Report of Travel to Japan, Jan. 15-26, 2000
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Purpose of travel: To present an invited paper on U.S. Stellarator design efforts at the Tenth International Toki Conference, the topic of which was "Physics and Technology for Steady State Plasmas" and to visit Japanese stellarator laboratories to discuss stellarator progress.

Abstract: The traveler attended the Tenth International Toki Conference at the National Institute for Fusion Science (NIFS) in Toki City, near Nagoya, and visited the Institute for Advanced Energy of Kyoto University in Uji, near Kyoto. He presented an invited talk at the Conference and the same talk as a lecture at Kyoto University. The conference featured papers on stellarator experiments, tokamak experiments, machine designs, theory and modeling, and technology, all on the topic of "Physics and Technology for Steady State Plasmas". The main message from the conference is that the critical issue of developing a sustainable, high-beta plasma configuration is beginning to take center stage in the magnetic fusion community. At NIFS, discussions on collaboration between U.S. stellarator designers and LHD experimentalists were held. At Kyoto University, construction of a new stellarator device, Heliotron-J, a "helical axis heliotron", was recently completed and first plasma was achieved.

Toki Conference, Jan. 18-21
The topic of the conference was "Physics and Technology for Steady State Plasmas". It featured invited papers (38 in all) on stellarator experiments (LHD, W7-AS, and TJ-II), tokamak experiments (Tore Supra, DIII-D, ASDEX-U, JT-60U, TEXTOR, Triam-1M), machine designs (NCSX, W7-X, ITER-FEAT, KSTAR), theory and modeling, and technology (PFCs, heating, diagnostics, plasma control). There were about 100 posters addressing details of these topics. The idea of organizing the conference around a topic, steady state, that cuts across concepts and spans physics and technology was a positive feature that made it more interesting to the traveler than long conferences that are all about tokamaks or all about stellarators. The conference included a tour of the National Institute for Fusion Science, including the impressive Large Helical Device (LHD) facility. Local civic leaders played a prominent role in the conference activities, expressing their support for fusion research and their enthusiasm for the local project.

The main message from the conference is that the critical issue of developing a sustainable, high-beta plasma configuration is beginning to take center stage in the magnetic fusion community. Some of the steady-state technology issues such as high-heat-flux first wall systems, superconducting magnets, and long-pulse heating have been recognized for some time, and progress can be seen as a result. The recent long-pulse experiments (up to 80 s) on the Large Helical Device (LHD) demonstrate the successful performance of an all-superconducting stellarator magnet system on an unprecedented scale. The discharges were sustained with megawatt-level negative-ion neutral beams (80 s) or ion-cyclotron radiofrequency waves (68 s), representing significant achievements for these heating technologies. In the first-wall area, the installation (now in progress) of a 25-MW, 1000-s power handling system in the Tore Supra tokamak, which has already achieved pulse lengths greater than 100 s, will keep that program at the forefront of attacking the difficult problem of integrating steady-state high-heat-flux technology with high-power plasma operation in a fusion device. The long-pulse experiments in LHD and Tore Supra have so far been at low beta.

The conference highlighted the physics challenge for steady-state magnetic confinement, which has begun to be appreciated in the last 8-10 years with the design of the Tokamak Physics Experiment (TPX) in the early 1990's and now KSTAR, and the rapid growth in emphasis on plasma control and power and particle handling research on experiments worldwide. The issue is one of sustaining a plasma configuration with high beta and enhanced confinement beyond plasma and plasma-wall timescales. In tokamaks especially, this raises issues of plasma control: control of profiles and unstable MHD modes, especially in plasma configurations with high bootstrap current fraction.

