

# NEW PARTICLE ACCELERATION TECHNIQUES

The next generation of electron-positron colliders will have to be linacs with very large accelerating gradients provided by more or less novel techniques.

Andrew M. Sessler

In 1932 John Cockcroft and Ernest Walton developed an electrostatic accelerator at the Cavendish Laboratory, thus starting the modern age of particle accelerators. Since then, our capabilities have increased tremendously, as may be seen in figure 1, which shows the energy of accelerators through the years. There has been an exponential increase in energy (the "Livingston curve")—but it is the envelope that displays this exponential behavior, not any particular technique. One can conclude that if we are to stay anywhere near the Livingston curve, new techniques need to be developed.

I shall describe some of the new techniques that will be employed as we build accelerators even more powerful than the colliders just completed (the Tevatron collider at Fermilab, Tristan at KEK in Japan and the Stanford Linear Collider), those under construction (LEP at CERN, HERA in Hamburg and UNK at Serpukhov) and those under design (SSC in the US and the Large Hadron Collider in the LEP tunnel).

Circular accelerators are already remarkably effective. In fact, no one has any ideas for improving them, other than in an evolutionary manner. For example, new superconductors may provide stronger bending magnets, or less demanding cryogenic requirements. (If the new high-temperature superconductors are to be useful for accelerators, they will require high critical current density and the material properties that will permit the formation of wire.) Needless to say, such evolutionary changes can be very significant.

For protons, even at beam energies very much greater than that of the 20-TeV SSC, circular accelerators are

quite adequate. Not so for electrons, where synchrotron radiation forces one to use linear machines. At 1 TeV, for example, an electron in the 50-mile-circumference SSC tunnel would radiate away more than half its energy in just one turn! Because center-of-mass energy increases only as the square root of beam energy in a fixed-target relativistic accelerator, all modern accelerators are colliding-beam devices. Thus, all of the research efforts on new acceleration techniques for high-energy physics are focused on linear electron colliders, and here I will consider only such schemes.

The Stanford Linear Collider will soon be providing experimenters with 100-GeV  $e^+e^-$  collisions. The two-mile-long linear accelerator that speeds these particles up to 50 GeV provides an accelerating gradient of 17 megavolts per meter—more or less the present state of the art for rf linacs. If we are to have TeV linear  $e^+e^-$  colliders of reasonable length, we will need an order of magnitude increase in accelerating gradients. We do not yet have such a capability in hand. Intense efforts are now underway at CERN, SLAC, KEK and Serpukhov to develop the techniques that would allow these labs to build TeV linear colliders early in the 1990s.

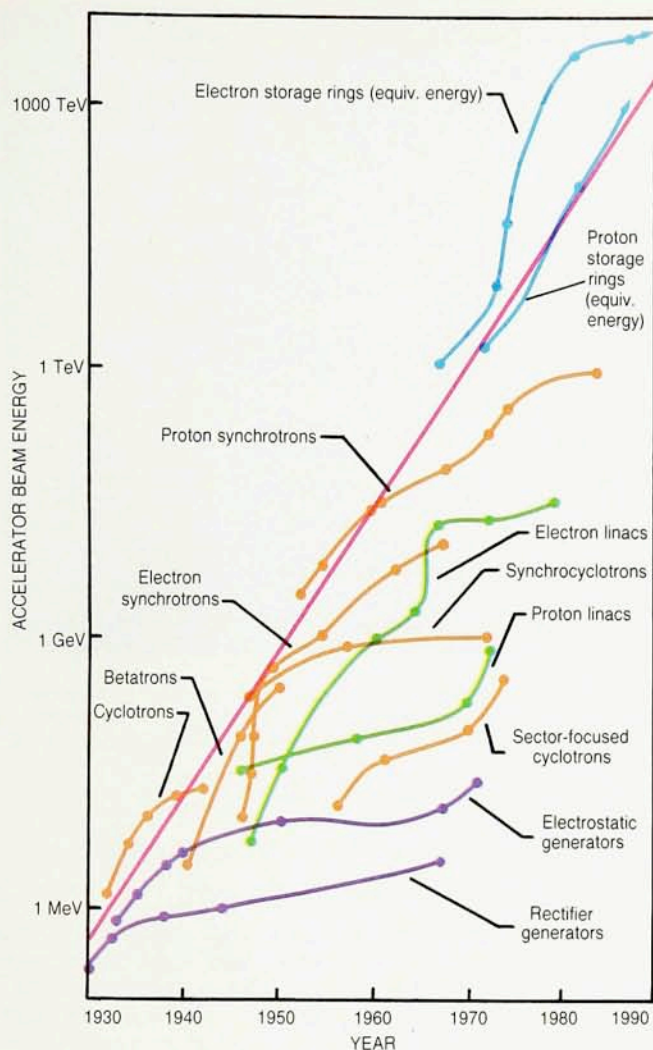
We will discuss only one aspect of such colliders—the acceleration process itself. The reader interested in other important aspects of linear colliders, such as damping rings, focusing systems and the disruptive interaction of the beams at collision, should consult the literature.<sup>1</sup> A number of recent conferences have been devoted to the subject of novel acceleration schemes, and the reader seeking more detail than can be included here may wish to consult their proceedings.<sup>2-6</sup>

## Categorizing accelerators

Particle accelerators do their work by means of the electromagnetic force. Because Maxwell's equations are

Andrew Sessler is a physicist at, and former director of, the Lawrence Berkeley Laboratory. He works in close collaboration with the Beam Research Program at Livermore.





