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Plasma Phys. Control. Fusion **53** (2011) 112001 (6pp) doi:10.1088/0741-3335/53/11/112001

BRIEF COMMUNICATION

Electron temperature fluctuations during sawtooth events in a reversed-field pinch

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Received 13 May 2011, in final form 22 August 2011
Published 13 October 2011
Online at stacks.iop.org/PPCF/53/112001

Abstract
Electron temperature fluctuations are correlated with the dominant $(m, n) = (0, 1)$ edge-resonant magnetic tearing mode during sawtooth events in the Madison Symmetric Torus reversed-field pinch. Electron temperature fluctuations in phase with the (0, 1) tearing mode are measured using high-repetition-rate Thomson scattering. Immediately prior to the sawtooth the (0, 1) island structure appears to be heat-confining, while during the sawtooth it assumes an isothermal character. Core electron temperature variation is also phase correlated with the (0, 1) mode, suggesting that the edge-resonant tearing mode has an effect on core electron thermal confinement during sawtooth events.

(Some figures may appear in colour only in the online journal)

In standard operation, reversed-field pinch (RFP) tearing modes produce cyclic oscillations (sawteeth) in all macroscopic quantities [1]. Owing to the rapid electron equilibration along field lines, electron temperature measurements provide an excellent tool for deducing the confinement properties associated with tearing mode induced magnetic fluctuations. In the following, high fidelity Thomson scattering (TS) data is used to describe detailed aspects of electron temperature behavior during sawtooth events in the Madison Symmetric Torus (MST) [2] RFP.

Recently, electron temperature fluctuations were correlated with the phase of core-resonant, poloidal mode number $m = 1$ tearing modes and coherent temperature structures were observed in the core of the plasma [3]. However, all $m = 1$ correlated fluctuations vanish 0.2 ms before the sawtooth and appear again 0.5 ms after the crash. This is the precise time when the edge-localized, $m = 0$, toroidal mode number $n = 1$ mode amplitude grows nonlinearly

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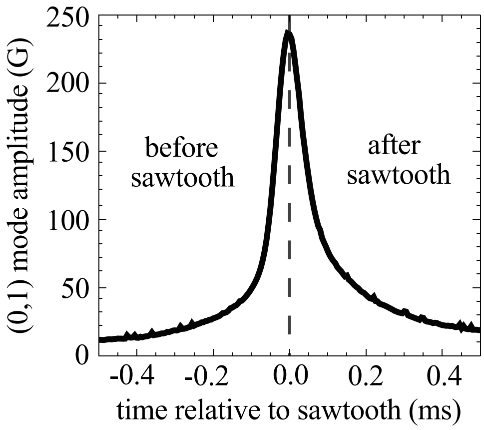

Figure 1. Ensemble-averaged (0, 1) mode amplitude through the sawtooth crash, measured at the wall. $t = 0$ is plotted as a vertical dashed line.

from 10 G to over 200 G and then crashes (see figure 1). During this time electron temperature fluctuations are phase-correlated with the rotating $(m, n) = (0, 1)$ magnetic island, forming electron temperature structures with varying behavior. The fluctuations correlated with the (0, 1) mode are absent 0.2 ms before the sawtooth and 0.3 ms after the sawtooth and are not present between sawteeth. Immediately prior to the crash an edge temperature fluctuation is observed which appears to be heat-confining, while after the sawtooth the edge fluctuation assumes isothermal characteristics.

Immediately after the crash the core electron temperature develops phase-correlated (0, 1) structure. Core electron thermal confinement is reduced significantly during sawtooth crashes with overall core heat loss of about 100 eV ($\sim$25%) in 0.2 ms [4, 5]. The results of the (0, 1) correlated electron temperature fluctuation analysis in the core and edge indicate that (0, 1) mode behavior during the sawtooth is directly correlated with aspects of the core electron thermal confinement.

