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CONFINEMENT DYNAMICS AND BOUNDARY CONDITION STUDIES IN THE REVERSED FIELD PINCH[†]

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CONFINEMENT DYNAMICS AND BOUNDARY CONDITION STUDIES IN THE REVERSED FIELD PINCH

The study of confinement dynamics, including investigation of the boundary conditions required for plasma sustainment, are central to the development of the Reversed Field Pinch (RFP) concept. Recently, several insights into confinement have emerged from a detailed investigation of RFP electron and ion dynamics. These insights derive from the recognition that both magnetohydrodynamic (MHD) and electron kinetic effects play an important and coupled role in RFP stability, sustainment, and confinement. In this paper, we summarize the results of confinement studies on the ZT-40M experiment, and boundary condition studies on the Wisconsin non-circular RFP experiment. A brief description of the newly commissioned Madison Symmetric Torus (MST) is also presented.

1. CONFINEMENT STUDIES ON ZT-40M

1.1. Ion Dynamics

In present ohmically driven RFPs, the electron-ion equilibration time is generally greater than the ion particle confinement time, and hence the ions are not expected to strongly heat through classical ohmic processes. For example, one dimensional transport simulations, where ions are heated only by equipartition with 150 eV electrons, predict an ion temperature of $\approx$ 25 eV during a sustained 120 kA ZT-40M discharge. To the contrary, observations from Doppler broadening[1], time-of-flight neutral particle spectroscopy[2], electrostatic neutral particle analysis[3][1], neutron emission rates[4], and ion implantation edge probe analysis[5] all indicate that the ion temperature is comparable to the electron temperature. Furthermore, for some discharge conditions, the ions can attain temperatures of up to 1 keV, exceeding that of the electrons by a factor of four[4].

A non-classical or direct ion heating mechanism is therefore indicated, and it is hypothesized that this heating results from fluctuational activity in the discharge. Within the context of MHD, the fraction of the total input power absorbed by fluctuations is estimated to be $P_F = 1 - \eta^K/\eta^W$, where η^K and η^W are the globally averaged plasma resistivities computed from magnetic helicity balance and energy balance, respectively[6]. (No explicit measurement of the spatial or power spectral properties of the fluctuations are necessary for this estimate, since it derives from the spatial dependence of $\mathbf{J} \cdot \mathbf{B}/B^2$ in the discharge.) The power absorbed by fluctuations can directly couple to plasma motion, for example, through tearing and reconnection processes [7] with subsequent ion thermalization. Although this coupling process is expected to be efficient, the precise mechanism is uncertain and as such, P_F provides an upper estimate of the power available for direct ion heating.

Evidence of fluctuation-driven ion heating can be evoked from the operational relation between T_i and P_F as follows. For nominal discharges, where $T_i \sim T_e$, P_F is 0.2 to 0.3. That is, approximately one quarter of the input power directly couples to the ions in order to maintain their temperature parity with

[1] In collaboration with P. G. Carolan and C. A. Bunting, Culham Laboratory, Euratom/UKAEA Fusion Association

the electrons. The remaining power goes into the ohmic electron channel. This proves to be the approximate ion power input required to balance ion losses as independently inferred by ion particle confinement time measurements, assuming weak ion-electron collisional coupling. Furthermore, 1-D transport simulations of ZT-40M discharges concur that for $T_i \simeq T_e$, 25% to 30% of the input power must directly heat the ions in order to balance losses dominated by ion recycling.

Under discharge conditions that tend to enhance fluctuational activity, it is possible to increase P_F above the level characteristic of nominal operation. For these discharges, one might expect that because the ions are relatively decoupled from the electrons, additional ion power absorption goes almost exclusively into ion heating. Furthermore, if the global ion confinement is not adversely affected, the increased ion power absorption should be directly manifest as an increase in ion temperature. This expectation is confirmed experimentally as shown in Figure 1, where the increase in P_F is strongly correlated with measured increases in ion temperature (by Doppler broadening) and loop voltage. Concurrently, the electron temperature (from Thomson scattering), total radiated power (from bolometry), and calculated plasma energy confinement time are observed to be relatively insensitive to the increased fluctuational power absorption.

