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Summary

The accomplishment of a high-power, free-electron laser (FEL) is dependent on efficient transfer of electron energy to the laser electromagnetic field and efficient recovery of the remaining electron energy. Electron energy transfer to the laser field occurs in a "wiggler". In the past, wigglers with a uniform period have been used. Recently, however, it has been proposed that a tapered wiggler would enhance the efficiency of energy transfer. In the Los Alamos Scientific Laboratory (LASL) experiments, the efficiency of energy transfer in tapered wigglers will be studied and recovery of a portion of the electron energy will be investigated. First, an amplifier experiment will be performed to demonstrate efficient energy extraction and laser gain of a tapered wiggler. In the second experiment, the FEL amplifier will be converted to an oscillator by increasing the duration of the electron beam pulse and by adding laser mirrors. In the third experiment, a racetrack beam-transport system will be added to the FEL oscillator to determine the recovery efficiency of the remaining electron energy.

Introduction

The objective of LASL's FEL program is to develop high-power FELs that will operate at optical wavelengths from the near infrared to the near ultraviolet. For these wavelengths, electron beams with energies above a few tens of MeV are required. To attain a high-power FEL at these wavelengths we must provide efficient transfer of the electron energy to the laser electromagnetic field and accomplish efficient recovery of the remaining electron energy.

Energy transfer from the electron beam to the laser field occurs in a "wiggler", which consists of a spatially periodic magnetic field. In past FEL experiments, a uniform wiggler with constant period of the magnetic field provided adequate gain but low efficiency of energy transfer from the electron beam to the laser field. Recent theoretical studies indicate that a tapered wiggler, in which the period of the magnetic field varies in accordance with the decreasing electron energy, would enhance energy extraction from the electron beam and thereby improve the efficiency of energy transfer.

Modern RF electron linear accelerators appear to have adequate beam characteristics (energy, energy spread, intensity and emittance) for high-power FEL operation. These linacs also provide a possible means for efficient recovery of the energy remaining in the electron beam at the exit of the wiggler. This may be accomplished by recirculating the electron beam through the linac at the proper phase for deceleration. A racetrack beam-transport system will direct the electron beam from the linac through the wiggler and back into a portion of the linac. The electron microbunches will return to the linac with the proper phase for deceleration so that electrons may transfer a fraction of their energy directly to the RF fields in the linac. The energy remaining in the electron beam after recirculation through the linac will be dissipated in a beam dump. With a tapered wiggler and

recovery of some of the energy remaining in the electron beam after traversing the wiggler, it may be possible to attain an overall efficiency of about 25% for an infrared FEL.

A series of experiments is planned at LASL to test these concepts. First, an amplifier experiment will be performed to determine the efficiency of a tapered wiggler. In this experiment, a high-power pulse from a CO₂ laser will be injected into the wiggler along with the electron beam. The intensity of the CO₂ laser pulse will be varied to simulate operation at various FEL powers. Measurements of the decrease in electron energy and the increase in the laser field will be made and the results compared with theoretical predictions. In the second experiment, the FEL amplifier configuration will be converted to an oscillator by increasing the duration of the electron beam pulse and by adding mirrors to form the laser oscillator cavity. Again, the electron energy spectrum and laser radiation will be examined to determine the energy extraction efficiency as well as the optical quality of the laser beam. In the third experiment, a racetrack beam-transport system will be added to the FEL oscillator to provide partial recovery of the energy remaining in the electron beam after traversing the wiggler.

Amplifier Experiment

The purpose of the amplifier experiment is to determine the efficiency of tapered wigglers for weak laser fields, as well as for high signal levels in and near the saturation condition. The energy gained by the laser field and the energy extracted from the electron beam will be measured. Electrons from the gun in the injector will be accelerated in a single-tank, standing-wave accelerator. The electron beam, after focusing, will traverse a doubly achromatic and doubly focusing transport system that bends the beam by 60° and directs the electrons, after further focusing, into the wiggler. A beam scraper in the center of the second dipole magnet will remove the low-energy tail of the electron-energy spectrum. After the wiggler, the electron beam will enter a momentum spectrometer consisting of a dipole analyzing magnet and an electron beam diagnostic system. Figure 1 illustrates the arrangement of the amplifier experiment.

Accelerator

An existing accelerator and beam line are being modified to satisfy the requirements of the amplifier experiment. A comparison of the parameters of the old and new accelerators is given in Table I.

The injector pulser has been completely rebuilt to provide a 5-ns pulse rather than the previous 1-μs pulse. The new accelerator structure is nearing completion; it consists of five sections that are bolted together to form a single tank. The existing modulator and klystron system will provide RF power for the new accelerator; only minor modifications to the RF drive were required. The expected electron pulse from the new accelerator is shown schematically in Fig. 2. The dashed curve represents the envelope of the electron pulse from the injector. The solid curve represents the temporal features of the bunched electrons from the accelerator. Electrons occur in microbunches characteristic of the 1.3-GHz radio frequency and the phase-angle spread used in acceleration.

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Fig. 1. Layout of the FEL amplifier experiment.

TABLE I
ACCELERATOR SPECIFICATIONS

	Old	New
o Energy (MeV)	3-6	20
o Frequency (GHz)	1.3	1.3
o Peak micropulse current (A)	20	20
o Operation	Steady State	Stored Energy
o Energy spread due to single bunch beam loading (%)	± 1	± 1
o Energy droop per micropulse (%)	~ 0	0.1
o Emittance at 20A (mr-mm)	$\sim 10 \pi$	$\sim 2 \pi$
o Length (m)	0.5	2.5
o Pulse length (ns)	300-1000	5

Fig. 2. Electron pulse for FEL amplifier experiment.

