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FREE-ELECTRON LASERS

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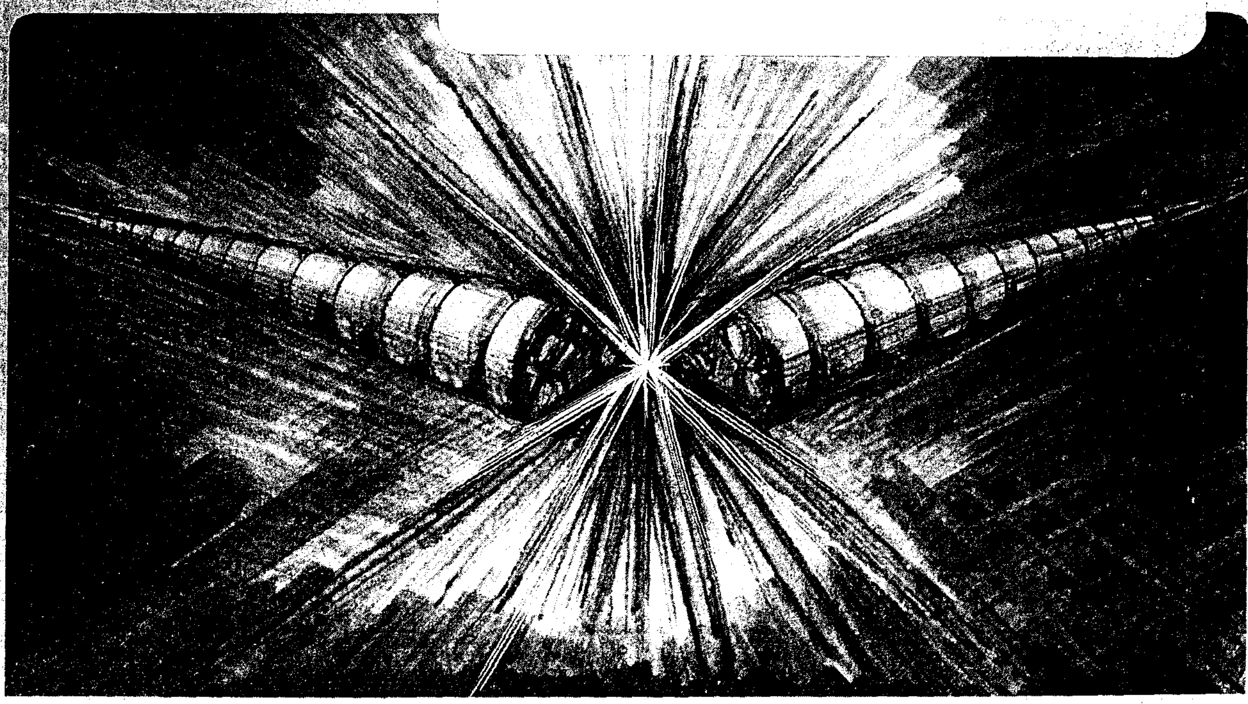

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FREE-ELECTRON LASERS

We can now produce intense, coherent light at wavelengths where no conventional lasers exist

The recent successes of devices known as free-electron lasers mark a striking confluence of two conceptual developments that themselves are only a few decades old. The first of these, the laser, is a product of the fifties and sixties whose essential characteristics have made it a staple resource in almost every field of science and technology. In a practical sense, what defines a laser is its emission of monochromatic, coherent light (that is, light of a single wavelength, with its waves locked in step) at a wavelength in the infrared, visible, or ultraviolet region of the electromagnetic spectrum. A second kind of light, called synchrotron radiation, is a by-product of the age of particle accelerators and was first observed in the laboratory in 1947. As the energies of accelerators grew in the 1960s and 70s, intense, incoherent beams of ultraviolet radiation and x-rays became available at machines built for high-energy physics research. Today, several facilities operate solely as sources of synchrotron light. Unlike the well-collimated monochromatic light emitted by lasers, however, this incoherent radiation is like a sweeping searchlight--more accurately, like the headlight of a train on a circular track--whose wavelengths encompass a wide spectral band.

Now, in several laboratories around the world, researchers have exploited the physics of these two light sources and have combined the virtues of both in a single contrivance, the free-electron laser, or FEL (1). The emitted light is laserlike in its narrow, sharply peaked spectral distribution and in its phase coherence, yet it can be of a wavelength unavailable with ordinary lasers. Furthermore, like synchrotron radiation, but unlike the output of most conventional lasers, the radiation emitted by free-electron lasers can be tuned, that is, its wavelength can be easily varied across a wide range. The promise of this new technology extends from the fields of solid-state physics, gas- and liquid-phase photochemistry, and surface catalysis to futuristic schemes for ultrahigh-energy linear accelerators.

Foundations

To understand the development of the FEL--and its promise--we must now back up and lay some groundwork, first by looking at the principles of the laser, then by outlining the evolution of ways for producing synchrotron radiation. All lasers, and their direct ancestor the maser, can be understood in the same terms. In essence, some form of energy is fed into a lasing medium, where it is "captured" in the form of fundamentally unstable energetic states. In a laser, electrons bound in atoms or molecules are promoted to excited energy levels, the result being an unnatural preponderance of excited atomic or molecular states known as a population inversion. The excited atoms or molecules then revert to their natural ground states, at the same time emitting light characteristic of the energy difference between the two states. As this spontaneously emitted light, with its well-defined wavelength, propagates through the medium, it stimulates the emission of more light of the same wavelength. (Thus the origin of the acronyms laser and maser: light--or microwave--amplification by stimulated emission of radiation.) The spontaneous decay of a few excited states thus leads to a cascade of decays, all contributing radiation of the same wavelength and phase, and propagating in the same direction as the stimulating wave. To intensify the effect, mirrors are placed at the ends of the laser cavity to reflect the light back and forth through the lasing medium. These mirrors also select a resonant optical wave and hence serve to sharpen up the frequency of the light. One of the mirrors may be only partially reflective, however, so a fraction of the confined radiation is emitted as an intense pulse of monochromatic light.

A very different set of physical principles is involved in the generation of synchrotron radiation, and the result is light with very different characteristics. Circular particle accelerators such as cyclotrons and synchrotrons use magnets to constrain charged particles to roughly circular orbits. A magnetic field exerts a force on a moving charge and thus bends its trajectory in a way that depends on the speed of the particle, its charge and mass, and the strength of the field. In addition, this bending force has a second important effect. According to electromagnetic theory, any charged particle subjected to a net force will emit radiation, the consequence being that particles circulating in a synchrotron emit radiation. For a relativistic electron (one whose velocity is close to the speed to light), the total power of this synchrotron radiation is given by

$$P = \frac{2}{3} \gamma^4 \frac{e^2 c}{R^2},$$

where e is the charge of the electron, c is the velocity of light, R is the bending radius, and γ is equal to E/mc^2. In the expression for γ, E is the electron's energy and m is its mass. Because of its strong dependence on

E, synchrotron radiation was weak, if it could be observed at all, in early, low-energy machines, and owing to the relatively large mass of protons, it is negligible in proton synchrotrons even today. Using modern electron machines, on the other hand, where the mass of the circulating particles is 1/2000 that of a proton, we can generate intense synchrotron radiation. Today, such synchrotron radiation sources are in operation throughout the world; in the U.S., they include facilities at the National Bureau of Standards, the University of Wisconsin, Cornell University, the Stanford Linear Accelerator Center, and the Brookhaven National Laboratory (2).

When nonrelativistic charged particles are constrained to a circular orbit, the weak synchrotron radiation they emit has a frequency very close to their orbital frequency ω_0. At relativistic velocities, however, this radiation contracts into a narrow cone pointing in the direction of the particle's instantaneous motion (see Figure 1). In addition, the frequency of the light is smeared over a range that extends from the orbital frequency to much higher frequencies, peaking in the region of $\gamma^3\omega_0$, where γ (the same parameter that appeared in the expression for power) is equal to $(1 - v^2/c^2)^{-1/2}$. Since, in operating synchrotrons, the electron velocity v is usually only slightly less than c, γ often has a value greater than 1000, making it readily practical to generate synchrotron radiation well into the x-ray region of the spectrum. Thus, we have a beaconlike source of intense light, lacking the monochromaticity and phase coherence of laser light, but with a spectrum that can be shifted around on the wavelength scale by varying the energy of the charged-particle beam that gives rise to it.

Notwithstanding the virtues of synchrotron radiation generated at the "bending magnets" of electron synchrotrons, thought was soon being given to a new class of devices known as "insertion devices" (so called because they are inserted into the straight sections of storage rings- synchrotronlike machines designed to store circulating particles for long periods, usually several hours.) In one of their most popular current forms, these insertion devices consist of blocks of a permanent-magnet material such as samarium cobalt ($SmCo_5$), located above and below the beam axis and oriented so as to impress an alternating magnetic field on the beam (see Figure 2). The resulting magnetic force causes the electrons to "wiggle" or "undulate" (the difference has to do with how much the electrons are deflected from their straight paths) as they pass through the insertion device and to emit synchrotron radiation at the same time. In contrast to the radiation emitted from bending magnets, however, this light is concentrated along a single axis, namely, the direction of the electron's net motion. The intensity of the light emitted into a unit solid angle is thus significantly enhanced. In addition, interference effects in undulators cause the emitted radiation to be sharply peaked at discrete wavelengths. A schematic illustration of the differences between radiation emitted by bending magnets, wigglers, and undulators is also shown in Figure 2.

Basic Principles of the FEL

The discussion of insertion devices leads directly to the concept of FELs, but one additional phenomenon is critical to the mechanism that makes an FEL work, namely, an electromagnetic force imposed on the electron beam by the field of the radiation. Before expanding on this point, we should note that the first device we will describe is a species of FEL known as an amplifier, so called because it takes an input pulse of radiation from an independent source (a CO_2 laser, for example) and amplifies it by means of the mechanism we are about to explain. Other FELs, generically referred to as oscillators, use end mirrors to confine and amplify the radiation produced, much like conventional lasers. In contrast to amplifiers, the origin of the radiation in these oscillators is the spontaneous emission we described above for wigglers and undulators. Still other FELs, so-called single-pass superradiant devices, produce an intense coherent signal from their own spontaneous emission, but without the benefit of mirrors.

