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Induction linac-driven free-electron lasers: status and future prospects*

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The free-electron laser (FEL) directly converts the energy of an electron beam to electromagnetic radiation. The properties of the radiation are intimately related to the characteristics of the accelerator that produces the electron beam. A radio-frequency (rf) accelerator produces a high-frequency (1-100 MHz) burst of short electron pulses (10-30 ps) at relatively low peak current. The burst typically lasts tens of microseconds. The low peak current (0.1-1 kA) implies that an FEL driven by an rf accelerator must operate with low single-pass optical gain and produce radiation pulses of relatively low peak power. By contrast, an induction linac (IL) accelerator produces an electron beam consisting of longer (50 ns), higher current (1-10 kA) pulses. These pulses can be produced in a variety of pulse formats, including a series of high repetition rate bursts or a cw pulse train. For equal average powers, the induction linac operates at a lower duty factor than the RF accelerator.

The high repetition rate and low single-pass gain inherent in an rf-driven FEL dictate that the laser system be configured as an oscillator. This allows the laser's electric field to build up over many passes around a high Q cavity. By way of contrast, the high-current capability of the IL system permits high single-pass optical gain, but the relatively low duty factor precludes oscillator operation; the pulses are neither long enough nor often enough to permit a field to accumulate in a cavity. The IL is thus configured as a MOPA (master oscillator/power amplifier) with a conventional laser serving as the MO. The following discussion will concentrate on the status of IL-driven FEL research at LLNL and give a description of several applications for the high-peak-power radiation produced by an induction linac FEL.

As discussed above, the IL-driven FEL must be configured as a power amplifier. In order for an amplifier to be useful, it must be capable of operating with high gain and high overall efficiency. The Electron Laser Facility (ELF) experiments at LLNL were specifically designed to demonstrate these two prerequisites. The experiments were conducted at 34.6 GHz in order to take advantage of the existing Experimental Test Accelerator (ETA), which operated at 4.5 MeV. These experiments demonstrated an extraction efficiency of more than 35% and an overall gain of 45 dB. In addition, as shown in Fig. 1, the results were well modeled by theoretical predictions.

Figure 1. Theoretical prediction and experimental results for 34.6-GHz experiments.

The ELF experiments were conducted at microwave wavelengths so that existing equipment could be used. In extending these results to optical wavelengths, not only are higher energy and higher quality electron beams required, but a new phenomenon, optical guiding, must be relied upon to maintain a close overlap of the electron beam and the optical beam. A metallic waveguide served this function in the ELF experiments, but the electron beam itself must confine the radiation field in an FEL amplifier operating at optical

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wavelengths. Should this not be possible, the interaction length and therefore overall efficiency of the amplifier will be limited by diffraction of the light beam.

To investigate FEL amplifier operation at optical wavelengths, we have designed and constructed an experimental FEL matched to the characteristics of the Advanced Test Accelerator (ATA), a 50 MeV induction linac located at LLNL's Site 300. This amplifier, named PALADIN, has been designed to operate at 10.6 μm for three reasons:

- 1) This is an appropriate wavelength for an amplifier driven by a 50-MeV electron beam;
- 2) A conventional laser (carbon dioxide) is available as the master oscillator;
- 3) The optical physics can be addressed at this wavelength.

Over the next several years, we hope to use PALADIN to answer some of the unresolved physics and technology issues relevant to future generations of shorter wavelength FELs. The key goal of PALADIN is to benchmark optical FEL performance against our numerical models of amplifier performance.

PALADIN will address the short wavelength FEL physics issues, but a new generation of Induction linacs is required to operate a visible wavelength FEL amplifier. A short section of an IL accelerator (ETA II) is now being assembled at LLNL. ETA II will incorporate much of the accelerator technology that has been developed since ATA was built. Magnetic switches, new accelerator cells, and advanced focusing coils are among some of the advances being tested on ETA II. One of the ETA II 10-cell assemblies (each cell results in 125 keV of acceleration) is illustrated in Fig. 2.

Figure 2. ETA-II 10-cell assembly.

In addition to serving as a test bed for integrating this new technology, ETA II will permit us to study the transport of high-brightness electron beams. It is essential that the acceleration process not degrade the electron beam properties: beam quality preservation is most difficult in the low-energy section of the accelerator. Several different transport strategies will be tested on ETA II and compared with the predictions of our numerical models of electron beam transport and acceleration.

Supporting technologies, such as wiggler, cathode, and optics development, are also being actively pursued at LLNL. These technologies are essential if FELs are to move out of the laboratory.

There are many applications of FEL amplifier technology. Three in particular are being examined at LLNL. The first application is the use of the FEL system as a laser driver for inertial confinement fusion (ICF) systems. The FEL could, in principle, achieve high pulse energy at the high efficiencies required for ICF, a particularly stressing application. A second application, providing a high-power microwave source to heat magnetically confined plasmas, was one of the motivations for the ELF experiment. This application looks particularly promising—we hope to conduct experiments on a Tokamak at LLNL in the future. The third application, using FELs to power high gradient accelerators, also looks very attractive. The high frequencies and high peak power achievable with an FEL should enable one to build a high-energy accelerator operating at several hundred MeV/m. We have conducted some initial experiments on high-frequency structures (shown in Fig. 3) which show that such high gradients can be achieved in simple waveguides.

Figure 3. High-frequency experimental structure.

Lawrence Livermore National Laboratory is currently conducting a broad-based free-electron laser science and technology program with applications related to new energy sources and new accelerators for high-energy physics research.

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