Experiments with the Free-Electron Laser

We have been experimenting with a concept for a free-electron laser that draws energy from an intense beam of high-energy electrons to amplify coherent microwaves and laser light.

Free-electron lasers (FELs), which use the kinetic energy of an electron beam to generate or to amplify a beam of coherent light, can be configured as either oscillators or amplifiers. In the oscillator design, the wiggler field is inside a resonant cavity. When the beam passes through the wiggler and cavity, the radiation, which builds up from noise inherent in the system, is confined within the cavity to interact with and modulate the electron beam. The rest is allowed to escape to become the usable laser beam.

In the amplifier configuration, an electron beam passing through a wiggler (a series of magnetic fields of alternating polarities) is simultaneously exposed to laser light of the desired wavelength. Under the influence of the laser light, the electrons tend to lock in and emit light in the same phase. The coherent signal grows in intensity as it passes through the amplifier.

For a given wiggler geometry (with the segments of the magnetic field as close together as practical) the frequency of the emitted light is inversely proportional to the square of the energy of the electron beam. Our Experimental Test Accelerator (ETA), with its 4.5-MeV electron beam, is suitable for FEL experiments in the millimetre (microwave) regime, whereas the operating regime for FEL experiments on our Advanced Test Accelerator (ATA), with its 50-MeV electron beam, is at micrometre (infrared) wavelengths.

Although experiments with both beams are based on the same design principles, there are fundamental differences in the two sets of experiments. The wavelength in the ETA experiments is 8.4 mm, relatively long with respect to the diameter of the electron beam (the region where the interaction with the radiation’s field takes place). This means that we must confine the microwave radiation and channel it through a conducting tube (a waveguide) to keep it from dissipating by diffraction. In the ATA experiments, by contrast, the operating wavelength (10.6 μm) is much smaller than the beam diameter so the radiation propagates like light through a refractive laser medium.

The two experiments also use different techniques to control horizontal spreading of the electron beam in the wiggler field, but in both cases the fields of the wiggler magnets focus the beam in the vertical direction. In our Electron Laser Facility (ELF), in which we perform experiments with the ETA, there is an external set of quadrupoles for horizontal focusing (see Fig. 1 for a schematic layout of the ELF). In our Paladin experimental facility, associated with the ATA, the
horizontal focusing comes from horizontal gradients established by the shaped poles in the wiggler magnet.

The Electron Laser Facility

The ELF, a free-electron laser operating in the microwave regime, is designed to test our physics models that predict high-gain and high-efficiency FEL operation at visible wavelengths. To do this, ELF must have well-defined initial conditions for both the electron beam and the radiation field so we can make meaningful comparisons between the theoretical predictions and the experimental results. In addition, we made ELF flexible enough that we can study the FEL parameter space and various operating modes.

As part of this built-in flexibility, we sized our wiggler to produce FEL resonance with 3.5-MeV electrons instead of the full 4.5 MeV of which the ETA is capable and arranged to use only part of the 4 kA of beam current available. This makes it possible to vary both energy and beam current on both sides of the optimum. Furthermore, although the accelerator can operate at one pulse per second, we run our FEL experiments at a reduced rate of one pulse every two seconds because that is the repetition rate of the wiggler's electromagnets.

The first step in tailoring the ETA beam for ELF is to pass the beam through an emittance selector (see Fig. 1), a filter that discards about 50% of the beam for being outside the desired beam radius or for having too much transverse momentum. Chromatic transport also shortens the output pulse, because the leading and trailing edges of the beam pulse are at a slightly different energy from that of the central portion.

To make the electron beam and the input microwave signal pass through the wiggler together, we put a fine-mesh screen ahead of the wiggler at 45° to the axis. This screen has a negligible effect on the electron beam, but it reflects 34.6-GHz microwaves efficiently into the rectangular waveguide that keeps them concentrated in the interaction region of the wiggler. We made the waveguide of thin stainless steel to make it easy for the wiggler's pulsed magnetic fields to penetrate.

