New sources of high-power coherent radiation

Free-electron lasers and cyclotron-resonance masers show considerable promise for producing previously unattainable levels of power at wavelengths ranging from millimeters to the ultraviolet.

Phillip Sprangle and Timothy Coffey

Recent progress in novel techniques for generating high-power coherent radiation promises to make available sources with a variety of new and exciting applications. Interestingly, the new techniques have more in common with those used in the earliest sources of coherent radiation—the various microwave generators—than with those used in the more recent optical lasers. Development of new sources based on these techniques is proceeding rapidly at research centers around the world, because the new sources have a great potential for extending the currently available range of wavelengths and levels of power, while maintaining high operating efficiencies. The areas of application that stand to benefit include spectroscopy, advanced accelerators, short-wavelength radar, and plasma heating in fusion reactors.

Conventional sources of coherent radiation, such as the magnetron, the klystron and the traveling-wave devices, have limited power output and efficiency at short wavelengths. To circumvent these limits, researchers have proposed many new concepts and mechanisms, as well as variations on the conventional approaches. Two types of sources that were first demonstrated around 1960 are currently the focus of much attention: free-electron lasers and cyclotron-resonance masers, both of which are powered by relativistic electron beams.

We begin this article with a brief description of the physical mechanism of these and other novel sources of radiation. Then we look at some of the present and future areas of application and give an overview of the relevant experimental programs. Free-electron lasers offer operating efficiencies of over 20% at millimeter wavelengths, and one can extend their operation to ultraviolet wavelengths while maintaining relatively broad tunability. Figure 1 shows free-electron-laser radiation at visible wavelengths. Cyclotron-resonance masers offer high efficiency and high power at centimeter to millimeter wavelengths.

Physical mechanisms

The terms free-electron laser and cyclotron-resonance maser refer to mechanisms. Each denotes a wide class of coherent sources that operate over a wide range of wavelengths, the words maser and laser having long lost their original limitations to microwaves and light. Although amplification by stimulated emission of radiation is fundamentally quantum mechanical, classical models are sufficient to understand both free-electron lasers and cyclotron-resonance masers.

Electrons radiate when they are accelerated. When an electromagnetic field of proper polarization and phase is imposed on a beam of electrons, the electrons will accelerate in such a way as to radiate coherently. The condition for coherence is that the radiation from the electrons reinforce the original imposed electromagnetic field. The electrons must be moving initially because they radiate at the expense of their kinetic energy. We call a coherent source an amplifier if the imposed field is from an external source, and an oscillator if the imposed field is generated internally by spontaneous radiation from individual electrons.

The free-electron laser, such as the one shown in figure 2, consists of an electron beam, an external "pump field" and the imposed radiation field.[1–4] The pump field, typically a static periodic magnetic field, can be any field that causes the moving electrons to oscillate transversely. Although the basic mechanism of emission does not rely on relativistic effects, the electrons must be highly relativistic to produce short-wavelength radiation.

The radiation wavelength in the free-electron laser, unlike in most conventional sources, is not fixed by the size of the structure. Furthermore, the lasing medium, being a pump field, cannot break down. Hence, in principle, large structures can generate short wavelengths at high power levels.

We will consider only the common pump field: a static periodic magnetic "wiggler" with its primary field component transverse to the electron and radiation beams, as shown in figure 3. Injected monoenergetic electrons stream through the periodic magnetic field and wiggle, or oscillate transversely, in the same direction as the radiation electric field, and thus can lose energy to the radiation field or gain energy from it. At the point of injection, the electrons are randomly phased and radiate incoherently, generating spontaneous bremsstrahlung radiation. However, the so-called "ponderomotive" wave produced by the beating of the wiggler and radiation fields bunches the electrons within the interaction region and generates coherent radiation in the process, as we will see. The ponderomotive, or trapping wave, originates from the $\mathbf{v} \times \mathbf{B}$ force on the electrons and causes them to bunch in the axial direction. The longitudinal ponderomotive wave, which excites a density wave, acts like the slow-traveling electromagnetic wave in conventional traveling-wave sources. The ponderomotive wave bunches the electrons by decelerating some and accelerating others. If the axial velocity v_0 of the electrons is slightly greater than the velocity of the ponderomotive wave, the average energy of the electrons decreases and the radiation field is enhanced. An excessive spread in the velocity of the electrons can greatly

Phillip Sprangle is head of the plasma theory branch, and Timothy Coffey is director of research, at the Naval Research Laboratory, in Washington, D.C.

