



stellarator news

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ATF Program Cut

In the latest round of financial rearrangements in Washington, the Advanced Toroidal Facility (ATF) suffered a severe setback. The budget for FY 1994 was cut by \$1 million, and it appears unlikely that there will be funding for operations in FY 1995.

The reconstruction of ATF is almost complete. It is hoped that ATF will be able to run some steady-state electron cyclotron heating (ECH) discharges later in this year.

Australia Signs IEA Agreement

Australia has recently signed the International Energy Agency's *Implementing Agreement for Cooperation in the Development of the Stellarator Concept*, which pledges collaboration between the signatory parties. The original 1985 signatories, Euratom and the United States (DOE) were joined in 1992 by Japan (Monbusho). Because Australia has no Governmental Agency involved with fusion, the Operating Agency will be The Australian National University, which operates the H-1 and SHEILA heliacs.



Around the Labs

H-1 Helic: First Results on Configurations and Quasi-Continuous Plasma Operation

The H-1 Helic has been operating routinely with continuous fields up to 0.2 T since March. Experiments to date have concentrated on magnetic configuration measurements and plasma formation using ion cyclotron range of frequencies (ICRF) in repetitive pulsed modes.

Field Structure

The electron beam mapping method employs a movable target consisting of 21 phosphor-coated wires to combine the best features of the fluorescent rod technique [1] and the coated mesh method [2]. The magnetic field during measurements is about 0.15 T, and the base pressure is below 2×10^{-6} torr. In these conditions spatial resolution of the system is better than 2 mm (limited by the CCD camera), and the number of toroidal transits detected is very large (but less than indicated in Fig. 1 right) and depends on the rotational transform of the magnetic configuration.

Experimentally observed nested surfaces (Fig. 1, right) are in very good agreement with computed flux surfaces (Fig. 1, left) for all magnetic configurations that avoid $\iota = 1$ or $3/2$ resonances. A systematic error of about 6 to 8 mm in the absolute position of the magnetic axis could be explained by the uncertainty in the position of the fluorescent target and could account for the observed 8-mm shift of the measured surfaces with respect to the computed ones. This result is consistent with accurate coil manufacture and location and insignificant perturbations due to coil connections.

More detailed information on minor displacements of the coils is obtained from the comparison of measurements with calculations of the magnetic configurations that include $\iota = 1$ surfaces, which are most sensitive to low-order symmetry breaking errors. Preliminary results suggest small (< 3 mm) residual error in the central ring position, which is within the range of mechanical adjustment. An experimental study of the most unstable configurations is under way using both fluorescent target and stellarator diode [3] techniques to check the surfaces at different toroidal locations.

Plasma Production

To complement the normal pulsed high-field operation typical of fusion confinement devices, the H-1 heliac can also be operated in a quasi-continuous mode at low magnetic field and plasma density. This mode of operation is convenient for basic plasma physics experiments

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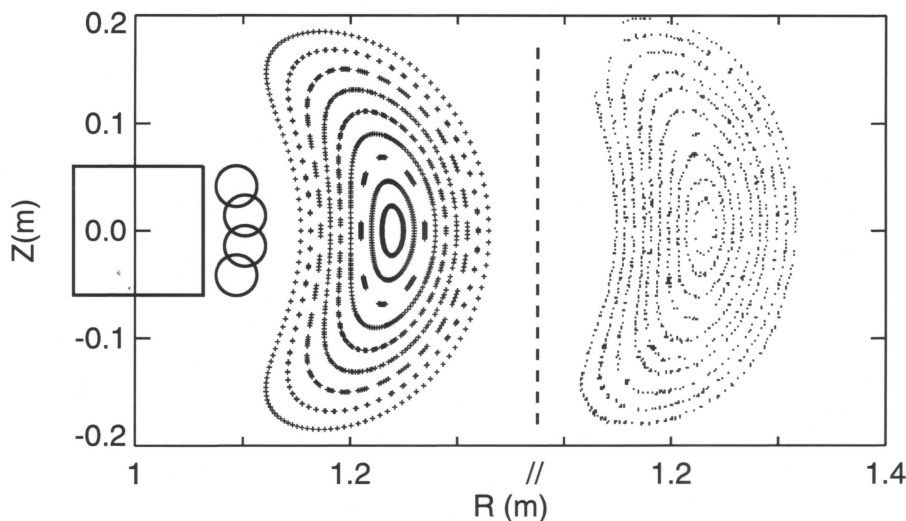


