stellarator news

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First plasma production in LHD

The first plasma in the Large Helical Device (LHD) was successfully produced on March 31, 1998, at the National Institute for Fusion Sciences in Toki, Japan. This most important milestone of the LHD project was achieved right on schedule.

The beginning of plasma operations in the LHD marked the completion of an 8-year construction project that began in April 1990. Including the early preparatory phase, the total time spent in bringing the LHD project to this point is almost 15 years.

This great success was made possible by the integration of the physics and technology research and development required for LHD. We have had to solve many critical issues in engineering, development, technical design, machine construction, and commissioning tests. We have integrated our solutions to these issues into LHD and expect that they will contribute to the progress of fusion technology in Japan and in the rest of the world. Our experience will be documented in a common data base, to be published in the near future, for the fusion community.

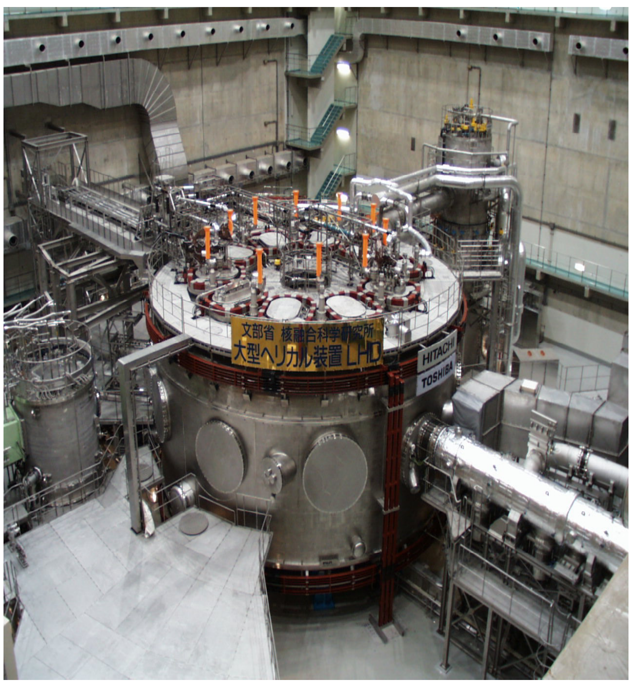

Fig. 1. Completed LHD as it appeared in April 1998.

The on-time achievement of first plasma and the satisfactory completion of the startup phase of LHD operation demonstrate the reliability and high capability that result from our technological standards in Japan. Now the LHD project is moving into the physics phase, which will explore the physics of currentless, disruptionless, and steady-state plasmas.

The assembly of LHD was completed at the end of December 1997, and commissioning tests began immediately after that in January 1998. Important milestones were (1) evacuation of the plasma vacuum chamber and the cryostat bell jar (January 20–February 14); (2) cooldown of the superconducting magnets (February 23–March 22); (3) excitation of the magnets (March 23–27); (4) discharge cleaning of the vacuum chamber (March 28–30); (5) conditioning of the gyrotrons (until March 30); and (6) installation and preparation of the diagnostics (until March 30). With the successful completion of all of these tasks before the end of March, LHD was ready to produce its first plasma on schedule.

Figure 1 shows the completed LHD, and Fig. 2 shows the first plasma, produced at 2:13 pm on March 31. Watching the plasma image appear on the TV screen was very exciting.

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Electron cyclotron resonance heating (ECRH) was supplied by two gyrotrons with frequencies of 84.0 and 82.6 GHz. The magnetic field was 1.5 T. The gyrotron system and other necessary equipment were connected to the central control system for the first time on that day. The plasma quality is rapidly improving. Figure 3 shows the increase in the plasma energy during the initial phase of experiments. Figure 4 shows a recent picture of the plasma. The boundary is clearly evident. This phase has included both wall conditioning with titanium gettering and 2.45-GHz electron cyclotron heating (ECH) discharge cleaning. Our present target for plasma energy is 10 kJ; this would mark the beginning of confinement experiments and achievement of the necessary conditions for neutral beam injection (NBI) heating in the second cycle.

The LHD experiment will soon reach the maximum level attained in any experimental program to date. The demonstration of a plasma temperature of about 10 keV will be realized within two years by increasing the heating power to 15 MW and the magnetic field to 3 T.

LHD will operate for about 2,000 hours per year. In Fig. 5, we show the experimental schedule for the next two years. This schedule supports a systematic program of research and development in fusion science and technology, an important task of the LHD project.

