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S-1 Spheromak Operations Finish on a Good Note

by Carol Phillips

While most of the Laboratory staff spent the morning of December 23rd preparing for the traditional holiday parties, members of the S-1 Spheromak group were firing the final plasma shots on the S-1 machine. At about 11:00 a.m., Director Harold Furth pushed the start button for the last time and, as the glow of the plasma discharge disappeared, the five-year S-1 research program ended.

"We finished with good feelings, with the sense that we'd accomplished many of the goals we set when the S–1 was first turned on in January 1983," said Dr. Masaaki Yamada, Experimental Project Head since S-1's inception. "Everyone connected with this project over the years put forth tremendous efforts, especially during the final year," he continued. "Although the S-1 was one of the smaller machines at PPPL, it was the largest spheromak-type device in the world, and our input has been well appreciated by the scientific community. It is now time for us to rest, digest the data, and think about the future."

Dr. John F. Clarke, Associate Director for Fusion Energy, Office of Energy Research, U.S. Department of Energy gave official recognition and appreciation for S-1's accomplishments. He commended PPPL and its staff on the research results obtained from the S-1 spheromak program. In his letter he wrote, ".....this record demonstrates that S-1 has been worthwhile and successful in advancing the goals of the fusion power development program. It is appreciated."

Dr. Bob Ellis, Jr., who headed the second half of S-1 fabrication and construction, observed, "The S-1 Project is another outstanding example of close cooperation between various groups at PPPL. Engineers working with physicists designed the various components of the machine — the vacuum vessel, the steady-state equilibrium field system, and the flux core, which contains poloidal and toroidal field coils powered by capacitor banks. PPPL technicians built, installed, and serviced the machine. Theorists provided computer simulations of the spheromak formation process, which were very helpful during the engineering design phase and when planning the experiments."

Dr. Alan Janos, who has also been with the project since the beginning and has worked on all aspects of the experiment including fabrication of S-1 (as Deputy Project Head) and operation of the Proto S-1, reflected, "It has been exciting to produce and understand such a novel magnetic configuration and to work with such dedicated and energetic people over this eight-year span of construction and research. Spheromak research continues at a few other laboratories. Maybe years from now another new thrust into spheromak research will occur."

Background

The "spheromak concept" was first studied theoretically in the astrophysical context in the mid 1950s; In 1958 at the 2nd International Conference on Peaceful Uses of Atomic Energy, Hannes Alfvén pointed out its possible relevance to controlled fusion. Then, in 1977, the spheromak concept was "reborn" in response to the Department of Energy's Alternative Concepts Program — a program designed to investigate innovative fusion concepts — as it appeared the spheromak might serve as a high-beta reactor concept.

The name spheromak — <u>spher</u>ical toka<u>mak</u> — was first introduced by Dr. Furth to describe the spherically shaped plasma (see Fig. 1). A spheromak plasma, like a tokamak plasma, has a "toroidal" configuration, but in the spheromak the toroidal magnetic field is produced entirely by plasma currents. Thus, there is no toroidal field outside the plasma, and there is no need for toroidal field coils. The poloidal fields are produced by toroidal plasma currents and external field coils. The spheromak configuration results in plasma behavior (stability, etc.) that is different and in some ways better than that of tokamaks.

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The spheromak design allows for a simpler coil and blanket topology (easier engineering) than for a tokamak and experimenters can move the plasma; the plasma can be created in one place and then allowed to burn in another separate region thus allowing for simpler first wall technology. Also, adiabatic compression can be conveniently applied to a spheromak plasma.

The S-1 experiment was designed to investigate the formation, equilibrium, stability, and confinement characteristics of spheromak plasmas; the scaling of confinement quality with various parameters; and the physics of sustaining the spheromak magnetic field configuration.

The Final Year

The final year was a particularly busy time for the S-1 group. In January 1987, they learned the machine would be shut down at the end of the fiscal year (September 30th) due to the tight financial situation in the U.S. magnetic fusion program. At this point, the group was heavily involved in design work for a current transformer. The plan was to use the current transformer to amplify the plasma current to create a more fusion-relevant, high-density, high-temperature plasma regime.

