Harold Furth: Fusion Pioneer

Ingenious theorist, master builder of experiments,
architect of the fusion program

1930 – 2002

Harold Furth: Fusion Pioneer

Ingenious theorist, master builder of experiments, architect of the fusion program

The Early Years

Harold Furth was a member of the first generation of fusion researchers. He worked on high magnetic fields and force-free magnetic coils for his Ph.D. dissertation at Harvard in the early-1950s. He joined Lawrence Berkeley and Livermore Laboratories in the mid-1950s, when fusion research was still classified. From the outset, Furth had an instinctive feel for plasmas, electrical currents, and magnetic fields and how they interact in ways that could sometimes lead to plasma-magnetic instabilities. As a result, he led pioneering investigations into many of the instabilities that have plagued magnetic confinement of plasmas, and he devised ingenious "magnetic bottles" to better confine hot plasmas.

In the 1950s, Furth and his colleague at the Lawrence Laboratories, Stirling Colgate, investigated plasmas which were subject to the "sausage instability" produced by the concave curvature of the magnetic field in the simplest and earliest confinement configuration, the "Z-pinch." To avoid this problem, Furth and Colgate built the stabilized pinch, which was predicted to be stable under the idealized assumption of a plasma with zero resistivity. This device extended plasma confinement, but was still far from sufficient for a fusion plasma due to instabilities allowed by the finite resistivity of the plasma.

In the early 1960s, Furth and Colgate invented the Levitron, a large ring of copper carrying large currents that was transiently "levitated" within the plasma in a vacuum chamber. The purpose of the copper ring was to produce magnetic fields that were convex toward the plasma. The purpose of the device was to allow the plasma temperature to increase thereby reducing the plasma resistivity; still the plasma instabilities persisted. A better theory was needed to take into account small but finite plasma resistivity.

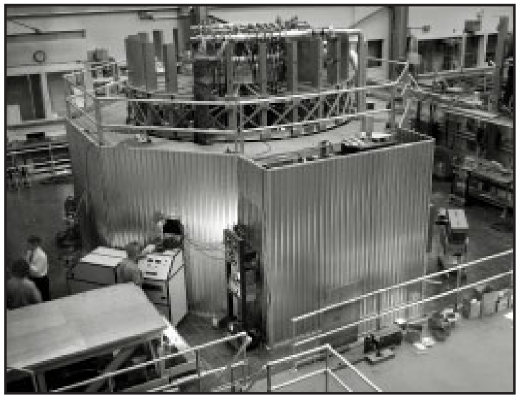
While at the Lawrence Livermore Laboratory in the early 1960s, Furth provided the conceptual basis for the first rigorous theory of resistive instabilities in magnetically confined plasmas, published jointly with John Killeen and Marshall Rosenbluth in 1963. This major work showed the inadequacy of the prevailing "ideal magnetohydrodynamic (MHD)" picture of confined

Superconducting Levitron

plasmas, and it led to the identification of certain types of magnetic instabilities that limited early fusion plasmas. Essentially, Furth and his co-workers showed that the electrical resistance of a plasma, although extremely small at high plasma temperature, could play a decisive role in determining the gross stability of a confinement configuration.

As a participant in a year-long scientific workshop with Soviet physicists held at Trieste, Italy, in 1965–6, Furth was instrumental in another major innovation in the theory of plasmas confined in toroidal (doughnut-shaped) magnetic configurations, leading to the replacement of "classical" transport theory by "neoclassical" theory. Together with his Russian colleagues Roald Sagdeev and Alex Galeev, Furth showed how collisions could transport particles and energy relatively rapidly across magnetic fields, because of the complicated particle orbits in three-dimensional "magnetic bottles." Because of the shape of these orbits when projected onto a plane, Furth introduced the terminology of "banana" to describe such orbits in an axisymmetric magnetic field such as occurs in the tokamak configuration, and subsequently used the term "super-banana" to describe the orbits of particles moving in nonsymmetric three-dimensional magnetic fields used in stellarator configurations.