More than 300 ports are available for collaborative research. We are increasing the necessary experimental tools such as heating systems and diagnostics. New proposals and contributions to the experiment from Japan and elsewhere will be welcomed.

Finally, Fig. 6 shows the new organizational structure for the LHD experiment. The team of the LHD experiment was reorganized in the institute which took over the responsibility for the LHD project when it advanced from the construction phase to the physics experiment phase.

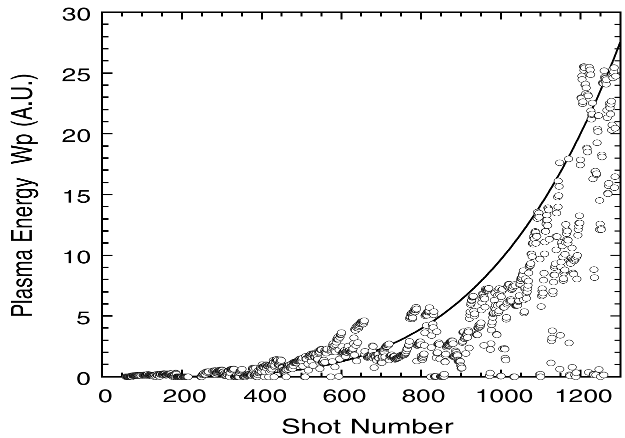

Fig. 3. Increase of plasma energy measured by a diamagnetic loop during initial phase of LHD experiment. The maximum energy is estimated on the order of 20 kJ. The precise value will determined after the diagnostics are fully calibrated.

Fusion research is based on the integration of plasma physics, fusion science, and reactor engineering. The LHD project has been supported by many collaborators in Japan and throughout the world. We would like to thank all of these people for their contributions.

In conclusion, we are very glad to have created our first plasma and are ready, too, in high spirits, for the coming physics experiment phase.

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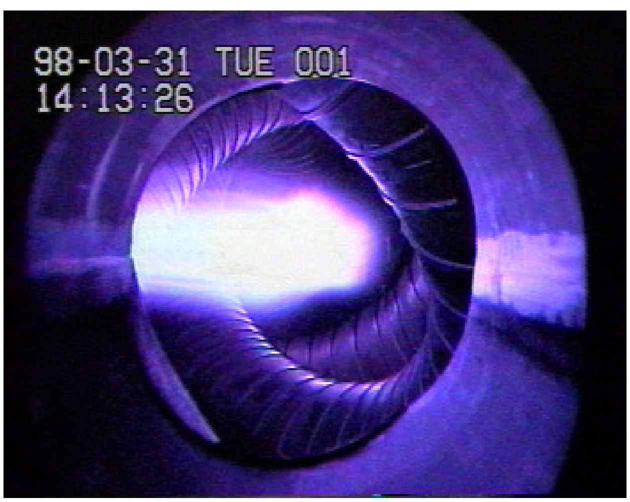

Fig. 2. TV image of the first plasma on March 31.

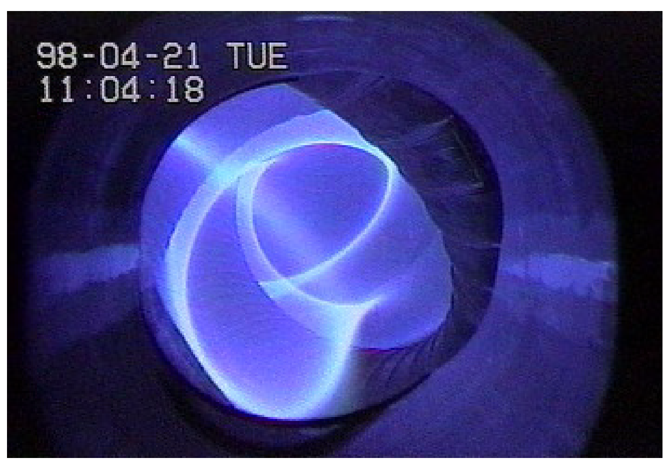

Fig. 4. TV image of the plasma at the end of initial phase of LHD experiment.

