9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

The Poloidal Particle Dynamic during Sawtooth Collapse on J-TEXT

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The "sawtooth" instability, a periodic internal collapse phenomenon observed in all tokamaks [1], is characterized by a gradual peaking of the electron temperature profile followed by rapid flattening in the central plasma. This rapid flattening manifests as a temperature collapse inside the inversion radius (r_s) and a subsequent increase between (r_s) and the mixing radius r_{mix}), with minimal perturbations beyond (r_{mix}) [1]. Sawtooth collapse is an important mechanism for preventing helium ash accumulation in fusion plasmas, but it can also generate harmful instabilities [2, 3] that pose significant risks to fusion devices.

Sawtooth collapse is widely understood to result from a reconnection process occurring on the q=1 surface. This process leads to the mixing of magnetic flux inside the q=1 surface with flux in the region between the q=1 surface and the mixing surface.

Previous experimental studies have investigated sawtooth behavior in detail using Soft X-Ray emission arrays (SXR) [4], Electron Cyclotron Emission (Imaging) systems (ECE(I)) [5], and Thomson Scattering systems (TS) [6]. Notably, ECEI provides direct 2D measurements of electron temperature perturbations across a cross-section, revealing features such as the X-point [7] and m/n=1/1 kink-like motion of the hot core [8]. These observations are consistent with the reconnection model description.

Despite these insights, experimental research on electron density perturbations across the entire cross-section during sawtooth collapse remains limited. Reflectometry observations in Tore-Supra revealed that the density evolution is decoupled from the temperature evolution, forming a distinctive crescent structure after collapse. This structure was attributed to fast electric drift velocity jets generated at the reconnection layer in rotating plasma. XTOR-2F code simulations produced a similar post-collapse density structure [9].

The 17-channel polarimeter-interferometer on J-TEXT revealed that during sawtooth collapse, density increases only occur locally within a specific poloidal direction in the region between r_s and r_{mix}. Furthermore, this direction is consistently opposite (high-field side or low-field side) to the dense core location of the 1/1 precursor. This asymmetry leads to a ~6% asymmetry in the density profile after collapse. In contrast, the temperature perturbation remains poloidally symmetric during collapse [10].

We propose that because the timescale of parallel diffusion is comparable to that of the sawtooth collapse, the interaction between evolving magnetic fields and parallel transport processes generates a poloidal particle flow along the magnetic field from the X-point region to the O-point region. The magnitude of this flow is comparable to parallel particle diffusion. Consequently, electron density increases become concentrated near the O-point. In contrast, the larger parallel heat diffusion causes electron temperature and density perturbations to decouple.

These findings suggest that since the particle parallel diffusion timescale aligns with the magnetic surface evolution timescale, such coupling effects should be incorporated into sawtooth collapse models. Understanding particle motion will be crucial for predicting profile relaxation during sawtooth collapse in future reactors with higher core densities.

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