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Transport Reduction in the MST Reversed Field Pinch via Plasma Edge Control

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I. Introduction

Confinement in present reversed field pinch (RFP) experiments is limited by large magnetic fluctuations which are driven primarily by gradients in the current density profile. Recent efforts to reduce transport in the RFP have focused on the mitigation of core-resonant modes with poloidal mode number m=1 by application of auxiliary current drive [1-4]. It is hoped that by controlling the current profile, one may reduce the source of free energy for the modes. One method for accomplishing this is to inductively alter the current profile by programming the poloidal electric field at the plasma boundary. This has been successfully applied in both the Madison Symmetric Torus (MST) [5] and the Reversed Field Experiment (RFX) [6] with substantial, though transient, increases in particle and energy confinement [1-3]. The degree and duration of the enhancement to confinement has been extended recently in MST by control of both the poloidal and toroidal loop voltages in such a way as to maintain a favorable edge parallel electric field for a longer time. New measurements of line-averaged density fluctuations in MST have given the first direct evidence for reduced fluctuations in the core of the discharge. In addition, the total particle flux is seen to drop in PPCD throughout the plasma consistent with much improved particle confinement.

An important result of this work is the realization that edge-resonant modes play a role in determining RFP confinement. The m=0 modes, resonant in the edge where the toroidal magnetic field is zero, are involved in a bursty instability which temporarily degrades confinement. An important feature of discharges with improved electric field control is the suppression of these bursts and hence the simultaneous reduction of both core- and edge-resonant magnetic modes. A second method of auxiliary current drive is available on MST which is well-suited to controlling m=0 modes. Electrostatic current drive from a set of miniature biased plasma sources [7] allows current to be driven in the extreme edge (r/a ~ 0.9) just outside where the m=0 modes are resonant. Experiments using electrostatic current drive to suppress or enhance m=0 modes confirm their importance in the global transport problem and demonstrate that small differences in the extreme edge of the plasma can have global consequences.

II. Inductive Current Drive

In the first inductive current drive experiments aimed at current profile control [1], a poloidal loop voltage pulse was applied to reduce toroidal flux and generate poloidal current in the edge of the discharge. (Hence, the technique was referred to as Pulsed Poloidal Current Drive or PPCD.) This has since been refined in MST by breaking the one large pulse into a sequence of 5 smaller pulses to give more pulse shaping flexibility [2]. The RFX experiment has demonstrated a form of oscillating PPCD in which no net flux is removed and cyclic periods of low fluctuations and improved confinement are produced [8]. In some sense, the present challenge is to find the optimal programming for the applied poloidal and toroidal voltages to minimize mode amplitudes and transport.

MST has recently made progress in this direction by combining poloidal and toroidal loop voltage programming. Specifically, after the series of poloidal loop voltage pulses has been applied, the toroidal loop voltage is reversed. This has the effect of suppressing parallel current on-axis and driving parallel current along the reversed magnetic field lines in the edge. This alters the current profile in the same way that the poloidal loop voltages pulses do – both act to flatten the parallel current profile. Periods of reduced fluctuation levels can be produced and sustained for up to 10 ms.

Measurements of line-averaged density and H_α emission show that the total particle flux drops substantially during PPCD. Moreover, density fluctuations drop throughout the entire plasma volume (Figure 1). This is the first direct measurement of core fluctuation reduction during PPCD in MST. Past measurements inferred changes in the core based on edge measurements.

One important consequence of the more complete electric field control is the reliable suppression of a bursty instability which temporarily degrades confinement during otherwise improved confinement periods [9]. This instability has different modal content than the standard RFP sawtooth and may be driven by any number of free energy sources including current or pressure gradients. The instability is expressed primarily in edge-resonant m=0 modes and leads to a relaxation of the steep current and pressure gradients in the edge.

When these bursts are suppressed for several ms, plasma beta increases and confinement improves. The electron pressure profiles also peak, due primarily to a peaking of the electron temperature profile (Figure 2). In low current discharges, the confinement improvement is best in MST with total plasma beta of about 14% and energy confinement time estimated to be about 10 ms (with the dominant uncertainty stemming from the lack of accurate Ohmic input power measurements). In high current discharges, the electron temperature on-axis reaches 840 eV and plasma beta is about 9%.

Langmuir probe measurements in the edge show that electrostatic fluctuations decrease during PPCD and that the electrostatic fluctuation-induced particle flux outside r/a ~ 0.9 is reduced. The measured electrostatic fluctuation-induced particle flux is not substantially affected at r/a ~ 0.9 in agreement with previous RFX measurements [10].

III. Electrostatic Current Drive

The enhanced confinement described above is achieved when both core-resonant m=1 and edge-resonant m=0 modes are reduced simultaneously. This, coupled with the observation of degraded confinement with m=0 bursts suggests that edge-resonant modes play some role in determining global confinement. A separate set of experiments has been carried out to investigate the role of the current profile in the extreme edge on edge-resonant modes and transport.

Current can be injected in a steady-state fashion at r/a > 0.9 with a set of electrostatic current sources in MST [7]. Electron current is injected from each source by applying a DC potential between a miniature high density discharge and the MST vessel. The injected current is highly directional, quite dense (J ~ 100 A/cm^2), and can be sustained for up to 10 ms. The sources can be oriented to inject current parallel to the pre-existing poloidal current (CO-injection) or antiparallel (CTR-injection). The presence of the sources in the edge degrades the plasma somewhat. However, the role of changes in the current profile can be isolated from other differences in the edge by contrasting similar CO and CTR discharges.