A global picture of ion dynamics thus emerges where fluctuation-driven ion heating dominates the relatively weak ion-electron collisional coupling. The fluctuations can result from MHD driven dynamo activity, as well as turbulence caused by other current or pressure driven instabilities. The importance of fluctuations in RFP ion dynamics implies a coupling to the electron dynamics as discussed below.

1.2. Electron Dynamics and Transport - Experimental

It has been widely observed that a large fraction of power transport in the RFP edge plasma flows asymmetrically[8-12]. The most striking evidence of this asymmetry is in the damage patterns on limiters and walls, which indicate strong preferential heating from the electron drift direction[2]. Recently, direct edge plasma measurements have ascribed this asymmetry to parallel thermal transport by energetic (long mean free path) electrons [9,11,13].

In ZT-40M, quantitative measurements of the edge plasma power flux were made using a calorimeter-Langmuir probe[11]. These probe measurements show that approximately four times more power flows anti-parallel to **B** than parallel to **B**, and that the power flux along **B** is substantial (≈ 25 kW/cm^2 at 1 cm interior to the vacuum vessel wall). Electrically biasing the probe also indicates that the power flux is primarily carried by electrons with an energy greatly exceeding the edge plasma electron temperature.

Further quantification of the edge electron energy spectrum was made using a specially designed electron energy analyzer[9,11]. The analyzer measures an energetic electron tail that grows in intensity during the first 4 milliseconds of the discharge, and then saturates. The energetic electrons move along **B** with a toroidal sense opposed to the applied electric field force at the edge (exterior to the reversal surface). Retarding potential measurements show that the energetic tail is well fit by a half Maxwellian, in that the tail electrons have a thermal en

[2]Along the local magnetic field **B**, and in the same sense relative to **B** as in the core of the discharge interior to the reversal surface.

ergy distribution, but their flow is unidirectional along **B**. The time dependence of the density and temperature of the tail distribution is shown in figure 2, for a 110 kA discharge. For reference, the central electron temperature/density and background edge electron temperature/density are 200 eV/2.4 $\cdot 10^{19}$ m^{-3} and 20 eV/8 $\cdot 10^{18}$ m^{-3}, respectively. At 5 milliseconds, the energetic electron temperature is in the 300 to 400 eV range, with a density of a few per cent of the background.

Because of geometrical effects inherent in the analyzer design, an accurate determination of the total energetic electron density is not possible from the analyzer data alone. That is, the analyzer can only accept electrons with a perpendicular energy of less than 80 eV. However, if the energetic electron temperature perpendicular to **B** is comparable to the parallel temperature, the power flux carried by the energetic electron distribution can totally account for the asymmetric power flux measured by the calorimeter-Langmuir probe. The energetic electrons also carry a net current density that is comparable to the mean current density in the edge plasma as independently measured by internal magnetic probes[14]. Even at a perpendicular temperature of 20 eV, the energetic electrons can still carry 30 % of the mean plasma current in the edge region.

Supporting evidence of energetic electron transport has also come from several additional measurements. During pellet injection, the pellets undergo strong deflections throughout the discharge volume. The deflections have been successfully modeled by asymmetric pellet ablation that results from the electron power flux along B[15]. An electron target experiment, where a copper target was inserted in the edge plasma and viewed with surface barrier diodes, further confirmed the directional asymmetry and high energy characteristics of the incident electron flux[16]. Finally, a fast infrared camera was used to monitor the temporal temperature distribution on the face of a limiter during plasma insertion. The limiter's thermal distribution showed strong preferential heating on the side intercepting the energetic electron flux[16].

The edge plasma data supports three major conclusions. First, the power flux asymmetry in the edge plasma is principally due to energetic, long mean free path electrons that flow along B. That is, collisionless, parallel transport largely determines electron confinement in the RFP edge plasma. Second, there is good reason to hypothesize, based on pellet injection behavior and supporting modeling, that collisionless, parallel transport significantly contributes in the pinch interior as well. Finally, the energetic electrons, as measured by the analyzer, carry a substantial fraction of the mean edge plasma current.

1.3. Electron Dynamics - Interpretations

Interpreting the experimental data and associated conclusions, with a view to understanding RFP electron confinement, requires adopting a model of electron transport. One useful model[17,13], which is consistent with the collisionless, parallel transport observations described above, is based on the electron thermal conduction theory of Rechester and Rosenbluth [18]. In this model, electrons are accelerated by the applied parallel electric field ($E_\parallel$ $\mathbf{E} \cdot \mathbf{B}/B$) in the core region of the discharge where $E_\parallel$ is maximized. A low level of magnetic field stochasticity, driven by magnetic field fluctuations, then allows the energetic electrons to transport across the mean magnetic fields.