Fig. 1. A comparison of computed flux surfaces (left) and experimentally mapped flux surfaces (right) in H1.

or for operation by students. Plasma is produced in this mode by an unshielded helicon-type [4] figure-eight-shaped antenna conforming approximately with the shape of the outer flux surface. Initial Langmuir probe measurements of plasma density and temperature distribution show both peaked (Fig. 2) and hollow profiles. The highest densities obtained with 30 kW of rf power (1/8th of the total installed rf power) are $n_e \sim 10^{12} \text{ cm}^{-3}$ and are obtained for centrally peaked plasma. The highest densities have so far been obtained in argon, and are accompanied by the onset of oscillations in the low kilohertz range similar to those observed in SHEILA [5] and identified as drift waves. In this regime, the plasma density is observed to jump by factors of up to 2 as critical values of either filling pressure or power are

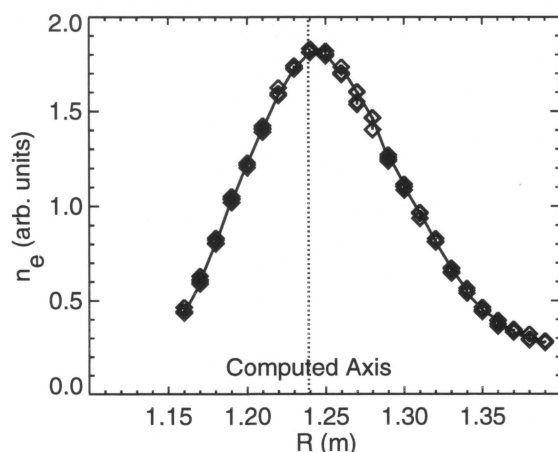


Fig. 2. Density profile in H1 in a dc discharge using 4-MHz microwave heating in argon (shots 1503–1598).

approached. Both positive and negative floating potentials (-200 V to 150 V) are observed, depending on conditions.

At present plasma is produced in a steady magnetic field of 0.03 to 0.15 T either continuously for a few seconds or pulsed at low-duty cycle (40 ms every 2 s) for several hours, restricted by heating of the antenna, protective limiters, and probes. Operation at such low magnetic field allows moderate values of beta to be obtained, approaching 0.1% even with the limited rf power used so far. While the low plasma densities are sufficient for many basic plasma physics experiments, higher densities are expected at higher magnetic fields as more rf power becomes available, with significantly higher densities expected in the pulsed 1-T mode to be tested next year.

REFERENCES

- [1] R. Jaenicke et al., Nucl. Fusion **33** (1993), 687.
- [2] R. J. Colchin et al., Rev. Sci. Instrum. **60** (1989), 2681.
- [3] G. G. Lesnyakov et al., Nucl. Fusion **32** (1992), 2157.
- [4] R. W. Boswell, Phys. Lett. **33A** (1970), 457.
- [5] X. H. Shi, B. D. Blackwell and S. M. Hamberger, Plasma Physics and Controlled Fusion **31**, No. 13 (1989), 2011.

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Boronization in Heliotron E

In Heliotron E, boronization has been successfully applied since July. Helium and $B_{10}H_{14}$ gases were introduced into the chamber through three inlet valves. $B_{10}H_{14}$ was vaporized in an oven heated at 50°C . The coating of boron on the chamber wall was made by a 2.45-GHz ECH discharge at $B = 0.045$ T without using any electrodes; this is unlike the usual dc glow discharges. The electron temperature and density were about 10 eV and 10^{10} cm^{-3} , respectively. Eleven hours of coating discharge deposited a layer of boron about 100 to 200 nm in thickness, which was measured by a surface probe placed at the wall position outside the divertor traces. For this coating, 10 g of $B_{10}H_{14}$ was used. A preliminary analysis showed that the deposited boron layer was similar to that produced by dc glow discharges.

