

## **Current Profile Dynamics and Core Magnetic Fluctuations in the MST Reversed-Field Pinch**

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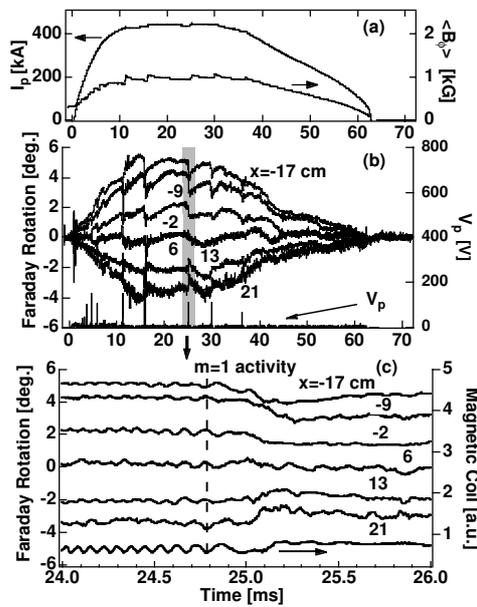
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RFP behavior, energy transport and dynamo effects, is determined in large part by magnetic fluctuations driven by the radial gradient in the parallel current density. It has long been considered that transport arises from stochasticity induced by overlapping magnetic islands, and that the current density profile is partly determined by the dynamo. Hence, measurement of magnetic fluctuations and the current density profile is essential to understanding the link between the current density distribution, fluctuations, and transport. Magnetic probes have been used to measure the edge current and magnetic field fluctuations, as well as the internal radial profiles in smaller, colder RFP plasmas. To date, however, direct non-perturbing measurement of the current density distribution and magnetic fluctuations in the core of a high-temperature RFP has been lacking.

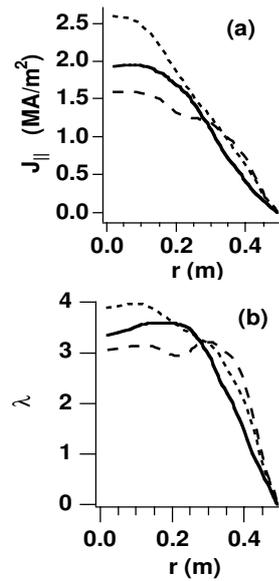
Recently, the internal magnetic field structure and core magnetic field fluctuations have been measured in a high-temperature RFP plasma using a newly developed fast-polarimetry system. The non-perturbing Faraday rotation measurement has up to 1  $\mu$ sec time response and  $\sim 1$  mrad phase resolution. MST polarimetry data for a standard sawtooth discharge with  $I_p=400$  kA is shown in Fig. 1. Each chord shows distinct sawtooth cycles, corresponding to the slow changes in the equilibrium (axisymmetric) magnetic field. With the time axis expanded to isolate an individual sawtooth crash ( $t=25$  ms), the typical crash or relaxation time scale is measured to be  $\approx 100$ -200  $\mu$ s. A clear coherent oscillation is observed on all chords prior to the sawtooth crash. The frequency ( $\sim 12$  kHz) of these fluctuations matches the dominant  $m=1$  tearing mode in MST (as measured by external magnetic coils). Finite coherence is observed for frequencies up to 100 kHz between polarimeter chords and an external magnetic sensor, indicating that the measured fluctuations are associated with magnetic activity.

