stellarator news

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News

Japanese National Institute of Fusion Science Established

July 1, 1989

Dear Colleague:

I am pleased to inform you that the National Institute for Fusion Science was established under the Japanese Ministry of Education, Science and Culture on 29th of May 1989. The majority of researchers at the former Institute of Plasma Physics, Nagoya University, have been transferred to the new institute, which has also been joined by parts of the Plasma Physics Laboratory, Kyoto University, and the Institute for Fusion Theory, Hiroshima University.

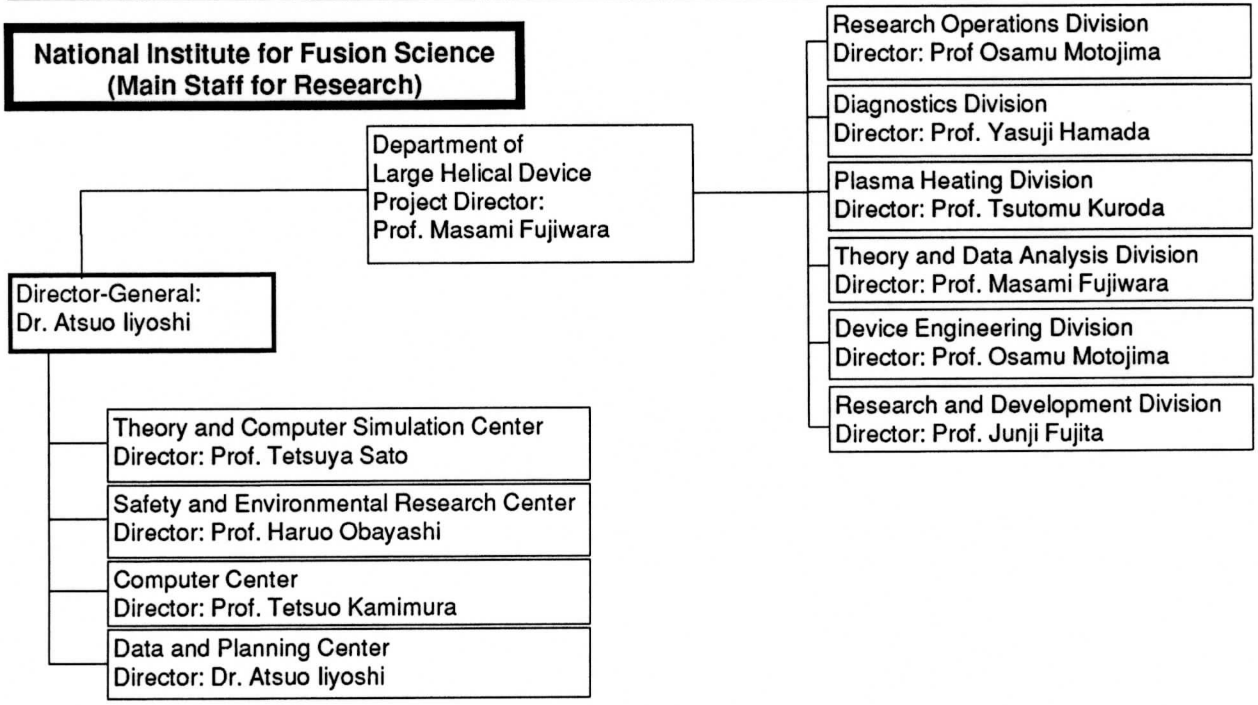
The goal of this institute is the promotion of research in fusion plasma physics and its applications both in Japan and around the world through intensive research collaboration.

As the major project of the institute, we are going to construct the Large Helical Device, and carry out related experimental and theoretical studies including computer simulation work. An organization chart is attached for your information. We believe this will make significant contributions to the understanding of toroidally confined plasmas as well as the development of steady state fusion reactors.

We are looking forward to fruitful collaboration with your organization.

