STRONG TOROIDAL ELECTRIC FIELD GENERATION DURING SAWTOOTH CRASHES

[1]W. Zhang and [1]Z. W. Ma

[1] Institute for Fusion Theory and Simulation, School of Physics, Zhejiang University, Hangzhou, China

Email: wzhang_ifts@zju.edu.cn

Abstract: Sawtooth crashes are a common phenomenon in tokamak operations and significantly impact plasma performance, particularly through their potential to trigger neoclassical tearing mode instabilities on other rational surfaces. Despite over four decades of observations, the fundamental physics governing the rapid magnetic reconnection during these events remains poorly understood. Given that the reconnection rate is directly proportional to the parallel electric field, it is theoretically expected that substantial toroidal electric fields are generated during rapid crash events. Recent experimental observations on DIII-D have confirmed the presence of a strong core inductive electric field during sawtooth crashes, measuring several orders of magnitude greater than the resistive diffusion of plasma current along the magnetic axis [1].
In this study, we employ the three-dimensional, toroidal-geometry, nonlinear MHD code CLT [2] to numerically investigate sawtooth crashes using three distinct models: resistive-, Hall-, and bi-fluid MHD. The bi-fluid MHD model differs from Hall-MHD primarily through the omission of the ion polarization drift term in the generalized Ohm's law. Figure 1 illustrates the temporal evolution of maximum toroidal electric field values obtained from these models. Initially, the toroidal electric field is balanced with resistive diffusion ($\eta J_0 \sim 3\times10^{-6}$). However, during sawtooth crashes, it exhibits significant amplification. While the Resistive-MHD model demonstrates a hundredfold increase in maximum value, both Hall- and bi-fluid MHD models reveal magnitudes up to 1000 times greater than resistive diffusion levels, aligning remarkably well with experimental observations.

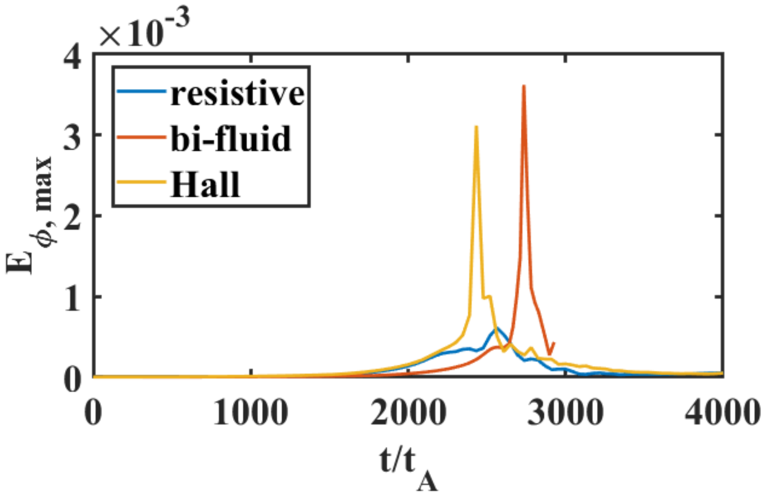

fig 1 Evolution of maximum toroidal electric field values during sawtooth crashes with resistive-, bi-fluid, and Hall-MHD models.

The generation of a strong toroidal electric field leads to fast reconnection during sawtooth crashes, accounting for the explosive growth observed in bi-fluid and Hall-MHD simulations (Figure 2). While the strong toroidal electric field and explosive growth are typically associated with two-fluid effects and often attributed to the parallel electron pressure gradient, our findings emphasize the critical role of the polarization drift term in the generalized Ohm's law during fast reconnection processes. Specifically, the bi-fluid MHD simulation yields a maximum growth rate of 0.0069, representing a 250% increase over its linear growth rate. In contrast, the Hall-MHD simulation achieves a maximum growth rate of 0.0106, surpassing the bi-fluid simulation by 50%.

The polarization drift term in the generalized Ohm's law is intrinsically linked to the formation of the quadrupole field. In this work, we provide a theoretical framework elucidating its essential contribution within the reconnection layer. The absence of this term effectively filters the kinetic Alfvén wave, which is crucial for fast reconnection in the presence of a strong guiding field. This mechanism explains the substantially higher maximum toroidal electric field observed in Hall-MHD simulations compared to bi-fluid simulations.

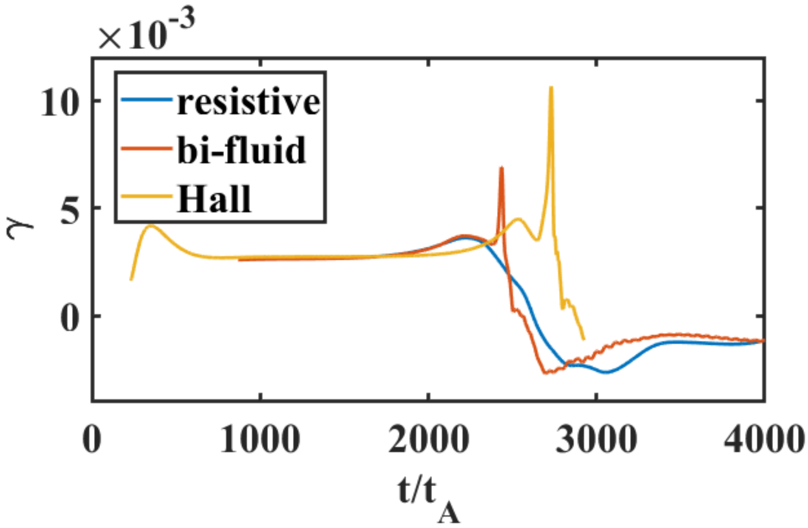

fig 2 Evolutions of the growth rate during sawtooth crashes with resistive-, bi-fluid, and Hall- MHD models.

ACKNOWLEDGEMENTS

This work is supported by the National MCF Energy R & D Program Nos. 2019YFE03090500, the Zhejiang Provincial Natural Science Foundation of China under Grant No. LDQ24A050001.

REFERENCES

[1] T.E. Benedett, J. Chen, D.L. Brower, W.X. Ding, Core inductive electric field during sawtooth crashes on DIII-D, Plasma Physics and Controlled Fusion, 66 (2024) 085009.
[2] W. Zhang, S.C. Jardin, Z.W. Ma, A. Kleiner, H.W. Zhang, Linear and nonlinear benchmarks between the CLT code and the M3D-C1 code for the 2/1 resistive tearing mode and the 1/1 resistive kink mode, Computer Physics Communications, 269 (2021) 108134.