Overview of Merging Spherical Tokamak Experiments and Simulations for Burning, High-Beta and/or Absolute Minimum-B Plasma Formation

Y. ONO[a], R. SOMEYA[a], S. ITO[a], J. XIANG[a], T. AMAHDI[a], M. AKIMITSU[a], S. KAMIYA[a], H. TANAKA[a], Y. CAI[a], H. YAMAGUCHI[a], S. TAKEDA[a], Y. FUNATO[a], H. TANABE[a], M. INOMOTO[a], M. GRYAZNEVICH[b], S. MCNAMARA [b], P. BUXTO[b], J. KOMPULLA[b], J. WOOD[b], V. NEMYTOVK[b]. G. MCCLEMENTS[c], C. Z. CHENG[d], H. HARA[e], S. USAMI[f], R. HORIUCHI[f]

[a]University of Tokyo, Japan, [b]Tokamak Energy Inc, [c]CCFE, Culham Science Centre, [d]Princeton Plasma Physics Laboratory, [e]National Observatory of Japan, National Institute for Fusion Sciences, ono@k.u-Tokyo.ac.jp

ABSTRACT

- High-power reconnection heating of merging ST plasmas has been developed in TS-3U, TS-4U, UTST, MAST and ST-40 experiments. All of them and PIC simulations confirmed the promising scaling of ion heating energy increasing with square of reconnecting magnetic field $B_{rec}^2 \sim B_p^2$ up to 2.3keV.
- The reconnection converts about half of B_p energy into ion thermal/ kinetic energy within short reconnection time, leading us to direct access to burning high-beta ST often with absolute min-B profile in ST-40/ TS-6.
- The produced high-β ST plasmas often have reversed-shear and absolute minimum-B profiles in the second stability regime for ballooning modes.

INTRODUCTION

The high-power reconnection heating of merging ST plasmas has been developed first in TS-3 up to T_i ~0.25keV using (a) merging STs and (b) counter-helicity (B_t) merging spheromaks with B_{rec}~0.05T in 1990's. Their B_{rec}^2-scaling of ion heating energy leads us to high-B_{rec} merging experiments in MAST up to T_i ~1.2keV (B_{rec}~0.15T) in 2015, and now in ST-40 experiment over T_i ~ 2.3keV (B_{rec}~0.3T) in agreement with recent PIC simulations and analytical kinetic/ two fluid model of rec. heating.