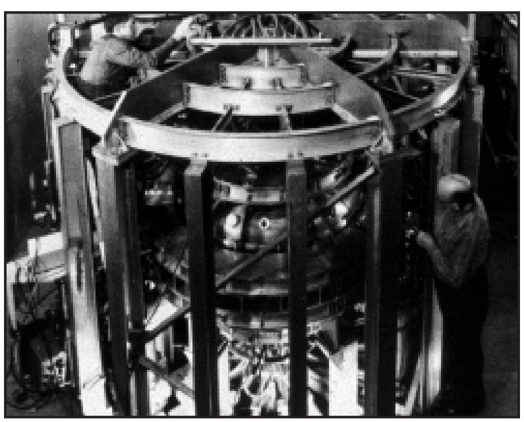
In the mid-1960s, Furth authored numerous theoretical papers with Marshall Rosenbluth on possible MHD-stable confinement configurations, especially those that involved "negative-V″," which should also ensure stability against at least one class of resistive instability. Over a period of years, this work led to the invention of several toroidal magnetic configurations that ranged from special types of stellarator to hybrid stellarator-tokamaks, and several novel configurations — Heliac, Tokatron, Spheromak — some of which are still in use today.



Floating Multiple (FM-1)

Princeton

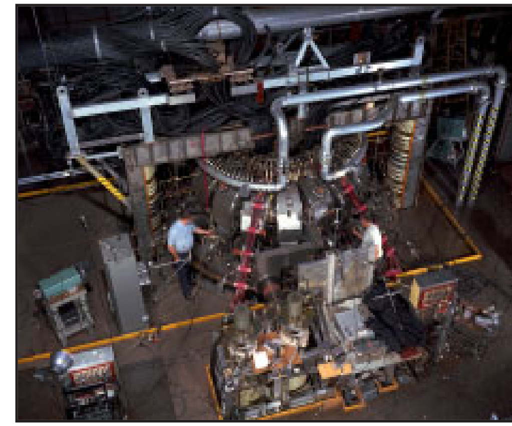
Harold Furth came to Princeton in 1967 as Professor of Astrophysical Sciences and Co-Head of the Experimental Division at the Princeton Plasma Physics Laboratory (PPPL). Shortly after coming to Princeton, he led a reassessment of possible new experiments for PPPL, and out of this study came decisions that would shape the future of fusion research in the U.S. The plan was for a series of confinement experiments that would elucidate the underlying physics of magnetically confined plasmas in relatively simple axisymmetric configurations with favorable MHD properties; PPPL subsequently built two experiments of this class, namely FM-1 and Spherator. At the same time, it was recognized that the tokamak, which was then pursued almost exclusively in the Soviet Union, was another configuration of this type. After the Russian breakthrough in tokamak research first reported in 1968 and confirmed in 1969, Furth seized this opportunity to redirect the PPPL program and quickly produced proposals for three new tokamaks at Princeton. The first of these was a conversion of the existing Model-C stellarator to a tokamak — Symmetric Tokamak (ST) — which was accomplished in six months, and within another six months had confirmed the results of the Russian tokamaks.



Spherator

The second proposal was for a novel variant of the tokamak, called the "Adiabatic Toroidal Compressor (ATC)," which was to incorporate strong additional heating (compression and neutral beams) of the plasma

beyond the inherent ohmic heating by the plasma current. This experiment came into being in the early 1970s and successfully confirmed that tokamaks could confine the very energetic ions produced by these heating schemes.



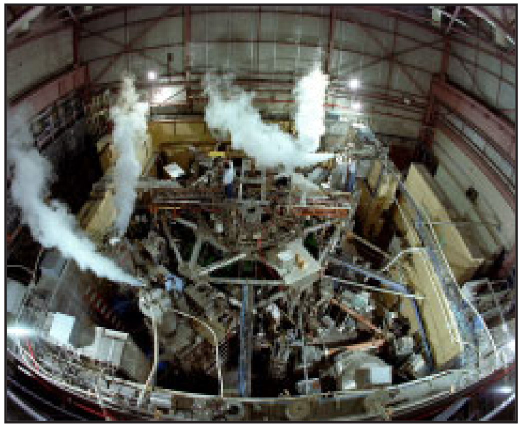
Symmetric Tokamak (ST)

The third proposal — the "Princeton Large Torus (PLT)" — was the most ambitious, and its goal was to test the scaling of energy confinement at three-times larger size than previous experiments and at near-reactor temperatures. This was to be a crucial test for tokamak confinement, since the theories of that day predicted a catastrophic drop in plasma energy confinement as the ion temperature approached reactor conditions. This device produced "first plasma" in December 1975, and by August 1978, it had achieved the first-ever fusion reactor-level plasma temperature (in excess of 60 million degrees Centigrade) in a tokamak. The pessimistic theories were wrong and the tokamaks were off and running.

