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A Biographical Memoir by

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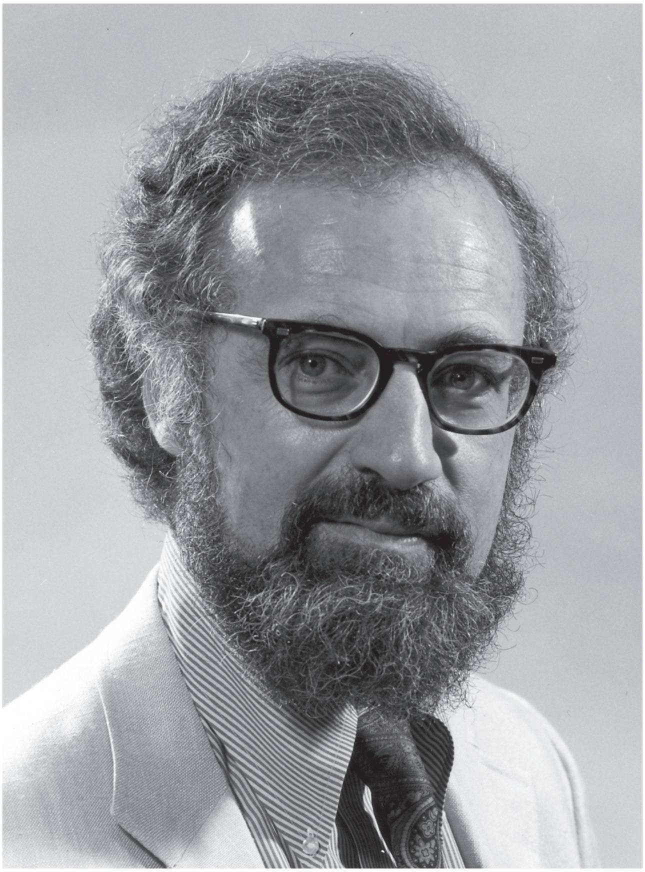

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HAROLD P. FURTH

January 13, 1930–February 21, 2002

BY T. KENNETH FOWLER

HAROLD FURTH, AN AMERICAN giant in the world of fusion research, died of heart failure in Philadelphia on February 21, 2002. He is buried in Princeton, where he spent most of his career at the Princeton University Plasma Physics Laboratory. Harold and I were collaborators in the pursuit of fusion energy, at Princeton in his case, at Livermore in mine. I am deeply saddened by his death and honored to be the one to record his career for the National Academy of Sciences.

Harold was elected to the Academy in 1976 for his many achievements in plasma physics, the underlying discipline for the magnetic confinement approach to harness nuclear fusion energy. From graduate school days Harold's forte was a deep understanding of magnetic fields, one of the areas in which plasma physics has enriched other disciplines, especially astrophysics. This served him well in his fusion career, in inventing new concepts and in understanding the ultimately successful tokamak involving in part currents created by the plasma itself. ("Tokamak" is a Russian acronym for a nuclear fusion device in which a plasma is confined in a toroidal tube by a magnetic field.)

Harold's main contribution to magnetic fusion research was the tokamak fusion test reactor (TFTR), which he proposed in 1973, and which provided the first definitive demonstration of controlled fusion energy in 1993-94, producing 10 megawatts of fusion power for about one second in a plasma of equal parts deuterium and tritium, the DT fuel of future fusion reactors. It was Harold who conceived the design concept that won the project for Princeton, and it was he who led the project to success, first as chief scientist and finally as director of the Princeton Plasma Physics Laboratory from 1981 until he stepped down for medical reasons in 1990.

The TFTR is far and away the most important accomplishment in the 50-year history of magnetic fusion research in the United States. The origin of TFTR in 1973, finally approved for construction in 1976, was a milestone in Harold's career. At the time, magnetic fusion was an emerging research program following early success with tokamaks in the Soviet Union and a sequel at Princeton. New management at the Atomic Energy Commission, seeing an opportunity for funding in the wake of the oil crisis of that time, was determined to embark on a tokamak experiment with actual DT fusion reactions, not just a simulation with ordinary hydrogen plasmas as in all past experiments, the nearer to a power reactor the better. Young physicists at the Oak Ridge National Laboratory rose to the challenge, while Princeton worried whether a facility with radioactive tritium was compatible with the campus environment, and all of us were concerned that the Oak Ridge proposal was too much to tackle.

