Magnetic Fusion

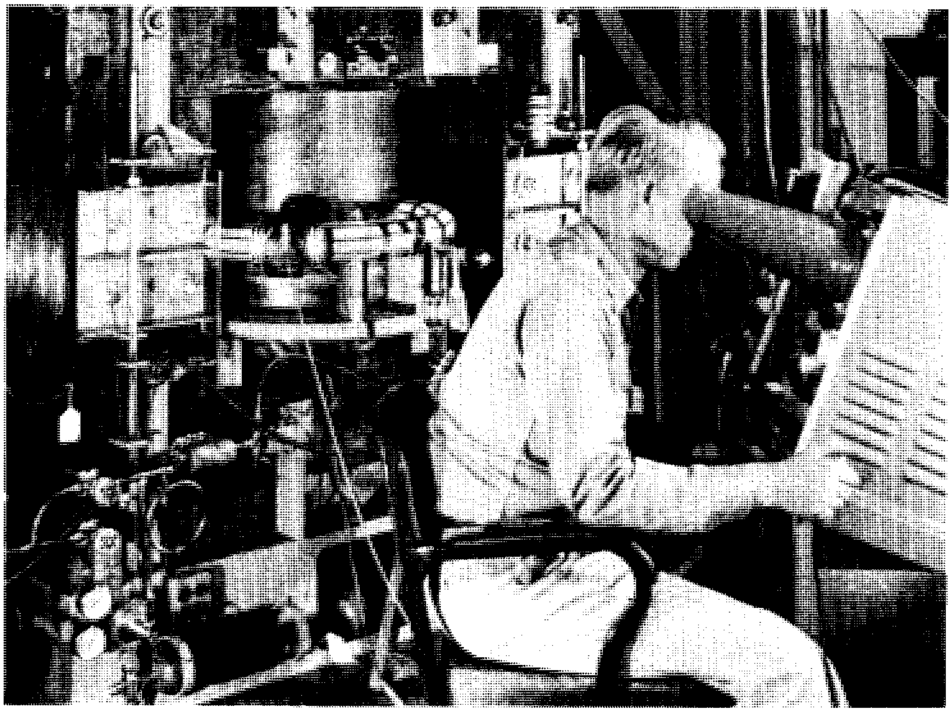
by James A. Phillips

During the war years while the Laboratory was thinking about ways to use nuclear energy to create violent explosions. Ulam, Fermi. Teller, Tuck, and others were also talking about using fusion of the light elements for the controlled release of energy and the production of useful power.

It had been understood since the '30s that the source of energy in the sun and other stars is thermonuclear fusion occurring in the very hot plasmas that make up the stars' centers, The thermal energy of the nuclei in these plasmas is so high that positively charged nuclei can penetrate the Coulomb barrier and approach so closely that fusion can occur,

To duplicate this process in the laboratory requires creating a plasma, heating it to thermonuclear temperatures, and confining it long enough for fusion reactions to take place. By 1946 the Los Alamos group concluded that the plasma would have to be heated to about 100 million degrees Celsius—ten times hotter than the sun's center and many orders of magnitude higher than any temperature yet achieved on Earth. Since a plasma that hot would quickly vaporize the vacuum container in which the plasma is created, some means for preventing the plasma's contact with the container walls was required. A "magnetic bottle," that is, a magnetic field of appropriate strength and geometry, was a possibility. A cylin-

Pipe-smoking Jim Tuck, John Osher foreground), and John Marshall (right) with "Picket fence, " one of the early magnetic fusion experiments.



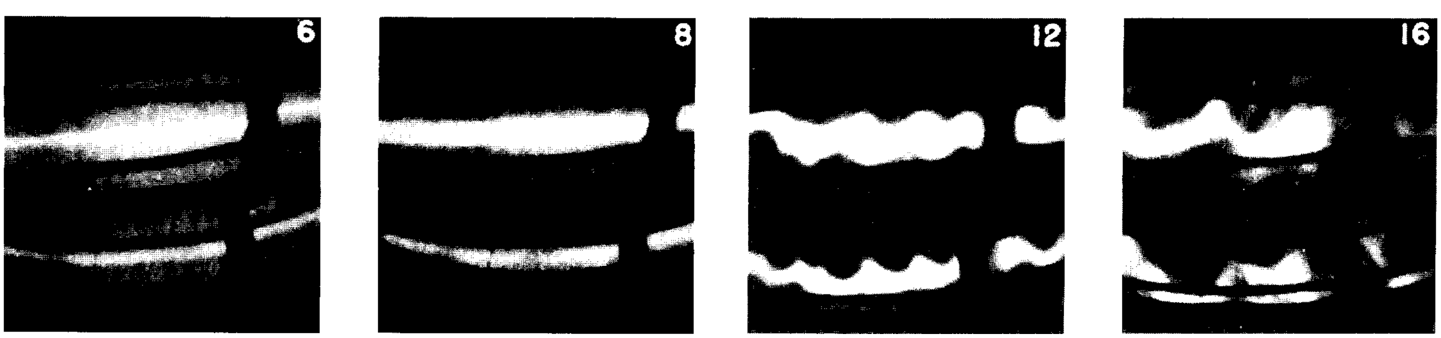
The Perhapsatron, which was built in 1952-53, was the first Z-pinch device at Los Alamos. The toroidal discharge tube surrounds the central core of an iron transformer.

