

ADVANCED ACCELERATOR CONCEPTS

While near-term ideas for e^+e^- colliders range from superconducting linacs to ultrarelativistic klystrons, future particle physicists may collide multi-TeV beams of particles accelerated by specially tailored plasmas.

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High-energy accelerators have been physicists' main tools for exploring the building blocks of matter for more than 60 years. During this time the particle energy has increased exponentially as a result of a combination of improvements in existing machines and the invention of new acceleration techniques. Historically, whenever a given type of accelerator has reached the limit of its performance, an innovative idea for particle manipulation, storage, cooling or acceleration has made possible experiments at ever higher energies. The tremendous increase in the energy of accelerators has not, however, been without an increase in capital costs. The cancellation of the Superconducting Super Collider makes timely an examination of possible alternative concepts for investigating some of the same physics.

All past and present acceleration schemes rely on the interactions of a charged particle with a component of an electric field parallel to its velocity. Slow-wave or near-field schemes require the presence of a nearby medium (such as a plasma or a waveguide) to give an axial component (parallel to the beam velocity) to the electric field of an electromagnetic wave, while far-field accelerators give the beam particles a transverse velocity component, parallel to the transverse electric field of a free-space wave.

Regardless of the specific acceleration mechanism, the overriding criteria in particle accelerator design are the accelerator's cost and the physics one can study with it. These in turn constrain the accelerator's size, its beam energy, its luminosity (which, multiplied by the interaction cross section, gives the event rate) and the efficiency with which it must convert electrical energy into particle kinetic energy. As shown in table 1, this means the highest-energy accelerators have many similar features. All these accelerators are colliders. All of the proton colliders are circular. The radii of circular e^+e^- colliders increase rapidly as their energy increases. (A linear collider effectively has an infinite radius.) The reasons for these characteristics apply equally to future accelerators.

A colliding-beam accelerator is more compact and energy efficient than a fixed-target machine, because more of a collider's beam energy is available to produce particles. According to relativistic scattering theory, only the energy

in the center of mass is available to produce particles. In a fixed-target machine the center-of-mass energy increases only as the square root of the beam energy, while in a collider with beams of equal energy, the center-of-mass energy is just twice the beam energy. Thus a 1-GeV e^+e^- collider will have as much center-of-mass energy as a 1-TeV fixed-target machine.

Whether to use electrons or protons and whether the collider should be linear or circular are questions whose answers depend on several factors. The advantage of a circular over a linear collider is that the former reuses the noninteracting beam particles for millions of subsequent collisions, while the latter dumps those particles and their energy into a beam dump after a single collision. As such, a linac must focus its particle beams to the smallest possible dimensions to maximize the event rate and minimize energy waste. All other things being equal, this would be a strong argument for all colliders to be circular.

Of course all other things are not equal. An electron is a fundamental particle, with all of its center-of-mass energy available to create particles, while a proton's energy is divided among its three quarks and its gluons. Unfortunately, above a certain energy a circular electron accelerator suffers severe synchrotron radiation losses, proportional to E^4/m^4R^2 , where E is the beam particle's energy, m is its rest mass, and R is the accelerator's radius of curvature. This expression tells us three things: First, because of their much larger mass, protons emit about 10^{-13} times as much synchrotron radiation as electrons of the same energy. Second, limiting synchrotron radiation losses by increasing the accelerator's radius requires increasing the machine's radius (and hence its cost) as the square of the beam energy. (A 0.5-TeV electron beam would lose over half its energy in a single turn of the 27-km LEP tunnel at CERN.) Third, for high-energy e^+e^- colliders, linear accelerators become an attractive option. This is why all proton colliders are circular and all future e^+e^- colliders will likely be linear.

In part because circular proton colliders are a mature technology and are scalable to higher energies, most advanced accelerator research has focused on e^+e^- colliders. The work can be divided into research on colliders that may be built in the next decade or so and research on advanced accelerator concepts that may offer alternatives further in the future. Here I will examine some of the near-term ideas and some longer-range, plasma-based

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Table 1. High-energy accelerators

Accelerator	Particles	Energy	Comments
LEP (CERN)	Electron-positron	48 GeV $\times$ 48 GeV	27-km circular collider; proposed LEP200 upgrade will be capable of 100 GeV $\times$ 100 GeV
Tristan (KEK, Japan)	Electron-positron	30 GeV $\times$ 30 GeV	3-km circular collider
Tevatron (Fermilab)	Proton-antiproton	1 TeV $\times$ 1 TeV	6.5-km circular collider
HERA (DESY, Germany)	Electron-proton	30 GeV $\times$ 820 GeV	Circular collider
SLC (SLAC)	Electron-positron	50 GeV $\times$ 50 GeV	3.2-km (mostly) linear collider
LHC (CERN)	Proton-proton	8 TeV $\times$ 8 TeV	Proposed circular collider in 27-km LEP tunnel
SSC	Proton-proton	20 TeV $\times$ 20 TeV	Terminated

acceleration schemes. Other ideas are discussed in the literature.

