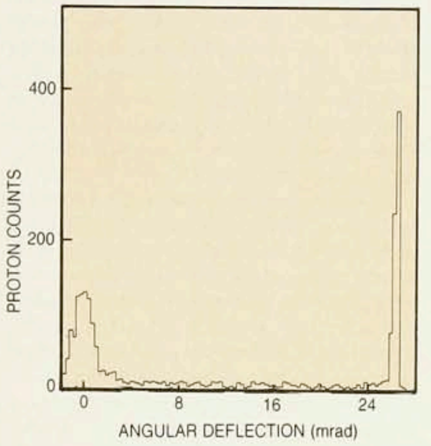
Channeling bends particle beams and generates x rays

As the energies of the particles they study climb toward 10^{12} electron volts (1 TeV), high-energy physicists find it increasingly difficult to bend their trajectories with large electromagnets. Even with superconducting coils, these magnets are limited by saturation to a few tens of kilogauss, so that a 500-GeV proton ring requires a radius of the order of a kilometer. But now, a Soviet–American collaboration at Dubna has reported[1] observing a phenomenon that may make it possible to bend 500-GeV protons with a radius of curvature not much more than a meter.

To achieve such bending with a magnet would require twenty *mega*gauss. In fact, the proton trajectories at Dubna were bent not by a magnet, but rather by the Coulomb field between the lattice planes of a bent silicon crystal. This is a new application of a phenomenon that has been known at low energies (a few MeV) since the mid-1960's, namely the channeling of charged particles along the planes or axes of (unbent) crystal lattices.

The Dubna experiment was done with 8.4-GeV protons, but with an eye to applications at much higher energies. This Soviet–American collaboration was in fact born at Fermilab three years ago with a 250-GeV experiment[2] in which protons and pions were shown to exhibit channeling in an unbent germanium crystal.

It was pointed out five years ago that when light particles (electrons or positrons) are channeled, they ought to emit a well-collimated "channeling radiation," analogous to synchrotron radiation. This channeling radiation has now been observed[3] by a Livermore–Stanford–Oak Ridge collaboration, for positrons and electrons channeling in a silicon crystal. Channeling radiation promises to offer a unique source of tunable, well-collimated, monochromatic, polarized hard x rays or γ rays. The discrete channeling-radiation spectrum also provides a new probe of the structure of the channeling crystals. At sufficiently high energies, light hadrons (pions) should also emit enough channeling radiation to help experimenters distinguish them from their heavier cousins.



Channeled bending of an 8.4-GeV proton beam at Dubna is indicated by the angular distribution of protons emerging from 1 cm of silicon crystal bent through 26 mrad (about $1\frac{1}{2}°$). The two peaks show the undeflected (0 mrad) and channeled (26 mrad) portions of the beam.

Channeling can occur when a charged particle enters a crystal in a direction close to a lattice plane or axis. The two somewhat different phenomena are called planar and axial channeling. In the former case, a positive particle is steered between two lattice planes, which are well approximated (especially at high energies) as sheets of positive charge. The trajectory oscillates about a potential minimum midway between the atomic planes, in an approximately harmonic Coulomb field. For negative particles the potential and the resultant motion are more complicated, with the atomic planes themselves being the minimum-potential surfaces. In the axial case, the channeled particles spiral in helical trajectories about atomic rows, which can be approximated as continuous lines of charge.

If the charged particle enters the crystal at less than the "critical angle" relative to the plane or axis, its probability of channeling is high. Outside the critical angle this probability drops rapidly to zero. For 3-MeV protons the critical angle is about a degree (depending somewhat on the crystal), but it was expected to decrease as $1/\sqrt{E}$ with increasing incident energy E. Thus, at 250 GeV, germanium crystal planes have to be oriented to within 20 microradians of the incident beam to achieve planar channeling.