To understand the basic mechanism by which energy is transferred from an electron beam to a beam of coherent radiation, thereby amplifying it, we imagine a single electron, together with a laser beam, moving through the gap of an undulator magnet, as shown in Figure 3. (FELs in which the electron beam is tenuous enough to allow us to ignore the mutual repulsion of the electrons are said to operate in the Compton regime.) The energy of the electron, the wavelength of the laser radiation, and the periodicity of the undulator field have been adjusted in this figure to give us the result we want. We shall look at this necessary interrelationship of parameters later; for the moment, let us simply refer to the requisite electron energy as the resonant energy. In the first frame of Figure 3, the electric field of the laser beam is zero at the position of the electron, which therefore feels no force (aside from that due to the magnetic field of the undulator). In the second frame, the electron has traveled one-quarter of an undulator period, and the laser field has advanced one-quarter of an undulator period plus one-quarter of a laser wavelength. The electron thus sees the maximum laser electric field, oriented in the same direction as the transverse motion of the electron. Since the electron is negatively charged, this field exerts a negative, or retarding, force on it. The electron is consequently decelerated, giving up energy to the laser field. No energy is exchanged in the third frame of Figure 3, but in the fourth, the electron is again decelerated and the laser field amplified. In the final frame, the situation in the first frame has been reproduced: The electron has moved through one full undulator period, and the laser field has moved one undulator period plus one laser wavelength. However, the electron has given up some of its kinetic energy to the laser beam, thereby amplifying the radiation. To pursue the analogy with a conventional laser, we can say that the laser beam has stimulated the emission of coherent radiation from the electron.

For a single electron, with just the right phase relationship to the electric field of the radiation, this energy-exchange mechanism is easy enough to visualize. The real situation, however, is slightly more involved. We see this when we realize that an electron entering the undulator one-half of a laser wavelength behind the one we just followed would feel a positive force in frames 2 and 4, and would as a result be accelerated by the laser field, thus taking energy from it. In a steady stream of electrons, therefore, some gain energy and some lose it; the net result, initially at least, is no amplification of the laser radiation.

Another consequence of some electron's losing energy and some gaining, however, is a bunching of the electron beam. In the reference frame of an "average" electron, the electrons that are accelerated move forward, whereas those decelerated fall back. As a result, all electrons tend toward some "average" electron position. (Over an undulator length of some meters, in fact, the electrons move beyond this average position and, in time, begin to oscillate about it.) This bunching process can be illustrated as shown in Figure 4, where electrons with a range of energies (vertical axis) and phases (horizontal axis) are trapped by the so-called ponderomotive potential.

Now we see how useful gain can be extracted from an FEL. If a beam of electrons with an energy slightly greater than the resonant energy is injected into the FEL, the electrons trapped by the ponderomotive potential will, in time, possess an average energy equal to the resonant energy. Therefore, some amount of energy, at most equal to the difference between the initial electron energy and the resonant energy, is transferred to the radiation field; this is the source of gain, or amplification, in an FEL. (By symmetry, of course, an electron beam with less than the resonant energy gains energy at the expense of the radiation field.)

Quantitative Considerations

We now return for a brief look at the most important parameters in the physics of FELs, namely, the energy of the electron beam (and thus the speed of the electrons), the wavelength of the laser radiation, and the length of the undulator period. We can begin by characterizing an electron beam having the resonant energy by the relativistic factor γ_r, defined such that the energy of a single electron is given by $\gamma_r mc^2$. The central requirement for FEL operation, then, is that, in the reference frame of electrons at this resonant energy, the wavelength of the radiation and the "wavelength" of the undulator be identical. According to the special theory of relativity, the undulator wavelength seen by the electron is

$$\lambda'_u = \lambda_u/\gamma_r,$$

where λ_u is the length of the undulator period in the laboratory frame. Similarly, the electron sees Doppler-shifted laser radiation, whose wavelength, in the relativistic limit, is given by

$$\lambda' = 2\gamma_r \lambda,$$

where λ is the wavelength in the lab frame. Setting $\lambda' = \lambda'_u$, we obtain

$$\lambda \simeq \lambda_u / 2\gamma_r^2 .$$

To see what this implies, consider that a "low-energy" electron beam of 5 million electron volts (MeV) has a γ of about 10, which would serve to amplify 500-μm infrared radiation in an undulator with a 10-cm period. A 500-MeV electron beam ($\gamma \simeq 1000$), on the other hand, would amplify 500-angstrom ultraviolet radiation using the same undulator.

Since the electron is actually wiggling as it proceeds through the undulator, rather than proceeding in a straight line, the equation above is inexact--as we have indicated. An exact statement of the resonance condition is

$$\lambda = \frac{\lambda_u}{2\gamma_r^2} \left[1 + \frac{1}{2} \left(\frac{eB\lambda_u}{2\pi m_e c^2} \right)^2 \right] ,$$

where B is the peak undulator magnetic field.

We next ask, at what rate does an FEL generate radiation? The answer depends on many things, but it is often given for two cases, one in which the FEL "just barely works" and a second--the high-gain case--where the FEL works very well indeed. In the former case, the output power following a single pass through the undulator is given by

$$P_{out} = P_{in}(1 + G_{low\ gain}),$$

where P_{in} is the initial photon power and $G_{low\ gain}$ is equal to approximately 536 $N^3\rho^3$, a quantity much smaller than unity. The parameter N is the number of magnetic periods in the undulator and ρ is a factor that contains many undulator and electron beam parameters.

In the high-gain regime, the expression for gain is quite different:

$$P_{out} \sim P_{in} \exp G_{high\ gain} ,$$

where $G_{high\ gain}$ is proportional to $N\rho$, which is now greater than unity. As we shall see in the case of the Livermore FEL, this exponential expression can lead to a power increase of many thousand-fold over a very short distance.

In connection with this discussion, several additional operational questions arise. For example, what happens as the properly matched electron beam loses energy and thus falls out of resonance with the wavelength of the laser radiation and the physical parameters of the undulator? The answer is that in a conventional FEL the efficiency with which energy is extracted from the electron beam begins to diminish as the beam travels along the undulator. Indeed, at a certain point, the undulator reaches "saturation," and no further energy extraction is possible. Fortunately, means are available for ensuring that the resonance condition persists for the length of the undulator. This is done by "tapering" the undulator, that is, either by fabricating an undulator whose period decreases as one moves from one end to the other or, more practically, by decreasing the strength of the undulator magnetic field in the downstream sections (as was done in the simulation of Figure 4). Tapered undulators open the door to highly efficient FELs.

One might also ask what constraints apply to the "quality" of the electron beam from which energy is extracted. The individual particles in a stable electron beam inevitably undergo transverse oscillations called "betatron oscillations." In a "bright" electron beam, however, these oscillations are relatively small, and a large proportion of the electrons are able to contribute efficiently to the gain of the FEL. FEL performance is therefore directly related not only to beam current but also to beam brightness.

Finally, we mention a "transverse effect," that is, one that has its origin in the finite transverse size of the electron beam. A limit to the length of an FEL is given by the diffraction of the light out of the electron beam. A measure of this limit is the Rayleigh length $\pi a^2/\lambda$, where a is the radius of the electron beam. The Rayleigh length is the distance along the beam over which the light is diffracted outward to a radius 2a. Remarkably, however, it has been predicted that the electron beam in an FEL can provide optical guiding of the light beam, somewhat like an optical fiber. This phenomenon awaits experimental verification, but it seems to admit the possibility of building very long, highly efficient FELs, as well as FELs that generate light in the vacuum ultraviolet and soft x-ray regions.

Ten Years of FEL Experiments

The modern era of FEL research began in 1975 when a group at Stanford University headed by John M. J. Madey used an FEL to amplify the 10.6-μm output of a CO_2 laser (3). Their 5.2-meter-long helical undulator caused the electrons to follow a spiraling trajectory, rather than a sinusoidal one, but the operating principles were otherwise the same as those outlined above. The following year, using electrons of somewhat higher energy, Madey demonstrated an oscillator that produced coherent radiation with a wavelength of 3.4 µm (4). These were clearly the seminal experiments for the work that is being done today, but theoretical and experimental inquiries into using a periodic magnetic field to produce and amplify coherent radiation go back to the early 1950s. In 1951 Hans Motz, then also at Stanford, proposed a concept that had the same configuration as an FEL, and he later built tubes that produced microwave radiation from mildly relativistic electrons (5). Later in the fifties, Robert M. Phillips, of General Electric, fabricated a series of devices he called ubitrons, which actually exploited the same mechanism at work in today's FELs (6). Following these early explorations, however, the field lay dormant until revived by several theoretical works around 1970 and by Madey's experiments five years later. (Madey was not aware of Phillips's work.)

The work by Madey and his co-workers confirmed theoretical expectations, and their experiments were the first to use relativistic electrons from a modern accelerator--in this case a superconducting linear accelerator. At first glance, however, this first FEL appears to have achieved only modest levels of performance. Operating as an amplifier, the FEL enhanced the power of the CO_2 laser beam by only 7%, and as an oscillator, it extracted only 0.01% of the electron beam energy. On the other hand, the FEL really was working: The power radiated by the electrons was 10^9 times greater in the amplifier than would have been radiated spontaneously by electrons passing through the wiggler (in the absence of the radiation field)!

Since the first successful experiments at Stanford, FELs have been operated in at least a half-dozen other labs, and many more are likely to be running within a few years. Rather than attempt a catalog of the world's FELs, however, we shall merely point to an example or two in each of three major categories of devices: (a) amplifiers operating in conjunction with linear accelerators (linacs), including those that operate in the so-called collective, or Raman, regime, where the simple picture of Figure 3 breaks down; (b) oscillators operating in conjunction with linacs; and (c) oscillators operating with recirculating beams.