Lessons of the first linear collider

The first linear collider, the Stanford Linear Collider, produces 50-GeV electron and positron bunches.¹ These bunches, each with about 3×10^{10} particles, are collided 120 times per second after being focused down to transverse dimensions of 2.6 by 0.8 microns. (See the news story on page 22.) To obtain this small spot size all the beam particles must be moving in nearly the forward direction, or in accelerator terminology, the beam emittance—the beam area in transverse (xp_x or yp_y) phase space—must be small. The critical goal of preserving the low emittance during acceleration becomes more difficult as the number of particles, and hence the interaction of the bunch with its electromagnetic environment (the conductors that make up the accelerating structures and so forth), increases. The success of SLC scientists in accelerating and colliding intense, low-emittance bunches is evident in the greater-than-hundredfold increase in weekly Z^0 production over the last two years.

The SLC polarized electron source, installed in spring of 1992, has greatly facilitated studies of polarization-dependent effects. In this source, electrons are preferentially emitted with longitudinal spin polarization when a circularly polarized Ti:sapphire laser beam strikes the photocathode. Great care is taken to avoid depolarization as the spins precess in the magnetic fields in the injector, damping rings, main linac and final focus. The initial polarization of 65–70% is reduced to about 60% at the collision point. The knowledge gained at the SLC will be essential to the operation of the next linear collider.

Much of the research² on the next collider has focused on a machine like that shown in figure 1, with an initial center-of-mass energy around 500 GeV (upgradable to 1–2 TeV) and a luminosity $\mathcal{L}$ on the order of 10^{33} – 10^{34} /cm² sec, about 10^4 times the SLC luminosity. Before discussing specific design concepts, it will be instructive to examine three fundamental constraints common to all designs, namely constraints on the required luminosity, the average power consumption and the synchrotron radiation (“beamstrahlung”) emitted during the collision. The complicated interplay among the parameters that define a collider design is discussed in the literature.³

Constraints on collider design

The desire to obtain experimental data at a reasonable rate fixes the luminosity $\mathcal{L}$ of the machine. In terms of the number of particles N in each bunch, the bunch transverse dimensions σ_x and σ_y , and the bunch collision frequency f , the luminosity is, for a bunch with a three-dimensional Gaussian profile, $\mathcal{L} = fN^2/4\pi\sigma_x\sigma_y$. (This ex-

pression neglects a “pinch” correction due to the superposition of the beams’ magnetic and electric fields. If the pinch is not too severe it enhances the luminosity.)

To achieve a luminosity of 4×10^{33} /cm² sec with 10^{10} particles per bunch and a transverse cross-sectional area of 3×10^{-3} μ m² would require bunches colliding 5000 times per second. The average power in the colliding beams would then be $2fN\gamma mc^2 = 4$ MW, where γmc^2 is the individual particle energy. The accelerator must therefore be quite efficient. Indeed, with an overall efficiency of 2.5% the average wall-plug power for such a collider would be 160 MW. Designs for future linear colliders envision power levels in the 100–200-MW range and efficiencies up to 20%. Average-power limitation is a serious constraint. One can, in principle “purchase” luminosity by using more average power: A given collider operated at a higher repetition rate will produce more events.

For a fixed final energy, the power varies as fE_a , where E_a is the accelerating gradient. For a fixed luminosity, higher gradients require more power, unless the number of particles being accelerated is increased and the repetition rate is decreased. Unfortunately, one cannot increase the number of particles indefinitely.

A particle accelerating in the axial field of the accelerator will generate wakefields—electromagnetic fields that interact with subsequent particles and can degrade beam quality. Most near-term collider schemes effect efficient transfer of rf energy to the accelerated particles by accelerating trains of bunches during each rf pulse. Unfortunately, if bunches are close enough to be accelerated by the same rf pulse, they are also close enough to interact through wakefields. At the SLC, wakefield instabilities have been controlled by making the transverse oscillation frequency of particles depending on position in the bunch. Additional techniques that would be needed at future colliders include the imposition of tight jitter and alignment tolerances, varying the resonant structure of the wake in different sections of the linac and designing structures with very low coupling to the beam except in the accelerating mode.

With present technology, increasing the gradient arbitrarily in a conventional accelerating structure eventually results in too great an average-power requirement. For this reason present designs for near-term colliders do not strive for gradients much higher than five times the 17 MV/m at the SLC.

Beamstrahlung—intense radiation that occurs as particles are deflected by the collective magnetic field of the opposing bunch—also limits the useful peak luminosities.⁴ A collision of two round beams, each with 10^{10} particles, 0.1-micrometer radius and 0.1-millimeter length, would result in fractional energy losses ranging from 0% on the beam axis to on the order of 25% at the beams’ peripheries,

In a 500-GeV linear collider, separate sources would generate 250-GeV beams of electrons and positrons, which would then be cooled in the damping rings, concentrated in the compressors, accelerated in the main linacs and collided in the detector region. Depending on the design, the collider accelerating gradient would be between 17 and 80 megavolts per meter, giving a total length for the collider between 6 and 30 kilometers. Higher energies may be reached by increasing the gradient or length. (Courtesy of Ronald Ruth, SLAC.) **Figure 1**

where the magnetic field is 10^4 tesla. The resulting beam energy spread reduces the useful luminosity. Also, for multi-TeV colliders, beamstrahlung photons are energetic enough to create e^+e^- pairs that increase the background in the detectors.

