

Progress in Improved Confinement and Beta in the MST Reversed Field Pinch with Current Profile Control*

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Improved confinement and beta have been obtained in the Madison Symmetric Torus¹ (MST) reversed field pinch (RFP) by (1) programmed modification of the inductive electric field and (2) current injection from localized electrostatic sources distributed around the surface of the plasma. Both are attempts to modify the parallel current profile to reduce fluctuations and transport associated with resistive MHD tearing instabilities. These instabilities play a major role in producing the “dynamo” which sustains the reversed toroidal field in the RFP, but they also cause particle and energy transport in the core. Resistive MHD computation has shown that auxiliary current drive in the outer region of the plasma (directed poloidally) is an effective replacement for the dynamo-driven current, allowing reduced MHD turbulence.^{2,3} We report here results of ongoing efforts to optimize the poloidal and toroidal inductive electric field programming in MST to achieve a more stable current profile, improving on previous results by lengthening the transiently reduced fluctuation period to ~10 ms. New MST record values for beta and the electron temperature, whose profile dramatically peaks, are measured, and the confinement in 200 kA plasmas exceeds the “constant beta scaling” which characterizes the fit to RFP best-shots from present and past devices.⁴ We also report results of current profile modification using sixteen electrostatic current sources in the edge of MST plasmas. The added current primarily affects poloidal mode number $m=0$ magnetic fluctuations, probably from the close proximity of the injected current to the safety factor $q=0$ surface. Although the improvement in energy confinement is not so great, the sensitivity of energy transport to $m=0$ modes was not previously appreciated, perhaps providing a clue to the cause of energy transport in the edge of RFP plasma which remains undetermined.

1. MODIFICATION OF THE INDUCTIVE ELECTRIC FIELD

The first current profile control experiments in MST used inductive pulsed poloidal current drive (PPCD) by transiently changing the toroidal flux, thereby inducing a poloidal electric field in the outer region of the plasma. (The toroidal inductive electric field programming was unaltered.) As a result, the fluctuation amplitude halved, the electron temperature increased $\leq 50\%$, and the energy confinement increased five-fold.^{5,6} In a similar, more recent PPCD experiment on RFX, a two-fold increase in energy confinement has been achieved, and the electron temperature profile was observed to peak in the core, associated with a large decrease in the heat diffusivity.⁷

In MST, modification of PPCD from a single large pulse⁸ to a series of four smaller pulses^{5,6} lead to greater fluctuation reduction. Here we report additional improvement by

adding a fifth PPCD pulse to better sustain the poloidal electric field, as well as adjusting the toroidal inductive electric field to reverse direction following the application of PPCD. A consequence of PPCD is increased negative toroidal magnetic field at the plasma surface. By reversing the direction of the toroidal electric field, current drive directed to increase the parallel current in the outer plasma is maintained longer. A necessary consequence of this programming is the active termination of the plasma current. Figure 1 shows the time history of (a) the poloidal and toroidal surface electric fields, (b) the parallel surface electric field ($\mathbf{E} \cdot \mathbf{B} / B$), and (c) the rms poloidal magnetic fluctuation amplitude illustrating the ≤ 10 ms period of reduced magnetic fluctuations which improves upon the ≤ 4 ms period obtained previously. Particularly noteworthy is a suppression of “small dynamo events”⁹ which appeared in MST’s previous PPCD experiments. These events are similar to sawteeth (large dynamo events) in that they produce toroidal flux, but they are smaller in magnitude and exhibit different precursory mode activity initiated by $m=0$ modes.

A major campaign was recently completed to characterize the confinement of these improved PPCD plasmas, including a measurement of the electron temperature profile at six points using a single-point Thomson scattering diagnostic scanned radially shot-by-shot. The $T_e(r)$ profiles measured in 200 kA and 400 kA PPCD plasmas compared with similar current standard RFP plasmas are shown in Fig. 2. The profile peaking with PPCD is dramatic. A record central $T_{eo} = 840$ eV was measured in 460 kA plasmas. The fueling was adjusted to produce similar line averaged densities for both the standard and PPCD cases ($\bar{n} \approx 0.8 \times 10^{19} \text{ m}^{-3}$ for 200 kA and $\bar{n} \approx 1.0 \times 10^{19} \text{ m}^{-3}$ for 400 kA). The density profile evolution measured with an 11-chord interferometer shows a slightly greater hollow profile in the core during PPCD. The ion temperature profile is not well known, so to estimate beta, we assume $T_i = 0.5T_e$ in standard plasmas and $T_i = 0.25T_e$ during PPCD based on neutral charge exchange and impurity ion chord measurements. For 200 kA plasmas, $\beta_{tot} = 2\mu_o \langle p \rangle / B_{tot}^2(a)$ increases from 6% to 12%, and for the 400 kA plasmas β_{tot} increases from 4% to 8%. The global energy confinement is usually calculated from the Ohmic input power derived from total input power subtracting the rate of change in magnetic energy. However, the strong time dependence makes this even more challenging than past PPCD experiments, and work is ongoing to refine this approach. Here we estimate the Ohmic input power from $\int \eta_{sp} J^2 dV$