Electron temperature is measured with multi-point, multi-pulse TS [6–8] using ‘pulse-burst’ mode [9]. Pulses travel vertically through the MST vacuum vessel and scattered light is collected at 21 spatial points from the core to the edge with $\sim$1.3 cm (2.6% of the plasma minor radius) resolution in the core and $\sim$2.2 cm (4.4%) resolution in the edge. Typical statistical measurement error is $\sim$10%. Thirty profiles are measured per discharge in 5 bursts of 6 pulses at 25 kHz. An ensemble of pulse-burst measurements from $\sim$50 discharges is used to determine electron temperature fluctuations. The macroscopic characteristics of sawteeth in MST are extremely reproducible, and the use of statistical ensembles to determine fluctuation amplitudes is a well-established technique for MST plasma conditions. An analysis time window of 0.2 ms was chosen as the best balance between resolution of time dynamics and fluctuation amplitude even though it results in some overlap in the ‘before’ and ‘after’ sawtooth measurements. Note that this time window choice allows inclusion of all 6 measurements in a burst in a fluctuation ensemble, although typically fewer measurements per burst are used because burst timing is random with respect to the sawtooth time.

Tearing modes in MST rotate at $\sim$10 kHz so electron temperature fluctuations cannot be well-determined from TS measurements alone. Instead fluctuations are correlated with the (0, 1) tearing mode using Bayesian analysis [10] of TS data and magnetic field pickup coil data [11]. To ensure accurate results, the analysis is performed only on discharges with plasma current between 385 and 420 kA and electron density between 0.85×10^{13} and 1.15×10^{13} cm^{-3}.

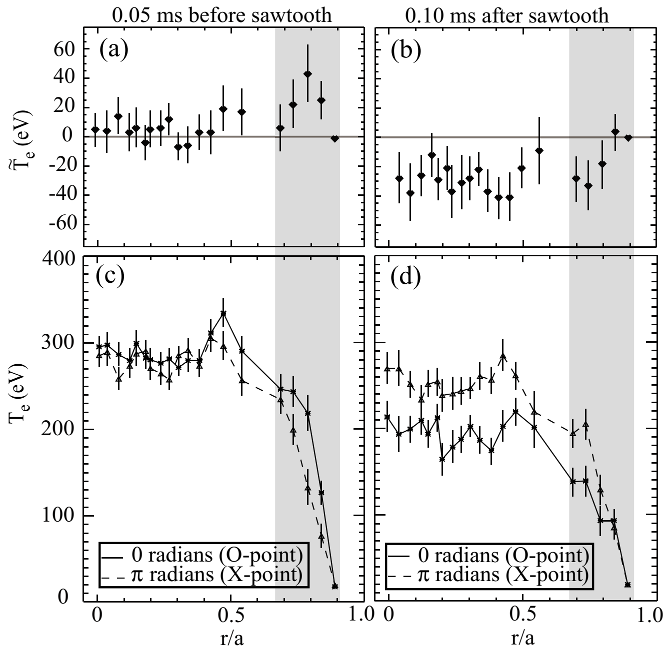

Figure 2. (0, 1) correlated fluctuation amplitudes (*a*) before and (*b*) after the sawtooth crash, and full electron temperature profiles at $\Delta_{TS} = 0$ and $\Delta_{TS} = \pi$ (*c*) before and (*d*) after the sawtooth crash. The horizontal axis is the normalized minor radial coordinate with $a = 0.52$ m. The gray areas highlight the regions of interest near the edge. Errors are estimated from the widths of the final probability distribution functions (PDFs) as determined by the Bayesian analysis.

Magnetic measurements are made at the wall of the MST vacuum vessel with a toroidal array of pickup coils. The model used in Bayesian analysis is

$$T_{e,\text{model}} = T_{e0} + \tilde{T}_{e(m,n)} \cos \Delta_{TS(m,n)} \tag{1}$$

where T_{e0} is the equilibrium component and $\tilde{T}_{e(m,n)}$ is the temperature fluctuation amplitude. $\Delta_{TS(m,n)}$ is the phase of the tearing mode measured by the toroidal array of pickup coils shifted to the physical location of the TS diagnostic. The definition of phase is chosen such that $\Delta_{TS} = 0$ when the O-point of the (0, 1) magnetic island is at the TS location and $\Delta_{TS} = \pi$ at the X-point. For a description of the (0, 1) magnetic island geometry with definitions of the O- and X-points, see figure 2 in reference [11].