Sincerely yours,

Atsuo Iiyoshi
Director General
National Institute for Fusion Science



National Institute for Fusion Science
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Around the Labs

Experiments on CHS

As announced in the preceding article, the National Institute for Fusion Science was started in May. The CHS experiment has continued to operate as a primary supporting experiment for the Large Helical Device project.

The main heating systems of CHS in 1988 were 28-GHz gyrotron and ICRF heating. We achieved an electron temperature of more than several hundred eV using ECH in the density range of $(2-5)\times10^{12}\mathrm{cm}^{-3}$ (hydrogen plasma). The total energy in the plasma was estimated to be 150 J. But the plasma parameters were rather poorer for the higher density operations in the range of $1\times10^{13}\mathrm{cm}^{-3}$. In 1988 we did not use titanium gettering for ECH experiments except for the ICRF plasma production experiments.

Two new heating systems were installed on CHS in March : 53-GHz gyrotron (200 kW/100 msec) and a neutral beam injector (40 keV/1.2 MW/ 1 sec). After the tuning and conditioning work, we started new heating experiments in June.

With 53-GHz ECR heating, the plasma parameters are improved for a high density region. The total energy measured by the diamagnetic loop is 380 Joules with the density $\bar{n}_e \simeq 1\times10^{13}\ \mathrm{cm}^{-3}$. The port-through power is ~ 90 kW and the pulse duration was 40 msec in this shot. No polarization control and no focusing control were used. The magnetic field is set at $B_t = 0.93$ T in order to locate the second harmonic resonance of 53 GHz ECH at the magnetic axis. Because the maximum magnetic field is presently limited to 1.5 T by the power supply, fundamental resonance experiments for 53 GHz ECH will not be available until the power supply is modified. The 28-GHz Klystron power (~ 1 kW) was applied to help the breakdown. We are scheduled to operate the 28-GHz and 53-GHz gyrotrons simultaneously to get higher heating power and improved heating efficiency.

The beam heating experiment has also started. The injector is movable for the purpose of varying the pitch angle of injected ions. We have started the experiment with a tangential co-injected beam (unbalanced injection). A 30 keV hydrogen neutral beam was injected into the target plasma produced by either 53-GHz ECH or 13-MHz ICRF heating. Using ECH to produce a target plasma for beam injection, both off-resonance heating and resonance heating worked well. Therefore, 1.5-T operation was possible for beam heating with the 53-GHz fundamental resonance located at the boundary region of plasma.

For these beam injection experiments, the total diamagnetic energy is about 2 kJ for 1-T operation and 3 kJ for 1.5-T operation, and the average plasma density is approximately several times $10^{13}\mathrm{cm}^{-3}$. The port-through beam injection power is about 600 kW, and the shine-through level is typically 30%. The plasma current that is induced in these beam injection experiments is a maximum of several kA in the same direction as the beam.

Titanium gettering was used for these beam heating experiments. Eventually, seven Ti balls, covering most of the area of the vacuum wall, were in use. Using the initial two Ti balls (which cover about 10% of the wall area) effectively suppressed the radiation collapse for up to 200 ms of beam heating. This time limit is imposed by the heat load to the unprotected wall. Additional titanium gettering helped to increase the plasma energy allowing stronger gas puffing. In some shots, the plasma energy increased after the gas puffing was stopped during the beam heating. Although this is still a transient operating regime, it indicates possibilities of controlling gas fueling for the improvement of confinement.

Further conditioning of the ion source is necessary to get the full operation of beam injector at 40 keV. To understand the transport in a low-aspect-ratio helical system, we are scheduled to vary the beam injection angle and make precise profile measurements.

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Status of Wendelstein W7 AS (April 1989)

During 3 months of experiments, 3500 shots with a typical pulse duration of 0.5 s were performed. All standard diagnostics are operating and 2 MByte of data per shot are accumulated and available for analysis. "Currentless" plasma was maintained by ECF heating and NBI heating.