**Advance** of accelerator beam energies since 1930. Though each successive technology eventually saturates, the envelope (red) of all these "Livingston curves" exhibits an inexorable exponential growth, maintained by the continued introduction of new techniques. Because our desires grow faster than the cost per volt falls, modern accelerators are very much more expensive than their predecessors. (For storage-ring colliders (blue) we plot the equivalent beam energy a fixed-target machine would need for the same center-of-mass energy.) **Figure 1**

linear, it is not difficult to construct a rather general theorem that provides a useful categorization of all accelerators.<sup>7</sup> Specifically, one can show that if a relativistic particle moving in vacuum at constant velocity interacts with any configuration of electromagnetic fields far from all surfaces of dielectrics or conductors, there can be no net acceleration of the particle. In particular, the theorem implies that the very intense electric fields at a laser focus ( $10^6$  MV/m, a hundred thousand times greater than the accelerating field of the SLAC linac) cannot be used to accelerate extremely relativistic particles.

At first sight it seems surprising that one can accelerate relativistic particles at all. But even relativistic particles do not move with strictly constant velocity, and accelerators can be built with conductors near the beam. As it traverses a medium or passes near conduc-

### Acceleration Alternatives

An electromagnetic wave in free space cannot accelerate particles traveling in a straight line. There are two classes of alternatives:

1. Slowing the electromagnetic wave; particles go in a straight line.

- a. conventional slow-wave structures
- b. new slow-wave structures such as "picker fences"
- c. dielectric slabs
- d. passive media
- e. plasma media

2. Bending the particles; electromagnetic wave goes as in free space.

- a. wiggling the particles with a static magnetic field
- b. wiggling the particles with an electromagnetic wave
- c. Allowing the particles to undergo cyclotron motion while proceeding longitudinally

tors or dielectrics, an electromagnetic wave slows down, and it can be made to resonate with a traversing particle. In this process, the wave develops a longitudinal accelerating component. Alternatively, we can bend the particles into serpentine trajectories; but this becomes more and more difficult at relativistic energies. A summary of these considerations is presented in the box above, which shows the division of proposed linear accelerators into two categories:

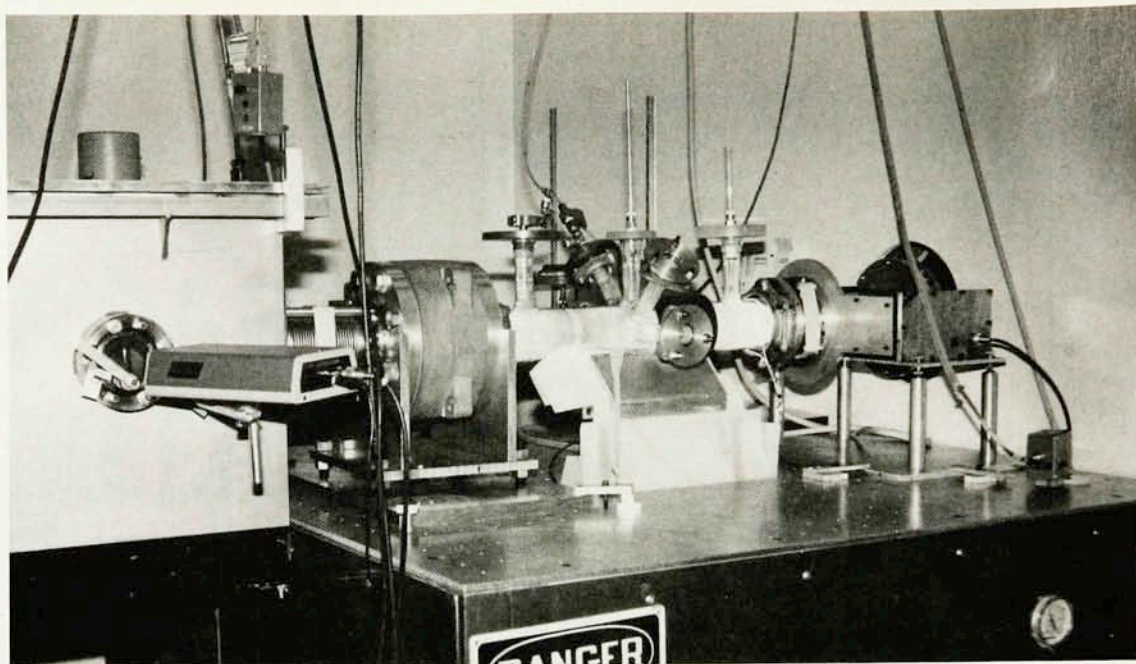
▷ those based on slowing down the electromagnetic accelerating drive

▷ those based on bending the paths of the particles.

We already have many accelerators based upon conventional slow-wave structures (item 1a). Typically, for electrons, these are disk-and-washer structures—for example the 2-mile-long SLAC linac. New structures (item 1b) are currently being modeled; they will be important at very short accelerating-field wavelengths such as those conveniently obtained from lasers. The exploitation of short wavelengths has also motivated the study of item 1c, dielectric slabs. By passive media (item 1d) we mean polarizable media, such as a gas below breakdown; into this category would fall the inverse Čerenkov-effect accelerator. Plasma accelerators (item 1e) are very different from conventional accelerators, and we shall see that they have great promise (and, needless to say, great problems).

The second general means of achieving particle-field resonance, namely bending the particles, is also the basis for the free-electron laser. (In an FEL, however, the





Beat-wave accelerator experiment at UCLA. Two laser beams and a 1.5-MeV electron pulse enter the plasma chamber from the right. The laser beat frequency excites a longitudinal density wave in the plasma, which the accelerating electrons ride like surfers. The fan-shaped structure houses the diagnostics. Figure 2

particles are being decelerated.) These are "fast-wave devices." That is to say, the walls do not have to be within a wavelength of the particles. Running a free-electron laser backwards would make an accelerator, and such devices have been proposed. However, any accelerator that employs trajectory bending will not be effective at very high energy, because of synchrotron radiation loss. Nevertheless, this limit is rather high—on the order of hundreds of GeV.

