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Plans and Present Status

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The Los Alamos free-electron laser oscillator experiment: plans and present status

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Abstract

Plans have been made to modify the Los Alamos free-electron-laser amplifier experiment to allow its use as an oscillator at 10.6 microns. Several major changes were required, all of which have now been completed. The necessity for these changes is discussed as are the details of their fulfillment. In some cases we have progressed to the point where we can report on the performance of the new systems. The present status is described.

Introduction

The Los Alamos free-electron laser (FEL) amplifier experiment was completed in 1982, and its findings were published in two parts: the electron beam¹ and the optical² results. These results are in excellent agreement with theoretical predictions. The experimental techniques and equipment designed to produce these results were found, in general, to be flexible and well suited to their purpose.

The next step will be an experiment in which the same apparatus and techniques are used to generate light, not amplify it. This step could not be performed with our amplifier equipment until several major changes had been made to it. These changes resulted in the following:

- 1 - achievement of a higher peak electron beam current
- 2 - provision for a longer current pulse
- 3 - construction of an optical cavity
- 4 - provision for radiation protection
- 5 - construction of additional wigglers
- 6 - provision for more extensive diagnostics

These changes have now been made and, in most cases, measurements have been made to judge the success of the new techniques and the performance of the new equipment.

It is the purpose of this paper to present our current plans for the oscillator experiment and to describe, wherever possible, the performance of the new equipment we have installed. The major part of this paper is occupied with a discussion of the six areas of major change presented above. In many cases the techniques used in the amplifier experiment will be used without modification. We refer you to the earlier papers^{1,2} for discussions of these techniques. Three companion papers present in more detail the buncher system,³ the electron beam diagnostics,⁴ and some of the theoretical work⁵ on which our understandings are based. Table 1 presents many of the most important parameters of this experiment.

Equipment modifications

Higher electron beam current

In the amplifier experiment, the peak current drawn from the electron gun was 1 A and it was bunched to ~5 A before being introduced into the accelerator and wiggler. With the tapered wiggler (7% taper in energy) at this current (1% spread in beam energy) ~1% optical gain was achieved. Clearly, a reliable, rapidly growing oscillation cannot be developed with such a low gain.

For the oscillator experiment, we improved the bunching system so that a 1-A gun current gives a 100-A wiggler current. To accomplish this, the current pulse emitted from the gun is collected for 5 ns and then bunched to a 30 ps width using a system of two 108-MHz sub-harmonic bunchers and one 1.3-GHz fundamental buncher. The paper of Fraser³ presents in detail the design considerations and system performance.

Long-current macropulse

In the amplifier experiment, the electron beam macropulse consisted of a few micropulses spaced by 0.7 ns and enclosed by an envelope 3 ns wide (FWHM). This macropulse interacted with a laser pulse of about the same length, 5 ns, and produced the single-pass energy

Table 1. Design Parameters

Optical

Wavelength	10.6 $\mu\text{m} \pm 10\%$
Optical power in cavity	~ 1 GW
Pulse length	30 ps
Rayleigh length	0.4 to 0.6 m
Mirror reflectivities	
Input mirror	99.5%
Output mirror	99.5-90.0%
Mirror separation	6.923 m
Precision of control of mirror separation	$\pm 1 \mu\text{m}$

Electron Beam

Energy	21 MeV $\pm 5\%$
Energy spread	$\pm 0.5\%$
Emittance	2π mm $\cdot$ mrad
Peak current	100 A
Micropulse length	30 ps
Micropulse separation	46.15 ns
Micropulse/macropulse	2000

Wiggler Performance at 40-A Current and No Energy Spread

Standard 12% taper	
Small signal gain	15%
Saturated power	~ 1 GW
Time to saturation	70 μs
No taper	
Small signal gain	100%
Saturated Power	~ 0.25 GW
Time to saturation	25 μs

extraction¹ and optical gain² that we measured. For the oscillator experiment, the optical signal must be given a chance to grow by means of repeated passes through the wiggler in the company of an electron beam micropulse. Some thousand passes are needed to reach saturation from the noise level. The time structure of our experiment, which satisfies this requirement and at the same time reduces power requirements and loading of the accelerator and bunchers, is shown in Figure 1.