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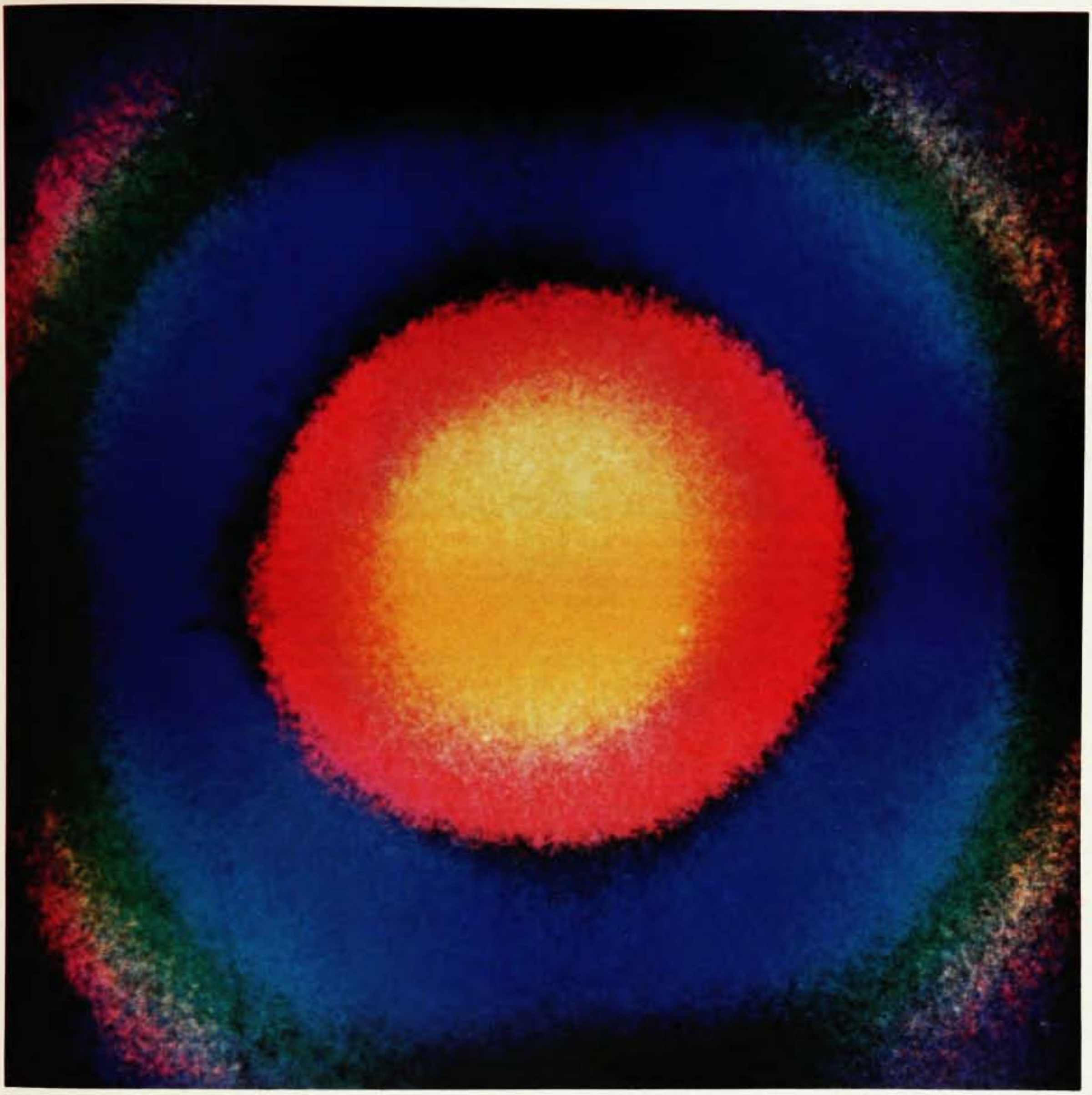


Far-field visible spontaneous radiation pattern from a free-electron laser. The laser used a wiggler magnet and was powered by electrons from the ACO storage ring at Orsay, France. The emission wavelength varies as the point of observation shifts off the beam axis. Figure 1

reduce the bunching and the extraction of energy, especially at shorter wavelengths.

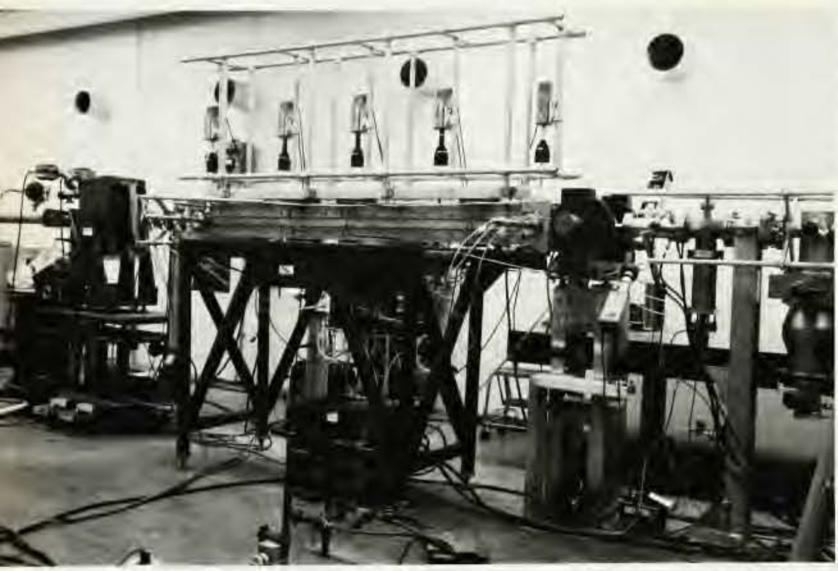
The $\mathbf{v} \times \mathbf{B}$ force that gives rise to the ponderomotive wave involves the electron wiggle velocity v_w, which is typically much less than the axial velocity v_0, and $\mathbf{B}_R$, the strength of the radiation magnetic field. The radiation frequency and wavenumber are related by the vacuum relation $\omega = ck$. The phase velocity v_{ph} of the ponderomotive wave is $\omega/(k + k_w)$, which is about equal to the electrons' axial velocity v_0; here k_w is the wiggler wavenumber. For the bunched streaming electrons, sychronism requires that the radiation frequency satisfy the relation

$$\omega = v_0 k_w / (1 - v_0/c)$$

For highly relativistic electrons the radiation wavelength λ is approximately $\lambda_w / 2\gamma_0^2$, where γ_0 is the relativistic gamma factor $(1 - v_0^2/c^2)^{-1/2}$ and λ_w is the wiggler wavelength shown in figure 3. The radiation wavelength is much smaller than the wiggler wavelength, and can be varied by changing the energy of the electron beam.

