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Numerical study on Ion and Electron Dynamics and the Role of Electrostatic Potential on Particle Heating in Merging startup in TS-6 experiment

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Magnetic reconnection in high guide field configurations is a central mechanism in both astrophysical and laboratory plasmas for converting magnetic energy into particle kinetic and thermal energy. In the context of spherical Tokamak (ST) merging startup, understanding ion heating mechanisms is essential for optimizing compact, high-β plasma formation. In the TS-6 experiment, strong electrostatic potentials were observed forming in the poloidal plane during reconnection, suggesting that ion acceleration and heating are largely driven by in-plane electric fields rather than inductive reconnection fields alone [1].

In this work, we investigate this mechanism using first-principles kinetic simulations of plasmoid coalescence performed with the fully three-dimensional setup, electromagnetic particle-in-cell code VPIC. The simulation domain models the coalescence of two parallel flux ropes under strong guide field conditions, mimicking the reconnection geometry of the TS-6 merging experiment. Key plasma parameters, including density, field strength, and system size, are chosen to match experimental conditions as closely as possible within computational constraints.

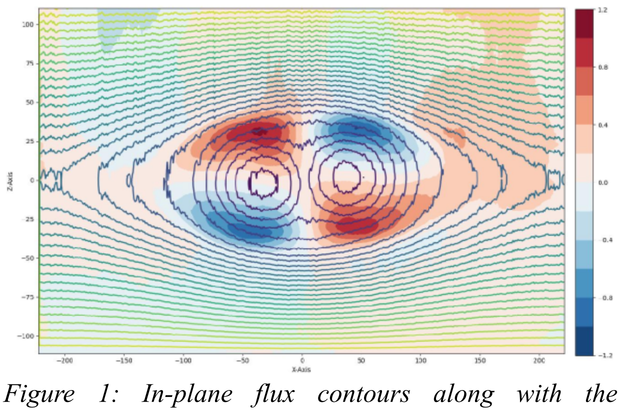

Figure 1: In-plane flux contours along with the electrostatic potential calculated from 3D VPiC numerical simulation

The simulations reproduce the formation of a quadruple electrostatic potential structure, generated by polarization and charge separation driven by field-aligned electron acceleration near the X-point. The resulting in-plane electrostatic field (Ep) exceeds the reconnection electric field (E‖) by a factor of 4–6 and drives substantial Ep × Bg ion drift, resulting in downstream acceleration and heating. Ion energy gain scales consistently with ΔTi ∝ (Ep/Bg)^2, in agreement with the experimental scaling of ΔTi ∝ Brec^2 observed in TS-6 [2,3].

Through parametric scans, we observe that the potential gap (ΔΦ) increases with both the reconnecting and guide magnetic fields, with a stronger dependence on Brec. These trends match the experimental measurements obtained from Langmuir probes and 2D ion Doppler tomography in TS-6. Additionally, simulations reveal asymmetry in the potential structure and electron heating around the separatrix, consistent with spatially localized soft X-ray emissions seen in the experiment [4].

This study demonstrates that electrostatic fields generated during high guide field reconnection play a dominant role in ion heating, especially in the downstream region, and provides kinetic-level confirmation of mechanisms previously inferred from two-fluid Hall-MHD models. The alignment between simulation and experiment reinforces the view that global polarization fields are key drivers of energy conversion during ST merging. These results also inform ongoing efforts to optimize ion heating efficiency in future ST designs and contribute to understanding energy partition in reconnection across scales.

References

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