ECF HEATING

The plasma is generated and heated by application of ECF at 70 GHz. In cooperation with IPF Stuttgart a rather sophisticated launching system has been developed. Focused beams (HE_{11} mode) are quasioptically guided by movable mirrors. The losses of the optimized transmission line, including the conversion losses to the final HE_{11} mode, are measured to be less than 10%. Thus, variable power deposition and current drive by the variation of $k_{\parallel}$ components are achieved. Experiments with the second-harmonic X-mode at a magnetic field of 1.25 T and with the fundamental O-mode at 2.5 T using 2 gyrotrons (400 kW) produced electron temperatures of up to 2 keV within the accessible density range. Measurements of the single-path absorption are in good agreement with ray-tracing calculations and show heating efficiencies close to 1. Nevertheless, the absorption mechanism needs further study to clarify the power deposition at the boundary and define the role of suprathermal electrons.

CONFIGURATIONAL EFFECTS ON CONFINEMENT

Systematic studies of the confinement as a function of the magnetic configuration for the accessible range of beta up to 0.5% at a field of 1.25 T found behavior similar to that observed on W 7A: deterioration of the confinement is associated with the existence of low-order resonant surfaces in the confinement region. Control of the boundary value of the rotational transform, far from resonances, and sufficiently low shear are necessary for optimal confinement. During discharges with long pulse duration, more than 200 ms, a bootstrap current, strongly dependent on the temperature profiles and additive to the rotational transform of the vacuum field, becomes stationary at values of up to 3 kA. Control of the net current for stationary conditions with good confinement was succesfully applied by three different methods: induced voltages by means of OH transformer, balanced neutral beam injection, and ECF current drive. Even fine tuning of the current density profiles by local ECF current drive seems possible and may be necessary for approaching higher beta.

TRANSPORT

Bootstrap current: The theoretical values of the neoclasical bootstrap current calculated by means of the DKES code (drift kinetic equation solver, by S.P. Hirshman and W.I. Rij of ORNL) on the basis of the measured density and temperature profiles were roughly consistent with the experimental observations in W 7 AS. The modification of the magnetic configuration by the bootstrap current is especially large at low field and with high temperature gradients. Operation at higher field may be favorable since, according to the scaling for the bootstrap current, the amplitude will be diminished. In addition, the contribution of the related poloidal field to the transform scales as 1/B.

Electron heat conduction: Some preliminary studies of the electron heat conduction have been made. Under conditions of optimal confinement, which were established at particular values of the rotational transform close to ⅓ and ½ by current control, the energy balance was evaluated on the basis of measured density and temperature profiles. For almost all discharges with different heating powers, the experimental values of the electron heat conductivity at the radius a/2 were in the range of 0.7 to 2 m^2/s. Towards the center slight increase is observed, but a strong increase is seen at the boundary. Especially at the boundary, significant discrepancies in relation to the theoretical predictions of the DKES code occur. Additional losses have to be assumed in the boundary region. So far the confinement regions with temperatures $T_e < 200$ eV seem to be rather fragile, taking into account perturbations by local heat and particle sources.

Particle balance: Estimates of the particle confinement based on H_α measurements and DEGAS code simulations indicate for some particular discharges consistency with neoclassical predictions for the particle flux in the plasma gradient region and anomalous fluxes at the plasma edge ($D \sim 1/10\, \chi_e$).Extension of the parameter range in future experiments will certainly help to clarify these phenomena.

IMPURITIES AND RADIATION

Up to now, in ECF discharges, radiation and impurities do not seem to be very important. A first estimate of the impurity content, based on spectroscopic measurements, soft X-ray data, and bolometric measurements, typically leads to oxygen and carbon concentrations of the order of 2–3%. Iron concentrations can increase up to 0.03%. Control of impurity sources and impurity transport will be studied during the next phase of experimentation (gas puffing, laser ablation, and pellet injection) and may become problematic with full use of the installed power on W 7AS at higher densities, as already being indicated during NBI experiments, including pellet injection for fast density buildup.