drical magnetic bottle could be produced, but the plasma particles would quickly be lost out the ends. On the other hand a toroidal, or doughnut-shaped, bottle would eliminate end losses, but, as Fermi pointed out, particles in a simple toroidal magnetic field will rapidly drift outward and strike the walls.

Calculations of the energy released by thermonuclear reactions versus the energy lost through radiative and other processes were also done in those early days. The conclusion was that in terms of energy balance a power reactor based on nuclear fusion was not impossible.

In 1950 Jim Tuck returned to Los Alamos (after a sojourn in his native England and at the University of Chicago) and began working on magnetic confinement with a "Z-pinch." In this scheme an electric field applied along the axis of a discharge tube drives an electric current whose self-magnetic field pinches the current channel toward the axis of the tube. It was thought that the pinching process would produce the high plasma densities and temperatures necessary for fusion. Tuck knew from the work of British scientists that building up the current rather rapidly to create high temperatures caused instabilities in the pinch. He suggested that the instabilities might be minimized by applying a small electric field across the length of the discharge tube and increasing the current slowly. In addition he wanted to try this slow Z-pinch in a toroidal discharge tube.

In late 1951 Tuck took his ideas for the slow pinch to Bradbury, who gave him $50,000 to see what he could do. By early 1952 Tuck and his group had scrounged some parts of an old betatron, gotten the shops to make a toroidal quartz tube, hooked up a bank of capacitors, and built the first Perhapsatron. (At the same time this group was making definitive cross-section measurements on the fusion of deuterium and tritium for the hydrogen bomb project.) By 1953 it was clear that this device produced a pinch, but that instabilities



Z-pinch instabilities observed in the first Perhapsatron experiments in 1953. The plasma, initially uniformly concentrated along the Z-axis, begins to break up and strikes the walls of the discharge tube in a few millionths of a second.

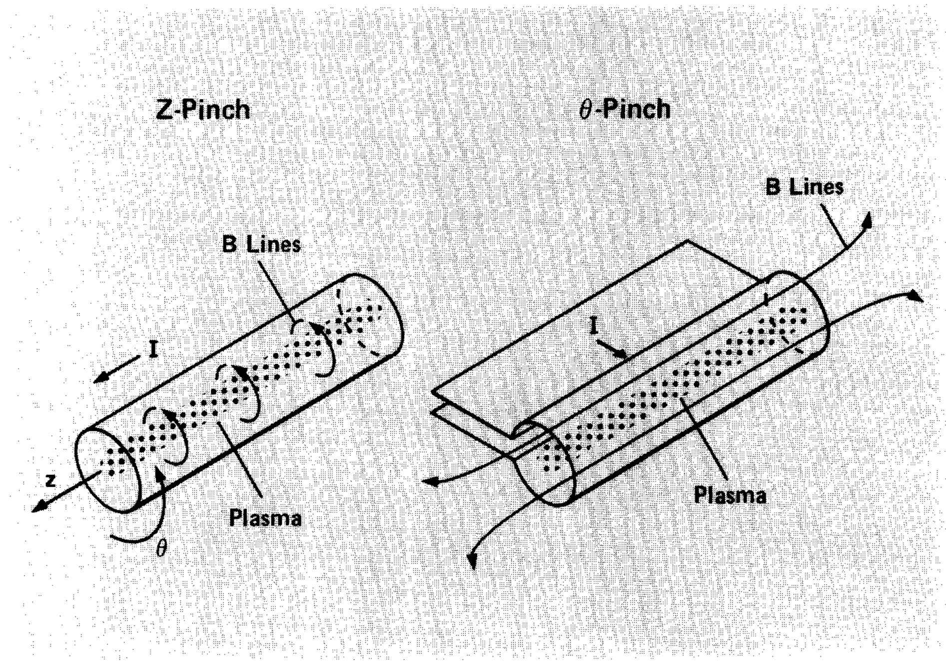
quickly dispersed the plasma.

The fast Z-pinch was the next idea to be tried. In 1954 Garwin and Rosenbluth, then at Los Alamos. suggested a theory indicating that a very strong electric field could form a pinch so fast that the heating of the plasma by its inward motion would initiate thermonuclear burn before the plasma had a chance to disperse. This theory led to experiments on microsecond time scales with a cylindrical tube. Again instabilities destroyed the plasma.

