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TITLE: HIGH-EFFICIENCY FREE-ELECTRON LASER RESULTS

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HIGH-EFFICIENCY FREE-ELECTRON LASER RESULTS

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Abstract

Results obtained with a tapered-wiggler free-electron laser demonstrate the concepts proposed by Morton for enhanced efficiency and show deceleration of electrons by as much as 7%, and extraction of more than 3% of the total electron-beam energy as laser energy when the laser is operated as an amplifier. The experiment is presently being reconfigured to examine its performance as a laser oscillator.

By looking at the free-electron laser as a particle accelerator working backwards, Morton[1] realized that the techniques used to accelerate particles could be used to improve the performance of free-electron lasers. In particular, he predicted the capture of electrons in "stable-phase" regions, or "buckets" in the electron phase space, and proposed that by decelerating the "buckets", the trapped electrons could be decelerated to extract significant amounts of their energy as optical radiation. In fact, since electrons not trapped in the stable regions are forever excluded from them—at least in the adiabatic approximation—phase-displacement techniques could also be used to accelerate or decelerate electrons in a free-electron laser.

In particle accelerators, the buckets are accelerated by changing the phase velocity of the rf field in the waveguide. In free-electron lasers, on the other hand, the interaction between the electrons and the (transverse) optical field is mediated by the wiggler magnetic field, which makes electrons at the resonant energy oscillate at the optical frequency, as shown in Fig. 1. In this case the velocity of the buckets is changed by varying (tapering) the period of the wiggler magnets along the length of the wiggler. In the absence of a prebuncher, only about half the electrons find themselves in the stable-phase regions at the beginning of the wiggler. These electrons follow the taper in the resonant energy of the wiggler and form a low energy peak in the electron distribution function at the end of the wiggler. The untrapped electrons are actually accelerated slightly and form a second peak slightly above the initial energy. If the electrons are injected into the wiggler with less than the resonant energy, the empty buckets pass downward through the electron distribution function as they decelerate. To conserve phase space as the stable-phase regions descend, the phase space outside the buckets—containing the electrons—must move up slightly. This is the principle of "phase-displacement" acceleration.

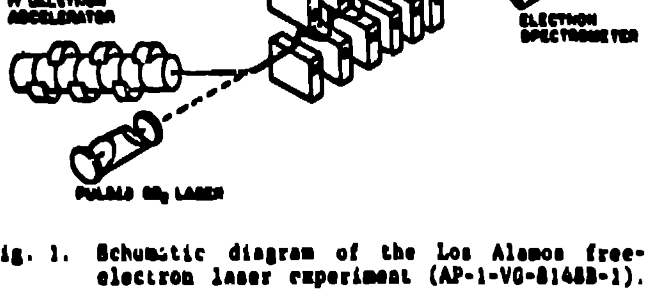

Fig. 1. Schematic diagram of the Los Alamos free-electron laser experiment (AP-1-VG-8148B-1).

To test these predictions, an experiment has been carried out with a 20-MeV electron beam, as shown in Fig. 1. The electron beam had an average current of about 250 mA, an energy spread of 0.5%, an emittance of 0.5 π mm-mrad, and a pulse length of 5 ns. The CO_2 laser had a peak power of 1 GW, operating on a single longitudinal and transverse mode, with a pulse length variable from 1 to 10 ns. The wiggler was 1 m long and used $SmCo_5$ permanent magnets to create a 0.3-T field with a period tapered from 2.7 cm at the entrance to 2.4 cm at the exit. Under design operating conditions with the electrons injected at the resonant energy, about half of the electrons are predicted to become trapped in the buckets and be decelerated about 7%.[2] The average deceleration under these conditions is predicted to be more than 3%. As shown in Fig. 1, the experimental diagnostics included an electron spectrometer to measure the energy spectrum of the electrons leaving the wiggler and an optical detector to measure the amplification of the CO_2 laser beam.[3] Only the results of the electron spectrometer are discussed here.

A typical electron spectrum is shown in Fig. 2. The spectrum displays the double-peaked electron-energy distribution function predicted by theory. The

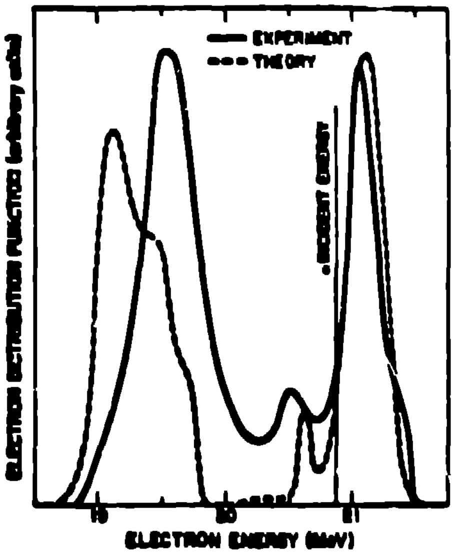

Fig. 2. Electron distribution function at an input optical power of 0.75 GW (AP-1-VG-9231).

high-energy peak near the original energy contains those electrons not trapped in the buckets, while the low-energy peak contains those electrons trapped in the buckets and decelerated with the taper in the wiggler period. Agreement with theory is quite good. For the conditions of this measurement, the trapped electrons represented about 60% of the total and were decelerated about 6.5%. The total extraction (corresponding to the average deceleration of the electrons) was about 3.5% of the initial electron energy. This is about an order of magnitude larger than has been obtained in experiments using uniform (untapered) wigglers.

