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TITLE HIGH-EFFICIENCY FREE-ELECTRON-LASER EXPERIMENTS

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High-efficiency free-electron-laser experiments

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Abstract

Experiments with a tapered-wiggler free-electron laser have demonstrated extraction of about 3% of the energy from the electron beam and measured the corresponding optical emission. These results are in excellent agreement with theory and represent an order-of-magnitude improvement over all previous results.

Tapered-wiggler amplifier

In the pioneering free-electron-laser experiments of Madey and coworkers,[1] a wiggler magnet having a constant period was used. In these and subsequent experiments, the efficiency for extracting energy from the electron beam and converting it to optical radiation was observed to be about 0.2%, in satisfactory agreement with theory. The efficiency observed in these experiments was low because as energy was extracted from the electrons and converted to optical radiation (corresponding to laser gain), the electrons slowed down and their oscillations in the wiggler field were no longer resonant with the oscillations of the laser field. However, theoretical calculations indicated that this effect could be compensated by reducing the magnetic-field period toward the downstream end of the wiggler and operating at very high optical intensity. In this way the efficiency could be improved by an order of magnitude.[2]

To test this prediction, the experiment shown in Fig. 1 was carried out. The electron beam had an average current of 250 mA at an energy of 20 MeV ± 0.5%. The CO_2 laser had a peak power of about 1 GW, single-mode, in a 5-ns pulse. The permanent-magnet wiggler was about 1 m long, with a peak field of 0.3 T. The period was tapered 12%, from 2.7 cm at the entrance to 2.4 cm at the exit.

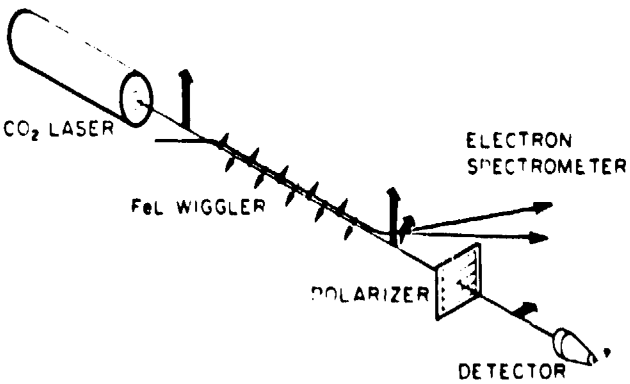

Fig. 1. Schematic diagram of the free-electron-laser experiment.

Electron-beam and optical results

To determine the energy extracted from the electron beam, the electron energy spectrum of the beam emerging from the wiggler was recorded with an electron spectrometer. A typical spectrum is compared with theory in Fig. 2. At sufficiently high optical-field strength, the experimental results show the two large peaks characteristic of tapered wigglers. The low-energy peak contains those electrons that were decelerated resonantly as the wiggler period decreased. The peak near the original energy contains those electrons that entered the wiggler at the wrong phase of the optical field and were, in fact, slightly accelerated. As the input laser power is decreased, the low-energy peak gets smaller, disappearing altogether below about 0.2 GW. The average extraction efficiency (average energy extracted from electrons as optical radiation ÷ initial electron energy) is shown in Fig. 3. The unusual inflection point in what is effectively a gain-saturation curve is due to the threshold effect for "trapping" electrons of the resonant energy and decelerating them with the wiggler taper.

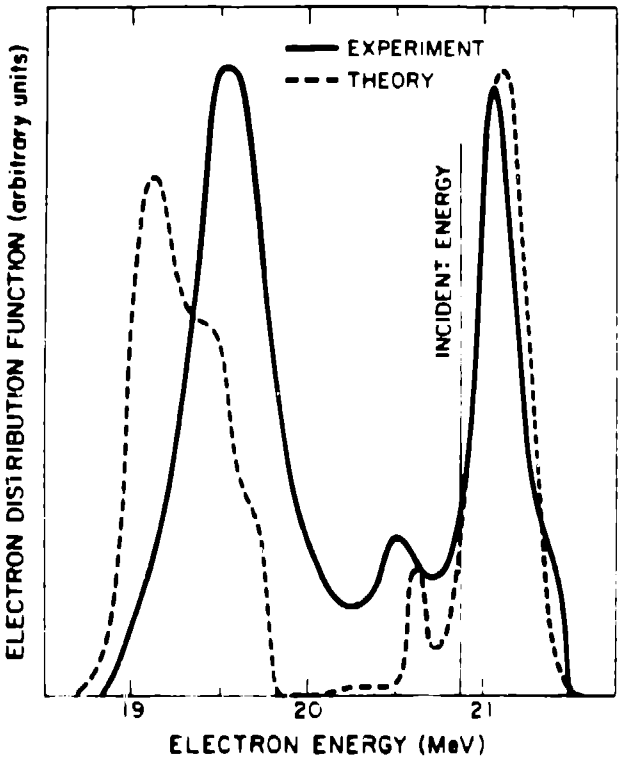

Fig. 2. Electron energy spectrum showing deceleration of electrons in tapered wiggler.

