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Annual Technical Progress Report to
U.S. Department of Energy
for
Plasma Research in the Madison Symmetric Torus (MST)

November 1, 1990 - October 31, 1993

Grant #DE-FG02-85ER53198

from

S.C. Prager, Principal Investigator
Department of Physics, College of Letters and Science
University of Wisconsin
1150 University Avenue
Madison, Wisconsin 53706

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II.B. PHYSICS RESULTS FROM MST

Below we present physics results divided into the four categories introduced in Chapter I (confinement optimization, transport measurements, fluctuations and fluctuation-induced transport, and fluctuation suppression). For simplicity, we highlight a subset of original MST results which are presented as 13 specific conclusions (not listed in order of importance), each followed by a brief elaboration. Within each of the four categories we also present other progress.

Note: references preceded by "C" refer to the publication list in Section II.C.

Confinement Optimization

1. Effective solid target boronization has been developed.

Boronization of the vacuum vessel has been accomplished^{C23} through a technique much simpler than the conventional glow discharge method. A hot-pressed boron carbide rod is inserted into the edge of RFP plasmas. Ablation of the rod results in an amorphous coating of boron and carbon on the wall. The deposition has been measured with surface sample analysis. Hydrogen reflux and impurity contamination are greatly reduced. This technique is a simplification and improvement of that developed in the TdeV tokamak.²

2. Clean, sawtooth-free, locked-mode-free, better confined plasmas have been obtained.

The confinement time in MST plasmas, particularly at high current, has been limited in part by sawtooth oscillations and locked modes. Sawtooth

oscillations, with periods of 2-5 ms, have been present in nearly all MST plasmas. During a sawtooth crash the sudden equilibrium change enhances the plasma wall interaction which is deleterious to confinement. In addition, sawteeth can initiate a carefully documented sequence of events leading to a locked mode and confinement degradation.^{C13} The sawtooth crash flattens the current profile, which produces a sudden inward shift in major radius, which then generates an impulsive field error at the poloidal cut in the conducting vessel. Rotating tearing modes lock to the pulsed field error. Once the modes become stationary they grow in amplitude (believed to be a field error generated instability), degrade confinement, and lead to premature discharge termination.

Very recently, discharges have been produced which have periods up to 20 ms during which sawteeth and locked modes are absent. As a result the impurity generation diminishes and the toroidal loop voltage drops below 10 volts. The net result is that the energy confinement time increases by approximately 50%. The cause of the absence of sawteeth is not yet understood, but is believed to be related to decreased impurity content which is a result of boronization. This work is still in progress.

Other progress :

Pellet injection has been employed in MST to transiently increase the plasma density.³ We used the pellet injector from Alcator C, which had been modified for the ZT40-M device. The injector was altered substantially at Wisconsin for adaptation to MST. Pellet injection doubles the density of a target plasma, although the profile quickly relaxes to that achieved at high density in the absence of pellets. Hence, no net improvement in confinement was achieved. However, contrary to results on ZT40-M, the pellet trajectory was only slightly curved and penetrated to the core. Strong pellet deflection from one-sided ablation by fast electrons was not observed, a favorable sign for injection into larger RFP devices, such as RFX.

In addition to boronization, the large array of general improvements described in Section II.A.2 have contributed to optimization of confinement.

Transport Measurements

3. Anomalous ion heating is correlated with tearing (dynamo) fluctuations.

It is well-known that in the RFP the ions are heated anomalously.⁴ Although the only external power input is Ohmic heating of the electrons, the ions can be hotter than the electrons, implying a non-classical ion energy absorption process. This is a very dramatic physics effect, critical to the power balance in the RFP. We have essentially proven experimentally that the anomalous heating is caused by the tearing fluctuations which underlie the MHD dynamo.^{C16,C23} In MST discharges the toroidal flux generation associated with the RFP dynamo occurs mainly during the sawtooth crash (except in the recent sawtooth-free discharges). During a 100 μ s crash the ion temperature increases by of order 100%, as measured by charge exchange analysis and Doppler broadening of carbon emission. At the same time the electron temperature decreases. This powerful ion heating mechanism is often attributed to viscous damping of tearing fluctuations.⁵ We have also introduced a model in which the heating arises from ion cyclotron damping of small scale fluctuations generated by the cascade from the large scale tearing modes.^{C12} The MST observation provides the first clear evidence linking the heating to the dynamo.