Within the context of this model, the underlying physical processes that drive the electron transport become qualitatively transparent. Electrons accelerated in the core will retain their directed velocity over a radial extent $\Delta r \approx [2\lambda D_F v_\parallel / v]^{1/2}$, where D_F is the magnetic diffusivity, λ is the electron mean-free path for cumulative 90° scattering, v is the electron speed, and electron guiding center orbits closely follow field lines keeping $v_\parallel \equiv \mathbf{v} \cdot \mathbf{B}/B$ approximately constant. The $\lambda \propto v^4$ dependence enables faster electrons to traverse most of the plasma radius without losing their velocity ($v_\parallel$) attained in the core. For example, it is estimated that in the core of ZT-40M, Δr is approximately equal to the minor radius for electrons travelling at greater than twice the thermal speed ($v_\parallel \geq 2\sqrt{2kT_e/m_e}$)[17]. This provides a simple mechanism for the production of fast, directed electrons that reach the edge plasma[13]. It should be noted that other models based on MHD[19], tangled field lines[20,21], or plasma sheath effects[22] can also produce strong edge currents. These various models are distinguished by their respective electron acceleration processes. The kinetic electron model is emphasized here, because it is a strong candidate to produce the energetic (300-400 eV), directional, current carrying electrons observed in the cool (20 eV) edge plasma.

For collisionless, parallel transport, the particle diffusivity D, which is essentially equivalent to the electron thermal diffusivity (χ_e), is given by the simple relation $D = D_F \mid v_\parallel \mid$. The magnetic field line stochasticity, D_F, is directly related to the magnetic field fluctuations in the sense that $D_F \approx (\delta B/B)^2 L_c$, where δB is obtained from a sum over the fluctuation spectrum and L_c is the correlation length of the fluctuations along the unperturbed field direction[18,23].

Further quantification of electron transport, in the form of diffusion coefficients and a demonstrable scaling law, requires identifying the underlying mechanisms that drive the field stochasticity. For example, turbulence associated with electrostatic resistive g-modes, where $\delta B/B \propto S^{-1/2}$, results in an electron confinement condition in which $\chi_e \propto \eta\beta^2/a^2$, and the electron β is constant ($S \equiv \tau_{Resistive}/\tau_{Alfven}$ denotes the Lundquist number)[23]. As another example, turbulence associated with current-driven resistive tearing, where $\delta B/B \propto S^{-1/3}$, results in confinement where $\chi_e \propto (\cdot v_\parallel \cdot /a) S^{-2/3}$ and in which electron beta drops as a function of the confining field[24]. Thus, although there exists reasonable evidence supporting collisionless parallel transport, the underlying physics remains quantitatively uncertain and subject to further study. Nevertheless, it is important to note that collisionless, parallel transport and related scaling can satisfy reactor projections[25], provided D_F scales appropriately with S.

One further ramification of parallel thermal transport is in plasma-edge interactions. Perturbations in the edge confining field, by either field errors or insertion of material objects such as discrete limiters, can lead to large localized power depositions on material surfaces. The large power flux, in turn, can degrade global confinement by impurity contamination with increased radiation. The global confinement can be degraded by non-classical processes as well[19,13,22]. Within the context of the transport model described above, the absorption of electron momentum at the plasma edge leads to an enhanced loop voltage over classical resistivity[13]. The size of the non classical contribution is a function of the rate of edge electron momentum deposition, which in turn is a strong function of the product λD_F. Qualitatively, this suggests that RFP devices should be designed

with a rather smooth, axisymmetric first wall and minimal magnetic field errors.

The fact that energetic electrons carry a significant edge (and possibly core) current strongly implies that they play an important role in global RFP sustainment, and general MHD discharge stability. This, combined with the perspective that MHD "fluid" processes are essential in determining the character of electron transport, qualitatively implies a strong coupling between the electron dynamics and related ion dynamics described above. What is difficult to assess quantitatively, is the self-consistent combined role of electron kinetic and MHD process in global RFP confinement. This understanding is necessary in order to develop scaling projections for confinement in future RFP devices.