After the boronization, a drastic decrease of light impurities (carbon, nitrogen, and oxygen) was observed in low-field ($B = 0.62$ T), neutral beam-heated plasmas initiated by the 35-GHz gyrotron from ORNL. The reproducibility of plasmas was also greatly improved. The stored energy increased to about 5 kJ. The average electron density and central temperature were $5 \times 10^{13} \text{ cm}^{-3}$ and 250 eV, respectively. The favorable effects of the boronization remained for more than 300 shots of typical Heliotron E neutral beam and ECH-heated plasmas. However metallic impurities (iron, chromium, and titanium) did not decrease. The behavior of the metallic impurity is an important subject. Higher-density plasmas are expected in the next experimental series utilizing heavy boronization.

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Temperature Fluctuations in the W7-AS Stellarator

In magnetically confined fusion relevant plasmas the experimentally observed electron heat transport is often found to be higher than the neoclassically expected one by more than an order of magnitude near the edge. Fluctuations of the plasma parameters electron density n_e , temperature T_e , and magnetic and electric fields B and E with proper phase relationships might be responsible for a certain amount of the observed increased flux.

While fluctuations of n_e and E are reported from both the plasma edge and the core [1] and probe measurement techniques for T_e fluctuations at the plasma edge are in progress, nothing is known about the existence of temperature fluctuations in the plasma core. If temperature fluctuations in the core appear in a similar parameter range as the fluctuations of the other parameters, then turbulent spectra up to several hundred kilohertz and spatial correlation lengths of about 1 cm are expected. A relative fluctuation level as low as a few tenths of a percent could be sufficient to explain a significant amount of the anomalous transport.

Standard electron cyclotron emission (ECE) temperature diagnostics provide the temporal and spatial resolution (10^{-6} s and 1 cm in both poloidal and radial directions), but the sensitivity to small-scale fluctuations is limited by natural fluctuations of the ECE due to the thermal nature of this radiation. If the radiation is observed with a heterodyne radiometer with predetection IF-bandwidth δf_{if} , which determines the spatial resolution, and postdetection video bandwidth δf_v , which determines the temporal resolution, the observed relative fluctuation level of the output signal is determined by $(2 \delta f_v / \delta f_{if})^{1/2}$.

Inserting the values to fulfill the demands on spatial and temporal resolution $\delta f_v = 1$ MHz and $\delta f_{if} = 500$ MHz, the sensitivity for temperature fluctuations is restricted to values above 6%. Smaller temperature fluctuations are buried completely under the thermal noise. To overcome the sensitivity barrier, correlation techniques must be applied. Various techniques can be used. We apply the most general arrangement, the intensity interferometer [2, 3]. Two equal but independent ECE multichannel radiometers viewing the same emitting volume along two crossed lines of sight are used (see Fig. 3). In this arrangement the intensity fluctuations of thermal radiation are correlated if the angle between two crossed lines of sight is smaller than a limiting value, depending on the spatial coherence properties of thermal radiation. If the angle is greater than this value, the thermal fluctuation

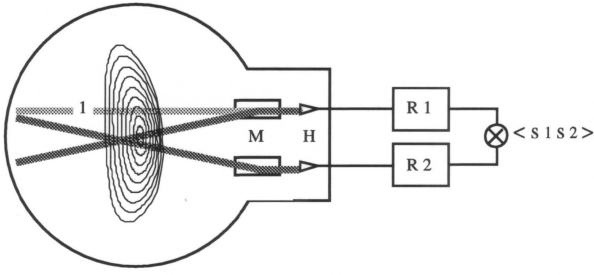


Fig. 3. Experimental arrangement for the ECE correlation experiment. Two identical radiometers, R1 and R2, are viewing the same emission volume in the equatorial plane of W7-AS along crossed lines of sight via adjustable mirrors M. Thermal fluctuations are uncorrelated above an angle of a few degrees, while the electron temperature fluctuations remain correlated. The latter are determined from the crosscorrelation $\langle s_1 s_2 \rangle$ of the two signals.

tuations are uncorrelated. The decorrelation angle is of the order of a few degrees. The temperature fluctuations seen by each of the radiometers remain correlated, however, and can be detected by correlation techniques. The whole experiment has been tested in the laboratory using a specially developed quasi-thermal microwave radiation source before being operated at the W7-AS stellarator [3].