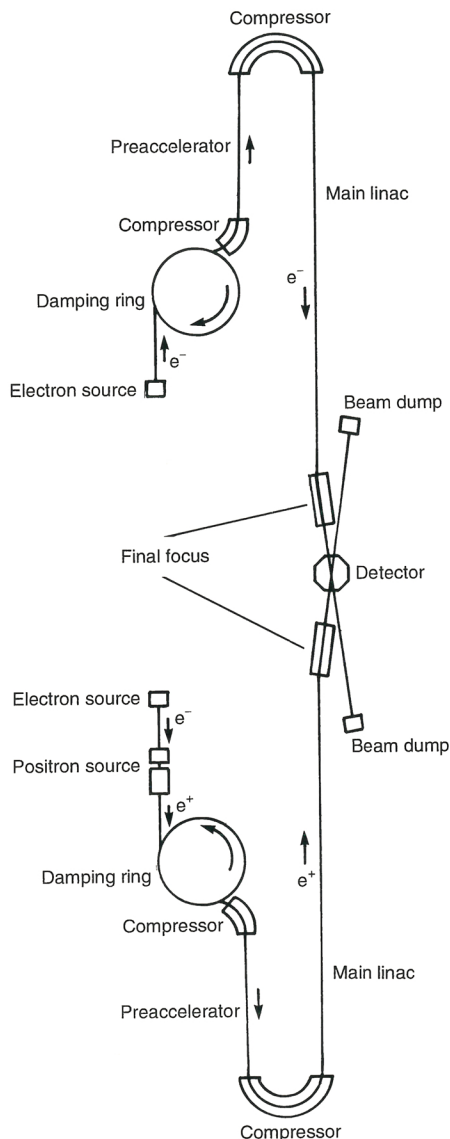
Significant reduction of particle self-fields and hence of beamstrahlung requires collisions of pancake-shaped bunches with widths from ten to one hundred times their heights. While this approach increases the useful luminosity, it also introduces more stringent tolerance and emittance constraints on the accelerator. The choice of a beam that has a much smaller height than width is in fact the natural one, since the damping rings, which reduce the transverse beam energy, produce beams having a smaller vertical emittance.

Technology limits the achievable beam flatness; beamstrahlung limits the luminosity that can be obtained from a single collision; and average power constrains the total number of collisions. Furthermore, to compensate for the decrease of production cross sections with increasing energy, the luminosity must increase as the square of the beam energy. Within these constraints (plus the additional constraint imposed by the Oide limit, discussed below), a working design of a 10-TeV collider is hard to achieve. However, the scaling laws discussed here are predicated on various assumptions. Should a concept arise that circumvents one or more of those assumptions, the scalings given here may become obsolete.

Near-term collider schemes

The four approaches to building the next linear collider all use the same acceleration mechanism as that at the SLC: The particles travel through slow-wave structures that have a mode with a phase velocity of c and a large axial electric field. The structures are powered by sources of electromagnetic waves at the frequency of the accelerating mode. At the SLC these sources are klystron tubes that generate intense pulses of S-band (2.8 gigahertz) power. No group has yet finalized design parameters for its version of the next linear collider.

The first and most conservative approach,⁵ pursued by Gustav Voss, Thomas Weiland and their colleagues at DESY and Darmstadt, is essentially a version of the SLC at ten times the size, and using a more powerful klystron tube. Such a scheme could rely heavily on present technology, but because the average beam power itself is in the megawatt region, the collider would have to improve on the SLC's overall wall-plug efficiency of less than 1%. Much of the inefficiency is in the transfer of power from the accelerating field to the particle beam. Increasing the charge of a single bunch until it extracts a substantial fraction of the rf power from the structure is impractical, because of undesirable energy spreads and wakefields.



Instead one would obtain the desired efficiency increase by accelerating a large train of bunches over a pulse length much longer than a fill time of the structure. (This was the original running mode of the SLAC linac before its energy upgrade.)

A second approach is the multinational TESLA proposal,⁶ which would be powered by high-efficiency superconducting rf cavities like those at DESY and LEP. A high-efficiency accelerator could accelerate a higher average current for a given power, eliminating the need to focus the beam to an extremely tight spot along with the corresponding requirements for extremely low emittance and strict construction and alignment tolerances. The difficulties with the superconducting approach lie in the present high cost and in achieving the desired gradient under accelerator operating conditions.

Proponents of the third approach,⁷ who include groups at SLAC, KEK in Japan and the Budker Institute of Nuclear Physics in Russia, favor a design similar to the SLC but with higher-frequency, higher-gradient (up to 100 MV/meter) sources powering the accelerator. Because the accelerator's transverse dimensions scale inversely with the rf frequency,

the field of a higher-frequency accelerator occupies less volume and hence stores less energy. A higher gradient of course means a significantly shorter collider for a given beam energy. While higher frequencies allow for higher gradients, they increase the severity of wakefields, necessitating smaller bunches and more stringent alignment and jitter requirements. The energy dependence of the final beam focus sets strict limits on allowable fluctuations in the amplitude and phase of the power, and none of the many potential rf sources has yet been operated with the desired efficiency, pulse length and power.⁸

Experiments by Juwen Wang and Gregory Loew⁹ have demonstrated that structures can be powered to accelerating gradients well over 100 MV/m, but further research is required to understand and control the “dark current”—small numbers of electrons that leave the surface of the structure and can lead to undesirable beam emittance growth.

