First plasma at Princeton's Tokamak Fusion Test Reactor

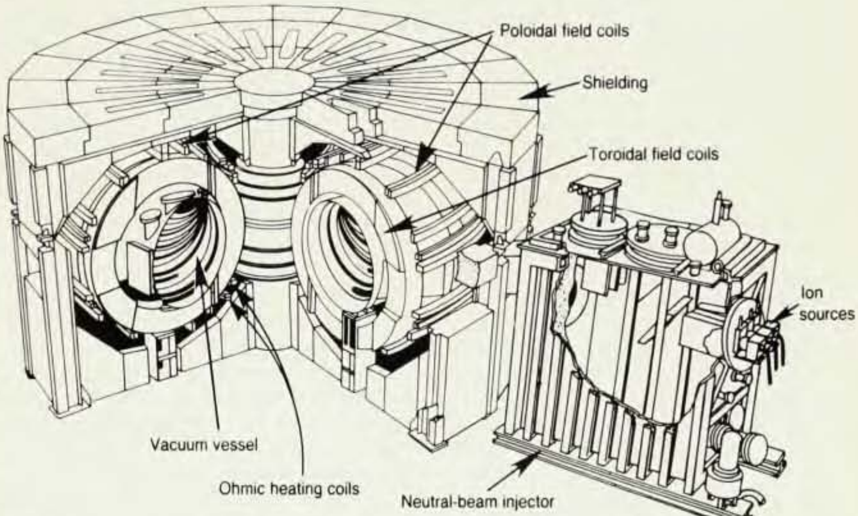
The first of a new generation of large tokamaks was completed just in time for Christmas. Princeton's Tokamak Fusion Test Reactor achieved its first test plasma in the early hours of 24 December. TFTR is one of four new tokamaks large enough to achieve plasma conditions that are expected to suffice for the demonstration of "scientific breakeven"—the output of fusion power equal to the input of heating power from external sources.

The Joint European Tokamak at Culham Laboratory in England, the largest of the four, is expected to be operational this summer. The other two—the Japanese JT-60 and the Soviet T-15—are scheduled to begin operation in 1985.

Harold Furth, director of the Princeton Plasma Physics Laboratory, explained to us that the design goal of TFTR was to build the smallest, most straightforward machine that one could confidently expect to achieve breakeven. "We wanted to avoid doing anything too clever or speculative." He describes TFTR as "a high-confidence extrapolation" of the Princeton Large Torus, which began operations in 1975.

By contrast, T-15 will use superconducting magnet coils and JT-60 will incorporate a poloidal diverter to skim impurities from the edge of the plasma. Neither of these technologies was well established when TFTR was proposed in 1974. Construction of the Princeton machine began two years later, and its total cost has been $314 million. It was built under the direction of Paul Reardon (now associate director for high-energy facilities at Brookhaven) and Don Grove (who now heads the TFTR project).

The Japanese and Soviet tokamaks, however, are not expected to employ deuterium–tritium plasmas. Using only hydrogen and deuterium, their goal is simply to study the confinement of plasmas at temperatures and densities that would suffice to achieve breakeven if enough tritium were present. The reaction $D + T \rightarrow He^4 + n + 17.6$ MeV is the most easily accessible of the fusion reactions being considered for commercial fusion reactors.



The Tokamak Fusion Test Reactor was completed at Princeton in December. The vacuum vessel, which contains the plasma, has major and minor radii of 2.65 and 1.1 meters. The confining magnetic field is produced by currents in the toroidal and poloidal field coils together with the 2.5-MA plasma current itself. This plasma current, which also contributes to heating the plasma, is induced by the transformer action of the time-varying current in the ohmic-heating coils. Four neutral beams (one shown here) of 120-keV deuterium atoms will ultimately inject 30 MW of additional heating power into the plasma. Deuterium–tritium experiments begin in 1986.

The TFTR experimental program calls for the first injection of tritium in 1986, to be followed promptly by the demonstration of scientific breakeven. JET is not expected to employ a D–T plasma until about three years later. The first D–T breakeven experiments at the TFTR in 1986 will be limited to ten 1-second "shots." Without this restriction, the output of 14-MeV neutrons from the D–T reaction would activate the tokamak structure to such a degree that one would have to go to remote-handling procedures. The Princeton group does not plan to install remote-handling capability until about 1989, when a second round of higher-output D–T experiments is undertaken. At present, DOE has approved the detailed TFTR experimental program only through 1986.

With a plasma volume three times that of TFTR, JET is the only tokamak of this generation that has some prospect of approaching D–T ignition—a completely self-sustaining thermonuclear burn without external heating. Because of its larger neutron output, JET will require remote handling as soon as its D–T experiments begin, about 1989.