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Optimization of Helias for W VII-X

Optimization of Helias [1] equilibria at finite beta was attempted with respect to the following set of criteria:

1. high quality of vacuum field magnetic surfaces,
2. good finite-beta equilibrium properties,
3. good MHD stability properties,
4. small neoclassical transport in the $1/\nu$ -regime,
5. small bootstrap current in the lmfp-regime,
6. good collisionless alpha-particle containment,
7. good modular coil feasibility.

Criteria 1 and 7 are taken into account by solving Helias boundary value problems with side conditions on the shaping parameters. Criteria 2 and 3 are satisfied by maintaining resistive-interchange and ballooning stability at an average beta of about 5%, for configurations with 5 periods and aspect ratio of approximately 10. While maintaining resistive-interchange stability is directly incorporated into the optimization, ballooning stability is taken into account through its driving terms [2]. Criteria 4, 5, and 6 are taken into account by optimizing the structure of $B(\theta,\varphi)$ in magnetic coordinates. Further parameters of this example are: magnetic well of 0.018, $\bar{\iota}(0)=0.83$, $\bar{\iota}(1)=0.96$ in the vacuum field; δ_e (equivalent ripple characterizing the $1/\nu$ transport and obtained by Monte Carlo simulations [3]) approximately 0.01 at half the plasma radius; reduction of the bootstrap current (obtained by Monte Carlo simulation of a stationary distribution function [4]) as compared to its value in the equivalent tokamak by a factor of approximately 10; collisionless alpha-particle loss (obtained by following guiding center orbits of a representative set of alpha particles) of approximately 10%.

[1] Nührenberg, J., Zille, R., Phys. Lett. A, **114A**, (1986) 129; **129** (1988) 113.
[2] Nührenberg, J., Zille, R., Sherwood Theory Conf. 1989, San Antonio.
[3] Lotz, W., Nührenberg, J., Phys. Fluids **31** (1988) 2984.
[4] Lotz, W., Nührenberg, J., Schlüter, A., J. Comput. Phys. **73** (1987) 73.

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Preliminary Studies of the Divertor Structure in the Proto-Cleo Stellarator

The divertor structure has been measured in the Proto-Cleo stellarator by using an array of 50 langmuir probes arranged to follow the helical winding in the 'stripe' of diverted particle flux. An additional 16-element probe array was located perpendicular to the helical coils and confirmed escaping plasma was localized near one polarity of conductor. The figure shows the local plasma density as a function of poloidal angle along the helix. It can be seen that some density is present at all locations, but peaking occurs near the outboard and inboard sides of the torus.The peak is especially sharp on the inboard side. Further experiments are in progress to examine the effects of applied vertical magnetic fields on this observed structure. The localization of plasma density along the helix will be exploited through installation of biasing plates at the locations of the observed peaks in the near future.

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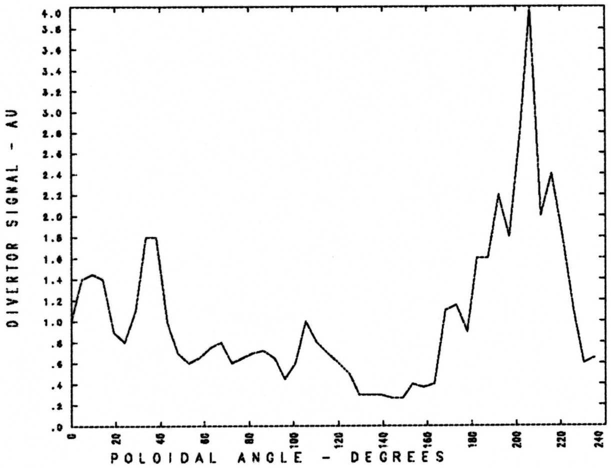

STORM planned at CIEMAT

In order to fill the temporal gap until the completion of TJ-II (1993) and to acquire expertise on ECRH with the available 28 GHz gyrotron, a new small stellarator called STORM has been planned at CIEMAT. It will share with the present TJ-I tokamak, a site, power supplies, data acquisition systems, and diagnostics. By necessity it shall be of simple construction (no extreme currents or accuracy), small size and cost but with at least, 10 cm average radius and the most similar as possible to the TJ-II magnetic configuration.