I will discuss four novel acceleration schemes, as well as several less radical approaches. The first two novel schemes are active-media devices: a laser-plasma accelerator and a plasma-wake-field accelerator. The other two novel proposals are slow-wave structures: the wake-field accelerator and the pulsed-power linac. In fact, most accelerators are slow-wave structures, and we shall see that within the confines of conventional structures there is still room for considerable variety. I shall consider four such "semiconventional" acceleration schemes.

### Laser-plasma accelerator

The laser-plasma accelerator in its first form was the beat-wave accelerator invented by John Dawson and Toshi Tajima at UCLA in 1979.<sup>8</sup> They proposed illuminating a plasma with two intense laser beams of angular frequencies  $\omega_1$  and  $\omega_2$ , whose difference is just the natural plasma oscillation frequency  $\omega_p$ . In this resonant condition, the plasma becomes very strongly bunched. That is, it develops a longitudinal density wave, which can then be employed for acceleration. The transverse electromagnetic field, quite ineffective for acceleration, has been converted into a longitudinal wave by this process. The accelerating electrons ride the plasma wave much like surfers. This development of "ponderomotive wells" can also be regarded as stimulated Raman forward scattering.

To determine the effectiveness of this process, and thus to appreciate its great promise, let us estimate the accelerating field one might obtain in a plasma. If the plasma bunches completely, then  $E_L$ , the longitudinal,

accelerating component of the electric field is given by

$$eE_L = mc\omega_p = 4\pi n r_0 mc^2$$

where  $e$ ,  $m$  and  $r_0$  are, respectively, the charge, mass and classical radius of the electron, and  $n$  is the plasma density. In a plasma, one can obtain densities of  $10^{17}$   $\text{cm}^{-3}$ , so that  $eE_L = 2 \times 10^4$  MeV/m. This is a very large gradient indeed!

Now we need to ask to what extent the plasma will bunch. Ponderomotive wave formation can be estimated analytically, and also evaluated numerically by particle simulation. The two approaches agree very well and indicate that bunching is incomplete; the accelerating gradient  $eE_L$  is reduced by a factor

$$\epsilon = \left[ \frac{16}{3} \left( \frac{eE_1}{mc\omega_1} \right) \left( \frac{eE_2}{mc\omega_2} \right) \right]^{1/3}$$

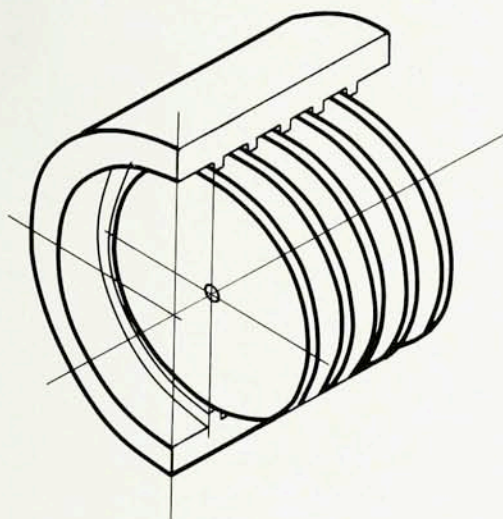
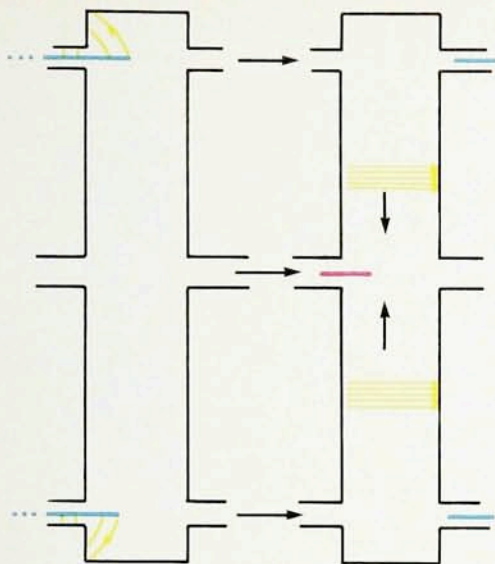
where  $E_i$  is the field strength of the input laser at frequency  $\omega_i$ . In practice, even taking the rise time of the laser into account,  $\epsilon$  can be as large as 0.7, so that one can expect to achieve very large acceleration fields.

One must make a rather uniform plasma along the length of the accelerator to maintain resonant excitation of the plasma wave. Recently a group at the Rutherford-Appleton Laboratory has obtained adequate uniformity in a "long" plasma 8 mm in length.<sup>9</sup>

Plasma stability is the really important point. To avoid ion effects such as "ponderomotive blowout," one must have a very short laser pulse—shorter than the ion plasma period. Even for such short pulses, adverse plasma phenomena such as laser filamentation and laser self-focusing can occur. In order to study these phenomena, two-dimensional particle simulation studies have been performed, supporting the analytic argument that one can probably find parameters that yield beneficial laser self-focusing but no filamentation.

Study has also been made of how one can add acceleration units in tandem. For one unit alone, the accelerated particles will soon pass the bottom of the





**Wake-field transformer** accelerating structure. This chain of disk-shaped cavities permits a ring-shaped bunch of low-energy electrons (blue) to drive a following bunch of high-energy electrons (red) along the axis. The driving bunch leaves behind a wake field (yellow), which is scraped off by the structure and transmitted inward toward the axis, where it becomes a strong accelerating field. **Figure 3**

ponderomotive well and begin giving energy back to the ponderomotive wave as they proceed up the next hill. Thus the accelerator must be terminated at an appropriate length. The maximum energy that particles can obtain in a single unit is given by

$$W_{\max} \approx \left( \frac{2\omega_1^2}{\omega_p^2} \right) mc^2$$

This maximum decreases with increasing plasma density, while the accelerating gradient  $eE_L$  increases with increasing plasma density. Thus, operation at a reasonably high acceleration gradient requires the "staging" of several accelerating units.

