Catching on to a Light Wave

Static electric forces and radio waves have been used to accelerate particles for physics experiments. Now it may be the turn of laser light.

By DIETRICK E. THOMSEN

In the half century or so that they have existed, particle accelerators have grown more and more energetic. They impart energy to particles (protons, antiprotons, electrons or positrons) that serve as probes of the details of material structure. As physicists have discovered finer and finer levels of material structure, they have needed more and more energy to probe them. In the process, accelerators have gotten bigger and more expensive. The largest today are a few kilometers in length or circumference. The Super Superconducting Collider, now on the drawing boards, could be up to 160 kilometers around and cost several billion dollars.

As accelerator building nears the upper limits of both finance and geography, physicists are looking for ways of making them smaller and cheaper. Using lasers to drive the acceleration could be one solution to the problem. Andrew M. Sessler of the Lawrence Berkeley Laboratory in Berkeley, Calif., who reviewed such proposals at the recent International Conference on Lasers '84 in San Francisco, pointed out that one of the largest accelerators now under construction, the Stanford Linear Collider (SLC), will impart 17 million electron-volts (17 MeV) of energy to an electron or a positron for every meter's length of its actual accelerating sections, adding up to 50 billion electron-volts (50 GeV) for its 4-kilometer length. Sessler estimates that the laser acceleration schemes now under consideration might reach 10 to 1,000 GeV per meter, an appreciable saving in space and the attendant costs of construction.

If laser driving techniques can be worked out, they will represent a revolutionary change in accelerator technology. The earliest accelerators, and those designed today for modest energies, use electrostatic means to accelerate the particles. All particles that can be accelerated are electrically charged, and it is on the charge that the accelerator works. In electrostatic accelerators two or more electrodes are charged so that there is a potential difference between them. The electric force generated by the potential makes the particles move from one electrode to the other, giving them energy as they fly. If the potential difference is 1 volt, the energy gained (by any particle) is 1 electron-volt.

There is a limit, in the hundreds of millions of electron-volts, beyond which electrostatic techniques are impractical. For higher energies, cyclically varying forces generated by radiofrequency waves in special waveguides are used. In a certain portion of every cycle the forces will be in the direction of acceleration, and the particles to be accelerated will get a forward kick each time this part of the cycle comes around. Various combinations of geometry of waveguides and shielding from adverse portions of the wave ensure that when the particles to be accelerated arrive at the start of an accelerating section, they catch on to the favorable part of the wave and stay with it.

Light waves do not present this possibility, according to Sessler. Most of their forces are transverse to the direction of propagation of the waves. In any practical kind of accelerator the direction of propagation of the waves should be the same as that of the particles to be accelerated. Light waves will provide significant longitudinal forces only at a focus or in conjunction with a surface. One way around the problem is to use a specially designed surface in conjunction with the light. Another is to introduce a material medium that will interact with the light and produce the desired longitudinal forces.

Such a material medium could be either an ionized gas — that is, a plasma — or an electrically neutral gas. Its introduction would be a radical change in accelerator technology. Past and present accelerators operate in high vacuum so that nothing can impede the flight of the accelerated particles. Here, a material medium may be necessary to get any acceleration at all.

Experiments using a plasma as the medium are under way at the University of California at Los Angeles. They involve beating together two laser beams of different wavelengths to generate a wave in the plasma. This plasma wave pushes the particles to be accelerated. Chan Joshi of UCLA and others described the work at the San Francisco meeting.

Sessler calls this method exciting, estimating that large energies could come from small accelerators — for example, 32 GeV energy gain in 32 centimeters. To get 32 GeV today requires a few kilometers of accelerator. However, there are drawbacks. Joshi lists two: "A plasma accelerator is truly a collective accelerator [the device makes the plasma move, and the moving plasma takes the particles to be accelerated along for the ride], and no such accelerator has ever been built. Also, plasmas are very unstable. Can we avoid instabilities?" Or, as Sessler puts the hypothetical complaint of an accelerator builder: "It's hard enough to build an accelerator; don't give me plasma problems in addition."

