

annealing of silicon, Van Vechten suggests, involve a relatively cool quasi-liquid-crystal phase "distinctly different from molten silicon."

Experiments employing time-resolved reflectivity, surface photoelectric emission and nanoscond x-ray diffraction have all recently lent support to the thermal melting model, while a Raman-scattering experiment appears to support Van Vechten. But the new

electron diffraction technique of Mourou and Williamson promises soon to provide our first direct look at lattice structures and their laser-induced changes on the crucial picosecond time scale. —BMS

## References

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# Laser-driven electron-positron colliders

By 1987, two very large colliding-beam accelerators, LEP at CERN and SLC at SLAC, should be providing high-energy physicists with 100-GeV collisions of electrons and positrons. But what of the next generation? With the 27-km-circumference LEP storage ring costing about \$400 million and consuming as much electrical power as a city of 150 000 souls, can one really afford to build significantly larger  $e^-e^+$  accelerators at the turn of the next century?

Head-on linear colliders (of which SLC is a hybrid prototype), with no synchrotron radiation loss, would have substantially lower power bills. But a pair of conventional rf linacs firing 300-GeV pulses of electrons and positrons at each other would constitute a structure almost forty kilometers long.

What one wants for the next generation, therefore, is a technology that can provide a significantly higher accelerating gradient than the 15 or 20 MeV per meter to which rf linacs such as the SLC 2-mile linac are limited. The extraordinarily intense electric fields that high-power lasers can generate offer a promising possibility. To investigate this possibility, a five-day Workshop on the Laser Acceleration of Particles was convened at Los Alamos last February. The Workshop looked in some detail at a half-dozen different laser accelerating schemes, some of which may eventually prove capable of accelerating electrons (and positrons) to hundreds of GeV with a gradient of several hundred MeV/meter.

For some visionaries, such an order-of-magnitude increase over presently available accelerating gradients is still too modest. At a conference on future accelerator technologies held at Oxford in October, a number of the ideas developed during and following the Los Alamos workshop were communicated to the European high-energy-physics community. In his introductory remarks, Abdus Salam (Imperial College, London, and International Centre for Theoretical Physics, Trieste) challenged the participants to come up with a concept that could lead to a practical 100-TeV ( $10^{14}$  eV) accelerator early in the next century. While Andrew

Sessler (Lawrence Berkeley Lab), chairman of the Los Alamos workshop organizing committee, thinks it more prudent to concentrate first on laser techniques that would offer a *single* order-of-magnitude advance over presently available accelerating gradients, Robert Palmer (Brookhaven) is urging the development of other laser accelerating schemes that he believes might indeed yield practical 10- or 100-TeV machines in twenty or thirty years.

Although the Los Alamos workshop dealt primarily with the acceleration of electrons and positrons, these laser accelerating ideas are presumably also suitable for protons and ions. Because such heavier particles present much less of a synchrotron-radiation problem, we will have a  $1000 \times 1000$ -GeV  $\bar{p}p$  synchrotron collider with a diameter of only 2 km—the Tevatron at Fermilab—by mid-decade. Frank Cole (Fermilab) suggests that a  $20 \times 20$ -TeV  $\bar{p}p$  collider is a reasonable prospect for the first generation of laser accelerators.

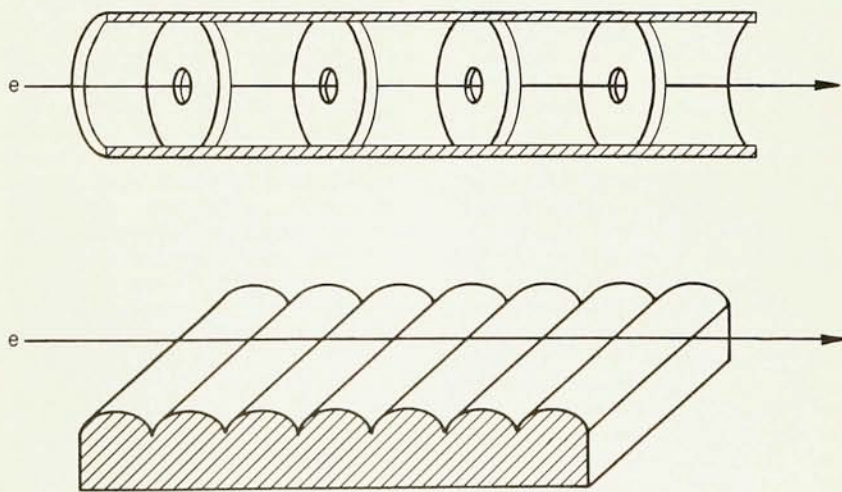
**Laser accelerating mechanisms.** Because the electric field of electromag-

netic radiation is always transverse to its direction of propagation, one cannot accelerate a charged particle simply by shining intense laser light at it. One needs a trick to couple the radiation to the particle by producing an accelerating field component parallel to the particle's motion. Such tricks fall into three broad categories:

