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

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Abstract. First measurements of the current density profile, magnetic field fluctuations and electrostatic (e.s.) particle flux in the core of a high-temperature reversed-field pinch (RFP) are presented. We report three new results: (1) The current density peaks during the slow ramp phase of the sawtooth cycle and flattens promptly at the crash. Profile flattening can be linked to magnetic relaxation and the dynamo which is predicted to drive anti-parallel current in the core. Measured core magnetic fluctuations are observed to increases four-fold at the crash. Between sawtooth crashes, measurements indicate the particle flux driven by e.s. fluctuations is too small to account for the total radial particle flux. (2) Core magnetic fluctuations are observed to decrease at least two-fold in plasmas where energy confinement time improves ten-fold. In this case, the radial particle flux is also reduced, suggesting core e.s. fluctuation-induced transport may play role in confinement. (3) The parallel current density increases in the outer region of the plasma during high confinement, as expected, due to the applied edge parallel electric field. However, the core current density also increases due to dynamo reduction and the emergence of runaway electrons.

1. Introduction

In several configurations of magnetically confined plasmas, the spatial structure of the current density is a major determinant of plasma behavior. In the reversed-field pinch (RFP), and related configurations in which the confining magnetic field is relatively small, the radial gradient in the parallel current density is predicted to drive fluctuations in the magnetic field. These magnetic fluctuations can affect the macroscopic plasma behavior in two ways. First, magnetic fluctuations can cause magnetic fields lines to wander stochastically. Energy and particle transport can then arise from particles streaming along the stochastic magnetic field lines. Second, fluctuations can generate a large-scale magnetic field through the production of current driven by the dynamo effect.

Thus, measurement of the time evolution of the radial profile of the mean current density (obtained after averaging over the poloidal and toroidal directions) as well as the fluctuating magnetic field, particularly in the high-temperature plasma core, is essential for an understanding of the fluctuations, transport, and dynamo physics. The effect of fluctuations on the current density profile is particularly strong during the crash phase of the sawtooth oscillation in the RFP. During this sudden event, the fluctuations vary significantly and are believed to alter the current density profile. Conversely, the effect of the current density on fluctuations is particularly evident during improved confinement RFP plasmas. In these plasmas transport is reduced through modification of the electric field (and current density) profile. The current density is altered, in a way to reduce fluctuations, by programming the electric field parallel to the edge magnetic field (known as pulsed parallel current drive, or PPCD).

During the past two years, work at MST on these subjects has focused on: (1) measurement of the current density profile during these two plasma conditions: sawtooth oscillation in standard RFP plasmas and improved confinement PPCD plasmas; and (2) measurement of magnetic field fluctuations (and the related current density fluctuations) as well as e.s. fluctuations in the core of a high-temperature RFP. Their relation to transport and dynamo in the RFP is investigated. To this end, we have developed a high-speed (up to 1 μs time response), non-perturbing Faraday rotation polarimetry system to measure the internal magnetic field structure (and its fluctuations), from which the current density is evaluated.[1] This has resulted in the first direct observation of broadband magnetic fluctuations in the core of a high-temperature fusion plasma by Faraday rotation (or any technique). A heavy ion beam probe (HIBP) is used to measure internal density and potential fluctuations.[2] The remainder of this paper will describe recent experimental results in these areas.

2. Equilibrium Current Density Profile Dynamics

Typical MST [R_0=1 m, a= 0.51 m] polarimetry data for a standard sawtoothing discharge with I_p=400 kA, $n_e(0)$ ~10^{19} m^{-3}, bandpass filtered at 20 kHz, are shown in Fig. 1. All chords show a strong correlation with the sawtooth cycle, even during the setup phase of the discharge (0-10 ms). Sawtooth crashes, characterized by changes in toroidal flux, are denoted by prompt increases in the average toroidal field, $\langle B_\phi \rangle$ and spikes in the surface poloidal voltage, V_p. As expected, the Faraday rotation angle changes sign about the magnetic axis due to a change in the direction of the poloidal magnetic field with respect to the polarimeter chords. Zero Faraday rotation angle indicates that the probing beam passes through the magnetic axis. The sawtooth crash represents a discrete dynamo event in the RFP.