One alternative configuration features an additional magnetic field, oriented longitudinally.[5] As we will see, this hybrid-field arrangement is one of the basic features of the cyclotron-resonance maser.

The nature of the electron-beam source and the way the electrons interact divide free-electron lasers into categories.[1-4] Free-electron lasers based on low-current beam sources such as rf linacs, microtrons or storage rings usually operate in the "Compton regime," in which primarily single particles interact, so that we can neglect collective or space-charge effects. In this regime the radiation gain—the growth rate along the interaction length—typically is low, so that practical radiation sources would be oscillators, which do not require high gain. Without enhancement, operating effi-



Free-electron-laser experiment employing a radio-frequency linear accelerator and a tapered wiggler. Here we see equipment that measures the energy spread in the electron beam (right), the tapered wiggler (center) and a time-resolved electron spectrometer (left). (Photograph from Mathematical Sciences Northwest Inc. and the Boeing Aerospace Company.) Figure 2

ciencies are generally less than 1%. With high-energy electron beams of high quality, or small spread in energy, free-electron lasers in the Compton regime can operate at optical or ultraviolet wavelengths.

Other free-electron lasers are based on intense relativistic electron beams from sources such as induction linear accelerators or pulsed transmission-line accelerators, which Hans Fleischmann has described[6] in these pages. These lasers operate in the "Raman regime," in which collective effects influence the radiation growth rate and the interaction efficiency. Nevertheless, the operating wavelength λ remains at about $\lambda_w/2\gamma_0^2$, as in the Compton regime. Pulse-line-generated beams from plasma-induced field-emission diodes typically have relatively flat voltage and current pulses that last a few tens of nanoseconds. The electron beam's low quality and low energy—typically in the MeV range—limit the free-electron laser to millimeter wavelengths. But beam currents in the kiloamperes allow the laser to operate as an amplifier.

A third operating regime, known as the high-gain Compton regime, has features of both the Compton and Raman regimes. Here the wiggler field is so strong that the ponderomotive force on the electrons is dominant over the space-charge forces, and the radiation gain is large.

Cyclotron-resonance masers are far more developed than free-electron lasers and are among the most efficient devices for generating coherent high-power radiation at centimeter and millimeter wavelengths.[7] The mechanism was proposed independently by Richard Q. Twiss, Jurgen Schneider, Andrei Gapanov and Richard Pantell in the late 1950s. Their early theoretical studies demonstrated that relativistic effects associated with monoenergetic electrons gyrating in a magnetic field could result in stimulated cyclotron emission rather than absorption. The first clearly defined experimental confirmation of the mechanism was reported by Jay Hirschfield and Jonathon Wachtel in 1964. Devices based on this mechanism, whether oscillators or amplifiers, are referred to as gyrotrons.

Scientists in the Soviet Union developed the gyrotron concept into a practical source of radiation during the 1960s and 1970s, primarily at Gorkii State University.[8] In the 1970s there were also major advances in the United States at the Naval Research Laboratory as well as at MIT, Yale University, Varian and Hughes. The demonstrated efficiences and power levels in the millimeter regime are impressive. The Gorkii group, for example, as early as 1975 developed a 22-kW cw oscillator that produced 2-mm radiation with a 22% efficiency.

At the heart of the cyclotron-resonance maser is a beam of nearly monoenergetic electrons streaming along and gyrating about an external magnetic field $B_0\mathbf{e}_z$, as figures 4 and 5 indicate. An imposed electromagnetic field of the form $\mathbf{E} = E_0 \cos(\omega t)\mathbf{e}_y$, closely approximates the field of the transverse-electric mode of a cavity or waveguide when ω is near one of the cutoff frequencies of the structure. This allows the electrons to radiate coherently. The electrons behave as individual oscillators in the cavity, gyrating about the magnetic field B_0 with a rotation frequency $\Omega_R = \Omega_0/\gamma$, where Ω_0 is the nonrelativistic cyclotron frequency eB_0/m_0c and γ is the usual relativistic mass factor calculated from the transverse electron rotation velocity $v_\perp$.

To understand the process of amplification, we will for simplicity consider only eight electrons, initially distributed uniformly and rotating in clockwise circular orbits as shown in figure 5a. With the radiation field polarized initially as shown, and with the electron orbiting frequency Ω_R slightly lower than the radiation frequency ω, those particles in the upper half plane ($x > 0$) will move closer to resonance with the radiation field and, therefore, lose energy to that field and increase their rotation frequency. Those in the lower half plane will move farther from resonance and hence gain energy and decrease their rotation frequency. The overall result is known as "phase bunching"; viewed after an integral number of wave periods $2\pi/\omega$, most electrons will be in the upper half plane, losing energy and amplifying the field. This mechanism requires only that the radiation frequency slightly exceed the rotation frequency, that the rotation frequency is energy dependent, and that all the electrons have roughly the same transverse rotation velocity $v_\perp$. The cavity length is chosen such that the electrons exit the cavity when their average energy is a minimum.