The UCLA experiment beats together two wavelengths from a carbon dioxide laser, 9.6 micrometers and 10.6 micrometers. At the moment the experimenters are concentrating on the mechanism of forming the beat waves and any possible competing processes that could take away energy. The waves do form, and it doesn't take great intensity of laser light, Joshi says. To get around plasma instabilities, he says, the trick is to use very short laser pulses — ones with a nanosecond rise time and half a nanosecond fall — so that plasma instabilities don't have time to form. The particles get out of phase with the wave after 3.3 meters, but you can inject them at 1 MeV, he says, and see significant energy gain.

It is a difficult experiment, Joshi says, and rich in the physics of waves interacting with waves, which the experimenters must understand for further progress. In conclusion Joshi calls it "an extremely promising start in exciting a fast plasma wave by beating two laser waves in a plasma. It is the first that unambiguously shows it."

At the University of Washington in Seattle, another plasma wave experiment by R. G. Berger, Robert D. Brooks and Z. Adam Pietrzyk seems to make plasma waves that are accelerated as they move through regions of continuously increasing density. Brooks told the meeting that they think they see electrons accelerated by this process. These experimenters believe that quite high rates of acceleration can be achieved by moving plasma waves through regions of varying density, particularly if the density can be made to vary periodically — which, Brooks says, "is hard to do physically." Predictions go as high as 100 GeV per meter.

A plasma is an active medium — it takes an important role in the action of acceleration. J. R. Fontana of the University of California at Santa Barbara proposes a passive medium, an electrically neutral gas. "All we want from it is an index of refraction," he says. When a light beam passes the boundary between substances with different indices of refraction, it bends. Given a material with the right index of refraction, two laser beams can be bent so that their waves interfere with each other. It makes a region where the forces are all in the direction of acceleration, and it should accelerate particles. This is known as inverse Cherenkov effect. The limits Fontana sees on the process are electrical breakdown of the gas and too many collisions between the particles to be accelerated and the gas.

Laser light striking an undulating surface, say a grating, at a low angle should also provide forces in the direction of acceleration. However, a disposable grating is necessary as the required light intensity will burn out the grating rather quickly — in 10 picoseconds, according to Robert B. Palmer of Brookhaven National Laboratory in Upton, N.Y. He figures that such an arrangement would need a narrow disposable grating and a laser with pulses that are short compared to 10 picoseconds. The solution is to use rows of droplets spaced a few micrometers apart. The droplets would be made by forcing liquid through a series of holes 1.5 micrometers across.

Technology for making such droplets exists. Sessler points out that it is used with ink in certain printing procedures. Ten picoseconds is short for a laser pulse, but Palmer points out that the Canadian National Research Council has a high-pressure carbon dioxide laser with pulses that can be compressed down to 2 picoseconds. He calculates that a 5-trillion electron-volt accelerator (5 TeV), which is five times the maximum energy of any existing accelerator, would require a length of 600 meters, 300 5-joule lasers and a repetition rate of 3 kilohertz.

Instead of an undulating surface, one can use an undulating magnetic field — in a device known as an inverse free-electron laser. The undulating magnetic field is provided by a so-called wiggler magnet. A free-electron laser is designed to take energy from high-energy electrons and use it to amplify a light beam. As the electrons pass through the undulating field they wiggle up and down. The wiggling induces them to radiate energy, and if there is a light wave passing through that resonates with the electrons, they will amplify that beam as they radiate. The *inverse* free-electron laser attempts to work the scheme the other way — extracting energy from the light and getting the electrons to absorb it.