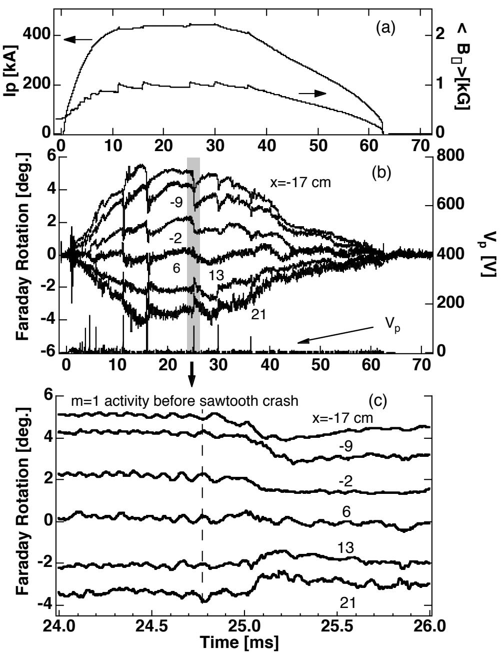

Figure 1: (a) Plasma current and average toroidal magnetic field, (b) Faraday rotation angle for standard Ohmic MST plasma from 6 polarimeter chords. (c) Expanded time scale.

In Fig. 1(c), the time axis is expanded to isolate an individual sawtooth crash (t=25 ms). The typical crash or relaxation time scale is measured to be ≈100-200 μs. A clear coherent oscillation is observed on all chords prior to the sawtooth crash. The frequency of these fluctuations matches the dominant m=1 tearing mode in MST (as measured by external magnetic coils) and peaks near ~15 kHz. Finite coherence between polarimeter chords and an external magnetic coil is observed at frequencies up to 100 kHz. Since the polarimeter measures the line-integrated product of density and magnetic field, $\alpha = c_F \int n_e B_z dz$ (1), changes observed in the Faraday rotation angle α may correspond to changes in both parameters.

Equilibrium analysis of the Faraday rotation data can be accomplished using any one of 3 independent techniques, of increasing complexity, to arrive at information on the current density distribution. The simplest analysis yields the central current density from the slope of the Faraday rotation profile across the magnetic axis which is directly proportional to J(0) [~dψ/dx]. The next approach employs a fitting method to solve the Faraday rotation equation [Eq.(1)] and yields the toroidal current density profile from Ampere's law. The most complex analysis utilizes a two-dimensional equilibrium reconstruction code (solving the Grad-Shafranov equation) to yield the current density as a function of magnetic surface coordinate. All three techniques provide consistent information on J(r).[3] To obtain the necessary polarimetry and interferometry data for equilibrium analysis, the system is first operated in polarimeter mode for 20-30 similar shots and then converted to interferometer mode for a similar number of shots to obtain the electron density. The data are ensemble averaged over the sawtooth cycle producing the profile change averaged over approximately 400 sawtooth events.

Faraday rotation profiles, taken from the ensembled data, at times immediately before (-0.25 ms) and after (+0.25 ms) the sawtooth crash are shown in Figs. 2(a) and (b), respectively. The magnetic axis corresponds to the point where ψ=0 and is shifted approximately 4-5 cm outward from the center of the conducting boundary. Reduced slope (dψ/dx), proportional to reduced current density on axis, is evident for the central chords after the sawtooth crash. The maximum rotation angle (absolute value) is larger on the inboard side due to the toroidicity of the plasma.

By use of the fitting technique, toroidal current density (J_ϕ) profiles corresponding to times before and after the sawtooth crash are generated and shown in Fig. 3(a). Corresponding fits to the measured Faraday profiles are shown as solid lines in Figs. 2(a) and (b). The toroidal current density indicates a clear 20% reduction in the plasma core, r < 0.2 m , and small increase towards the outside, r > 0.2 m, immediately following the sawtooth crash. After the crash, the flattened profile begins to slowly narrow and peak on axis until the next sawtooth or relaxation event. The toroidal current density is very small in the edge where the toroidal field reverses and the parallel direction is predominantly poloidal.

