Progress Towards Confinement Improvement Using Current Profile Modification In The MST Reversed Field Pinch

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Abstract. Recent current profile modification experiments on the MST reversed field pinch have resulted in improved performance and elucidated the role of the current profile in determining confinement. During transient experiments in which the current profile is modified inductively, new profile measurements show that both the electron thermal diffusivity and particle diffusivity can decrease by more than an order of magnitude compared to standard plasmas. Concurrent with this improvement in energy confinement, density fluctuations associated with core-resonant tearing modes are reduced by more than an order of magnitude over the entire plasma cross-section. Edge resonant modes (poloidal mode number m=0) are shown to affect confinement and are controllable by current drive in the extreme plasma edge–indicating the significance of edge modes in addition to the core-resonant m=1 modes. Finally, experiments are underway to demonstrate new non-inductive current profile control techniques using lower hybrid waves and electron Bernstein waves.

1. Introduction

MHD simulations have shown that the addition of localized non-inductive current drive in the periphery of the RFP can reduce the magnitude of the magnetic fluctuations responsible for its poor confinement[1, 2]. The magnetic fluctuations in the RFP are due to resistive MHD instabilities (tearing modes) caused by current profile peaking; thus confinement in the RFP is ultimately the result of a misalignment between steady-state inductively driven current profiles and current profiles which are stable to tearing modes. If a technique such as rf current drive can be developed to non-inductively sustain a current profile linearly stable to all tearing modes, the confinement of the RFP and its potential as a reactor concept are likely to increase.

There is substantial experimental evidence supporting the idea that the current profile plays an important role in RFP confinement. Indeed, transient modifications of the current density profile using inductive techniques have shown previously that magnetic fluctuations can be reduced and the energy confinement can be improved five-fold[3–5] in the MST reversed field pinch[6]. A pulsed poloidal electric field is applied–a technique known as pulsed poloidal current drive (PPCD). Several new results have improved the understanding and performance of PPCD, and given promise that future experiments using non-inductive current profile control can lead to additional confinement improvements.

The MST work on this theme during the last two years has focused on: (1) quantifying and optimizing the confinement improvement during PPCD; (2) understanding the mechanism by which changes to the current profile modify tearing mode stability; and (3) developing and identifying non-inductive techniques suitable for current profile modification. The remainder of the paper will address progress in these three areas.

2. Improved control of PPCD plasmas

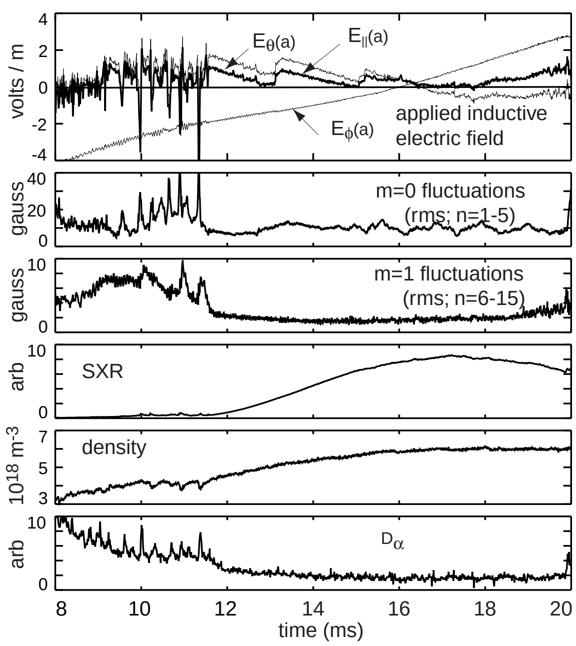

Figure 1: 200 kA PPCD plasma using improved $E_{||}$ programming. The applied toroidal (E_ϕ) and poloidal (E_θ) electric fields at the plasma surface; the rms fluctuations of $\tilde{B}_\phi(a)$ associated with the m=0 modes resonant a the reversal surface; the rms fluctuations of $\tilde{B}_\theta(a)$ associated with the m=1 modes resonant in the plasma core; SXR-soft xray emission; line average density; D_α emission.