The stability of the Z-pinch could be improved by adding a longitudinal magnetic field, and a series of experiments were done over the next few years with Perhapsatrons incorporating such a field. Neutrons from the fusion of two deuterons were detected, but it was quickly shown that this fusion was caused not by heating but by acceleration of some of the plasma particles. Thermonuclear temperatures had not been reached.

The first experiment in which *thermonuclear* fusion was achieved in any laboratory was done in 1958 with the Scylla I machine. This experiment was based on the "@pinch," a pinch produced by a very short. intense pulse of current in a coil outside the discharge tube. The measured energy distributions of the neutrons, protons, and tritons from the Scylla I experiments gave definitive evidence that the plasma reached a temperature of about 15 million degrees Celsius and that the neutrons were the result of thermonuclear fusion.

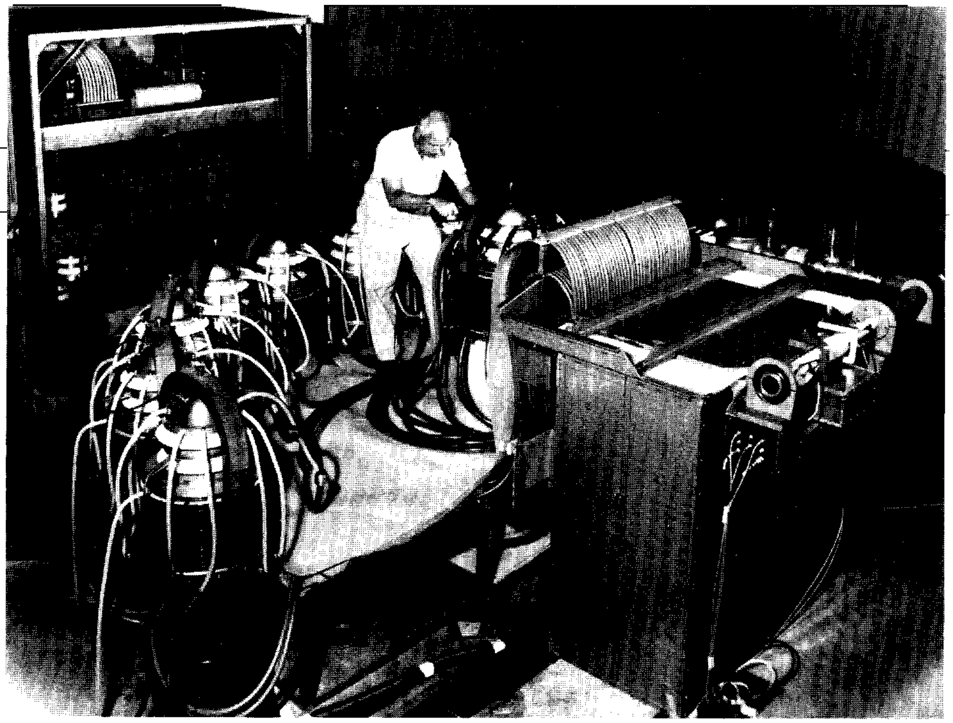
Attempts were made over the next decade to scale up the 6-pinch experiment in order to improve the confinement times. In 1964 plasma temperatures of approximately 40 million degrees Celsius and a few billion deuteron-deuteron fusion reactions per discharge were achieved with the Scylla IV device, but the plasma confinement times were less than 10 millionths of a second, The largest 6-pinch machine was Scyllac, a toroidal machine completed in 1974. Experiments with Scyllac demonstrated the behavior of high-density pinches in toroidal geometry. However, during this time the national fusion research program began to examine the technologies required for fusion reactors. The fast risetime, high voltage, and fast feedback systems required for a Scyllac-type O-pinch machine did not project to an attractive reactor. Work on Scyllac was discontinued in 1977.