► **Media accelerators**, in which the radiation couples to the particle by way of a medium through which the radiation propagates. Inverse Čerenkov acceleration and plasma beat-wave acceleration are two examples of this idea—exploiting, respectively, the refractive index of the medium and the electrostatic fields generated by density waves in a plasma.

► **Near-field accelerators**, in which the laser beam propagates within a wavelength of a periodic conducting structure. This is also the basic idea of the conventional rf linac. Substituting 1-cm radiation from a free-electron laser for the usual radio-frequency drive, one hopes to reduce linac dimensions by an order of magnitude. A far more radical miniaturization might be achieved by employing 10-micron,  $\text{CO}_2$ -laser drive—in which case one would use a 10-micron grating in place of the usual linac structure.

► **Far-field accelerators** would couple the particle beam to the laser radiation by perturbing the particles' trajectories to include an oscillating transverse component in phase with the radiation. In an inverse free-electron-laser accelerator this would be done by passing the particle through a magnetic wiggler of the kind used in free-electron lasers (PHYSICS TODAY, July 1979, page 19). Another such scheme, the



**In all near-field accelerators**, a periodic conducting structure converts incident electromagnetic radiation to an accelerating mode, with phase velocity matched to the beam. The accelerating field occurs only within a wavelength of the conducting surface. The conventional rf electron linac (top) uses periodic irises to slow the phase velocity. Sessler proposes scaling such structures down by using 1-cm radiation from a free-electron laser in place of the rf drive. Palmer proposes a more radical miniaturization, using a 10-micron laser drive, effectively reducing the linac structure to a 10-micron diffraction grating (bottom).

two-wave accelerator, would replace the wiggler magnet by a slow microwave field.

The Los Alamos workshop divided itself into three working groups that examined the promise of these three categories in some detail, reporting their conclusions at final plenary sessions. From the findings of these groups and subsequent work inspired by the workshop, the following three schemes have emerged as particularly promising for high-energy physics in the not-too-distant future.

**The plasma beat-wave accelerator.** In 1979 Toshi Tajima (now at the University of Texas) and John Dawson (UCLA) suggested that one could accelerate an electron beam traversing a plasma by illuminating the plasma with intense laser light at two frequencies whose difference is the natural oscillation frequency of the plasma. The interference beat wave, they pointed out, would generate traveling density waves in the plasma. Electrons could be accelerated by the electrostatic forces resulting from this plasma bunching; they would ride the plasma waves (at almost the speed of light), much like surfers.

Thus the beat-wave accelerator is something of a hybrid between laser accelerators and collective accelerators, a rival class of concepts of which the best known is probably the electron "smoke" ring idea proposed by V. I. Veksler in the 1950s (PHYSICS TODAY, February 1968, page 51). Like other collective accelerators, the BWA depends on an aggregation of charges to accelerate the particle. But what makes the BWA particularly attractive, Sessler asserts, is that one can get much higher charge densities and smaller bunching dimensions in the laser-plasma interaction. While a more conventional collective accelerator involves charge densities typical of relativistic electron beams (less than  $10^{14} \text{ cm}^{-3}$ ) and bunching dimensions on the order of a centimeter, plasmas can easily achieve charge densities of  $10^{18} \text{ cm}^{-3}$ , and the bunching length is only an order of magnitude longer than the laser wavelength. With these higher charge densities and shorter distances come the very high electrostatic fields that Sessler believes might eventually achieve accelerating gradients on the order of 10 GeV/m. The short plasma-density wavelength would also permit one to raise the luminosity of a linear collider by having very short electron (and positron) bunches. Luminosity becomes an ever more serious issue as colliders go to higher energy, because the  $e^+e^-$  cross section falls as the inverse square of the energy.

Chan Joshi reported to the workshop that he and his colleagues at UCLA had recently demonstrated the beat-wave generation of plasma density waves

with a low-power  $\text{CO}_2$  laser producing only  $10^{10} \text{ watts/cm}^2$ . He and his colleagues at the National Research Council in Ottawa have also succeeded in accelerating electrons to about 1 GeV by the BWA mechanism, using an intense  $\text{CO}_2$  laser at NRC.