With the news that S-1 would be shut down, program physicists were forced

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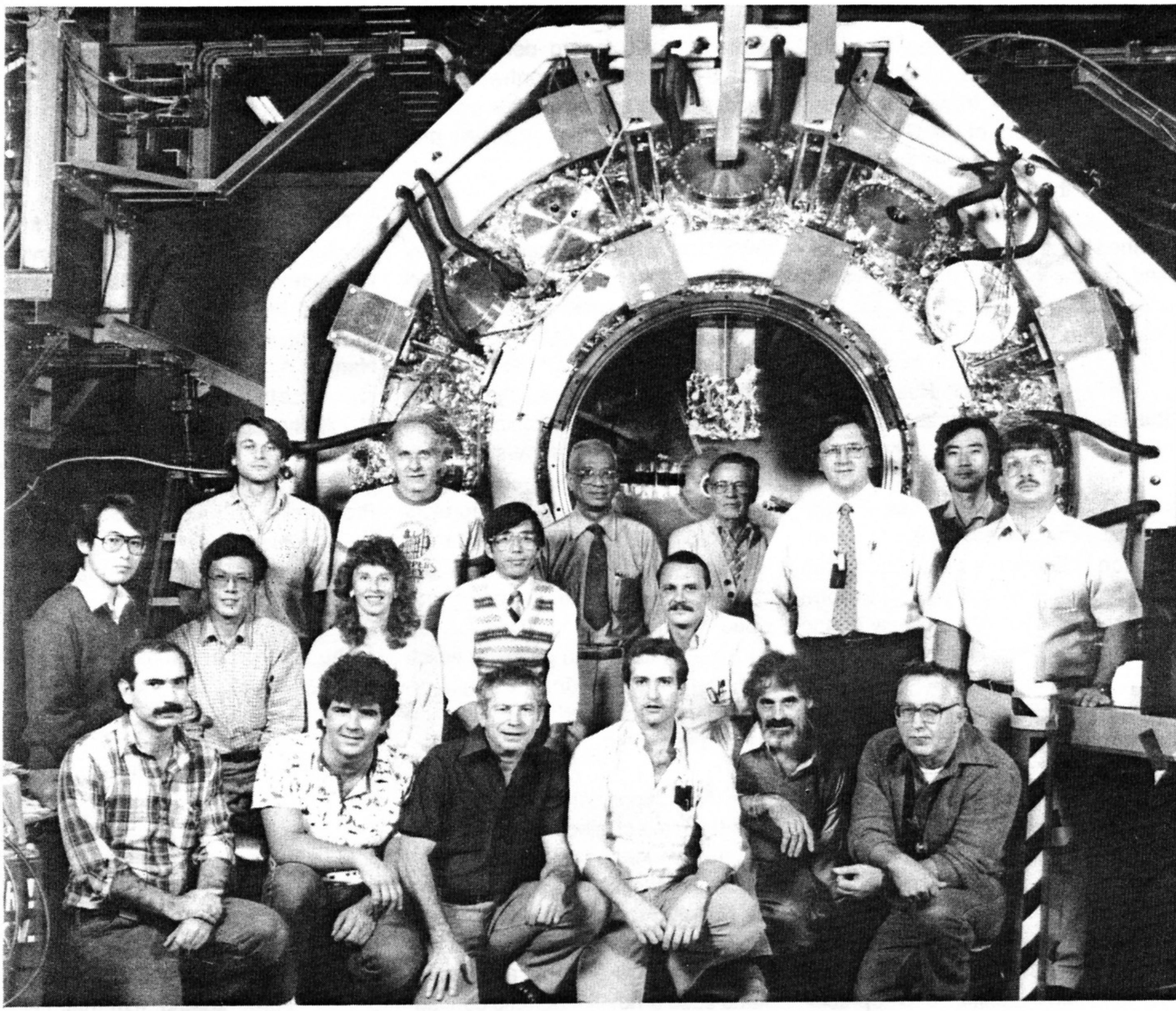

John Peoples and Ed Farris

"Tremendous efforts" were made by S-1 staff members during the final months of S-1 operation. Shown kneeling, left to right, are Fred Levinton, John Swatkoski, Al Malone, Bob Mayo, Fred Wood, and Ray Pysher. Center, left to right, Yasushi Ono, Norio Satomi, Rosemarie Fuchs, Masaaki Yamada, and Jim Faunce. Standing, left to right, are John Bilinski, Dick LaBaw, Bob Ellis, Jr., Frank Lawn, Jim Chrzanowski, Masayoshi Nagata, and Alan Janos. Not pictured: T.-K. Chu.