2. CONFINEMENT STUDIES AT WISCONSIN

2.1. Poloidal Divertor Studies

In order to investigate the dynamics of an RFP located far from a conducting wall, a four-node poloidal divertor configuration was studied on the Wisconsin non-circular RFP experiment. The plasma was localized far from the wall by the limiting action of a magnetic separatrix, formed by the combination of toroidal currents in the plasma and four divertor rings. The plasma dimensions were relatively large, with a 1.39 m major radius, 0.35 m average plasma minor radius, and 0.56 m average wall minor radius. A typical theoretical equilibrium flux plot is shown in Figure 3.

Using aided reversal, RFP plasmas were formed with currents of 135 kA, toroidal field reversals lasting $\sim$ 1 ms, line-averaged densities of $\sim$ 1 to $2{\cdot}10^{19}$ m^{-3} and central electron temperatures of $\sim$ 55 eV. However, a large stationary asymmetry in the magnetic field ($\delta B/B \sim 40\%$) developed at roughly the time of toroidal field reversal at the wall. This asymmetry had mainly an m=1, n=5 characteristic. In contrast, the early non-reversed portion of the divertor discharge, and large non-circular RFP discharges formed in the same device without divertor rings[26] were symmetric.

If the tenuous plasma region outside the separatrix is "vacuum-like", then it is plausible to expect that MHD stability results for a cylindrical plasma bounded by a vacuum region, with a distant conducting wall, are relevant to this configuration. Indeed, a plasma with a vacuum layer thickness of 60 % of the plasma radius (equivalent to the divertor configuration) might be linearly unstable to m=1, current driven modes[27]. Also, non-linear MHD numerical simulations of a cylindrical RFP with a distant conducting wall indicate the fluctuation dynamics are dominated by large-amplitude, internally resonant m=1 modes[28]. The failure of the poloidal divertor plasma to obtain a symmetric, RFP-like equilibrium may be due to excessively large MHD instabilities occurring late in the RFP setup phase that result from the lack of a nearby stabilizing conducting boundary.

2.2. The Madison Symmetric Torus

Future RFP confinement studies at Wisconsin will be performed on the new Madison Symmetric Torus (MST). MST is significantly larger than other existing RFP devices, with a major and minor radius of 1.5 m and 0.52 m, respectively (Figure 3). It also incorporates an unconventional design in that a single 5 cm thick aluminum torus serves as the vacuum vessel, the toroidal field winding, and the conducting shell, which facilitates disassembly and diagnostic access.

The design necessitates voltage gaps exposed to the plasma for both the toroidal and poloidal fields. These gaps are protected by special ceramic insulators which have proven reliable for up to at least 200 Volts. Field errors at the gaps are reduced by special flanges and precise placement of the poloidal field primary winding. (The poloidal field winding is tightly wound around the 2.0 Volt-second iron core.) A distributed winding is also used to reverse-bias the iron core which results in less than one gauss of error field in the plasma volume. The vessel is pumped by a manifold through an array of 193, 3.8 cm diameter holes in order to minimize field errors that would otherwise be produced by large pump ports. The magnetic islands produced by all the residual errors should be limited to less than one tenth of the minor radius, and distortions at the plasma surface to less than one centimeter.

The MST began operation in June of 1988, and to date has achieved RFP discharges up to 400 kA for 10 msec. Work is still under way in improving the base vacuum, wall cleanliness, pre-ionization and field error minimization. Expected MST performance ranges between 400 kA and 1 MA for up to 40 msec, depending on RFP confinement scaling. MST research will focus on investigating RFP boundary condition physics, with initial experiments planned to test the effect of plasma proximity to the wall using movable toroidal rail limiters.

