High-Beta Characteristics of First and Second-Stable Spherical Tokamaks in Reconnection Heating Experiments of TS-3

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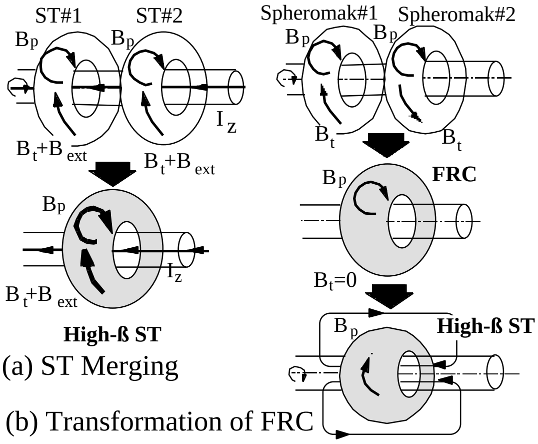
Abstract. Novel CS(center solenoid)-less formations of ultra-high-beta Spherical Tokamaks (ST) have been developed in the TS-3 merging experiment using high power heating of magnetic reconnection. In Type-A merging, two STs were merged together to build up the plasma beta up to $ß_T≈0.5$. In Type-B merging, an oblate FRC formed by two merging spheromaks with opposing toroidal field B_t, was transformed into an ultra-high-beta ($ß_T≈0.8$) ST by applying external B_t. We made (1) the BALLOO code stability analyses of the produced STs for the first time and concluded formations of the first-stable / marginally second-stable STs by Type-A merging and the second-stable STs by Type-B merging and also unstable STs by both mergings. The obtained ballooning-stable regime was almost consistent with measured high-n instabilities. The stable regime became larger significantly by increasing the hollowness of current profile and broadness of pressure profile. This paper also addresses (2) normalized betas $ß_N$ of thus produced STs as large as 6-17 for comparison with the Troyon scaling and (3) a promising B^2 scaling of the reconnection heating. Those facts indicate that the axial merging is one of the most efficient startup methods for high-beta STs without powerful CS.

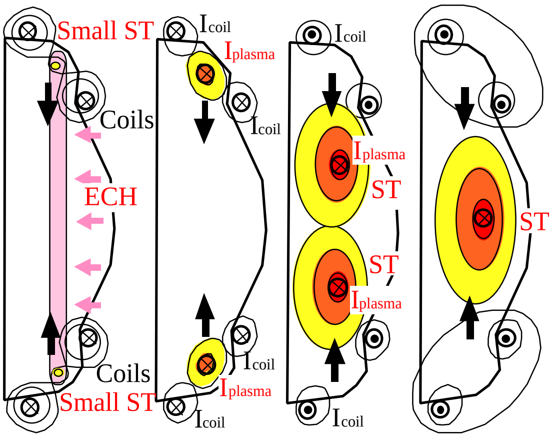
1. Introduction

Novel CS(center solenoid)-less formations of ultra-high-ß Spherical Tokamaks (ST) have been developed in the TS-3 merging experiment using high power heating of magnetic reconnection[1]. As shown in Figs. 1, Type-A and B mergings were used for high-ß ST startup. In Type-A merging, two STs were merged together to build up the plasma ß. In Type-B merging, an oblate FRC was initially formed by two merging spheromaks with opposing toroidal field B_t[2,3] and was transformed into an ultra-high-ß ST by applying external B_t[1]. These unique methods enable us to explore the unknown second-stable (ultra-high ß) regime of STs and also to investigate effects of current/ pressure profiles (hollowness/ broadness) on high-ß staibility of STs. Note that these mergings provide significant heating power (≈1-30MW in TS-3) within the short reconnection time (<<the confinement time). The future promising startup scheme of high-ß ST without use of center solenoid is illustrated in Fig. 1(c) based on Type-A merging. Two STs are produced



(a) ST Merging

(b) Transformation of FRC



(c) Proposed High-ß ST Startup

FIGS. 1. CS-less startup methods for high-ß STs: (a) merging of two STs (Type-A), (b) transformation of FRC produced by counter-helicity merging (Type-B) and (c) proposed merging startup for large scale experiments based on (a).

around the X-points between two PF coils and are merged together for high-ß ST formation. Its electrodeless/ CS-less startup by axisymmetric merging has significant advantages over the present CHI and RF startups. Our TS-3 and 4 devices are now demonstrating this scheme using internal PF coils instead of external PF coils.