After many trials and optimisation the chosen configuration is an $l=1$ / $m=6$ Torsatron. It has an $l=1$, 6-turn, helical coil with winding modulation given by $\phi = 1/6\ (\theta + 0.4 \sin \theta)$ and with a major radius of 0.6 m and a minor radius of 0.24 m. Two sets of vertical field coils provide dipolar and quadrupolar vertical field components. The winding modulation is opposite to the usual in ultimate torsatrons and is essential to achieve a deep magnetic well. It makes the helix direction closer to the vertical on the inner side of the torus than on the outer one.

For the reference current settings ($I_{hc} = 280$ kA, $I_{vf1} = -122$ kA, $I_{vf2} = -49$ kA), the average plasma radius is 10 cm, and the rotational transform at axis is 0.30, with a shearless radial profile. The magnetic axis, placed at $R_{ax} = 0.58$ cm for $\phi = 0$, has a slight helicity (2.5 cm); most importantly, a deep magnetic well of 6.9% depth exists. Magnetic field intensity at axis for $\phi = 30$ is 0.5 T, which is suitable for second harmonic ECR heating at 28 GHz.

The VF coils allow some configuration flexibility by means of magnetic axis shift; the axis can be positioned between 0.61 and 0.52 m. In this way the rotational transform can be varied between 0.14 and 0.4 while always maintaining an average radius greater than 7 cm. The magnetic well is optimal for the reference case, disappearing gradually for extreme axis shifts. The engineering design of the device is now well under way and the machine is expected to start working at the begining of 1990.

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Status of ATF
(July 1989)

Since the last Newsletter in May, the ATF program has concentrated on extending research capabilities and testing them in plasma operation. The ATF device has been commissioned successfully to B = 2.0 T. Initial efforts to optimize operation at 1.9 T show that the stored energy with fundamental ECH at 1.9 T has increased by a factor of two over comparable 1-T operation, reaching up to 3.5 ± 0.5 kJ at $\bar{n}_e = 1.2 \times 10^{19}\mathrm{m}^{-3}$ with ECH power of 0.20 MW. With the addition of 0.70 MW of coinjected NB power, the stored energy increased to 6.0 ± 0.5 kJ at $\bar{n}_e = 1.4 \times 10^{19}\mathrm{m}^{-3}$. These results are in rough agreement with the LHD scaling predictions.

Preliminary results with four getter sources show some increase (by about 20%) in stored energy and extended time before plasma collapse over comparable operation with two getter sources. Scans of ECH polarization with fundamental heating at 1.9 T indicate that o-mode polarization is better than x-mode but the optimum is rather broad around the o-mode direction. An ORNL 8-barrel pellet injector has been installed and commissioned. A 1.2-km/s, r = 0.9-mm pellet was injected, increasing plasma density up to $\bar{n}_e = 4 \times 10^{19}\mathrm{m}^{-3}$. Fluctuation measurements using the fast reciprocating Langmuir probe provided by the TEXT Group show density and floating potential fluctuation of orders of 20% in the scrapeoff layer [$\bar{r} = (1.1\text{–}1.2)\ \bar{a}$].

In the forthcoming months, the above enhancement capabilities [with addition of additional configuration control provided by the mid-VF(vertical field)] will be integrated for optimal plasma performance, and comprehensive studies of transport and fluctuations will be carried out.