4. High beta ($\approx 10\%$) obtained in large size plasmas near $I/N = 2 \times 10^{-14}$ A-m.

The RFP reactor concept is predicated upon the expectation that beta will remain high as plasma size and current is increased. MST represents a significant jump in size from its predecessors (except for the early Zeta device). Its minor radius is two times larger than the next largest device (HBTX). The attainment of high beta values in MST^{C5} implies the constancy of beta with machine size. However, we find that beta tends to decrease with current and energy confinement time is roughly constant. With the improvements described in Chapter III, we hope to achieve high density operation ($I/N = 2 \times 10^{-14}$ A-m) at large current.

Other Progress :

Other substantial transport-related measurements have included soft x-ray tomography, fast electron studies, scaling trends, and rudimentary density and temperature profile studies.

The presence of a significant component of energetic electrons in the RFP edge is well-known.⁶ We have investigated extensively the fast electrons (with energies in the edge about three times the bulk temperature) with an electrostatic electron energy analyzer and an insertable pyroelectric bolometer. We find, as observed earlier in ZT40-M, that the fast electrons carry a significant portion of the edge current. In addition, core superthermal electrons measured with the Si(Li) PHA system have temperature 2-3 times the central bulk electron temperature and density as high as 20% of the bulk electron density (resulting in a large contribution to beta at low density).

We have investigated the scaling of various quantities. Of particular interest is the variation of beta and energy confinement time with plasma current. We can vary current from 200 kA to 650 kA. However, as described earlier, at high current confinement is likely affected by locked modes, as well as sawteeth oscillations. The recent sawtooth-free plasmas will offer the opportunity to investigate whether these trends are intrinsic to the RFP or a feature of the sawteeth present in the discharges then under study.

Initial rudimentary information on the electron energy profile has been obtained with Thomson scattering operated at two points (in different discharges) and a FIR laser interferometer operated with 4 chords (for electron density). We find that the temperature is nearly equal at $r = 0$ and $r = a/2 = 26$ cm, whereas the density profile is peaked. This is consistent with the expectation that core energy transport is large, and confinement is provided by the outer portion of the plasma.

Fluctuations and Fluctuation Induced Transport

5. Nonlinear three wave coupling of magnetic fluctuations in k-space has been measured directly and is in semi-quantitative agreement with nonlinear computational predictions of resistive MHD tearing modes.

Nonlinear coupling of spatial Fourier harmonics determines, in large part, the spectrum of fluctuations and the resulting transport in a plasma. Theoretical models of fluctuations and transport are built upon assumptions of the nonlinear

interactions. Yet direct experimental observation of nonlinear coupling is difficult and rare. We have directly measured three wave coupling of spontaneous fluctuations in k-space for the first time in plasma physics (coupling in the frequency domain has been obtained previously for electrostatic fluctuations^{7),C11}

Nonlinear coupling is characterized by the bi-coherence which measures the triple correlation $\langle B(k_1)B(k_2)B(k_3) \rangle$, where the wave numbers satisfy the sum rule $k_1 = k_2 + k_3$, and $\langle \rangle$ denotes an ensemble average (consisting of several hundred time samples in MST). We have measured the bi-coherence of magnetic fluctuations with an extensive array of small magnetic coils, consisting of coils at 64 toroidal locations and 16 poloidal locations. Thus, we obtain both poloidal and toroidal mode coupling up to mode numbers $n = 32$ and $m = 8$.

To interpret the results we compute the bi-coherence generated by a 3D, nonlinear, resistive MHD code which treats tearing fluctuations. The code is run several hundred times to generate a statistical ensemble. We find good agreement between the experiment and code (exact comparison is limited by the different Lundquist numbers in the experiment and code).