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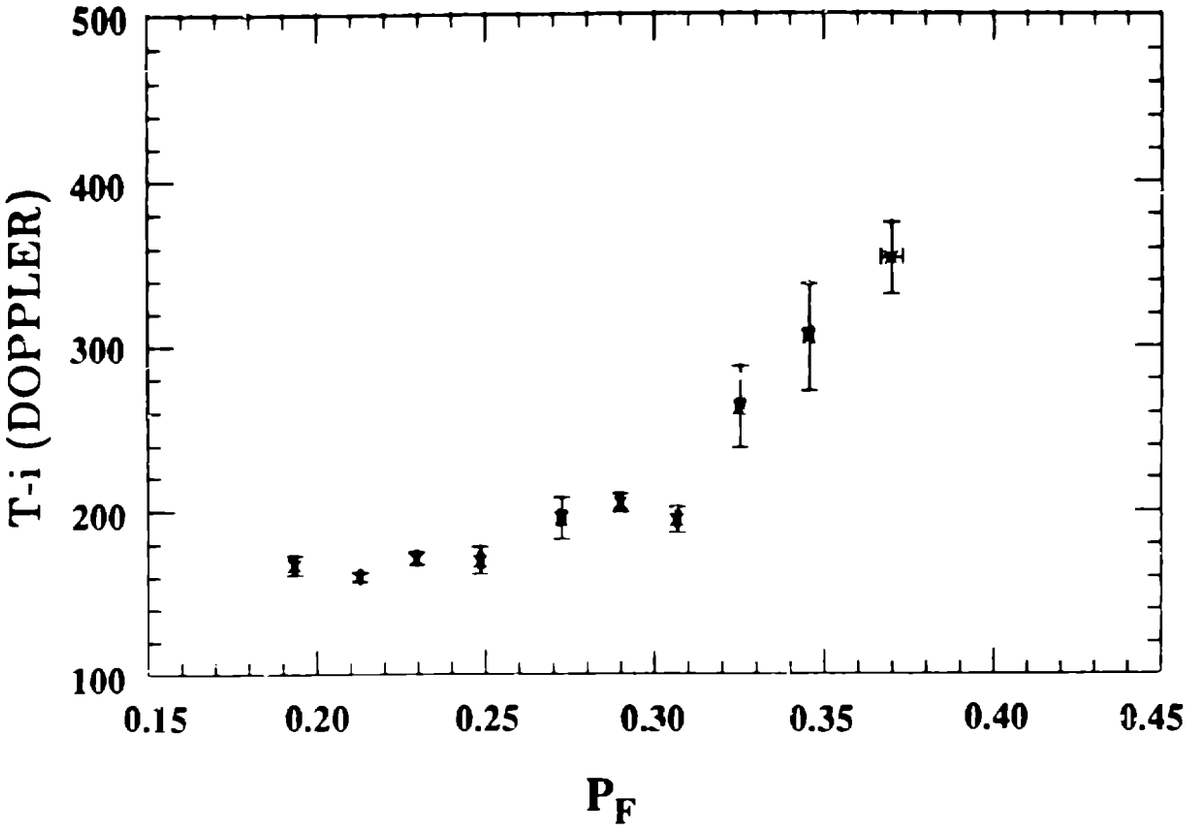
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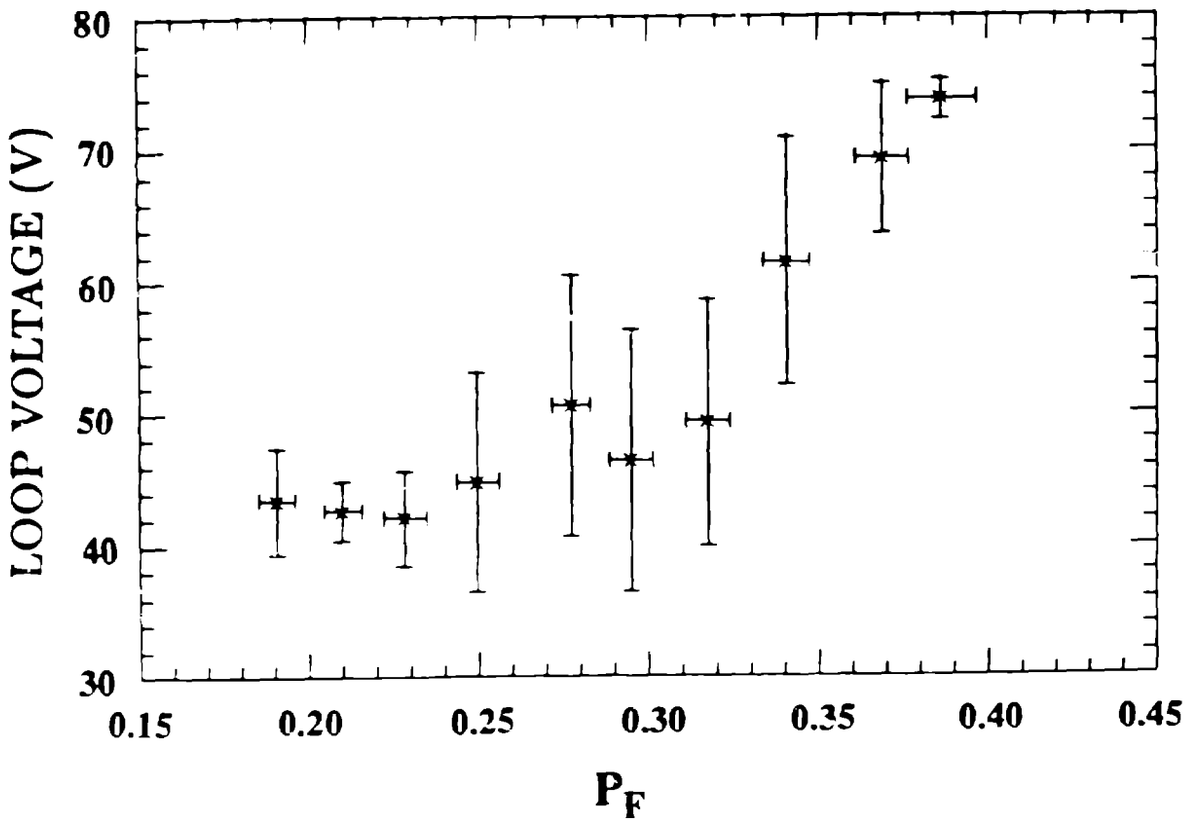