One must, of course, be concerned with the efficiency of the accelerator. The overall efficiency of the laser-plasma accelerator is a product of component efficiencies:  $\eta_L$  for generating the laser light,  $\eta_W$  for exciting the plasma

waves, and  $\eta_p$  for transferring the wave energy to the accelerating particles. The full efficiency,  $\eta_L \eta_W \eta_p$ , can easily become quite small.

Experiments have been started on the laser-plasma accelerator, or the more modest goal of generating beat waves, at UCLA, Rutherford-Appleton Laboratory in England and INRS-Energie in Canada. Figure 2 shows the experimental setup at UCLA. The UCLA group, led by Chan Joshi, and the Canadian group, led by Francois Martin, have achieved<sup>10</sup> accelerating gradients of the order of 500 MeV/m. The Canadian group has succeeded in accelerating electrons from 0.6 MeV to 2.5 MeV.

## The wake-field accelerator

The wake-field accelerator is based on the observation that an intense beam, passing near a conducting surface, will leave fields behind—a wake. This is a well-known effect that has been calculated and measured in great detail. Generally it is regarded as an adverse effect; intense beams passing through a cavity leave behind a wake that "loads down" a cavity and makes it "droop" in energy.

It was pointed out by Gustav Voss and Thomas Weiland at DESY in Hamburg in 1983 that an accelerator could be based upon use of the wake field.<sup>11</sup> It turns out, however, that if the beam to be accelerated is located in the same region of space as the wake-producing beam, the wake will not be particularly large. What is needed is a "wake-field transformer." Figure 3 shows a possible realization of this concept. A ring-shaped beam of low-energy electrons passing through a cylindrical conducting structure leaves behind a wake, which is then transmitted radially inward to become a strong accelerating field on the axis, along which the high-energy beam is traveling. In this way one might obtain accelerating gradients of 150 MeV/m. The primary difficulty is to create and control the wake-producing beam. If it is well defined and short in length, it will produce a strong wake. An experiment to prove the principle of this new mechanism is now under way at DESY. First results, in which electrons have indeed been accelerated, demonstrate the validity of this concept.

## The plasma-wake-field accelerator

Pisin Chen and his colleagues at UCLA pointed out in 1985 that an efficient way of producing the plasma wave for a laser-plasma accelerator would be to make use of a particle beam.<sup>12</sup> One would excite the plasma with an intense bunch train of high-energy electrons rather than by the beat wave of two laser beams. Because intense bunch trains are readily available, it is relatively easy to study this mechanism experimentally, and such work is currently under way in a collaboration between the University of Wisconsin and the Argonne National Laboratory.<sup>13</sup>

The plasma-wake-field accelerator is subject to the same restriction I've discussed above for wake-field accelerators in general. Because none of the plasma-wake-field configurations proposed so far are transformers, the plan is to tailor the driving pulse train so as to make the wake significant and thus achieve strong excitation of the desired plasma wave.

## The switched-power linac

The switched-power linac is a slow-wave structure conceptually quite similar to the wake-field accelerator. Both employ a cylindrical geometry and achieve enhancement of the accelerating voltage pulse by means of a radial transmission-line pulse transformer. The difference is that in the wake-field transformer the pulse is created by an intense electron ring, whereas in the switched-power



linac a current pulse would be produced by switching—probably by a laser pulse on a photocathode. The concept has been conceived and developed by William Willis and his coworkers at CERN and Brookhaven.<sup>14</sup>

The scheme exploits two ideas in particular: that a distributed power source leads to high power density and thus high accelerating gradients; and that a short pulse length implies high peak power, low stored energy and thus limited heating. The high power density requires a high, pulsed charging voltage. High gain requires that the switched energy be very much larger than the laser energy, and high efficiency requires that the switched energy be comparable to the stored energy. Thus the switched-power concept quickly leads to a study of high-voltage breakdown, to the development of a photocathode and its associated laser, and to the problem of aligning the laser with the photocathodes and the disks of the accelerator structure. A scale model, built at CERN, is shown in figure 4. The development program there has been going on for two years. At least another two years will be required to demonstrate one stage of a switched-power linac.

An alternative to the photocathode switching under consideration at CERN and Brookhaven would be a solid-state switching scheme being studied at the Universities of Rochester and Osaka. There are questions of efficiency, jitter, high-voltage breakdown, lifetime, repetition rates and the like. In particular, the photocathodes would have to operate in the novel situation in which the photon flux is very high and brief and the electric fields on the switch are very strong. Initial studies have achieved photocurrent densities of  $10^4$  A/cm<sup>2</sup> with surface fields of 0.06 GV/m (gold-tungsten wire cathodes of 50- $\mu$ m diameter). Work is now devoted to increasing the field to about 1 GV/m, to obtain  $10^5$  A/cm<sup>2</sup> with a quantum yield of  $10^{-2}$ . This would represent an order of magnitude increase over present quantum yields.

In the switched-power scheme, as in the wake-field and laser-plasma accelerators, one faces the important question of reproducibility. In linear colliders, one imagines bringing into collision beams that are a fraction of a micron wide. Such extreme beam compression is necessary if one is to obtain useful collision rates with beams that collide only once before they are disposed of. Can these acceleration concepts lead to beams whose jitter from pulse to pulse is much less than a micron? We don't know yet. Conservative people will go with a "conventional linac," where a great deal is known about deflecting modes and jitter. Such people elect to put their inventive talents into developing novel power sources. In the remainder of this article, I will describe some of their efforts.

