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RESULTS OF THE LOS ALAMOS NATIONAL LABORATORY FREE-ELECTRON LASER EXPERIMENT*

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Abstract

An experiment to test a high-power, high-efficiency free-electron laser (FEL) is being conducted. The principal components are described and preliminary results are presented.

Introduction

A FEL is a device for converting the kinetic energy of an electron beam into light. It has the potential for high power and high efficiency and should be broadly tunable in wavelength. Such a laser was first proposed [1] and operated [2] by Madey and his coworkers. It worked at low efficiency and relatively low power because of gain-limiting saturation effects. Since these pioneering efforts, Madey has performed new measurements, [3], and three groups [4,5,6] within the United States have attempted to solve the saturation problem and to work towards higher efficiency and power. The three groups all have built amplifier (not laser) experiments in which a laser and electron beam are simultaneously focused into a complex "wiggler" magnetic structure in such a way that, during their interaction there, part of the electrons' energy is extracted and transferred to the laser beam. The amplifier configuration is simpler than that of a laser but still allows examination of the interaction of interest. Use of high-power electron and laser beams causes the interaction within in the wiggler to be strong and its effects upon the beams to be unambiguous.

Below we will discuss the major components used in the Los Alamos experiment and the special requirements demanded of them. We will then briefly present our preliminary results.

Major Components

The efficiency of energy extraction from the electron beam depends directly upon the intensity of the laser beam. It is, therefore, desirable to use a laser of the highest possible power and to focus it into the interaction region in the optimum manner, holding aberrations in the beam close to the minimum possible. To accomplish this, we employ a low-power, pulsed monochromatic CO_2 laser with seven amplifying stages carefully controlled so that the resulting 1- to 2-GW beam is focusable to a spot size close to the diffraction limit.

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The optical gain realized by our FEL amplifier depends linearly upon the electron beam current that can be focused into the interaction region and that also fits inside the cone of laser light. These requirements for high current and excellent focusability can presently be met only by linear accelerators of excellent design that operate at energies above ~20 MeV. We have built such an accelerator. It delivers a pulsed beam of 1.0-A average current with adequate focusability, that is, emittance less than 2π mm-mrad, and energy spread of less than ±1%.

Both beams use complex transport systems whose primary purpose is to deliver the electrons to the wiggler interaction region with the correct focus and cone angles but otherwise unmodified in quality. In addition, the electron transport system includes a set of slits that allows straggling electrons to be intercepted, further reducing the energy spread to ±1/4%.

The wiggler is an assembly of several hundred permanent magnets designed to force the electron beam to undergo sizable periodic transverse oscillations. The laser light can interact with the electrons only through their transverse motion and only if the period of the wiggler, the wavelength of the laser, and the energy of the electrons are in "resonance." Strong magnetic fields are needed to optimize the interaction. The length of the wiggler is a crucial parameter that should be large to increase the length of time the beams interact but that should be small to allow a sharp focus of the laser beam. There is an optimum length that, under our conditions, is about 1 m.

With major components that perform well, the most crucial feature of the experiment is the spatial and temporal alignment of the two beams with each other and with the geometric and magnetic axes of the wiggler. We have spent considerable effort to make these alignment procedures convenient and precise. The temporal widths of the two pulsed beams are 5 ns (FWHM), that is, about 2 m long. Timing adjustments to achieve good longitudinal overlap are accomplished by moving a set of mirrors to vary the path of the laser beam until the optimum pulse overlap is obtained. Transverse beam alignments within the wiggler must be accurate to within 0.1 to 0.2 mm and are much more difficult to accomplish. This is largely due to the difficulty in passing the electron beam through the wiggler in a line that is straight to within ~0.1 mm. Forces causing significant curvature include the following: forces from the earth's or other stray fields, weak forces in the body of the wiggler caused by nonuniform magnets there, unbalanced magnetic forces caused by the wiggler's magnets at its entrance, and forces caused by the gradients of the wiggler's fields if the electron beam is aimed off-axis in the wiggler.

We have systematically reduced these forces as follows: forces from stray fields have been reduced by surrounding the wiggler with an iron shield. The wiggler has been assembled from sets of magnets matched in properties so as to cause only insignificant unbalanced forces in the body of the wiggler. The entrance and exit regions have been designed so that forces introduce no gross curvature to the electron beam. Adjustable magnets in these regions provide the opportunity for fine tuning. To achieve this tuning we have threaded a fine wire through the wiggler and have supplied it with a current calculated to force it into exactly the same path as the electron beam. This wire has been carefully examined and the movable magnets have been set in their optimum positions. The overall displacement of the wire from a straight line then has been found to be less than 0.1 mm when the wire is centered in the wiggler's aperture, that is, on its geometric axis. In a similar way, we have shown that if the wire (or electron beam) is displaced from this axis it will be bent by forces generated by field gradients, forcing it to oscillate around the axis with a wavelength approximately twice the wiggler's length. This oscillation must be made very small in amplitude to provide good overlap of the electron and laser beams.

To accomplish this crucial alignment step, we have used a low-power HeNe laser beam that is carefully aligned with the CO_2 laser beam. The HeNe beam is directed along the wiggler axis and viewed on a screen at the far side. At each end of the wiggler, movable cross hairs have been accurately positioned on the axis. The HeNe laser is then aimed through the cross hairs so that their images are centered on the viewing screen.

Within the wiggler, the HeNe beam is viewed on three fluorescent screens (entrance, middle, exit) that are movable onto the axis of the wiggler. The HeNe laser beam is intercepted by these screens and presents three targets for the electron beam that are at the same time exactly on the axis of the wiggler and represent the path followed by the CO_2 laser beam. Several sets of electron beam-steering coils are used to force the electron beam to hit each of its targets. This procedure has proved to be very convenient, but it assures only that the electron beam passes through three points that are on the wiggler's axis and common with the CO_2 laser beam. Any remnant curvature between these points can be removed by ten sets of magnetic "trim" coils mounted around the wiggler.

Results

Energy extraction measurements have been performed on the electron beams, and optical gain measurements are in progress. The optical measurements are complex, and the theory behind them is described elsewhere. [7] The electron beam is examined in a simple manner using a magnetic spectrometer, a fluorescent screen, and a TV camera. The effect of the interaction on the electron beam is to increase its energy spread from the original value of less than 1% to more than 10% and to shift its average value up or down a few per cent. We have already observed both of these effects and are now engrossed in detailed examinations of the rich structure revealed. Additional, more recent results will be presented at the meeting.

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