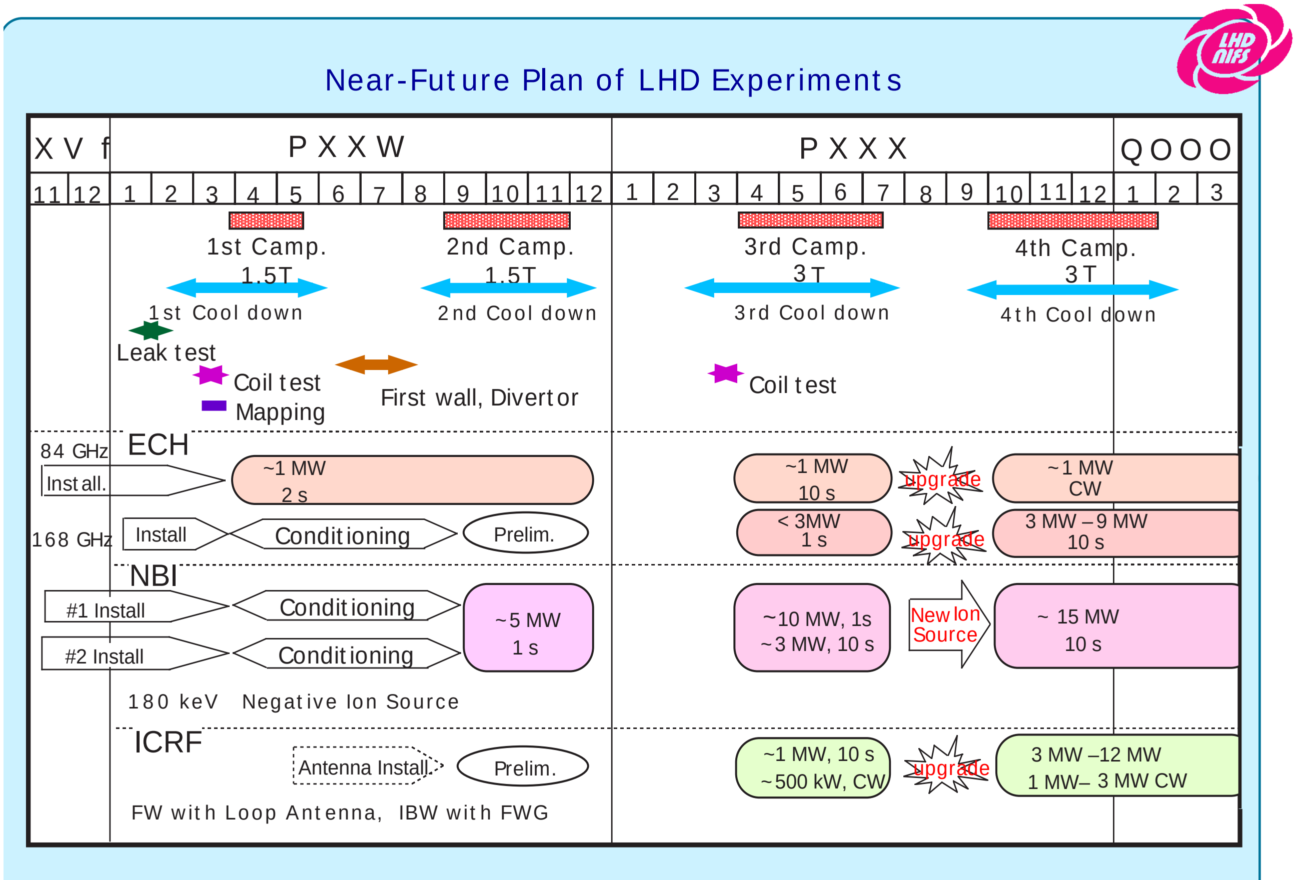

Fig. 5. LHD experimental schedule for the next two years.

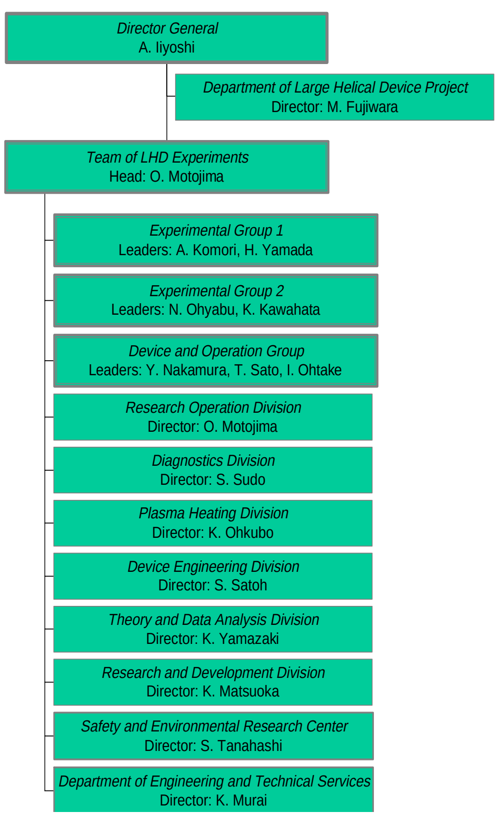

Fig. 6. New organization chart for the LHD experiment.