Since the measured Faraday rotation angle ( $\Psi$ ) depends on both the density and magnetic field,  $\Psi = c_F \int n B_z dz$ , it is necessary to separate the two in order to isolate the fluctuating magnetic field. The fluctuating portion of the Faraday signal can be written as

$\tilde{\Psi} = c_F(\int B_{0z} \tilde{n} dz + \int \tilde{B}_z n_0 dz)$ . For all polarimeter chords shown in Fig. 1, the  $\int B_{0z} \tilde{n} dz$  term is negligible leaving  $\tilde{\Psi} \approx c_F \int \tilde{B}_z n_0 dz$  [1]. The line-integrated magnetic fluctuation amplitude can be estimated from the relation  $\overline{\tilde{B}} \equiv (\bar{n}_0 \Delta z)^{-1} \int n_0 \tilde{B}_z dz \equiv (c_F \bar{n}_0 \Delta z)^{-1} \tilde{\Psi}$ . Using the measured line-averaged density ( $\bar{n}_0$ ), chord length ( $\Delta z$ ) and Faraday rotation data (Fig. 1), we find the time-averaged rms amplitude of the magnetic field fluctuations,  $\overline{\tilde{B}} \sim 33$  G or  $\overline{\tilde{B}}/B_0 \sim 0.6\%$ . The polarimeter rms noise level is  $\sim 10$  G. Since the density profile is centrally peaked, the line-averaged  $\overline{\tilde{B}}$  measurement is weighted to the plasma core. In addition, output from the nonlinear resistive MHD simulation predicts that the eigenfunctions for the dominant tearing modes in MST (i.e.,  $m=1$ ,  $n=5-10$ ,  $f \sim 10-20$  kHz) peak in the plasma core. Both of these factors suggest that the measured  $\overline{\tilde{B}}$  is primarily a measure of magnetic fluctuations in the plasma core.



**Figure 1.** (a) Plasma current and average toroidal magnetic field, (b) Faraday rotation angle for standard Ohmic MST plasma from 6 polarimeter chords. (c) Expanded time scale.

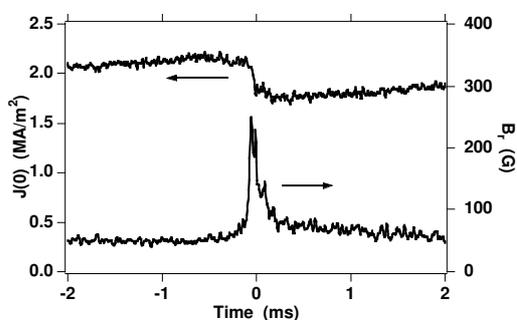


**Figure 2.** (a) Parallel current density and (b)  $\lambda$  profiles for times 0.25 ms before (solid), 0.25 ms after (long dash) sawtooth crash, and during PPCD (short dash).

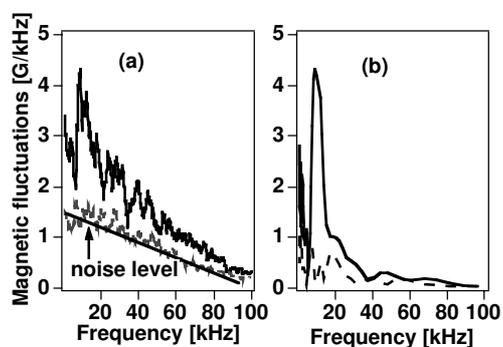
Equilibrium magnetic field measurements and equilibrium reconstruction indicate the  $q=m/n=1/6$  rational surface is located between chords ( $x=13$  and  $21$  cm) and ( $x=-9$  and  $-17$  cm). The  $\pi$  phase change observed on the polarimeter chords across this region (see Fig. 1 (c)) is consistent with expectations for a current channel associated with the island. By applying Ampere's law to the loop between adjacent chords, one can estimate the toroidal

current perturbation associated with the island. A maximum occurs when choosing chords with out-of-phase oscillations indicating the current density perturbation for the ( $m/n=1/6$ ) mode is approximately  $\tilde{j}_{m=1,n=6} / J_0 \sim 3\%$  with spatial extent  $< 8$  cm.

