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SAWTOOTH PRECURSOR OSCILLATIONS ON DIII-D

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Abstract **–The sawtooth oscillation, observed in tokamak plasmas with a central safety factor of less than unity, is a periodic disruptive instability characterized by a slow ramping of central plasma density and temperature, followed by a fast relaxation resulting in flattening of both profiles. Elongated, neutral beam heated discharges on the DIII-D tokamak exhibit multiple precursor oscillations with mode number *m*/*n* = 1/1. The dominant *m*/*n* = 1/1 mode oscillates at the plasma rotation frequency. A down-shifted mode also appears early in the sawtooth ramp. A normalization of electron cyclotron emission imaging (ECEI) data which removes the contribution of slow electron temperature profile evolution reveals that both modes are consistent with an underlying quasi-interchange plasma displacement.**

Sawtooth oscillations on the DIII-D tokamak are accompanied by a variety of pre and post-cursor oscillations with mode number *m*/*n* = 1/1 and higher harmonics thereof. Plasma shaping has been observed to influence the nature of these modes, resulting in discharges which exhibit either long-lived, quasi-stable precursors or none at all [1]. The MHD spectra associated with sawteeth in elongated, low triangularity discharges are composed of a dominant *m*/*n* = 1/1 mode oscillating at the plasma rotation frequency, and a down-shifted mode which appears early in the sawtooth ramp. Interpretation of these modes, however, is complicated by spontaneous redistribution of plasma current during the sawtooth ramp.

A secondary slow relaxation of the temperature profile is routinely observed midway through the sawtooth period. Fitted current profiles constrained by motional Stark effect (MSE) measurements imply that this so-called relaxation event, or RE, corresponds to a transition from a hollow current profile with an off-axis minimum in the safety factor, *q*, to a centrally peaked current profile with a single rational flux surface where *q* = 1. Core temperature also transitions from a flat profile to one which is peaked on axis.

Electron cyclotron emission imaging (ECEI), recently commissioned on the DIII-D tokamak [2], is a novel diagnostic system capable of providing localized, 2D images of electron temperature fluctuations. The dominant *m*/*n* = 1/1 mode oscillating at the plasma rotation frequency and the down-shifted mode arising early in the sawtooth ramp are readily identified in the auto-correlated ECEI data. They may be imaged individually by applying high order digital frequency filtering which retains several harmonics and therefore does not modify the 2D shape of the mode. Under an approximation of rigid-body rotation, the complete poloidal mode structure of these stable, periodic oscillations has been reconstructed from the instantaneous diagnostic view. The elongation of the plasma, κ, which is 1.65 for the case shown, is not included when mapping the data to the poloidal plane. However, circular approximation of the mode provides a unique and enlightening visualization tool.

Under the assumption of a divergence free convection, the observed fluctuation in electron temperature is related to plasma displacement, ξ, by $\delta T_e / \langle T_e \rangle = -\xi \cdot \nabla \langle T_e \rangle / \langle T_e \rangle$. When the mean electron temperature profile, denoted by the bracketed quantities, is taken from an ensemble average over the entire sawtooth period, the slow (~15 Hz) evolution of the temperature profile is included in the image of the perturbation. This results in the normalized temperature eigenmodes shown in Figure 1 (a) and (b), which are strikingly different. In Figure 1 (a), a hot, approximately circular, temperature island appears to be displaced by a cold, crescent-shaped depression. This is due to the temperature profile being peaked on axis. In contrast, a partially flattened core temperature profile results in the appearance of an elongated hot temperature island in Figure 1 (b). Taking the mean temperature profile from ensemble averages much shorter than the resistive diffusion time (yet encompassing many fast oscillations) allows the temperature fluctuations shown in Figure 1 (c) and (d) to be obtained. It is revealed that the two perturbations, though oscillating at different frequencies (5 and 7 kHz, respectively), exhibit similar 2D structure with anti-symmetric hot and cold temperature islands.