U.S. stellarator program plan

The U.S. stellarator community proposes a significant expansion in the national stellarator program to capitalize on recent innovations in the stellarator concept that could lead to a more attractive fusion power plant, fill a serious gap in the world stellarator program, and offer unique opportunities for fusion science studies. The goal of the expanded program is to develop the knowledge base needed for compact, high-beta, good-confinement stellarators.

Stellarators are an essential part of an innovative U.S. Fusion Science Program

Stellarators have the potential for an attractive reactor featuring inherently steady-state, disruption-free operation; low recirculating power; and good confinement and beta. Because of this, stellarators are a large part of the world fusion program with large experimental investment and substantial performance. Stellarators have a magnetic topology similar to that of tokamaks. However, while tokamaks have two-dimensional symmetry, stellarator configurations are fully three-dimensional (3-D). The extra dimension makes available a richly diverse set of configurations, providing significant additional design freedom that can be used to optimize for fusion performance or for studies of particular plasma physics properties at minimum cost. Control of the q-profile, the bootstrap current, and the radial electric field is possible using external coils. These capabilities are complementary to the advances of the axisymmetric tokamak program and allow novel solutions to some of the problems of developing advanced toroidal configurations, particularly disruptions and current drive. An expanded stellarator program provides the opportunity for synergy, combining the physics understanding developed in the tokamak program with the demonstrated control and design advantages of stellarators, potentially shortening the reactor development path and broadening the U.S. Fusion Energy Science Program.

As part of an innovative U.S. program to improve the attractiveness of fusion reactors and decrease development costs, the U.S. stellarator program is focused on compact configurations with reduced transport and with beta limits at least as high as those in the advanced ARIES tokamak reactor studies.

The international stellarator program is focused on large-aspect-ratio, currentless, nonsymmetric configurations

The largest new fusion facilities are stellarators: the Large Helical Device (LHD) now operating in Japan and the Wendelstein 7-X (W7-X) under construction in Germany are $0.5 billion to $1 billion facilities that feature superconducting coils. These facilities are designed to demonstrate steady-state ,disruption-free stellarator operation and a level of performance that allows extrapolation to devices capable of burning plasma operation. The large world stellarator program has contributed to development of the computational techniques for configuration optimization and has overcome earlier concerns about coil complexity. However, there are gaps in the world program that present opportunities for innovation. The foreign stellarators, including smaller experiments, have plasma aspect ratios ranging from 5 to 11 and extrapolate to very large reactors; low aspect ratios (< 5) are unexplored. The W7-X experiment was explicitly designed to minimize the bootstrap current, while LHD is expected to have bootstrap current smaller than that of a comparable tokamak because of its magnetic structure. None of the foreign stellarator devices takes advantage of the bootstrap current, magnetic symmetry, or drift-orbit omnigeneity in its design strategy. The large non-U.S. stellarator programs will extend stellarator research to new levels of size and performance, but will not cover the full range of issues important for compact stellarator development.

Opportunities and key issues for a U.S. stellarator program

Recent development of two new confinement-optimized configurations holds the promise that a low-aspect-ratio stellarator, which would allow a more compact stellarator reactor, can be developed with good confinement and high beta. These configurations make use of the self-generated bootstrap current, which allows potentially higher equilibrium and stability beta limits than can be generated otherwise in low-aspect-ratio stellarators, while relaxing some of the constraints on the external coils. However, these configurations require investigation of the helical fields required from external coils to prevent the kink instabilities and disruptions observed in tokamaks. In addition, the theoretically predicted beta limits, the reduction of neoclassical transport through magnetic symmetry or omnigeneity, the role of higher plasma flow shear in reducing anomalous transport, compatibility of the bootstrap current with required profiles, startup, and power and particle handling must be demonstrated in these new configurations. In short, promising compact stellarator concepts have been developed to the point of readiness for experimental testing.