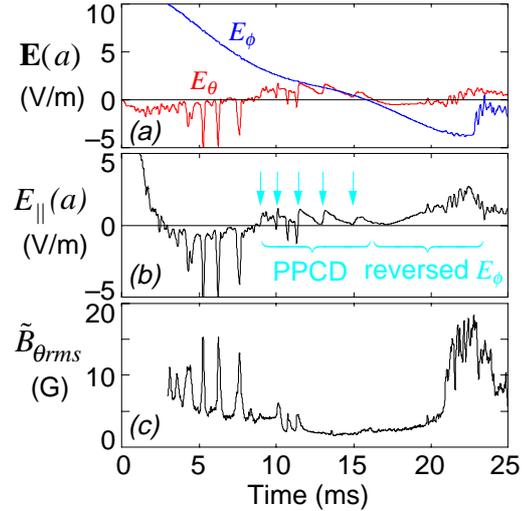


Fig. 1. (a) Surface electric field components, (b) parallel electric field, and (c) magnetic fluctuation in a 200 kA PPCD plasma.

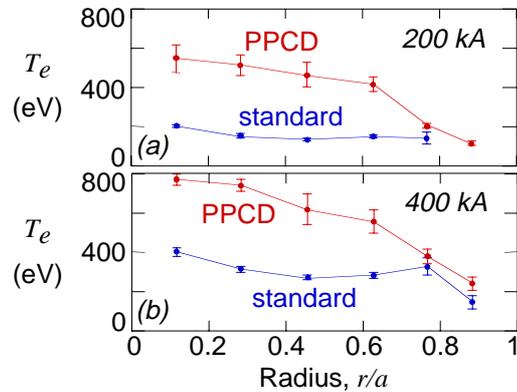


Fig. 2. Electron temperature profiles in (a) 200 kA and (b) 400 kA standard and PPCD plasmas.

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assuming Spitzer resistivity using the measured $T_e(r)$ and an assumed spatially constant $Z_{eff} = 2$ (consistent with measured chord-averaged bremsstrahlung radiation). The current profile comes from a toroidal equilibrium fitting code which also provides a measure of the trapped particle fraction, resulting in a $\leq 2X$ increase in the resistivity. Under these assumptions, the global energy confinement time reaches 6 ms in the 200 kA PPCD plasmas and 5 ms in 400 kA plasmas. The strong peaking of the temperature profile implies a large decrease in the heat diffusivity. Initial estimates of the heat diffusivity from a local electron power balance analysis (assuming Spitzer heating) show $\chi_e \approx 10 \text{ m}^2/\text{s}$ over most of the plasma during PPCD. The confinement in 200 kA plasmas exceeds by a substantial margin the constant beta scaling,⁴ demonstrating this is not an upper limit to RFP confinement.

2. ELECTROSTATIC CURRENT INJECTION

An alternate method of current profile control using current injection from electrostatic sources has also been tested in MST. Up to 16 miniature plasma sources¹⁰ are inserted into the plasma edge, each providing $\approx 500 \text{ A}$ of current when biased $\leq 300 \text{ V}$ relative to the conducting shell surrounding the plasma. Each source locally produces a $\sim 3 \text{ cm}$ diameter electron stream which spreads toroidally and poloidally by following the equilibrium magnetic field lines. With 16 sources distributed around the torus, the total injected current approaches an axisymmetric current sheet. The radial position of the sourced current is adjustable, fixed at 5 cm in from the shell surface for results reported here. The added current is expected to diffuse radially inward, thereby modifying the current profile in the intended fashion. Clear evidence of this diffusion has been difficult to establish, and the modification of the current profile is not well known. However, the small change in $m=1$ magnetic fluctuations shown below suggests either the current diffusion or the magnitude of the sourced current are insufficient to achieve the hoped for reduction of magnetic turbulence in the core.