- In JT-60U, they have run for 2.7 s at high normalized beta (meaning β_N>2, I believe, where β_N is a commonly used figure of merit that expresses the ratio of beta to standard tokamak beta limits) and β_NH>6, where H is the enhancement factor over ITER-89P confinement scaling.
- The ASDEX-Upgrade has run for ~6 s at β_N≈2 and H≈2.6, and density about 30% of the Greenwald limit with central safety factor (q_0) about 1. The highest achieved β_NH is 7 (for less than 6 s, though). Beta is limited by neoclassical tearing modes (NTM). They have increased the NTM β_N limit from 2.2 to 2.6, H from 2.6 to 3.0, and the Greenwald fraction from 0.3 to 0.5 by increasing the triangularity from 0.2 to 0.3. Using electron cyclotron counter-current drive to control double tearing modes, they have produced reverse shear discharges with q_0>2, about 55% bootstrap current, and steep but transient internal transport barriers. It is clear that ASDEX-Upgrade has achieved improved performance through control (plasma shaping and current profile control). They plan to extend this line of research by machine modifications to increase triangularity, optimize neutral beam aiming, and use RF current drive, with the goal of a 10-s noninductively sustained discharge.
- The DIII-D program maintains its focus on advanced-tokamak operation, pursuing high values of β_NH (>10), pulse duration (5-10 s), and bootstrap fraction (>50%).

Planning for future tokamak experiments also emphasizes advanced-tokamak plasma control issues. Modeling results were shown for proposed current profile control experiments with neutral beams and lower hybrid waves on JET to improve confinement and stability and make progress toward steady-state, high-bootstrap scenarios. Capabilities for advanced-tokamak operation are being incorporated to a limited degree into the design of ITER-FEAT, although its basic Q≈10 scenario is based on ELMy H-mode tokamak operation. The new superconducting

KSTAR tokamak, under construction in Korea, will be the primary facility for research on extending the advanced tokamak to long pulse lengths (20-300 s) in the next decade.

In stellarators, advances in magnet and heating technology have led to long-pulse discharges, while improving beta, confinement, and power handling are key physics issues.

- In LHD, they have obtained energy confinement times up to 0.3 s (a stellarator record) and confinement enhancement factors over the ISS95 empirical scaling of up to 1.6. The best confinement is obtained in configurations where the vacuum magnetic axis is shifted in by 0.15 m from the nominal 3.75-m position. With neutral beam heating power of 3.9 MW and magnetic field of about 2.8 T, they have obtained $T_e \approx T_i \approx 3.5$ keV at $n_e = 10^{19}$ m^{-3}. At low field (1.3 T), they reported β up to 2.4%, a stellarator record, in NBI-produced, ICRF-heated discharges. The highest beta values are obtained with pellet injection. Although the shifted-in configuration in which these results were obtained is theoretically unstable at zero beta according to the Mercier criterion, the MHD levels were very low ($\delta B/B \sim 10^{-4}$) and there were no disruptions. They believe beta is being limited by confinement and the available heating power, not instabilities. Bootstrap currents are calculated to be about 20-30 kA in the experiments and are not believed to have much effect so far.
- The W7-AS is preparing a major program to address stellarator power and particle handling issues by installing a divertor. Installation of target plates is to be completed in Summer, 2000. An array of saddle coils installed to control the divertor field line connection lengths has already been operated. The divertor is compatible with rotational transform (ɨ) of 5/9 (0.56) plasma configurations. The envisioned high-power divertor operating scenario is a high-density (>10^{20} m^{-3}) H-mode with complete detachment. They have studied the conditions for getting into the H-mode at high density: high power, gas puffing, and a very sensitive dependence on ɨ.

The traveler presented an invited talk, “Design of Compact Stellarator Experiments,” discussing the status and future plans for the NCSX and QOS experiments now being designed by U.S. stellarator researchers. Conference participants applauded the attention being given to all-new optimized coils for NCSX, as an alternative to the re-use of existing PBX-M coils, which are thought by many to overly constrain the design. The traveler’s expenses associated with attending the conference were supported by NIFS.

Discussions at NIFS during Toki Conference

The medium-scale Compact Helical System (CHS) experiment, recently installed at the NIFS Toki site after being moved from the Nagoya University campus, was undergoing pre-operational tests during the conference. First plasma was considered imminent.

