CONTROLLING MAGNETIC TURBULENT TRANSPORT IN THE RFP*

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1. Introduction

A large part of the parallel current that flows in the outer region of a reversed field pinch (RFP) plasma cannot be maintained by toroidal induction, since it is mostly poloidal current. Instead, it is generated internally by the plasma through a turbulent dynamo relaxation mechanism. The RFP configuration is therefore usually viewed as inextricably linked to dynamo turbulence. Since dynamo normally appears with a spectrum of ~1% magnetic fluctuations, the field becomes stochastic, enhancing energy and particle transport. Reducing these poloidal mode number $m=1$ and $m=0$ MHD tearing fluctuations is the foremost challenge to improving RFP confinement. This might happen 'naturally' for a favorable scaling of the fluctuation amplitude with plasma size and temperature (i.e., Lundquist number)[1], or possibly for a 'single helicity' dynamo with just one instability[23].

A different, direct control approach to RFP concept improvement has emerged in recent years. If the necessary poloidal current can be driven externally, there is no need for a dynamo, thereby reducing magnetic turbulence and freeing the RFP from relaxation processes. Equivalently, the added current drive maintains a more stable current profile. This idea, based on a strong MHD theoretical[4] and experimental foundation, motivates ongoing current profile control experiments in the Madison Symmetric Torus (MST), with excellent progress to date. Relative to normal MST plasmas, the energy confinement time in plasmas with added inductive pulsed poloidal current drive[5] (PPCD) increases as much as nine-fold, from 1 ms to 9 ms[6]. The (total) beta value increases from 9% to 14%, exceeding for the first time and by a substantial margin the RFP 'constant beta' scaling. The electron temperature profile $T_e(r)$ peaks, and $T_e(0)$ exceeds 1.0 keV in higher current 470 kA plasmas. The average electron thermal diffusivity is reduced to a few times larger than typical of tokamak plasmas (to ~5 m^2/s). Development of refined current drive, both inductive and non-inductive using rf techniques (lower hybrid and/or electron Bernstein waves), constitutes a major goal for the MST program.

2. Fast electron confinement and magnetic stochasticity

The confinement of high energy electrons is sensitive to magnetic fluctuations, which act as 'test' particles streaming along field lines. Fast electrons are detected in MST via hard x-ray (HXR) emission in the range 10-250 keV, measured by a CdZnTe solid-state detector.

This diagnostic has been developed in collaboration with the Tore Supra group using a design similar to the HXR detectors installed on their tokamak[7]. Figure 1 shows the time evolution of the total HXR flux from a central chord in a 400 kA PPCD plasma. The evolution of the m=1 and 0 rms magnetic fluctuation amplitudes measured by coil arrays at the plasma surface are also plotted, along with the applied parallel-to-B inductive electric field at the plasma boundary to illustrate PPCD programming. The HXR emission increases markedly as soon as the magnetic fluctuation decreases, then decreases abruptly following PPCD when the fluctuations rise. Figure 2 shows the HXR energy spectra. A roughly three order-of-magnitude increase in emission at high energies during PPCD implies greatly improved fast electron confinement and substantially reduced magnetic diffusivity. The toroidal loop voltage in the core during PPCD is <5 V, requiring $>10^4$ toroidal transits to reach 80 keV. Kinetic modeling using the CQL3D Fokker-Plank code[8] is underway to quantify electron transport using the measured HXR emission. A set of 16 detectors viewing the plasma cross-section will soon be installed to permit radial transport studies.

