Merging Start-up of High-Beta ST with NBI in TS-4 Experiment

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Non-inductive plasma start-up is a key for ST fusion reactors because of their narrow space for the CS coils. The plasma merging method [1], which has been developed in TS-3, TS-4, UTST and MAST, is a promising candidate for non-inductive plasma start-up to form a high-beta ST (β ~ 40 [%]). In TS-4 experiment, two low-beta STs (β ~ 10 [%]) are created individually by a pair of fluxcore, as shown in Fig.1 (a). They are compressed by the PF coils, and merge on the midplane ($Z = 0$) through magnetic reconnection, causing a significant ion heating [2]. It relaxes to a high-beta ST, and decays rapidly without using the CS coils. A 2-D (10×9) array of magnetic probes is located on the R-Z plane in the cylindrical vacuum vessel of TS-4 for the purpose of measuring poloidal and toroidal magnetic fields B_z and B_t. They are used to calculate magnetic fields, poloidal flux Ψ, poloidal and toroidal current density j_t and j_z, and so on. Pressure function $P(\Psi)$ and poloidal current function $F(\Psi)$ at magnetic flux surfaces are also calculated and fitted by the least-squares method. Three NBI devices are under installation in TS-4 with a total power of 1 [MW], as shown in Fig.1 (b). In this work, we utilized for the first time NBI (#1 & #2, ~ 0.4 [MW]) as auxiliary heating to maintain the high-beta ST formed by the plasma merging method.

Fig. 2 (a) shows time evolutions of poloidal flux Ψ, dissipation power of total energy dW/dt and NBI output power P_{NBI} of merging STs with NBI, without NBI and a single ST.

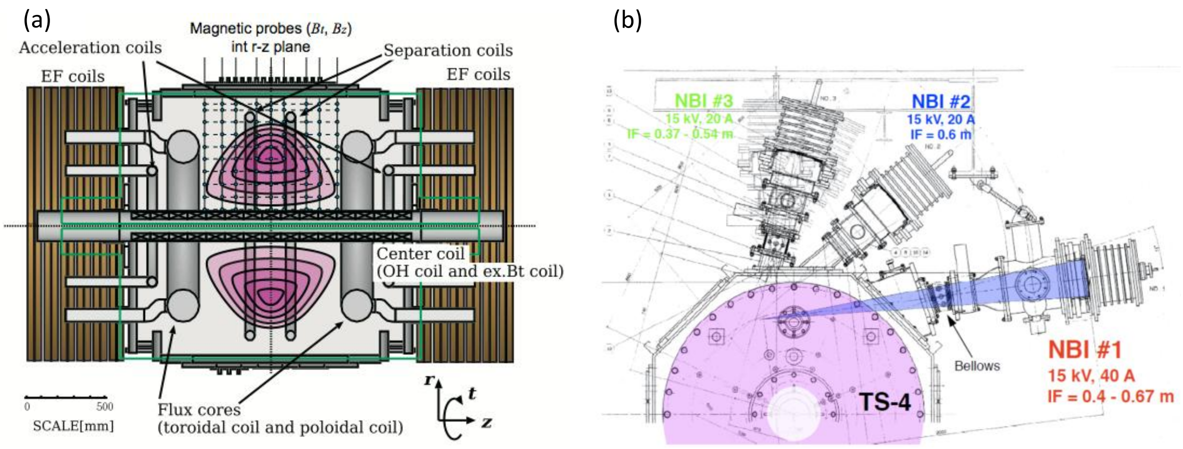

Fig. 1 (a) Schematic view of TS-4 ST device and (b) three NBI devices installed in TS-4.