Based on poloidal magnetic field measurements by polarimetry and external magnetics, the toroidal equilibrium reconstruction (MSTFIT) gives the parallel current density  $J_{||}(r)$  and  $\lambda(=\mu_0 a J_{||}/B)$  profiles as shown in Fig. 2. We observe that both the  $J_{||}$  and  $\lambda$  profiles experience a slow peaking during the sawtooth rise phase, and a sudden flattening during the crash [2]. This is consistent with the MHD model of the dynamo, which drives the plasma toward a more stable (flatter  $\lambda$ ) state during the crash. As the  $\lambda$  profile peaks, magnetic fluctuations increase, eventually becoming large enough to drive the profile relaxation.



**Figure 3.** Changes in core magnetic fluctuation amplitude and current density on the axis during a sawtooth cycle [crash occurs at  $t=0$ ]. Data ensemble averaged over 400 sawtooth events.



**Figure 4.** (a) Radial magnetic field fluctuation spectrum, and (b) coherence weighted spectrum for standard sawtooth (solid line) and PPCD (dashed line) plasmas in MST.

A strong correlation between internal magnetic field fluctuations and the current density dynamics is experimentally observed. The magnetic field fluctuation amplitude for ensembled data is  $\overline{\tilde{B}} / B_0 \sim 1\%$  (before the crash) but varies significantly during the sawtooth cycle as shown in Fig. 3. The magnetic fluctuation amplitude is fairly constant until 100  $\mu$ s before the crash, when it jumps over four-fold. The equilibrium current density gradually increases during the slow ramp phase of the cycle and promptly (100-200  $\mu$ s) drops 20% at the sawtooth crash. The enhanced magnetic fluctuations are predicted to generate a dynamo electric field which acts to reduce toroidal current density in the core and increase poloidal current at the edge[2,3] as evidenced by the observed toroidal flux increase at the crash.

Recently, it has been experimentally demonstrated[4] that appropriate programming of the electric field parallel to the edge magnetic field (known as pulsed parallel current drive, or PPCD), can greatly enhance the RFP confinement properties. During PPCD operation,

the parallel current density appears to increase across the entire profile being more peaked on axis than the pre-sawtooth crash case (see Fig. 2). However, for  $r > 0.3$  m,  $J_{\parallel}(r)$  is quite similar to the post-sawtooth crash case. This is also reflected in  $\lambda(r)$  indicating the profile is being maintained closer to the more stable post-crash relaxed state by application of PPCD.

Modeling has predicted and experiment suggests that improved confinement is largely attributed to suppression of  $m=1$  core-resonant tearing modes and associated transport [5,6]. Energy and particle confinement times have been increased 10-fold while the magnetic fluctuations, as measured by external coils, are halved. New direct measurement of core magnetic fluctuations shows that the fluctuation reduction extends to, and is actually stronger in, the plasma core. The core radial magnetic field fluctuation frequency spectrum for a high-confinement PPCD plasma is shown in Fig. 4(a) along with the broadband fluctuation spectra for a standard sawtooth discharge (5 ms time average). Here it is seen that the magnetic field fluctuation amplitude is reduced across the entire spectrum (by a factor of 2 for the core modes,  $f \sim 10$ -20 kHz). In fact, the fluctuation spectrum measured during PPCD is essentially the same as the polarimeter noise spectrum implying that we are limited by the instrumental resolution. In an effort to extract the coherent portion of the spectrum from these data, we plot the coherence-weighted frequency spectra in Fig. 4(b). (The coherence weighted spectra is the product of the fluctuation spectrum and computed coherence between the  $x=6$  cm polarimeter chord and an external magnetic coil.) Here we see the coherent portion of the spectrum (10-20 kHz), which corresponds to the dominant core modes, is reduced four-fold during PPCD. This indicates that the core fluctuation amplitude is more strongly suppressed than at the edge. A change in the radial structure of the fluctuations is implied. The reduction of core magnetic fluctuations strongly correlates with increased particle and energy confinement. Current peaking during PPCD may be explained by a reduction in the dynamo effect and the emergence of high-energy runaway electrons that accompany the fluctuation reduction.

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