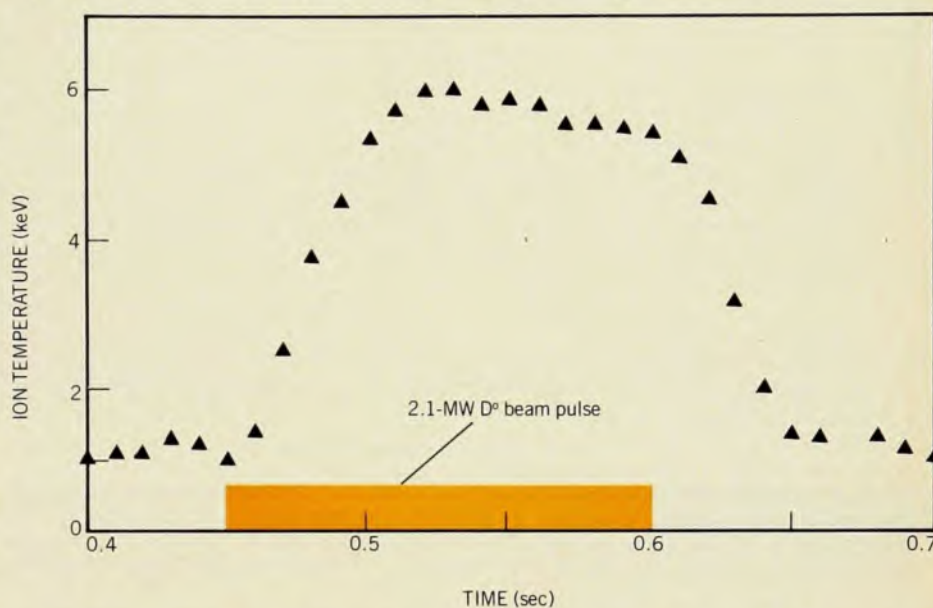


search & discovery

PLT reaches high temperature in a collisionless plasma

New experimental results at the Princeton Large Torus have shown that a low-density tokamak plasma can be heated to a record-breaking temperature for tokamaks without any serious instabilities occurring. Many plasma theorists had anticipated that at higher temperatures and lower densities trapped-particle modes would limit the temperature rise in the PLT experiment, in what was considered a worst-case situation—a collisionless plasma. Because such trapped-particle instabilities have not shown up, many fusion physicists feel encouraged that a power-producing tokamak reactor need not be nearly as large as some had feared. But the full implications on reactor size are not known.

At the 7th International Conference on Plasma Physics and Controlled Nuclear Fusion Research held in Innsbruck, Austria in August, Robert Goldston of Princeton reported that when a plasma was heated with 2.1 MW of neutral-beam power, the PLT group, headed by Wolfgang Stodiek and Harold Eubank, obtained an ion temperature of 5.5 keV. The previous record for tokamaks was also held by PLT, which achieved 2.2 keV last December. The PLT neutral-beam injectors were developed and built at the Oak Ridge National Laboratory. The high ion temperature was achieved when



Charge-exchange ion temperature as a function of time during the discharge of PLT. When 2.1 MW of neutral deuterium were injected into a hydrogen plasma, the average ion temperature was measured as 5.5 keV with a variety of diagnostics. Data reported at the Innsbruck meeting.

the central particle density, n , was $4.5 \times 10^{13} \text{cm}^{-3}$ and the energy confinement time, τ_E , was 20 msec. Thus the product of energy confinement time and density was of the order $n\tau_E = 10^{12} \text{cm}^{-3} \text{sec}$. In tokamaks, the product $n\tau_E$ has been

found to scale up roughly with the square of the density and the square of the plasma radius. The record-breaking value of $n\tau$ was achieved in the high-magnetic-field Alcator tokamak at MIT this

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Helium atoms probe silicon surface by diffraction

Atomic beams are providing a new probe for determining the surface structure of semiconductor crystals. Mark J. Cardillo and Gordon E. Becker of Bell Labs have recently been able to obtain diffraction patterns of thermal-energy helium atoms from the (100) and (111) surfaces of silicon. Their results¹ appear to be the first observation of atom diffraction from an elemental semiconductor.