High-efficiency operation requires a large ratio of transverse to longitudinal electron velocity $v_\perp/v_z$. This ratio is typically between 1 and 3, and demonstrated efficiences are as high as 60%.

Potential applications

Ultimately, the importance of new sources of coherent radiation will be determined more by their utility than by their novelty. Free-electron lasers and cyclotron-resonance masers have exciting potential applications as sources for spectroscopy, accelerators, radar and plasma heating.

Spectroscopy. A National Academy of Sciences study concludes[9] that the free-electron laser is a promising source for spectroscopy at far-infrared wavelengths greater than 25 microns, and at ultraviolet wavelengths less than 200 nm. This laser's coherence, narrow bandwidth, tunability and stable high power would be especially important in condensed-matter physics and surface chemistry, and in the spectroscopy of atoms, molecules and ions. The short time duration and thus high peak power available from some free-electron-lasers would allow

Table 1. Free-electron-laser experiments

Using rf linacs and microtrons

Laboratory	Class	Wavelength (microns)	Beam energy (MeV)	Peak current (A)
Stanford U.	Amplifier	10.6	24	0.1
Stanford U.	Oscillator	3.3	43	1.3
Los Alamos	Amplifier	10.6	20	10
Los Alamos	Oscillator	10.6	20	30–60
Mathematical Sciences Northwest/Boeing	Amplifier	10.6	20	5
TRW	Amplifier	10.6	25	10
TRW/Stanford U.	Oscillator	1.6	66	0.5–2.5
NRL	Oscillator	16.0	35	5
Bell Labs*	Amplifier	100–400	10–20	5
Frascati*	Amplifier	16	20	0.6

Using pulse-line-generated beams**

Laboratory	Peak power (MW)	Wavelength (mm)	Beam energy (MeV)	Beam current (kA)
NRL	1	0.4	2	30
NRL	35	4	1.35	1.5
NRL/Columbia U.	1	0.4	1.2	25
Columbia U.	8	1.5	0.86	5
Columbia U.	1	0.6	0.9	10
MIT	1.5	3	1	5
Ecole Polytechnique	2	2	1	2

Using electrostatic and induction linacs

Laboratory	Accelerator	Wavelength (mm)	Beam energy (MeV)	Peak current (A)
UCSB	Electrostatic accelerator	0.1–1	6	2
UCSB	Electrostatic accelerator	0.36	3	2
NRL	Induction linac	8	0.7	200
LLNL	Induction linac	3–8	4	400

Using storage-ring beams

Laboratory	Storage ring	Wavelength (microns)	Beam energy (MeV)	Beam current (A)	Gain per pass (%)
Orsay	ACO	0.5	240	2 (peak) 0.03 (average)	0.07 (measured)
Frascati	ADONE	0.5	600	10 (peak) 0.1 (average)	0.02 (measured)
Novosibirsk	VEPP-3	6	340	20 (peak)	0.4 (measured)
Brookhaven	VUV	0.35	500	108 (peak) 1.0 (average)	2 (calculated)
Stanford U.	ARRL (planned)	0.5	1000	200 (peak) 1.0 (average)	—

All entries in tables 1 and 2 represent typical values.
*Microtron beam source.
**Typical pulse times are tens of nanoseconds.

important new applications of radiation ranging in wavelength from 25 to 1000 microns. Pulses as short as tens of picoseconds could probe the dynamics of charge carriers in semiconductors and the dynamics of phonons, plasmons and superconducting gaps. High-power tunable picosecond pulses at wavelengths under 200 nm would substantially strengthen studies of fast chemical kinetics, photochemistry and vibrational relaxation processes that involve more than one photon.

Accelerators. As noted[10] at a recent workshop on laser acceleration of particles, affordable high-power sources of centimeter waves could lead to shorter high-energy accelerators. Conventional rf accelerators use microwave klystrons that generate about 25 MW of peak power. Recent developments indicate that free-electron lasers and cyclotron-resonance masers could generate gigawatts. These higher powers would mean fewer power tubes and possibly lower total cost. Researchers must resolve practical and scientific questions, however, before they can demonstrate that these new sources would deliver this power with acceptable efficiency and stability.

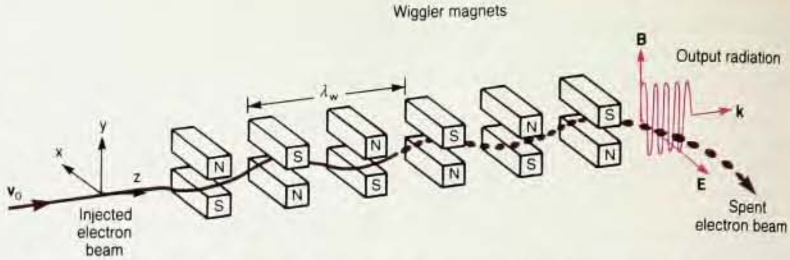
It may be possible to accelerate particles by reversing the dynamics of the free-electron laser.[10] The electric field of an intense laser beam, such as from a CO_2 laser, together with a wiggler could produce a large-amplitude ponderomotive wave to trap and accelerate electrons. One could energize the trapped electrons by increasing the wiggler field's period or amplitude or both. Accelerating gradients could exceed 100 MeV/m, but laser-beam diffraction would limit the acceleration length, so that electrons would gain at most a few GeV in a single stage. A major question is how to refocus the laser beam for multistage acceleration.