This study proves the experimental reality of nonlinear coupling in k-space and the veracity of nonlinear MHD. Since tearing fluctuations occur in many situations beyond the RFP (e.g., tokamaks) the results have general significance.

6. Low frequency current density fluctuations agree with tearing mode theory, and high frequency microturbulence is resonant locally ($m/n \approx q$)

Magnetic fluctuations in the RFP are clearly separable into the dominant low frequency ($f < 25$ kHz in MST) long wavelength tearing fluctuations, and high frequency micro-turbulence (correlation lengths < 2 cm). Low frequency current density fluctuations have been measured in MST with a multi-coil probe designed to detect non-axisymmetric, as well as axisymmetric, fluctuations.^{C9} The magnitude and phase of the fluctuations agree with the prediction of nonlinear computation of tearing modes.

The microturbulence resembles that in a tokamak. We have measured the k-spectra of the turbulence in the outer 20% of low current plasmas using multi-coil probes. We find that m/n varies spatially with safety factor q .^{C9} Since q changes sign with radius this yields vivid evidence of resonance. The reversal

surface where $q = 0$ is at $r = 44$ cm. We observe that over the 4 cm span from 42 cm to 46 cm, the toroidal mode number at which the fluctuations peak varies from $n = 25$ to $n = -25$, while m remains unchanged.

7. Magnetic fluctuation induced particle transport is ambipolar and small.

In MST, we have developed methods to measure transport fluxes from magnetic fluctuations for the first time in fusion plasmas. All transport fluxes arising from fluctuations can be related to a specific quadratic products of fluctuating quantities. Measurement of the appropriate products would constitute a direct measurement of fluctuation induced transport. In the edge of several toroidal experiments, electrostatic fluctuation induced transport has been measured; these measurements are considered to be the only clear evidence for such transport. We have successfully developed techniques for the analogous measurements of magnetic transport. Particle transport from parallel motion along a fluctuating magnetic field is given by $\Gamma_e = -\langle \tilde{j}_{\parallel e} \tilde{B}_r \rangle / eB$ and $\Gamma_i = \langle \tilde{j}_{\parallel i} \tilde{B}_r \rangle / eB$ where Γ_e and Γ_i are the ion and electron radial particle fluxes, and $\tilde{j}_{\parallel e}$ and $\tilde{j}_{\parallel i}$ are the fluctuating electron and ion parallel currents. The nonambipolar component of the particle flux (the charge flux) is given by $\Gamma_i - \Gamma_e = \langle \tilde{j}_{\parallel} \tilde{B}_r \rangle / eB$, where $\tilde{j}_{\parallel} = \tilde{j}_{\parallel i} + \tilde{j}_{\parallel e}$. We have measured this correlated quantity using the current density fluctuation diagnostic described above and found the nonambipolar flux to be zero with an uncertainty of 5% of the total particle flux.^{C9} The flux is ambipolar over the measurable frequency range up to 250 kHz. Ambipolarity at low frequency is anticipated from the phase relation between current and magnetic field fluctuations as predicted for tearing modes. For high frequency microturbulence, ambipolarity, averaged over a mode width, is a consequence of Ampere's law for modes with a small component of $\tilde{B}_{\parallel}$.⁸ We note that the non-ambipolar flux is also the magnetic Reynold's stress, a force which can cause perpendicular flow within a magnetic surface.

Ambipolarity yields no information on the individual species transport, only that the electron and ion flux are equal. Thus, we have also measured the electron particle flux from magnetic fluctuations given by $\Gamma_e = -\langle \tilde{j}_{\parallel e} \tilde{B}_r \rangle / eB$. An electrostatic electron energy analyzer has been developed to measure the electron current density fluctuation, $\tilde{j}_{\parallel e}$. The analyzer is two-sided so as to detect the total parallel electron current. The result is that the electron flux is small compared to the total particle flux (with the caveat that, to date, only the current from

electrons with energy greater than 50 eV has been measured). This result is not surprising since ambipolarity constrains the electrons to travel radially at the ion rate, which is small due to their low parallel velocity.