Linac amplifiers. The first Stanford FEL, successfully demonstrated in 1975, is, of course, an example of an FEL amplifier operating in conjunction with a linac; however, a look at more recent such systems considerably illuminates the possibilities of FELs. Prominent within this class of FEL is a series of devices operated as early as 1977 by groups from the Naval Research Laboratory (NRL). Among the most recent results are those from a group headed by Steven H. Gold, which has extracted high power from both a single-pass superradiant FEL and an FEL amplifier (7). The superradiant device has produced 75 MW of output power, centered at a wavelength of 4 mm (but with a broad frequency spectrum), and the amplifier has generated 17 MW from a monochromatic 7-kW input signal at 8.6 mm. In contrast to the low efficiencies of the first FELs, these experiments extracted, respectively, 6% and 3% of the electron beam energy.

Two features of these experiments are especially notable. First, both were complicated (at least from a theoretical point of view) by the presence of a solenoidal guide field along the axis of the undulator. This axial field was imposed both to form and confine the high-current beam (1000 amps in one case, 600 amps in the second) and to enhance the performance of the FEL. The proper choice of an axial field--one that causes the electrons to spiral at the same frequency as their undulator-induced oscillations--can significantly enhance the emission of radiation. The second feature of interest can be directly attributed to the high current of the electron beam used in these experiments. Because of the high density of electrons, we are no longer able to rely on the mechanism of Figure 3, where we considered only the interaction of individual electrons with the radiation field. Instead we are in the Raman regime, where the density of the electrons is such that they are best regarded as an electron fluid in which mutually repulsive forces are balanced by external guiding or focusing fields. In this regime, a better model for visualizing the extraction of energy from the electrons and its deposition in the radiation field is an interaction between waves in the electron fluid and the electromagnetic wave (8).

The NRL superradiant experiment is of a type that we have alluded to but not discussed so far. Like an FEL amplifier, it is a "single-pass" device, that is, one that operates without mirrors. However, unlike an amplifier, there is no input signal; instead, the output radiation is said to grow "from noise." Like any other wiggler or undulator, an FEL undulator produces incoherent synchrotron radiation with a broadly peaked spectrum. It is this radiation, then, produced in the upstream end of the FEL, that gets the process of coherent amplification rolling. The coherent radiation that eventually emerges can reach very high power levels (as the NRL experiment demonstrated), but the spectrum tends to be much broader than the sharply peaked emission of an amplifier, which uses a monochromatic input signal, or an oscillator, with its resonant optical cavity. In the case of the NRL superradiant experiment, the relative linewidth was about 4%.

A second FEL that extracts energy from a relatively low-energy, but high-current, electron beam has reached record power levels at the Lawrence Livermore National Laboratory (9; Figure 5). Donald Prosnitz from Livermore and a group from the Lawrence Berkeley Laboratory have successfully operated this FEL since 1984. Unlike the NRL experiments, the Livermore FEL operates without a solenoidal guide field, and because it operates at a higher electron beam energy (3.3 MeV as compared with 1.25 MeV and 0.9 MeV for the two NRL experiments), it can be characterized as a Compton-regime laser. The Livermore FEL has been run both as a superradiant device and as an amplifier. In the latter configuration, the 3-meter-long untapered undulator, using an electron beam with 850 amps of current, boosted input pulses of 8.6-mm radiation having a peak power of 30 kW to 200 MW. With a current greater than a kiloamp and a tapered undulator, the same input power has produced radiation with a peak power of 1.8 GW, an increase of some 60,000-fold.

One important feature of the Livermore FEL is its "simplicity"--that is, our ability to understand it as a Compton-regime device, together with the absence of a solenoidal field. It has thus been possible to compare experimental results with a fairly well-developed theory. The agreement, in fact, is excellent, thus encouraging efforts to extend the results to much shorter wavelengths. Indeed, such an experiment is under way, which will use a larger linac at Livermore, capable of accelerating 10 kA of electrons to 50 MeV, in an effort to realize high gain and high power at infrared wavelengths (10 μm).

Linac oscillators. In FEL work to date, a practical dichotomy has existed between devices coupled to high-peak-current, relatively low-energy accelerators and those operated in conjunction with low-peak-current, high-energy machines. Since the wavelength of the laser light varies inversely with the square of the electron-beam energy, and since output power depends on electron-beam current, this dichotomy has tended to lead to high-gain, long-wavelength FELs on the one hand and low-gain, short-wavelength FELs on the other. Accordingly, the most notable FELs that have lased in the near-infrared and visible regions have been oscillators, since the gain per pass is typically rather low, at least by comparison with the amplification in the NRL and Livermore-Berkeley experiments. (Considerable effort is now being put into dissolving this dichotomy, especially by increasing the peak current in radio-frequency linacs.)

An illustrative example of an oscillator coupled to a linac is one at Stanford's superconducting linear accelerator (the same machine first used by Madey in the mid-seventies). The experimental team, headed by John Edighoffer and George Neil of TRW, Inc., and Alan Schwettman and Todd Smith of Stanford, has focused on the effect of wiggler tapering on laser efficiency at 1.6 μm (10). The electron-beam energy was 66 MeV, but the highest achievable peak current was only 2.5 amps. Consequently, the radiation field could be amplified by only 7% during each pass through the 5.4-meter wiggler. Confined between the end mirrors of the oscillator, however, the radiation achieved an intracavity power level of 460 MW. The peak power of the output was 1.2 MW, 10^{10} times the peak power of the spontaneous wiggler radiation.

The TRW-Stanford wiggler was tapered by widening the gap between the opposite poles of the downstream wiggler magnets, thus reducing the strength of the field felt by the electrons. A modest taper of 1% increased the efficiency of energy extraction from 0.2-0.4% to 1.1%, a dramatic confirmation of theoretical expectations.

Other notable linac-based FEL oscillator experiments have been conducted at the Los Alamos National Laboratory (11) and at Mathematical Sciences Northwest, Inc., now Spectra-Physics (12).

<u>Recirculating-beam oscillators</u>. Two FEL experiments--one in France, at Orsay, and a second in Santa Barbara, California--have involved oscillators operated

in conjunction with recirculating electron beams. One reason for exploiting this concept is the obvious attraction of reusing the electrons that pass through an FEL, rather than discarding them. With a recirculating beam, one merely pumps back into the electrons the energy they give up to the emitted radiation (at most, a few percent of the total). Another reason, however, which was dominant at Orsay, is to make use of the high-energy electrons available only in a storage ring, in an effort to reach short wavelengths.

The Orsay effort--a collaborative undertaking of teams from the Laboratoire pour l'Utilisation du Rayonnement Electromagnétique (LURE) and Stanford, headed by Yves Petroff and John Madey, respectively--centered around a small storage ring named ACO (13). The experiment was arranged so that the round-trip time of radiation within the optical cavity was equal to the spacing between electron bunches in the ring. As a consequence, continuous lasing could be expected, limited only by the beam lifetime in the storage ring. Nonetheless, a twofold challenge remained in using ACO. First, the size of the ring limited the undulator length to 1.3 meters, which in turn severely reduced the maximum possible gain from the FEL. This was so because gain is proportional to the cube of undulator length. Second, the ultraviolet radiation emitted by the undulator when the storage ring was operated above its minimum energy destroyed the end mirrors of the oscillator cavity.

The ultimate success of the experiment, then, depended on two experimental modifications. For one, the ring was operated at only 160 MeV, rather than the 240 MeV originally intended. The wavelength of the light eventually produced increased correspondingly, from 488 to 650 nm, and mirror damage was reduced. The second trick was the conversion of the undulator into an optical klystron. This meant, in effect, replacing three central periods of the undulator with a single period having a stronger magnetic field. This new configuration enhanced the formation of electron bunches, thus increasing the power gain obtained in the final periods of the undulator. (The TRW-Stanford group later incorporated a "dispersion section" that achieved the same result in their tapered FEL.) As a result of these measures, lasing became reliable (see Figure 6), though the power observed (60 mW peak) and energy extraction efficiency (0.0024%) were modest in comparison with longer-wavelength lasers. On the other hand, given the Orsay configuration, an extraction efficiency greater than 0.0060% is theoretically impossible. This is the Renieri limit--valid in any storage ring--which is imposed by the heating of the electron beam caused by the undulator--heating that must be balanced by the cooling effect of the bending magnets around the rest of the ring.

The second recirculating-beam FEL--at the Quantum Institute at the University of California at Santa Barbara (Figure 7)--derives its uniqueness from two facts (14). First, it uses an electrostatic accelerator very similar to the old-fashioned Van de Graaff to generate high-energy electrons, and second, it has been intended from the start as a tool for experimental research, rather than an object of research. The accelerator, called a Pelletron, has already achieved greater than 95% efficiency in recycling electrons (and 99% is envisioned), which considerably ameliorates the 0.3% efficiency of the FEL itself. This is in contrast with FELs based on high-energy linacs, which may extract energy from the electrons with much higher efficiencies, but which require a continuous supply of fresh electrons and thus can never achieve overall efficiencies greater than a few percent. (This statement will have to be amended if energy recovery techniques are ever developed, as Los Alamos is now attempting to do.) Another contrast with most other FEL oscillators is the long electron pulse length at Santa Barbara. Both the TRW-Stanford laser and the Orsay FEL, for example, relied on short pulses of electrons entering the optical cavity with a frequency equal to the round-trip time of the radiation within the cavity. At Santa Barbara, on the other hand, the electron pulse is several tens of microseconds long, which allows the radiation to make many round trips during the duration of a single bunch.