Before the sawtooth a positive edge $\tilde{T}_{e(0,1)}$ is observed and after the sawtooth the edge $\tilde{T}_{e(0,1)}$ is negative, suggesting different electron temperature behavior due to rapid (0, 1) mode growth. The electron temperature fluctuation amplitudes are plotted in figures 2(*a*) and (*b*). The effect of the electron temperature fluctuations on the full electron temperature, $T_e = T_{e0} + \tilde{T}_{e(0,1)} \cos \Delta_{TS(0,1)}$, is shown in figures 2(*c*) and (*d*). Before the sawtooth the O-point appears to confine heat across a radial region where the X-point maintains a gradient, as shown in figures 2(*c*) and 3(left). This is consistent with the formation of a heat-confining island, which refers to the state where temperature is stored within flux surfaces associated with a magnetic island chain.

After the crash, the edge electron temperature at the toroidal phase associated with the O-point is lowered relative to the X-point and appears flattened, suggesting that the (0, 1) magnetic island creates an electron temperature island with isothermal behavior. An isothermal island

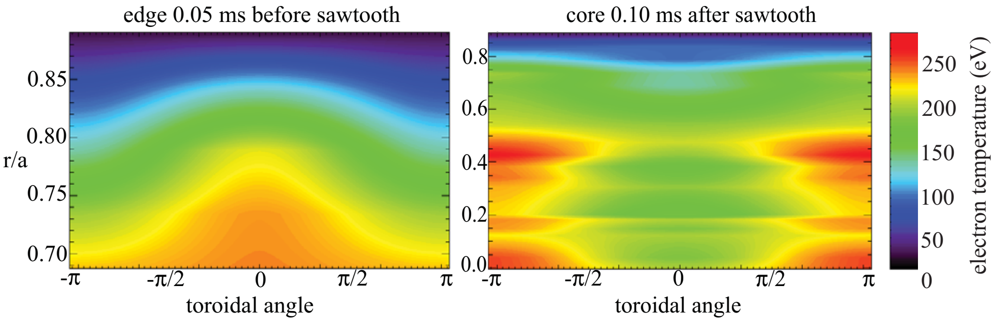

Figure 3. (Left) contour plot of the electron temperature at the edge of MST prior to the sawtooth. Heat is confined at $\Delta_{TS} = 0$ compared with $\Delta_{TS} = \pi$. (Right) contour plot of the electron temperature variation due to (0,1) correlated fluctuations after the sawtooth, from core to edge. Note that the ordinate range of the plots differs.

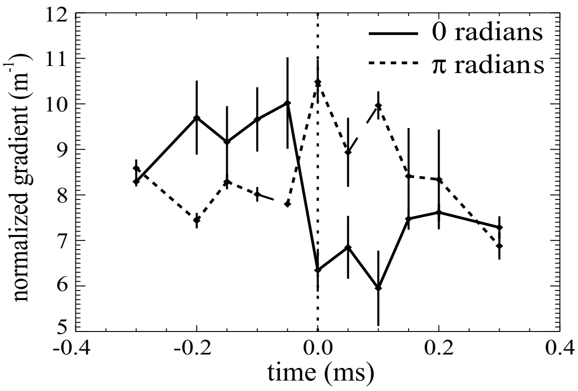

Figure 4. Normalized edge electron temperature gradient at the O-point (0 radians) and the X-point (π radians) of the magnetic island through the sawtooth crash. $t = 0$ is denoted by the vertical line. Errors are propagated through the calculations using the widths of the final PDFs.

refers to a state where temperature has equilibrated along each flux surface associated with an isolated magnetic island chain. Figure 2(*d*) exhibits this characteristic near $r/a \sim 0.8$–0.85, the expected location of the (0, 1) magnetic island chain. This behavior is not observed prior to the crash.