Radar. Most radar operates at microwave frequencies primarily because centimeter-wave power tubes and components are available and atmospheric losses are low. The free-electron laser and cyclotron-resonance maser promise millimeter-wave radar. Atmospheric absorption, although generally higher at millimeter wavelengths, has minima at 35, 94, 220 and 325 GHz. Relative to conventional microwave radar, millimeter-wavelength radar would have narrow beamwidths, large bandwidths and small antennas. Narrow beams permit tracking at low angles of elevation. Large bandwidths enhance resistance to interfering signals—or to electronic countermeasures in the case of military radar—and permit high-range resolution. Millimeter waves are less affected by fog, clouds, rain or smoke than are optical or infrared waves.

A number of issues concerning millimeter-wave radar remain to be resolved. The typical cyclotron-resonance maser uses a high magnetic field and requires superconducting magnets. Free-electron lasers, even at millimeter wavelengths, are now too large for most radar applications, and their high operating voltages are also a problem. The lack of millimeter-wave components has been another practical problem, but these components are developing rapidly.

Fusion power. The problems of plasma heating still prevent practical magnetic-confinement-fusion power reactors. Practical high-power sources at millimeter wavelengths could solve some of these problems.

Recent experiments on the Oak Ridge ISXB Tokamak, using a 35-GHz cyclotron-resonance maser developed at the Naval Research Laboratory, demonstrated large absorption through electron-cyclotron resonance.[7] The absorption heated the electrons significantly, but because of the low plasma density, the ions, as expected, were not measurably heated. These results imply that high-power cyclotron-resonance masers can heat fusion-reactor plasmas at the required high densities and long confinement times. Free-electron lasers are expected to be less efficient than cyclotron-resonance masers in producing millimeter waves and thus less suitable for plasma heating.



Basic components of a free-electron laser. The pump field is produced by a periodic arrangement of magnets—a "wiggler"—in which the electrons undergo transverse oscillations. The small transverse component of velocity, known as the wiggle velocity, is in the direction of the radiation electric field **E**, and can cause the electrons to lose energy and amplify the radiation field. The interaction between the electrons and the radiation field occurs over the entire length defined by the wiggler magnets. Figure 3

The success of high-power sources of coherent-radiation in any of the potential applications discussed above would be an important development. However, as with any new technology, we can expect the unexpected, implying that we have yet to identify the most important applications.

Enhancing efficiency

In free-electron lasers operating in the Compton regime, a radiation gain per pass of only 0.1 and an intrinsic efficiency of only 1% are typical. In this regime the intrinsic efficiency is given by the reciprocal of twice the number of wiggles in the interaction length. In the Raman regime, high gains are possible, with efficiencies as high as 15%.

One can increase operating efficiencies substantially either by converting the electron kinetic energy to radiation energy with greater efficiency or by recovering a portion of the electron kinetic energy after the electrons interact with the trapping wave. In principle, one can dramatically improve the efficiency with which the electrons transfer their energy to the wave, increasing it from about 1% to 20% in the Compton regime. One approach is to decrease gradually the trapping wave's phase velocity v_{ph}, which is $\omega/(k + k_w)$ or approximately $c(1-\lambda/\lambda_w)$. By spatially decreasing the wavelength λ_w of the wiggler field, one decreases the phase velocity v_{ph}. In this approach, the electrons remain trapped and lose a large fraction of their kinetic energy to the radiation field.

Instead of decreasing the phase velocity v_{ph}—or in addition to doing so—one can apply a longitudinal accelerating force to the trapped electrons to enhance the efficiency. An external

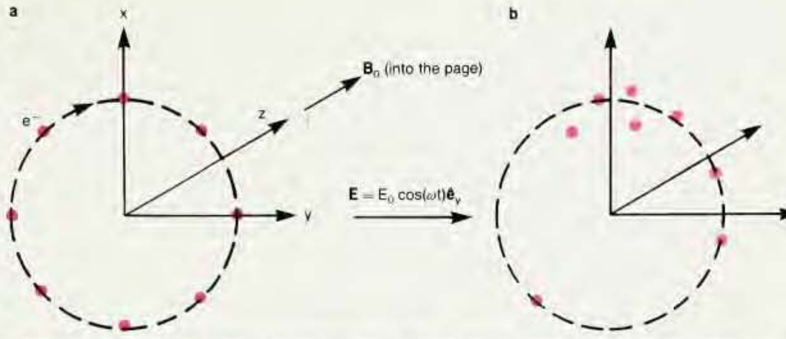
Table 2. US experimental cyclotron-resonance masers

Oscillators

Laboratory	Frequency (GHz)	Power (kW)	Efficiency (%)	Pulse duration
Varian	28	340	45	Continuous
Varian	60	120	38	Continuous
NRL	35	340	54	1 μsec
MIT	140	180	30	1 μsec
Hughes	60	240	30	100 msec

Amplifiers

Laboratory	Frequency (GHz)	Power (kW)	Efficiency (%)	Pulse duration (microsec)	Bandwidth (%)
NRL	35	10	8	1.5	2–13
Varian	28	65	9	1000	1
Varian	5	120	26	50	6
Yale U	6	20	10	1	11