The linacs described above would require thousands of rf power sources, each of which would have to operate at high power levels and with an efficiency on the order of 50%. The complexity of such a design has motivated

a more novel approach, the two-beam accelerator,^{10,11} in which the rf power to accelerate a high-energy beam is extracted from a parallel-propagating, intense, low-energy drive beam. The overall efficiency can be quite high, because the drive beam is not wasted but instead is reaccelerated and used to generate power again. Schematics of two-beam accelerator configurations are shown in figure 2. A previous *PHYSICS TODAY* article by Andrew Sessler (January 1988, page 26) dealt in some detail with designs of two-beam accelerators that used free-electron lasers to extract high-frequency rf power from the drive beam.

Another variant of the two-beam accelerator, under study by Wolfgang Schnell and collaborators at CERN, produces 30-GHz power by decelerating an intense (at least 40 kiloamps) 3 GeV beam bunched at 30 GHz in transfer structures—essentially an ultrarelativistic analog of the klystron. The energy lost by the drive beam is replenished by superconducting cavities like those being developed for LEP200, the proposed energy upgrade to LEP. Because the interaction length is long, the power extraction must be carefully designed to avoid the wakefields that can destroy the drive beam. The production of sufficient rf power and the requisite 40-kiloamp, bunched beam represent a major challenge. Possible beam sources include photocathodes and free-electron-laser bunching. Figure 3 shows a fully engineered prototype of a 30-GHz accelerating section for the CERN Linear Collider. Experiments¹¹ at the CLIC Test Facility at CERN have already reached 50 MV/m, over 60% of the design gradient. A scaled prototype at 11.4 GHz has been tested at KEK, reaching peak gradients of 135 MV/m.

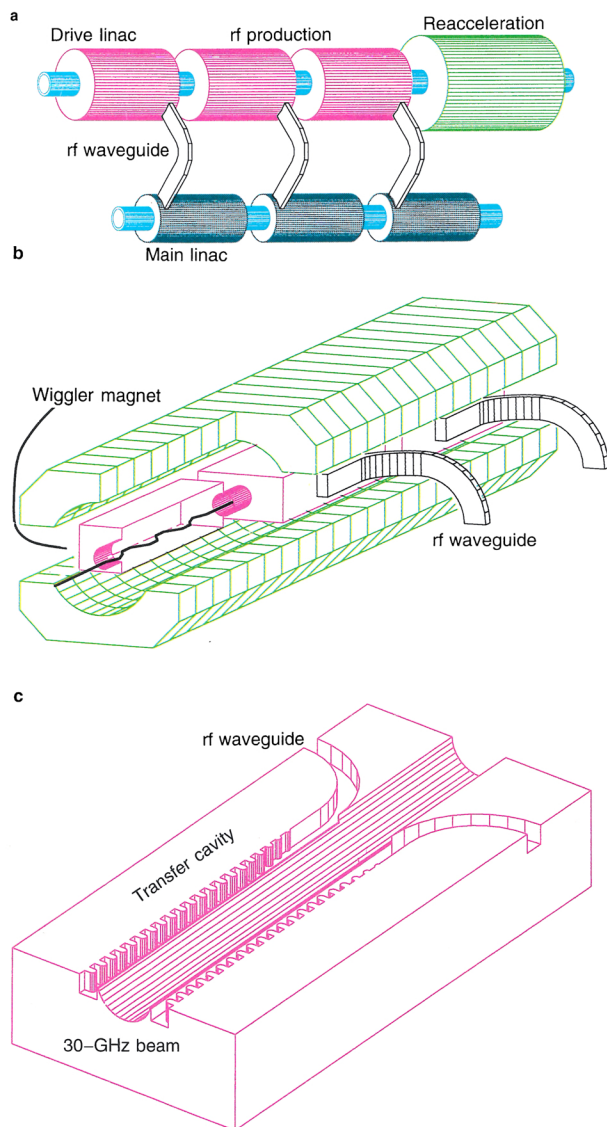
Each of the major concepts described above has a significant experimental program dedicated to resolving the critical technical issues—such as alignment, tolerance, wakefields, instrumentation, final focus and operation of the accelerator with multiple bunches—remaining before it can be proposed as a full-scale collider. As seen in table 2, accelerator test facilities are being built at SLAC, DESY, KEK, CERN and BINP.

Plasma beat-wave accelerators

The primary challenge in all plasma acceleration schemes is to produce a substantial plasma density perturbation with a phase velocity equal to c . At present the most promising concepts are plasma beat-wave acceleration and plasma wakefield acceleration. Calculations and experiments indicate that the fractional plasma density modulation obtained by these methods can be substantial.