The wiggler magnet in the ELF consists of a 2.94-m array of rectangular solenoids. Disregarding end effects, which must be treated separately, it takes four solenoids for

Fig. 1

Schematic diagram illustrating the layout of the Electron Laser Facility (Elf) on the Experimental Test Accelerator (ETA). High-energy electrons from the ETA pass first through an emittance selector that transmits only those electrons whose radius and transverse momentum are less than a chosen value. Electron lenses focus the beam through a fine metal screen and into the entrance of the wiggler, while a microwave signal reflects off the same screen and propagates together with the electron beam through the wiggler. Then a magnet diverts the remaining electron beam, and the amplified microwave output goes into a diagnostic chamber for measurement.
each of the 30 wiggler periods. We use the first and last of these periods to match the electron beam to the wiggler's equilibrium orbit. The maximum wiggler field that we can generate with this magnet is 0.5 T. To allow some flexibility in tuning the wiggler field, we chose to have the resonance occur at about 0.4 T; this dictates the resonant beam energy of 3.5 MeV. We also provided a separate power supply for each pair of periods, so that we can control not only the amplitude of the wiggler field but also its profile along the axis.

Transporting the electron beam through the interaction region requires both vertical and horizontal focusing, the former from axial components of the wiggler field and the latter from continuous horizontal focusing quadrupoles. The vertical focusing is about four times stronger than the horizontal focusing, which gives the beam an elliptical cross section.

Figure 2 shows one of the three 1-m segments of the wiggler magnet, the most visible structure of which is the external quadrupole array for horizontal focusing. Inside these magnets are the forms that support the solenoids that produce the wiggler field. The interaction region runs down the center of this complex magnet.

Beyond the interaction region, we bend the electron beam to one side with a magnetic field and guide the powerful amplified microwave signal into an evacuated tank 1.2 m in diameter, 2.4 m long, and lined with microwave-absorbing material. In this tank the microwaves spread out rapidly and are absorbed by the liner with virtually no reflection. At the far end of the tank, antennas sample a small fraction of the radiation (<0.01%) at various spatial locations so that less than 0.01% of the input signal reaches the far end of the tank. This lets us measure a known fraction of the signal without danger to the sensitive diagnostic instruments.

In addition to measuring the FEL amplifier's gain (the ratio of power out to power in) as a function of the wiggler's length, field strength, and field profile, we are interested in also...
Fig. 3
A typical ELF detuning curve showing the variation in microwave output as a function of the field strength of the wiggler magnets. The peak at 0.378 T indicates the resonant magnetic field for an 800-A beam of 3.5-MeV electrons with a brightness of $2 \times 10^4 \text{A/(cm}\cdot\text{rad})^2$.

Fig. 4
Microwave output power from the ELF as a function of distance along a wiggler with a uniform magnetic field, comparing theory (curve) with experimental points. The power rises exponentially (straight upslope) to a maximum, then decreases and begins to oscillate about a level at a fraction of its peak value no matter how much longer we make the wiggler.

measuring the spatial mode purity of the amplified signal and the frequency harmonics associated with the FEL. We can also measure the evolution of the phase of the radiation along the interaction region. Finally, we can study how varying such parameters as beam current and input power affects FEL performance.

Figure 3 is a typical result from a detuning experiment in which we varied the field in the wiggler's first segment to locate the resonant value of the magnetic field and kept the field in the other two segments at a very low value. With a 3.5-MeV, 800-A beam whose brightness is $2 \times 10^4 \text{A/(cm}\cdot\text{rad})^2$, the detuning curve has a full width at half maximum of 10% and a peak at a magnetic field of 0.378 T.

To study the FEL amplifier's gain as a function of length in its fundamental design mode (uniform magnetic field), we turn up the field in subsequent two-period segments to the resonance field strength (0.378 T). At first the signal grows rapidly, increasing about two thousandfold in a 1-m section, but at 180 MW it saturates, dropping down to oscillate about a lower value (Fig. 4). At the maximum power in this mode, about 7% of the electron beam's energy has been converted into microwaves.