Scientific breakeven is described by the condition $Q = 1$, where Q is the ratio of power output from the fusion reaction over heating-power input to the plasma. The demonstration of breakeven has long been sought as a necessary proof-of-principle for the tokamak scheme. There is of course no discontinuous change in the physics of the D–T plasma precisely at $Q = 1$. "It's rather like going to the North Pole," Furth suggests. The landscape is pretty much the same for hundreds of miles around. Dale Meade, who heads the TFTR experimental research program, prefers the analogy to Fermi's demonstration of a neutron multiplication factor of unity in the first atomic pile—proving the fission-reactor principle.

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If the energy distribution of the deuterons and tritons in the tokamak plasma is thermal, with a mean temperature of 10 keV (1.2×10^8 kelvin), the necessary condition for $Q=1$ is that $n\tau$, the product of the ion density and the energy confinement time, must be 6×10^{13} sec/cm^3. But not all the deuterons in the TFTR plasma will have a thermal energy distribution. For the first demonstration of $Q=1$, the primary heating source for the plasma will be four powerful beams of 120-keV neutral deuterium atoms, providing 30 megawatts of heating power. The heating beams are electrically neutral so they may easily penetrate the confining magnetic field. Once inside the tokamak plasma, the deuterium is quickly ionized and the resulting high-energy deuterons have a much higher D–T fusion cross section than do the slower thermal deuterons. Under these conditions, the Princeton group calculates, one can achieve $Q=1$ with an $n\tau$ of only 1×10^{13} sec/cm^3. The TFTR should however be capable of an $n\tau$ of at least 6×10^{13} sec/cm^3. With the addition of ion-cyclotron-frequency heating (DOE willing), the second phase of D–T experiments in 1989 may be able to achieve $Q=2$ with ion temperatures in excess of 20 keV.

The TFTR vacuum vessel has a major radius of 2.65 m and a minor radius of 1.1 m. It should achieve a plasma current of 2.5 megamps, about five times that of the smaller Princeton Large Torus, which in 1980 reached a record ion temperature of almost 7 keV, with an $n\tau$ corresponding to $Q=0.02$. PLT did not use a D–T plasma. TFTR will in fact be the first magnetic-confinement device capable of achieving a significant fusion output. The fusion output of PLT is not, however, entirely negligible. Its pure deuterium plasma produces about 3×10^{13} D–D fusion reactions per pulse.

The energy confinement of a tokamak plasma improves with size, much as a large rock loses heat more slowly than a small rock of similar shape. But the details of this improvement are not yet clear. With major and minor radii twice those of PLT and other tokamaks of its generation, TFTR will provide an important opportunity to investigate the scaling of τ with the geometry of the plasma torus. For a long time it was thought that τ scales as a^2 (where a is the minor plasma radius) and is relatively insensitive to the major radius R. Recent experiments at the MIT Alcator-C, however, have found that τ improves more like aR^2 with purely ohmic heating.

This raises the question of how confinement scaling depends on the mode of plasma heating. With the introduction of neutral beam heating in recent years, there were disturbing indications that τ was deteriorating. But recent experiments at the Asdex tokamak at Garching (near Munich) appear to indicate that these adverse effects of neutral-beam heating can be overcome by careful tailoring of the temperature and density profiles of the plasma torus.

The experimental program at TFTR begins this year with ohmically heated hydrogen plasmas. Ohmic heating generated by the plasma current is important only at relatively low temperatures. As the temperature increases, the decrease of the electron Coulomb-scattering cross section radically decreases the resistivity of the plasma. TFTR will also employ adiabatic compression heating. In 30 milliseconds one can reduce the major plasma radius from 3.1 to 2.1 m, while shrinking its minor radius by 20%. Compression experiments this year will study the efficacy of compression heating, while at the same time investigating the scaling of confinement with R and a. Late in the year, the first two neutral beams will be installed, providing 10 MW of heating power.

In 1984 the two neutral beams should be heating hydrogen and deuterium plasmas to temperatures of three (perhaps even four) keV. At the end of the year the remaining two neutral beams will be installed, bringing the beam heating power up to 30 MW.

In 1985, Meade told us, with a plasma current in excess of 2 MA and minor radius varying from 85 to 45 cm, one will begin to see for the first time how the confinement time of a large plasma scales at reactor temperatures around 10 keV. The Princeton group will study the relative merits of two different heating modes. In the "strong compression mode," the plasma ring will be adiabatically compressed from 3.1 to 2.1 m in R and from 55 to 45 cm in a. The plasma current in this small-minor-radius mode will be limited to 1.5 MA. In the alternative "quasistatic, high-current mode," the minor radius will be 85 cm and the plasma current will go up to 2.5 MA.