## Two-beam accelerators

Two-beam accelerators have been studied for some years now by our group at the Lawrence Berkeley and Lawrence Livermore Labs and, more recently, by Wolfgang Schnell and his coworkers at CERN.<sup>15</sup> The concept is illustrated in figure 5. Instead of many thousands of power tubes arrayed along the length of the accelerator, one would employ a single high-intensity driving beam of low-energy electrons, parallel to the high-energy beam one seeks to accelerate. The idea makes sense because it is rather easy to make high-power beams of low-energy electrons. This same capability is also an important reason for the great interest nowadays in high-power free-electron lasers.

The two-beam scheme is essentially an attempt to miniaturize conventional rf accelerating structures so that one obtains extraordinarily large accelerating gradients with high efficiency. The low-energy driving beam

provides the short-wavelength rf power essential to this miniaturization. We are speaking of wavelengths on the order of 1 cm, in place of the 10-cm microwave power that present-day rf linacs get from klystron arrays.

The driving beam can give up its energy in at least two ways: It can either be passed through an undulator, thus functioning as a free-electron laser, or it can be bunched and passed through resonant "transfer cavities." As it feeds out microwave power along the length of the accelerator, the driving beam's energy can be replenished by pulsed induction-linac modules or superconducting rf cavities placed along its path. Figure 5 shows a two-beam accelerator with FEL undulators and induction-linac units. An induction accelerator is well matched to the requirements of a collider; it produces high peak power for a short pulse length, and it can be pulsed repeatedly.

The generation of rf power in the two-beam accelerator is very efficient over a wide range of frequencies because energy not given up by the driving beam need not be resupplied by the energy-supply system. Thus, the operating efficiency of a two-beam accelerator can be very high—approaching 100%.

The two-beam concept offers considerable latitude in the choice of rf frequency; it can thus be chosen for linear-collider considerations rather than by consideration of the availability of power sources. As the rf frequency  $f$  is







Scale model radial transformer line for the switched-power linac scheme, built at CERN to study transformer ratio as a function of pulse length. A transformer ratio of more than 20 was observed, in good agreement with theory, and not sensitive to drive imperfections. **Figure 4**

increased, the energy stored in the accelerator decreases as  $f^{-2}$ , because the transverse size of the linac is proportional to the wavelength. Thus the average rf power also scales as  $f^{-2}$  and the operating cost decreases with increasing frequency. The accelerating gradient at which one can operate the linac increases with frequency, roughly as  $f^{0.88}$ , because spark breakdown is inhibited as the pulse is shortened in time and the frequency is increased. Thus one can attain a desired electron energy with a shorter linac. The high gradient does, however, require high rf power, which is a major component of the capital cost. But for many schemes the total capital cost, as well as the operating cost, is less for the smaller, higher-gradient linac.

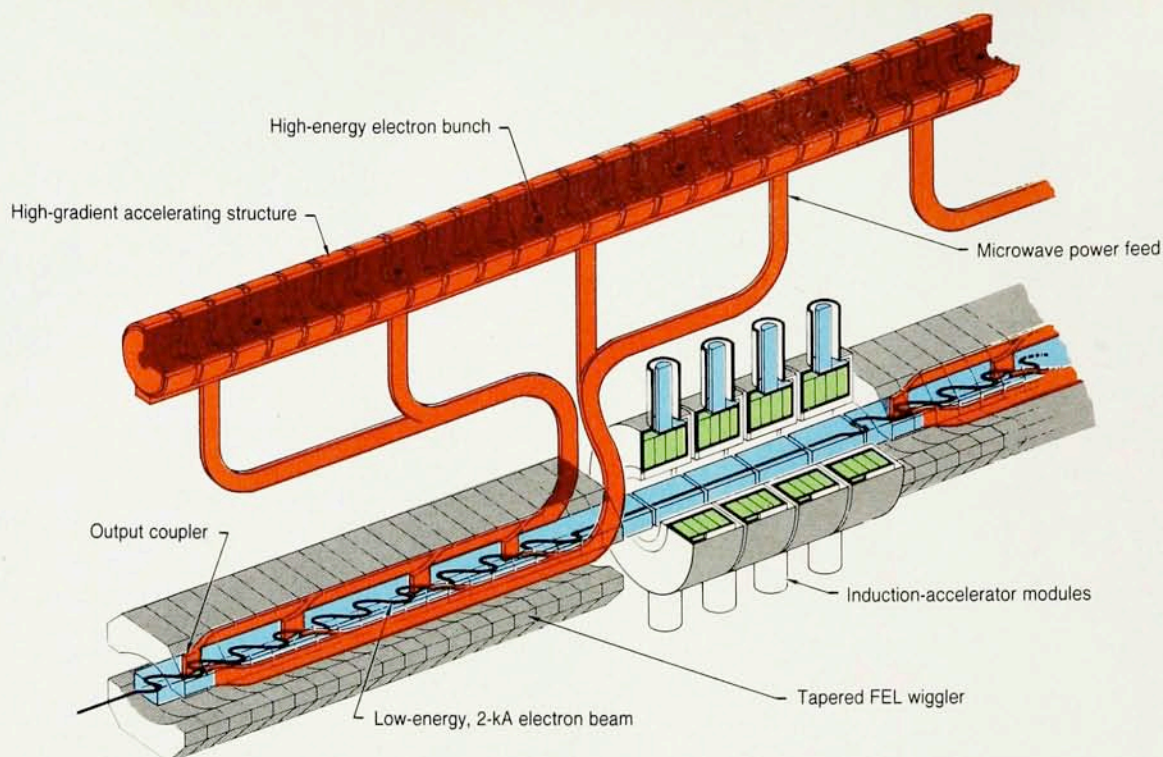
However, as the linac grows smaller with increasing rf frequency, it becomes ever more difficult to fabricate. Furthermore, adverse wake-field effects in the high-energy beam become more severe. The longitudinal beam-induced wake field scales as  $f^2$ ; the transverse wake as  $f^3$ . For example, dipole fields, which cause the beam to snake and twist, vary as the inverse cube of linear dimensions;

the harm they do increases like  $f^3$ .