Laser

The CO₂ laser system for the amplifier experiment is composed of a re-injection oscillator/pre-amplifier (developed in LASL's Antares laser fusion program) and a Lumonics Model 600 amplifier. The location of the laser and beam path relative to the accelerator and wiggler are shown in Fig. 1. This system is expected to produce at least 1 J in a single

1-ns pulse on a single laser line, P(20), at a repetition rate of 1/10 Hz. The output will be in a single longitudinal mode, having a nearly Gaussian spatial profile, with adequate focusability (Strehl ratio of 0.5 anticipated); Fig. 3 shows a schematic of the laser.

Five major elements can be noted: 1) the 2-m cavity oscillator containing both a high-pressure, high-gain medium and a low-pressure low-gain smoothing tube, used to select a single mode for oscillation; 2) the electro-optical switch used to pass only a short part (1-5 ns) of the oscillator's output; 3) the four-pass intermediate amplifier, which uses the same gain medium as the oscillator; 4) the combination of spatial filter, isolator, and beam expander that improves the beam's quality, protects the intermediate amplifier from reflected light, and prepares the beam for the final amplifier; and 5) the final amplifier, a commercially available three-pass Lumonics 600 amplifier.

From the final amplifier, the polarized light will be led to the wiggler by copper mirrors and a salt window. The sizes of the windows and mirrors and their spacings from the wiggler are determined by their damage thresholds.

The focal length of the final mirror is determined by the energy density desired at the focal spot and its depth of focus within the wiggler. These are chosen in a complex way to maximize the gain of the wiggler.

Fig. 3. The 10.6- μ m laser system.

Wiggler

The wiggler, which contains the spatially periodic magnetic field, is composed of 320 nearly identical SmCo_5 permanent magnets. Each magnet is 3-1/2-cm long and 1/2-cm by 1/2-cm in cross section. 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 will be about 3 kG and the aperture for the electron and laser beams will be about 9 mm. To maximize the efficiency of energy extraction from the electron beam, the period of the magnetic field will be uniformly tapered by 12%. The overall length of the wiggler will be about one meter. Magnetic shields and trim coils will be provided to assure the proper electron trajectory within the wiggler. Removable fluorescent screens, viewed by vidicons, will be provided at the entrance, center and exit of the wiggler to assist in the alignment and superposition of the electron and laser beams.

Diagnostics

An energy-spectrum measurement will be the main electron beam diagnostic. The energy spectrum will provide details of the energy extracted from the electrons in the interaction between the laser beam and the wiggler field. The spectrum will be determined in a spectrometer consisting of an analyzing magnet, converter screen and an imaging system shown schematically in Fig. 4.

Initially, a sensitive vidicon will be used to view the converter screen. With this arrangement, the spectrum of the entire 5-ns electron pulse will be obtained. If necessary or desirable, a gateable image intensifier will be added. This intensifier would be gated by a signal from the laser Pockels cell and with proper delay of the gate, the energy spectrum of the electrons arriving only during the 1-ns laser pulse would be obtained.

Laser diagnostics will be provided to measure both the laser spatial intensity distribution within the magnetic wiggler and the energy gained from the

Fig. 4. Electron-beam diagnostic for FEL amplifier experiment

electrons. The necessary optical diagnostics and their relative deployment about the magnetic wiggler are indicated schematically in Fig. 5. Because gain occurs only during the electron micropulses from the RF linac, and because the micropulses occupy only a small fraction of the RF cycle, the average laser gain is at least a factor of 30 smaller than the peak gain. To observe this small gain, we must suppress the CO_2 -laser signal after it traverses the wiggler. Various techniques, including polarizers, hot CO_2 gas absorbers and differential detection, used either singly or in combination, are being considered for the diagnostics of FEL gain.

Fig. 5. Laser diagnostics for FEL amplifier experiment.

Oscillator Experiment

The objective of the oscillator experiment is to study FEL operation with a tapered wiggler from start-up to full power. The gain of a tapered wiggler is dependent on signal level. At low level, near start-up, the gain is less than at higher levels where trapping of the electrons in the laser field occurs. The

effects of this gain variation during the laser pulse are expected to be evident in the quality of electron and laser beams at the exit of the wiggler. Changes in the electron beam emittance and energy distribution during the pulse will be of interest in the design of the eventual energy-recovery system. Characteristics of the laser beam will be of fundamental importance. These include the laser beam power during the pulse as well as the pulse energy and beam quality.

For the oscillator experiment, the configuration used in the amplifier experiment will require modification. Mirrors will be added to form a laser oscillator cavity and the electron pulse length will be extended to 100 μ s, to allow the FEL oscillations to build up from noise. To optimize the gain, improvements in the electron beam current and wiggler parameters (taper and magnetic field) will be required. To minimize the losses, the best quality optics (mirrors and windows) will be required.

Energy Recovery Experiment

The purpose of the energy recovery experiment is to determine the increase in FEL efficiency, afforded by recovery of a portion of the energy remaining in the electron beam after the wiggler. In this experiment the electron beam, after traversing the wiggler, will be directed back into a portion of the accelerator. The electron microbunches will be returned with the proper phase so that they may do work on the

linac fields and transfer a fraction of their energy to these fields. A schematic of the racetrack configuration of the accelerator and FEL for energy recovery is shown in Fig. 6.

Fig. 6. Schematic diagram of the racetrack system for recovering the energy of the electrons leaving the FEL.

Present Status

The amplifier experiment has been designed and construction of the apparatus is underway. Completion is scheduled for early 1981. Amplifier experiments will begin upon completion of the apparatus, and will continue for a number of months. Design and construction of the oscillator experiment will begin in 1981 with experiments planned for 1982. Energy recovery experiments with the racetrack configuration are presently scheduled for 1983.