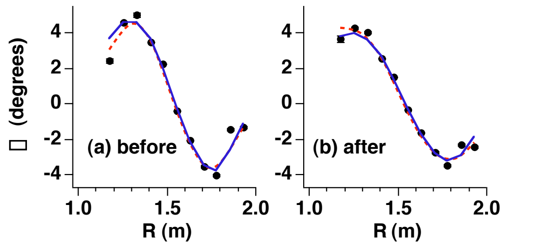

Figure 2. Measured Faraday rotation profiles at times (a) 0.25 ms before and (b) 0.25 ms after the sawtooth crash. Symbols represent the measurement points (error bars approximately equal symbol size), solid lines the functional fit and dashed lines the MSTFIT matching.

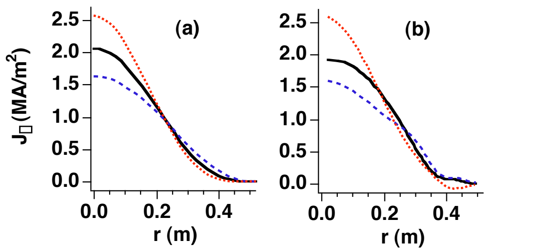

Figure 3. Toroidal current density profile generated by (a) functional fit approach and (b) MSTFIT for times 0.25 ms before (solid), 0.25 ms after (long dash) the sawtooth crash and during PPCD (short dash).

The toroidal current density determined from the equilibrium reconstruction code MSTFIT[4] is shown in Fig. 3(b). Inputs to the toroidal equilibrium code include the external magnetics, pressure profiles, motional Stark effect measurements of B(0), as well as the Faraday rotation data. The corresponding fits to the Faraday rotation profile (see Figs. 2(a) and (b)) are nearly indistinguishable from the fitting result, and both match the measured Faraday rotation profile quite well. The current density profile is very sensitive to changes in the Faraday profile. Differences in toroidal current density shape between the functional fit and equilibrium reconstruction approaches provide an indication of errors in the resulting profiles. Both results show the same general features of a peaking current density distribution which flattens significantly at the sawtooth crash. The current density decrease can potentially be explained by the MHD dynamo which is predicted to drive anti-parallel current in the plasma core.[5]

High-confinement plasmas are achieved in MST by inductively driving parallel current in the edge through a process called Pulsed Parallel Current Drive or PPCD. PPCD acts to suppress sawteeth and reduce the m=0 and m=1 resistive tearing modes that limit energy and particle confinement in RFP plasmas. Field reversal is maintained via external drive rather than the dynamo. For these improved-confinement plasmas, both the energy and particle confinement time are observed to increase ten-fold.[6,7] As shown in Fig. 3, from both the fitting method and MSTFIT equilibrium reconstruction, distinct peaking of the toroidal current density in the plasma core is observed during PPCD. The toroidal current density on axis increases by 30% compared to the pre-sawtooth-crash value while the current tends to decrease at the edge. This peaking may be explained by a reduction in the “dynamo effect” and the emergence of high-energy runaway electrons that accompany the fluctuation reduction.

The parallel current density $J_{//}(r)$ and $\lambda(=\mu_0 a J_{//}/B)$ profiles output from the toroidal equilibrium reconstructions are shown in Fig. 4, where λ is the normalized measure of the parallel current density that determines tearing mode stability and is a spatial constant for the minimum energy Taylor state. We observe that both the $J_{//}$ and λ profiles experience a slow peaking during the sawtooth rise phase, and a sudden flattening during the crash. This is again consistent with the MHD model of the dynamo, which drives the plasma toward a more stable (flatter λ) state during the crash. As the λ profile peaks, magnetic fluctuations increase (as will be shown later), eventually becoming large enough to drive the profile relaxation. During PPCD, the parallel current density appears to increase across the entire profile being more peaked on axis than the pre-sawtooth crash case. However, for r > 0.3 m, $J_{//}(r)$ 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.