The CHS team has been exploring designs for a quasi-axisymmetric stellarator, CHS-qa, as a successor to the current CHS. A poster was presented at the Toki Conference, but there was little beyond what was presented at the International Stellarator Workshop in Madison last Fall. They are using plasma configuration designs of J. Nuehrenberg's (IPP-Greifswald) which are optimized for good particle confinement in the vacuum condition. (In contrast, the more ambitious quasi-axisymmetric NCSX is optimized for both confinement and stability against several mechanisms at finite beta with bootstrap currents.) There was no further information on the laboratory's future plans for CHS-qa beyond the current study phase.

The traveler inquired about analytical tools used by LHD. The RESORM code (K. Ichiguchi) is used to study resistive interchange modes. Stabilizing effects of viscosity and heat conductivity are currently being studied. The three-dimensional equilibrium code HINT (R. Kanno) is used to study the island-healing effects of finite current (up to ~100 kA with an ohmic-like spatial distribution), though some say HINT has difficulty with the high-shear in LHD. The current reduces the island width by shifting the $\iota=1/2$ surface out of the plasma. They plan to look at bootstrap-like profiles. The TOTAL code (K. Yamazaki) is a new predictive/interpretive transport code built around the U.S. equilibrium code VMEC and neutral beam code HFREYA. For divertor-related studies of the magnetic field structure outside the last closed flux surface, they use the German DIAGNO code, which is built around VMEC.

The traveler discussed LHD high-beta studies with Project Head O. Motojima and experimentalists S. Sakakibara and H. Yamada. The highest beta values to date (2.4%) are with pellet injection and they plan to upgrade their injector for larger pellets. They value their U.S. collaboration (with M. Gouge, ORNL) on pellet technology. There are no profile data yet with pellet injection due to interferometer tracking problems. They use x-ray array data and VMEC to reconstruct equilibria. Low-n ideal MHD instabilities are analyzed with the STEP code in collaboration with M. Wakatani of Kyoto University. Ideal ballooning is treated with the German CAS3D code, which predicts a ballooning beta limit of 3% for the conditions analyzed. However, their main focus is the ideal interchange mode which they think is most relevant to what is observed experimentally so far.

The traveler proposed a collaboration to study LHD high-beta data with tools being used by U.S. designers. This was positively received and should be pursued in future visits to NIFS by U.S. stellarator physicists over the next several months. There is little data available at present, however, and it is necessary to build a collaborative relationship with the LHD physicists over time in order to have a productive collaboration.

K. Yamazaki urged us to support U.S.-Japan high-beta MHD workshops which include both tokamaks and stellarators. There have been two recently (one at San Diego last September and one at JAERI in early January) and the next one is planned to be at PPPL after the October APS-DPP meeting. They want to promote scientific interaction between tokamaks and stellarators in the context of the STA-Monbusho merger. They appreciated J. Manickam's (PPPL) stellarator presentation at the most recent one. Scientifically, it is a good thing and should be supported to the best of our ability.

Visit to Kyoto University, Institute of Advanced Energy, Jan. 24-25

The Institute of Advanced Energy (IAE) was the site of Japan's "Heliotron" series of stellarators that preceded LHD. Recently they completed construction and began operation of a new device, Heliotron-J, which they call a "helical axis heliotron", which replaced the Heliotron-E. The laboratory is much reduced in size since the traveler's last visit there in 1986, due to the shift of key personnel and activity to LHD. However, there is still a core group of capable experimentalists who previously worked on Heliotron-E, as well as a good group of theorists.

The Heliotron-J (major radius 1.2 m) is much smaller than Heliotron-E (2.2 m) but was built using parts of the Heliotron-E machine structure and some of the secondary coils. The core device (helical-field coils and vacuum vessel) is new. Many of the Heliotron-E diagnostics and heating equipment (or parts thereof) are available but as yet few are actually connected to the new device. Operating budgets and support staff are very limited. The traveler asked about involving students in Heliotron-J in order to augment the effort and train a new generation of fusion scientists, and they indicated it was their intention to do so. This year they were only able to operate in November and December in order to achieve first plasma; plasma operation with resume in April when the new fiscal year starts. Meanwhile they are preparing to do flux-surface mapping experiments, which will use a fluorescent rod swept across the cross section and viewed by a CCD camera, starting in February.

