectra agree quantitatively with those calculated in end-to-end simulations that modeled the accelerator and beam line with the accelerator code PARMELA and the FEL with the 3D FEL code FELEX.[16]

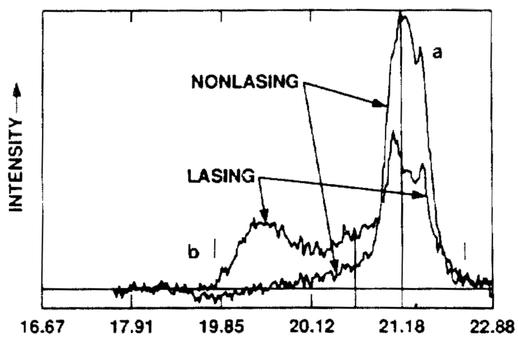

Fig. 4. Trapping and deceleration of electrons by prebuncher-12%-wiggler combination (a) electron spectrometer display without lasing and (b) with lasing.

Efficiency

The highest efficiency that we had previously achieved with the 12% wiggler was ~2.0%. It was probably limited by nonlinear behavior of the dielectric mirrors and emittance growth of the e-beam. The highest efficiency now measured is 4.4%. The measured extraction efficiencies are in reasonable agreement with end-to-end three-dimensional pulse calculations using PARMELA and FELEX.[13]

Detuning

Previously, the 12% tapered wiggler had detuning curves similar to those of the uniform wiggler, not in agreement with simulations. After our improvements to the FEL, both tapered wigglers show quite different properties. The highest efficiencies are now observed when sidebands are suppressed by cavity length detuning, in agreement with simulations. The same qualitative behavior is seen in the 30% taper wiggler. Lasing builds up during the macropulse with a single-line spectrum, then drops as sidebands develop. This behavior is shown experimentally in Fig. 5a. The same behavior is seen theoretically in Fig. 5b, which is a one-dimensional simulation using the code FELPS. As yet, numerical simulations of the effects of detuning with tapered wigglers have not shown a complete correlation with our experimental observations.

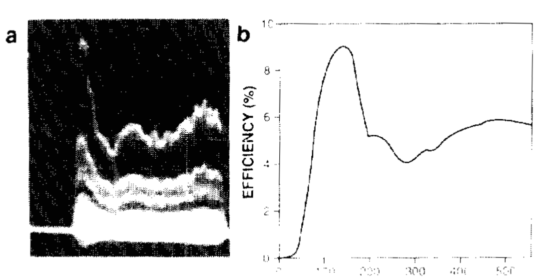

Fig. 5. (a) macropulse of light intensity vs time showing overshoot before sidebands develop; and (b) a simulation of (a).

Conclusions

The experiments at the Los Alamos Free-Electron Laser during the past year have significantly increased our understanding of the physics of rf FEL oscillators and our confidence in both simple physical models and numerical simulations. Although there are still uncertainties in the values of a number of our beam parameters, the FEL performs in qualitative agreement with physical models and in reasonable quantitative agreement with numerical simulations.

The Los Alamos FEL is currently being completely rebuilt with a laser-driven photoelectric injector. This change is expected to enhance its performance and allow new experiments that will extend our knowledge of the physics of these devices.

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