Important questions then arise as to whether these high-ß STs reveal the ballooning stability window, especially the second-stable regime or not and how our reconnection heating can be upscaled for future large-scale experiments. We made (1) model analyses of those STs for the first time using the BALLOO stability code[4], revealing the ballooning stability window consistent with measured high-n instabilities. This paper also addresses (2) comparison with the Troyon scaling for $ß_N$ value and (3) a scaling study of the reconnection heating.

2. Experimental Setup

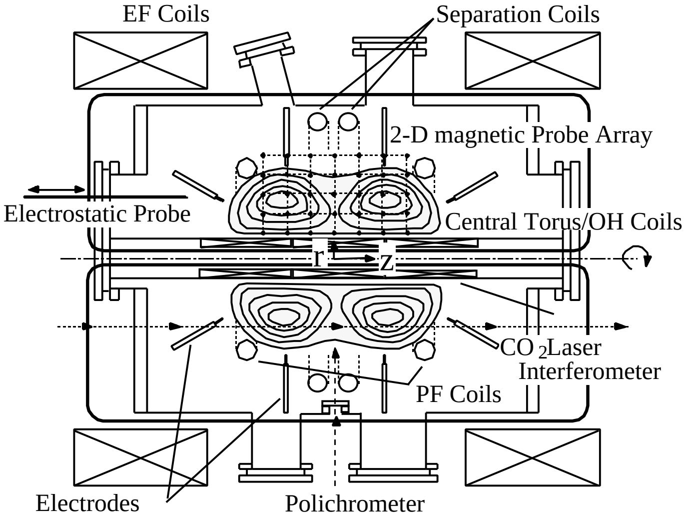


FIG. 2. TS-3 ST/CT Merging Device (R=0.18-0.22m, R/a=1.5, B_0≈0.5kG, T_i=10-200eV, T_e=10-40eV, n_e=2-10×$10^{19}m^{-3}$).

Type-A and B mergings were used to perform the CS-less startups of high-ß STs in the TS-3 device [1-3], as shown in Fig. 2. Its cylindrical vacuum vessel with length of 1m and diameter of 0.8m has two poloidal (PF) coils for poloidal flux injection into two STs/ spheromaks. Two sets of eight electrode pairs were used for toroidal flux injection into two spheromaks for Type-B merging. Their B_t polarities were determined by those of the electrode discharge currents. Two STs or spheromaks with R≈0.2m R/a≈1.5 were produced and were merged together in the axial direction. The plasma heating powers for the Type-A and B mergings were about 30MW and 2-10MW, respectively. Each merging toroid initially had major radius R≈0.18-0.22m, T_i≈T_e≈10eV, n_e≈2-10×$10^{19}m^{-3}$ and B≈0.5kG. Their merging speed was controlled by magnetic pressure of the PF coil currents and the separation coil currents on the midplane. An CS (or OH) coil with diameter ≈0.12m was used to provide volt-second only for current sustainment (≈200μsec) after the high-ß ST formation. Seven thin arrays of magnetic pickup coils were inserted on the r-z plane of the vessel to measure directly the 2-D magnetic field profile. A polichrometer with an optical multi-channel analyzer was used to measure radial profiles of ion temperature T_i and velocity V_i by means of the Doppler width and shift of carbon and hydrogen lines. An electrostatic probe array was inserted to measure the radial profiles of electron temperature T_e and density n_e. Poloidal flux contours, current density profiles and plasma pressure profiles were calculated from those 2-D magnetic field profiles and T_i, T_e, and n_e profiles.

3. Experimental Results

Figure 3 shows the toroidal betas $ß_T$ of the STs by Type-A and B mergings and single low-ß STs as a function of the Troyon factor I/aB_t. The single STs were produced without merging process. They had $ß_T$≈0-0.15 almost equal to those of START STs. In Type-A merging, ion