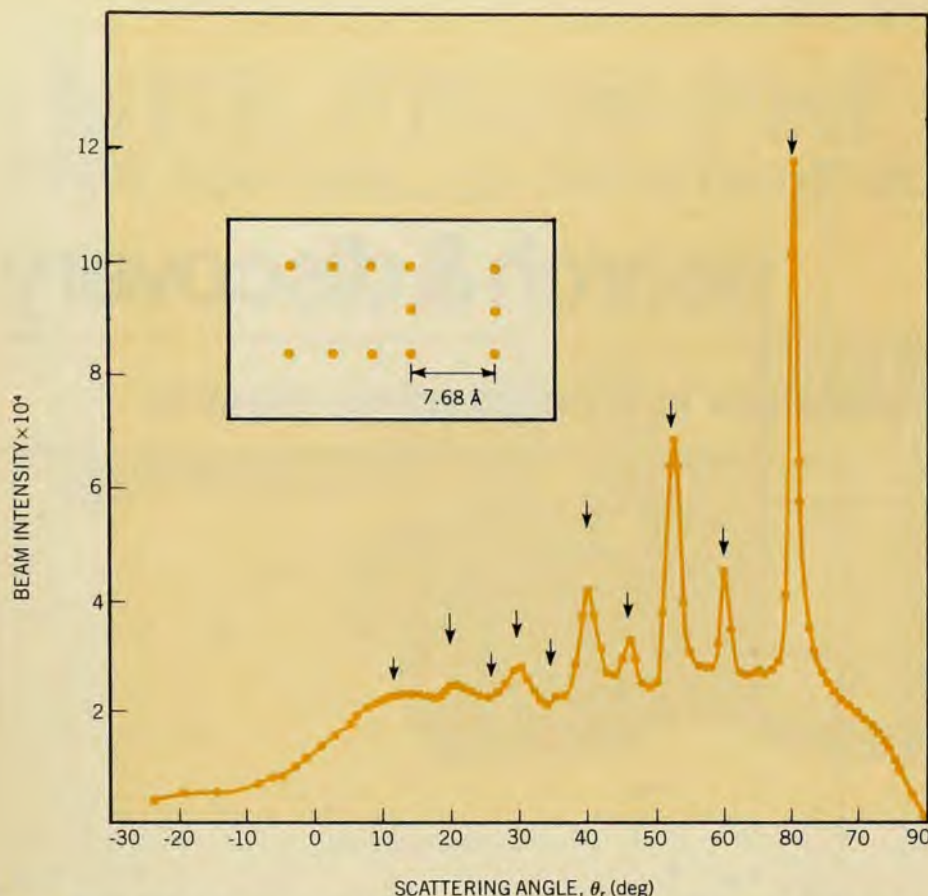
Otto Stern and his collaborators in Frankfurt were the first to observe, in 1930, the diffraction of atoms at a crystal surface. In those and subsequent experiments ionic crystals (usually alkali halides) were generally used, because they give rise to prominent and clear diffraction patterns and because their surfaces

are easy to prepare. More recently, with improvements in technique, diffraction of atoms has become a useful tool for studying crystal surfaces.

Another technique that has been useful over the past twenty years for studying surface phenomena is low-energy electron diffraction (LEED), which also dates back to the early days of quantum mechanics and the experiments of Clinton J. Davisson and his coworkers at Bell Labs. The low-energy electrons, however, penetrate into the crystal to some extent, so that the observed diffraction is due to several layers of atoms near the crystal surface. Atoms at thermal energy do not penetrate the crystal to any appreciable extent; the diffraction one sees is therefore due ex-

clusively to surface features. At the other extreme, photons penetrate very deeply into most crystals, so that x-ray diffraction gives information about the bulk structure of crystals. In many crystals—particularly semiconductors—the arrangement of atoms on the surface may differ considerably from their arrangement within the bulk of the crystal; in those cases the surface is said to be “reconstructed.” Atom diffraction and LEED provide complementary information about the outermost surface and about the transition region between the body and the surface.

Recent experiments. Several groups have been working on the diffraction of atoms from crystal surfaces. A group in



Diffraction of helium atoms from the (100) surface of silicon as observed by Cardillo and Becker. The intensity of the scattered helium beam is plotted as a function of the scattering angle, θ . The incident angle is 70° and the wavelength of the helium atoms is $0.57 \text{ \AA}$. The inset shows the arrangement of the crystal unit cells for a two-domain 2×1 net for the (100) surface of silicon.