"The free-electron laser works," says Sessler, "— or one thinks it works" (SN: 12/8/84, p. 359). An Italian physicist, Claudio Pellegrini, has worked out specifications for an inverse free-electron laser. With a 10,000-watt carbon dioxide laser and an undulator field of 1 tesla, an energy gain of 289 GeV should be possible. Sessler comments that this is 200 GeV in 2 kilometers or so. The SLC, when it is completed in a year or two, will be the most energetic conventional linear accelerator of electrons in the world. It will get 50 GeV in a little over 4 km.

Certain combinations also seem possible. M. A. Piestrup of Adelphi Technology in Woodside, Calif., and J. A. Edighoffer of TRW propose combining the inverse free-electron laser and the inverse Cherenkov effect into a gas-loaded inverse free-electron laser. The index of refraction provided by the gas, they figure, will change the synchrony between the laser light and the electron beam so as to reduce the undulator's magnetic field. This would reduce the amount of energy that the electrons lose to synchrotron radiation. As the electrons gain energy, they also lose it, and one of the necessities is to keep the gain higher than the loss. In published proposals for simple inverse free-electron lasers, Piestrup says they find the loss to synchrotron radiation very high. ☐

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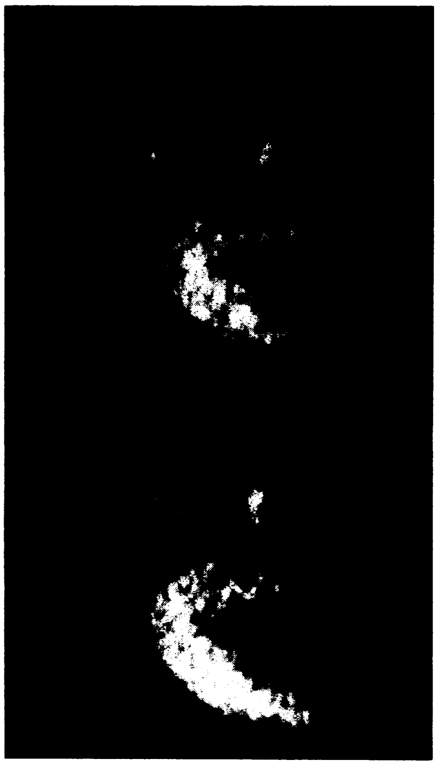

A fetus begins opening its eye in the sequential images at right. Half of the face is "illuminated" by the imaging technique. A fully open eye of another fetus is shown in the image above. Such images reveal movements of the eyelids and eyes, both spontaneous and in response to stimuli.

While there isn't much for the fetus to see *in utero*, its eyes are already in motion, Birnholz finds. He has used ultrasound to observe patterns of eye movement during the second half of gestation. One pattern is movement of the pupil from a central position to the outer, lower corner of the eye, followed by a return to its central position. This movement is normally present by 16 weeks, Birnholz finds. But another pattern — a complex, nonrepetitive sequence of brisk, jerky movements — was observed only after 24 weeks. This pattern is a component of the rapid eye movements (REM) observed in newborn infants, Birnholz says.

Still later in gestation, he observes an inactivity of the fetal eyes, resembling deep sleep. This normally occurs after 36 weeks gestation. Earlier inactivity might be interpreted in some cases as accelerated development due to stress and in other cases as an analog of coma.

Like the blink response, eye movements can be used to assess fetal well-being and recognize abnormal development. An observation of rapid eye movements indicates that the fetal brain is working properly, Birnholz said at the recent meeting in Anaheim, Calif., of the Society for Neuroscience. He also has observed eye movement abnormalities in fetuses with abnormal brain structures (SN: 8/29/81, p. 142).

From ultrasound imaging, Birnholz and Farrell now expect "a quantum advance in knowledge" of normal fetal development. But Birnholz also warns scientists not to project capabilities onto the fetus from brief glimpses provided by ultrasound. For example, sequential views of a 34-week-old fetus show eyes scrunched closed and mouth wide open. It is tempting to speculate that these images illustrate crying *in utero*, Birnholz says. But, he cautions, no one knows for certain. ☐