8. Electron energy transport from magnetic fluctuations has been measured and is small in the edge.

The electron energy transport by magnetic fluctuations, Q_r , is given by $Q_r = \langle \bar{q}_{||e} \bar{B}_r \rangle / B$ where $\bar{q}_{||e}$ is the fluctuating parallel heat flux ($\bar{q}_{||e} = \int v_{||} v^2 \tilde{f}(\mathbf{v}) d\mathbf{v}$). The quantity $\bar{q}_{||e}$ is extremely difficult to measure in a plasma; thus, there has heretofore been no measurement, in any plasma, of energy flux from magnetic fluctuations. We have developed an insertable pyro-electric bolometer which has successfully measured $\bar{q}_{||e}$ beyond $r = 46$ cm (the "scrape-off region" extends to about $r = 49$ cm). The pyro-electric crystal, which produces an electrical signal in response to incident heat flux, is situated in a small movable housing. Electrons enter through an aperture 1 mm in diameter. The diagnostic detects frequencies up to about 100 kHz, including both the low frequency tearing modes and the high frequency microturbulence. The signal is then correlated with $\bar{B}_r$ measured with a movable magnetic probe to obtain the radial heat flux.

We find that at $r \approx 46$ cm the energy flux from magnetic fluctuations is roughly ten times smaller than the total energy flux. In the scrape-off region the fluctuation induced flux increases to about half of the total flux. An interpretation of this radial variation is that in the scrape-off region the fluctuating field lines intersect the limiters, yielding measurable fluctuation induced transport. In the edge plasma, at smaller radii than the scrape-off region, the surfaces are not broken since the dominant magnetic fluctuations are not resonant in the edge. These measurements disprove the notion that the locally resonant magnetic microturbulence is responsible for edge transport in the RFP. A major remaining goal is to extend these measurement to smaller radii to test the expectation that the magnetic tearing fluctuations drive energy transport in the core.

9. Edge particle transport from electrostatic fluctuations is large.

The particle flux from electrostatic fluctuations has been determined by measuring the quantity $\Gamma = \langle \tilde{n} \tilde{E}_\perp \rangle / B$ with Langmuir probes, similar to

techniques employed in several tokamak experiments. We find that this fluctuation induced flux is roughly equal to the total particle flux obtained by using H_α radiation to infer the particle source rate.^{C8} Thus, as in the tokamak, particle flux in the RFP edge can be approximately accounted for by electrostatic fluctuations.

10. Edge electron energy flux from electrostatic fluctuations is small.

Edge electron flux from electrostatic fluctuations is obtained by measuring $Q_r = \langle \tilde{p}_e \tilde{E}_\perp \rangle / B$. The fluctuating electron pressure, $\tilde{p}_e$, is deduced from fluctuating density and temperature obtained from a triple Langmuir probe. We find that the fluctuation induced energy flux is small compared to the total energy flux (by about a factor of seven).^{C8} This raises a puzzle in that neither electrostatic nor magnetic fluctuations can account for edge energy transport. However, the former conclusion is accompanied by the caveat that the Langmuir probe data are interpreted with the common assumption that the electron distribution function (both equilibrium and fluctuating) is a Maxwellian. In the MST edge there is a population of fast electrons (about 130 eV vs a 30-40 eV bulk temperature) which might render this assumption inaccurate. We are presently investigating the hypothesis that transport of fast electrons by electrostatic fluctuations is the cause of edge energy transport. Circumstantial support for this view is provided by the observed strong correlation between potential fluctuations and parallel heat flux fluctuations.

11. The fluctuation-induced Hall effect (the Hall dynamo) is small, but not negligible.

During tearing fluctuations the current profile is relaxed according to the Ohm's law for the mean fields with fluctuations included. This is important in many situations, including the RFP dynamo⁹ and sawtooth oscillations in tokamaks.¹⁰ It has been suggested that for both the RFP and tokamak the Hall term arising from fluctuations, $\langle \tilde{\mathbf{j}} \times \tilde{\mathbf{B}} \rangle$, could be significant. We have measured the Hall term and find that it is indeed non-negligible.^{C31} However, in MST the Hall term can account for no more than 25% of the Ohmic current (under the assumption of unity effective charge number, $Z_{\text{eff}} = 1$) and less than 25% if

$Z_{\text{eff}} > 1$ (which is more likely). Thus, it is not a significant contributor to the RFP dynamo.