Channeled trajectories experience very little small-angle scattering. For positive particles, channeling also reduces the probability of close interactions (nuclear reactions, large-angle Rutherford scattering, bremsstrahlung and the like), sometimes by orders of magnitude, because it keeps the trajectories away from the atomic planes. They also lose less energy by ionization or (in semiconductor crystals) carrier-pair generations, because they travel through the interatomic region of lowest electron density. Channeled negative particles, by contrast, can lose more energy to these processes than they would in unchanneled motion through the crystal.

High-energy channeling. Walter Gibson of the State University of New York at Albany has been making use of low-energy channeling for more than a decade, primarily to measure lifetimes of excited nuclear states and to study impurities in crystal structures. After a CERN–Aarhus (Denmark) group began the first serious high-energy studies (1 to 15 GeV/c) of channeling in 1975, Gibson's Albany–Lehigh group and Richard Carrigan (a Fermilab particle physicist) approached a Fermilab–Dubna–UCLA collaboration at Fermilab in hopes of extending channeling to the hundred-GeV range. The drift-chamber setup this collaboration had built to measure the very small scattering angles in their kaon form-factor experiment, Gibson told us, seemed to him well suited to monitor the minute angular tolerances involved in high-energy channeling. The new collaboration replaced its liquid-hydrogen target by a "hyperpure" germanium crystal 2 cm long, and proceeded to demonstrate the channeling of protons and positive pions up to 250 GeV, and negative pions at 35 GeV.

Although theory had predicted that channeling would persist at very high energies, albeit with ever-decreasing critical angle, the group was eager to see whether or not the channeling parameters would in fact scale with energy as predicted by the largely classical standard theory. Furthermore, the collaborators wanted to learn if channeling could in practice be done amidst the technical complexities of the multi-hundred-GeV environment, with angular tolerances that set extremely stringent demands for crystal lattice perfection.

0031-9228/80/050017-06/$00.50 © American Institute of Physics

Besides demonstrating that channeling could be done at the highest available energies with existing techniques, the Fermilab experiment verified the predicted scaling behavior and observed the suppression of nuclear interactions for channeled high-energy particles. This latter effect might have been useful in the kaon form-factor measurement. In such experiments one is only looking for collisions of K mesons with the electrons in the hydrogen target. But kaon–proton interactions also occur, and they constitute a background noise to the measurement of the electromagnetic form factor. Carrigan told us that the strong suppression of nuclear interactions in channeling could perhaps be exploited to provide "pure electron targets," at least for positively charged beams.

Bending. Eduard Tsyganov, leader of the Dubna contingent at Fermilab, suggested that one might be able to steer high-energy particles by channeling them through bent crystals. There is of course a limit to how sharply one can deflect a fast particle without having it derail out of a crystal channel. Tsyganov calculated the centrifugal term introduced into the channeling potential by bending, and concluded that it sets a "critical radius" of curvature that increases linearly with the energy of the channeled particles. For a 250-GeV proton in silicon this critical radius would be about half a meter—three orders of magnitude smaller than the tightest curve one could achieve with a conventional bending magnet.

Tsyganov invited his Albany and Fermilab collaborators to join him at Dubna, to see if they could achieve channeled bending of an 8.4-GeV proton beam. The limiting factor at Dubna turned out to be not the critical radius (2 cm at 8.4 GeV), but rather the ability to bend a single crystal of silicon without breaking it. The group was able to achieve a 1.5-degree bend in one centimeter's length of a 2-mm thick silicon crystal, corresponding to a bending radius of 38 cm.

The bent crystal succeeded in turning the 8.4-GeV proton beam through 1.5 degrees—but with a curve so gentle it could just as well have channeled a 150-GeV beam, had one been available at Dubna. The group plans to extend these bending experiments to higher energies at the Soviet Union's Serpukhov accelerator, and perhaps eventually at Fermilab.

Applications. No one is likely in the foreseeable future to build a high-energy accelerator or storage ring with bent crystals replacing magnets in the primary ring. For one thing, the well-ordered crystal structure required for channeling would not survive the high beam intensities typical of primary circulating beams. For another, there is an energy-dependent "dechanneling length" in which the channeled beam falls to $1/e$ of its intensity. Even though this dechanneling length increases linearly with energy, it is still only about a meter at 1 TeV. But for the lower-intensity secondary beams that carry high-energy particles from the primary ring to the experimental areas, channeled steering might well be feasible. At Fermilab energies these beams are so "stiff" that it requires kilometer-long secondary beam lines just to get them out of each other's way.