First experiments on W7-AS have been conducted using purely ECRH heated plasmas at $B = 2.5$ T characterized by broad, flat density profiles with a central density of $5 \times 10^{19} \text{ m}^{-3}$ and peaked temperature profiles with a central temperature of about 1.5 keV [4]. The four channels of each radiometer are located in the gradient region at the high field side of the profile, while ECE observation is from the low field side to minimize interference with suprathermal emission. Discharges with stationary phases of at least 0.5 s are necessary to do the cross-correlation analysis with sufficient accuracy.

Fluctuations have been found in the frequency range up to 150 kHz. The relative level depends on the radial position. In the range $0.5 < r_{\text{eff}}/a < 0.75$, accessible in this experiment, the fluctuation level is of the order of 0.5%, as seen in the upper curve of Fig. 2. A main problem of this kind of measurement is the finite optical depth τ of the emitting volume. Only in the limiting case of high

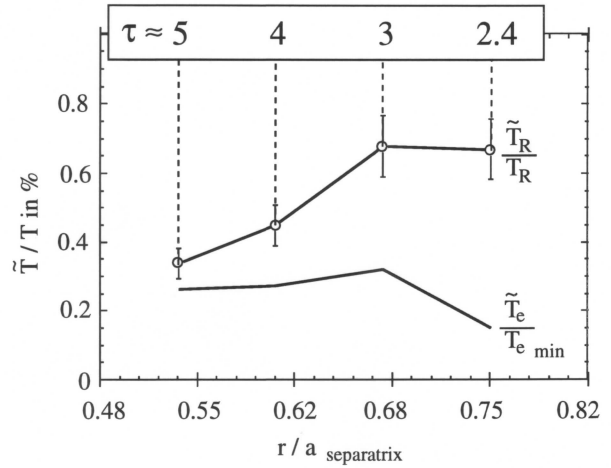


Fig. 4. Measured fluctuation levels at W7-AS at $t_{\text{edge}} = 0.53$, ECRH heated plasmas at $B = 2.5$ T, e.g., discharge 23440. Due to the finite optical depth, density fluctuations increase the fluctuations of the radiation temperature T_R (upper curve). The measured values can be corrected to give the electron temperature fluctuations when assuming a fixed value of density fluctuations and the local value of the optical depth (τ). The corrected values (lower curve) give a minimum value of the electron temperature fluctuations.

optical depth, the radiation temperature T_R measured by the ECE diagnostics approaches the electron temperature T_e according to the simple relation $T_R = T_e [1 - \exp(-\tau)]$.

The optical depth is proportional to the product $n_e T_e$; therefore, density fluctuations might increase the measured fluctuation level of the radiation temperature via a modulation of the optical depth. Information on density fluctuations is available from reflectometry for the shots discussed. Because of the flat density profiles, reflectometry measurements are only possible outside $r_{\text{eff}} = 12$ cm. Here $\tilde{n}_e/n_e = 2\%$ (increasing to 10 to 15% at the very edge of the plasma) is measured. Assuming this value as an upper limit throughout the radial range accessible with the intensity interferometer, the measured fluctuation levels of the radiation temperature must be corrected, resulting in clearly lower electron temperature fluctuation values, assuming that temperature and density fluctuations are in phase. The resulting minimum level of T_e fluctuations is shown in the lower curve of Fig. 4.

To estimate the transport relevance of the measured temperature fluctuations, a number of assumptions have to be made: A phase relation for maximum transport ($\pi/2$) has been assumed between the fluctuating quantities $\tilde{T}_e$ and $\tilde{E}$. The E -field fluctuations are replaced by fluctua-

tions of the potential assuming $\tilde{E} = k_{\perp} \tilde{U}$ with the fluctuation wavevector perpendicular to the B -field at a value $k_{\perp} = 2 \text{ cm}^{-1}$. The potential fluctuation level, $e\tilde{U}/kT_e$, is assumed to be 2%. To characterize the fluctuation-driven heat flux dQ (as given in [1]), an equivalent electron heat diffusivity χ_e can be estimated as $\chi_e = dQ / n_e \nabla T_e$, resulting in a value of about $0.3 \text{ m}^2/\text{s}$ as an average value in the radial range considered. A typical experimental value of χ_e for the discharges discussed is $1 \text{ m}^2/\text{s}$, as obtained by heat wave experiments or power balance analysis. The comparison of these estimations shows that the measured temperature fluctuations, under the assumptions made, can be transport relevant.