The injected current can be directed to increase or decrease the background current density (co-injection or counter-injection) by rotating the sources. In this way, the effects of the directed current can be separated from other effects such as plasma biasing which occurs equally for either co- or counter-injection. The beneficial effects of plasma biasing have been previously reported using ≤ 8 of these same sources arranged for balanced co- and counter-injection.¹¹ Strong modifications to the plasma flow are produced, and the particle confinement time increases $\sim 50\%$, consistent with a measured decrease in edge electrostatic fluctuations known to cause particle transport. Plasma biasing, however, does not significantly affect magnetic fluctuations which are the dominant source for energy transport in the RFP, consistent with no substantial change in energy confinement with plasma biasing.

Directional current injection primarily affects $m=0$ modes resonant at the toroidal field reversal surface near to the radial position of the injectors. With co-injection, the time averaged $m=0$ mode amplitudes are decreased, and with counter-injection, they are enhanced. This is summarized in Fig. 3 where the amplitude of the $n=6$ mode (the dominant core-resonant $m=1$ mode) and the $n=1$ mode (the dominant $m=0$ mode) are shown as a function of the total injected current. With increasing co-injected current, the $n=1$ mode amplitude decreases, whereas with increasing counter-injected current, the amplitude increases by a small amount. In contrast, the $n=6$ mode amplitude appears insensitive to the direction of the added current. The sensitivity of $m=0$ modes to the injected current probably results from the

close proximity of the sourced current to the $q=0$ surface. Although the $m=1$ modes are not changed, the Ohmic input power (Fig. 3c) is reduced (energy confinement improved) when the amplitude of the $m=0$ modes decreases with co-injection. Although not as dramatic a decrease in input power as for PPCD, it reveals a sensitivity of energy confinement to the $m=0$ mode amplitude not seen before. The cause of energy transport in the edge of the RFP remains a mystery, so this behavior suggests that $m=0$ magnetic fluctuations play a role in the energy transport process at the edge in analogy to the role of $m=1$ magnetic fluctuations in the core.

A robust and dramatic result of co-injection is a lengthening of the sawtooth cycle¹² period. This is illustrated in Fig. 4 displaying the shot-averaged Ohmic input power for ~ 50 identical shots. Current injection causes the normally randomly phased sawtooth events to occur almost identically in each shot, allowing the sawtooth cycle variation to survive the shot averaging process. The evolution of the $m=0,1$ mode amplitudes is correspondingly altered, cycling as usual except for the increased period. Hence, the peak amplitudes of the $m=0,1$ modes just before the crash are roughly the same as without current injection. The changes in Fig. 3 primarily result from the altered sawtooth period. This behavior suggests the nonlinear processes which initiate the sawtooth's global magnetic reconnection are moderated by $m=0$ modes whose behavior is strongly affected by the injected current.

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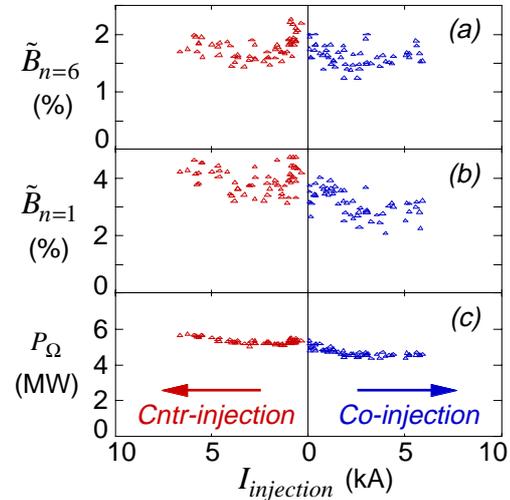


Fig. 3. Time-averaged amplitudes of (a) the $n=6$ mode, (b) the $n=1$ mode, and (c) the Ohmic input power as a function of co- and counter-injection.

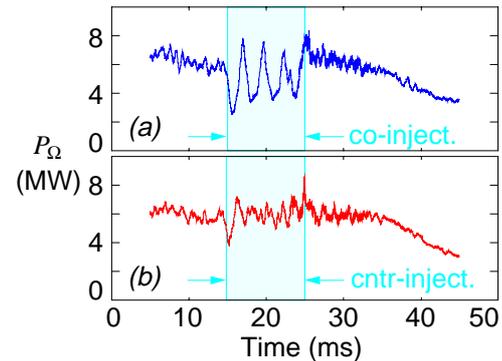


Fig. 4. Evolution of the Ohmic input power shot-averaged for ~ 50 shots of (a) co-injection and (b) counter-injection. Injection is on from 15-25 ms.