As shown in Figure 3, average magnetic fluctuation amplitudes are lower during CO-injection than during CTR-injection. This difference is consistent with the idea that modes should be more stable with flatter parallel current profiles. Dynamically, what is observed is that a large portion of this difference is due to a change in the timescale for relaxation oscillations (sawteeth). Since mode amplitudes peak at each sawtooth event, a decrease in the sawtooth frequency results in a decrease in the average mode amplitude. This effect is more significant for m=0 modes because they peak more strongly than m=1 modes during a sawtooth crash.

Confinement also appears to differ modestly with the two directions of current drive. Measured electron density and temperature are higher with CO-injection and the Ohmic input power is lower. The difference in energy confinement times is estimated to be about 20-30% but is sensitive to unknown details in the radial profiles of density and temperature.

IV. Summary

Improvements in auxiliary current drive continue to yield improvements in RFP confinement. Two different methods of auxiliary current drive in MST yield qualitatively similar control of magnetic fluctuations and transport. Inductive current drive via control of both poloidal and toroidal loop voltages gives the best quantitative performance with plasma beta up to 16% in low current discharges and peaked central electron temperature profiles. Electrostatic current drive illustrates in a direct way the reduction of magnetic fluctuations and transport when additional parallel current is driven in the edge of the RFP. Recent data indicate that control of edge-resonant modes is an important factor in achieving optimal performance and that small changes in the extreme edge of the plasma can have global consequences.

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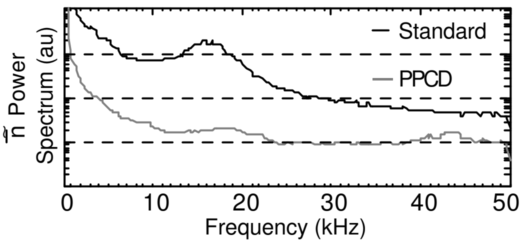

Figure 1. Line-averaged density fluctuation power spectra in PPCD and standard discharges.

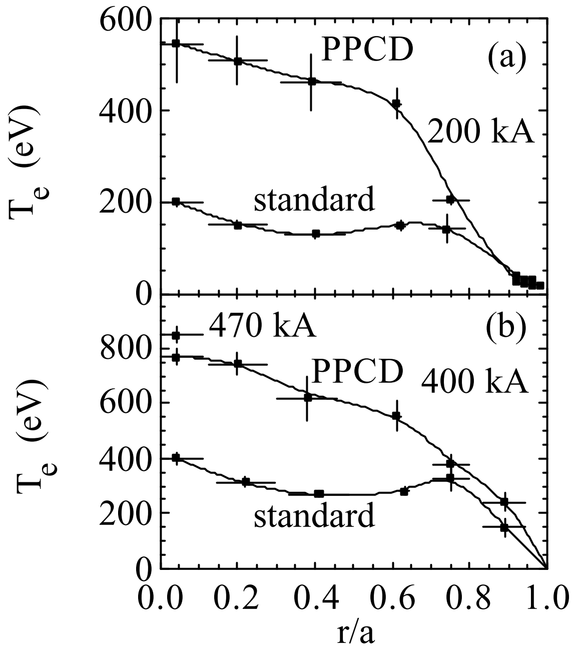

Figure 2. Measured electron temperature profiles in (a) 200 kA and (b) 400 kA discharges with and without PPCD. The central T_e for 470 kA with PPCD is also shown.

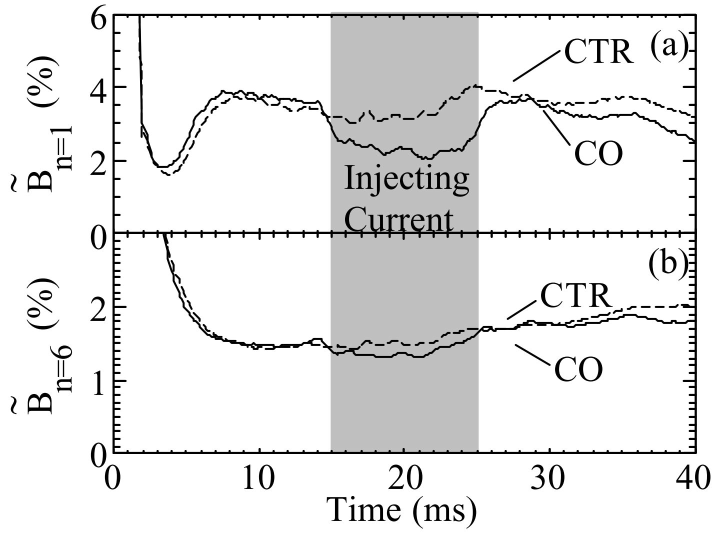

Figure 3. Time evolution of the total (a) n=1 (m=0) and (b) n=6 (m=1) magnetic field fluctuation amplitudes at the plasma boundary in co- (solid) and counter-injection (dashed) discharges. Each curve is the smoothed average of more than 50 shots.