Carrigan is particularly interested in another possible application of channeled bending. Recent surprising results indicate that some charmed particles live long enough to travel on the order of a centimeter before decaying. Ordinarily these decays are very difficult to study against a heavy background of unscattered and longer-lived tracks. He suggests that one might be able to steer this background out of the way by bent crystals, leaving the charmed decays much easier to see.

For more than ten years unbent crystals have been used to measure the lifetimes of isomeric nuclear states at low energies. If an excited state originates in a lattice plane and one knows its velocity, one can measure its lifetime if it travels on the order of one interatomic distance before decaying. The intensity of decay products emerging along the lattice planes is a sensitive measure of how far from the nearest atomic plane the decays occurred. Decay products having to travel near the planes are "blocked" by the lattice centers, while those traversing the interplanar channels are relatively unhindered. An Albany–Aarhus collaboration, led by Chi-Ree Sun (Albany), is about to extend this technique to the lifetime of the short-lived η meson. Until now, the lifetime of the η has been measured only indirectly, by the Primakoff effect. These model-dependent measurements have to date given seriously discrepant results at different energies.

Channeling radiation may prove useful in the increasingly difficult task of particle identification at very high energies. The radiation emitted by the channeled particles as they wobble or spiral through a crystal increases with decreasing mass, just like synchrotron radiation. Carrigan and others are calculating the channeling radiation intensity from TeV pions, to see if the number of photons they generate is sufficient to distinguish them from heavier particles such as protons and kaons.

Channeling radiation was first predicted a few years ago by Richard Pantell and Robert Terhune at Stanford, and independently by M. A. Kumakhov and by A. A. Vorobiev and his colleagues in the Soviet Union. Pantell and his Stanford colleagues, Richard Swent and Mark Alguard, working with Barry Berman and Stuart Bloom at Livermore and Sheldon Datz of Oak Ridge, have recently reported the first observation of channeling radiation, with 28- and 56-MeV electrons and positrons at the Livermore linear accelerator. The Livermore group had demonstrated the channeling of relativistic positrons ten years ago.

Because positive particles see an almost harmonic potential between the silicon crystal planes, the planar channeling radiation is particularly simple for positrons. For a harmonic oscillator the quantum states are equally spaced in energy, so that channeling radiation, which results from transitions between "bound states" in the planar potential, is nearly monochromatic and plane polarized. For electrons, which see a more complex potential near the atomic planes, one sees multiple plane-polarized transition lines, blending into a continuum at high energies; and for axial channeling, which involves helices of opposite sense with equal probability, the radiation is unpolarized.

Pantell points out that the complexity of the electron channeling spectrum conveys useful information about the potentials in the crystal, which are of particular interest to him. He stresses the importance of channeling radiation as a tool to probe the structure of the crystal in which it originates. From the x-ray spectrum of channeled electrons, the group has been able to study crystal potentials with a resolution of 0.1 Å.

The 56-MeV positrons generate an extremely well-collimated, plane-polarized beam of 40-keV x rays, with a 15 to 25% bandwidth. Channeled electrons and positrons in the 30- to 60-MeV range are a good source of hard x rays from about 20 to 150 keV, easily tuned by changing the incident energy or the channeling crystal, and capable of bursts as short as 10 picoseconds. This is well suited to complement existing synchrotron-radiation sources such as Stanford's electron–positron storage ring, which produces very little x radiation above 20 keV. (See PHYSICS TODAY, August 1979, page 22. The PEP storage ring now under construction at Stanford will eventually provide synchrotron radiation up to 100 keV.) A 100-microamp beam of 55-MeV electrons channeling in silicon, Pantell told us, would generate an x-ray beam peaking at 130 keV with an intensity of 0.7 milliwatts per cm^2 per 10% bandwidth. With GeV electrons and positrons, channeling becomes a source of gamma rays with energies up to hundreds of MeV. At Serpukhov, the Albany–Dubna–Fermilab group is setting up to produce 130-MeV gamma rays with 15-GeV channeled electrons and positrons.