Transient modifications to the RFP current profile are possible by programming of the surface toroidal and poloidal electric fields (see Fig. 1); the latter requiring a change to the applied toroidal magnetic field. In the last two years, the duration of the improved confinement has been extended through improvements to the toroidal field power supplies and by modifications to the Ohmic heating power supplies which allow reversed toroidal electric fields. The E_θ programming is controlled by the firing of a sequence of discrete supplies; the new programming has decreased the period between stages such that a positive E_θ is maintained. The $E_{||}$ is maintained following poloidal current drive by changing the direction of E_ϕ. These modifications allow a parallel electric field, driving parallel current at the edge of the plasma, to be maintained for more than 10 ms (see Fig. 1).

The application of a sustained $E_{||} = \langle \mathbf{E} \cdot \mathbf{B} \rangle / \langle B \rangle$ at the plasma edge shows a dramatic effect on the MHD behavior of the discharge and results in a two-fold reduction in magnetic fluctuations. It is found that sustainment of high confinement improvement requires elimination of the m=0 bursts seen at 10-12 ms in Fig. 1, and that a positive $E_{||}$ is required at the edge for this suppression.

3. The Role of the Current Profile in Improving Confinement

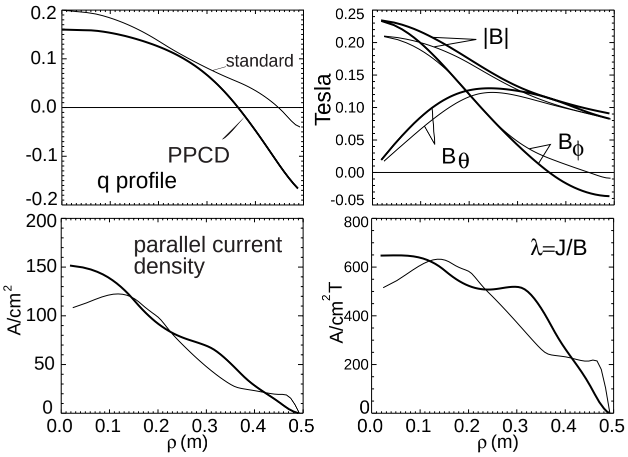

Figure 2: Equilibrium reconstructions for 200 kA standard and PPCD discharges. q profile, B profiles, $J_{||} = \langle \mathbf{J} \cdot \mathbf{B} \rangle / \langle B \rangle$ profile, $\lambda = J_{||}/B$.

Although the PPCD experiments are consistent with improved MHD stability associated with the auxilary current drive, a detailed understanding of how the current profile is changed and how the modified current profile affects the MHD stability of the discharge is still emerging. The first issue is to assess the differences between a standard and a PPCD current profile.

A direct measurement of the current density is only possible in the extreme edge of the MST plasma using an insertable Rogowski coil. The complete current density profile is determined from MHD equilibrium reconstructions constrained by data from insertable probes, the edge magnetic probe arrays, pressure profile measurements, and a newly operational motional Stark effect diagnostic suitable for use in low magnetic field plasmas.[1]

From the comparison of 210 kA standard and PPCD plasmas shown in Fig. 2 it is clear that the current profiles of PPCD plasma are different than a standard discharge. The first notable difference is that the PPCD provides additional current in the region $0.25\mathrm{m} < \rho < 0.40$ m which results in a flattening of the λ profile. The toroidal field programming results in a plasma equilibrium with large shear in the edge from the deep reversal, and a lower value q_0 in the center. This current should strongly influence the stability of the m=1 core resonant tearing modes; it is approximately the region where simulations have shown additional current is needed for reducing MHD fluctuations[1].

The next notable difference between current profiles is the distinct reduction and steepening of the current profile in the extreme edge (see Fig. 2 for $\rho > 0.45$ m) during PPCD and a corresponding peaking of the current density in the core ($\rho < 0.2$ m) of the plasma. This reduction is only observed during the m=0 burst free periods of improved confinement (not just with the application of edge current drive). The reduction in the edge current and peaking of the core current during PPCD can be explained by considering the terms in the parallel Ohm's law $J_{||} = \sigma(E_{||} + E_{MHD})$, where $E_{MHD} = \left\langle \tilde{\mathbf{v}} \times \tilde{\mathbf{b}} \right\rangle_{||}$ is a fluctuation driven $\mathcal{EMF}$ associated with the tearing mode activity. In standard discharges, the current in the extreme edge has been shown to be driven primarily by an E_{MHD} associated with the m=0 modes[7]; when the amplitudes of these modes are reduced during PPCD and the resonant surface moves

[1]The technique used here is to determine the magnitude of B in the core, rather than the pitch angle of the magnetic field

further away from the boundary, the edge current is also significantly reduced[8]. The increase in central current (like the reduction in extreme edge current) is also consistent with reduced magnetic fluctuations associated with a reduction in E_{MHD} in the central region associated with locally resonant m=1 modes which act to redistribute current from the core to the edge[9].