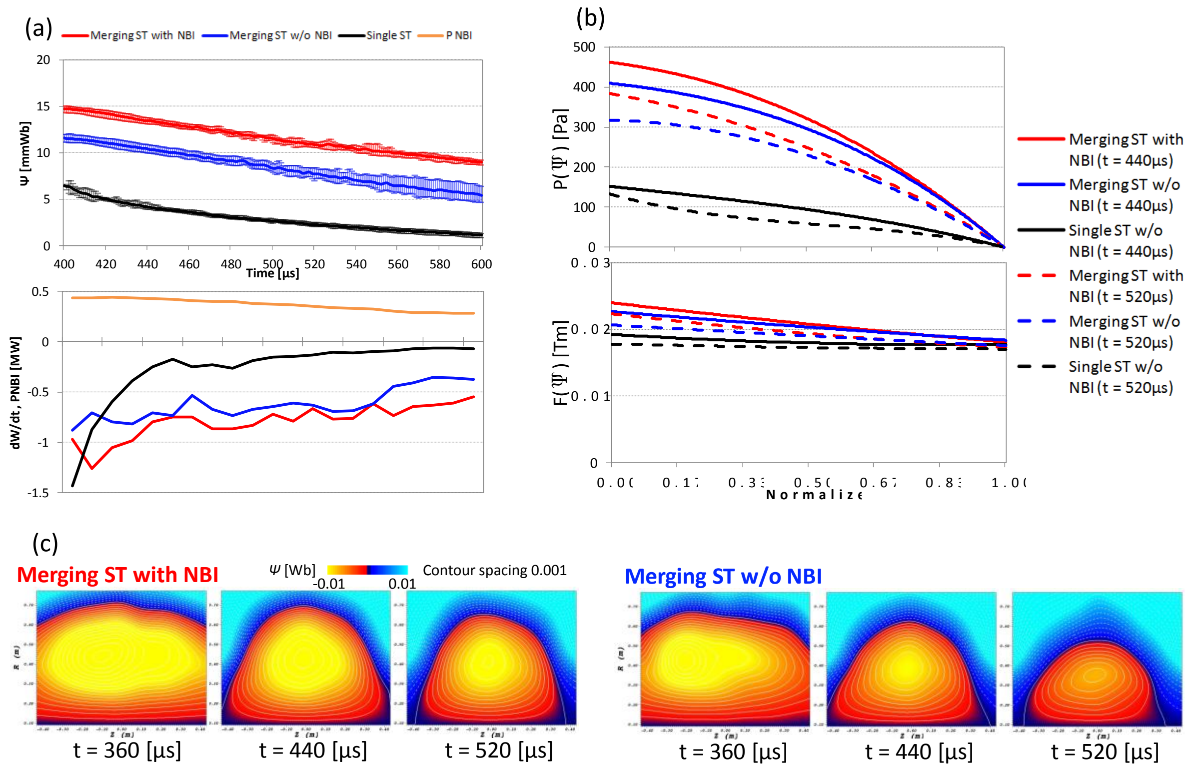

Fig. 2 Time evolutions of (a) poloidal flux Ψ, dissipation power of total energy dW/dt with NBI output power P_{NBI}, (b) thermal pressure $P(\Psi)$ and poloidal current $F(\Psi)$ as a function of poloidal flux Ψ, and (c) R-Z poloidal flux Ψ contours and colors.

Unlike the single ST, the merging ST had better confinement especially just after merging. Since NBI power is maintained during the ST formation, it contributed to pre-ionization rather than improving energy confinement in this experiment. Fig. 2(b) shows thermal pressure $P(\Psi)$ and poloidal current $F(\Psi)$ as a function of poloidal flux for those STs at t = 440 [μ s] (solid lines) and 520 [μ s] (dashed lines) respectively. The merging STs have paramagnetic toroidal field and a broadened pressure profile. The NBI maintains the high pressure profile as well as plasma flux surfaces, as shown in Fig. 2 (c).

