Laser physics

Advances in free-electron lasers

from M.W. Poole

FREE-electron laser (FEL) research is continuing to break new ground; experimental configurations already exist and further modifications are being planned. The potential rewards for the successful development of such a coherent radiation source are very great, whether for radar and telecommunications, fusion energy research, photochemical processing (such as isotope separation) or fundamental research in topics such as non-linear spectroscopy. Ambitious plans are being laid for a 500-Å device and this technology is probably at least as promising as any other for the ultimate goal of an X-ray laser.

The recent announcement that yet another group has joined the increasing band of successful FEL experimenters has significance beyond its initial results. The massive resources of the Lawrence Livermore National Laboratory in California, aided by scientists from Berkeley, have now been brought to bear on the development of this exciting new technology. It seems inevitable that they and their major rivals at the Los Alamos National Laboratory could dominate future progress. Their latest results have demonstrated both exceptionally high gain (~3,000) and attractive energy-transfer efficiency (~ 5 per cent) for millimetre waves and the race is now on to extend this to shorter wavelengths.

So far there have been two very distinct FEL communities: those using electron accelerators with beam-current densities sufficiently low that energy transfer is dominated by a single-particle (Compton) interaction, and those with access to intense beams where collective (or Raman) effects become important. The former groups have led the way since the first FEL demonstration by John Madey's team at Stanford University in 1976; important developments were summarized last year in these columns (Pidgeon, C.R. *Nature News and Views* **308,** 772; 1984) which noted that four oscillators had operated over the range 0.6–10.6 μm, and since then a fifth device has extended this to 400 μm at the University of California, Santa Barbara. In fact the intense-beam workers could claim a better pedigree that extends back to the ubitron — an early centimetre wave device — and the cyclotron maser that was the centre of attention at the Naval Research Laboratory (NRL) in Washington at the time of the Madey experiments. It was the chance detection of submillimetre output from a cyclotron maser, caused by interaction of the electron beam with its 20-mm generated radiation reflected off a window, that first initiated a long programme of FEL work at NRL over the past decade, culminating in the reporting of huge gains (120 dB m^{-1}) at 35 GHz (Gold, S.H. *et al. Phys. Rev. Lett.* **52,** 1218; 1984). However, all intense-beam FEL experiments until recently have found it necessary to use an additional solenoidal field to focus the large electron beams along the length of the interaction region; such a field can contribute strong cyclotron emission that has led to ambiguities in the interpretation of the output from these devices.

What the Livermore/Berkeley collaboration has been able to announce (Orzechowski, T.J. *et al. Phys. Rev. Lett.* **54,** 889; 1985) is a 35 GHz amplifier with high gain and efficiency that exhibits remarkably good agreement with theoretical expectations over a very wide range of signal levels. The experiment was started with the aim of extending collective FEL outputs down to wavelengths similar to those of the Compton devices; this would, for example, allow immediate application of the FEL to plasma heating of fusion mirror machines. Since then, President Reagan's Strategic Defence Initiative has injected financial adrenalin into FEL activities and high power at visible wavelengths is now the declared objective.

The new amplifier, ELF (electron laser facility), is based on the Livermore experimental test accelerator, a linear induction device that can deliver beams of up to 10 kA at 4.5 MeV, although only for short pulses of 30 ns at about 1 Hz. In fact the experiments have been carried out at slightly lower energy and with the electron current heavily collimated to about 500 A to reduce the beam cross-section in the interaction region. A 3-m-long pulsed electromagnet of 98-mm periodicity induces the required energy transfer between the electrons and an accompanying wave supported by a thin stainless steel waveguide. Additional quadrupoles assist the electron beam focusing but there is no axial field.

First, the team explored the 'superradiant mode' (laser terminology for amplification from an initial noise signal, in this case the spontaneous synchrotron radiation emitted by a relativistic electron in any magnetic field) and achieved an amplification of 13.4 dB m^{-1} down the periodic magnet. Next, a 60-kW pulse from a magnetron was injected into the interaction region and emerged as a very impressive 80 MW peak output power. In fact the FEL goes into saturation after about 2.2 m and thereafter its power oscillates along the length of the interaction.

A crucial feature of the Livermore approach has been to develop theoretical models in parallel with the experimentation; this has involved extensive computer simulations to include such three-dimensional behaviour as the off-axis electron trajectories and the transverse electromagnetic mode characteristics. Their reward has been an encouraging agreement of predicted and observed FEL behaviour that sets a standard for others to emulate. In the near future the group intends to investigate enhanced efficiency to push the saturated power to still higher levels. At present the efficiency limit is set by the loss of energy from the electron beam detuning the resonant interaction between the charged particles and the wave. To overcome this the Livermore periodic magnet has 15 separate power supplies that can progressively lower the field strength along the interaction region to match the reducing electron energy, thus maintaining the resonance condition. Eventually, Livermore hopes to switch the experiment to an even more powerful induction linac, the advanced test accelerator; this might then permit the same extraordinary performance to be achieved in the infrared region.

Meanwhile, the single-particle FEL community has not been idle. A revolutionary new oscillator in the far infrared has been produced by Elias, one of Madey's original team at Santa Barbara. This takes a giant step towards extremely high average power FEL operation, because the accelerator is a 3 MV Van de Graaff facility that can in principle provide continuous wave electron beams rather than the low-duty cycles typical of most other accelerators. To achieve this would require almost all of the electron beam to be recovered after passing through the FEL, returning it to the high-voltage terminal by a suitable deceleration and collection process; this group has already demonstrated that this can be done. A laser with multikilowatt average power output cannot be far away.

The United Kingdom Heriot Watt–Glasgow–Daresbury collaborative FEL project is now fully assembled at the Kelvin Laboratory, East Kilbride. Spontaneous emission has been detected at both infrared and visable wavelengths, the latter making use of higher harmonic emission generated in the powerful periodic magnet system. Laser oscillation above threshold at 10.6 μm is now being attempted and it is also hoped to demonstrate a wide tuning range. Subsequently to this it is intended to study FEL action on a higher harmonic, a topic of great current interest as it promises to extend FEL operation down to wavelengths previously considered unattainable on such medium-energy (10 – 100 MeV) accelerators. Apart from this project, sadly almost all funded FEL research is now concentrated in the United States. □

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