At present, results from the Santa Barbara group, headed by Luis Elias (also a collaborator in the first successful FEL experiments at Stanford), are at 400 μm, but following an upgrade of the Pelletron energy from 3 MeV to 6 MeV, workers there expect to be generating tunable far-infrared radiation down to 100 μm. In addition, Elias has proposed an extension of the laser's capabilities by means of a "two-stage" FEL. The first stage of such a device would generate far-infrared radiation in the usual way. The second stage, however, would rely on the electromagnetic field of this infrared radiation, rather than the field of a magnetic undulator, to induce oscillations in an electron beam. These oscillations would be of very short period and would thus produce radiation in the ultraviolet, an impressive prospect with electrons of only 6 MeV. In addition, this should, for the first time, require quantum mechanical corrections to the classical treatment of FELs.

Applications

Many of the most promising uses for FELs can be identified simply by asking what one might do with an efficient, tunable, high-power pulsed laser at wavelengths where no such device now operates. In the following paragraphs, we shall try to suggest a few answers to this question, then turn to some other possibilities that are based on the FEL as a generator of copious short-wavelength microwaves.

As suggested by Figure 8, FELs are of particular interest as sources that might produce infrared (especially far-infrared) or ultraviolet radiation. The far-infrared, or submillimeter, region of the spectrum ($50 < \lambda < 1000$ μm) is of interest primarily to solid-state physicists; consequently, surface and solid-state studies are at the focus of research plans for the Santa Barbara FEL and for a far-infrared FEL being built at AT&T Bell Laboratories (15). At somewhat shorter wavelengths, FELs are attractive to chemists and molecular spectroscopists.

Throughout the infrared and ultraviolet, one can envision extensions of techniques already perfected with available lasers (16). Visible pulses from dye lasers, for example, have made possible few-picosecond studies of vibrational relaxation processes in solids and liquids and excitation-deexcitation mechanisms in biological systems. Similar fast-pulse FELs in the infrared would permit parallel transient studies of, for example, phonons, plasmons, and superconductor quasiparticles. In addition, short pulses from a high-power infrared FEL might be synchronized with those from a pulsed visible laser to allow pump-probe measurements of charge-carrier dynamics in semiconductors, as well as high-resolution studies of vibrational and rotational states in liquids. Among the most important surface studies are those aimed at understanding, and ultimately enhancing, surface-catalyzed reactions. Vibrational spectra of adsorbed molecules, resolved to the microsecond time scale, are needed to study kinetically significant species on good catalysts; the possibility of such studies will be much enhanced with infrared FELs. It has even been suggested that homogeneous catalysis rates might be greatly improved by the selective vibrational excitation of adsorbed molecules (17).

In the midst of the infrared "fingerprint" region ($2.5 < \lambda < 50$ μm), the CO_2 laser, with its fundamental at 10.6 μm, has contributed profoundly to molecular spectroscopy. Its high peak power, for example, has made possible studies of upper vibrational levels, which can now be reached by multiphoton absorption. A tunable, high-power source in this region would extend these and other studies to a much wider range of molecules. Carbon dioxide lasers have also been used in studies of laser-induced thin-film deposition, where the laser causes the dissociation of gas-phase reactants, which then react with the substrate surface (18). Here again, the FEL, with its high power and tunability, has been heralded as a way of widening the range of available laser frequencies.

In the context of processes with industrial potential (such as thin-film deposition), another virtue of the FEL is especially important, namely, its efficiency in converting wall-plug power to optical power. Only the CO_2 laser is economical enough to be commercially exploited today; the hope is that the infrared FEL may open the door to the industrialization of laser-induced photochemistry, especially chemical chain reactions.

A second region of the spectrum where the FEL's future is promising is the ultraviolet, where the radiation can be used to excite electronic, rather than vibrational and rotational, transitions in molecules. Once again, much of the promise is in extending the domain of the conventional laser. Tunable, short-pulse lasers are not readily available below about 250 nm; as a consequence, high-resolution absorption spectroscopy and time-resolved resonance Raman spectroscopy over much of the vacuum ultraviolet region await an intense, tunable light source (19). Ultraviolet FELs may also prove useful for industrial applications: Just as an infrared FEL might extend the range of the CO_2 laser in such processes as thin-film deposition, an ultraviolet FEL could serve as an adjunct to visible and ultraviolet excimer lasers for large-area deposition of dielectric and metallic films and for gas-phase powder synthesis (18).

Microfabrication by laser-controlled chemistry is yet another emerging technology in need of high-power sources in the ultraviolet (20). The idea here is similar to that for thin-film deposition. Ultraviolet light is used to induce a chemical reaction in a gas or liquid, which in turn reacts with an underlying substrate. One such method, laser direct writing, uses a finely focused beam to induce a reaction of micrometer or submicrometer dimensions; in a second method, laser projection, the image of a mask is projected on the substrate surface, and the chemical reaction occurs only in the exposed areas. For microelectronics applications, both methods would benefit from ultraviolet sources with higher power, higher repetition rates, and wider frequency ranges that those of available excimer lasers.

Medicine is another field, less obvious at first glance, where researchers have expressed interest in the properties of FELs (21-23). Today, lasers are used primarily for microsurgery (the province mainly of the CO_2 laser) and for phototherapy (especially tumor vaporization and the control of bleeding lesions with the Nd:YAG laser). Despite the widespread use of these available conventional lasers, it has been suggested that FELs may offer an attractive alternative to both. A less well-established use of lasers exploits their photochemical, rather than their thermal, effects. Photodynamic tumor therapy is aimed at producing either excited singlet-state oxygen or free radicals at tumor sites, the purpose being to bring about local cell death. This form of therapy depends on the in vivo excitation of dyes, which then produce the desired therapeutic agent, either by direct dissociation or by energy transfer reactions. High power is not needed in the radiation source, but the tunability of the FEL may prove a useful virtue as new dyes are developed and tested (21).

Perhaps the best-publicized of possible FEL applications is its use as an antimissle system. In one scenario for such a system, an FEL would produce prodigious power at a wavelength of about 1 μm, which could be directed through the atmosphere to orbiting mirrors that would then direct the radiation toward enemy missles shortly after launch. It is such schemes as this that have prompted some of the largest and most productive FEL research programs, including those at Livermore and Los Alamos. Also of interest to the military is the concept of FEL-based microwave radar. Operating at millimeter wavelengths, such radar is seen to offer high resolution (because of its short wavelength and sharp pulses), long range (because of its high peak power), and resistance to interference (because of its tunability). One problem to be overcome is the complexity and size of the high-power millimeter-wave FELs that have operated to date.

At least two other applications also lie in the microwave region, where the "competition" is microwave sources such as klystrons and gyratrons, rather than conventional lasers. One possible application is the use of FELs to generate microwaves or submillimeter radiation to heat the plasma in magnetic fusion tokamaks, where high power and good efficiency are practical prerequisites. A second is in high-energy physics. Here, the aim of the experimenter is to observe and understand the products of particle collisions at ever-higher energies--these energies serving, in effect, as probes of ever-smaller physical dimensions. This quest for higher energies has been satisfied over the past five decades by a succession of innovative concepts for accelerating particles, each innovation pushed to its limits before being superseded by the next. Today, we have circular proton-proton and electron-positron colliders, either on the drawing boards or under construction, that are likely to be the last of their breed; they are already tens of kilometers in circumference. Succeeding them will probably be linear colliders that exploit new and efficient sources of power--sources that might increase the energy of electrons or positrons by several hundred MeV for every meter they travel, rather than the ten or twenty MeV/meter currently feasible.

The use of a microwave FEL as just such a power source is the underlying concept for a Two-Beam Accelerator, illustrated schematically in Figure 9 (24). At the Livermore FEL, a group has already produced accelerating gradients of 180 MeV/meter in a very small accelerator test section (25).

Still other possibilities include the use of FELs for isotope separation, communications, and inertial-confinement fusion. An active group working at Frascati, Italy, in fact, has been motivated primarily by the promise of using FELs to separate isotopes of uranium (26).

In conclusion, it can be said that the principles of the FEL have been well-demonstrated in several laboratories around the world. In their simpler incarnations, they are even well-understood theoretically--perhaps as well-understood as the conventional laser. Whether they will prove themselves as practical a tool as the laser is another question, one that must await the developments of the decade ahead.

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Figure Captions

Figure 1. Synchrotron radiation is emitted by charged particles (usually electrons) constrained to circular orbits within particle accelerators. At nonrelativistic velocities (speeds much less than the speed of light), the pattern of emitted radiation resembles a torus and is nearly equal in intensity at all angles within the plane tangent to the electron's orbit (top drawing). At velocities near the speed of light, however, the radiation pattern becomes a narrow, sweeping searchlight within the plane of the orbit (bottom). The spectrum of synchrotron radiation also changes with increasing speed. At low speeds, the frequency of the light is close to the orbital frequency of the electrons; at relativistic speeds, the frequency distribution extends as a continuum to much higher frequencies.

Figure 2. Conventional insertion devices produce intense synchrotron radiation by causing a beam of electrons to oscillate in a horizontal plane in response to a spatially periodic magnetic force. In contrast to the sweeping searchlight of synchrotron light produced by bending magnets, these so-called wigglers and undulators produce more narrowly confined radiation. In addition, whereas the radiation from bending magnets and wigglers (which behave like strings of oppositely oriented bending magnets) is smeared out over a wide range of frequencies (peaking in the neighborhood of $\gamma^3\omega_0$, where ω_0 for wigglers is an "equivalent" circulation frequency), undulator radiation appears at discrete frequencies and has much higher peak power. The reason for this is that radiation from the different "bends" of an undulator interferes constructively, a fact that also leads to a flux per unit area that scales as N^2, where N is the number of undulator periods. The spectrum for

a wiggler is the same as that for a bending magnet having the same parameters, but the flux is greater by a factor 2N (since the electrons get bent twice in each period).

