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FREE-ELECTRON LASER RESULTS*

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Summary

The Los Alamos free-electron laser (FEL) amplifier experiment was designed to demonstrate high efficiency for transfer of energy from an electron beam to a light beam in the magnetic field of a tapered wiggler. Initial results indicate an energy transfer consistent with theory. Distinct groups of decelerated electrons as well as accelerated electrons are clearly present in the energy spectrum of electrons emerging from the wiggler when the laser light is present. The observed energy decrease for the electrons captured in the decelerating bucket is ∿6% and the average decrease of the entire energy distribution is ∿2% for the conditions of these initial measurements.

Introduction

Theoretical studies predict an order of magnitude improvement in the efficiency of a FEL when the magnetic field of the wiggler is tapered.[1] With a proper taper of the period and strength of the wiggler field, the energy transferred from the electron beam to the laser radiation can be expected to increase from a few tenths of one per cent to more than a few per cent. According to this theory, at sufficiently high laser power (few gigawatts) potential wells are formed by the laser and wiggler fields that trap some of the electrons. These potential wells and the trapped electrons can be decelerated by properly tapering the wiggler field, resulting in ∿10% of the trapped electrons' energy being transferred to the laser radiation. The untrapped electrons do not participate significantly to the energy exchange, and their energy is only slightly perturbed. The average deceleration of the electrons is expected to be a few per cent.

A series of FEL experiments with tapered wigglers is planned at Los Alamos. The series includes amplifier and oscillator experiments, as well as recovery of a portion of the energy remaining in the electron beam after it has passed through the wiggler. A description of these experiments has been given earlier.[2]

FEL Amplifier Experiment

The first activity is an amplifier experiment. The purpose of this experiment is to demonstrate high efficiency for the energy transfer from an electron beam to laser radiation in a tapered wiggler. The experiment is designed to simulate the high-power conditions that will exist near saturation of the laser gain. Measurements will be made of the electron energy loss and the increase in laser-radiation intensity.

The essential components of the FEL amplifier, as shown schematically in Fig. 1, are an electron accelerator, a beam-transport system, a wiggler, a pulsed CO_2 laser, and diagnostics for both beams after they have traversed the wiggler. The layout of these components is shown in Fig. 2.

Accelerator

The accelerator was designed and built specifically for this experiment. It consists of an injector, a fundamental-frequency buncher, a single accelerating tank, and an rf system operating at a 1.3 GHz frequency and a 20 MW peak power. The injector provides an 80-keV electron pulse with a peak current of a few amperes and a duration of 3 ns (FWHM). After bunching in a single-cavity buncher, the electrons are accelerated to 20 MeV in a standing-wave, side-coupled accelerating structure. This structure consists of 24 side-coupling cells and 25 main cells, the first 4 of which form a tapered-ß section with an initial ß of 0.75. The linac operates in the stored-energy mode, with a gradient of ∿8 MeV/m.

Beam Transport

To obtain collinearity of the electron and laser beams, it is necessary to provide a bend in the electron beam line. A doubly achromatic beam-transport system consisting of three dipole magnets is used to bend the electron beam by 60°. Focusing and steering is by a pair of quadrupole triplet magnets and steering coils located at appropriate positions along the beam line. A number of view screens and current transformers are also located at convenient positions along the beam line. A beam scraper is located in the middle of the second dipole magnet where the energy disperison is the

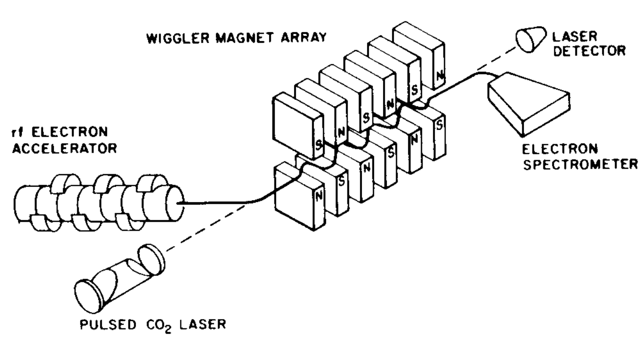

Fig. 1. Schematic diagram of the FEL amplifier experiment.