As shown at the top of Figure 1, a complete experiment is performed in from 1 to 10 s. Then, each experiment consists of a macropulse occupying $\sim 100 \mu\text{s}$. Next, each macropulse consists of 2000 micropulses, spaced by ~ 50 ns, the round-trip time of an optical signal in our resonator. Finally, each micropulse is ~ 30 ps wide and 100 A high.

It is no trivial matter to develop a macropulse of uniformly shaped and uniformly spaced micropulses. The problems are found mainly in the electronics driving the gun and in the rf systems driving the bunchers and accelerators. The success achieved with the gun's electronics are demonstrated in Figure 2, which shows the shape of a typical micropulse, and in Figure 3, which shows a macropulse as emitted from the gun. For this illustration, only 200 micropulses are shown in the macropulse so that the variations from micropulse to micropulse can be seen. We have measured an amplitude variation of a few per cent and a maximum timing error relative to the accelerator's rf field of 1-2 ns.

When the macropulse is introduced into the bunchers, a major perturbation to their performance is noted. Figure 4 shows the gross perturbation in the rf field, produced by the electron beam in the first subharmonic buncher. The bunchers act much like the cavities in a klystron where large fields are excited by the beam, fields that slow down and extract energy from the electrons. We control these undesired fields, using probes to detect their presence and feedback systems to adjust the phase and amplitude of the rf signal being fed to the bunchers. By correct use of these control measures, the buncher fields can be kept constant in phase and amplitude except for a short interval (10 μs) at the beginning of the macropulse. Figure 5 shows the degree of control that can be achieved. The cost of these measures is high, however. The rf power needed to control the undesired fields is proportional to the square of the beam current and can be very large. For example,

Figure 1. Time dependence of current pulses.

Figure 2. Single micropulse of current from gun. One division represents 2 ns horizontally and 1 A vertically.

Figure 3. Two hundred micropulses in a macropulse. One division represents 1 μs horizontally and 1 A vertically.

Figure 4. The rf field in subharmonic buncher. The electron beam is introduced at A and ends at B. One division represents 20 μ s horizontally and is uncalibrated vertically.

Figure 5. The rf field with feedback control on. Same sensitivities as in Figure 4.

~1 kW is needed to excite an empty buncher cavity to the fields needed for bunching. A 1-A gun current induces undesirable fields that require another 1 kW to cancel. A 2-A current needs 1 kW for the desired excitation plus 4 kW for cancellation, etc. Being limited to 5 kW by our rf supply, we cannot successfully bunch gun currents of more than 2 A.

The accelerators have the same kind of beam-loading problem as the bunchers, but the problem is eased considerably by two factors: the phase of the induced fields differ by 90° and are therefore easier to handle for accelerators compared to bunchers; and, the rf field or, equivalently, the energy density is much higher in accelerators compared to that in bunchers. Therefore, if the same energy were delivered to an accelerator and a buncher by the electron beam, the percentage loading of the accelerator would be much less, thus easier to handle.

A final concern introduced by the long macropulse is its rf energy and power requirements. The oscillator experiment needs somewhat more peak power and several thousand times more average rf power than the previous amplifier experiment. We revised our rf system accordingly. Most difficult was the provision of an rf klystron able to handle this increased power and the other requirements of the pulse scenario. We settled on using two klystrons and split the accelerator into two sections, each to be supplied by a single klystron. This arrangement has the advantage that the separate phase and amplitude controls needed for the two sections afford useful flexibility (as with the subharmonic bunchers) to accommodate space charge and other problems that may be encountered in the beam-transport system.

Optical cavity

The optical cavity is adjusted in length so that the round-trip time for an optical pulse is ~50 ns, that is, the 60th subharmonic of the accelerator frequency and the frequency at which gun pulses are emitted. The cavity mirrors are composed of multilayer coatings on ZnSe substrates so that the mirror on one end essentially is completely reflective at 10 microns, whereas that on the other end can be selected to have from 0.5 to 5% transmission. The mirrors can be tilted remotely with piezoelectric actuators and their separation adjusted with a computer-controlled dc motor. The computer is interfaced with a HeNe interferometer, mounted on the mirrors so that the mirror spacing can be held constant in the face of ambient temperature variations or moved in a flexible manner to satisfy our other requirements. The mirrors are mounted external to the wiggler's vacuum system, thus two Brewster-mounted NaCl vacuum windows are a part of the optical cavity.

