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High Power Heating of Magnetic Reconnection in Torus Plasma Merging Experiments

Yasushi Ono[1], Horoshi Tanabe[1], Hideya Koike[1], Taishi Kaneda[1], Hironori Hatano[1], Moe Akimitsu[1], Asuka Sawada[1], Syunsuke Usami[2], Ritoku Horiuchi[2]

[1] University of Tokyo, Japan, [2] National Institute for Fusion Sciences, Japan

Since 1985, we have been investigating toroidal plasma merging and its magnetic reconnection for high-power heating of spherical tokamak (ST) and field-reversed configuration (FRC), using TS-3 (ST, FRC: R~0.2m, 1985~), TS-4 (ST, FRC: R~0.5m, 2000~), UTST (ST: R~0.45m, 2008~) and MAST (ST: R~0.9m, 2000~) devices. We merge two toroidal plasmas in the axial direction, forming a magnetic reconnection point at the contacting point of the two toroids. The reconnection transforms a part of reconnecting magnetic field energy of the two merging toroids mostly into ion thermal energy of the produced new toroid, causing high power heating of reconnection within short reconnection time.

Our merging experiments realized a significant ion heating up to 0.25keV in TS-3 and 1.2keV in the world-largest ST: MAST [1,2], as shown in Fig. 1(b). We made detailed 2D elucidation of ion and electron heating in TS-3 and TS-4 ST merging experiments [3-5]. They revealed clear energy-conversion mechanisms of reconnection: huge outflow heating of ions in the downstream and Ohmic heating of electrons at around the X-point. The reconnection outflow accelerates ions up to 70% of Alfven speed of reconnecting magnetic field and they are thermalized by shock-like density pileups in the downstreams.

The series of experiments agree that the reconnection heating energy is proportional to square of the reconnecting magnetic field B_{rec}, as shown in Fig. 1(a). The guide toroidal field $B_t=B_g$ does not affect the bulk heating of ions and electrons, probably because the reconnection/ outflow speeds are determined mostly by externally driven inflow by the help of several fast reconnection mechanisms. Their mechanisms are qualitatively agree with PIC simulations by Horiuchi [5,6] and with the Hinode satellite observation of solar coronal heating [1]. We already made clear the promising scaling and characteristics of reconnection heating: (i) its ion heating energy that scales with B_{rec}^2, (ii) its energy loss lower than 10%, (iii) its ion heating energy in the downstream 10 time larger than its electron heating energy at around X-point and (iv) low dependence of ion heating on the guide field $B_t=B_g$. The B_{rec}^2-scaling is obtained when the current sheet is compressed to the order of ion gyro-radius ρ_i, as shown in Fig. 2(a')(b'). In the case of insufficient compression: $\delta>\rho_i$, the measured T_i was lower than the value for the high compression cases, as shown in Fig. 2 (c').

Those reconnection heating characteristics lead us to the up-graded high magnetic field merging experiments: TS-U (2017~) in University of Tokyo and ST-40 in Tokamak Energy Inc. (2017~). This paper will summarize major progresses in those international and interdisciplinary reconnection heating experiments for reconnection heating physics, fusion plasma startup/ heating and its direct access to ignition

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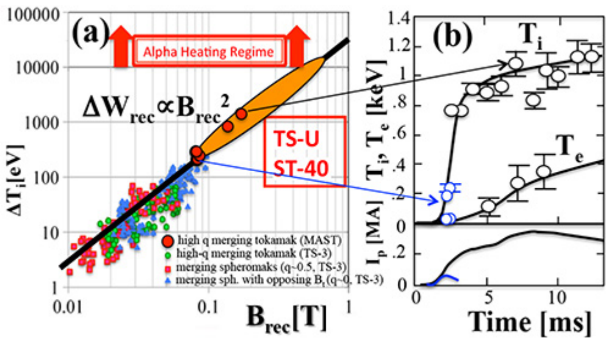

Fig. 1 (a) Dependence of ion temperature increment ΔT_i, on reconnecting magnetic field B_{rec} for two merging STs with finite $B_t=B_g$ and two merging spheromaks with opposing B_t (zero B_g). (b) T_i, T_e and plasma current I_p evolutions of two merging STs in MAST (black line) and those of two merging spheromaks with opposing B_t in TS-3 (blue lines)[5].

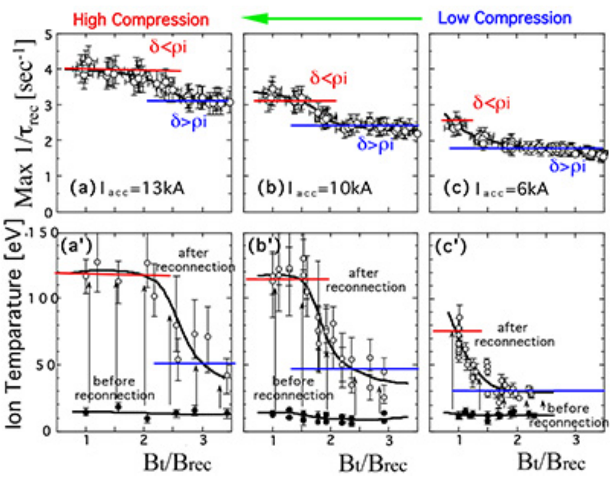

Fig. 2 Averaged reconnection rates $1/\tau_{rec}$ of two merging ST plasmas (top) and their ion temperatures T_i before and after magnetic reconnection (bottom) as a function of B_t/B_{rec} for three different acceleration (compression) -coil currents: (a) I_{acc} = 13 kA, (b)10 kA, and (c) 6 kA.