Fluctuation and Transport Reduction

12. A novel prototype current injector has been developed for electrostatic current injection.

A major goal of future MST research is to flatten the current density profile to reduce fluctuations and transport. In the proposed work we will attempt current profile flattening through electrostatic injection of edge current. To this end, we have completed an extensive program to develop a prototype current injector. An injector must be clean (not produce impurity influx) and must produce a unidirectional high current density. Such electrostatic helicity injection experiments elsewhere typically use either a biased "simple" electrode or a thermionic emissive electrode (e.g., lanthanum hexaboride).

We have tested both of these conventional schemes and found that at the required high current density there was large impurity release from plasma bombardment of the biased electrodes. Thus, we developed a novel injector, or miniature plasma gun, in which electrons are extracted from a plasma. This plasma source injector consists of a plasma produced by a gas discharge between an anode and cathode; the anode is then biased relative to the MST chamber for electron extraction. The injector size is 3 cm by 6 cm. The prototype injector satisfies all criteria of high current density ($\approx 60 \text{ A/cm}^2$) with no observed impurity reflux. With a 250 V bias (relative to the MST chamber) the injector emits 600 A. The current flow pattern was mapped with a movable Rogowski coil. The new injector, described more fully in Chapter VI, permits the initiation of a full-scale injection experiment to suppress fluctuations. It will also be useful for helicity injection, or current modification experiments, in tokamaks.

13. Transient Ohmic current profile broadening reduces fluctuations and suppresses sawteeth.

Ohmic modification of the current profile has been accomplished for an early test of whether profile flattening reduces fluctuations. A several ms poloidal voltage pulse is applied. The resulting edge poloidal electric field drive

poloidal current, thereby somewhat flattening the current density profile. The poloidal electric field unavoidably reduces the toroidal flux in the plasma. Hence, the experiment is inherently transient and is intended only to examine the relation between current profile and fluctuations.

MST discharges are usually accompanied by sawteeth oscillations which are preceded by growing tearing fluctuations. The sawtooth crash reduces the peakedness of the current density profile. When the poloidal voltage pulse is applied the current profile is flattened to roughly its post-sawtooth state. Concomitantly, the tearing fluctuations are reduced to a value slightly below that at the end of a sawtooth crash, there are indications of slight improvement in confinement, and sawteeth are eliminated during the pulse. Thus, there is clear evidence that modification of the current density profile can regulate the fluctuations as expected. Further detail is provided in Chapter VI.

II.C MST PUBLICATIONS SINCE 1990

MST publications since 1990 are listed below. Eight additional papers are in preparation or have been submitted for publication.

1. S.C. Prager, A.F. Almagri, et al., "First Results from the MST Reversed Field Pinch," *Physics of Fluids* **B2**, 1367 (1990).
2. S.C. Prager, "Transport and Fluctuations in Reversed Field Pinches," *Plasma Physics and Controlled Fusion* **32**, 903 (1990).
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7. W. Shen and J.C. Sprott, "Modified Polynomial Function Model for Reversed Field Pinches," *Phys. Fluids* **B3**, 1225 (1991).

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10. T.D. Rempel, et al., "Turbulent Transport in the MST Reversed Field Pinch," *Phys. Fluids* **B4**, 2136 (1992).
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17. E. Scime and S. Hokin, "Design and Calibration of a fast-time Resolution Charge Exchange Analyzer," *Rev. Sci. Instr.* **63**, 4527 (1992).
18. S. Hokin, R. Fonck, and P. Martin, "A Simple Multi-foil Spectrometer for Routing Carbon and Oxygen Measurements," *Rev. Sci. Instr.* **63**, 5038 (1992).
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