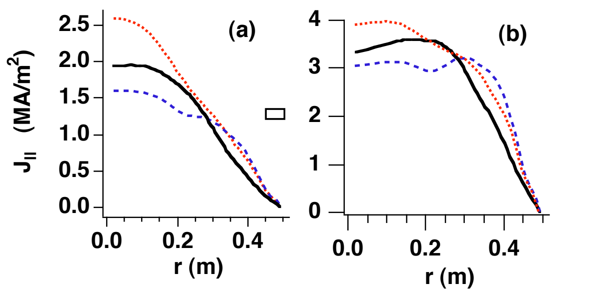

Figure 4. (a) Parallel current density and (b) λ profiles for times 0.25 ms before (solid), 0.25 ms after (long dash) sawtooth crash, and during PPCD (short dash), generated from MSTFIT equilibrium reconstruction code.

3. Fluctuation Measurements

By taking advantage of the fast polarimeter time response (~1 μs), direct information on the interior magnetic field fluctuations in MST can be obtained. However, since the measured Faraday rotation angle depends on both the density and magnetic field, it is necessary to separate the two in order to isolate the fluctuating magnetic field.[8,9] By rewriting the Faraday rotation equation in terms of the equilibrium and fluctuating quantities for each variable (e.g., $\psi = \psi_0 + \tilde{\psi}$, $B_z = B_{0z} + \tilde{B}_z$, $n_e = n_0 + \tilde{n}$), the fluctuating part becomes $\tilde{\psi} = c_F(\int B_{0z}\, \tilde{n}\, dz + \int \tilde{B}_z\, n_0\, dz)$. Here the second order term, $c_F \int \tilde{B}_z\, \tilde{n}\, dz$, is negligible because both $\tilde{n}$ and $\tilde{B}_z$ are small. From this equation we see that the fluctuating part of the polarimetry signal is the sum of the fluctuating electron density weighted by equilibrium magnetic field, and the fluctuating magnetic field weighted by equilibrium density.

For all polarimeter chords shown in Fig. 1(c), the $\int B_{0z} \tilde{n}\, dz$ term is negligible, leaving $\tilde{\alpha} \approx c_F \int \tilde{B}_z n_0 dz$. By using measured values for equilibrium poloidal magnetic field and electron density fluctuations, it can be shown that $\int B_{0z} \tilde{n}\, dz < 0.04^{\circ}$, which is less than the polarimeter rms noise level (0.1°). Finite contributions from the toroidal magnetic field to the Faraday signal resulting from misalignment have also been considered and found to be negligible.

Confirmation that the measured fluctuations are magnetic is realizedby examining the change in the amplitude and phase of the polarimetry signals. Phase measurements indicate that fluctuations (both density and magnetic field) with frequencies >5 kHz have poloidal mode number m=1 in MST. For an m=1 density perturbation, we observe a minimum, $\int \tilde{n} dz \approx 0$, for a chord going through the magnetic axis and a π-phase change for chords on opposite sides. However, the measured $\tilde{\alpha}$ shows a maximum at the magnetic axis with 0-phase change. In addition, the π-phase observed on $\tilde{\alpha}$ away from the magnetic axis occurs near the mode resonant surface. Both these observations are consistent with expectations for m=1 magnetic perturbation. For the central chord (i.e. x=6 cm), the fluctuating Faraday rotation signal provides a chord-integrated measurement of radial magnetic field fluctuations.