As shown in Fig. 3, the average energy extracted from the electron beam depended on the initial energy of the electrons. Maximum extraction (deceleration) occurred when the electrons entered at the resonant energy, corresponding to the velocity of the buckets at the wiggler entrance. However, by injecting the electrons at too low an energy, they could be accelerated instead of decelerated, by the principle of phase displacement. This corresponds, of course, to laser absorption rather than gain.

Figure 4 shows the saturation behavior of the laser amplifier as the input laser power was increased. Since the slope of a line connecting the origin with a given data point is proportional to the amplifier gain, it is clear that the small signal gain (below about 0.2 GW) was smaller than the saturated gain (from about 0.2 to 1.0 GW). This is in good agreement with theoretical predictions. The inflection point near 0.2 GW is due to the threshold (around 0.1 GW) for the formation of stable-phase regions (buckets). Since the gain of an oscillator is equal to the loss when the oscillator reaches saturation, these results suggest that such a laser might not start from noise without some external help. Indeed this will be the case for highly tapered wigglers. However, in the present experiments the small-signal gain at wavelengths slightly shorter than the resonant value is larger than the gain at resonance, enough to exceed the saturated gain. Thus, when oscillator experiments are attempted it is expected that the laser will start at a slightly shorter wavelength and then "chirp" downward in frequency to the resonant wavelength as the oscillator saturates.

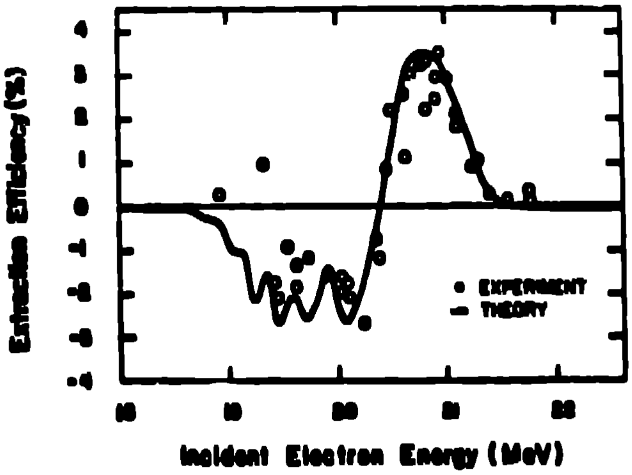

Fig. 3. Average energy extraction at an input optical power of 0.75 GW (AP-1-VG-9548).

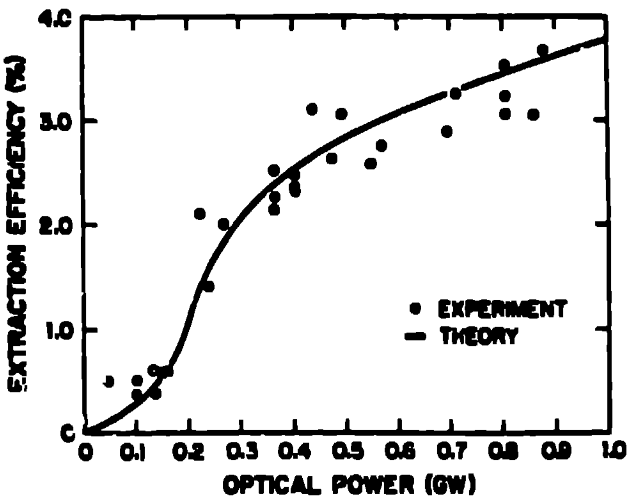

Fig. 4. Saturation of the free-electron-laser amplifier at an incident electron-beam energy of 20.9 MeV (AP-1-VG-9226).

At the present time, the experiment is being reinstalled in a new shielded vault for operation as a laser oscillator. For this purpose it is necessary to provide an optical resonator, and to increase the peak electron-beam current and macropulse length. The optical resonator uses a near-concentric design to focus the laser to a small spot in the wiggler. A HeNe laser permits alignment to about 1 μrad, and an interferometer is used to control the length to about 0.1 μm. A subharmonic buncher is being installed to increase the useable peak current to about 50 A. This is sufficient for a gain of 10-30% per pass, depending on the wiggler taper. An emittance less than 2 π mm-mrad and an energy spread less than ±1% will be required. To minimize the energy spread, the accelerator has been split into two sections, which may be phased with respect to one another in such a way as to cancel the effects of single-bunch beam loading.[4] To give the oscillator time to start from noise, a new rf system has been constructed using two Litton L3707 klystrons. These produce about 3.5 MW each, in pulses 100 μs long.

In summary, the results of laser amplifier experiments demonstrate the principles of tapered wigglers proposed by Morton[1] and confirm quantitative theoretical predictions of high extraction efficiency. Oscillator experiments will be undertaken to explore the performance in this mode of operation.

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