Figure 3. A wiggler or undulator can behave as an FEL amplifier when the "wavelength" of the periodic magnetic field, the energy of the electron beam (hence the speed of the individual electrons), and the wavelength of a co-propagating laser beam are suitably interrelated. Shown here are five snapshots of a single electron as it passes through one period of a wiggler; the fifth frame reproduces the conditions of the first (the laser radiation having gained one full wavelength on the electron), so that the illustrated process will be repeated along the length of the wiggler. In frames 1, 3, and 5, the electron feels no effect due to the electric field of the laser radiation, but in frames 2 and 4, the electric field exerts a retarding force on the transverse motion of the electron, thus causing it to lose energy. This energy, transferred to the radiation field, constitutes the amplification, or gain, of the FEL.

Figure 4. A computer simulation illustrates the process of electron bunching and energy extraction. In each of these illustrations, the full width of the horizontal axis (representing phase) corresponds to one optical wavelength in the reference frame of the electron; γ is plotted along the vertical axis. Initially, the electrons were distributed uniformly from left to right, and their energies were spread symmetrically about the nominal beam energy of about 20 MeV ($\gamma = 40$). The first frame of the simulation shows some electrons gaining energy (and moving to the right) and other losing energy (and moving to the left) as they are influenced by the ponderomotive potential of the

radiation field. In the subsequent frames, most of the electrons are trapped by this potential, thus forming a bunch that gives up significant energy as radiation. The phases of the trapped electrons continue to oscillate as their average energy decreases; avoiding amplification of light at this so-called bounce frequency is a problem one must face in operating an efficient FEL. The different colors given to the electrons represent different initial transverse momenta.

Figure 5. The Livermore-Berkeley undulator comprises three one-meter-long modules, one of which is shown here. The external windings establish a quadrupole focusing field; the undulator itself is visible as alternating light- and dark-colored blocks above and below the rectangular beam aperture.

Figure 6. The tunability of FEL radiation is illustrated by the colors of light that has been observed at Orsay in recent experiments at 220 MeV. The corresponding wavelengths range from 4600 angstroms (blue) to 6500 angstroms (red). The tuning was done by varying the magnetic field strength in the undulator, a parameter that enters into the equation for the resonance condition on account of its effect on the magnitude of the electrons' undulations as they pass through the FEL.

Figure 7. The Santa Barbara FEL is dominated by the large yellow electrostatic accelerator seen behind the ring itself in this photograph. The 5.6-meter-long undulator is located in the straight section of the ring at the left of the photo. The circulating electron beam passes through the undulator, then back up the accelerator, where more than 95% of its energy can be recovered and used for reacceleration.

Figure 8. The greatest promise for FELs is to fill the gaps in the spectrum of currently available sources of high-power coherent radiation. The most obvious gaps exist in the far infrared, where no sources exist; in the ultraviolet, where no tunable high-power sources exist; and at few-millimeter wavelengths, where conventional microwave sources produce only low power. In this plot, the peak powers of several high-power lasers are shown, together with the approximate tuning ranges of some commercially available devices. Neodymium-glass and CO_2 lasers developed for inertial fusion experiments have produced peak powers in excess of a terawatt. (The peak power of the tunable lasers is not meant to be depicted here.) Peak powers and wavelengths for successful FEL experiments are shown with solid triangles.

Figure 9. In an imagined Two-Beam Accelerator, an intense, low-energy beam of electrons in an FEL would provide the power for accelerating a second beam of electrons to very high energies in a high-gradient linac. This power, in the form of microwave radiation, would be transmitted by waveguides to the high-gradient structure, where the electric field of the radiation would provide the accelerating force. The energy lost by the electrons in the FEL would be periodically replenished by induction accelerator modules. An accelerating gradient of 180 MeV/meter has already been demonstrated in a very small section of an accelerating structure (inset photo).

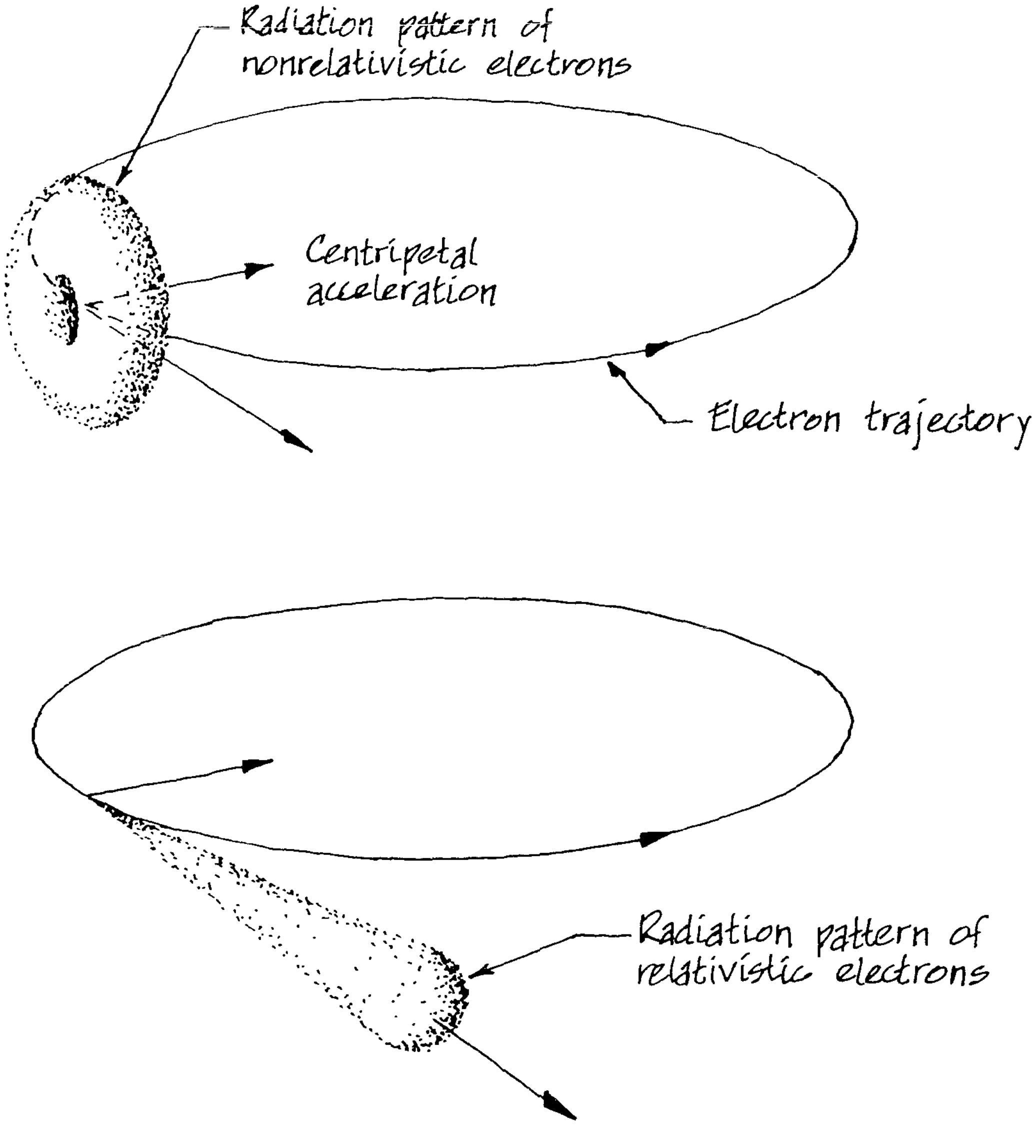
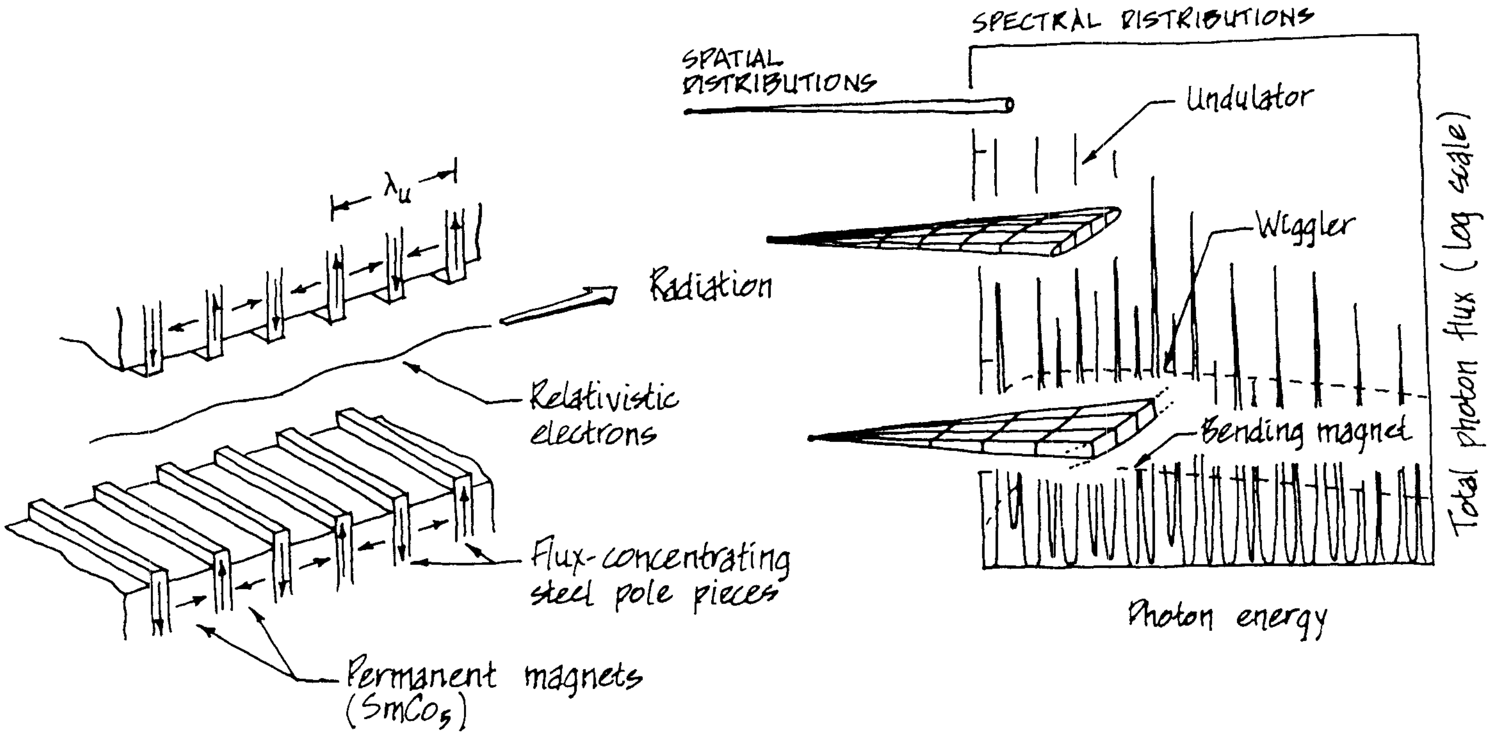
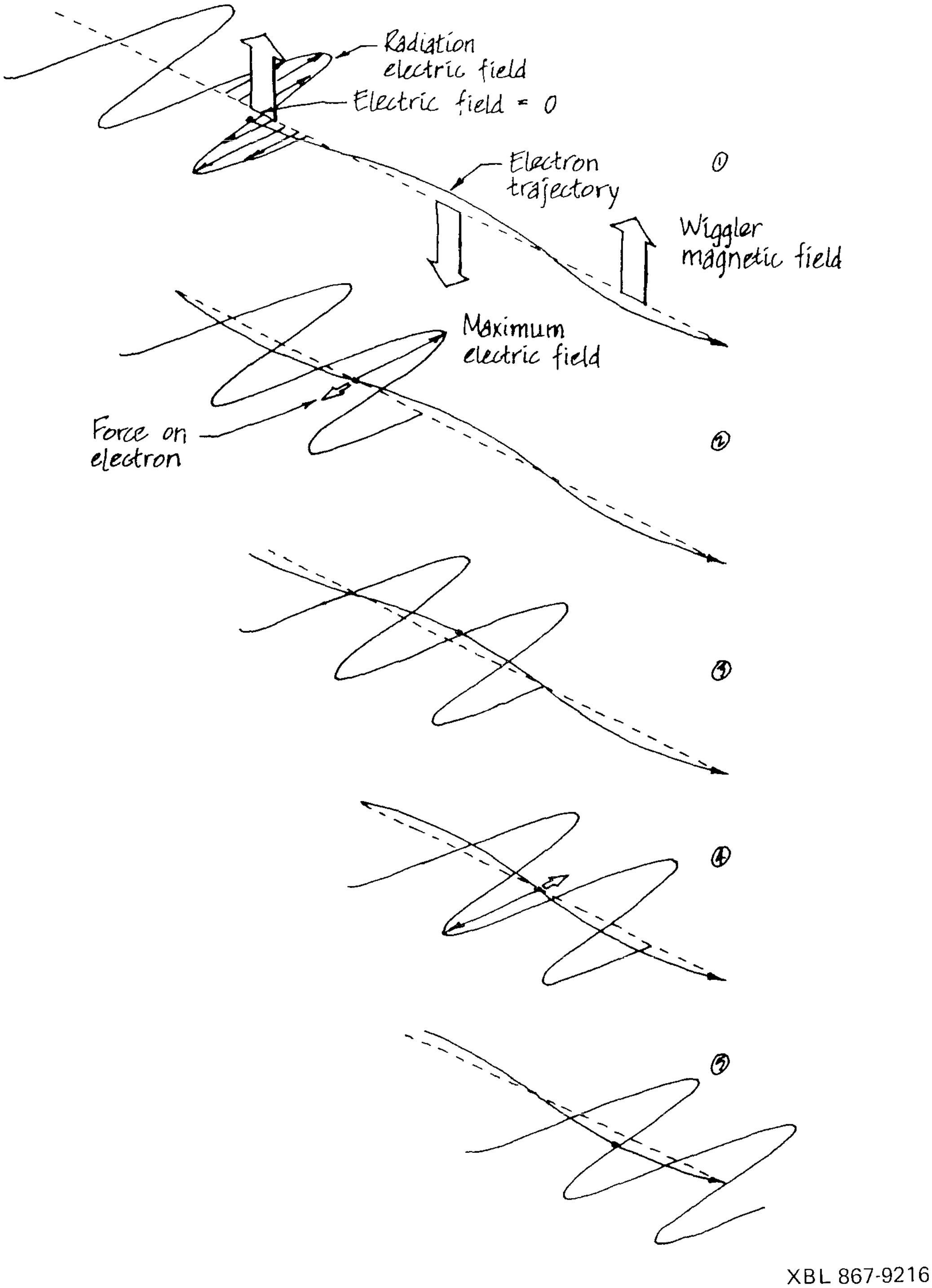