Things came to a head at a meeting I attended in Washington in late 1973. By then Harold was prepared. One issue was leakage of heat through electrons, most mysterious of the many mysteries plasmas hold, and something Harold had hoped to end run—a theme he continued to pursue in his defense of TFTR in the late 1990s as the place to study direct heating of DT ions by the energetic alpha particles produced by fusion reactions without recourse to electrons as the intermediary. Along this line in 1971 Harold, John Dawson, and Fred Tenney published a paper about a concept, called the two-component torus, whereby fusion energy would be produced directly by fusion reactions of energetic neutral beams with ions in a plasma, again without the need to heat electrons to fusion-reaction temperatures. At a crucial point in the meeting after the attendees had begun to accept something less than ignition as the goal, Harold went to the board, saying, “If that’s all you want.” He then outlined the TFTR proposal that led in 1986 to a new record temperature of 200 million degrees Celsius, and in December 1993 to more than 6 megawatts of fusion power for a second or so, and the design goal of 10 megawatts a few months later.

Harold Furth was born in Vienna, Austria, on January 13, 1930. After studying at the Ecole Internationale in Geneva he immigrated in 1941 with his parents to the United States, where he graduated at the head of his class from the Hill School in 1947. He then entered Harvard University, where he completed graduate studies in 1956, with an intervening year at Cornell. His introduction to physics came through his experiments identifying cosmic rays in photographic emulsions permeated by high magnetic fields.

After Harvard Harold worked at the University of California Radiation Laboratory at Berkeley and Livermore from 1956 to 1967. There he soon began the fruitful collaboration with Stirling Colgate that led to Harold’s first experimental work on plasma confinement devices that might eventually serve as fusion reactors, initially in a linear pinch in which the mutual attraction of parallel currents in a plasma applies a constricting force that confines the plasma column. Instability of the pinch had inspired an improved version with an externally applied magnetic field parallel to the current. When this too exhibited unstable turbulence, probably due to plasma resistivity omitted in the theory, Furth and Colgate proceeded in a totally different direction with the invention of the levitron, a large conducting ring levitated in space and charged with a current that provided confinement for a plasma surrounding the ring, without resort to the internal force of plasma currents used in the pinch device. Harold later constructed a levitron called FM-1 at Princeton.

Meanwhile, the importance of resistivity not lost on him, Harold provided the conceptual basis for a theory of resistive instabilities in magnetically confined plasmas, published jointly with John Killeen and Marshall Rosenbluth in 1963. Characteristically Harold had been able to visualize what happens when twisting plasma columns in turn twist magnetic field lines embedded in them, causing localized sheet currents needed to prevent the tearing and reconnection of the field lines. Resistivity destroys these sheet currents, allowing tearing to happen, at a rate enhanced by the thinness of the sheet currents. Resistive instability turned out to play an important role in natural phenomena, such as the Earth's magnetotail and other aspects of solar physics and cosmology. Applying resistive instability theory in this way was an early example of cross-fertilization of plasma physics learned from fusion research with other fields of science.

During a year-long workshop at Trieste in 1965-66, Harold joined Soviet colleagues Roald Sagdeev and Alex Galeev in showing how Coulomb collisions among plasma particles could transport them across the magnetic field of devices like the Soviet tokamak much faster than they could in idealized models, by virtue of complicated particle orbits in the twisted magnetic field of the tokamak. It was Furth who dubbed these distorted orbits "bananas," as he had pictured them in thinking through the transport process, now called neoclassical transport. While neoclassical transport degrades heat confinement of the ions, it also later became the basis for others to predict and then measure the self-generated "bootstrap" current in tokamaks that greatly diminished the requirement for external power to maintain the current in a steady-state tokamak.

After arriving at Princeton in 1967 as professor of astrophysical sciences and co-head of the Experimental Division at the Princeton Plasma Physics Laboratory, Harold assumed leadership in planning new experiments, shortly before the breakthrough announcement in 1968 that the Soviets had achieved a record temperature of 10 million degrees Celsius in one of the tokamak devices called T-3. Harold first did not believe the Soviet claims, blaming the results on runaway electrons that did eventually prove to be the explanation of another device touted by the Soviets, called TM-3.

Once convinced Harold quickly led the Princeton laboratory toward proposals for three tokamaks, one by converting their largest stellerator into a tokamak and two new devices—the adiabatic toroidal compressor that would provide additional heating by squeezing the plasma, and the Princeton large torus (PLT) in which the plasma would be heated by neutral beams created by accelerating ions to the energies required for fusion and then neutralizing them in flight, to be captured in the plasma when they become ionized again by collisions with plasma electrons and ions. All three proposals were funded by the government, leading to a quick confirmation of the Soviet results at Princeton in 1970 and record tokamak temperatures exceeding 60 million degrees Celsius—sufficient for fusion ignition—in the PLT in 1978.