**The inverse free-electron-laser accelerator.** "At the workshop," Sessler told us, "we thought the IFEL accelerator would be limited to a few GeV. And a year before that we thought the idea wouldn't work at all." But in the months since the workshop, he explained, Claudio Pellegrini (Brookhaven) has "designed on paper" an IFEL system that could in principle accelerate electrons to 300 GeV.

In the IFEL, the beam traverses the oscillating magnetostatic field of a wiggler whose periodic wavelength must grow from about 10 cm at the start to several meters at the downstream end, so that the transverse oscillating velocity of the accelerating electrons remains in phase with the electric field of the laser light running along the beam. The primary problem has been maintaining a sufficiently intense laser focus over distances long enough to provide adequate integrated acceleration. Even with a giant  $10^{14}$ -watt laser like Antares (currently under construction for fusion studies at Los Alamos), one would only get adequate acceleration where the laser beam is focused down to a diameter of a few millimeters. With the single-focus optical systems considered at the workshop, this accelerating region would only be a few meters long—yielding 10 GeV electrons at best. [One would of course require a high-power laser with a much greater coherence length than Antares, or Shiva/Nova at Livermore. The inertial-fusion work for which these lasers are intended (PHYSICS TODAY, November 1979, page 20) do not require a high degree of coherence.]

Since the workshop, Pellegrini has addressed himself to the design of a multiple focusing system that would keep the laser light sufficiently intense over several kilometers. Beginning with a concept put forward at the workshop by Salvatore Solimeno (University of Naples), he has designed a metallic "optical waveguide," consisting of two parallel plates a few millimeters apart between which the laser light (and the electron beam) would pass, reflecting alternatively off the two surfaces while maintaining a focused electric-field intensity of about  $2 \times 10^{11} \text{ V/m}$  for several kilometers on the axis along which the beam runs. At the metal surfaces the intensity would be less, preserving the surfaces from damage.

With this multiple-focusing scheme and a sufficiently powerful, coherent and efficient laser (perhaps a  $\text{CO}_2$  laser,

or even a free-electron laser), a practical 300-GeV accelerator a few kilometers long "is at least a theoretical possibility," Pellegrini told us. The problem of focusing high-intensity laser light over long distances is not unique to the IFEL scheme, Pellegrini points out; it needs to be investigated further in connection with most of the other laser acceleration proposals as well.

Instead of increasing the wiggler wavelength toward the downstream end as the electrons gain energy, one might consider increasing the magnetostatic field strength while keeping the wiggler periodicity constant. But this alternative, Pellegrini has calculated, would cause a synchrotron-radiation problem as bad as one has with circular accelerators; one would lose the key advantage of the linear configuration.

**A scaled-down linac** using 1-cm radiation from a free-electron laser in place of the usual rf power is the concept to which Sessler has given most of his personal effort. He envisions, in effect, a two-beam accelerator, with a low-constant-energy, high-intensity electron beam running parallel to the lower-intensity, high-energy beam being accelerated in the main linac structure. The low-energy beam serves as a free-electron-laser source of 1-cm-wavelength radiation that is fed across by waveguides to the parallel accelerating structure.

The transverse dimensions of a linac are perforce of the order of the wavelength of the radiation powering the acceleration. In the single-pulse mode required for colliding linacs, the dissipated power is proportional to the cross sectional area of the machine. Thus by scaling down the wavelength of the accelerating radiation by an order of magnitude from the 10-cm rf drive of the present SLAC linac, one could reduce the wasted power consumption of a linear collider by a factor of a hundred.

A second virtue of shorter-wavelength power sources, Sessler points out, is that the correspondingly higher frequencies minimize the problem of spark breakdown, which would ultimately limit the increase of accelerating gradients and decrease of cavity dimensions. As frequencies go up, charge has less time to accumulate and thus threaten sparking before the polarity is reversed.

"With 30-GHz (1-cm) free-electron-laser power we could presumably get up to gradients of several hundred MeV/m," Sessler told us. He regards this order-of-magnitude increase over present rf linacs as a judiciously modest first step. With such an accelerating gradient, he points out, one could fit a  $300 \times 300$ -GeV pair of head-on linear

colliders onto the SLAC site.

Denis Keefe (LBL) stresses, however, that the present SLAC linac is far from being limited by sparking. Its gradient could be increased by a factor of seven, he told us, before breakdown became a worry. But that would raise the power bill by a totally unacceptable factor of fifty—most of it wasted in the accelerating structure and the waveguides. The key issue, he argues, is finding a way to develop high-power microwave sources that supply energy to the beam with reasonable efficiency.