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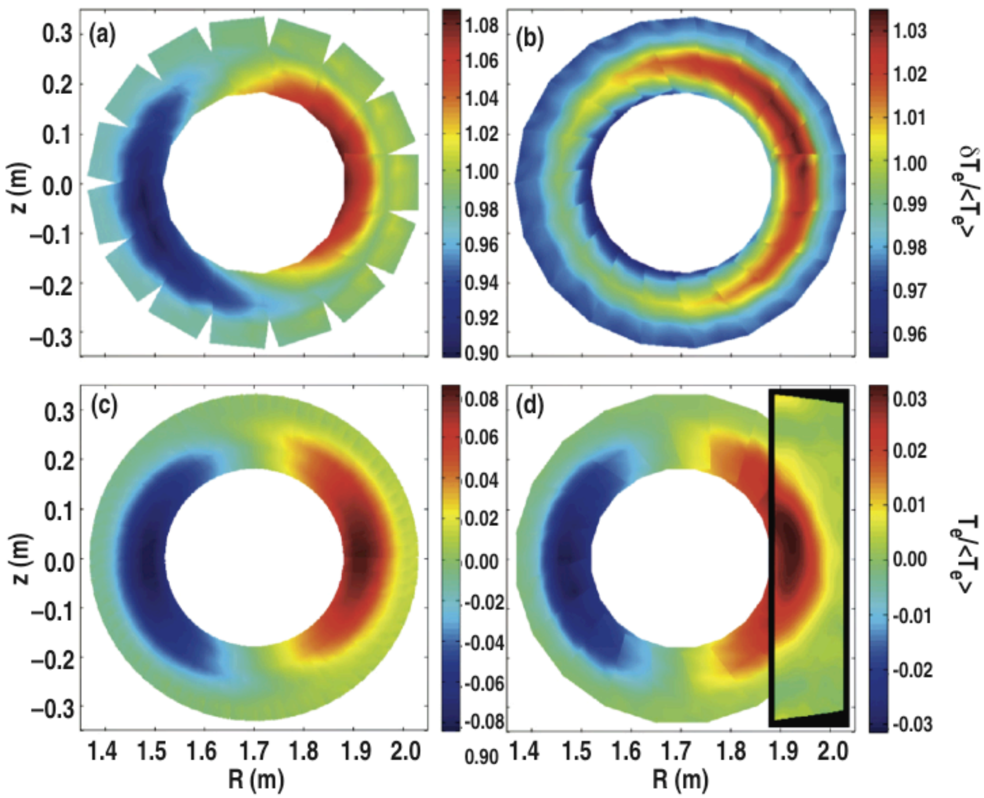

Fig. 1. Two distinct m/n = 1/1 electron temperature perturbations are identified during the sawtooth ramp. The normalized electron temperature of each poloidal mode is reconstructed under an approximation rigid-body rotation in (a) and (b). While on-axis temperature peaking occurs, the dominant m/n = 1/1 mode, (a), is manifest as a circular hot temperature island accompanied by a crescent shaped cold island. It oscillates at the plasma rotation frequency, which is in this case ~7 kHz. Early in the sawtooth ramp, while the core temperature profile is partially flattened, a down-shifted 5 kHz oscillation, shown in (b), is also present and appears as an elongated hot temperature island. When the contribution of slow (~15 Hz) electron temperature profile evolution is removed, as in the corresponding plots of (c) and (d), the 2D temperature fluctuations are found to be indistinguishable. The complete instantaneous view of an electron cyclotron emission imaging array is overlaid in (d) for reference.

In assuming that electron kinetic pressure, density, and temperature are all three conserved on a surface of constant magnetic flux, ψ, the plasma displacement may be decomposed into orthogonal components ξ_θ and $\xi_\psi = \xi \cdot \nabla\psi / |\nabla\psi|$, such that ξ_θ is oriented along an isothermal and hence gives rise to no temperature perturbation. Under this assumption of isothermal flux surfaces, radial plasma displacements corresponding to the temperature perturbations of Fig. 1 may be described by $\xi_\psi = \xi_{\psi 0} \cos\theta$, where $\xi_{\psi 0}$ is an approximately Gaussian function of plasma minor radius. Furthermore, it may be inferred that the resulting lines of convection within the core are parallel. This description favors the identification of a quasi-interchange convection cell with a broad region of poloidal return flow [3]. Great care must be taken in this interpretation, however, since poloidal flow is not directly measured by ECEI.

In summary, the poloidal structure of m/n = 1/1 modes has been obtained with ECEI under the approximation of circular, rigid-body rotation. This visualization tool has been applied to both the dominant m/n = 1/1 sawtooth precursor and a downshifted mode appearing early in the sawtooth period, revealing both to be consistent with a quasi-interchange plasma convection. Applying the assumption of a divergence free displacement, a convection cell is inferred with a uniformly directed displacement of the core plasma and a broad region of poloidal return flow. While ambiguity remains in this interpretation due to the lack of a direct measurement of poloidal displacement, Fig. 1 clearly demonstrates that quasi-interchange behavior may not be precluded on the basis of a normalized temperature, $T_e/\langle T_e \rangle$, eigenmode alone.

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