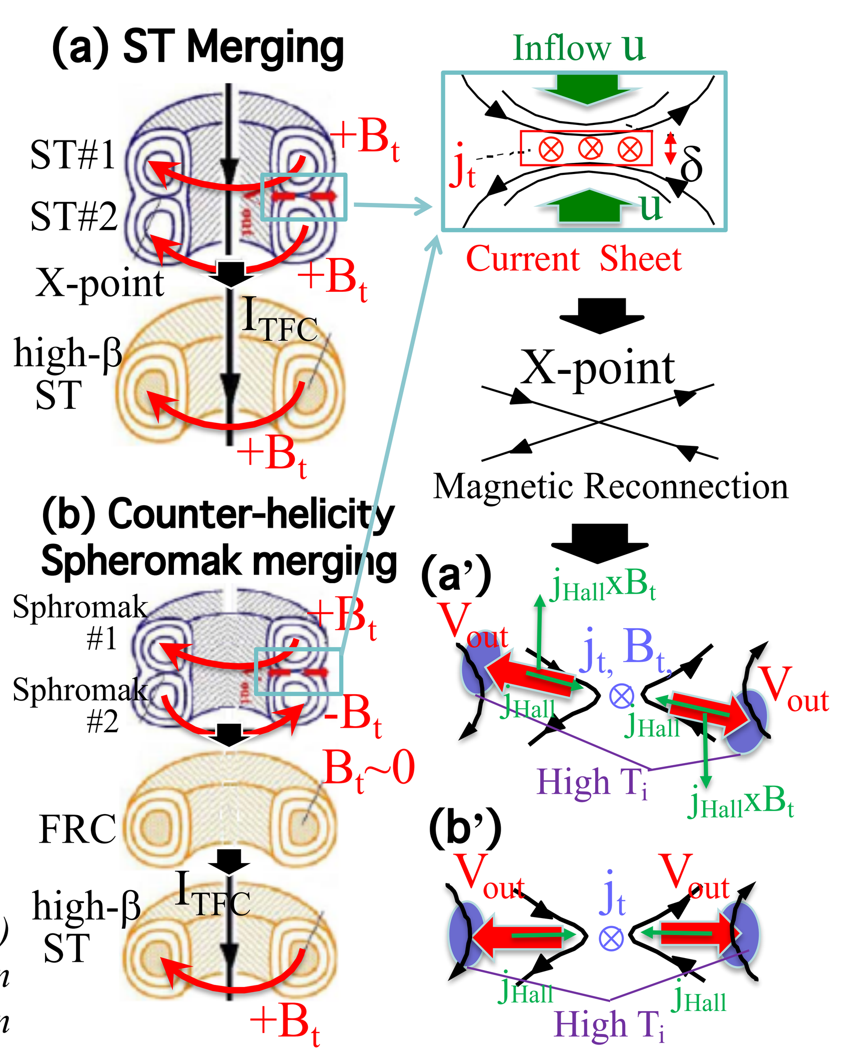


FIG. 1 (a) Two merging ST plasmas to form a high-beta ST, (b) two merging spheromaks to form an FRC and its transformation to a high-beta ST and (a')(b') their corresponding reconnection regions.

RECONNECTION HEATING FOR FUSION AND ITS SCALING

All of merging experiments and PIC simulation agree that the ion heating energy of reconnection scales with B_{rec}^2~ B_p^2 (poloidal field) in Fig. 2. The rec. heating convert about the half of poloidal magnetic energy into ion heating energy within a short rec. time, causing huge heating power. Unlike conventional Ohmic heating decreasing with $T_e^{-3/2}$, the huge rec. heating has almost no T_e dependence, suggesting transformation of merging ST plasma directly to burning plasma keeping nτ about constant without using any additional heating like NBI, as shown by red arrows in Fig. 3(a)(b).

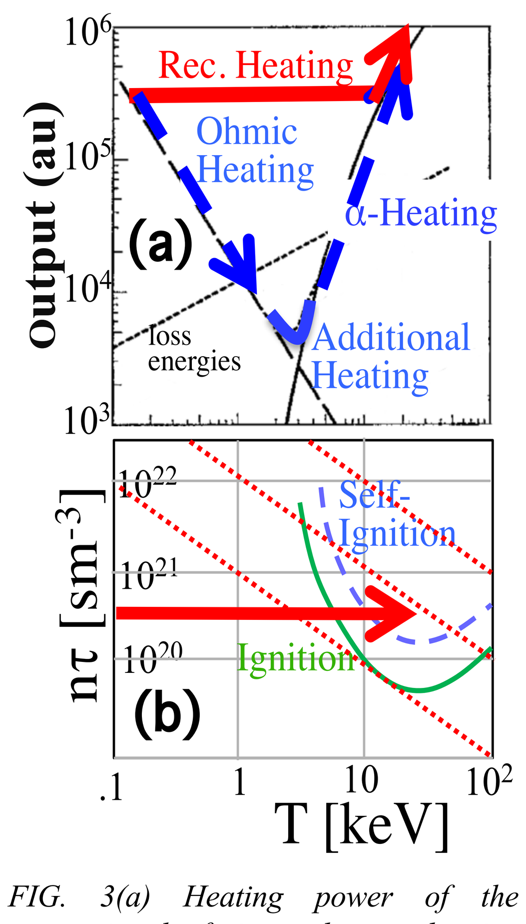


FIG. 3(a) Heating power of the conventional fusion plasma heating composed of ohmic and additional heatings and that of the reconnection heating as a function of temperature, (b) trajectory of the reconnection heating to ignition and self-ignition regimes in the space of temperature (T) and density times confinement time (nτ).