Harold never stopped inventing improved magnetic configurations, such as the bean-shaped tokamak with improved stability properties (PBX-M) in 1985, and the spheromak that is totally self-generated by currents inside the plasma.

After TFTR began experiments with real deuterium and tritium (DT) fuel, Harold also pursued new ways to enhance fusion power production without relying solely on thermal reactions in a DT plasma with equilibrated temperatures among all particle constituents.

Even before becoming the director of the Princeton Plasma Physics Laboratory, Harold had emerged as the intellectual leader of magnetic fusion research in the United States and a tireless advocate for fusion energy. The esteem accorded him by colleagues is evident in remarks at a memorial service at Princeton a few months after his death. “Harold Furth was a special person, in a special place, at a special time,” noted Anne Davies, current director of the Office of Fusion Energy Sciences at the Department of Energy. “Scintillating” is the word Marshall Rosenbluth chose to describe Harold. “When he came into a room or joined a discussion, the air fairly crackled with wit, logic, scientific insight, and forceful leadership. Everybody’s creativity level went up in an effort to keep up with Harold.”

Harold’s protégé and currently director of the Princeton laboratory, Rob Goldston, spoke for most of us. “Harold was a giant of fusion science, a person of untiring energy and boundless optimism. He buoyed all of us. Harold led the U.S. fusion program to tremendous growth in the 1970’s and 1980’s. Indeed, many of the scientific accomplishments even in the 1990’s are the result of his leadership. We will all miss him.”

As in everything else he touched, Harold was a brilliantly successful laboratory director and an influential, respected leader in the international fusion community. Perhaps his greatest disappointment as director was a failure to procure funding for the compact ignition tokamak (CIT) as a follow-on to TFTR and, as the name implies, the first demonstration of a plasma that burned by itself. Harold had garnered strong support from the U.S. fusion community, but as Washington and the public lost interest in energy in the 1980s, CIT was not to be, despite strong recommendations for a revival of the idea by the Fusion Policy Advisory Committee of 1990, chaired by Guy Stever. That committee did recommend immediate funding for DT operation in TFTR, long delayed, and that was done, as related above.

Harold was a revered mentor and colleague of young scientists, including experimentalist Rob Goldston, theorist Nathaniel Fisch, and many others. He held some 20 patents, primarily in the areas of controlled magnetic fusion technology and metal forming with pulsed magnetic fields. He published over 190 technical papers.

Harold served on numerous government committees over the years and on scientific advisory committees at other laboratories, including the Max Planck Gesellschaft. He served on the Board of Editors for the following journals: *Nuclear Fusion, Plasma Physics and Controlled Fusion, Journal of Fusion Energy, Reviews of Modern Physics,* and *Physics of Fluids.* At the National Academy of Sciences' National Research Council he was a member of the Board on Physics and Astronomy of the Division on Engineering and Physical Sciences.

Harold was a fellow of the American Physical Society, the American Association for the Advancement of Science, and the American Academy of Arts and Sciences. He received the E. O. Lawrence Memorial Award from the U.S. Atomic Energy Commission in 1974; the James Clerk Maxwell Award from the American Physical Society in 1983; the Joseph Priestly Award from Dickinson College in 1985; and the Delmer S. Fahrney Medal from the Committee on Science and the Arts of the Franklin Institute in 1992.

On a personal level Harold will long be remembered for his engaging wit, always kind if a little irreverent. It is fitting to conclude with an example, written in his twenties when he first came to Livermore prior to his later move to Princeton. This was his poem about Edward Teller that was published in *The New Yorker* magazine in 1956, reprinted in Teller's *Memoirs*:

Perils of Modern Living

Well up beyond the tropostrata
There is a region stark and stellar
Where, on a streak of anti-matter,
Lived Dr. Edward Anti-Teller.

Remote from Fusion's origin,
He lived unguessed and unawares
With all his anti-kith and kin,
And kept macassars on his chairs.

One morning, idling by the sea,
He spied a tin of monstrous girth
That bore three letters: A.E.C.
Out stepped a visitor from Earth.

Then, shouting gladly o'er the sands,
Met two who in their alien ways
Were like as lentils. Their right hands
Clasped, and the rest was gamma rays.

I WISH TO THANK colleagues quoted in this memoir and to express appreciation for much assistance from Dolores Lawson of the Princeton Plasma Physics Laboratory.

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