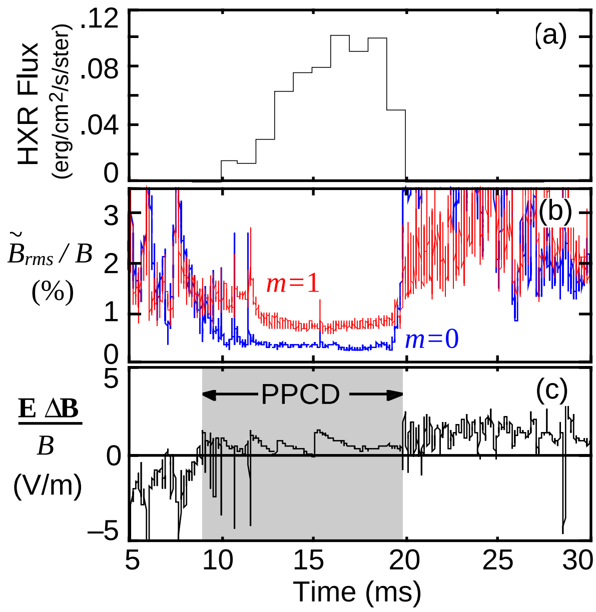

Fig. 1 (a) Total HXR flux, (b) rms m=1 and m=0 fluctuations at r=a, and (c) parallel inductive electric field at r=a.

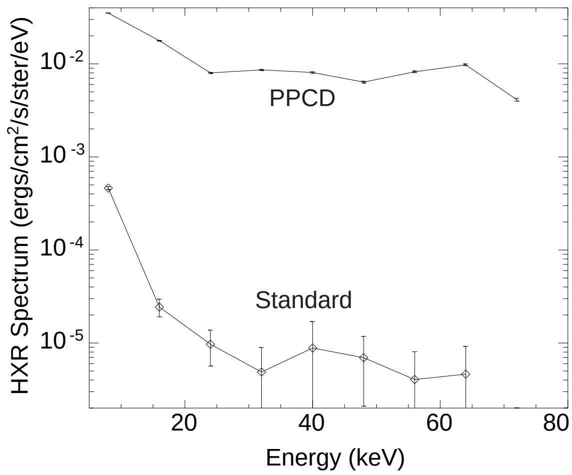

Fig. 2 Energy spectra of the HXR flux from PPCD and standard plasmas.

The edge magnetic fluctuation amplitudes shown in Fig. 1(b) are a good indicator of the internal structure, but not a direct measure of the fluctuations inside the plasma which lead to reconnection and stochasticity. MST's FIR laser system[9] has been upgraded for use as a high speed 11-chord polarimeter, providing the first nonintrusive measurement of magnetic fluctuations in the core of MST (or perhaps any fusion plasma). In particular, the Faraday rotation observed on a vertical chord passing through the magnetic axis measures the radial magnetic field fluctuation, which governs reconnection. Moreover, chord averaging favors sensitivity to poloidal mode m=1 fluctuations, exactly those expected in the RFP core. Figure 3(a) shows sample central chord Faraday rotation data illustrating the ~10 kHz magnetic fluctuation normally observed in MST plasmas. The phase between different radially viewing chords identifies this as an m=1 perturbation, well correlated with edge magnetic measurements. Figure 3(b) shows frequency power spectra of the fluctuating Faraday angle in standard and PPCD plasmas, directly confirming the anticipated reduction of magnetic fluctuations in the core. Much of the remaining fluctuation power in the PPCD spectrum is instrumental in origin. Development of a 3-laser system is underway to simultaneously measure density and magnetic fluctuations across the plasma radius.

3. Profiles and confinement

The addition of several new diagnostics on MST is providing important internal profile measurements necessary to understand and quantify current profile modifications and confinement. Two diagnostic neutral beams[10] facilitate measurements of the majority ion properties via Rutherford scattering, minority ion properties via CHERS, and internal magnetic field by the motional Stark effect (MSE). Figure 4 shows the majority ion temperature profile in 400 kA PPCD plasmas, along with the electron temperature profile measured with a movable single point Thomson scattering diagnostic (a multi-point Thomson