Phase distribution of gyrating electrons. This simplified representation shows the initial phase distribution (at **a** in figure 4) and the distribution after an integral number of wave periods (at **b** in figure 4). Figure 5

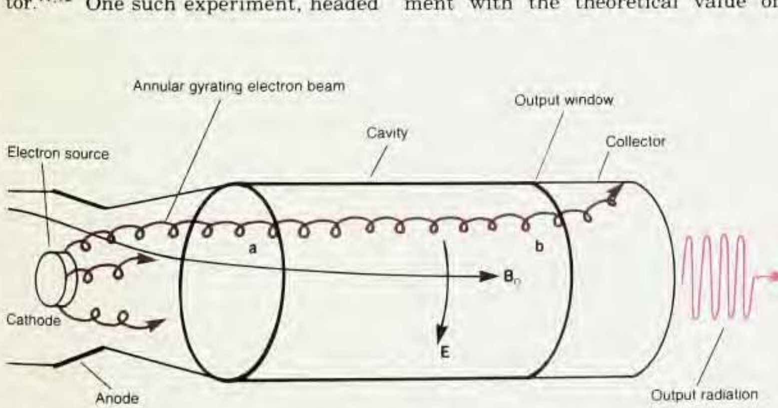
uniform axial electric field can provide this accelerating force. A more practical approach is to decrease the spatial amplitude of the wiggler field. In either case, the resulting phase shift of the trapped electrons is such that they perform work on the trapping wave, enhancing the radiation. Norman Kroll of the University of California at San Diego and Marshall Rosenbluth of the University of Texas at Austin have found that instabilities can arise in the trapped-particle mode of operation, resulting in sideband radiation.[4]

In cyclotron-resonance masers, one approach to achieving higher than intrinsic efficiency is to contour the radiation field in the cavity by varying the radius of the cavity wall, as shown in the left half of figure 6. Electrons entering the cavity start phase bunching where the field amplitude is small. The electrons give up relatively little energy until they enter the high-field region. There they radiate more efficiently because they are highly bunched and closer to resonance.

In an alternative approach to efficiency enhancement, experimenters contour the external longitudinal magnetic field axially, as shown on the right side of figure 6. They make the magnetic field near the input smaller than normally required, allowing the electrons to bunch in phase without losing or gaining much energy. Again, as the phase bunching increases, the electrons go into a higher magnetic field and move closer to resonance. In addition, one can recover as much as 90% of the longitudinal energy of the spent electrons.

Experiments

Pioneering in free-electron-laser experiments in the Compton regime is a Stanford University group using the Superconducting Linear Accelerator.[11,12] One such experiment, headed by John Madey,[12] is sketched in figure 7 and listed second in table 1. The 43-MeV electron beam macropulses used in this experiment were 1.5 msec in duration and consisted of 1-mm-long micropulses spaced 25.4 m apart. Spontaneous incoherent radiation from the electrons built up into intense coherent radiation at 3.3 microns, because the gain of the free-electron-laser process peaks near that wavelength. Madey's group carefully separated the optical resonator mirrors so that the round-trip bounce time of the radiation pulses just matched the time between electron micropulses. In the presence of the electron micropulse, the radiation pulse velocity is slightly less than the velocity of light in a vacuum, an effect known as "laser lethargy."[4] In the Stanford experiment, the measured peak output power through a mirror of 1.5% transmittance was 6 kW; hence, the peak radiation power within the resonator was 400 kW. The measured linewidth $\Delta\lambda/\lambda$ of the saturated radiation was about 0.006. The 6% measured gain per pass was in fair agreement with the theoretical value of about 10%.



Cyclotron-resonance-maser oscillator, in schematic view. The electron source is a magnetron injection gun. The cathode emits an annular beam that gyrates about an applied magnetic field $\mathbf{B}_0$ as it propagates through a cavity. The cavity operates in a transverse-electric mode near its cutoff frequency. The spent electron beam is collected, and radiation is emitted through an output window. Figure 5 compares the uniform electron phase distribution at **a** with the bunching at **b**. Figure 4

At Los Alamos, Charles Brau and his coworkers are developing a highly efficient free-electron-laser oscillator source.[4,12,13] (See PHYSICS TODAY, August 1983, page 17.) This free-electron laser will employ an rf linac accelerator and radiate at 10.6 microns. The experimenters will vary the wiggler wavelength and amplitude spatially and recover part of the energy of the spent electron beam. They anticipate a 20% overall efficiency and an average output power of 100 kW.

At Mathematical Sciences Northwest and Boeing Aircraft, a group led by Jack Slater is developing[12,13] an optical free-electron-laser oscillator that will radiate at 0.5 microns. It employs a radio frequency linac beam with a peak current of 100 A.

Experimenters at the Naval Research Laboratory, in a recent free-electron-laser experiment[13] using an intense relativistic electron beam from a pulse-line generator, produced 35 MW of 4 mm radiation with 2.5% efficiency. (See table 1.) The energy spread of the injected electron beam was uniquely low. Experimental programs at Columbia University, MIT and Ecole Polytechnique are also employing high-current beams generated by pulse lines, as the list in table 1 indicates.[4]

At the University of California, Santa Barbara, Luis Elias and Gerald Ramian are conducting experiments[4,12] with a 6-MeV Van de Graaff accelerator to evaluate a dc energy-recovery scheme. (See table 1.) Their free-electron laser is designed to operate at 200 microns and achieve an output power of 12 kW.