Whichever heating mode proves best will be employed in 1986 for the D–T breakeven experiment. Before the D–T shots begin, the degree of activation generated by the 2.5-MeV neutrons produced in D–D fusion reactions will be carefully checked against activation and shielding calculations. If the shielding proves adequate, the D–T experiments will begin, starting with small admixtures of tritium. The schedule of D–T experiments is strongly constrained, Meade told us, by the requirement that no more than 5×10^4 curies of the highly radioactive tritium are permitted on site at any one time.

When the full complement of tritium is added to the plasma, the group confidently expects that $Q=1$ will be demonstrated within a month or two. The ten D–T breakeven shots in 1986 should produce a total of 10^{19} 14-MeV neutrons. This is expected to produce an activation of no more than 100 millirem/hr (decaying below 10 mr/hr after a year), levels at which remote handling will not be necessary; long-handled tools should suffice until the next round of D–T shots in 1989.

After the breakeven demonstration in 1986, the group will return for the time being to non-tritium experiments. A number of such further confinement experiments have already been approved. The plan for the following years is to seek DOE approval for the installation of ion-cyclotron-frequency heating facilities. With 50 MW of combined ICF and neutral-beam heating power one hopes to get up to ion temperatures of 20 to 30 keV, sufficient, one hopes, for $Q=2$.

By 1989, with the installation of remote-handling capability, the second phase of D–T experiments could begin. "This would provide our first detailed look at the physics of α-particle confinement in a fusion device," Meade told us. Though no serious problems are anticipated, it is possible that the 3.5-MeV alphas, which would provide most of the heating that keeps an ignited plasma going, could generate unforeseen instabilities. While TFTR is not expected to reach ignition, "these experiments should tell us precisely what will be needed to achieve and maintain ignition in a reactor-core experiment," Furth explains.

Bruno Coppi (MIT) and his collaborators argue that the most expeditious approach to tokamak breakeven and ignition would be the construction of small "ignitor-type" tokamaks with very high magnetic field intensities supporting high plasma currents and densities (see PHYSICS TODAY, May 1981, page 17). He expresses optimism that a first-generation ignitor, with a major radius about ⅓ that of TFTR, could achieve $Q=5$ and perhaps ignition.

The S-1 spheromak. Since 1975, the Princeton Plasma Physics Laboratory has undertaken the construction of only two new machines: TFTR, which is aimed at maximizing the predictability of performance, and the S-1 spheromak, which aims to maximize innovation. By coincidence, these two philosophically opposite projects were completed almost simultaneously. The S-1, a relatively modest $8-million machine designed to provide the first large-scale test of the spheromak concept, produced its first plasma at the end of January. The S-1 group is headed by Masaaki Yamada.

The spheromak configuration is an alternative magnetic-confinement scheme, Furth told us, that attempts a number of radical technological improvements relative to the tokamak. Whereas the plasma in both cases is toroidal, the spheromak containment vessel is not. The S-1 is a 3-meter-diameter affair, shaped something like a hamburger patty. Unlike the toroidal vessel characteristics of tokamaks, the hole of its plasma doughnut is not threaded by coils or inner walls. All field-generating coils are external to the plasma ring. The plasma current itself generates the confining toroidal magnetic field, obviating the need for the toroidal-field coils that thread the hole of a tokamak ring. The S-1 plasma, about the size and shape of a truck tire, is therefore free to move around in its containment vessel.

"If we succeed in forming a stable plasma smoke ring in S-1," Furth told us, "we will attempt to extract it through a porthole." Such a scheme in a commercial reactor would afford the technologically attractive prospect of separating the region in which the plasma is formed and heated from the region where it burns and gives up its heat. One would generate a plasma ring, compress it, heat it and *then* move it to a region surrounded by thermal blankets before adding tritium.

The spheromak configuration was first discussed almost thirty years ago in an astrophysical context by Arnuls Schlüter and Reimar Lüst in Munich, and in the fusion-reactor context by Hannes Alfvén in Stockholm. Unlike TFTR, Furth suggests, the success of S-1 is far from "assured." But if it works, it could be the basis for a commercial fusion reactor that might be far more attractive from an engineering point of view than any of today's mainstream approaches. —BMS

Newly discovered pulsar is 20 times faster than Crab pulsar

Of the more than three hundred known radio pulsars in our galaxy, the most recently discovered is surely the strangest. On 12 November, a group of radio astronomers led by Donald Backer (Berkeley) announced[1] by International Astronomical Union telegram that they had found a pulsar in the constellation Vulpecula with a period of 1.558 *milliseconds*—twenty times shorter than that of the Crab pulsar, the fastest pulsar previously seen. The period of the first recorded pulsar, 1.337 seconds, discovered in 1967 by Jocelyn Bell and her colleagues at Cambridge, is much more typical.