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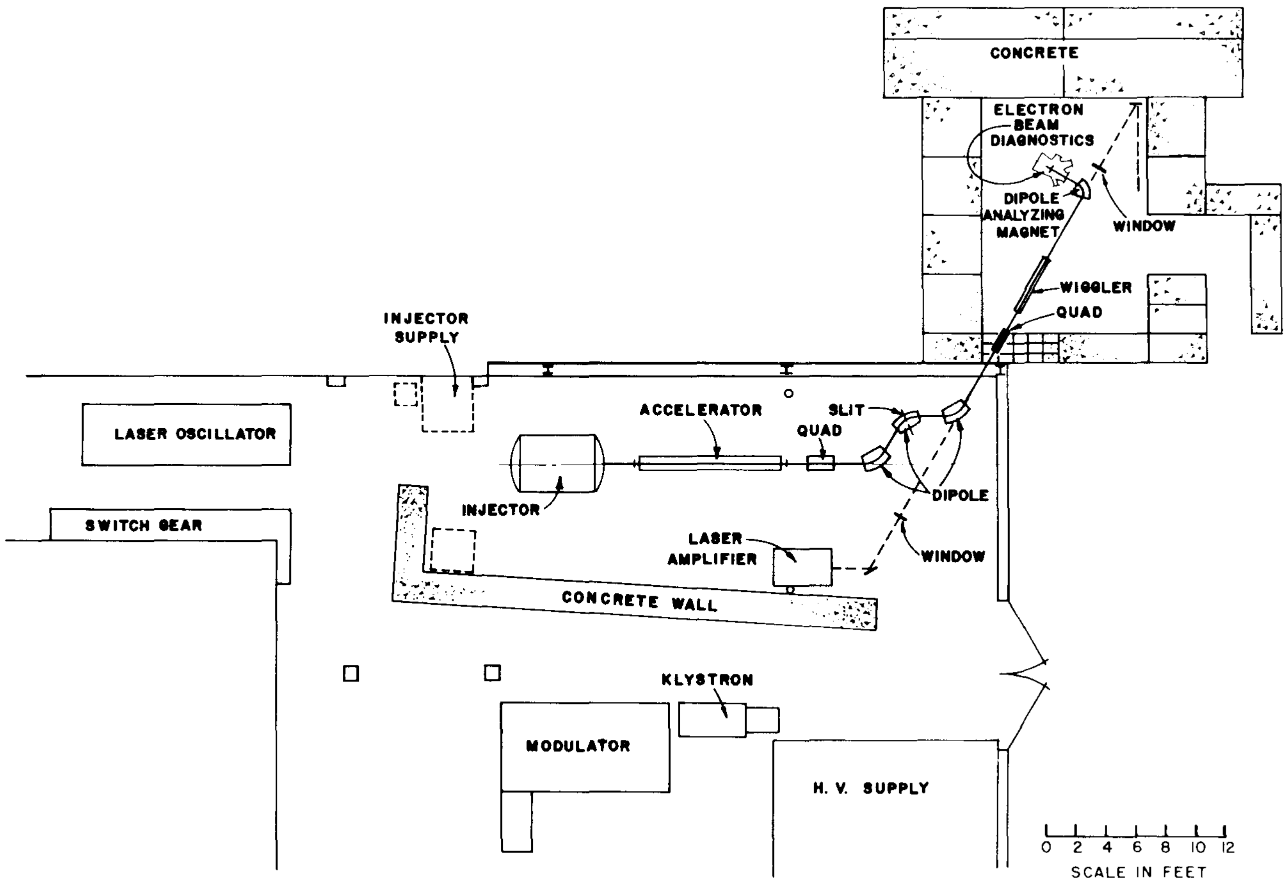

Fig. 2. Layout of the FEL amplifier experiment.

largest. This scraper is used to remove the low-energy tail of the electron energy spectrum and to reduce the energy spread of the transmitted electrons to ±0.5%.