In 1979 John Dawson and Toshiki Tajima recognized that the electric field of a plasma density modulation could be used to accelerate particles.¹² In this scheme, two copropagating laser beams with slightly different frequencies are injected into a plasma. The beams beat against each other, and if the beat frequency is close to the plasma frequency ω_p , the beat wave of the two lasers resonantly

Two-beam accelerator schemes. **a:** The rf power for accelerating the high-energy beam in the main linac is extracted from an intense beam of low-energy electrons in a drive linac parallel to the main linac. **b:** Free-electron laser cavities, in which wiggler magnets force the drive beam to oscillate and radiate at the rf frequency, may serve as the rf sources. **c:** An alternative rf source would consist of transfer structures, in which a beam bunched at the rf frequency would be decelerated and forced to radiate at that frequency. In both schemes, the energy lost by the drive beam would be replenished in reacceleration modules. **Figure 2**



drives a plasma density modulation. Because both frequency and wavenumber conservation hold, the difference in laser wavenumbers imposes the wavelength of the plasma wave. Thus the frequencies are chosen so that $\omega_p = \omega_1 - \omega_2$ and $k_p = k_1 - k_2$, where $\omega_p^2 = 4\pi e^2 n/m$, with $-e$ the electric charge, n the electron density and m the relativistic mass of a plasma electron.

The phase velocity of the plasma density wave then equals the group velocity of the radiation:

$$\frac{\omega_p}{k_p} = \frac{\omega_1 - \omega_2}{k_1 - k_2} \approx v_g \approx c \left(1 - \frac{\omega_p^2}{2\omega^2}\right)$$

Here the electromagnetic waves in the plasma satisfy $\omega = \sqrt{k^2 c^2 + \omega_p^2}$. When the laser frequencies are much greater than the plasma frequency, the phase velocity of the plasma wave is nearly c .

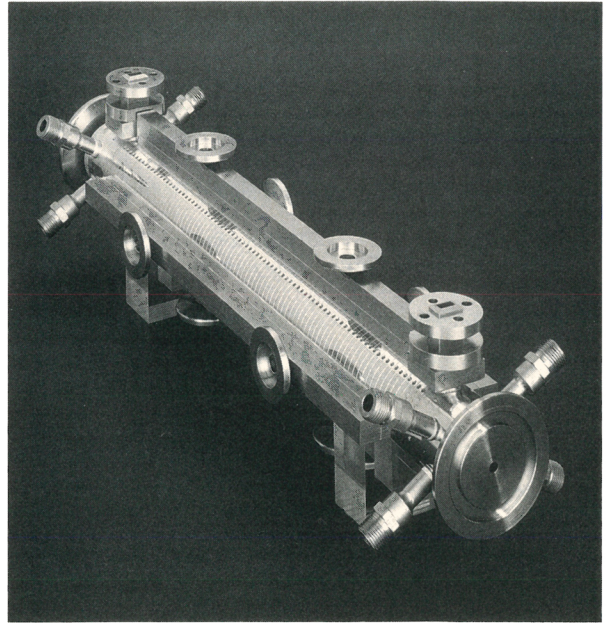
For a periodic plasma density modulation of amplitude $\varepsilon = \delta n/n$, where δn is the perturbed electron density and n the unperturbed density, Poisson's equation gives the longitudinal electric field due to this perturbation to be $k_p E = 4\pi e \delta n$. If the plasma modulation is to be used for acceleration it must have a phase velocity nearly equal to c ; hence, with $\omega_p \approx k_p c$, the accelerating gradient E , in gigavolts per meter, is approximately $\varepsilon \sqrt{n}$ (with n expressed in units of $10^{14}/\text{cm}^3$). There are several recent reviews of laser propagation in plasma with application to accelerators.¹³

Initial beat-wave experiments concentrated on generating and diagnosing large-amplitude plasma waves. Recently a significant milestone was reached when Chan Joshi and coworkers at UCLA¹⁴ accelerated electrons to energies of 28 MeV over an interaction length on the order of 1.3 cm. In their experiment a two-frequency beam from a 200-GW CO₂ laser (with lines at 10.5 and 10.2 μm) was focused onto the plasma, as shown schematically in figure 4. They used optical scattering to study the temporal and spatial properties of the plasma oscillation generated by the laser, and they probed its electric fields directly by measuring the energy gain or loss of the electrons in a 2-MeV beam that passed through the plasma. They analyzed the accelerated electron spectrum with a sector magnet and a cloud chamber, silicon surface barrier detectors, a quartz Čerenkov emitter coupled to a streak camera, and a gaseous Čerenkov emitter (an energy threshold detector) coupled to a photomultiplier tube. The peak gradient was 2.2 GeV/m, roughly corresponding to a 23% density perturbation in a plasma with an ambient density of $9 \times 10^{15}/\text{cm}^3$. The interaction length, and hence the final energy, in the UCLA experiment was limited by laser diffraction. The beat-wave scheme requires that the frequency difference of the two laser beams be close to the plasma frequency. This requirement imposes constraints on the uniformity and reproducibility of the plasma density.