Careful alignment of the cavity is essential so that the mode that begins to oscillate is centered on the wiggler and electron beam axes. This is accomplished with an auxiliary

HeNe laser that is injected into the cavity through one of the mirrors and exits from the other end. The coatings and substrates used allow a considerable transmission at 0.633 nm and still provide sufficient reflectivity to partially trap the HeNe radiation within the cavity. The consequence of this trapping, that is, multiple reflections from the mirrors, can be seen in the beam leaving the cavity. When the injected beam lies on the cavity's optical axis, the multiple reflections are superimposed so that the exiting beam is circular and bright. When the injected beam is even slightly off-axis, the exiting beam is spread out and weak.

Once the HeNe beam is aligned with the optical axis, it is next used to test the wiggler alignment by illuminating two cross hairs mounted at opposite ends of the wiggler and exactly on its magnetic axis. Images of the cross hairs appear in the "bright spot" mentioned above. When each cross hair is centered in the bright spot, the optical axis and wiggler axis are superimposed.

Finally, the same HeNe beam is used to align the electron beam by allowing both beams to strike one of three fluorescent screens that are mounted in the wiggler and can be inserted into the beams. Both an electron beam spot and a laser spot are seen on the screens. When these spots are superimposed on all three screens by adjusting the beam's steering, all three axes are superimposed.

Adjustment of the cavity length initially will be guided by monitoring the pulsed spontaneous emission from the electrons. If the length is correct, the optical pulses produced by all of the electron micropulses in a macropulse and their echoes from the mirrors will be superimposed in a special way. For example, the 30th echo of the 1st micropulse will fall exactly on top of the 29th echo of the 2nd micropulse, the 28th echo of the 3rd micropulse, etc. The pulses observed will, therefore, be a combination of many individual pulses. An incorrect cavity length will cause the individual pulses to be spaced apart, producing an exponentially enveloped group whose shape indicates the sense and amount of error in the length.

Provisions have been made to attach apertures and filters of various kinds within the cavity mirrors. Apertures will be used to control the transverse mode content of the beam, whereas sharp cutoff filters will be used to modify the growth of sidebands of the main oscillating frequency due to synchrotron oscillations or other similar effects.

Radiation problems

The major facilities change required for the oscillator experiment was a transfer of all equipment to a new underground vault. This move was required because of the roughly 10,000-fold increase in average current and the concomitant increase in x rays and neutrons. The underground nature of the vault and the use of concrete shield blocks at strategic positions make radiation levels outside the vault negligible. Within, however, the radiation level is much too high for occupancy when beam current is on. In addition, there is concern over the effects of the radiation on optical detectors and other sensitive components. Most of these effects can be reduced by local shielding, but radiation damage to the many fluorescent screens by direct electron bombardment cannot be avoided. We plan to replace our conventional phosphors with thin, high-purity quartz wafers and to view the Cerenkov radiation from these targets. Quartz has high resistance to high-energy radiation, and this approach has the additional advantage that Cerenkov radiation is emitted with no delay. Thus, the time structure of the radiation observed can be used directly to infer the time structure of the electron beam.

Wiggler designs

As discussed above, one of our major tasks is to provide an electron beam current of 100 A so that our standard tapered wiggler will oscillate strongly and achieve saturated power during a 100- μ s macropulse. An untapered wiggler, on the other hand, should accomplish this at a current of 10 A. To be safe, we plan to begin our experiment with an untapered wiggler. After laser oscillations are seen with it, we shall insert wigglers of progressively more extreme tapers until oscillation cannot be achieved. Accordingly, we have built a second untapered wiggler and have developed a technique for "wedging" either of our wigglers so as to increase or decrease its effective taper. Wedging involves placing a series of spacers of varying thickness between the half-wiggler containing the "top" magnets and the half-wiggler containing the "bottom" magnets. In this way the field strengths can be reduced gradually down the wiggler's axis. Using a 1-mm-maximum spacer, we can alter the effective taper by 6%, thus we will achieve effective tapers in wavelength of 0, 6, 12, and 18% with only two different basic wigglers.