Wiggler

The wiggler provides a spatially periodic magnetic field.* It is composed of 314 nearly identical $SmCo_5$ permanent magnets, each 0.5 cm by 0.5 cm in cross section and 3.5 cm long. The magnets are arranged to provide 40 periods of the magnetic field, including matching fields at each end. The matching fields are produced by a one-half period section that allows a smooth transition from zero to full magnetic field at the entrance and exit of the wiggler. The peak field at the center is 3 kG and the aperture for the electron and laser beams is almost 9 mm. The wavelength of the magnetic field is tapered by ∿12% to maximize energy extraction from the electron beam. The wiggler is 1 m long and is equipped with magnetic-shields and trim coils to assure the proper electron trajectory within the wiggler. Removable fluorescent screens, viewed by vidicons, are provided at the entrance, center, and exit of the wiggler to assist in the alignment and superposition of the electron and laser beams.

*We are indebted to Klaus Halback for his continued technical guidance in wiggler design.

Laser

The CO_2 laser for the amplifier experiment consists of a reinjection oscillator/preamplifier (developed at Los Alamos for the Antares laser fusion program) and a Lumonics Model 600 amplifier. It operates on a single mode (P20), has a peak power of 1 GW with a pulse length variable from 1 to 10 ns. The laser beam is transported by copper mirrors and enters the vacuum beam line through a salt window. This beam is focusable in the wiggler to a spot size close to the diffraction limit.

Diagnostics

The planned diagnostics include an electron spectrometer to measure the energy spectrum of the electrons leaving the wiggler and an optical detection scheme to measure the amplification of the laser beam. The electron spectrometer consists of a dipole magnet that bends the electron beam by 90°, a fluorescent screen and a vidicon imaging system. With this system, the electron-energy spectra taken with and without the laser signal can be compared for various initial electron energies. These data provide the details of the energy gained or lost by the electrons.

The optical detection system to be used to measure amplification of the CO_2 beam is presently being developed.[3]

Predictions

The operating conditions for the first measurements are listed in Table I. Under conditions for optimum energy extraction, ~40% of the electrons are expected to be trapped in the potential well and to be decelerated by ~7%. These lower energy electrons are expected to form a distinct peak. The rest of the electrons, which are only slightly perturbed, are expected to remain in a peak near the incident energy.

Table I

EXPERIMENTAL PARAMETERS

Accelerator	
Electron energy	20 MeV
Peak current	8 A (within energy spread)
Energy spread	±1/2%
Emittance	2π mm•mrad
Electron beam diameter	1 mm
Pulse duration	3 ns (FWHM)
Laser	
Wavelength	10.6 μm
Pulse duration	5 ns (FWHM)
Pulse energy	4 J
Focus diameter	3 mm
Wiggler	
Length	1 m
Taper (wavelength)	12%
Wavelength	2.7 to 2.4 cm
Cycles	40
Aperture	8.8 mm
Magnetic field	0.3 T (max)

Results

A typical electron spectrum is shown in Fig. 3. The spectrum displays the double-peaked electron-energy distribution characteristic of tapered wigglers. The high-energy peak near the original energy contains those electrons not trapped in the pondermotive potential, whereas the low-energy peak contains those electrons trapped in the pondermotive potential and decelerated with the taper in the wiggler field. For the conditions of this experiment, the trapped electrons represented ~30% of the the total and were decelerated ~6%. The total extraction (corresponding to the average deceleration of the electrons) was ~2% of the initial electron energy. This is about an order of magnitude larger than was obtained in previous experiments using uniform (untapered) wigglers.