The United States should invest more resources in stellarator research

The United States should undertake a ten-year proof-of-principle program to develop the knowledge base needed for compact, high-beta, good-confinement stellarators. To do so would fill the gap in the world program and would further key aims of the U.S. fusion program: confinement concept innovation, fusion science understanding, and plasma physics advancement. These aims can be advanced at modest cost; the immediate needs can be met with investments far less than those of lhd and W7-X.

the proposed national stellarator research program

An integrated program of experiment, theory, and systems studies is planned. It will consist of well-coordinated research drawing on several elements: (1) a flexible, reconfigurable proof-of-principle facility; (2) a new concept exploration experiment; (3) the present Helically Symmetric Experiment (HSX) at the University of Wisconsin; (4) experimental collaboration with the international stellarator program in specific areas; (5) theory focusing on concept optimization and key stellarator issues; and (6) systems studies to guide the concept optimization tradeoffs. The six program elements, which cross-link with each other to provide a coherent, well-integrated program, are depicted schematically in Fig. 1. The proof-of-principle facility must be reconfigurable to ensure that experimental tests of the new developments coming out of the program can be conducted expeditiously.

At present, two promising transport optimization strategies for compact stellarator design have been developed theoretically: quasi-axisymmetry and quasi-omnigeneity. Both make use of the bootstrap current, but to different degrees, to make a more compact configuration than the currentless W7-X. Both look attractive for compact stellarator reactors, but each has distinct complementary advantages. Both must be developed experimentally to maintain the broadest possible scientific base for the program's ultimate success. A determination of which is the better strategy will be one of the program's goals. The new proof-of-principle facility will provide sufficient plasma performance and machine capability for integrated testing of a compact stellarator configuration with high beta and bootstrap currents that can form the basis for extrapolation to more reactor-relevant performance. In order to minimize cost, it is desirable to take advantage of an existing facility, the PBX-M tokamak, and modify it for the proof-of-principle stellarator tests. The quasi-axisymmetric concept is more compatible with the PBX-M constraints, so this configuration will be chosen for the initial tests. The facility will be modified to test improved configurations as they are developed by the program. A new concept exploration facility will be constructed to test the basic optimization principles of quasi-omnigeneity. The HSX, nearing operation, will be the first test of improved neoclassical transport and reduced parallel viscosity in quasi-symmetry. The HSX will also investigate high effective transform and very low plasma currents, features not covered in the compact stellarator proof of principle (PoP) program. Other small-scale supporting experiments are needed to investigate specific scientific and technical issues in support of the compact stellarator PoP program.

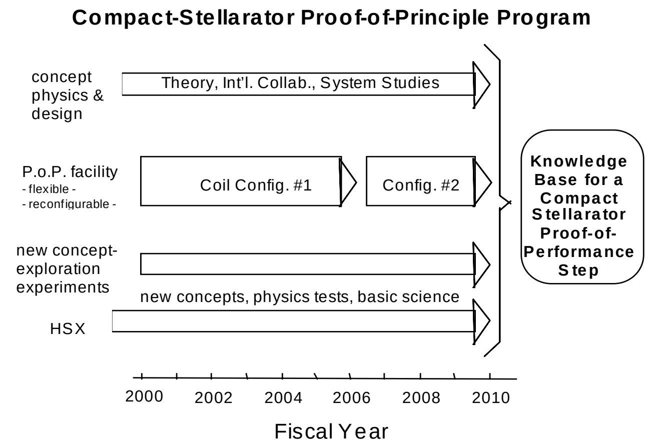

Fig. 1. Road map for the proposed stellarator proof-of-principle program.

The program will include collaboration with the international program in focused areas both to understand key issues for extrapolation of stellarator performance and to test optimization features at higher plasma parameters. A robust theory and concept optimization effort will continue to develop new configurations, incorporate physics advances from other parts of the program, and develop understanding of experimental results from U.S and international experiments. Systems studies will guide the fusion optimization trade-offs in concept development, e.g., cost/benefit trade-offs between aspect ratio, beta limit, and confinement improvement; limits on acceptable energetic-particle orbit losses; and integration of physics optimization with reactor optimization considerations and constraints.

Anticipated program costs are summarized as follows: (1) proof-of-principle facility, in the range of $25 million to construct and $20 million/year to operate; (2) HSX, $1.6 million/year; (3) new concept exploration experiments, $2 million/year; (4) international collaboration, $1.5 million/year; (5) theory, $3.5 million/year; and (6) system studies, averaging $1 million/year. The program budget will reach a plateau level of $30 million/year All elements of the program are necessary to adequately develop the concept and ensure proper balance.

If this plan is carried out, in ten years the resulting knowledge base will be sufficient to permit comparisons with steady-state tokamak-based power plant designs and will provide a basis for proceeding to the next step, a proof-of-performance program to study more reactor-relevant plasmas in a compact stellarator configuration.

The U.S. stellarator community is eager to seize these opportunities and contribute strongly to the innovative U.S. Fusion Energy Science Program.

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