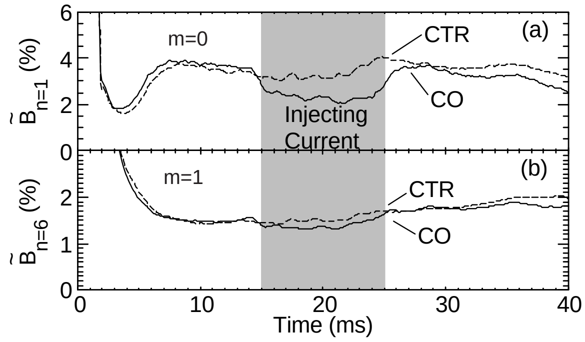

Figure 3: Time evolution of the total (a) n=1 (m=0) and (b) n=6 (m=1) magnetic field fluctuation amplitudes at the plasma boundary in co- (solid) and counter-injection (dashed) of electrostatic current sources. Each curve is the smoothed average of more than 50 shots.

An important ingredient in obtaining the best performance with PPCD has been the simultaneous reduction of m=1 and m=0 modes. In standard discharges, m=0 modes are resonant close to the wall and appear in conjunction with strong nonlinear coupling of core resonant $m = 1$ modes. During PPCD the m=0 modes are resonant further from the wall and often exist at large amplitudes despite suppressed $m = 1$ activity. Empirically, these modes limit improved confinement and are sensitive to details of the edge: by sustaining the applied parallel electric field at the edge in combination with good wall conditioning and low density, both $m = 0$ and $m = 1$ modes can be reduced for 10-20 ms long periods.

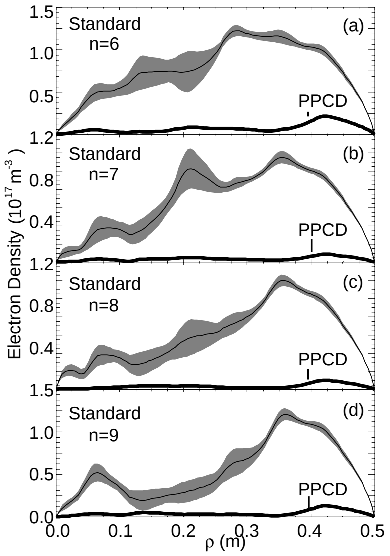

Figure 4: Radial electron density fluctuation profiles determined from the 11 chord FIR interferometer array during both standard and PPCD discharges for a variety of m=1 modes.

Control of $m = 0$ activity appears to depend sensitively on the magnitude and duration of the applied parallel electric field, implying that these modes may be very sensitive to the edge current profile. Non-inductive current drive experiments using electrostatic current sources support this hypothesis. In these experiments, current is injected from insertable electrodes at $r/a = 0.9$, slightly outside the m=0 resonant surface in standard RFP discharges[10, 11]. Fig. 3 shows ensemble averages of the m=0 and m=1 mode amplitudes for current injection co- and counter- to the background current. When co current is injected, it is in the sense to stabilize the m=0 modes. This experiment also shows a change in the period of the relaxation oscillations (sawteeth), believed to be regulated by $m = 0$ modes; co-injection increases the sawtooth period. These results are consistent with MHD computation in which nonlinear coupling between the m=0 and m=1 modes lead to sawtooth relaxation oscillations[12]. Reduction of the m=0 amplitude affects the m=1 modes through nonlinear coupling. This is confirmed experimentally by removing the m=0 modes (by operating without B_ϕ reversal) and observing that the effect of the current injection on m=1 modes disappears.