Taking Salam's challenge seriously, Robert Palmer is seeking to miniaturize the rf linac by another three orders of magnitude. Powered by 10-micron CO<sub>2</sub>-laser light, the linac structure would be reduced to a glorified diffraction grating, generating an accelerating gradient on the order of 10 GeV/m. "If I can't improve things by several orders of magnitude, he told us, 'I'm not interested.'" Conventional rf linacs, he argues, can almost certainly be pushed another order of magnitude. LEP is expected eventually to achieve a collision energy of 260 GeV, and rf linac sections with 100-MeV/m gradients have been built as laboratory prototypes. The laser-accelerator pioneers should therefore be looking much further down the road, he contends. "100 TeV may be pie in the sky, but sooner or later we'll need pie in the sky."

A metallic diffraction grating, like any other periodic conducting structure (glass will also do at optical frequencies) serves the basic linac function of converting plane-wave transverse modes of incident radiation at comparable wavelengths to accelerating modes whose slower phase velocities match the velocity of the particles to be accelerated.

Two potential problems of the 10-micron grating accelerator have raised doubts about its usefulness as an ultra-high-energy accelerator: The high field intensities necessary for 10-GeV/m would turn any grating surface into a plasma. Secondly, electron beams would be limited to very low intensities. Palmer addresses these concerns by talking of a "consumable" grating. The grating (or the beam) moves over a few millimeters to a fresh patch after each beam pulse. Plasmas generated at surfaces diffuse slowly enough, he argues, that the plasma retains its periodic structure throughout the accelerating pulse. With regard to low electron-beam intensities, he points out that this could be compensated for by very high repetition rates. A pulsed CO<sub>2</sub> laser operating at a megacycle would provide adequate luminosity for a multi-TeV linear collider, he calculates. No such laser has yet been built, he concedes, but he is

optimistic that it can be done.

"The potential of laser-driven accelerator devices justifies the devotion of resources for their further study and experimental exploration," the executive summary of the recently published Workshop Proceedings<sup>1</sup> says. "A similar workshop in a year or two will again be most valuable in assessing progress... and defining new goals and directions." Present assessments of the

relative merits of different schemes, Sessler cautions, must be regarded as highly tentative. "Our view of the inverse free-electron-laser accelerator, for example, has twice been radically changed in the last two years." —BMS

## Reference

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# Lynch report on synchrotron radiation

Last summer the Solid State Sciences Committee of the National Academy of Sciences convened a subcommittee on synchrotron radiation facilities. The subcommittee was established to help assess the present status of the facilities and make projections for their future utilization.

The National Synchrotron Light Source has just been dedicated by DOE at Brookhaven. At the start of FY 1983, the Stanford Synchrotron Radiation Laboratory was transferred from NSF to DOE. One reason for the transfer was that the Office of Management and Budget wanted to consolidate support of the two major US facilities in one agency with the goal of improving management processes for facilities support.

NSF supports the University of Wisconsin Synchrotron Radiation Center, which has operated Tantalus for 15 years, and where Aladdin is now coming into operation. NSF also supports CHES, the synchrotron radiation source at the 4-8-GeV Cornell Electron Storage Ring.

Besides studying the status of synchrotron radiation research and facilities in the US, Donald Stevens, who is deputy director of the DOE Office of Basic Energy Sciences, told the Solid State Sciences Committee that his Of-

fice needs guidance on the relative merits of synchrotron radiation and neutron sources, the two most expensive research fields Basic Energy Sciences supports. In addition, there is pressure on Basic Energy Sciences to establish a committee resembling the High Energy Physics Advisory Panel, a committee to identify and establish priorities for future facilities. The question he posed to the subcommittee was, "Compared to other needs, is the US overextended in synchrotron radiation?"

By the end of September, the subcommittee, headed by David Lynch (Iowa State University), provided information needed for the FY 1984 budget process. And in January the subcommittee's report was released by the National Academy.

The subcommittee found that the use of synchrotron radiation (see the special issue of PHYSICS TODAY in May 1981) has undergone rapid growth in the last five years, even more than was anticipated in 1976, when a similar group was also convened by the Academy's Solid State Sciences Committee. The 1976 report led to construction of the two storage rings at the Brookhaven National Synchrotron Light Source (an 800-MeV ring for uv and soft x rays and a 2.5-GeV ring for x rays, both just



Aladdin's first stored beam with a reasonable lifetime (halflife 20 min) was celebrated in May at the University of Wisconsin Synchrotron Radiation Center by Ed Rowe (left) and Bill Winter.