Summarizing: Fluctuations of the electron temperature have been seen in W7-AS at 2.5 T in ECRH plasmas. The most general method to decorrelate the thermal noise level in ECE measurements has been applied for the first time. It seems that T_e fluctuations exist with a relative level of 0.3% around $r/a = 0.5$. The turbulent spectrum extends to about 150 kHz. Assuming optimal phase relation between $\tilde{T}_e$ and $\tilde{E}$, the measured fluctuation level can be transport relevant. A number of error sources, that is, crosstalk in the radiometers, beam refraction, influence of the heating source (ECRH), suprathermal emission, B -field fluctuations, etc., are found to be only of minor significance.

REFERENCES

- [1] P. C. Liewer et al., *Nucl. Fusion* **25** (1985), 543.
- [2] S. Sattler and H. J. Hartfuss, "Evidence for Temperature Fluctuations in the W7-AS Stellarator," *Proc. of the Workshop on Local Transport Studies in Fusion Plasmas, Varenna, Italy, 1993*.
- [3] S. Sattler and H. J. Hartfuss, *Plasma Phys. Contr. Fus.* **35** (1993), 1285.
- [4] S. Sattler and H. J. Hartfuss, *Phys. Rev. Lett.*, submitted for publication, September 1993.

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Transition of the Radial Electric Field due to Electron Cyclotron Heating in CHS

There are generally two stable states in the stellarator plasmas, the ion and the electron roots. In a stellarator reactor, it is an important scenario to attain the electron root with higher energy confinement time through heating electrons in the startup phase. In the Heliotron-E device, the radial electric field at $r \sim 0.7\text{--}0.9a$ is found to be positive (the electron root) for the low-density plasma ($n_e < 1 \times 10^{13} \text{ cm}^{-3}$) and negative (the ion root) for the high-density plasma ($n_e > 2 \times 10^{13} \text{ cm}^{-3}$). In the Wendelstein VII-A stellarator, the observed electric field in the plasma with ECH (at $n_e \sim 5 \times 10^{13} \text{ cm}^{-3}$) is consistent with the theoretical prediction. In ATF, the positive electric field is observed for a low-density plasma with ECH at $n_e \sim 5 \times 10^{12} \text{ cm}^{-3}$. In the Compact Helical System (CHS), the observed radial electric field is negative in the typical neutral beam (NB) heated plasmas. The electric field becomes more negative near the plasma edge for higher electron densities.

It is generally observed that ECH has an associated effect of density pump-out both in tokamaks and stellarators. In CHS, it is observed that the particle confinement becomes worse in the plasma with second harmonic ECH if the resonance is at the low-field side than at the high field side. One of the candidates for the mechanism of density pump-out is the outward flux due to poor confinement of the electrons that are perpendicularly accelerated by ECH.

The neutral beam in CHS is tangentially injected to sustain the plasma and to utilize a charge exchange spectroscopy (CXs) diagnostic. Poloidal rotation and ion temperature are measured with CXs. The radial electric field is evaluated from the observed poloidal rotation and the ion pressure gradient using a radial momentum balance equation for fully ionized carbon. In the momentum balance equation, a toroidal rotation has a little contribution to the radial electric field because the toroidal rotation damps due to a viscous damping force caused by the helical ripple. The second harmonic ECH is superimposed on an NBI-heated target plasma to enhance the electron particle flux. The density in the target plasma is controlled to stay below the ECH cut-off density. The focus point of ECH is located at $\rho = 0.5$ in the low field side, where ρ is a normalized radius. The line-averaged electron density decreases with the superposition of ECH. The enhanced electron flux is controlled by changing the ECH injection power ($P_{\text{ECH}} = 85, 105, \text{ and } 140 \text{ kW}$). Figure 5 shows the radial profile of poloi-