In past work, the reduction of fluctuations in the core during PPCD has been inferred from measurements of magnetic fluctuations at the plasma edge. Density fluctuations have now been measured in the core with an eleven-chord FIR laser interferometer. By inverting the chordal signals, for m=1 fluctuations, the radial profile of the fluctuation amplitude is obtained. During PPCD the density fluctuations decrease markedly over the entire plasma (see Fig. 4). Moreover, by correlating the density fluctuations with the edge measured magnetic fluctuations, specific toroidal harmonics of the density fluctuations were obtained. This has revealed that the core density fluctuations are indeed reduced.

4. Particle and Energy Confinement Improvement

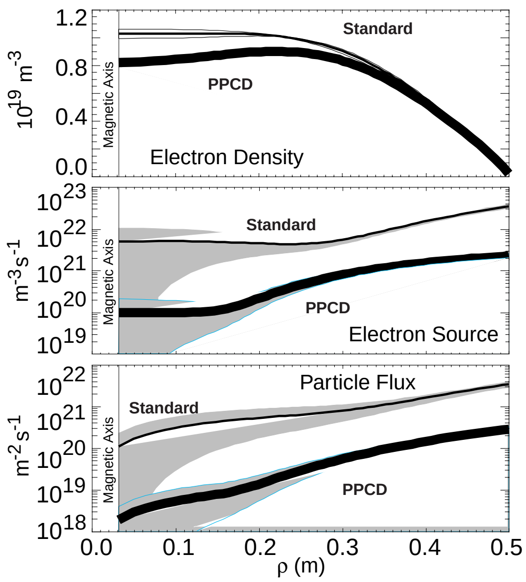

Figure 5: Radial profiles of a) electron density, b) electron source (dominant impurities included) and c) electron radial particle flux for standard and PPCD discharges. The shaded regions indicate the upper and lower bounds obtained by inverting monte-carlo perturbed data.

Recent diagnostic developments, including an upgrade of the Thomson scattering system and implementation of an array of D_α detectors, have facilitated the first power and particle balance analysis of electron thermal and particle transport in the MST and allowed the improved confinement in PPCD to be quantified. Experiments have measured electron temperatures (see Fig. 5) and densities under standard and enhanced confinement operating modes for several levels of current. Here we focus on a comparison between profiles of a conventional RFP and PPCD discharges at 210 kA.

Transport analysis employs a 2D equilibrium reconstruction of the current density profile based upon magnetic diagnostics and a mapping of the profile measurements to a flux surface geometry. The equilibrium also provides a geometry for inverting line-integral measurements of the electron density and D_α emission. Power deposition is calculated from the measured current density profile and estimates of the neoclassical (Hirshman-Sigmar) resistivity; trapped particle corrections to resistivity are found to be significant for RFP equilibria.

The radial electron flux has been measured in both standard and PPCD plasmas, through spectroscopic determination of the ionization source and interferometric measurement of the density profile. With PPCD, we observe that the particle flux decreases by an order of magnitude over the entire cross-section, with the core showing the most dramatic reduction (Fig. 6). With PPCD the global particle confinement time increases about eight-fold from 0.6 ms to 4.7 ms. From measured density gradients, and the measured time derivative of the electron density, a particle diffusivity is inferred under the assumption that the particle flux $\Gamma = -D\nabla n_e$; the particle diffusivity drops by an order of magnitude in over the outer half of the plasma during PPCD as shown in Fig. 7.

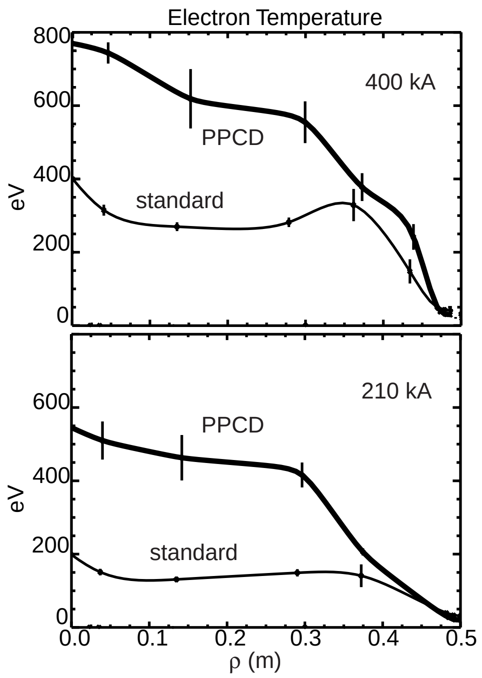

Figure 6: Electron temperature profiles in (a) 200 kA MST standard and PPCD discharges, and (b) 400 kA standard and PPCD discharges.