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Meeting Reports

The following reports are discussion group summaries from the Seventh International Stellarator Workshop, which was held in Oak Ridge, TN, USA, in April, 1989.

Discussion on Instabilities and Fluctuations

H. Zushi and J. L. Johnson

We started by noting that stellarators seem to perform best with some inward shift, indicating that favorable transport properties seem to be more important than average magnetic well with respect to confinement. Harris noted that MHD instabilities present a limit on the inward shift that can be accommodated but that some inward shift allows operation in an interesting plasma regime with relatively low collisionality. Similar considerations should guide the Madrid and Canberra groups as they plan their early experiments.

Johnson noted that the phase relation between the magnetic field and potential fluctuations forms a basis problem for the use of nonlinear coupling of plasma instabilities to explain anomalous transport. Hamberger noted that this is especially true when only one mode is present, but his plasma was collisional and the resistivity provided sufficient phase shift for his drift wave measurements to be a reasonable picture. There was some agreement that these considerations are serious in collisionless plasmas but that the interaction of multiple instability modes can destroy the coherence properties often enough that they are valid explanations for transport.

There was some discussion of the value of stellarator studies for understanding tokamak confinement problems. There was general agreement that the basic phenomena are transferable, with stellarators providing new possibilities for separating the different physical mechanisms. It was strongly noted that confinement in the outer part of the plasma is the most serious concern in both types of devices.

Discussion on Advances in Configuration Optimization

J. Nührenberg and M. Wakatani

The starting point of this discussion was a reconsideration of the classification of stellarators as described in the 1988 Progress Report on Stellarators. It was stated that unifying tendencies between lines I (high-transform, high-shear stabilized), and II (moderate-transform, shear/magnetic-well stabilized) and between lines III (moderate-transform, low-shear, reduced $j_{\|}$, magnetic-well stabilized), and IV (high-transform, low-shear, magnetic-well stabilized) are being observed. Statements supporting this observation were: i) Some basic properties of Heliotron-E, ATF, CHS, and LHD can be described in a diagram of torsatron coil aspect ratio versus number of periods. ii) Quasi-helically symmetric stellarators are a toroidal analog of helically symmetric heliacs. iii) Papers in the Workshop showing these tendencies were O2-6 and O4-3 for lines I and II and O3-6, O3-7 and O4-5 for lines III and IV. It was stated that these tendencies may foster development towards two next-generation devices which could possibly be the LHD and W-VII-X.

Concerning the optimization procedure, two groups (IPP Garching and ORNL) stress the usefulness of optimization of the shape of the plasma boundary as a tool to survey stellarator configurational space. It was stated that as far as the Japanese program is concerned this approach could possibly be applied to a device following LHD, because for this device itself coil specification is already well under way and only a few coil parameters remain to be specified.

A list of optimization goals was discussed which comprised the following items: (1) vacuum field flux surfaces, (2) equilibrium, (3) stability, (4) neoclassical and anomalous transport, (5) bootstrap current, (6) alpha-particle confinement, (7) coils and divertors.

It seems that there is growing evidence (O2-5, O2-6, 4P-2) that the Mercier stability limit has to be taken seriously, so that this stability criterion is a useful design tool.

It was stated that no experiment has yet seen less than neoclassical transport and some (O2-4) have claimed large neoclassical electron heat conductivity. Trapped particle modes were considered to be important candidates for explaining anomalous transport. It was pointed out that improvement of confinement by reducing anomalous transport will become an important subject in stellarator research.

Discussion on Configuration Effects

J. H. Harris, H. Zushi, H. Renner, H. Wobig, and F. Rau

In the area of topological stability, experimental studies have shown that for sheared systems (Heliotron-E, ATF, CHS, Uragan-3M, etc.), in which $\iota\!\!\!-(r)$ passes through low-order resonances, field errors must be controlled carefully (as has been found in the experiments); on the other hand, these configurations are not sensitive to small plasma currents. In shearless systems the major resonances can be avoided by maintaining accurate control of the total transform; for these configurations, experiments (W-VII AS) have demonstrated that control of the plasma current is essential.