The monochromatic channeling x rays may prove useful in chemistry and laser development, by raising atoms to specific excited states. The well-collimated beams may also serve to reduce the dosages required in diagnostic and therapeutic x-ray exposures. For material studies, channeling radiation would provide tunable, polarized, narrow-bandwidth x-ray beams for fluorescence and absorption spectroscopy. —BMS

References

1. A. F. Elishev et al., Phys. Lett. **88B**, 387 (1979).
2. R. A. Carrigan Jr et al., Nucl. Phys. **B163**, 1 (1980).
3. M. J. Alguard et al., Phys. Rev. Lett. **42**, 1148 (1979); R. L. Swent et al., Phys. Rev. Lett. **43**, 1723 (1979).

China emphasizes laser research

One of the eight scientific fields receiving special emphasis in the People's Republic of China these days is lasers. At the International Quantum Electronics Conference to be held in Boston this June, seven of the fifteen papers submitted from China were accepted. For the conference as a whole, 150 papers were accepted out of 450 submitted, suggesting that the Chinese are now competitive internationally.

Generally, the most advanced laser research I saw during my recent three-week visit to China (PHYSICS TODAY, March, page 32) was at the Institute of Optics and Fine Mechanics in Shanghai. But a number of other institutes and university physics departments also showed me laser research or development projects.

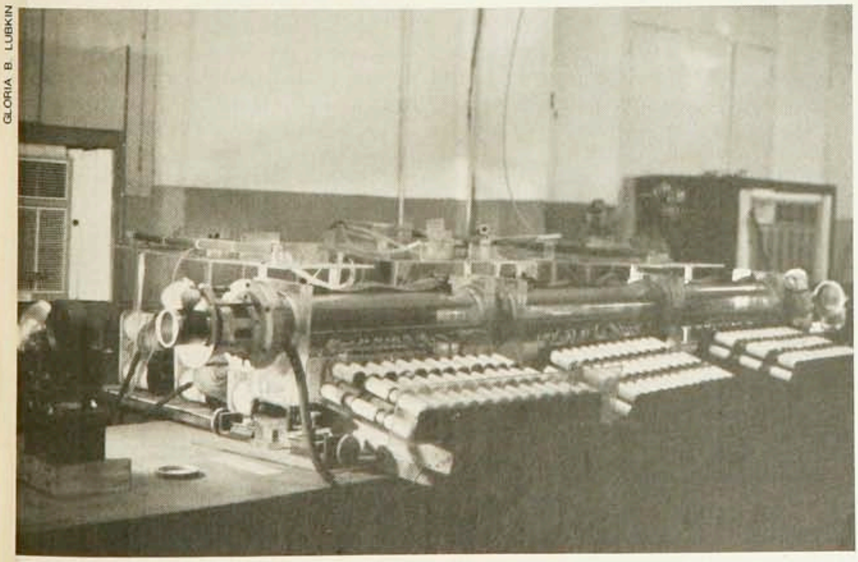
Laser research began in China in 1961, and three years later Academia Sinica established the Shanghai Institute of Optics and Fine Mechanics as a center for laser research, vice-director Teng Hsi-ming told me. At present, the Institute has 1400 staff members. However, 600 of them are doing production of equipment and parts, because they are unavailable commercially. Of the remaining staff, 500 are university graduates, and of those, 200 are PhD level or equivalent.