Putting these diverse considerations together, we currently think that the frequency should be somewhere between 10 and 30 GHz. Our LBL-Livermore group has fabricated a 4-inch-long prototype section of a 30-GHz structure, using a brazing technique that is typically employed for rf linacs. Alternatively, one can use an electroforming process, with the result shown in figure 6. Both methods appear to be acceptable, demonstrating that frequencies as high as 30 GHz (a wavelength of 1 cm) can be employed in a linac. Furthermore, our group has achieved an accelerating gradient of 180 MeV/m in a small (five-cell) 35-GHz structure, using Livermore's ELF electron laser facility as the rf power source.

The LBL-Livermore group devoted considerable effort to the FEL version of a two-beam accelerator. Our Livermore colleagues, led by Donald Proznitz and Thaddeus Orzechowski, have shown that the FEL is a copious source of microwave power.<sup>16</sup> They have obtained more than 1.8 GW at 35 GHz from the ELF, a 3-meter-long undulator with a 1.1-kA beam of 3-MeV electrons passing





**Two-beam accelerator** envisioned by the Berkeley-Livermore group. A high-gradient miniature of a conventional rf accelerating structure is fed short-wavelength microwave power from an adjacent high-current beam of low-energy electrons serving as a free-electron laser as it undulates through wiggler magnet arrays. The energy this driving beam gives up to the high-energy electron beam is replenished by induction-linac modules along the way. **Figure 5**

though it. The efficiency of this conversion was greater than 40% from beam energy to microwave energy. Problem areas that remain to be studied, and there are many, include phase control of the rf, transverse stability of the driving beam, and the transport of intense microwave power from the FEL to the acceleration gaps.

All of these problems appear to be solvable, but at the expense of simplicity. The phase control of the rf, for example, is particularly difficult. Because of the powerful amplifier action of the FEL, the rf phase is sensitive to beam current, wiggler field and beam energy. So far, the only method devised to control phase is to discard the rf when its phase is unacceptable and reinsert proper-phase rf at a small cost of emittance growth in the driving beam wiggling its way through the FEL.

The transfer-cavity alternative, often called the relativistic klystron version of the two-beam accelerator, shown in figure 7, is now the object of considerable effort by a SLAC-Berkeley-Livermore collaboration, and also by the CERN group. It does seem to remove some of the problems associated with the FEL, but one should note that the FEL has been demonstrated to produce power, while the relativistic klystron thus far exists only on paper. People have investigated transfer-cavity problems such as longitudinal and transverse beam dynamics and the proper design of the cavities. Transverse beam dynamics is of particular concern because the very small transfer cavities enhance transverse instability, causing "beam breakup."

### Klystrons, lasertrons and gyroklystrons

Finally, I will describe three other possible sources of short-wavelength power for a high-gradient rf linear accelerator.

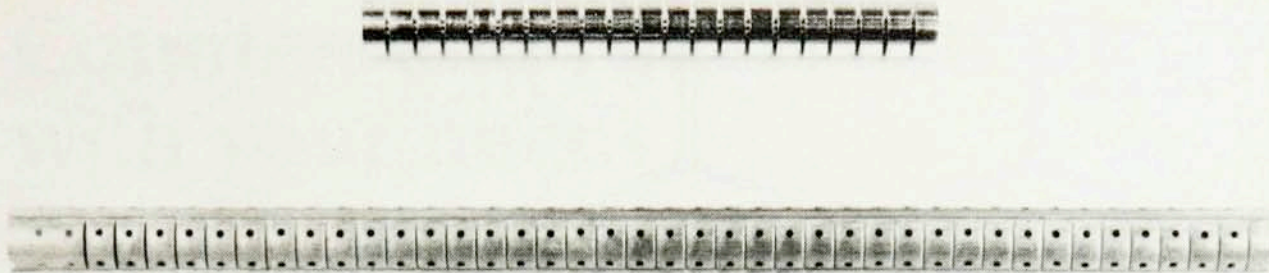
**The klystron**, until now the power amplifier of choice for electron-positron linear colliders, is an electron-beam tube usually containing two cavities. In the first cavity a velocity modulation is imposed on the tube's electron beam and the bunched beam then radiates coherent microwaves into the second, tuned output cavity. The SLAC linac operates in the "S band," at a wavelength of 10 cm, so that S-band klystrons have been the subject of extensive development. Having been upgraded to serve as the accelerator for the Stanford Linear Collider, the linac now accelerates electrons and positrons to 50 GeV. More than two hundred 65-MW klystrons line the great gallery atop the linac, feeding it rf power in 3.5-microsecond pulses.

A klystron operating in the S band has produced 150-MW peak power in a pulse of 1 microsecond. The high-energy linear colliders we envision for the next generation will have to operate at significantly shorter wavelengths. Experiments at SLAC have shown that an accelerating gradient of more than 200 MeV/m can be achieved at the 3-cm wavelength regime, the so-called X band. As klystrons are designed for higher frequency, the output power decreases as the cavities must be made smaller, reducing the klystron's beam current.