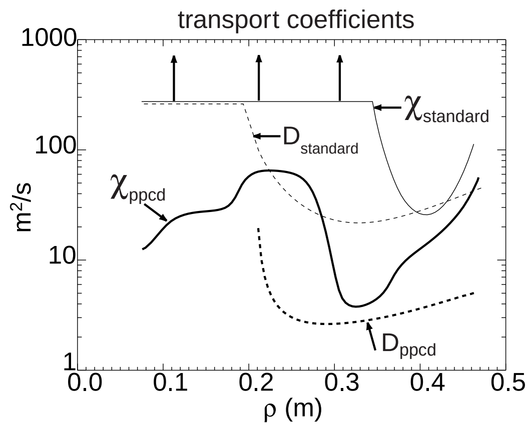

Figure 7: Profiles of electron thermal diffusivities χ_e and particle diffusivities D measured in 210 kA standard and PPCD plasmas. The arrows indicate that the diffusivity is unresolvable or inconsistent with a diffusive transport law.

The energy confinement time and the conducted electron heat flux are determined from a power balance based upon the measured temperature profiles. Z_{eff} is not measured in these discharges, but inferred from power balance estimates of the dissipated power compared to the Poynting flux of energy into the plasma: here we assume a constant Z_{eff}=2. For an estimation of the power flow in the electrons, we have considered the included the effects of convected heat flux (determined from the particle flux), and the time rate of change of the local pressure. We also assume that the conducted electron heat flux is described by $q_e = -\chi_e \nabla T_e$. Under these assumptions, χ_e is found to decrease by more than an order of magnitude during PPCD, reaching $\chi_e < 10\, m^2/s$ over a significant volume of the plasma as seen in Fig. 7. The most dramatic change occurs at $\rho = 0.3$ m where evidence of a transport barrier is seen. Correspondingly, the energy confinement time increases from τ_E =1.5 ms to τ_E =9 ms.

Finally, there is substantial evidence for non-diffusive transport in the RFP. We routinely observe hollow density profiles in which core transport cannot be explained by a diffusive, diagonal transport matrix. This is also true for electron temperature profiles in some standard plasmas.

The improved particle and energy confinement is consistent with the strong reduction in MHD activity and supports the notion that core transport is dominated by magnetic fluctuations. Measurements of the hard x-ray spectrum have shown the presence of runaway electrons in PPCD plasmas, giving further support that magnetic fluctuations have been greatly reduced in the core; fast electrons are more affected by magnetic transport than thermal electrons. Fokker-Plank simulations have shown that the presence of suprathermal electrons implies low transport rates.

5. Future Tools for Current Profile Modification

PPCD is inherently transient and coupled to the conductivity profile; thus, future progress seems likely if localized non-inductive current can be applied. Two RF current drive schemes for improved control of the current profile are being pursued: a lower hybrid current drive and electron Bernstein wave current drive. Both have the potential of providing well-localized, efficient poloidal current drive in the edge region[2, 13].

The LH scenario uses an 800 MHz, high-$n_{||}$ interdigital line antenna to launch the slow wave in the LHRF. The high-$n_{||}$ (~ 7) is required for accessibility, while the frequency is chosen to avoid the LHCD density limit and to facilitate the construction of a compact slow-wave antenna. An interdigital line antenna has been constructed and low-power (< 10 watts) experiments have shown that 70% of the available power is coupled to the plasma. RF probe measurements have detected the launched wave. The present system (a 200 kW klystron) has successfully operated at 20 kW into plasmas. Near-term experiments will focus on looking for evidence of electron heating and a determination of the power deposition profile.

New theoretical work has shown that the EBW can be used for efficiently driving well localized current by controlling $n_{||}$ through appropriate choice of poloidal launch angle[14]. This is only possible if a technique for launching the EBW can be developed. The possibility of coupling to the EBW has in part been shown by measuring emission. An EBW radiometer has measured thermal levels of electron cyclotron emission (radiation temperatures of about 80% of the electron temperature) with X-mode polarization. By reciprocity the measurements validate the mode conversion process necessary for coupling externally launched power to the EBW.