As shown in Fig. 4, the average energy extracted from the electron beam depends on the initial energy of the electrons. Maximum extraction occurs when the electrons enter at the resonant energy, corresponding to the velocity of the potential energy wells at the wiggler entrance. In fact, by injecting the electrons at too low an energy, they may be accelerated instead of decelerated, corresponding to laser absorption instead of gain.

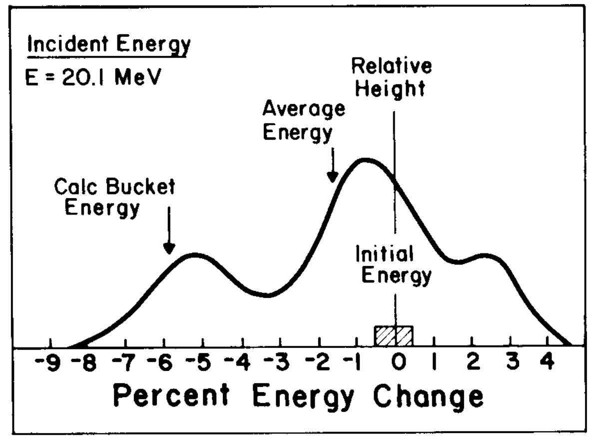

Fig. 3. Typical measured electron-energy spectrum.

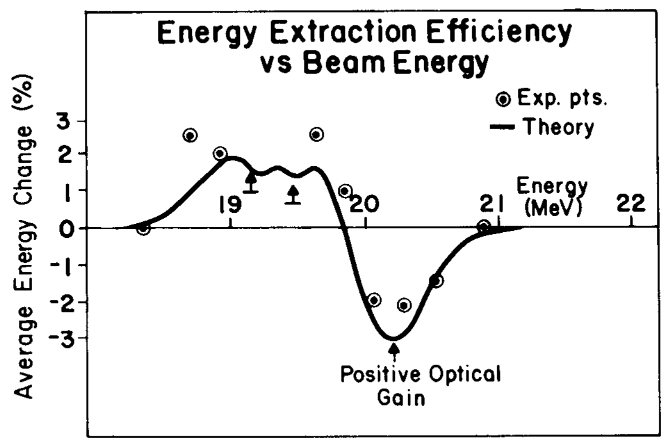

Fig. 4. Experimental and theoretical average-energy extraction as a function of incident electron energy.

Although the results reported here must be regarded as preliminary, they are in good qualitative and satisfactory quantitative agreement with the theoretical predictions of tapered wigglers; they demonstrate an order-of-magnitude improvement over the performance of conventional, untapered wigglers.

References

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2. W. E. Stein, C. A. Brau, B. E. Newnam, R. W. Warren, and J. G. Winston, "LASL Free-Electron Laser Experiments," IEEE Trans. Nucl. Sci. 28, Number 2, (1980).

3. B. E. Newnam, K. L. Hola, R. W. Warren, and J. C. Goldstein, IEEE J. Quantum Electron., QE-17, 1480 (1981).

Discussion

These preliminary data indicate the main peak may have also moved down a little, rather than showing that the uncaptured electrons are actually accelerated. We emphasize that these are very early results that do indicate that deceleration of a substantial group of electrons has occurred to about the right degree. Alignment and the beam being in the center of the wiggler are very crucial to the operation of the device.

In the next phase of testing, we will also use optical measurements; for example, cross-polarization techniques will be used on the laser beam itself, and a hot CO_2 cell will be used to differentially absorb the laser beam. We have not measured the micropulse current, but infer from the macropulse and the assumption that the micropulse width is 30 ps (measured on other accelerators) that the current is $\sim$10 A.

We haven't used optical measurements yet, so we have not observed spontaneous emission or used it to tune the beam. The tapered wiggler gives a tuning advantage because it isn't necessary to have the electron beam energy exactly right--interactions occur over a wide band. We can adjust and measure the energy rather well, however.

After the optical measurements on the amplifier experiment, we will extend the system to an oscillator with a 100-μs pulse.