In 1964, physicists at the Shanghai Institute of Optics and Fine Mechanics, using a neodymium-glass laser with 100-MW output, observed air breakdown and nonlinear transmission of a laser beam, three years after nonlinear optical effects were first observed in the US. In 1965, inertial-confinement experiments began there with a neodymium-glass laser. The following year the ten-year Cultural Revolution began, undoubtedly hurting laser research throughout China, even the applied work. But by 1973, with a single beam emitting 10 GW, experimenters heated a frozen deuterium plane target and observed 1000 neutrons (with a boron trifluoride detector and with a plastic scintillator). A year later, the laser output was increased to 100 GW with a pulse length of 2–4 nanosec. Again using a plane target—either LiD_2 or CD_2—they observed 2×10^4 neutrons.

Shortly after the end of the Cultural Revolution—in 1977—experiments at the Institute began with a six-beam laser; each beam produced 100 GW for 1 nanosec. Each final output rod of the laser has a 70-mm diameter. The system has now been improved to operate in 100-picosec pulses, too. (For comparison, the six-beam Zeta laser-fusion facility at the University of Rochester produces 3–4 TW at 50 picosec or 1 kJ at 1 nanosec; each of its six beams has a final rod diameter of 90-mm.)

In 1977, when the Shanghai experimenters aimed their laser at a glass microballoon filled with neon gas, they observed compression of the shell (by means of an x-ray pinhole camera). Now the system is being used to irradiate a glass microballoon filled with either deuterium or neon.

During a lab tour, I saw the huge laser array, visited the target-chamber room, and saw a variety of diagnostics: BF_3 detector, plastic scintillator, x-ray pinhole camera, x-ray line spectrometer with a spatial resolution of several tens of microns, a cw spectrometer, an x-ray calorimeter and a Faraday cup.



GLORIA B. LUBKIN

TEA carbon-dioxide laser at Academia Sinica's Institute of Optics and Fine Mechanics in Shanghai has an output of 20 J lasting 1.5 nanosec. Its amplifier is electron-beam controlled.

In 1978, a group at the Institute of Physics in Peking reported using four-wave mixing to study the properties of liquid crystals. One of the group members was Yuen-Ron Shen of Berkeley, who was spending his sabbatical in Peking. A similar experiment was subsequently reported earlier this year by Amnon Yariv and his Caltech collaborators. The Institute of Optics and Fine Mechanics showed me four-wave mixing of two-phase conjugation in a dye solution. They had been interested in demonstrating that the effect could be produced in a highly absorbing medium as well as a transparent one. By modulating the infrared output of a laser, the Institute of Optics and Fine Mechanics experimenters were able to produce a visible output—putting on a colorful demonstration for me in the bargain. Conversion occurs in a nanosecond. Wu Tsun-kai told me he believes the quantum efficiency of the system can be greater than unity.

At the Institute of Optics and Fine Mechanics, Teng told me, is an active program to study nonlinear optical distoration of materials; the Institute is trying to raise the threshold for self-focusing. Teng also showed me a TEA carbon-dioxide laser with an output of 20 J lasting 1.5 nanosec. Its amplifier was electron-beam controlled. (For comparison, the Helios CO_2 laser at Los Alamos has produced 4 kJ in a 1.5-nanosec pulse.)

The Institute of Metallurgy in Shanghai started doing laser annealing in the fall of 1978, with the help of Bernhard Deutch from Aarhus University in Denmark. Since then the Institute has used the technique in a layer of silicon or gallium arsenide after ion implantation to raise the solubility limit—resulting in a higher conductivity. The Institute is also doing laser epitaxy: After depositing an amorphous layer (several thousands of angstroms thick) on a substrate, the experimenters convert the layer to a crystalline form with laser annealing. The Institute has also been doing laser metallization: The experimenters evaporate a thin film of AuGe on a GaAs substrate and then use laser annealing to produce an ohmic contact between the GaAs and the AuGe.

The Institute of Physics in Peking is exploring new methods for optical information processing. Chen Yuan-song showed me his group's efforts to produce a Walsh transformation optically, as has already been done elsewhere for Fourier transformations. The group is working with a one-dimensional eight-sequence complex Walsh matrix. Their coherent source is a helium–neon laser. Their optical components are computer-generated holographic lenses. Each lens has six degrees of freedom; so 24 degrees of