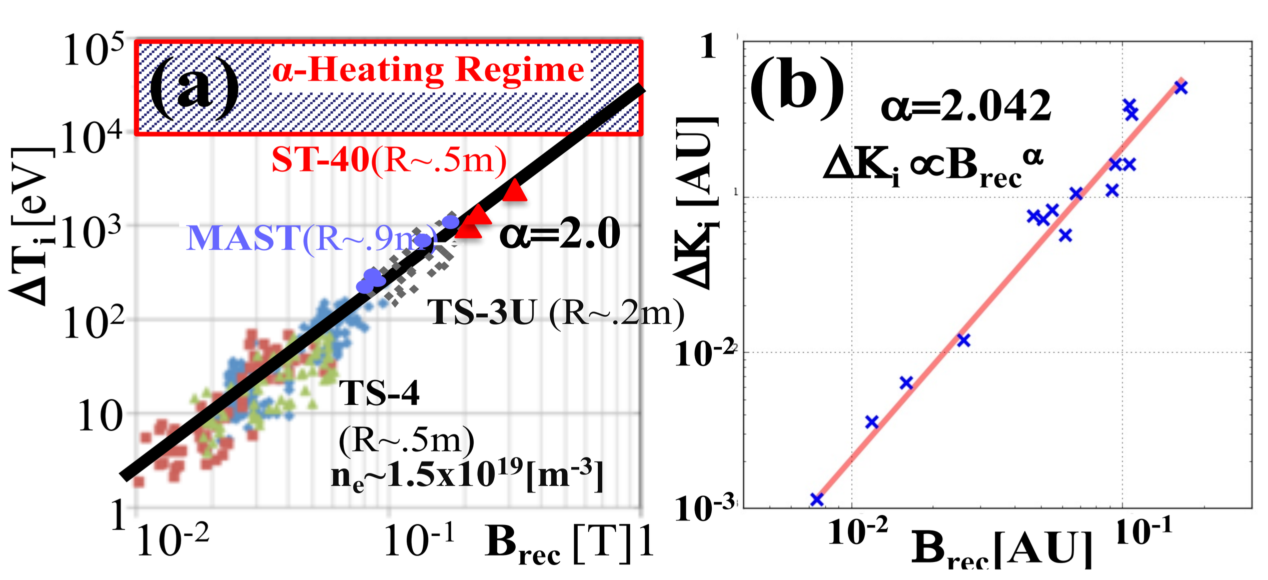
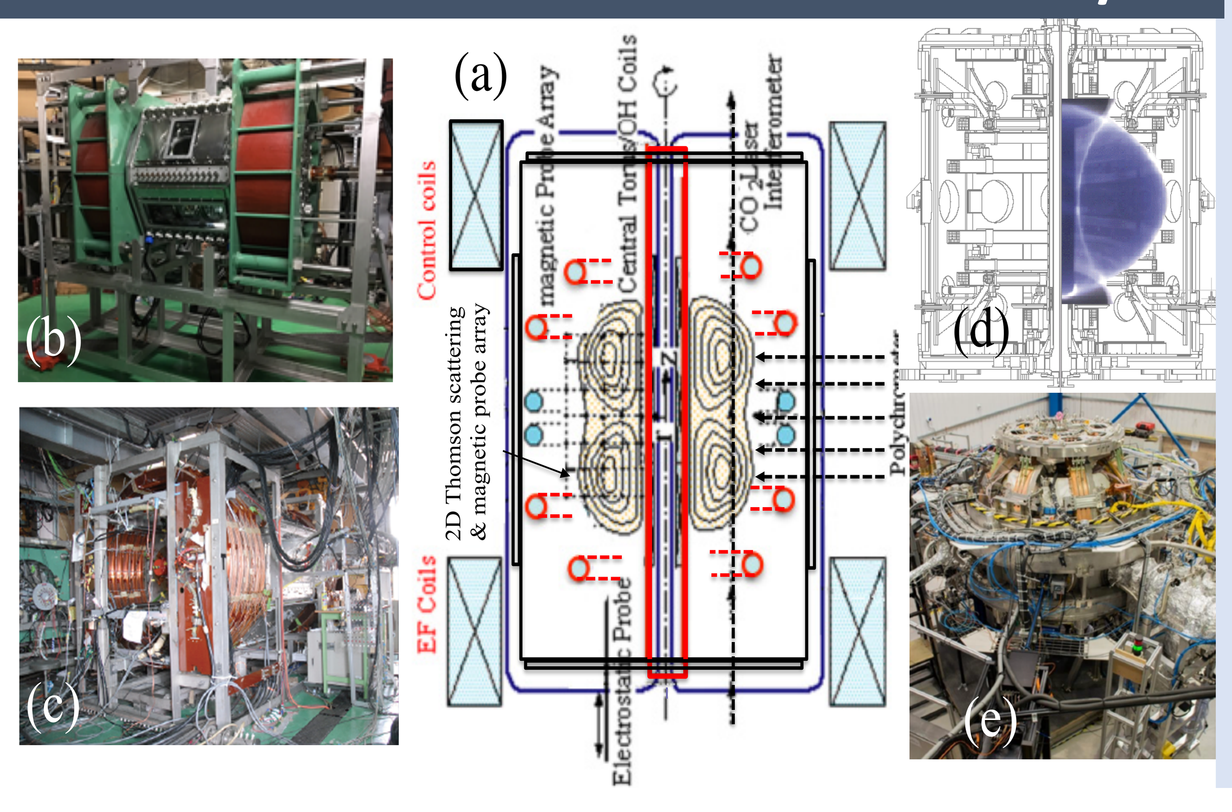