In order to confirm NBI effect to the merging ST, we calculated the beam trajectories of the trapped ions using the 2-D ST equilibrium reconstructed by applyng the Grad-Shafranov equation to the measured profile [3]. In this experiment, both NBI #1 and #2 were injected at R = 0.6 [m]. The Monte Carlo method was used to calculate where neutrals are transformed into ions. Then ion trajectories were numerically traced by solving the ion motion with Coulomb collisions with electrons as a form of viscosity. In this calculation, the hydrogen neutral beam with energy of 15 [keV] and total NBI power of 0.4 [MW] was assumed. Fig. 3 (a) shows the beam ion trajectory from the initial position of (R, Z) = $(0.6, 0)$ [m] during 80 [μ s] duration at toroidal cross-section and poloidal cross-section with poloidal

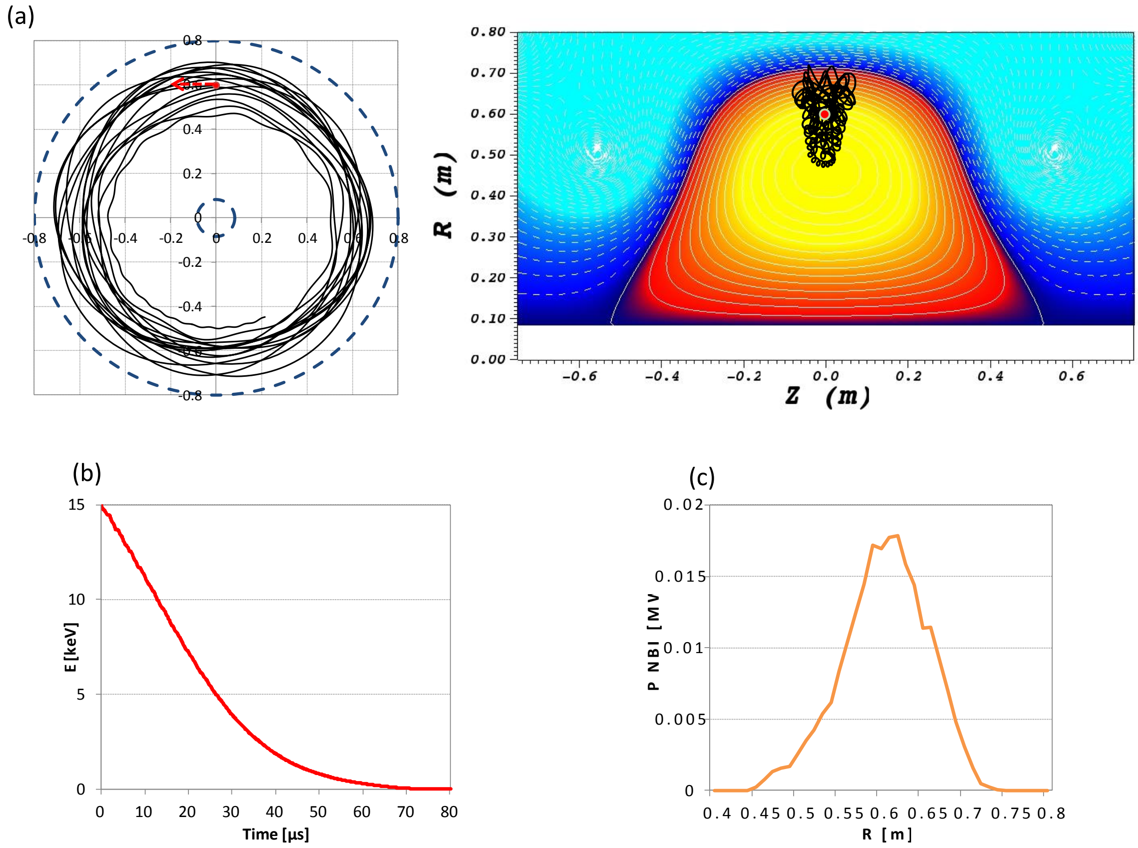

Fig. 3 (a) The beam ion trajectory from the initial position of (R, Z) = (0.6, 0) [m] during 80 [μ s] duration at toroidal cross-section and poloidal cross-section with poloidal flux Ψ used in this calculation, (b) time evolution of the trapped ion energy, and (c) radial profile of the absorbed NB power.

flux Ψ used in this calculation. Because of the magnetic topology of an ST, the beam trajectory spread on R-Z plane. Slowing-down time of the trapped ions is about 35 [μ s], as shown in Fig. 3 (b). Trajectories of 10000 particles were also traced to see the beam confinement and power deposition properties. 569 particles were not ionized because of shine-through losses, and 3868 particles were quickly lost due to the inadequate location of ionization. The rest of the 5563 particles were well confined and deposited the entire energy into the plasma electron. The radial profile of the absorbed NB power is shown in Fig. 3 (c). Since the NBI devices installed in TS-4 were designed not only for the ST but also for the Field-Reversed Configuration, the injection position is located outboard of the magnetic axis.