Two free-electron-laser experiments powered by induction linacs are underway in the US, as table 1 indicates. Both operate in the high-gain regime. The Naval Research Laboratory's induction linac experiments, headed by Chris Kapetanakos and John Pasour, feature a uniquely long pulse duration of about 2 microsec, enabling the free-electron laser to operate as an oscillator. At present, this free-electron laser operates as a superradiant amplifier generating 4.2 MW at a wavelength of 8 mm and an efficiency of 3%. At Lawrence Livermore National Laboratory, experiments led by Donald Prosnitz and Andy Sessler use the laboratory's 5 MeV Experimental Test Accelerator. Because of this accelerator's short beam pulse of 30 nsec, the laser will operate as an amplifier.

A number of free-electron-laser experiments use electron storage rings (See table 1), with the wiggler being in one of the straight sections. One such storage-ring experiment, headed by Claudio Pellegrini[4] at Brookhaven National Laboratory, will operate at 500 MeV and a peak current of 108 A. The radiation gain should be a few percent at a wavelength of 0.35 microns.

Future direction of research. Charles Roberson, of the Office of Naval Research, and his coworkers suggest[4] the possibility of powering free-electron lasers with intense cyclic electron beams generated by racetrack induction accelerators or modified betatrons. Such sources, however, are still in a proof-of-principle stage of development.

Because wiggler wavelengths are typically at least a few centimeters, optical free-electron lasers require electron beams with energies of at least 50 MeV. Beam energies could be lower with use of a high-frequency electromagnetic pump field, such as an intense laser beam or the output of another free-electron-laser. With a CO_2 laser pump and a 1-MeV electron beam, a free-electron laser could in principle radiate at optical frequencies.

Another interesting possibility for avoiding high beam energies is a two-stage free-electron laser using a single electron beam. The radiation produced in the first stage, which would employ a wiggler field, would become the pump field for the second stage. However, in this scheme, and in the scheme using lasers to generate an electromagnetic pump field, the gain per pass is low, and because beams with extremely low energy spreads are necessary, the trapping efficiency is low.

The electron beam from the Advanced Test Accelerator at Livermore is expected to produce 500-GW pulses of electrons, which could, in principle, generate tunable multigigawatt pulses of radiation at near-optical frequencies.

Maser experiments. Experimenters commonly use magnetron injection guns to produce electron beams for cyclotron-resonance masers (see figure 4). These thermionic sources can generate several amperes and electron energies as high as 100 keV.

To generate millimeter-wavelength radiation with cyclotron-resonance masers, experimenters usually use superconducting sources for the magnetic field. At the fundamental cyclotron harmonic, one needs a 34-kG magnetic field to generate radiation at 94-GHz, or 3 mm. It is possible to overcome the need for superconducting magnets in the generation of millimeter waves by operating at higher cyclotron harmonics, because the required magnetic field is reduced by a factor approximately equal to the harmonic number. The efficiency at the second harmonic remains high and with some designs can be higher than at the fundamental frequency. Generally, however, the efficiency falls sharply beyond the second harmonic.

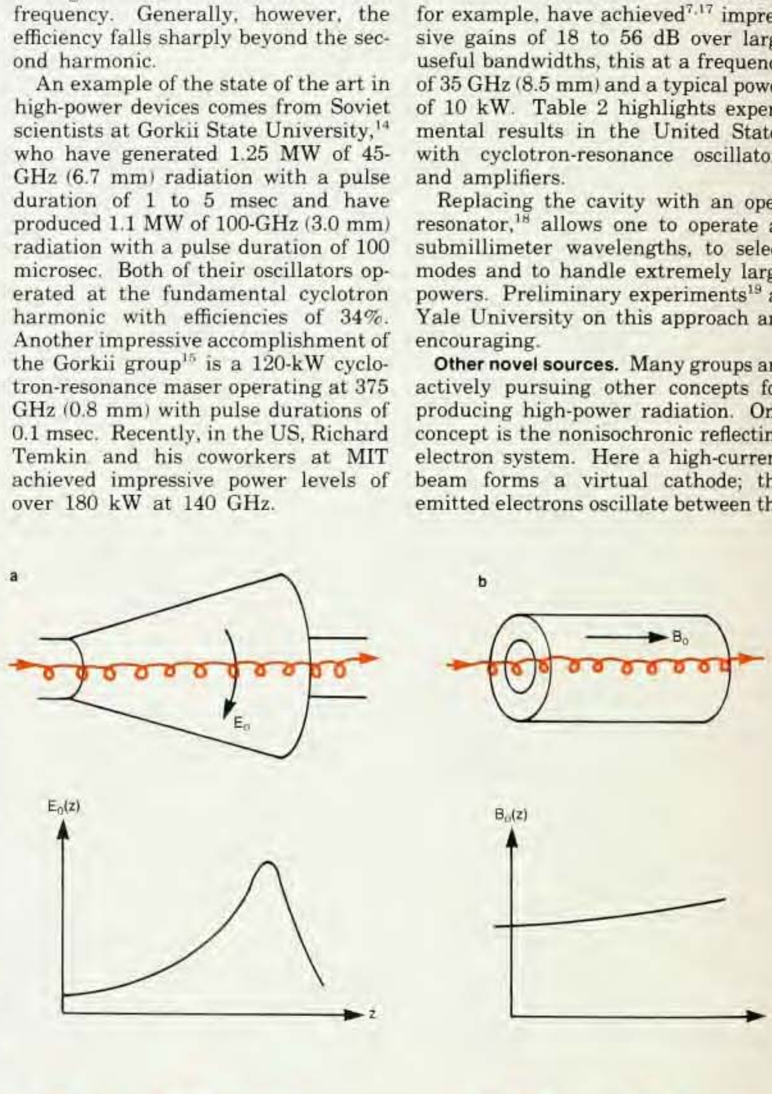
An example of the state of the art in high-power devices comes from Soviet scientists at Gorkii State University,[14] who have generated 1.25 MW of 45-GHz (6.7 mm) radiation with a pulse duration of 1 to 5 msec and have produced 1.1 MW of 100-GHz (3.0 mm) radiation with a pulse duration of 100 microsec. Both of their oscillators operated at the fundamental cyclotron harmonic with efficiencies of 34%. Another impressive accomplishment of the Gorkii group[15] is a 120-kW cyclotron-resonance maser operating at 375 GHz (0.8 mm) with pulse durations of 0.1 msec. Recently, in the US, Richard Temkin and his coworkers at MIT achieved impressive power levels of over 180 kW at 140 GHz.