Radiation pattern of
nonrelativistic electrons
Centripetal
acceleration
Electron trajectory
Radiation pattern of
relativistic electrons
XBL 867-9214

Fig. 1



XBL 867-9215

Fig. 2



Radiation electric field
Electric field = 0
Electron trajectory
Wiggler magnetic field
Maximum electric field
Force on electron
①
②
③
④
⑤
XBL 867-9216

Fig. 3

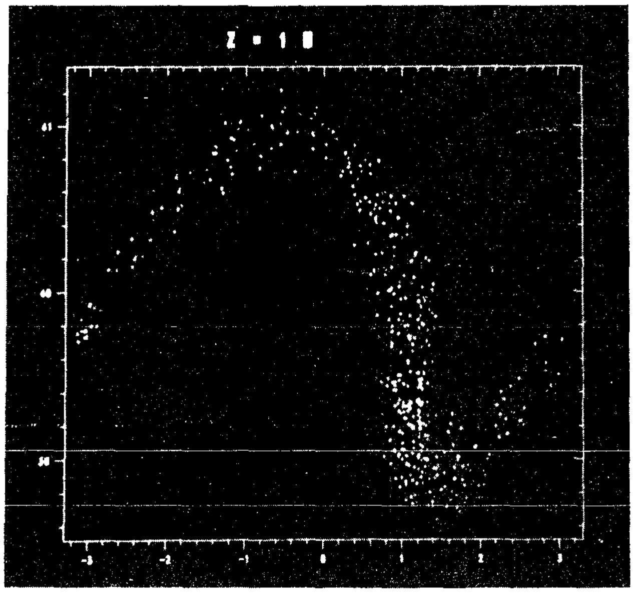
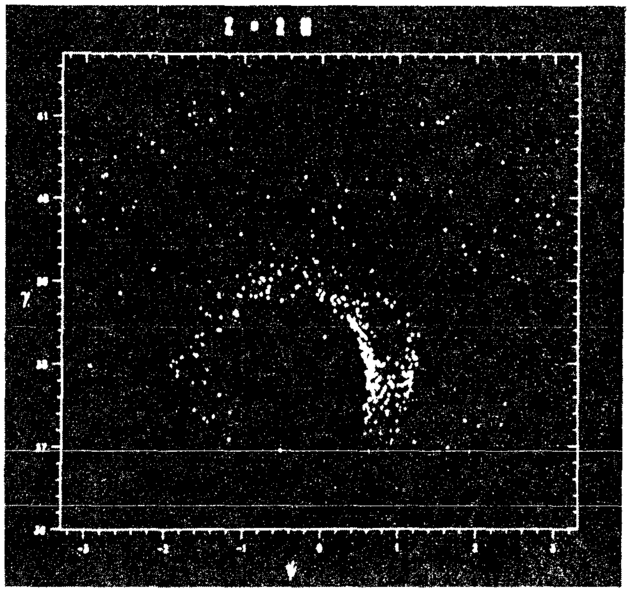


Fig. 4a CBB 864-3350



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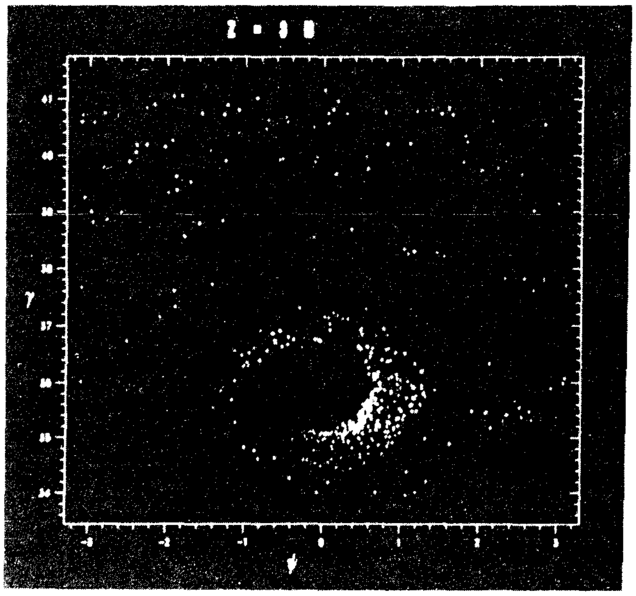

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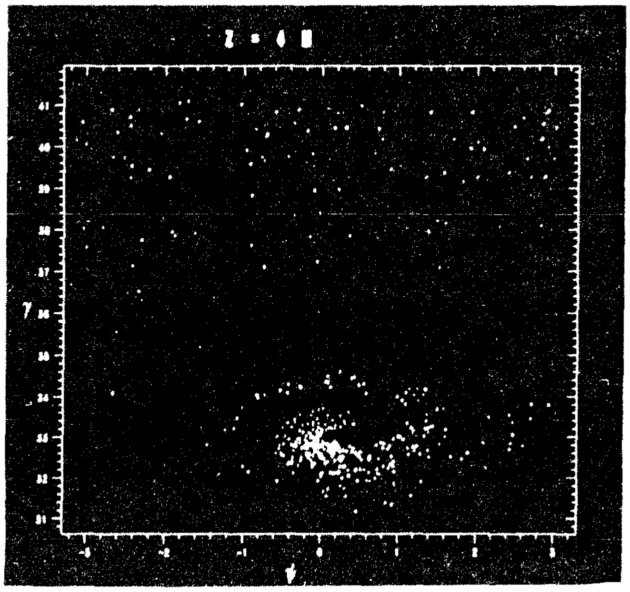