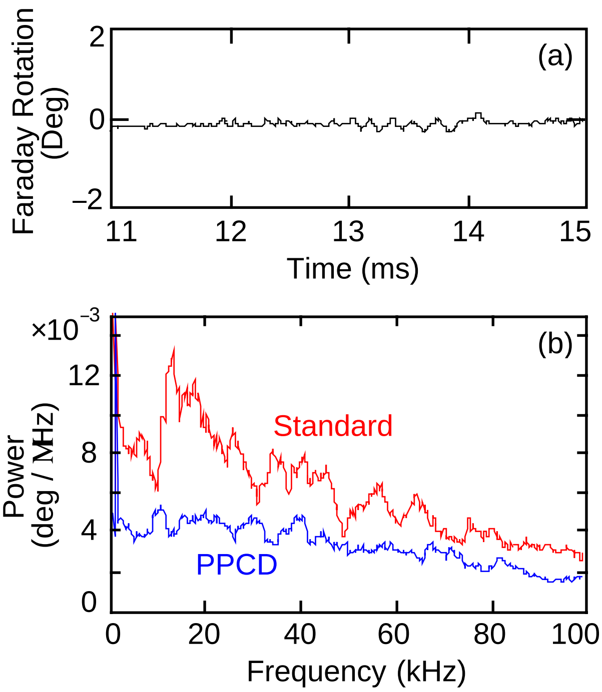

Fig. 3 (a) Faraday rotation angle showing fluctuation corresponding to internal m=1 modes, and (b) frequency power spectra in PPCD and standard plasmas.

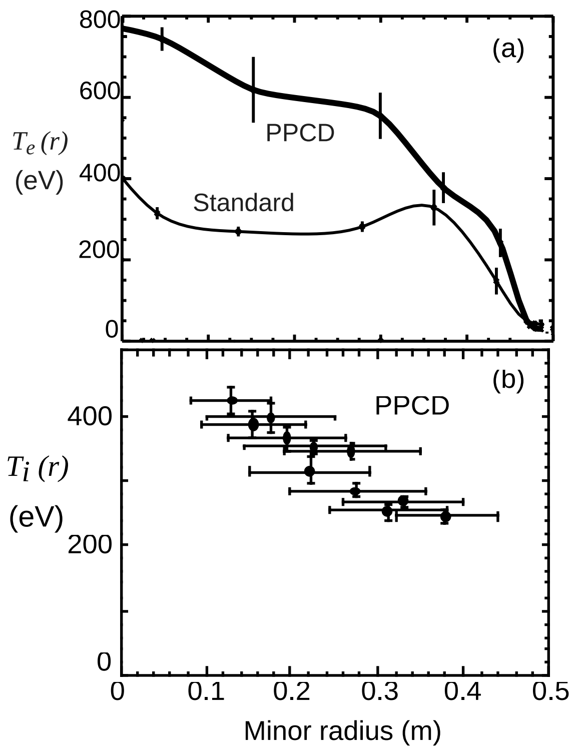

Fig. 4 (a) Electron and (b) majority ion temperature profiles.

system is under construction). An MST record high central electron temperature of $T_e(0)$=1.1 keV has been achieved in 470 kA PPCD plasmas. Ion temperature profile data for standard plasmas are under analysis, but it is know the ions are not heated as strongly as electrons during PPCD (both majority and minority species). Since the ions are anomalously hot in standard RFP plasmas, probably via a turbulent heating mechanism associated with the dynamo, the ion heating power with PPCD is likely reduced (implying increased ion energy confinement).

The Ohmic input power is calculated from the temperature profile and current profile output from toroidal equilibrium reconstructions constrained by the usual set of global magnetics (plasma current, toroidal flux, etc.), $B_\theta(r)$ from11 polarimetry chords, and a single point MSE measurement of $B(0)$ near the magnetic axis (particularly noteworthy since $B < 0.5$ T). The effective charge is not well known but conservatively Z_{eff}<2. The nine-fold increase in energy confinement quoted above is for 210 kA plasmas. For 400 kA plasmas the increase is seven-fold. Note that the increased electron temperature shown in Fig. 4 occurs with a *reduction* in heating power, a clear indication of reduced heat transport. The combination of increased confinement and beta at 210 kA exceeds the long standing ‘constant beta scaling’ by roughly an order of magnitude, proving this scaling is not fundamental to the RFP configuration.

Substantial changes in the current profile are expected and observed. At the extreme edge, the current density decreases but its profile steepens, directly measured with probes.[11] The decrease is consistent with a measured reduction in the dynamo emf.

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