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A review of recent simulation studies of sawtooth with CLT

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Sawtooth is one of the most common phenomena in Tokamaks when the safety factor at the magnetic axis is below 1.0. Sawtooth plays an important role in Tokamak performance because it can trigger neo-classical tearing mode instabilities on other rational surfaces, which are deleterious for plasma confinement. It can also influence the confinement of particles. Although sawtooth has been observed over 40 years, there are still two crucial issues that have not yet been well understood, i. e. fast pressure crash and incomplete reconnection during sawtooth oscillations. Besides, a steady-state with the non-axisymmetric magnetic field, which is recently observed in DIII-D, MAST, JET, and JT-60U, is believed to be related to the sawtooth oscillations. However, the physical mechanism for the sawtooth oscillations leading to the steady-state is still not clear.

In this presentation, we will try to address these three problems (i.e., the fast pressure crash, the incomplete reconnection during sawtooth oscillations, and the steady-state of sawtooth oscillations) based on simulation results from CLT.

I. Fast pressure crash in sawtooth oscillations

The first toroidal Hall-MHD simulation study about sawtooth with an explicit method is carried out with CLT. We find that the Hall effect can lead to the explosive growth of the resistive-kink mode at the nonlinear stage. The explosive nonlinear growth of the resistive-kink mode mainly results from the structural transition of the current sheet in the Hall-MHD simulations. At the nonlinear stage, the geometry of the current sheet turns into X-type from Y-type, resulting in the significant acceleration of the reconnection process. As a result, the pressure crash in Hall-MHD simulations is much faster than that in resistive-MHD simulations. In Hall-MHD simulations, the pressure crash time is about 20 μs, which agrees well with experimental observations. Not only the crash time but also the pressure distributions during the sawtooth crash are also consistent with the recent experimental observation in TEXTOR (Park et al., PRL 2006). The simulation results indicate that the fast pressure crashes during sawtooth oscillations mainly result from fast magnetic reconnection dominated by Hall effect.

II. Plasmoids resulting in the incomplete reconnection

When the Lundquist number S is larger than a critical value, the current sheet becomes thin and elongated, and the secondary tearing mode is triggered in the nonlinear stage of the resistive-kink mode. The secondary magnetic islands eventually merge into a large magnetic island with the m/n=1/1 helicity, which suppresses the further development of the resistive-kink mode and finally leads to the incomplete reconnection. Another evidence for the incomplete reconnection is that the safety factor at the magnetic axis keeps $q_0 < 1$ during the whole reconnection process, which is consistent with experimental observations (McGuire et al. POP 1990).

III. The second parameter regime of the viscosity for quasi-steady state of sawteeth in Tokamaks

We find that there are two parameter regimes of the viscosity for sawtooth achieving a steady-state. With a sufficiently high or low viscosity, the system eventually evolves into a steady-state. In the intermediate regime of the viscosity, the sawtooth exhibits a normal sawtooth oscillation. Since present Tokamaks operate in the low viscosity regime, the quasi-steady state in the low viscosity and high plasma beta is more relevant to experimental conditions. In the steady-state, the mode structure, the magnetic field, and the flow patterns are all non-axisymmetric and with the m/n=1/1 helicity, which may be related to the stationary state observed in DIII-D (Petty et al. PRL 2009) and in some other Tokamaks.

References

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