The line-integrated magnetic fluctuation amplitude can be estimated from the relation $\bar{\tilde{B}} \approx (\bar{n}_0 \Delta z)^{-1} \int n_0 \tilde{B}_z dz \approx (c_F \bar{n}_0 \Delta z)^{-1} \tilde{\alpha}$. Using the measured line-averaged density ($\bar{n}_0$), chord length (Δz) and Faraday rotation, we find the time-averaged rms amplitude of the magnetic field fluctuations, $\bar{\tilde{B}}_r$ ~ 33 G or $\bar{\tilde{B}}_r / B_0$~0.6%, for the data shown in Fig. 1(c). The polarimeter rms noise level is ~10 G. Since the density profile is centrally peaked, the $\bar{\tilde{B}}_r$ measurement is weighted to the plasma core. In addition, output from a 3-D, nonlinear, resistive MHD simulation[10] predicts that the eigenfunctions for the dominant tearing modes in MST (i.e., m=1, n=5-10, f~10-20 kHz) peak in the plasma core. Both of these factors suggest that the measured $\bar{\tilde{B}}_r$ is primarily a measure of magnetic fluctuations in the plasma core.

Global magnetic field fluctuations are generated by current fluctuations in the vicinity of the resonant surface. The data shown in Fig. 1(c) are for a time where a single m=1, n=6 mode dominated all other core-resonant modes. Equilibrium magnetic field measurements and equilibrium reconstruction (not shown here) 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 π phase change observed on the polarimeter chords across the q=1/6 surface [see Fig. 1 (c)] is consistent with expectations for a current channel associated with the magnetic island. The fluctuating toroidal current ($\tilde{I}_{\phi}$) for this mode can be estimated using Ampere's law:

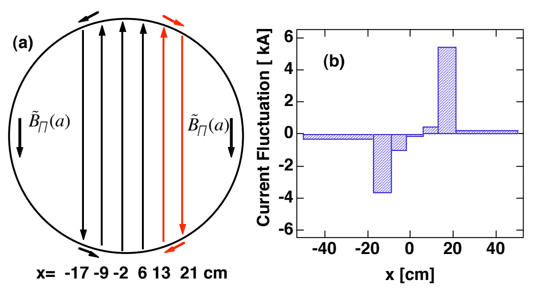

Figure 5. (a) MST cross section showing chord positions and loops used to calculate current perturbation. Arrows indicate the direction of fluctuating magnetic field. (b) Spatial distribution of fluctuating toroidal current.

$$\oint_L \tilde{\vec{B}} \bullet d\vec{l} \approx \left[\int \tilde{B}_z dz \right]_{x1} - \left[\int \tilde{B}_z dz \right]_{x2} \approx \mu_0 \tilde{I}_\phi , \qquad (2)$$

where L represents the closed loop formed between any 2 chords as shown in Fig. 5(a). Contributions from the portion of the loop along the plasma edge but between the chords are negligible due to both the short distance and small fluctuation amplitude. Evaluating Eq.(2) between outboard chords (x_1=13 and x_2=21 cm) gives $\tilde{I}_\phi \approx \frac{2}{\mu_0} \int \tilde{B}_z dz \approx \frac{2\tilde{\Psi}}{\mu_0 c_F \bar{n}_0} \approx 5.4$ kA. Taking $\tilde{\Psi} = \int n_0 \tilde{B}_z dz \approx \bar{n}_0 \int \tilde{B}_z dz$ is a good approximation for MST plasmas where the electron density profile is flat in the core and the fluctuating magnetic field falls off rapidly towards the wall.

By taking the loop between adjacent pairs of chords, the spatial distribution of the fluctuating current can be obtained as shown in Fig. 5(b). For adjacent chords with out-of-phase oscillations, the two terms in Eq.(3) add. When applying Ampere's law to adjacent chords with in-phase oscillations (e.g., x_1=6 and x_2=13 cm), the toroidal current perturbation is small because the two terms of Eq.(3) essentially cancel. The fluctuating current distribution shows an m=1 nature as expected (m/n=1/6), peaking sharply at the resonant surface with spatial extent ≤ 8 cm. Precise measurement of the current perturbation spatial extent is limited by chord spacing. The average current density perturbation for this large (m/n=1/6) mode is approximately $\tilde{j}_{m=1,n=6} / J_0 \sim 3\%$ before a sawtooth crash in MST. This value is comparable to predictions from a 3-D, nonlinear, resistive MHD simulation using the DEBS code[10] which has been widely utilized to investigate RFP dynamics.