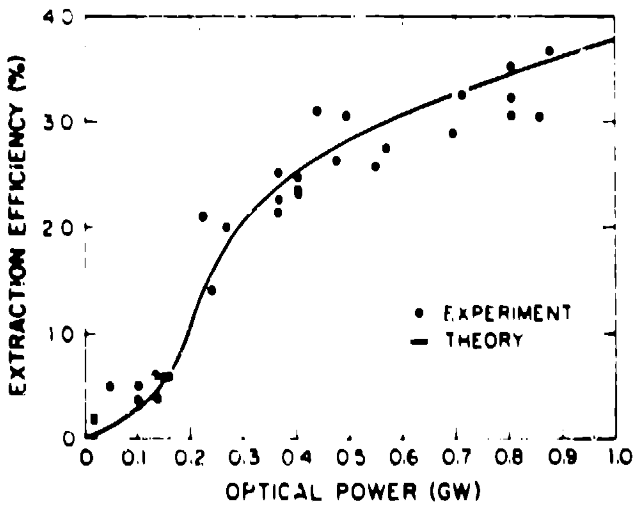

Fig. 3. Average extraction efficiency of tapered wiggler.

Because of the low (5-A) peak current of the electron beam used in these experiments, the peak laser gain was rather small, about 1%. Moreover, because the current from rf linacs of the type used in this experiment appears in short (~30-ps) pulses repeated at 1.3 GHz, the free-electron-laser gain corresponded to less than 0.1% when averaged over the CO_2 laser pulse. However, it was possible to observe this gain by suppressing the CO_2 laser pulse as shown in Fig. 1.[1] Because the CO_2-laser radiation is polarized vertically, it could be largely removed by means of a Brewster-angle polarizer oriented horizontally.[4] Because the wiggler was oriented 22.5° from horizontal, the optical radiation from the free-electron laser could pass through the polarizer with only modest attenuation. In addition, it was possible in the experiments to pick off the laser signal entering the free-electron laser and subtract it from the output signal. This improved the signal-to-noise ratio by about an order of magnitude, and made it possible to measure the gain with about a factor-of-two accuracy. To this accuracy, the value of the gain and the dependence of the gain on electron energy agree well with the electron-energy measurements. To remove the remaining CO_2-laser radiation, the beam was passed through a cell containing hot CO_2, where it was absorbed. The free-electron-laser radiation, on the other hand, was broadband (corresponding to ~30-ps pulses), and passed through the hot CO_2 with attenuation only near the band center.

In this way it was possible to remove the CO_2 radiation completely and to observe only the free-electron-laser radiation. Because this technique removed the electron radiation at precisely the wavelength of the incident CO_2 laser, most of the information about laser gain was lost. However, the signal-to-noise ratio was considerably enhanced, and the (relatively clean) data are still rich in free-electron laser physics. For example, when the electron beam interacts with the optical field, the electrons become "bunched" (density modulated) at the optical frequency and harmonics thereof. This causes the electrons to radiate coherently, instead of randomly, and enhances the emission by many orders of magnitude. In fact, without the CO_2 laser to bunch the electrons, the spontaneous radiation (commonly referred to as synchrotron radiation) was too small to observe in this experiment. When the electrons were bunched by the CO_2 laser, the coherent emission was observed to be quadratic in the electron-beam current, as shown in Fig. 4. This was expected theoretically, and contrasts with the linear dependence of spontaneous emission. Using band-pass filters, it was possible to observe harmonics of the 10.6-μm radiation generated by the electrons in the wiggler. These are also orders of magnitude stronger when the electrons are bunched by the CO_2 laser than when they are not.

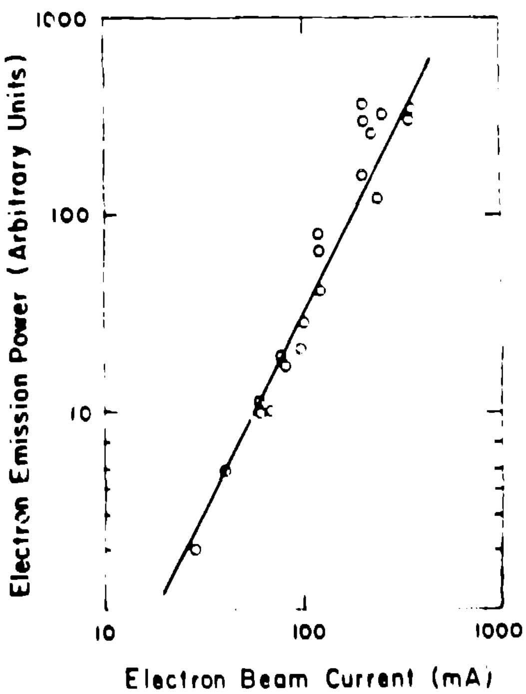

Fig. 4. Quadratic dependence of coherent electron emission upon electron beam current.

Acknowledgment

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References

1. Madey, J. M. J., et al., Phys. Rev. Lett. 36, 717 (1976) and Phys. Rev. Lett. 38, 892 (1977).
2. Kroll, N. M., et al., IEEE J. Quantum Electron. QE-17, 1436 (1981).
3. Newnam, B. E., et al., IEEE J. Quantum Electron. QE-17, 1480 (1981).
4. Renieri, A. and Marino, A., private communication.