Theoretical expectations are that finite-β effects can distort the transform profile into an unfavorable shape (e.g., double valued) and must be compensated by control of the external shaping fields (e.g., ATF) or reduction of the equilibrium currents by design (W-VII AS → Helias); this area has not yet been investigated in detail in the experiments. A series of experiments in torsatrons (Heliotron-E, ATF, and CHS) indicates that a small inward shift ($\Delta R/R \approx 0.02$) of the vacuum magnetic axis appears to improve confinement. There is evidence that this is due to the improvement of particle orbit confinement, although magnetic island effects and stability also play a role in some cases. These findings would appear to support efforts to optimize new configurations (W-VII X, LHD) by carefully shaping the $|B|$ contours.

Experimental studies of plasma stability (ATF, Heliotron-E) show evidence of magnetic well stabilization of MHD interchange modes; again, these provide support for the working hypotheses (marginal stability criteria) used in the design of the new configurations.

There is ample experimental evidence of the importance of plasma-wall interaction effects in determining the quality of stellarator confinement: this underlines the importance of integrating the design of divertor/limiter structures in device design. Extensive studies of diverted flow patterns in helical divertors are in progress on Heliotron-E and ATF, and this problem is important in the LHD design studies. In the case of the Helias configurations studied for W-VIIX, the rotational transform profile is chosen to avoid major resonances in the confinement region, and the edge is determined by the combined effects of any "natural" islands that are present and the symmetry-breaking perturbations that result in the actual realization of the field. Study of these effects is important both for the design of divertor structures and to determine the effective minor radius to use in estimating confinement properties.

As our understanding of individual phenomena in stellarators improves, the level of detailed analysis applied in the development of new configurations satisfying a host of criteria grows. This is evident in both the LHD and W-VIIX configuration development efforts. Efforts to devise new types of configuration that satisfy (sometimes conflicting) diverse requirements are still continuing, as witness proposals for novel heliotron configurations with reversed toroidal field (Zushi), the l=2/4 configuration under study at the Institute of General Physics, and the low-R/a configuration studies at ORNL.

People

On May 29, 1989, Atsuo Iiyoshi was appointed Director-General of the new Japanese National Institute for Fusion Science. In this position, he has responsibility for the promotion of research in fusion plasma physics and its applications.

Professor Iiyoshi is a plasma physicist who received a Ph.D. from Keio University in 1965. After participating in research at Princeton University and Culham Laboratory, he was appointed professor at Kyoto University in 1971. For the past year, he had been Director of IPP at Kyoto University.

Announcements

Toki Conference

The first "International Toki Conference on Plasma Physics and Controlled Nuclear Fusion" will be held at Toki Bunka-Plaza in Toki City, 4–7 December 1989. This conference is organized by the newly established National Institute for Fusion Science, aiming at developing further the activities of fusion research in the world through the presentations and discussions held during this conference.

The Institute's major project, the Large Helical Device Project, will contribute significantly to the development of steady-state fusion reactors. We are now beginning construction on the new site for the Institute in Toki-city, near Nagoya. We are therefore inaugurating a series of annual International Toki conferences; these meetings will be devoted to topics of current international interest in fusion research. The conference will be composed as follows:

Date: 4–7 December 1989
Place: Toki Bunka-Plaza, Toki City
Topic: Next Generation Experiments in Helical Systems
Scope of the conference:

- To review the present status and latest achievements in the design study of the next-generation helical systems.
- To review the experimental and theoretical investigations of the physics in existing helical systems.

Working language: English
Publications: The bulletin will be distributed at the conference. The proceedings will be prepared and sent to the participants after the conference. Those who wish to attend and contribute a paper are kindly requested to contact Prof. J. Fujita. The necessary information will be sent.
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The final program will appear in the next issue of *Stellarator News.*