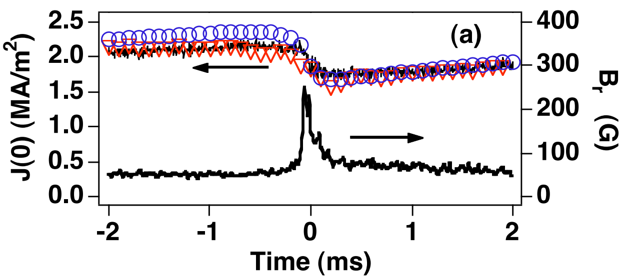

Figure 6. (a) Comparison of J(0) and $\tilde{B}_r$ through a sawtooth cycle[crash occurs at t=0]. Measured J(0) from slope model [solid line], cylindrical equilibrium model [open circles, Δ = 7%], and fitting method [open triangles].

A strong correlation between internal magnetic field fluctuations and the current density dynamics is experimentally observed. Direct experimental measurement shows that the current density on axis drops by 20% during the sawtooth relaxation. The magnetic field fluctuation amplitude for ensembled data is $\tilde{\bar{B}}_r / B_0$~1% (before the crash) but varies significantly during the sawtooth cycle as shown in Fig. 6. The magnetic fluctuation amplitude is fairly constant until just before the crash, when it jumps over four-fold within ~50 μs. The enhanced magnetic fluctuations are predicted to generate a dynamo electric field ($E_{MHD} = \langle \tilde{v} \times \tilde{B} \rangle_\parallel$) which acts to reduce toroidal current density in the core (see Figs. 3 and 6) and increase poloidal current at the edge (Fig. 4) as evidenced by toroidal flux increase at the crash (see Fig. 1(a)), according to parallel Ohm's law $J_\parallel = \sigma (E_\parallel + E_{MHD})$.[3,11,12] Here, E_{MHD} is a fluctuation driven EMF associated with tearing mode activity. In the future, localized measurements of $\tilde{v}$ will allow direct measurement of the dynamo EMF in the plasma core.

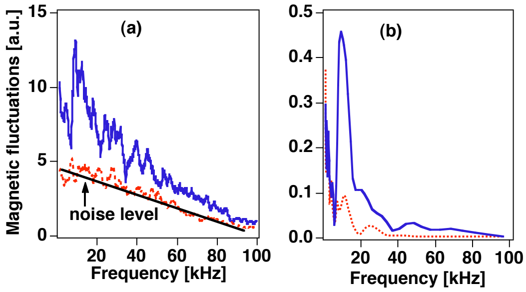

Figure 7. (a) Radial magnetic field fluctuation spectrum, and (b) coherence weighted spectrum for standard sawtoothing (solid line) and PPCD (dashed line) plasmas in MST.

The core radial magnetic field fluctuation frequency spectrum for a high-confinement PPCD plasma is shown in Fig. 7(a) along with the broadband fluctuation spectrum for a standard sawtoothing discharge (using 5 ms time average). Here it is clearly seen that the magnetic field fluctuation amplitude is reduced across the entire spectrum (by at least a factor of 2 for the core modes, f~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. 7(b). The coherence weighted spectra is the product of the fluctuation spectrum and the computed coherence between the x=6 cm polarimeter chord and an external magnetic coil. Here we see the coherent portion of the spectrum from 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 flattening of the $J_{//}$ profile (Fig. 4) at the edge (acting to suppress the magnetic fluctuations) and increased particle and energy confinement.