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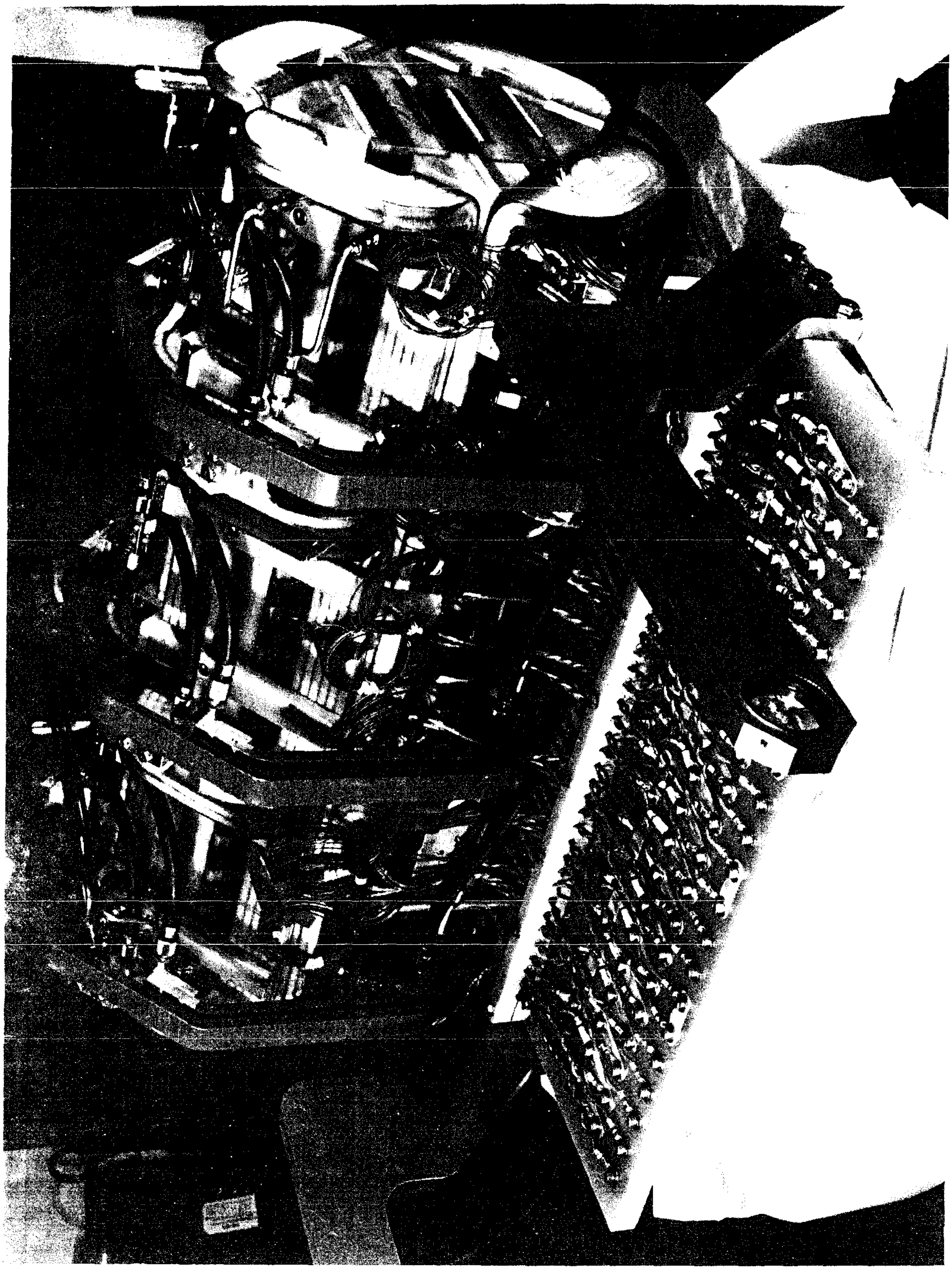
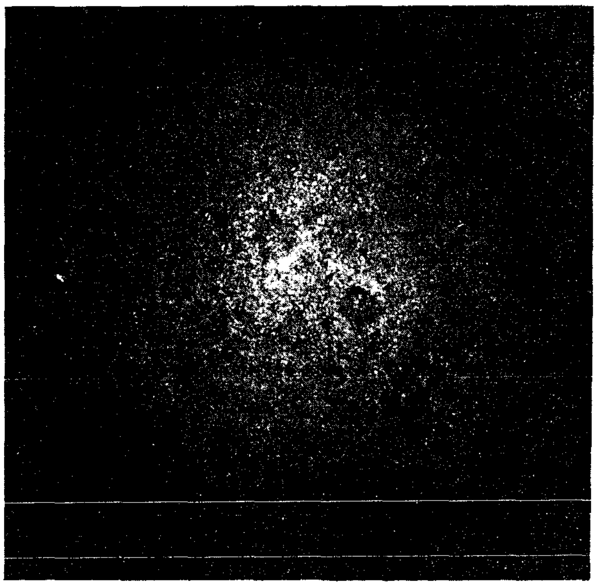


CBB 832-1765

Fig. 5



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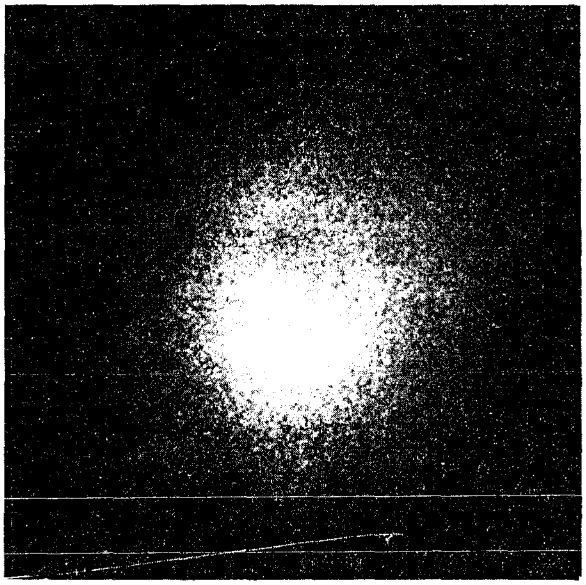

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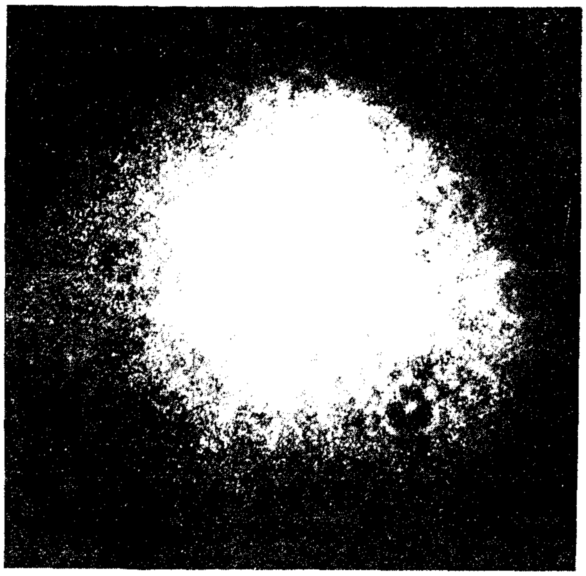

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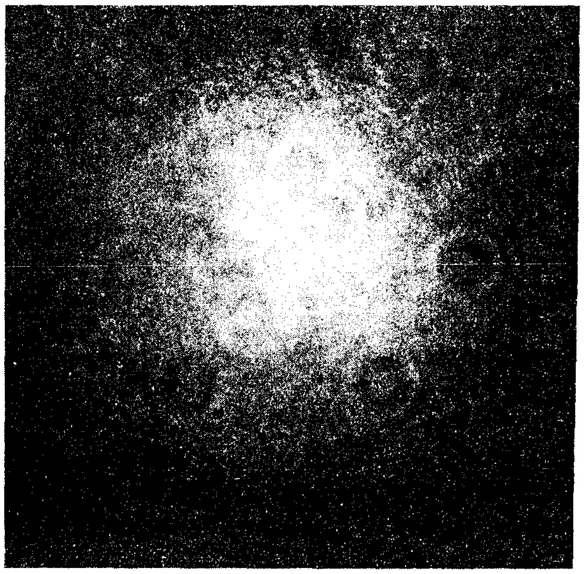