A development program is under way at SLAC to build a 100-MW, 2- $\mu$ sec klystron operating in the X band with 65% efficiency.<sup>17</sup> The rf pulse will have to be further compressed because at these wavelengths the rf must fill the accelerating structure in 100 nanoseconds. A compression scheme can be devised, but it requires very long sections of waveguide (2000 feet for a 2- $\mu$ sec pulse). For still shorter rf wavelengths, conventional klystrons do not seem to be suitable for linear colliders.

A second development program at SLAC, in collabora-





High-gradient accelerator section, 10 cm long, fabricated at Livermore as part of the two-beam accelerator study. The completed copper disk-and-washer structure (bottom) is made by electroforming copper over an aluminum "mandrel" (top) and then removing the aluminum with strong hydroxide. This miniature rf structure is resonant at 1 cm, an order of magnitude shorter than the wavelengths of present-day high-energy linacs. **Figure 6**

tion with Livermore, employs pulse-forming devices, using saturable inductors pioneered at Livermore to make a short-pulse (50–100 nsec) klystron.<sup>17</sup> They are planning to put a megavolt pulse on an X-band klystron in the expectation that a peak power on the order of a gigawatt may be obtained from klystrons at very short pulse widths. The development confronts problems associated with large cathode-anode stresses and with the cathode current-density responses to the fast rise times (15 nsec) of very short pulses. The group aspires to efficiencies on the order of 70%.

**The lasertron** is a microwave power tube that employs a photoemission cathode illuminated by an optical pulse train of the proper microwave structure to produce a bunched electron beam directly at the cathode. This lasertron beam is accelerated to high voltage and immediately passed through an rf output structure to produce microwave power for the linac. In a high-peak-power device there is considerable charge in each bunch, requiring that the lasertron beam be confined transversely by an axial magnetic field, and that it be rapidly accelerated to limit longitudinal spreading. As in all microwave power tubes, the spent lasertron beam is dumped in a collector. Lasertrons are under active development at SLAC, KEK and Orsay.<sup>18</sup> The idea is also being studied at the Texas Accelerator Center and at Los Alamos.

The attractiveness of a photoemission cathode stems from the ease with which one can directly modulate the emission at high frequency, and from the very high current densities one can readily obtain. The lasertron development program at SLAC involves learning to prepare robust high-current-density photocathodes capable of operating for long periods in the environment of a high-power microwave tube. Because photoemission cathodes are typically far more sensitive than thermionic cathodes to degradation or destruction by residual gases, one needs a very good vacuum system. Furthermore, photocathodes generally require alkali metals for their activity, which makes the operation of high-voltage guns more difficult.

The laser itself is a complex system, far more costly than a filament transformer. The necessity of getting the illuminating light to the cathode can add significantly to the complexity of the basic device. In general, photoemission cathodes operating in actively pumped ultrahigh-vacuum systems have not shown very long lifetimes, and the ability of these cathodes to deliver the large total charge required over the operating life of a microwave power source has not yet been demonstrated.

On the other hand, the lasertron is in many ways

simpler than thermionic devices, so it may be possible to produce a relatively inexpensive unit. Because the photocathode emits only while illuminated, only a dc power supply or a very simple modulator is needed, as opposed to the complex and expensive modulators necessary for devices with thermionic emission cathodes. This is true, however, only if the very large voltages required to accelerate bunches before they disassemble due to space charge can be held in dc.

If they are to be useful for future linear colliders, lasertrons must be extended to shorter wavelengths. The lasertron is, however, subject to the same wavelength scaling law as the klystron; both give decreased output power as the frequency is increased. Recently, the Texas group has proposed a non-axial-symmetric "sheet beam" lasertron for delivering high power at high frequency.

**Gyrotron oscillators** have been developed for heating thermonuclear fusion plasmas at short wavelengths (5 mm), with very high average power (300 kW), high peak power (300 MW) and high efficiency (50–65%). Although some effort has been made to develop gyrotron amplifiers (as distinguished from oscillators), a group at the University of Maryland has only recently begun to develop a high-peak-power gyrotron tube.<sup>19</sup>

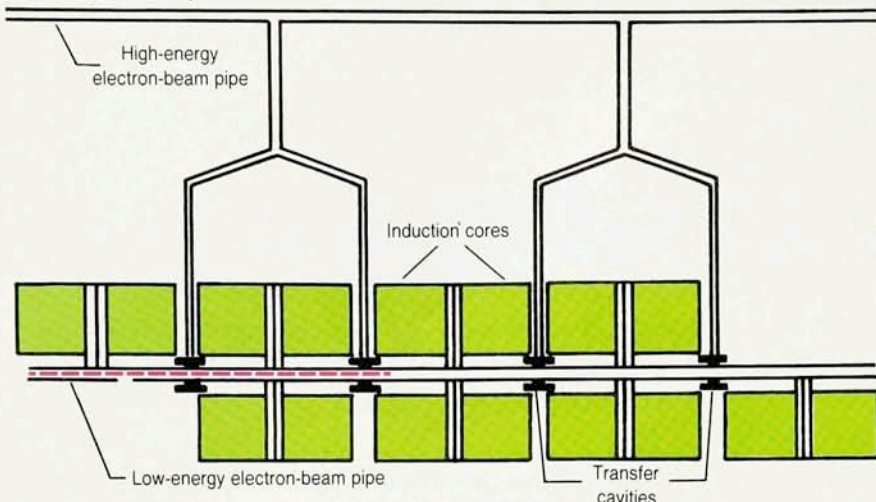
The basic idea of the gyrotron (also called a cyclotron-maser or gyroklystron) is to produce a near resonance between a harmonic of the electron cyclotron frequency and an output cavity mode. A longitudinal magnetic field causes the gyrotron's spiraling electron beam to bunch, thus generating coherent short-wavelength radiation.