Plasma wakefield accelerators

The laser wake-field accelerator^{12,13} excites the plasma with an extremely intense, short (on the order of the plasma period) laser pulse. The plasma wake travels at the group velocity of the laser pulse. Roger Falcone and coworkers have recently made direct observations of the laser wakefield in a plasma,¹⁵ and a collaboration at the Institute of Laser Engineering at Osaka University reports generating laser wakefields with gradients of 30 GV/m over a distance of 0.6 mm.

Even if the plasma exhibited no instabilities deleterious to the acceleration process, the final energy attainable in a plasma accelerator would be limited by a few



Prototype accelerator for CERN Linear Collider. This 30-GHz accelerating structure would generate power for a high-energy accelerator by decelerating an intense low-energy beam bunched at 30 GHz. The high frequency of the device imposes manufacturing tolerances on the order of 1 micron, necessitating the use of diamond-tool machines during its fabrication. (Courtesy of Ian Wilson, CERN.) **Figure 3**

basic phenomena. First, the difference between the plasma-wave phase velocity and the particle velocity c leads to a detuning of the phase of the accelerating field. A second limit arises from energy depletion of the laser pulse by the plasma wave, although this is not a significant limitation in present experiments. The most severe limit arises from light diffraction. The diffraction length of a laser pulse is $\pi w^2/\lambda$, where w is the width of the laser beam at its thinnest and λ is the laser wavelength. The generation of a high gradient requires the excitation of a large-amplitude plasma wave, which in turn demands an intense laser field and therefore a small laser spot size. This smaller spot size causes greater diffraction and thus reduces the total interaction length.

Two solutions have been proposed for overcoming diffraction: relativistic guiding and plasma-channel guiding. The first is based on the inverse dependence of plasma frequency on the relativistic mass of plasma electrons. The velocities of the plasma electrons are largest (and hence the plasma frequency is smallest) where the laser field is most intense—at the center of the pulse. Because the phase velocity of an electromagnetic wave in a plasma increases with increasing plasma frequency, this nonlinear mechanism tends to focus the laser. If the laser pulse has sufficient power, the propagation will be similar to that in an optical fiber.

For wakefield accelerators, however, laser pulses must be on the order of one plasma period long. In such cases, as Phillip Sprangle and coworkers first pointed out,¹³ the ponderomotive force generates an increased plasma density at the head of the pulse that cancels most of the relativistic guiding. Thus for pulses shorter than a plasma

Table 2. Linear collider test facilities

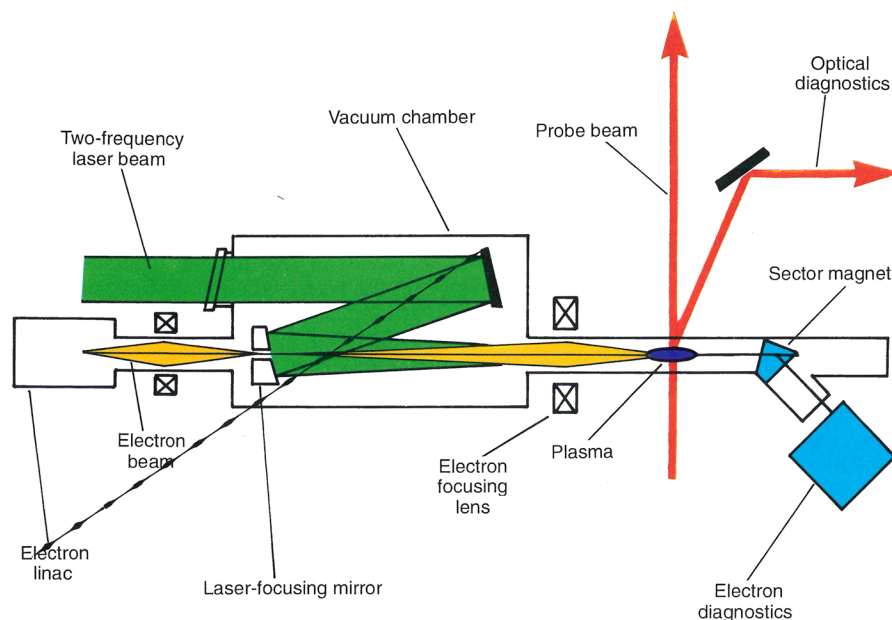
Facility	Description	Construction completion
SLAC		
FFTB (Final Focus Test Beam)	Prototype final focus for future linear collider. Focus SLC 50-GeV beam to spot size of 60 nm × 1 micron (75 nm × 2 microns already achieved)	1993
NLCTA (Next Linear Collider Test Accelerator)	540-MeV, 50-MeV/m prototype high-frequency (X-band) linac (upgrade to 1080 MeV with 100 MeV/m)	1996
DESY		
TESLA Test Accelerator	500-MeV linac to explore technical and economic feasibility of the superconducting approach	1996 or 1997
SBTA (S-Band Test Accelerator)	500-MeV 3-GHz linac to study multibunch beam dynamics	1996
KEK		
ATF (Accelerator Test Facility)	1.5-GeV S-band linac injector and prototype damping ring to produce beams with parameters appropriate for injection into main linac of a future collider	1996
CERN		
CTF (CLIC Test Facility)	Power transfer and acceleration with 50-MeV beam	1993
CTS (CLIC Test Structure)	10-meter prototype of CLIC two-beam accelerator	1997
BINP		
VTF (VLEPP Test Facility)	500-MeV linac to study 14-GHz acceleration and intense bunch beam dynamics	?

period, relativistic guiding is ineffective. Plasma-channel guiding is a possible alternative approach.