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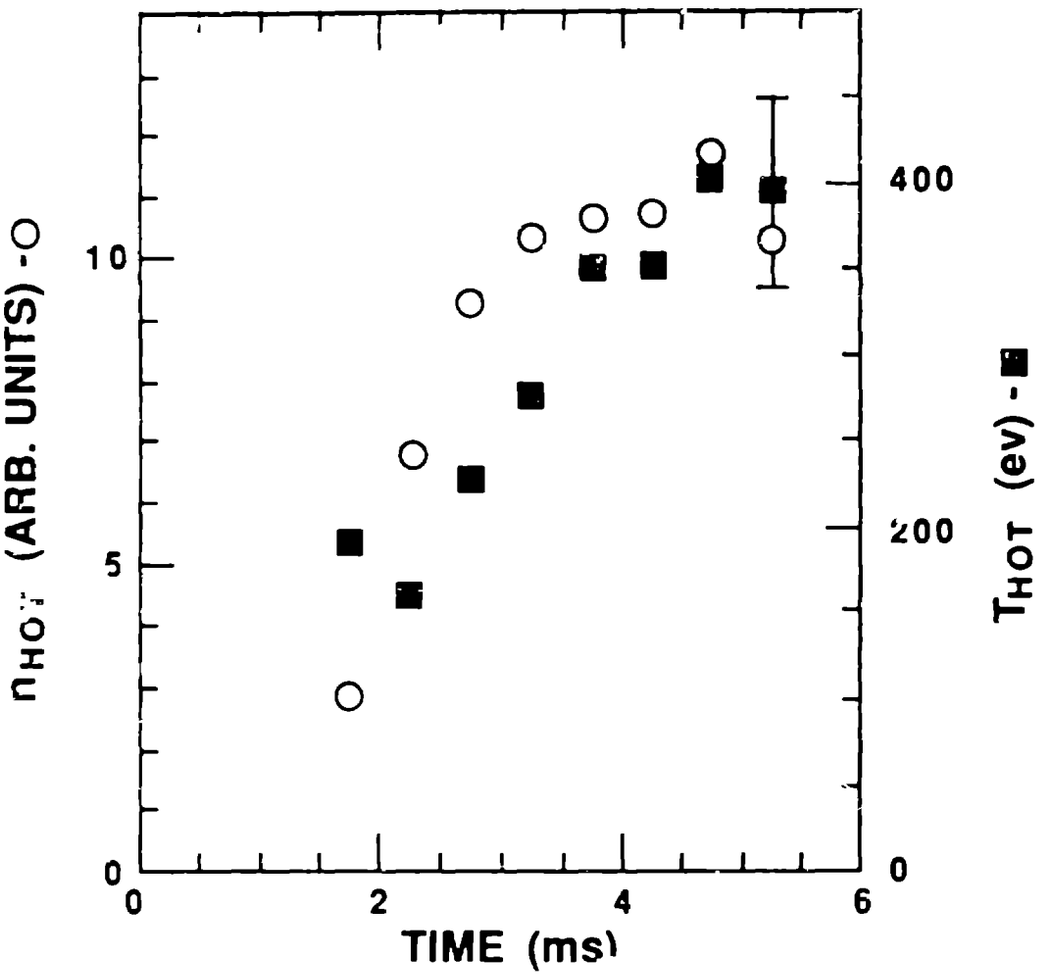
Fig. 1. Ion Temperature (T_i) and loop voltage vs. fluctuation-driven power absorbtion (P_F).