To increase the cavity volume and thereby avoid excessive thermal loading and competition among modes, high-power millimeter-wave cyclotron-resonance masers will have to operate in highly "overmoded" cavities, that is, in cavities that support many frequency modes at the same time. Recent results[16] show that one can stabilize highly overmoded cyclotron-resonance masers by adding a small prebunching cavity in front of the large energy-extraction cavity.

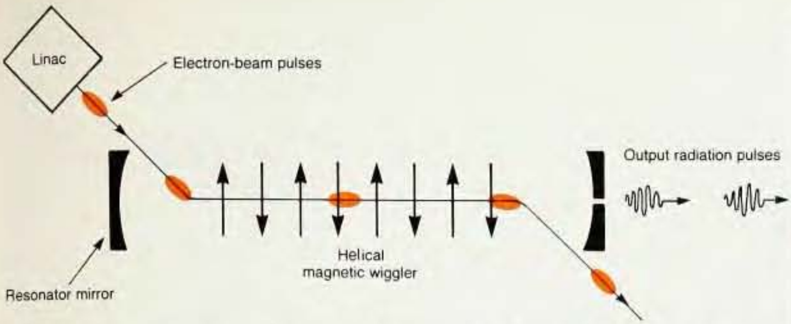
Prospects for practical cyclotron-resonance amplifiers are great. Researchers at the Naval Research Laboratory, for example, have achieved[7,17] impressive gains of 18 to 56 dB over large useful bandwidths, this at a frequency of 35 GHz (8.5 mm) and a typical power of 10 kW. Table 2 highlights experimental results in the United States with cyclotron-resonance oscillators and amplifiers.

Replacing the cavity with an open resonator,[18] allows one to operate at submillimeter wavelengths, to select modes and to handle extremely large powers. Preliminary experiments[19] at Yale University on this approach are encouraging.

Other novel sources. Many groups are actively pursuing other concepts for producing high-power radiation. One concept is the nonisochronic reflecting electron system. Here a high-current beam forms a virtual cathode; the emitted electrons oscillate between the



Efficiency enhancement methods used in cyclotron-resonance-maser oscillators. These are the two most common enhancement techniques. In **a**, the radius of the cavity wall increases longitudinally so that the field in the cavity varies as shown. In **b**, the radius of the cavity wall is constant, but the longitudinal external magnetic field varies. The diagrams at the bottom show the electron phase distributions at various points within the cavities. Figure 6



Oscillator using a pulsed electron beam. This is a schematic diagram of a typical free-electron-laser oscillator. The source is a radio frequency linear accelerator. The spacing of electron pulses and the length of the resonator are such that the reflecting pulses of radiation are synchronized with the incoming beam pulses. The mirror on the right is partially transmitting, so that a small fraction of the radiation pulses transiting the resonator can escape. The wiggler magnets are 3.3 cm apart over a total distance of 5.3 m. The magnetic field is 2.3 kG. Figure 7

actual and virtual cathodes, bunch in phase and generate radiation copiously. Our own experiments[20] on this source, which is compact, tunable and simple, have produced over 100 MW of 3-cm radiation.

Coherent Cherenkov radiation is a less novel but interesting source of millimeter waves. Some experiments produce this radiation by directing a relativistic electron beam along a dielectric surface. In one such experiment[4] at Dartmouth College, John Walsh, Kevin Felch and their coworkers achieved efficiencies of 10% and power levels of 100 kW at a wavelength of 4 mm.

One novel relativistic magnetron can generate unprecedented levels of coherent radiation at centimeter wavelengths. In experiments[21] headed by George Bekefi at MIT, a relativistic magnetron driven by an electron beam from a pulse line produced microwaves at a power level of 10 GW.

The history of science shows that applications, technology and theoretical concepts usually evolve together. In the case of high-power sources of coherent radiation, we are now witnessing rapid evolution in all these areas. Our ultimate understanding and the most important applications probably remain to be seen.

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We gratefully acknowledge assistance from Cha-Mei Tang in preparing this article.

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