To provide a more fundamental variation in wiggler design, we shall make a minor change in the wiggler cartridges so that they can be inserted backward in the beamline. The wiggler then will operate in the phase-displacement manner described in Ref. 6. Our

calculations⁷ show that the gain of such a reversed configuration is nearly the same as that of the direct one, but that frequency chirp as the optical field builds up is less and the growth of sidebands may be substantially suppressed. Our main interest in the reversed configuration is chirp and sideband control.

Finally, we are in the process of building a third wiggler, although its taper has yet to be defined. Our major goals are to find a better compromise between small signal gain and saturated power to reduce chirp and to eliminate sideband growth. We are now performing computer simulations of the behavior of wigglers with tapers that vary smoothly following some power law from untapered at the beginning to strongly tapered at the end. We are also examining the behavior of more exotic tapers.

Augmented diagnostics

In the amplifier experiment, the main electron beam-diagnostic apparatus consisted of a spectrometer to disperse the beam, a fluorescent screen target for the beam, and a vidicon TV camera viewing the screen. We use the same approach in this experiment, except that we now use a means for separating the images produced on the screen at different times during the 100- μ s macropulse. We accomplish this in two different ways: by gating "on" the TV camera for such a short time that it sees only the image produced by a single micropulse and by deflecting the electron beam after it leaves the wiggler in a direction perpendicular to that produced by the spectrometer. The image produced on the screen represents a 3-D plot of electron current versus beam energy and time in a macropulse. The two techniques and their relative advantages are discussed further in a companion paper.⁸

The optical diagnostic system is much more extensive than that employed in the amplifier experiment. It includes the following instruments:

- (1) A liquid-helium-cooled, mercury-doped-germanium detector for 10- μ m radiation. This detector is sensitive enough to measure spontaneous emission from the electron beam and its response is very fast, that is, ~ 200 ps. We will use this instrument to assist in the initial setup of the oscillator cavity, in particular to determine the correct separation of the mirrors as discussed above.
- (2) Two spectrometers. The first will have many stations where detectors can be placed to view the build-up of fields at chosen wavelengths during the macropulse. Multiple detectors can be placed so as to monitor relative growth rates at different wavelengths, for example, to reveal chirp and sideband growth versus time. The second spectrometer will use a Pockels cell and can be gated "on" for a single micropulse. Its detector is a multielement pyroelectric device that will provide a measurement of the optical signal's wavelength content at the chosen time during the macropulse. Both of the spectrometer systems produce both time and wavelength information and, thus, should give redundant information. We plan to use both systems because of concern over the reproducibility of successive macropulses and the desirability of acquiring complete information concerning time and wavelength behavior on a single macropulse.
- (3) Near- and far-field pattern and focusability measuring apparatus. These devices, an infrared-imaging vidicon camera and various pinholes and auxiliary detectors, will be used to measure the spatial pattern of the optical beam extracted from the laser cavity and its time dependence. From these measurements we can infer the mode content of the beam and detect any transverse or longitudinal motion of its focal point. Motions of this kind will be measured from macropulse to macropulse and during a macropulse.
- (4) Wavefront-measuring devices. If the measurements discussed in (3) above show that the optical beam is sufficiently stable, we will measure the shape of the wavefronts of the optical beam near its focus. This will be done using a Smartt interferometer,⁹ a device that, in a simple manner, produces both a reference and sample wave from the beam being treated. The interference between these waves produces a fringe pattern that will be viewed by an infrared-imaging vidicon. The wavefronts can be reconstructed from these fringes. Although desirable, it is difficult to use a Pockels cell to gate this system without seriously distorting the wavefronts. Thus, the success of these wavefront measurements depends upon the reproducibility of the wavefronts during a complete macropulse. A significant frequency chirp or sideband growth may destroy the fringe pattern.

Present status

All components of the oscillator system have been constructed and the major parts are now assembled. The gun has delivered currents up to ~ 5 A with good emittance. The subharmonic bunchers work well. The accelerator has achieved a beam energy of 21 MeV. Attention presently is centered on the adjustment of the five feedback control systems associated with the bunchers and accelerators. All of the other accelerator and optical systems are ready to be tested.

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