FIG. 2. (a) Dependence of ion temperature increment ΔT_i on reconnecting magnetic field B_{rec} of two merging STs and spheromaks under n_e~1.5 x10^{19}m^{-3} in TS-3, TS-3U, TS-4, MAST and ST-40 device and (b) the corresponding ΔT_i dependence on B_{rec} in 2D PIC simulations by Inoue and NIFS group.

Merging/ RECONNECTION HEATING EXPERIMENTS IN JAPAN/UK

Fig. 4 (a) shows vertical cross-section of TS-3U ST /spheromak merging device with 2D magnetic probe arrays, 2D ion Doppler tomography for T_i and 2D Thomson scattering for T_e, (b)(c) shows photos of TS-3U & TS-4U (UTokyo) and (d)(e) photos of MAST (Culham Lab.) and ST-40 (Tokamak Energy Inc.).



OUTFLOW HEATING & HOLLOW PRESSURE & TEMP. FORMATION

- In Fig. 5, the bi-directional outflow V_r~40km/s equal to 70% of poloidal Alfven speed dumps at two downstream positions where T_i, n_e and |B| peak in TS-3, MAST and ST-40 as a common ion outflow heating mechanism that validates the B_{rec}^2-scaling.
- The hollow profiles of T_i and |B| are maintained in the produce high-β STs. We can confirm the hollow T_i and |B| profiles at t=40μs in Figs. 5 (c) (d), in agreement with ring-type high T_i region observed in 2D PIC simulations of ST merging in Fig. 6(d).

FORMATION OF REVERSED SHEAR & ABSOLUTE-MINIMUM B

- The high-power rec. heating produces the reversed shear profile as well as the hollow toroidal current and thermal pressure profiles in the produced high-β ST, in Fig. 6.
- The absolute min-B profile was clearly measured in TS-3U and TS-4U in Fig. 7 and high-β STs produced in MAST & ST-40 merging exp. without B-measurement have similar double-peaked/ hollow profiles of T_i and ion pressure U_i.
- During merging/ rec. of private flux from the periphery to the core, the outflow speed becomes max. in the middle of merging, probably forming the hollow pressure, q & |B| profiles.
- Fig. 7 shows how |B| profile of STs depends on q-value from 0 to 1.5 under constant poloidal flux. The high-β ST with high B_t at small radius area has wider abs. min-|B| area at around magnetic axis in sharp contrast with FRCs with zero-B point at magnetic axis and at geometric axis.
- Our Balloo code analysis indicates the high-β ST with abs. min-B produced by Fig. 1 (b) merging is located in the second-stable regime for ballooning instabilities.

