THE SCALING OF THE ION HEATING AND ELECTROSTATIC POTENTIAL IN SPHERICAL TOKAMAK

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1 INTRODUCTION

Magnetic reconnection, a fundamental plasma phenomenon, plays a pivotal role in energy conversion processes across astrophysical and laboratory environments [1,2]. Its applications extend to the generation of solar flares, tokamak instabilities, and plasma heating in fusion devices. This paper explores the experimetal and numerical influence of in-plane floating potentials on ion heating during merging startup. Conducted using the Tokyo University Spherical Tokamak device (TS-6) [3] and 3D kinetic model by LANL VPIC code [4], the study investigates how floating potentials is directly proportional to the toroidal (TF) and poloidal magnetic fields which consequetively affect ion heating rate.

In high-guide field magnetic reconnection, where the guide field (Bg) greatly exceeds the reconnecting magnetic field (Brec), particles accelerate through energy conversion mechanisms, particularly near the X-point. These conditions create a unique environment for studying charge separation and its role in plasma heating. The TS-6 device, with its diagnostic capabilities, provided the ideal platform for these experiments aimed to understand how in-plane electrostatic fields contribute to ion acceleration and heating. The TS-6 setup (Fig1(a)) consists of a cylindrical vacuum vessel equipped with internal poloidal and toroidal field coils. These coils induce plasma rings, which are then merged at the mid-plane to initiate magnetic reconnection. High-speed imaging, ion Doppler tomography, and Langmuir probes were utilized to measure ion temperatures, floating potentials, and magnetic fluxes. During reconnection, plasma toroids move toward the mid-plane, where the merging process leads to a significant rise in ion temperatures due to energy conversion from magnetic to thermal forms.

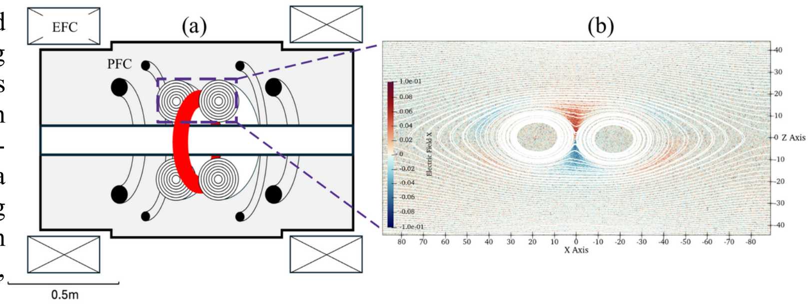

Fig1: (a) Schematic view of TS-6 spherical Tokamak using Merging-compression start-up. The red circle shows the current layer region. (b) The 2D render of ion outflow velocity in kinetic simulation corresponding the experimental setup.

2 EXPERIMENTAL AND NUMERICAL RESULTS

The formation of the quadruple potential structure during reconnection was linked to charge separation effects that satisfy MHD criteria. This structure, characterized by radial asymmetry, played a central role in shaping the in-plane electric field and driving ion acceleration. The study revealed that the in-plane electrostatic field (Ep) was significantly stronger than the induced electric field (Et) at the X-point, highlighting its role in energy conversion. This insight advances our understanding of how magnetic reconnection facilitates ion heating, with potential applications in improving plasma heating techniques for fusion energy research. To study the scaling of the potential gap responsible to energy conversion conversation and heating, a 3D kinetic simulation VPIC has been developed. Fig1(b) illustrated the ion outflow profile corresponding to the limited region of the experimental setup by using the two plasmoids coalescence model [4] with out of plane magnetic potential defined as $A_y = B_0 \lambda \ln\left[\cosh\left(\frac{z}{\lambda}\right) + 0.4\cos\left(\frac{x}{\lambda}\right)\right]$ where λ-equilibrium current sheet thickness and B_0-initial magnetic field, with a constant out-of plain guiding field B_g. The ion to electron current carrying velocities ratio equals the temperature ratio Ti0 = Te0. The simulation domain is $x \in [-2\pi\lambda, 2\pi\lambda]$, $y \in [-0.5\pi\lambda, 0.5\pi\lambda]$, and $z \in [-\pi\lambda, \pi\lambda]$. We use perfectly conducting boundaries reflecting for particles at y, z, and periodic boundaries in the x-direction. The mass ratio mi/me = 200 and the ratio of the electron plasma frequency to the electron gyrofrequency ωpe/Ωce = 2. A major finding of the study was the linear correlation between the floating potential gap (ΔΦ) and the magnetic fields Brec and Bg. This relationship underscores the role of charge separation in enhancing in-plane electrostatic fields, which dominate over the parallel inductive electric fields. The in-plane fields contribute directly to ion acceleration, driving ions to higher temperatures. Notably, the floating potential exhibited radial asymmetry, with stronger potentials observed on the high-field side of the plasma. This asymmetry was attributed to variations in the guide field strength, influencing the charge separation process and the resulting potential structure. Ion heating during ST merging was found to scale quadratically with the reconnecting magnetic field, a result consistent with previous experiments. Higher Brec values led to increased energy conversion efficiency, allowing more magnetic energy to be transformed into ion thermal energy. This scaling relationship highlights the critical importance of magnetic field configurations in determining plasma heating outcomes. Additionally, the guiding toroidal field significantly influenced the floating potential gap and ion heating. While higher guide fields enhanced charge separation and in-plane electric fields, excessively strong fields suppressed ion heating due to reduced ion viscosity and acceleration efficiency. Numerical simulations using a three-dimensional kinetic model (VPIC [4]) supported the experimental results. Fig2 show the measured electrostatic potential (a) and the calculated in numerical framework (b) both picturing the quadruple structure of electrostatic potential. The simulations demonstrated linear dependencies of the floating potential gap on Brec and Bg, validating the observed scaling relationships as shown in Fig2 (c,d). Increasing the ratio of the guide field to the initial magnetic field seem to be aligned with the theoretical expectations [5] as increasing the guide field leads to the enhancement of charge separation processes. On the other hand, increasing the reconnecting magnetic field linearly increases the value of potential gap. In this cas, it is experimentally expected that $E_{rec} \sim C.\ B_g\ .\ B_{rec}$, where C =3.2e3 is the coefficient between potential gap and reconnecting magnetic field which is valid in the presented kinetic simulation including 20% overpredicted.