dal rotation velocity $v_\theta(\rho)$ measured with CXS at 15 ms after the ECH is turned on in these power scan experiments. The experiments for the plasmas with $P_{ECH} = 85, 105$, and 140 kW were carried out for a target plasma with a fixed density. As a reference plasma, we choose the plasma such that the line-averaged density is adjusted to be as low as those for the plasma with $P_{ECH} = 140$ kW to eliminate the density dependence of the radial electric field. The plasmas with $P_{ECH} = 105$ and 140 kW rotate in the ion-diamagnetic direction which means that the electric field is positive, while only a small rotation velocity is observed for the target plasma, the reference plasma, and the one with $P_{ECH} = 85$ kW. Figure 6 shows the observed radial electric field profiles for the reference plasma and that with $P_{ECH} = 140$ kW. The large positive electric field is observed near the plasma edge for the plasma with $P_{ECH} = 140$ kW

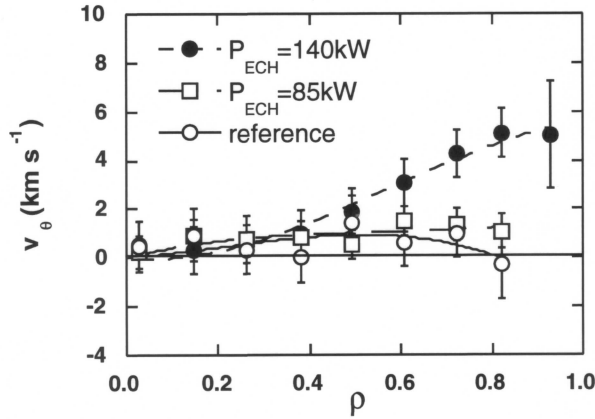


Fig. 5. Radial profiles of poloidal rotation velocity.

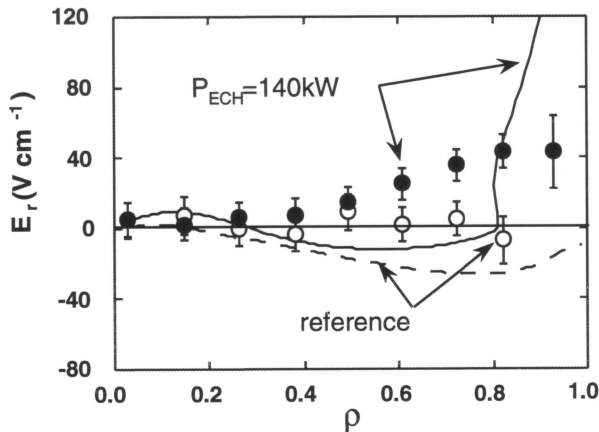


Fig. 6. Radial electric field profiles. Open and closed circles show observed radial electric fields. Broken and solid curves show calculated ones.

(~ 44 V/cm at $\rho = 0.82$). Theoretically, the radial electric field is evaluated from an ambipolarity equation, $\Gamma_e^{NC} + \Gamma_{ECH} = \Gamma_i^{NC}$. Here, we assume that ECH enhances only electron particle flux and not the ion particle flux. The neoclassical fluxes Γ_i^{NC} and Γ_e^{NC} are estimated from Kovrizhnykh's formula of neoclassical transport that covers the whole collisionality regime by using the fitting curves for $n_e(\rho)$, $T_e(\rho)$, and $T_i(\rho)$. The profile of the enhanced particle flux $\Gamma_{ECH}(\rho)$ is deduced from the continuity equation using the density decay after the ECH is turned on. Although the enhanced flux Γ_{ECH} becomes large when the plasma is heated with the higher P_{ECH} , it does not change much even though the higher P_{ECH} is injected after the transition of the radial electric field occurs.

The profile of the calculated electric field shown in Fig. 6 is not in agreement with that of the observed electric field for the plasma with $P_{ECH} = 140$ kW. The calculated electric field is more positive at the plasma edge ($\rho > 0.8$) and is more negative at the core region than the observed electric field. The ambipolarity equation may contain multiple solutions and can cause discontinuities in the electric field profile because it must be satisfied on each magnetic surface. If the transition of the radial electric field occurs in the outer region, the electric field diffuses into the inner region under the influence of the perpendicular viscosity. To explain the transition phenomena qualitatively, we restrict our results to the electric field at $\rho = 0.82$. It is theoretically predicted that the electric field at $\rho = 0.82$ for the plasma with $P_{ECH} = 85$ kW is still negative. If the additional electron loss flux Γ_{ECH} is small, the ambipolarity constraint does not affect the radial electric field very much. However, if Γ_{ECH} is increased and becomes large enough to have multiple solutions, a transition in the electric field occurs. The observed transition is qualitatively explained by the theoretical model based on the ambipolarity equation.