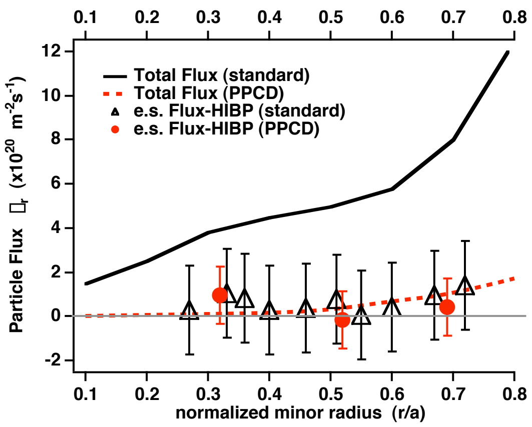

Figure 8. Preliminary electrostatic fluctuation-induced particle flux measurements by HIBP.

A heavy ion beam probe (HIBP) is employed to make simultaneous measurements of density and potential fluctuations in the region 0.25<r/a<0.72. Using reasonable assumptions for wavenumber, the flux is estimated to be an order of magnitude too small to account for the total particle flux between sawtooth crashes, as shown in Fig. 8. The fluctuations are dominated by the large-amplitude tearing modes and show substantial variation from realization to realization. During PPCD, reduction of the total radial electron flux over the entire cross section reveals the strong influence of magnetic fluctuations on the core particle transport.[7] The flux estimated from e.s. fluctuations during PPCD is not significantly changed but the total flux has decreased to fall within the data scatter. This suggests the possibility that the e.s. fluctuation-induced particle flux may contribute appreciably to the overall particle transport during PPCD. However, since the data scatter is significantly larger that the actual flux, the role played by e.s. fluctuations during PPCD remains under active investigation.

Temporal evolution of the magnetic fluctuation frequency spectra, as measured by the fast polarimeter, are shown in Fig. 9 for a PPCD discharge where the magnetic fluctuations were not completely suppressed. During the time of improved confinement (12-20 msec), a low-

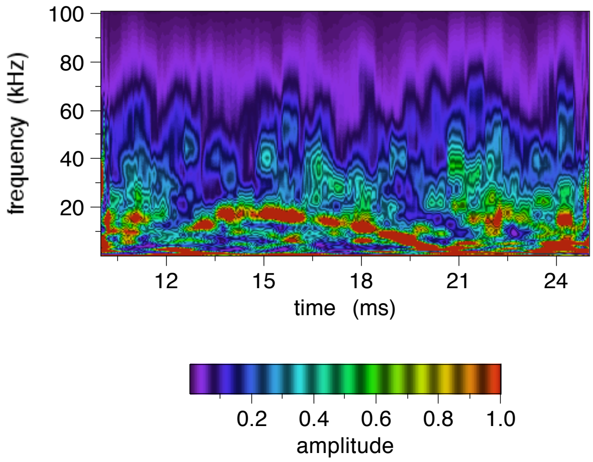

Figure 9. Time evolution of Faraday rotation fluctuation spectrum during a quasi-single-helicity PPCD shot on MST.

frequency mode (5-20 kHz, n~6) is observed to spin-up and then slow down. Peaking of the core current density during PPCD (Figs. 3 and 4) may act to destabilize the innermost resonant resistive tearing modes. The mode amplitude also varies considerably with time and appears to have a bursting nature. These dynamics are observed on all chords and are a topic of current investigation.

4. Summary

The current density profile, magnetic (and current density) fluctuations and e.s fluctuations have been measured for the first time in the core of a high-temperature RFP. The current density, as determined from both measurement and equilibrium reconstruction, peaks during the slow ramp phase of the sawtooth cycle and flattens promptly at the crash. Measured core magnetic fluctuations are observed to increase four-fold at the crash linking profile flattening to magnetic relaxation and the dynamo. Core magnetic fluctuations are observed to decrease at least two-fold in plasmas where energy confinement time improves ten-fold. In this case, the radial particle flux is also reduced, raising the possibility that core e.s. fluctuation-induced transport may play a role in governing the overall confinement. The parallel current density increases in the outer region of the plasma during high confinement, as expected, due to the applied edge parallel electric field. However, the core current density also increases due to dynamo reduction and the emergence of runaway electrons.

Acknowledgements

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