The energy conversion process is a global phenomenon rather than a localized reconnection event. Since electrons move much faster than ions along these field lines, a radial Hall current consistently flows toward the X-point within the current sheet. Additionally, the current sheet creates both negative and positive potential wells and hills, which promote ion acceleration. The ion flow is ultimately driven by the electric field generated by the quadrupole electrostatic potential structure. When the current sheet is compressed by external flow, the quadrupole structure becomes more pronounced, increasing the effective resistivity of the current sheet. This leads to an increase in outflow speed, bringing it closer to the Alfven speed of the reconnecting magnetic field.

In conclusion, the study of in-plane floating potentials during ST merging offers critical insights into the mechanisms of ion heating and energy conversion in plasma physics. The enhancement of the electrostatic potential is critical to increase ion energy gain. The TS-6 experiments revealed the dominant role of in-plane electrostatic fields in driving ion acceleration, with strong correlations between floating potential gaps and magnetic fields. By elucidating the relationships between magnetic fields, floating potentials, and ion heating, the study provides a framework for optimizing plasma heating in tokamaks. The results demonstrate that manipulating magnetic field configurations can enhance energy conversion efficiency, a critical factor for achieving the conditions necessary for nuclear fusion.

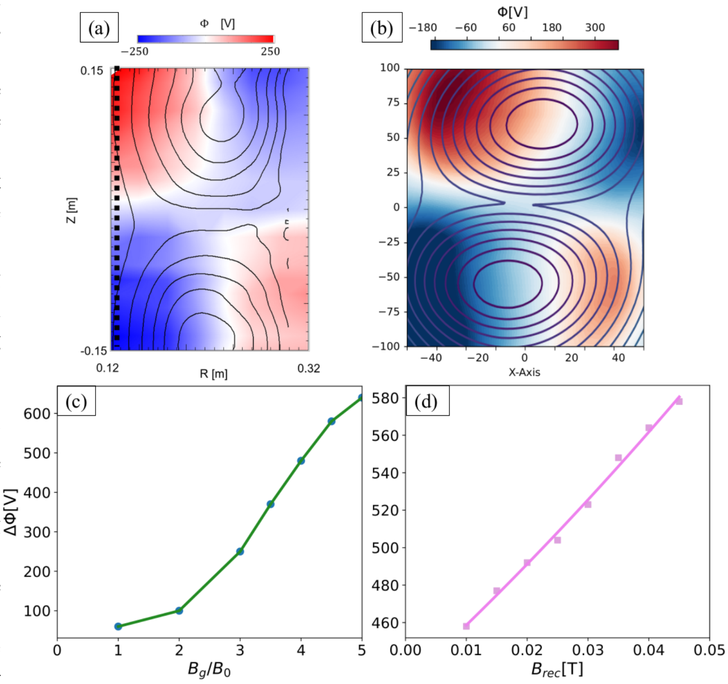

Fig2: The electrostatic potential profile along with poloidal flux contours in TS-6 experiment (a) and 3D kinetic simulation of plasma merging (b). Dependency of potential gap as a function of guide field (c) and reconnecting magnetic field (d)

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