6. Summary

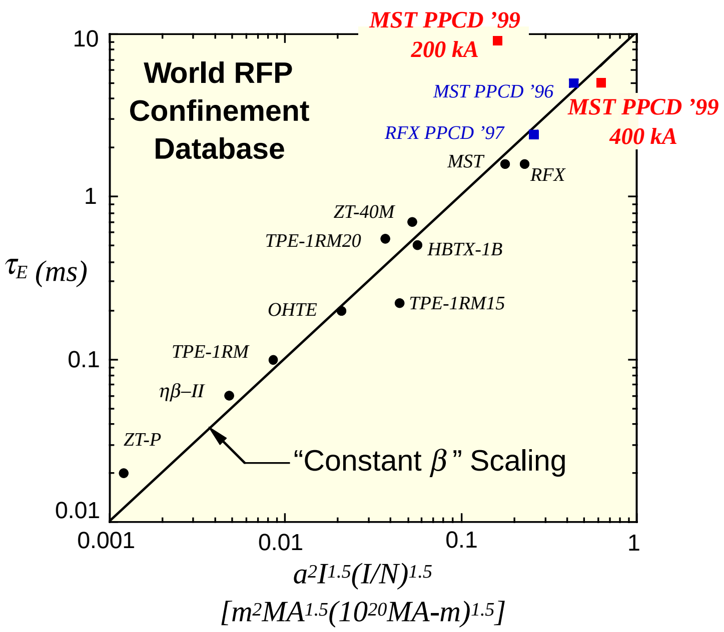

Figure 8: World data base of RFP confinement.

The recent experiments on MST confirm that current profile modification leads to significant improvement in RFP confinement. This is illustrated by examining the world data base of RFP confinement shown in Fig. 8. The recent MST results deviate for the first time from the constant β scaling which accurately describes conventional RFP confinement.

In summary, the main confinement results from the past two years are: (1) Improved programming of the toroidal and poloidal loop voltages has improved the performance of PPCD. (2) Measurements of the current profile indicate flattening of the λ profile, and a reduction of extreme edge current and increase of core current density of PPCD plasmas relative to standard MST plasmas. (3) Profile measurements show both the thermal diffusivity and particle diffusivity are decreased sharply over much of the plasma. (4) Density fluctuations associated with core-resonant tearing modes are reduced by more than an order of magnitude over the entire plasma, providing the first direct evidence of fluctuation reduction in the core. (5) Edge resonant modes (poloidal mode number $m = 0$) are shown to affect confinement and are controllable by current drive in the extreme plasma edge–indicating the significance of edge modes in addition to the previously targeted core-resonant $m = 1$ modes which have been the focus of past work.

7. References

[1] SOVINEC, C. et al., Nuc. Fusion **39** (1999) 777.

[2] UCHIMOTO, E. et al., Phys. Plasmas **1** (1994) 3517.

[3] SARFF, J. S. et al., Phys. Rev. Lett. **72** (1994) 3670.

[4] SARFF, J. S. et al., Phys. Rev. Lett. **72** (1994) 3670.

[5] BARTIROMO, R. et al., Phys. Rev. Lett. **82** (1999) 1462.

[6] DEXTER, R. et al., Fusion Technol. (1991) 131.

[7] FONTANA, P. et al., Phys. Rev. Lett. **85** (2000) 566.

[8] CHAPMAN, B. et al., Phys. Plasmas **7** (2000) 3491.

[9] HARTOG, D. D. et al., Phys. Plasmas **6** (1999) 1813.

[10] FIKSEL, G. et al., Plasma Sourcses Sci. Techn. **5** (1996) 78.

[11] CRAIG, D. et al., Phys. Rev. Lett. **79** (1997) 1997.

[12] ORTOLANI, S. et al., *Magnetohydrodynamics of Plasma Relaxation*, World Scientific, 1993.

[13] FOREST, C. B. et al., Radio-frequency wave experiments on the MST Reversed Field Pinch, in *, Radio Frequency Power in Plasmas–Thirteenth Topical Conference, Annapolis, MD*, AIP Press, 1999.

[14] FOREST, C. B. et al., Phys. Plasmas **7** (2000) 1352.