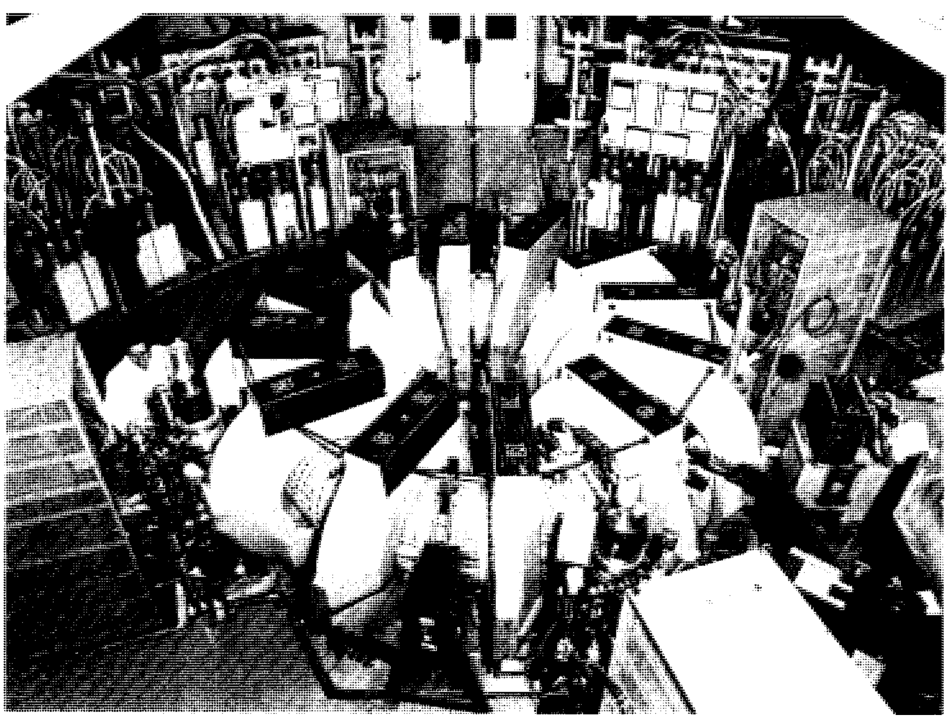
In the Z-pinch an electric field applied along the axis of a discharge tube produces a current I whose self-magnetic field* B *pinches the current channel toward the axis. In the O-pinch the magnetic field is created by a current flowing in the 0 direction through a coil outside the discharge tube. In both cases the pinching process produces high plasma temperatures and densities.

In the meantime work on the Z-pinch, which had been abandoned in 1961, was revived in 1967. Advances in experiment and theory have led to further improvements of the toroidal Z-pinch approach, the most significant of which is the reversed-field pinch. It is similar to the early stabilized Z-pinches of the Perhapsatron days, but addition of a reversed toroidal magnetic field further increases plasma stability. Present-day experiments are carried out with better vacuum pumps and with metal, rather than glass, container walls. These improvements reduce contamination of the plasma by impurities and thereby reduce radiative energy losses and cooling of the plasma. Also, computer simulations have helped provide better magnetic field configurations for the reversed-field pinch.

The reversed-field pinch is one of the alternative approaches to controlled fusion being studied in the United States. It offers distinct advantages for a fusion reactor. Since its magnetic field configuration allows a greater plasma pressure to be confined for a given magnetic field pressure, it offers the possibility of more energy output per unit plasma volume. Other possibilities it offers are ohmic heating to ignition and a reduction in reactor complexity. Overall, the reversed-field pinch offers a new option in magnetic fusion: a compact, high-power-density reac-



Scylla I, the 0-pinch device that in 1958 produced the first thermonuclear fusion in any laboratory. The high-voltage capacitors are on the left and the discharge tube is on the right. This machine and the Z-pinch Perhapsatron S-4 were displayed in Geneva in 1958 at the Second International United Nations Conference on Peaceful Uses of Atomic Energy.



ZT-40M, the latest Los Alamos reversed-field pinch experiment. Toroidal and poloidal current windings are wound on the outer surface of the torus. The large objects surrounding the torus at several positions are the iron transformer cores.

tor system that should provide fusion power at a lower cost than conventional magnetic confinement approaches.

Our latest development on the reversed-field pinch is the ZT-40M experiment. This experiment has considerably exceeded its original objectives: plasma temperatures of about 4 million degrees Celsius have been achieved with a toroidal current of 200 kiloamperes. The magnetic field configuration is maintained for about 25 milliseconds. An upgraded version of ZT-40M is planned to explore how plasma confinement times scale with increases in plasma size and toroidal current.

In addition to the reversed-field pinch program, a compact toroid approach to magnetic fusion was initiated between 1976 and 1979 at Los Alamos. A compact toroid has a toroidal plasma configuration in which the major magnetic confinement fields are created by internal currents in the plasma rather than by currents in external conductors. This arrangement simplifies the confinement geometry and thereby eliminates the need for a toroidal vacuum vessel and toroidal magnetic field coils. Like the reversed-field pinch, the compact toroid offers the possibility of compact, high-power-density reactor systems.

Two compact toroid approaches are being pursued, each having a different magnetic field configuration and shape. The FRX-C experiment (a field-reversed configuration) has demonstrated favorable confinement scaling with size and has achieved impressive Lawson parameters (density times confinement time) of about 4 x 10^{11} seconds per cubic centimeter compared with the approximately 10^{14} seconds per cubic centimeter required for fusion energy break-even. Ion temperatures from I to 7 million degrees Celsius have been achieved. In the CTX experiment stable spheromak configurations lasting a record time of 2 milliseconds have been produced, We are currently studying methods for changing from pulsed to steady-state spheromak operation. ■