It is clear that just making the wiggler longer will not increase the output power, which would simply continue the oscillation shown in Fig. 4. However, we can increase the output power by tuning the magnetic field of each two-period segment in turn for maximum output power, starting just before the saturation point. With the experimental data presented in Fig. 5a, we reach a power of about 1000 MW and convert 34% of the electron-beam energy to microwaves instead of only 7%. Other experiments have yielded efficiencies as high as 45% with peak output power of 1.7 GW. Figure 5b shows the agreement between the theoretical and the experimentally determined tapered-magnetic-field profile required to achieve this increased output.
Paladin Experiment
Our ELF experiments showed that we could achieve high-power microwave output and high conversion efficiency in a single-pass FEL amplifier with the use of a tapered-wiggler field profile. The goal is to do the same to produce visible light. In the optical regime, however, waveguides and focusing quadrupoles do not work, and the requirements for electron beam quality are more stringent. Before we can design such a high-power optical FEL, therefore, we need to demonstrate optical guiding of the electromagnetic wave and horizontal focusing of the electron beam without quadrupoles.

Paladin (Fig. 6), our experiment to do this, will use the 50-MeV beam from our ATA and operate just above the visible portion of the spectrum in the infrared at a wavelength of 10.6 μm. As in ELF, the electron beam first goes through a filter that collimates it and accepts only electrons with precisely the right emittance. The beam then goes through a set of bending magnets that shift it onto a parallel beam line, giving the carbon-dioxide laser that provides the infrared light to be amplified a clear line of sight into and through the wiggler. Table 1 lists the wiggler parameters for the Paladin experiments.

Figure 7 is a cut-away view of a one-period section of the Paladin wiggler. Unlike the ELF wiggler, which is composed of pulsed air-core solenoids, the Paladin wiggler uses iron-core electromagnets powered by direct current. To achieve the needed magnetic flux of 0.27 T in the gap without saturating the iron cores, we "biased" the poles with permanent magnets that drive a reverse flux through the iron and shift the saturation point of the hysteresis curve to a higher field.

A readily apparent feature of the pole tips is their curvature; the gap increases still more to about 1 GW. (b) Magnetic field profile required to produce the maximum output power, showing the good agreement between experiment (black) and theory (blue).

Table 1  Wiggler parameters for the Paladin experiment.

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<tr>
<th>Wiggler parameter</th>
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<td>Magnet period</td>
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<td>Pole-to-pole gap</td>
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<td>Length</td>
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Fig. 5
The effect of tapering the wiggler's magnetic field. (a) Microwave output power from the ELF as a function of distance along a wiggler with an appropriately tapered magnetic field. Instead of saturating, the power increases still more to about 1 GW. (b) Magnetic field profile required to produce the maximum output power, showing the good agreement between experiment (black) and theory (blue).
Fig. 6
Diagram of the Paladin experiment on the 50-MeV Advanced Test Accelerator. As before, the high-energy electrons pass first through an emittance selector. In this case, however, they then go through a double-bend deflector that lines them up with a wiggler aligned with the beam from a carbon-dioxide laser.

Fig. 7
Cut-away drawing showing one period (a pair of magnets of opposing polarities) of the Paladin wiggler magnet. Unlike the ELF wiggler magnets, which are air-core solenoids, the magnets in the Paladin wiggler have iron cores and permanent magnets to increase the saturation field. The concave pole pieces make the magnetic field stronger at the edges of the beam than in the center, providing a horizontal focusing force on the electron beam to match the vertical focusing supplied by the alternating fields of the wiggler magnets.

between them is largest near the axis and diminishes on either side, producing the gradient that focuses the electron beam horizontally. We shaped the poles to make the horizontal focusing match the vertical focusing provided by the wiggler fields, producing an electron beam with a circular cross section.