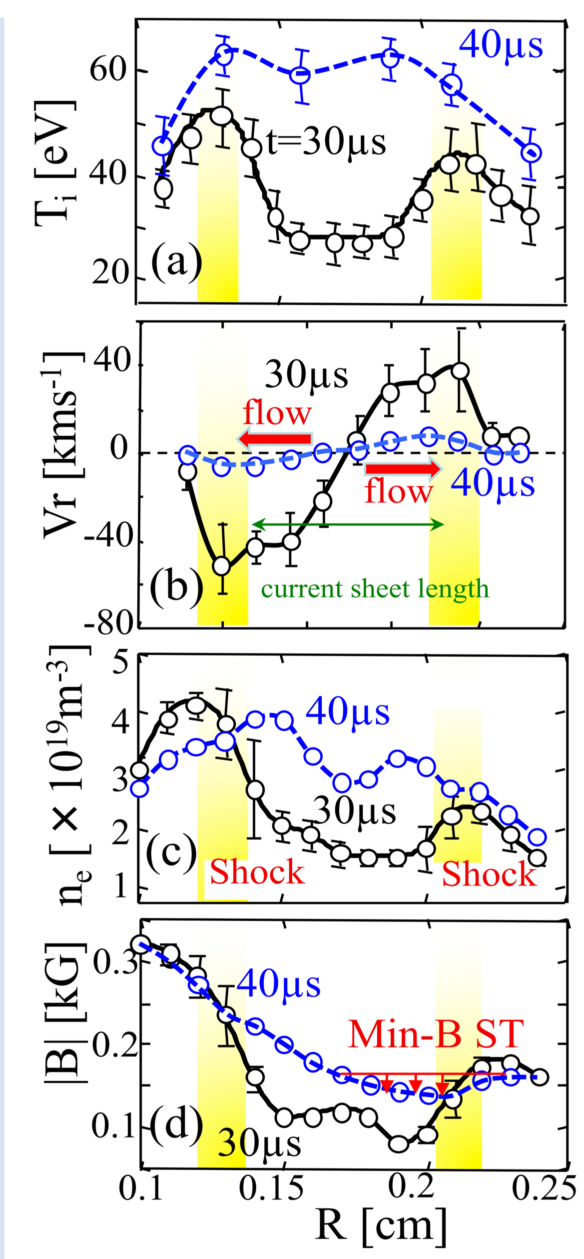


FIG. 5. Radial profiles of (a) ion temperature T_i, (b) radial velocity V_r, (c) electron density n_e and (d) absolute value of magnetic field |B|. during (t=30μs) and after (t=40μs) ST merging in TS-3U.

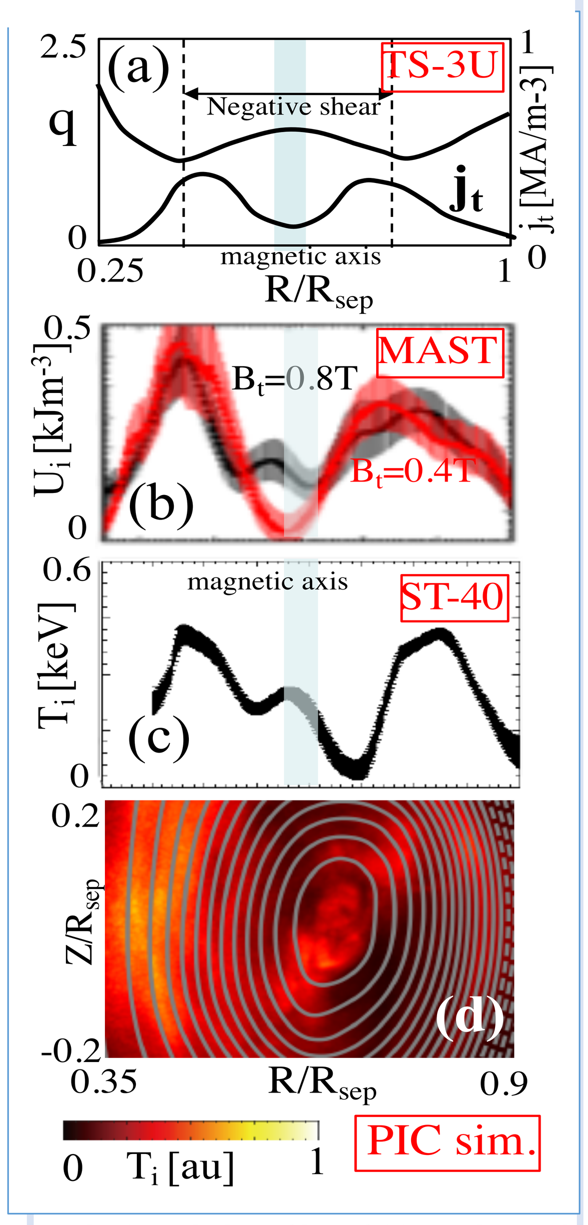


FIG. 6. Radial profiles of (e) q value and toroidal current density j_t in TS-3U, (f) ion pressure U_i for B_t=0.4T, 0.8T in MAST[12], (g) ion temperature T_i in ST-40, (h) R-Z contour of T_i in PIC simulation after the new STs are produced by merging STs.