We precisely analyzed the merging STs with and without NBI by the MHD equilibrium reconstruction and stability code: MEUDAS [4]. Tab. 1 shows results of MHD equilibrium reconstruction and pressure-driven instability analysis of the merging STs with and without NBI. The ST plasma with NBI was a high-beta state of over 40 [%]. Fig. 4 shows the pressure gradient of the MHD equilibrium and the marginal profile for ballooning

Tab. 1 Results of MHD equilibrium reconstruction and pressure-driven instability analysis of the merging STs with and without NBI at t = *440* [μs].

t = 440 [μ s]	R [m]	a [m]	A	κ	δ	Iplasma [kA]	R*Bt [Tm]	β [%]	β stable [%]
with NBI	0.39	0.31	1.28	1.33	0.47	93.1	0.0181	43.5	39.9
w/o NBI	0.36	0.27	1.31	1.24	0.46	74.3	0.0184	32.2	32.0

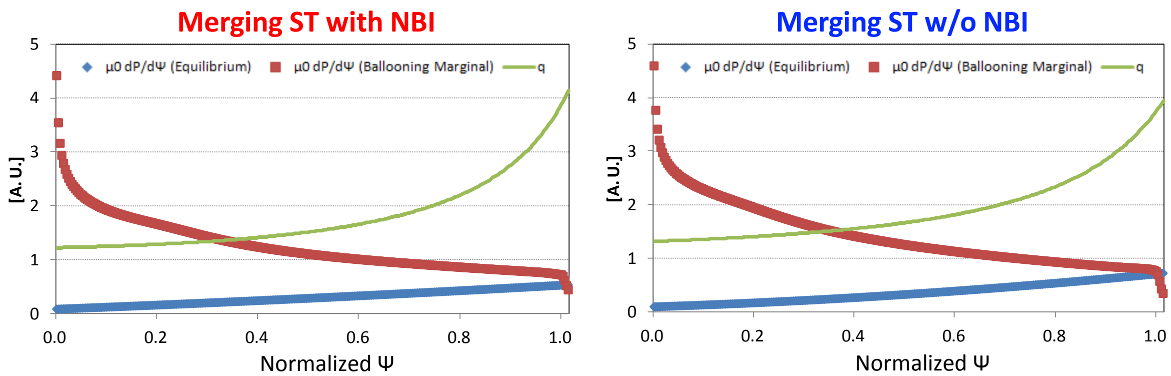

Fig. 4 The pressure gradient of MHD equilibrium and ballooning marginal state, and safety factor q profile at magnetic flux surfaces at t = *440* [μs].

instability which is calculated by solving the ballooning mode equation with zero growth rate, and safety factor q profile at magnetic flux surfaces. Due to the normal shear, the interchange mode was stable at all magnetic flux surfaces by judging from Mercier criterion. However, the ideal ballooning mode is unstable at the magnetic flux surfaces near the plasma edge. This did not change whether using NBI or not.

In conclusion, we have developed the plasma merging start-up for a high-beta ST formation and the NBI with a total power of 0.4 [MW] for its auxiliary heating and sustainment. The merging increases the beta of the ST significantly over 30 - 40 [%] within short reconnection time. Since the NBI power was maintained for the whole discharge, it mainly contributed to pre-ionization, slightly keeping plasma shape and decreasing total energy dissipation. The beam trajectory calculation indicates the beam trap-rate of 55.6 [%]. Our pressure-driven instability analysis indicates the merging ST plasmas are stable to the interchange mode but unstable to the ballooning mode near the plasma edge. Now we are installing the third NBI device and are planning to increase the total NBI power over 1 [MW].

References

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