The traveler attended the weekly Heliotron-J group meeting on Jan. 24. They were pleased to see their first plasma accomplishment reported in Jim Rome's "Stellarator News". The traveler presented his Toki Conference talk at this meeting since few of the staff were able to attend the conference.

The traveler discussed Heliotron-J physics with the experimental group leader F. Sano, theorist Y. Nakamura, and experimentalist T. Mizuuchi. Sano talked about the strategy for suppressing anomalous transport. The elements are: achieving a high pressure gradient (via local fueling with pellets and local heating with ECH), a radial electric field (via radial neutral beam injection), and maintaining a large gap (about 5 cm, I believe) between the last closed flux surface and first wall. Nakamura explained the configuration design strategy, which relies on a strong "bumpy field" component to confine trapped particles to straight sections where the   B drift is low. Mizuuchi is interested in divertor issues and has been studying the magnetic field structure outside the last closed flux surface, using vacuum field-line following calculations. In its standard configuration, Heliotron-J has an ergodic divertor like LHD's, but can also create various island divertor configurations, albeit at the expense of plasma volume. The U.S. design team will need to address these topics in the near future and Mizuuchi, who has been thinking about them carefully, could be a good collaborator.

The Director of the IAE Laboratory for Complex Energy Processes, T. Obiki, expressed keen interest in the U.S. plans for stellarator experiments, as well as support. Like the Toki Conference participants, he advocated looking beyond the PBX-M coils in the design of NCSX.

Persons Contacted

Toki Conference and NIFS

M. Fujiwara, Japan, NIFS Director
O. Motojima, Japan, LHD Project Head
S. Sakakibara, Japan, LHD high beta experiments
H. Yamada, Japan, LHD high beta experiments
K. Yamazaki, Japan, LHD experiment
S. Okamura, Japan, CHS, CHS-qa
N. Noda, Japan, Toki Conference Chair, NIFS
C. Alejaldre, Spain
G. S. Lee, Korea
O. Gruber, Germany
H. Wobig, Germany
K. McCormick, Germany
F. Wagner, Germany
P. Politzer, U.S.A.
R. Blanken, U.S.A.
M. Abdou, U.S.A.
R. Nygren, U.S.A.
M. Porkolab, U.S.A.
J. Li, China
R. Amrollahi, Iran

Kyoto University

T. Obiki, Director, Laboratory for Complex Energy Processes
F. Sano, Heliotron-J Experiment Head
T. Mizuuchi, Heliotron-J Experiment
Y. Nakamura, theorist
J. Vasp, visitor, Spain

Literature Acquired

1. Book of Abstracts, 10th International Toki Conference
2. List of Participants, 10th International Toki Conference
3. Brochure on Institute of Advanced Energy, Kyoto University
4. T. Mizuuchi et al., “Structure of Edge Magnetic Field in Heliotron-J,” Toki Conference paper.
5. F. Sano et al., “Experimental Program of Heliotron-J,” Toki Conference paper.
6. M. Wakatani, Y. Nakamura, et al., “Studies of Helical-Axis Heliotron,” poster presented at 17th IAEA Fusion Energy Conference in Yokohama, Oct., 1998.
7. K. Ichiguchi, “Effects of Dissipation on Interchange Mode in Heliotron Plasma,” Toki Conference paper.

Itinerary

Jan. 15-16	Travel from Princeton residence to Osaka, Japan.
Jan. 17	Travel from Osaka to Toki City.
Jan. 18-21	Toki Conference and visits to NIFS, Toki City.
Jan. 22-23	Travel from Toki to Kyoto and weekend.
Jan. 24-25	Visit to Kyoto University, Institute of Advanced Energy
Jan. 26	Travel from Kyoto, Japan to Princeton residence.