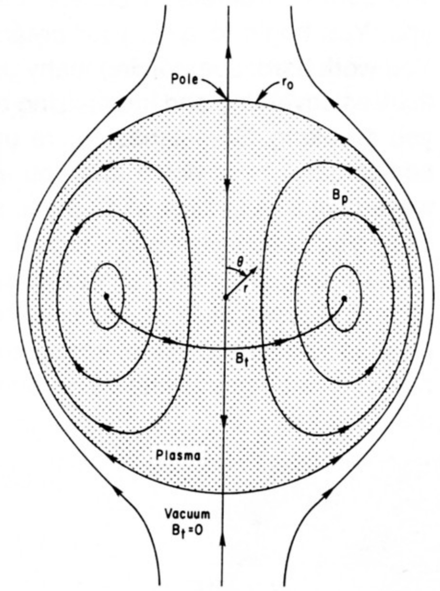

Fig. 1. Idealized spheromak configuration.

to reassess what could be accomplished in the remaining months of operation. They decided to continue with the basic idea of studying magnetic confinement features of the spheromak plasma, but to change the method used to obtain the desired plasma conditions. Instead of the current transformer, they decided to use a compression coil scheme. This method would take advantage of one of the unique features of spheromaks, i.e., no coils or vacuum vessel linking the torus. Given the limited time and resources, this scheme seemed to offer the best chance for success.

Engineers immediately started to work on designing and building the compression coils and power supplies and their controls, and physicists started to work on designing the final experiments. The coil shop was responsible for winding the coils, and the vacuum shop, along with Laboratory technicians, fabricated and installed the new components.

Despite everyone's best efforts it became apparent in the spring that additional time would be needed to do the experiments. A request was made to the Department of Energy (DOE) to extend the deadline. A formal review of the Spheromak Project took place in July and, on the basis of the Review Panel's favorable recommendations, DOE extended the shutdown deadline to the end of the calendar year — which for the Laboratory was December 23rd.

From July to September operation of the S-1 was halted to install and test the new compression coils inside the vacuum vessel. Power supply and plasma stability problems kept both the engineers and physicists "on their toes" for the next couple of months.

"Still," according to Dr. Yamada, "at the time of the American Physical Society Meeting in early November, it wasn't clear that we would be able to do the experiments. Then in the beginning of December everything started coming together. Existing problems started disappearing and the plasma started behaving. On December 9th we began the final experimental run. Between that day and December 23rd we fired about 2,000 shots. We got some very interesting data!

"When we finally got the S-1 running, the support we received from various groups at the Laboratory was exceptional. You must remember this occurred during the holiday season, yet everyone worked whatever hours were needed. Very kind and earnest support was given by the MG Group, the Computer Group, and, as always, S-1 technicians and engineers. Our group secretary, Rosemarie Fuchs, spent many long hours keeping the paperwork up to date, relaying messages, and helping everyone stay organized."

Final Results

In his "State of the Laboratory" address, Dr. Harold Furth said "the preliminary results from the [S-1] compression experiments looked good," and he thought "the concept would be interesting to pursue at higher field strengths in the future."

Final results from the S-1 experiments are still being analyzed and they look very exciting. Evolution of the magnetic configuration was mapped out by internal probe-based flux plots, and it was found that the S-1 plasma could be compressed successfully, while keeping its unique profile intact (Fig. 2). Because of the limited time for plasma optimization, the compression factor was kept relatively small (20-30%). Even so, a significant increase

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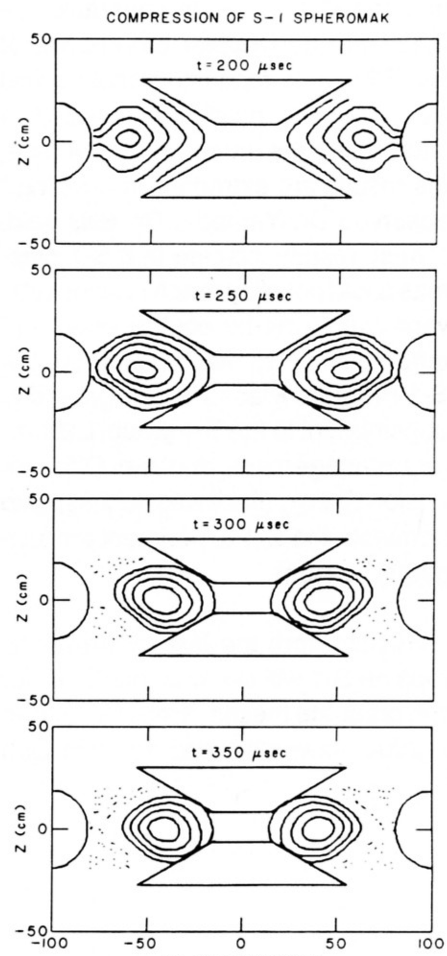