Figures 2(*c*) and (*d*) and 3(left) show the edge electron temperature gradient affected by the (0, 1) correlated electron temperature fluctuations. The edge gradients are quantified at the toroidal phases associated with the O- and X-points of the magnetic mode and are normalized to the average core T_{e0}, shown in figure 4. Before the crash the gradient at the O-point is enhanced by the electron temperature fluctuation, consistent with a heat-confining island. After the sawtooth the confining gradient at the O-point is reduced, consistent with an isothermal island, and remains smaller than the gradient at the X-point until ~0.2 ms after the crash.

The core electron temperature correlates with the phase of the edge-resonant (0, 1) magnetic tearing mode after the sawtooth event. Finite negative fluctuation amplitudes are observed across the entire minor radius of the plasma from 0 to 0.15 ms, indicating that the core electron temperature is reduced at the toroidal phase corresponding to the O-point of the mode. The finite core fluctuations can be seen at 0.1 ms in figures 2(*b*) and 3(right).

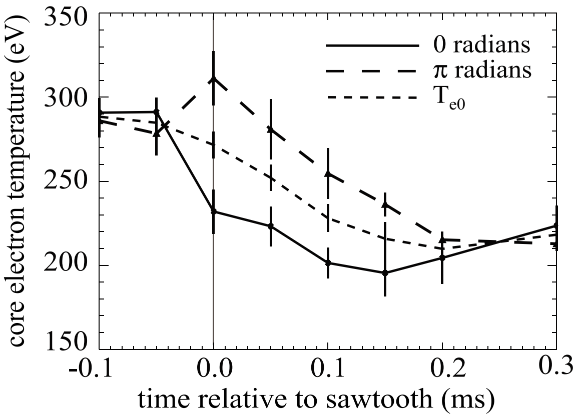

Figure 5. Comparison of core electron temperature at $\Delta_{TS} = 0$ and $\Delta_{TS} = \pi$ with the equilibrium electron temperature, T_{e0}. Errors are propagated through the calculations using the widths of the final PDFs.

Figure 5 compares core electron temperature at toroidal phases corresponding to the O- and X-points of the (0, 1) mode with the equilibrium electron temperature, T_{e0}. T_{e0} reproduces the expected core electron temperature evolution through the sawtooth crash by dropping nearly 100 eV, suggesting a simple description of core electron thermal confinement through the sawtooth. When the (0, 1) magnetic island grows prior to the crash, it confines heat. At the crash, the edge electron temperature gradient at the toroidal phase associated with the O-point is reduced while an isothermal island forms. This allows rapid heat flow out of the core at the toroidal phase associated with the O-point, giving the observed core (0, 1) electron temperature fluctuation. T_{e0} responds to this heat sink and cools in 0.2 ms. The result is a core electron temperature about 100 eV colder after the sawtooth crash.

In conclusion, electron temperature fluctuations are correlated with the dominant $(m, n) =$ (0, 1) magnetic tearing mode during sawtooth events in the MST RFP. Observed fluctuations at the edge indicate a heat-confining electron temperature island before the sawtooth. The island exhibits isothermal characteristics after the crash. The edge fluctuation during the sawtooth lowers the confining edge electron temperature gradient at the O-point of the (0, 1) magnetic island and a core fluctuation appears with reduced electron thermal confinement. It appears that the growth and subsequent crash of the edge-resonant (0, 1) mode amplitude during the sawtooth has a direct effect on core electron thermal confinement. While the eigenfunction of the (0, 1) tearing mode is non-zero in the plasma core, the nonlinear magnetic island associated with this mode does not penetrate deep into the core region of MST. As such, a possible reason for the correlation of the (0, 1) activity and the core temperature response is nonlinear coupling between the core-resonant $m = 1$ tearing modes and the edge-resonant $m = 0$ mode. Future work will increase the radial resolution of the TS diagnostic near the edge and improve time resolution, allowing better characterization of the edge electron temperature structure.

Acknowledgments

The authors would like to thank C R Sovinec, E Parke, M T Borchardt, A F Falkowski, and A P Beardsley. This work is supported by the US Department of Energy and the National Science Foundation.

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