Radio pulsars slow down as they age. Because the Crab pulsar is known from the historical record to be less than a thousand years old (the supernova that gave it birth was observed by Chinese astronomers in the 11th century), previous pulsar searches had restricted themselves to looking for periods longer than about 10 milliseconds. Any pulsar younger than the Crab, it was supposed, would have a nebula bright enough to have been seen anywhere in the Galaxy; and anything older would be slower. Furthermore, the newly discovered pulsar, with a spin rate of 642 Hz, comes perilously close to the upper limit at which neutron stars would be centrifugally unstable—about 2000 Hz. Its equatorial velocity, assuming it to be a neutron star with a radius of about 10 km, is 13% of the speed of light.

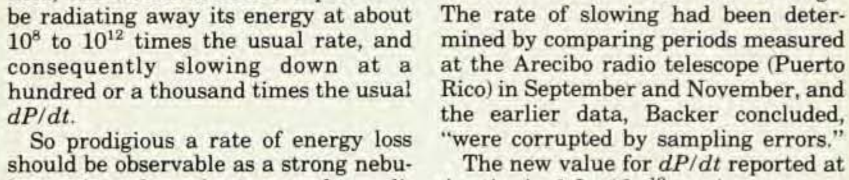
The pulsating radio signals that characterize pulsars represent only a very small fraction of the energy these highly magnetized, spinning neutron stars radiate into their environment. Although the pulsar's principal energy-loss mechanism is thought to involve both electromagnetic radiation and the acceleration of plasma particles by the star's complex, corotating magnetosphere, the expression for the energy-loss rate in most models turns out to look very much like the classical formula for magnetic dipole radiation. For a given magnetic field strength, the rate of energy loss in such models is proportional to P^{-4}, where P is the period of spin and pulsation, and the rate at which the pulsar slows down, dP/dt, goes like P^{-1}.

As determined by the observed P and dP/dt, most pulsars appear to have surface magnetic field intensities on the order of 10^{12} gauss. (Our Sun, for comparison, has a surface field of about *one* gauss.) If the newly discovered millisecond pulsar had such a typical field, one would therefore expect it to be radiating away its energy at about 10^8 to 10^{12} times the usual rate, and consequently slowing down at a hundred or a thousand times the usual dP/dt.

So prodigious a rate of energy loss should be observable as a strong nebular region of synchrotron and x radiation surrounding the star, such as one sees for young, fast pulsars like the Crab. Neither the Einstein x-ray telescope nor the radio observations have seen any such extended source associated with the millisecond pulsar, nor has one seen the shell of supernova remnant debris one would expect with such a rapidly spinning, and therefore presumably young, pulsar.

The first November telegram reported a dP/dt of a few times 10^{-14} sec/sec, suggesting an age of only a few thousand years and a power output a thousand times that of the Crab. Such a high rate of rotational energy loss excited widespread enthusiasm that gravitational radiation from the star might be seen by a number of gravitation-wave detectors sensitive in the kilohertz range. This first flush, however, was dampened a month later at the 11th Texas Symposium on Relativistic Astrophysics in Austin, when Backer reported[2] that the original estimate of dP/dt had been far too large. The rate of slowing had been determined by comparing periods measured at the Arecibo radio telescope (Puerto Rico) in September and November, and the earlier data, Backer concluded, "were corrupted by sampling errors."

The new value for dP/dt reported at Austin is 1.3×10^{-19} sec/sec, an extraordinarily slow rate of spindown, corresponding to an age estimate of several hundred million years and a power output five hundred times less than the Crab. The fastest pulsar turns out to have by far the slowest deceleration. How could a pulsar so old be spinning so rapidly and losing energy so slowly? On the other hand, when the original very rapid spindown rate of 10^{-14} sec/sec was announced, a number of theorists had quickly point-



Waveform of the pulsating radio signal from the millisecond pulsar recently discovered at Arecibo by Donald Backer and his colleagues. The full period of 1.558 milliseconds shows a primary peak separated from a secondary peak by about 180°. The two peaks presumably come from the opposite magnetic poles of the rapidly spinning neutron star. Most of the pulse width seen here is attributed to the signal-averaging instrumentation rather than the intrinsic signal.