The Paladin wiggler will eventually have five sections, each 5 m long. We will conduct initial experiments with one of these sections to test electron-beam transport, measure the detuning curve (amplification versus wiggler field strength), and explore the region of exponential gain (the steep up-slope in power versus length illustrated in Fig. 4). Figure 8 shows an assembled 5-m section of the Paladin wiggler.

As we have mentioned earlier, one of the key purposes of the Paladin experiment is to test mechanisms for optical guiding. Instead of being confined in a waveguide, as in ELF, the radiation in an optical FEL propagates in the transverse electromagnetic mode known as TEM\(_{00}\) (that is, the electric and magnetic fields are always at right angles to each other and to the direction of propagation) and is diffraction limited. With the input laser focused near the entrance of the wiggler to an 8-mm-diameter spot (to match the electron-beam size in the wiggler), a freely propagating laser beam (without the electron beam) would diffract with a Rayleigh range of about 5 m. In the exponential-gain region, each point in the interaction region becomes a new source of well-directed radiation in the TEM\(_{00}\) mode, and diffraction "starts over" for this new radiation. Since the gain is exponential, most of the new radiation originates near the end of the region and largely escapes loss by diffraction. The result of this "gain guiding," in which the properties of the amplifying medium determine the laser-beam profile, is, in effect, to reduce greatly the rate of diffraction.

Beyond saturation, gain guiding is no longer effective. However, theory
suggests that the wiggling electron beam itself should then channel the coherent radiation in the TEM\(_{00}\) mode in much the same way as does an optical fiber. Paladin will be the first experiment to test this effect.

In addition to studying electron beam transport, mode propagation, harmonic generation, and the growth of sidebands, as in ELF, Paladin will enable us to study additional FEL phenomena, such as mode cleanup. In theory, if a laser were to inject light vibrating in a mixture of modes into the wiggler, all the undesirable modes would diffract away and only the TEM\(_{00}\) mode should be amplified. This effect, if it can be demonstrated, would greatly simplify the laser's specifications.

**Summary**

We have demonstrated a free-electron laser, a device that converts the kinetic energy of a beam of relativistic (high energy) electrons oscillating in a periodic magnetic field (a wiggler) into coherent electromagnetic radiation (microwaves). We are also building the equipment to do the same at the (shorter) wavelengths of infrared light. The FELs we are working with are not self excited; each amplifies coherent radiation that is injected into it.

Our FEL experiments in the microwave regime, conducted at the ELF, used 30-ns bursts of 3.5-MeV electrons from our ETA and produced up to 1-GW pulses of 34.6-GHz microwaves with a conversion efficiency (electron beam energy into microwave energy) of 34%. With this device we were able to investigate electron beam transport through the wiggler, vertical and horizontal focusing of the electron beam, and amplifier gain as a function of wiggler length and the strength and longitudinal distribution of the magnetic field. We also investigated the spatial mode purity of the amplified signal as well as the harmonic frequencies associated with the FEL.

In the ELF experiments, we were able to confine the microwaves (so as to promote interaction with the electron beam) with a waveguide made of thin stainless steel to admit the pulsed magnetic fields of the wiggler, but it is not feasible to construct a waveguide tuned to optical wavelengths. To extend the FEL concept to amplify light signals, we need to demonstrate optical guiding mechanisms that will operate in this environment.

We have recently started an FEL experiment to operate at a wavelength of 10.6 \(\mu\)m, in the infrared region of the electromagnetic spectrum. This experiment (named Paladin) uses the pulsed 50-MeV beam of our ATA. This device uses shaped wiggler magnetic fields to provide both vertical and horizontal focusing. In addition to replicating the same kinds of experiments performed on ELF, Paladin will allow us to study "gain guidance" and electron light piping as means of exceeding the diffraction limits in order to increase the output power.

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**Key Words:** Advanced Test Accelerator (ATA); Electron Laser Facility (ELF); Experimental Test Accelerator (ETA); free-electron laser (FEL); Paladin experiment; wiggler.