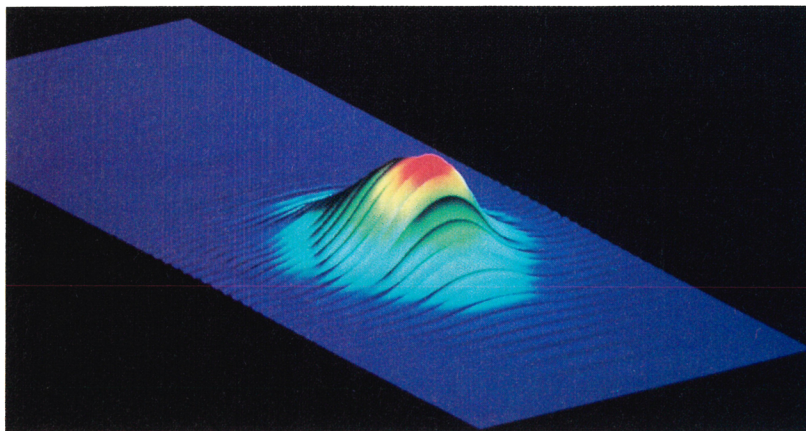
In plasma-channel guiding, one tailors the plasma's transverse density so that its minimum is at the center of the laser pulse. This guiding is linear and thus works independently of the laser power. Calculations show that a hollow plasma channel, while not easy to realize experimentally, has attractive properties for plasma acceleration.¹⁶ The channel provides optical guiding. The laser excites a surface mode on the inside of the channel. The fringe fields extend into the center of the channel and produce an accelerating field that is substantially more uniform (and hence better suited to accelerating a low-emittance beam) than that in a homogeneous plasma.

Figure 5 shows a simulation of a hollow plasma channel. In initial experiments, Howard Milchberg and coworkers have propagated a laser pulse over tens of diffraction lengths through a plasma channel.¹⁷

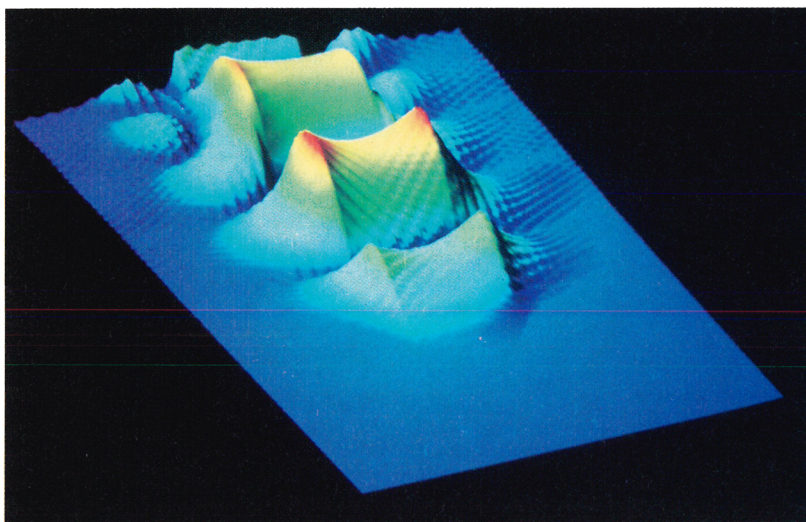
Plasma is, of course, unlike an optical fiber. As noted by Gennady Shvets and myself, the plasma density perturbation couples a given longitudinal slice of radiation with the slices that follow it. The head of the laser pulse can change the dielectric properties of the plasma channel seen by the tail of the pulse, leading to pulse degradation.¹⁸ Another concern in the plasma-based schemes is that the high gradients cannot, because of the volatile nature of the plasma, be maintained with the stringent phase and amplitude requirements over interaction lengths much



In the plasma beat-wave experiment at UCLA depicted by this schematic the beat waves from a two-frequency laser beam (green) resonantly drive an electron-density oscillation in a plasma (purple), which in turn generates large electric fields. A 2-MeV electron beam (orange) is accelerated through the plasma, and the energies of the accelerated electrons are analyzed using the magnet and electron diagnostics. The acceleration gradient of the plasma was determined by dividing the energy gained by the electrons by the length of the plasma. (Courtesy of Chan Joshi, UCLA.) **Figure 4**



a



b

Simulation of a laser wakefield accelerator. **a:** This three-dimensional plot profiles the intensity (perpendicular to the blue rectangle) of a short, intense, radially symmetric laser beam in the axial direction (along the length of the blue rectangle) and in the transverse direction (along its width) after the beam has propagated two diffraction lengths in a hollow plasma channel. **b:** A similar plot shows axial and transverse profiles of the electric field generated as the laser excites surface modes along the channel. The false color in these images also measures intensity: Warmer colors (red) correspond to greater laser beam intensities in **a** and greater plasma field in **b**. (From ref. 16.) **Figure 5**

greater than a diffraction length.