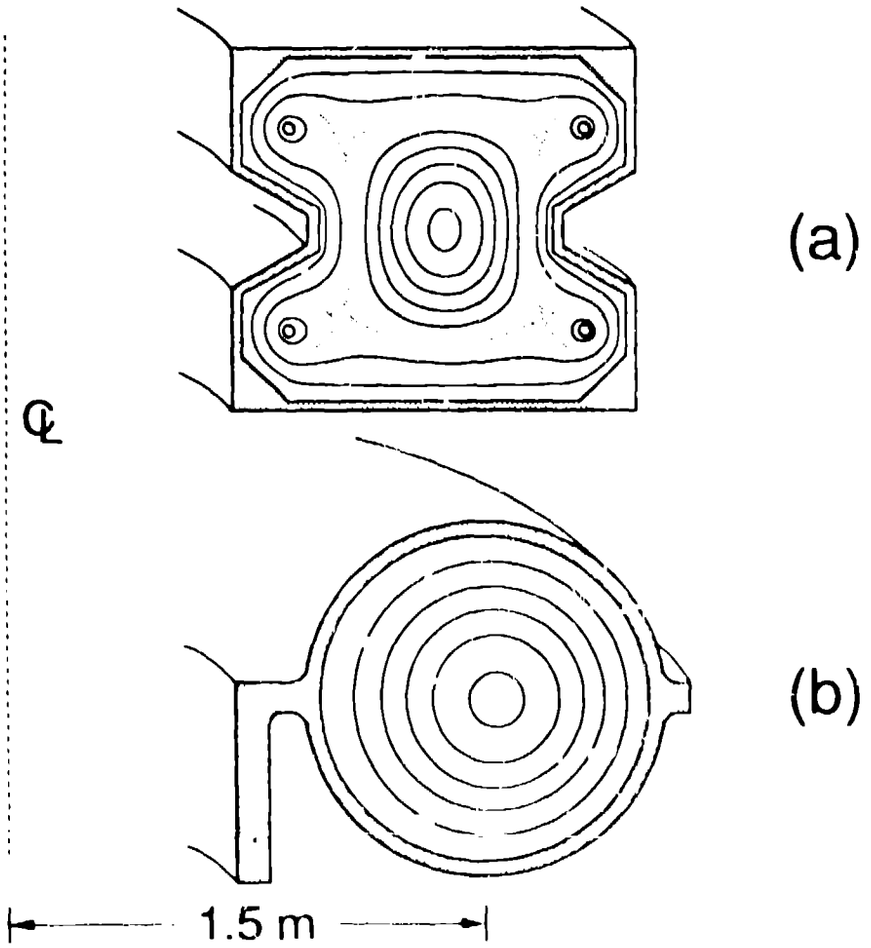
Fig. 2. Plot of n_{HOT} and T_{HOT} vs. time showing the tendency towards saturation after 4 ms. The error bar represents the random error contributions typical for both n_{HOT} and T_{HOT}.

Fig. 3. Equilibrium poloidal flux plots for (a) the four-node poloidal divertor RFP and (b) the Madison Symmetric Torus (MST).


500
400
300
200
100
T-i (DOPPLER)
0.15
0.20
0.25
0.30
0.35
0.40
0.45
P_F


LOOP VOLTAGE (V)
80
70
60
50
40
30
0.15
0.20
0.25
0.30
0.35
0.40
0.45
P_F


10
5
0
0
2
4
6
400
200
0
TIME (ms)
T_HOT (ev) - ■


(a)
℄
(b)
1.5 m