The suppression of unwanted modes is the paramount issue here. Also of concern are wall losses and space-charge depression, both of which must be kept within acceptable bounds. These considerations work in opposite directions; the suppression of unwanted modes is most easily achieved by using a small cavity in which few modes are excited. On the other hand, wall losses are minimized by working in a large cavity, and space-charge depression is minimized by using a large-radius, low-density beam.

Phase stability in the gyroklystron is a crucial consideration for use in large linear accelerators, where hundreds or even thousands of microwave amplifiers must be synchronized. While this is a demanding requirement, especially for the modulator, it is within the state of the art. Because prior studies of gyroklystrons have been plagued by spurious oscillations, stability is of special concern.

The Maryland design is for a 10-GHz tube producing 2- $\mu$ sec pulses with a peak power in excess of 30 MW and an efficiency of 45%. Studies indicate that the design can be scaled up to power levels exceeding 150 MW. This would





Relativistic klystron version of the two-beam accelerator. Instead of passing through an FEL wiggler, the driving beam of low-energy electrons is bunched and sent through resonant transfer cavities, thus producing copious microwave radiation, which is sent to the high-gradient accelerating structure. Here we show one period of such an accelerator. **Figure 7**

be accomplished by increasing the voltage, radius and current of the tube's beam while maintaining its intensity. Just as in the conventional klystron, the gyroklystron's output pulse would have to be further compressed so that it matches the requirements of the accelerating structure.

## Continuing the growth

There is clearly no lack of ideas for new acceleration schemes. They range from evolutionary developments of conventional power sources to completely new concepts such as the laser-plasma accelerator. Furthermore, there are already modest experimental programs associated with each of the approaches discussed here. Success in some of these developments is crucial to the building of future high-energy electron-positron colliders.

But conventional accelerators are very effective and very large. Something really new is not going to compete until it has undergone extensive development and modeling. That process will be lengthy and expensive, but necessary if we are to continue to see, as we have in the past, the exponential rise in the accelerator energy available to high-energy physicists shown in figure 1, and hence the continuation of high-energy physics as an experimental science.

## References

1. B. Richter, in *Laser Acceleration of Particles*, AIP Conf. Proc. 130, C. Joshi, T. Katsouleas, eds., AIP, New York (1985), p. 8.
2. P. B. Wilson, in *1986 Linear Accelerator Conf. Proc.*, SLAC-303, Stanford Linear Accelerator Center, Stanford, Calif. (1986), p. 585.
3. B. Richter, in *Proc. 1984 ICFA Seminar on Future Perspectives in High Energy Physics*, KEK-841, KEK, Tsukuba, Japan (1984), p. 226.
4. P. J. Channell, ed., *Laser Acceleration of Particles*, AIP Conf. Proc. 91, AIP, New York (1982).
5. J. Mulvey, ed., *The Challenge of Ultra-High Energies*, ECFA 83/68, Rutherford Laboratory, Didcot, UK (1982).
6. *The Generation of High Fields for Particle Acceleration to Very High Energies*, ECFA 85/91, CERN 85-07, CERN, Geneva (1984).
7. C. Joshi, T. Katsouleas, eds., *Laser Acceleration of Particles*, AIP Conf. Proc. 130, AIP, New York (1985).
8. F. Mills, ed., *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, AIP, New York (1987).
9. A. M. Sessler, *Am. J. Phys.* **54**, 505 (1986).
10. T. Tajima, J. M. Dawson, *Phys. Rev. Lett.* **43**, 267 (1979).
11. A. E. Dangor *et al.*, in *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, F. Mills, ed., AIP, New York (1987), p. 112.
12. C. E. Clayton, C. Joshi, C. Darrow, D. Umstadter, *Phys. Rev. Lett.* **54**, 2343 (1985).
13. F. Martin *et al.*, in *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, F. Mills, ed., AIP, New York (1987), p. 121.
14. G. A. Voss, T. Weiland, in *The Challenge of Ultra-High Energies*, ECFA 83/68, J. Mulvey, ed., Rutherford Laboratory, Didcot, UK (1982), p. 287.
15. H. Dehne *et al.*, *Proc. 12th Int. Conf. on High Energy Accelerators*, Fermilab, Batavia, Ill. (1983), p. 454.
16. P. Chen, J. M. Dawson, R. W. Huff, T. Katsouleas, *Phys. Rev. Lett.* **54**, 693 (1985).
17. J. Rosensweig *et al.*, in *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, F. Mills, ed., AIP, New York (1987), p. 231.
18. W. Willis *et al.*, in *Laser Acceleration of Particles*, AIP Conf. Proc. 130, C. Joshi, T. Katsouleas, eds., AIP, New York (1985), p. 421.
19. S. Aronson, in F. Mills, ed., *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, AIP, New York (1987), p. 283.
20. A. M. Sessler, in *Laser Acceleration of Particles*, AIP Conf. Proc. 91, P. J. Channell, ed., AIP, New York (1982), p. 154.
21. A. M. Sessler, S. S. Yu, *Phys. Rev. Lett.* **58**, 2439 (1987).
22. W. Schnell, in *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, F. Mills, ed., AIP, New York (1987), p. 17.
23. T. Orzechowski, B. Anderson, J. Clark, W. Fawley, A. Paul, D. Prosnitz, E. Scharlemann, S. Yarema, D. Hopkins, A. Sessler, J. Wartele, *Phys. Rev. Lett.* **58**, 2172 (1986).
24. M. Allen, private communication.
25. C. K. Sinclair, in *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, F. Mills, ed., AIP, New York (1987), p. 298.
26. M. Yoshioka, in *Int. Symp. on Advanced Accelerator Concepts*, AIP Conf. Proc. 156, F. Mills, ed., AIP, New York (1987), p. 313.
27. K. R. Chu *et al.*, *IEEE Trans. Plasma Sci.* **P5-13**, 424 (1985). ■