Wakefields in plasmas can be generated¹⁹ by electron beams as well as by laser pulses. Accelerators based on this concept are known as electron-beam wakefield accelerators. Ideally, a low-energy intense bunch would generate a large-amplitude plasma wave that would accelerate a trailing bunch to high energy. The plasma would transfer power from one bunch to the other. It has been shown, however, that a short intense bunch will generate an electric field in the plasma that is at most twice the decelerating field that it itself feels. Thus for short drive bunches the energy gain of a trailing bunch is at most twice the energy loss of the driver. The way around this problem is to tailor the longitudinal profile of the drive bunch carefully so that it has a slow rise (over many plasma periods) followed by a rapid falloff. As with laser-plasma schemes, one must consider the action of the plasma on the drive beam, efficiently couple drive power to the plasma and efficiently convert plasma-wave energy into kinetic energy of the accelerated particles.

In proof-of-principle experiments²⁰ at Argonne and at KEK and Tokyo University researchers have demonstrated that electron beams can in fact generate plasma wakes, in agreement with theoretical predictions. These experiments used beams with densities on the order of $10^{10}/\text{cm}^3$ —many orders of magnitude less than the density needed for high-energy physics experiments.

While recent experiments have led to significant ad-

vances in our understanding of beam-plasma and laser-plasma interactions and have verified theoretical predictions concerning the excitement of longitudinal and transverse fields in a plasma, the feasibility of efficient acceleration of intense, low-emittance particle bunches using plasmas will probably require a decade or more to be determined. In any event, plasma-based accelerators may prove useful as compact sources of relatively low-energy beams for a variety of research applications. A much less demanding application, the plasma lens, may be the first use of plasma in linear colliders.

The plasma lens

While the extremely strong longitudinal fields that can be generated in a plasma make it a potentially attractive accelerator, the transverse fields in a plasma also can be intense and may provide an exceptionally powerful lens. The plasma lens for high-energy colliders has been intensively investigated.²¹ It is easiest to understand in the underdense limit, in which the bunch density exceeds that of the plasma.

The underlying physical mechanism for the plasma lens is the expulsion of plasma electrons by the self-electric field of an electron beam. The outward radial force on beam electrons from the beam self-electric field is balanced, to order $1 - (v/c)^2$, where v is the beam velocity, by the inward pinch force from the self-magnetic field. Plasma electrons are expelled because they feel only the

outward radial force from the beam electric field. A strong focusing force is created by the remaining ions (which, because of their larger mass, are motionless over the time scale of an electron bunch). For even a modest plasma density ($10^{14}/\text{cm}^3$) this focusing force is higher than one can obtain using conventional magnets.

Positron bunches passing through a plasma lens would draw electrons in from the surrounding plasma rather than expelling them as does an electron bunch. While no plasma-lens experiments have yet been performed with positrons, the resulting focusing field may be rather nonuniform.

Since luminosity depends inversely on the beam size, it may seem that a more powerful lens is always desirable. Katsunobu Oide was the first to show that this assumption is false.²² The bending of the particles by the lens can lead to synchrotron emission, which changes the particle's energy and therefore its focus. Further, because synchrotron radiation is a quantum process, it leads to a lower limit on the attainable spot size (the Oide limit). This limit, while not severe for the next-generation linear colliders, becomes significant at multi-TeV energies. A plasma lens with its plasma density increasing all the way into the interaction region could provide a partial solution to this problem.²³ However, the presence of the plasma at the interaction point would create undesirable background in the detectors.

Other accelerators

This article has concentrated on near-term and plasma-based schemes for future e^+e^- colliders. Many groups at universities and national laboratories are investigating other exciting ideas for beam handling, beam cooling and acceleration. The possibility of colliding muons, fundamental particles whose rest mass m_μ is $105.7 \text{ MeV}/c^2$, between that of the proton and that of the electron, is of significant interest.²⁴ The heavier muon mass means that one can achieve many of the same physics goals as the SSC would have with a significantly smaller circular muon collider, with only about an order of magnitude more synchrotron radiation than at the SSC. The major challenge is to produce, accelerate and collide a sufficient number of low-emittance muons within a time frame on the order of a muon lifetime, $2.2E_\mu/m_\mu c^2$ microseconds, where E_μ is the muon energy. One possible scenario for a muon collider is that protons hitting a stationary target would produce pions, which would decay into muons, which would in turn be cooled, accelerated and finally collided.

There is also interest within the high-energy community in $\gamma\gamma$ and $e^-\gamma$ colliders, in which an intense laser beam would be backscattered by an electron or positron bunch before the bunch is focused, producing energetic photons that would then be collided with each other or with electrons.²⁵ A future linear collider may incorporate in one machine capabilities for e^+e^- , $e^-\gamma$ and $\gamma\gamma$ collisions.

The exciting progress, based on extensions of existing accelerator technology, that has been made on different approaches toward the development of the next linear collider should make possible the construction of a 500-GeV machine within the next decade. The more remote future could see the development of multi-TeV colliders, perhaps based on concepts or techniques yet to be discovered.

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