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Meetings

Presentations at the Meeting of the Division of Plasma Physics of the Americal Physical Society

At the Thirty-Fifth Annual Meeting of the DPP-APS in St. Louis, Missouri held November 1-5, 1993, Rex Gandy of Auburn University presented an invited paper entitled *A Study of Magnetic Islands as Hamiltonian Systems on the Compact Auburn Torsatron*.

The following papers were presented as posters:

ATF Status and Plans, ATF Team

Offset-Linear Energy Confinement Scaling in the ATF Torsatron, R. A. Dory, M. Murakami, and the ATF Team

Drift-Wave-Like Density Fluctuations in the ATF Torsatron, J. H. Harris, M. G. Shats, K. M. Likin et al.

Fast Ion Behavior During Neutral Beam Injection in ATF, R. J. Colchin, M. R. Wade, C. E. Thomas et al.

Upgrades to the Heavy ion Beam Probe on ATF, J. J. Zielinski, K. A. Connor

Application of the PIES MHD Equilibrium Code to the ATF Stellarator, J. L. Johnson, D. A. Monticello, and A. H. Reiman

Experimental Evidence of Three-Wave Coupling on Plasma Turbulence, C. Hidalgo, B. Braças, E. Sanchez et al.

Magnetic Surface Mapping in the TJ-I U Torsatron, E. Ascasibar, C. Alejandre, L. Almoguera et al.

Experimental Study of Magnetic Fluctuations in a Low-aspect Ratio Heliotron CHS, S. Sakakibara, H. Yamada, O. Motojima et al.

High Energy Neutral Particle Measurements in a Low-Aspect Ratio Heliotron/Torsatron Device, T. Ozaki, S. Okamura, S. Morita et al.

An Experimental Study of Magnetic Islands as Hamiltonian Systems, G. J. Hartwell, R. F. Gandy, J. D. Hanson et al.

Experimental Study of Chaotic Behavior of Magnetic Field Lines on the Compact Auburn Torsatron, H. Lin, R. F. Gandy, G. J. Hartwell et al.

Electric Potential Measurements in Low Density Plasmas in the Compact Auburn Torsatron, Q. Zhang, S. Knowlton, R. Gandy et al.

Energetic Ion Trajectories in the Vacuum Magnetic Field of the Compact Auburn Torsatron, S. Knowlton, G. Sasser, R. Gandy et al.

HSX: A Helically-Symmetric Toroidal Experiment, D. T. Anderson, F.S. B. Anderson, M. Coronado et al.

HSX: Engineering Design and Expected Plasma Parameters, F. S. B. Anderson, D. T. Anderson, P. G. Matthews et al.

Spectral Analysis of Fluctuations in the Interchangeable Module Stellarator, P.G. Matthews, D. T. Anderson, F. S. B. Anderson et al.

The Effects of Viscous Damping and Ion-Neutral Collisions on Flows in IMS, B. J. Peterson, D. T. Anderson, F. S. B. Anderson et al.

Radial Electric Conductivity and Plasma Flows in Tokamaks and Stellarators, J. N. Talmadge, M. Coronado, B. J. Peterson et al.

Assessment of Stellarators as Reactors, J. F. Lyon and K. Gulec

Modular Stellarator Configuration Studies, J. A. Rome, R. H. Fowler, J. F. Lyon et al.

A Stellarator Configuration for Reactor Studies, P. Garabedian

Stability of Bootstrap Current Driven Magnetic Islands in Stellarator Configurations, C. C. Hegna and J. D. Callen

Ion Cyclotron Heating Antenna Designs for the Advanced Toroidal Facility, D. A. Rasmussen, S. C. Aceto, D. B. Batchelor et al.



People

New APS Fellows

At the DPP-APS meeting in St. Louis, Günter Grieger (IPP, Garching, Germany) and Alan Reiman (PPPL, Princeton, USA) were made Fellows of the American Physical Society.