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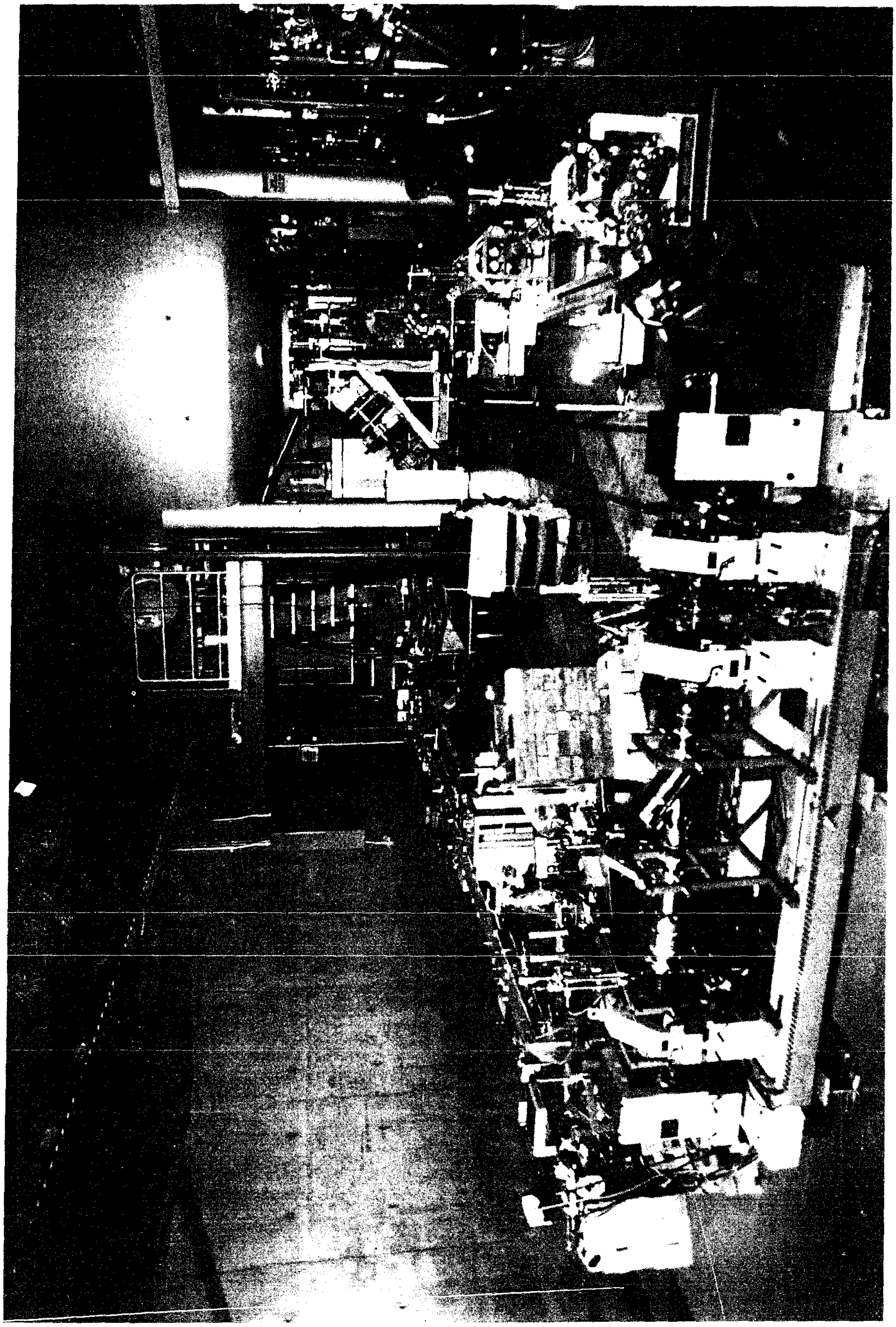
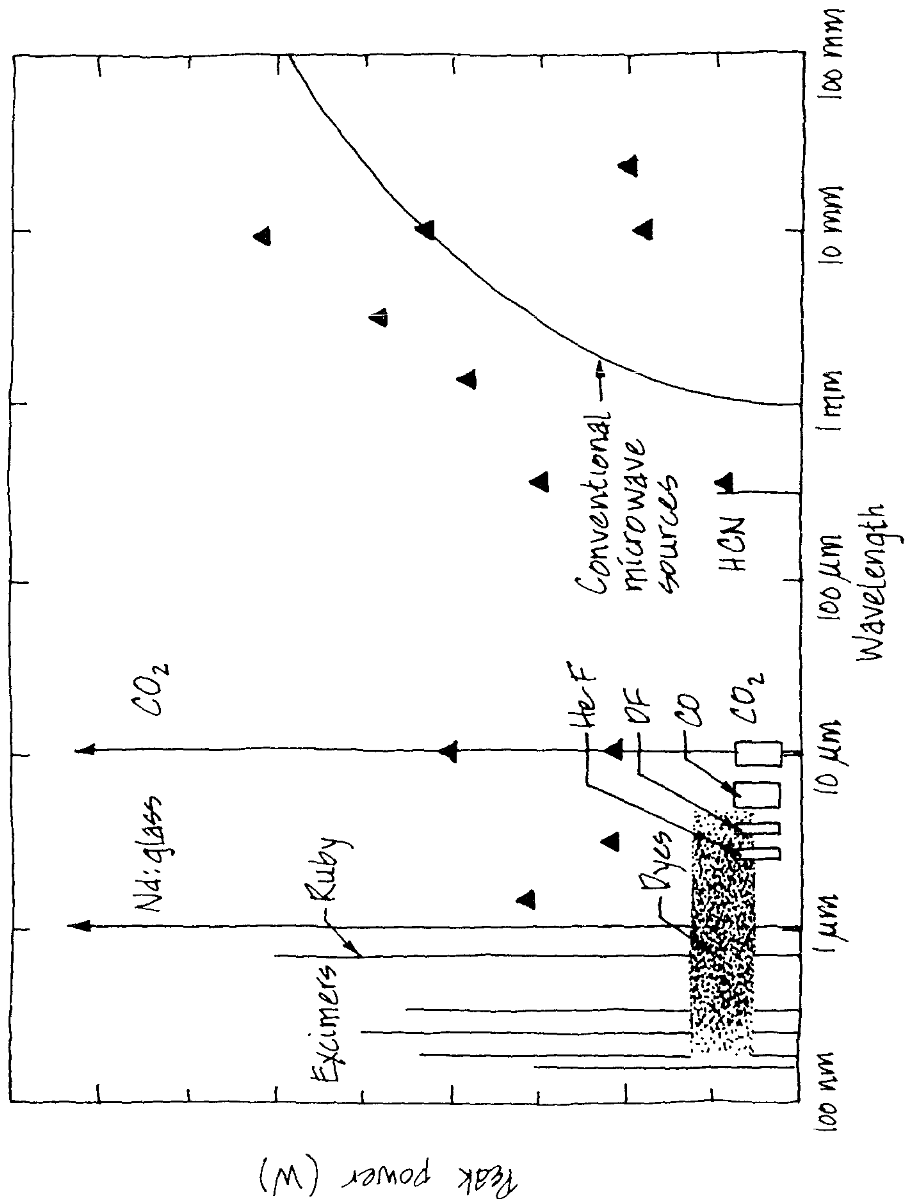


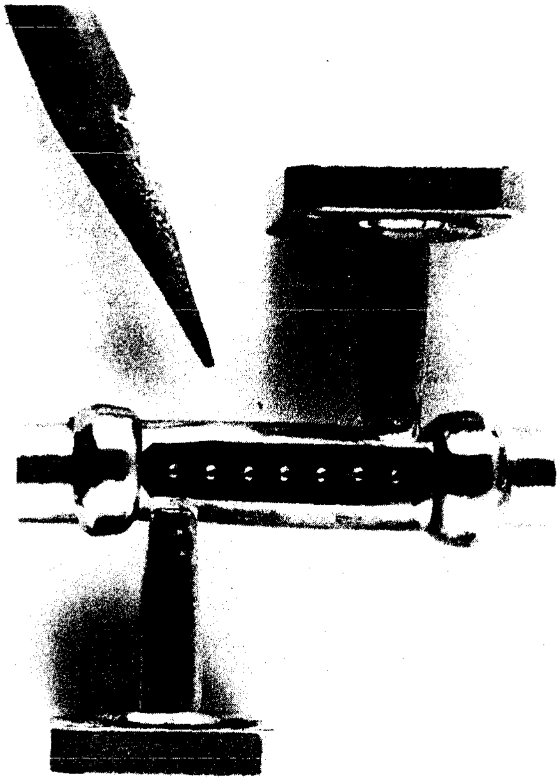
CBB 866-5093

Fig. 7



XBL 867-9218

Fig. 8



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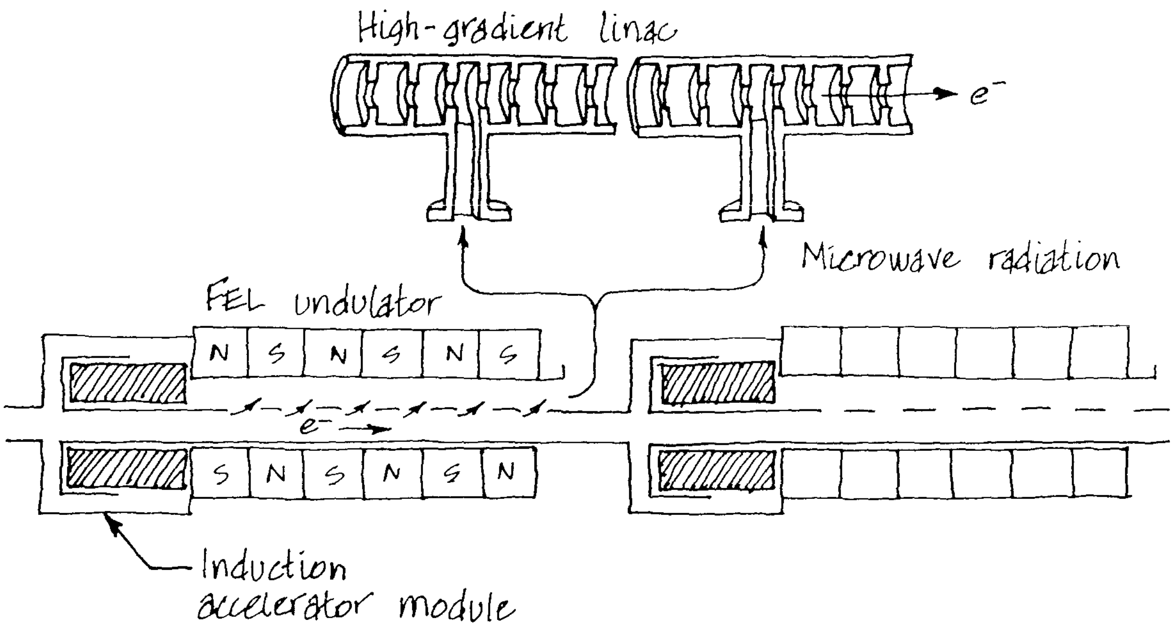

XBL 867-9217

Fig. 9