Throughout this period, while spending most of his time designing new experiments, Furth did not neglect the theoretical underpinnings of his field. Indeed, he returned to his earlier work on resistive instabilities and showed how a particular mode of instability — called the "tearing mode" — could explain the weak magnetic disturbances sometimes seen in tokamaks, usually named after their Russian discoverer Sergei Mirnov. For several years, Furth wrestled with the issue of how these relatively benign instabilities could combine together to produce the more catastrophic "disruption" which can, in off-normal

Adiabatic Toroidal Compressor

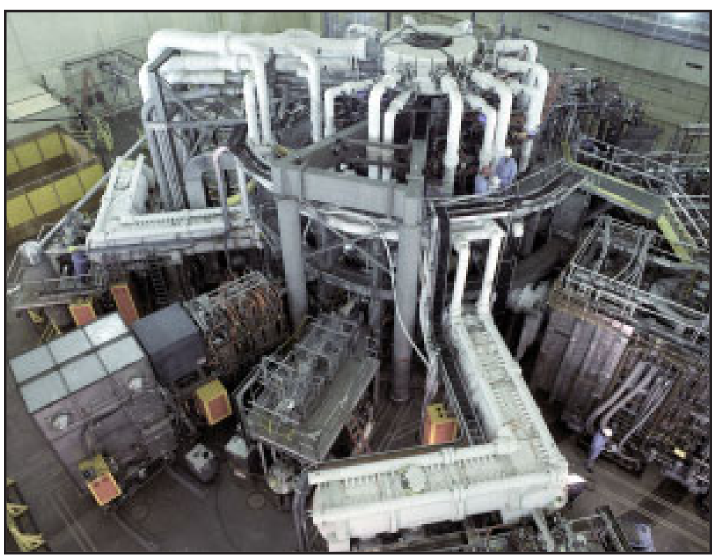
cases, terminate the tokamak plasma. Later, when Furth's ideas were embodied in large-scale three-dimensional computer simulation codes, they proved to be essentially correct.



Princeton Large Torus (PLT)

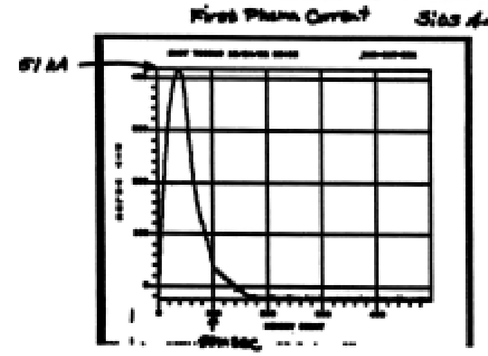
Tokamak Fusion Test Reactor

Even prior to the breakthrough of 1978, Furth and others were developing ideas for the follow-on step. In 1971, Furth with colleagues John Dawson and Fred Tenney published a landmark paper showing that energetic ions injected into a plasma could enhance the fusion yield because of the reactions between the two ion components in the plasma, i.e., the energetic injected ions and the thermal plasma ions. This new insight led to the development of a proposal for a fusion experiment that, for the first time, would produce significant amounts of fusion power. Initially in 1973–4, the proposal was called the "Two-Component Torus." When



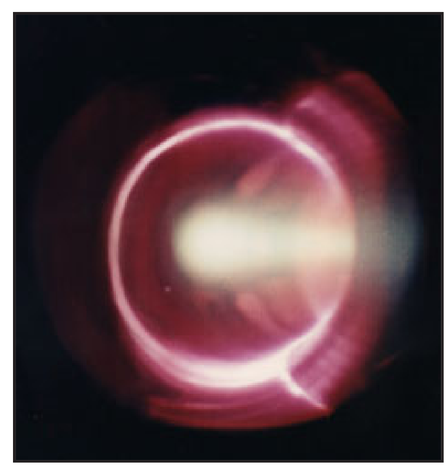
Tokamak Fusion Test Reactor (TFTR)

the oil embargo caused an energy crisis in the U.S., with cars lined up for blocks trying to buy gasoline, this proposal found its way to Washington, where Congress and both the Nixon and later the Carter Administrations were looking for proposals to relieve the U.S. dependency on foreign oil. The proposal was developed into a more ambitious project and was renamed the "Tokamak Fusion Test Reactor (TFTR)," which was approved for construction in 1976. In 1981, Furth was appointed Director of PPPL and became the intellectual driver for the U.S. fusion program during next decade. In 1982, at 3:05 in the morning of Christmas Eve, TFTR flashed its first plasma. Barely three years later, TFTR was establishing historic breakthroughs in fusion — record fusion temperatures of 200 million degrees Centigrade and record values of the principal measure of fusion performance, the "Lawson product" (fuel density multiplied by confinement time), one half of that needed for a self-sustained fusion reactor.