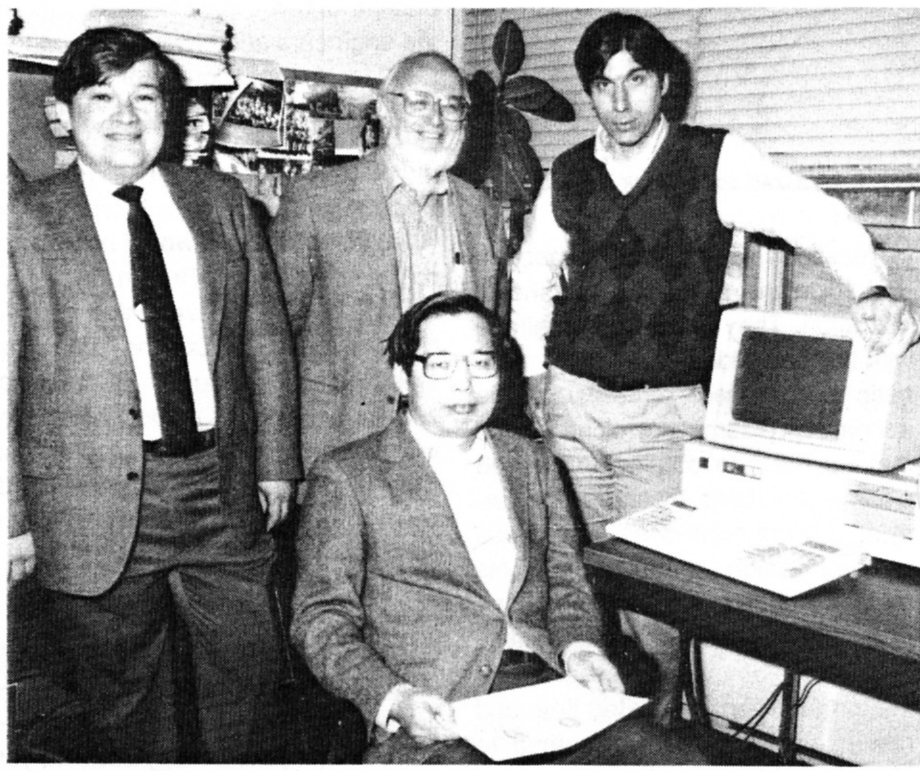
Fig. 2. Experimentally measured contour plots of poloidal flux showing the change in the minor cross section of the S-1 spheromak plasma during compression. At t = 200 μsec, the plasma begins to be pinched off from the flux core. Compression pushes the plasma towards the center. The funnels at the top and bottom help to stabilize the plasma. (783065)

of the plasma energy was observed. With this compression factor, the highest plasma pressure in S-1 operating experience, $n_{e0}T_{e0} \simeq 8 \times 10^{18}$ keV m^{-3}, was obtained which exceeded previous records by a factor of 2. An increase in the electron temperature from about 30-40 eV to 80-130 eV was also observed. The electron density typically increased from 5×10^{19} m^{-3} to 8×10^{19} m^{-3}.

The beta value of the plasma (about 5%) was generally found to stay constant with compression, thus confirming the constant-beta scaling observed during earlier stages of S-1 operation. The ion temperature, as measured by Doppler broadening of low-Z impurity radiation, reached 500 eV. "Although caution is needed in interpreting the ion temperature data, the results are extremely interesting," observed Dr. Yamada. Dr. Ellis said, "These results indicate that S-1 plasmas could possibly reach reactor-relevant conditions by compression and other techniques that were part of the S-1 Program Plan. It was a great disappointment to the S-1 group, Laboratory management, and the Office of Fusion Energy that it was necessary to terminate the S-1 experiment for budgetary reasons."

Results from the last experimental runs on S-1 will serve as the basis for two graduate theses. "Bob Mayo, from Purdue University, and Yasushi Ono from the University of Tokyo, worked side-by-side with PPPL physicists, putting in many long hours, and contributing significantly towards our research efforts," said Dr. Yamada.

Looking back over the last eight years, Dr. Yamada reflected that the S–1 machine represented to him the "American Spirit." "First you have an idea," he said, "an idea that stretches the imagination. You believe in your idea — that it can be a reality — and you convince others to believe with you. You begin to build your dream. You work hard, overcoming many difficulties, inventing and improvising as you go along. Sometimes you're up, sometimes you're down, but you always give it your best shot. If you're lucky you reach your original goal. If you are not, you may have to adjust your goal just a bit. But, when you're finished, you've created something new, something that has never been done before." O



John Peoples

Computer simulations were very helpful during the engineering design phase and when planning experiments. Shown are engineers Phil Heitzenroeder (left) and Yung-Chiun Sun (seated), experimentalist Bob Motley (center), and theorist Steve Jardin (right).

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