Genoa under Giovanni Boato, for example, has used helium atoms and hydrogen molecules to probe surfaces of graphite and silver. Robert P. Merrill and his co-workers at Cornell have examined tungsten and other metals. A group at the University of California at San Diego under David R. Miller has used the inelastic scattering of atoms to examine the behavior of phonons at the crystal surface. And a group at Penn State headed by Daniel R. Frankl is now investigating the two-dimensional band structure of alkali-halide surfaces using atomic helium. There is a concomitant interest in theoretical work related to these problems as well, and groups at Case-Western Reserve, San Diego, State University of New York at Stony Brook, Madrid, and the University of Virginia, among others, are investigating the theoretical aspects of the scattering.

To obtain their beam, the Bell Labs experimenters used a high-pressure expansion nozzle that produces a supersonic, collision-free beam with a relatively narrow, adjustable velocity range. In their experiments, helium speeds ranged from about 1 km/s to about three times that, with a spread (full width at half maximum) of 12%. The corresponding wavelengths are $1.06 \text{ \AA}$ to $0.32 \text{ \AA}$. The scattered beams are in general extremely

weak (10^{-3} or 10^{-4} times the incident intensity in Cardillo and Becker's experiments, for example) and require very sensitive, but by now standard, detection techniques. The atomic beam was chopped at the source and then detected with a quadrupole mass spectrometer and a lock-in amplifier.

The major difficulty in observing the diffraction is in obtaining a clean, regular surface. In these experiments, the crystal was cut and polished outside the vacuum chamber, but cleaned and annealed *in vacuo*. The scattering, and presumably therefore the crystal surface, degrades within minutes, due to adsorption of residual gases even at ultra-high vacuum (about $6 \times 10^{-10} \text{ Torr}$). Cardillo and Becker therefore heated the crystal frequently to drive off adsorbed gases. The brief heating completely restored the intensity of the specular reflection, and, by implication, the crystal surface.

Results. From their data, Cardillo and Becker have confirmed the 2×1 two-domain structure of the Si(100) surface obtained with LEED. The basic structure has a fourth-order periodicity as well, a periodicity that is often difficult to see with LEED. More recently they have obtained data to demonstrate a 7×7 reconstruction of the Si(111) surface consistent with that obtained from elec-

tron-diffraction measurements. As in the diffraction of light, the intensity of the interference maxima is modulated by an envelope due to the internal structure of the unit cell; in this context the peaks in the envelope are often called "rainbow maxima." The atom diffraction data can thus give information not only about the regularities of the crystal surface, but also about the details of the contours within the unit mesh. Structural calculations for the (100) and (111) reconstructed surfaces of silicon are now underway at Bell Labs.

Atom diffraction is clearly a powerful tool for the examination of crystal surfaces. Needless to say, the application of this technique to semiconductors can be expected to have implications for technology, because as integrated circuits take up smaller and smaller volumes, the surface effects become more and more important. Furthermore, the geometry of the surface clearly plays a role in the formation of any junction, and therefore in the function of junction devices. As yet, the information about semiconductor surfaces is far from complete, and the new results can be expected to have a considerable impact.

—TVF

Reference

1. M. J. Cardillo, G. E. Becker, *Phys. Rev. Lett.* 40, 1148 (1978).

Brookhaven light source invites user interest

To plan for the use of the National Synchrotron Light Source facility at Brookhaven National Laboratory, the lab is asking for expressions of interest or intent from potential users. The facility is now under construction; groundbreaking ceremonies were held 28 September. It is to consist of two electron storage rings, a 0.7-GeV ring to provide radiation between the infrared and about $10 \text{ \AA}$, and a 2.5-GeV ring whose spectrum will extend down to about $0.1 \text{ \AA}$ (see *PHYSICS TODAY*, March 1977, page 17). The smaller ring is scheduled to be available for users by mid-1981; the larger is expected to be ready in late 1981 or early 1982.

The facility will provide a number of equipped beam lines for general users from universities, government and industrial laboratories, as well as Brookhaven staff scientists. In addition, some beam lines will be available for dedication to specialized uses by a Participating Research Team. Such a team can take a primary role in designing, constructing and maintaining a specialized beam line and will, in turn, for an agreed-upon time period have exclusive use of the beam for a fraction of the scheduled beam time.

Expressions of interest or intent both from potential general users and from potential members of Participating Research Teams should be sent to Martin Blume, Department of Physics, Brook-