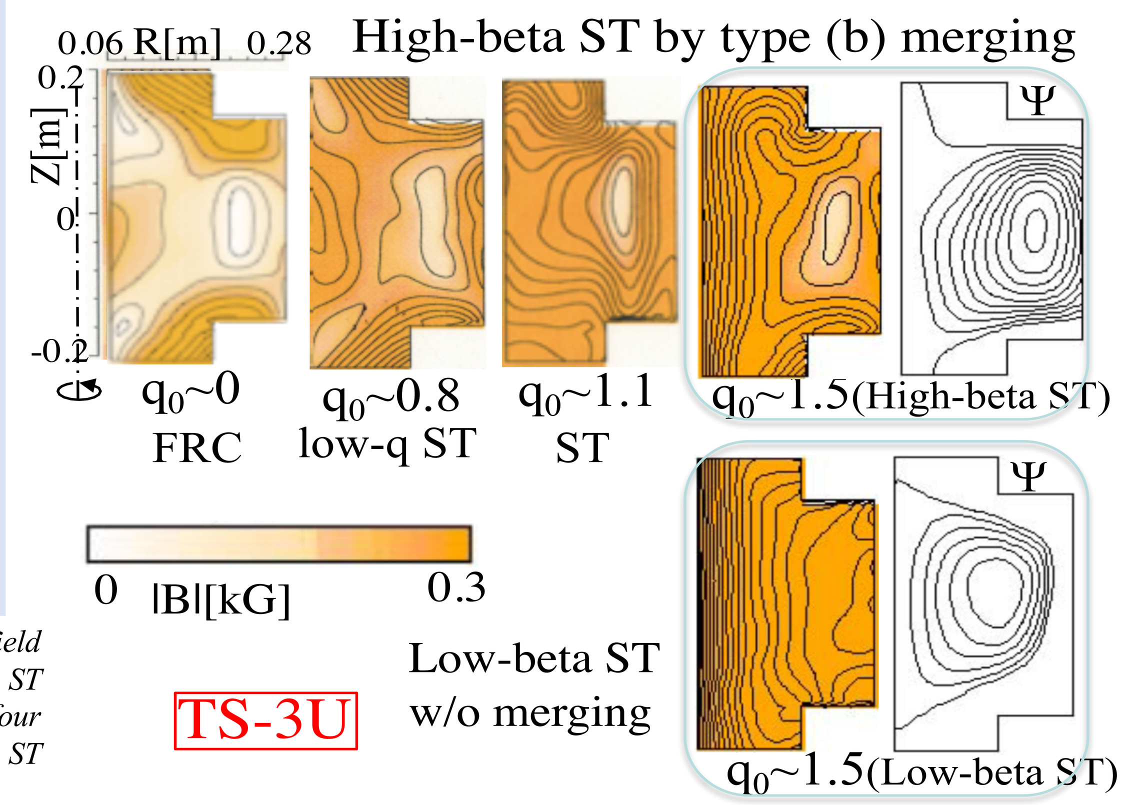


FIG. 7. 2D contours of absolute value of magnetic field |B| (and poloidal flux Ψ for q_0~1.5) of the high-beta ST plasmas produced by type (b) merging in Fig. 1 for four different center q-values q_0 and that of low-beta ST without merging.

CONCLUSIONS

- All merging experiments, PIC simulations & theory confirmed the promising B_{rec}^2-scaling of rec. ion heating energy up to 2.3keV (under 1.5x10^{-19}m^{-3}) The rec. heating converts about ½ of reconnecting (poloidal) magnetic energy to ion thermal/ kinetic energy through the rec. outflow if we compress the current sheet to the order of ρ_i, triggering the fast reconnection. Unlike Ohmic heating power that decrease with $T_e^{-3/2}$, the rec. heating with no T dependence can transform the merging STs into burning plasmas without any additional heating like NBI.
- We found the interesting characteristics of the produced high-β STs: hollow T_i and thermal pressure profiles, forming the reversed shear and absolute mini-B profiles which are located in the second-stability regime.
- This cost-effective rec. heating can transform the merging STs directly to α-heating region with the optimized T_i area in the Lawson diagram.