Plot of TFTR first plasma current.

The TFTR spent another decade exploring the science of ultra-high-temperature fusion plasmas, before returning to the centerpiece of its original mission — to introduce tritium for the first time into experimental fusion plasmas. (Previously, all fusion experiments had used hydrogen or its heavier isotope, deuterium, which should produce similar plasma behavior, but without significant fusion reactions.) Introduction of deuterium-tritium (DT) into TFTR produced the historic DT experiments in December 1993, when more than 6 MW of fusion power was produced. Later, TFTR went on to produce more than 10 MW of fusion power, which was the highest fusion

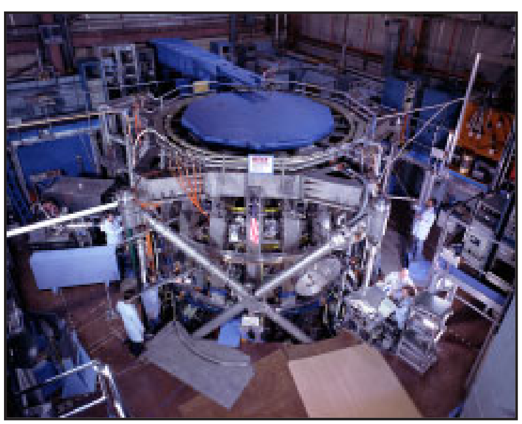


TFTR Plasma

power ever achieved in the laboratory. In the last years of operation, TFTR focused on using its superb diagnostics and well-controlled plasmas to gain new insights into the science of plasma confinement. In doing so, TFTR discovered many new phenomena, such as a reduction of plasma turbulence and enhancement of plasma confinement by sheared plasma flows, an area that is now a central focus in the fusion program. The TFTR was shut down in April 1997. Although Furth relinquished the Directorship of PPPL in 1990, he remained a keen contributor of ideas and insights to the TFTR program.

Spheromak (S-1)

Despite the successes of the TFTR program in demonstrating the controlled release of fusion energy, Furth was driven by the goal of finding an even superior "magnetic bottle" — which he called a "better mousetrap." This led him to invent and support a range of different magnetic configurations including the "Spheromak" in 1983 and the "bean-shaped tokamak" in 1985. These ideas were put to experimental tests in the "S-1" and "PBX-M" (Princeton Beta Experiment-Modification) devices, respectively. Furth also thought "outside the box" with fundamentally new ideas on how to improve the fusion reactivity by using polarized nuclei — a proposal of the early 1980s. He continued work in the 1990s, extending the original two-component tokamak idea to novel schemes for channeling the energy of fusion-reaction products into the generation of energetic reacting ions.



Princeton Beta Experiment-Modification (PBX-M)

1990s

In the 1990s, Furth continued to pursue a vision for

nuclear fusion. In the 150th Anniversary Issue of Scientific American, devoted to Key Technologies of the 21st Century, Harold Furth imagined how energy derived from nuclear fusion could become a reality. In looking ahead, in imagining where breakthroughs might occur, Furth returned to the arena of his earlier ideas, looking for new methods in improved confinement through the complex twisting of magnetic field lines or for methods by which ions might be maintained at much higher temperature than electrons in a fusion reactor.

In the late 1980s as encouraging results came in from TFTR, JET (Joint European Torus in the United Kingdom) and JT-60 (Japanese Tokamak in Japan), Furth led the U.S. effort to design a next-step burning plasma experiment called the Compact Ignition Tokamak (CIT) in which the plasma would be sustained by the fusion reactions. Declining interest in a new energy source led to reduced support for fusion research, and the project while initially in the 1989 fiscal year budget, did not go forward. Taking the step to a burning plasma and optimizing the plasma configuration for fusion energy remain today as challenges for fusion research.