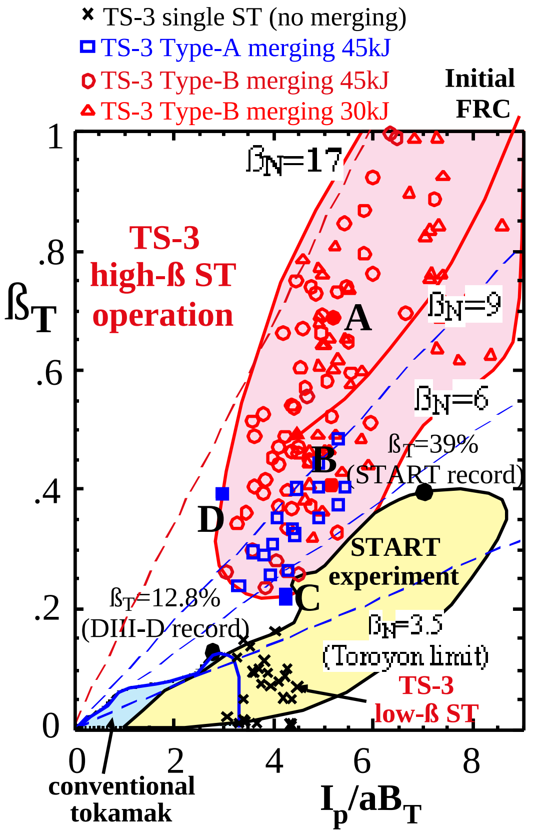


FIG.3. Toroidal betas ß$_T$ of the single STs (no merging) and high-ß STs produced by Type-A and B mergings as a function of I/aB$_t$.

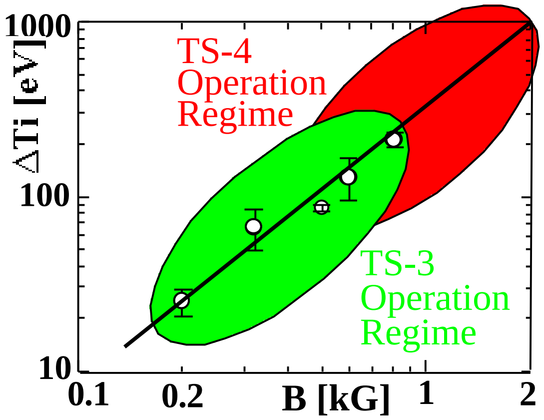


FIG. 4. Dependence of Ion temperature increment ΔT$_i$ during Type-B merging on initial magnetic field B of merging toroids.

acceleration effect of magnetic reconnection converted a part of the poloidal magnetic energy of merging ST into ion thermal energy W$_i$ (T$_i$≈30-100eV>>T$_e$≈10-30eV), quickly increasing ß$_T$ to 0.2-0.5. Its normalized beta ß$_N$ increased up to 10, transforming the initial low-ß STs into the high-ß ones quickly and efficiently. The Type-B merging converted the whole toroidal (and a part of poloidal) magnetic energy W$_t$ of merging spheromaks (ß$_T$≈0.1, T$_i$≈T$_e$≈ 10eV) into W$_i$ (T$_i$≈80-200eV>>T$_e$≈10-30eV) of the produced FRC and the fast application of external B$_t$ transformed it into the high-ß ST with ß$_T$≈0.4-1, T$_i$≈60-170eV>>T$_e$≈10-30eV. During the external toroidal field rump-up, the ST started moving from I/aB$_t$≈∞ to each position plotted in Fig. 3, because the produced FRC had zero B$_t$. Its normalized beta ß$_N$ increased up to 17, exploring the new ultra-high-ß regime. The maximum ß$_N$ of thus formed ST was much higher than that obtained by the conventional heating of OH (or CS) coil, suggesting that the pressure/ current profile control effect of the merging enabled the ST to attain the ultra-high-ß regime.

This heating mechanism of merging/ reconnection revealed its promising B^2-scaling of heating energy. Figure 4 shows ion temperature increment ΔT$_i$ of the produced STs as a function of initial B-field of merging toroids in the case of Type-B merging. It was clearly observed that ΔT$_i$ increased approximately with B^2. The measured scaling factor was between 1.8 and 2.3, depending on operational conditions. This scaling agrees well with the following theoretical prediction. We already observed that the Type-B merging/ reconnection converted the whole toroidal magnetic energy W$_t$ of two merging spheromaks into the ion thermal energy increment ΔW$_i$ of the produced FRC/ST with efficiency η≈0.8[2]. Hence, ΔW$_i$ is calculated from $\Delta W_i = 3/2\int nk\,\Delta T_i dv = \eta\int B_t^2/2\mu_o dv = \eta W_t \approx 0.8 W_t$, if the heating (reconnection) time << the confinement time. Since the density n≈constant, ΔT$_i$ should increase with B^2. The Type-A merging also revealed the similar dependence of heating power on magnetic field because both methods utilize just the similar energy conversion effect of magnetic reconnection. This fact suggests that next keV-class heating experiment can be demonstrated by increasing B up to 2-3kG. The power supply for the TS-4 device is being upscaled to produce kG-order STs and spheromaks for sub-KeV heating experiment.

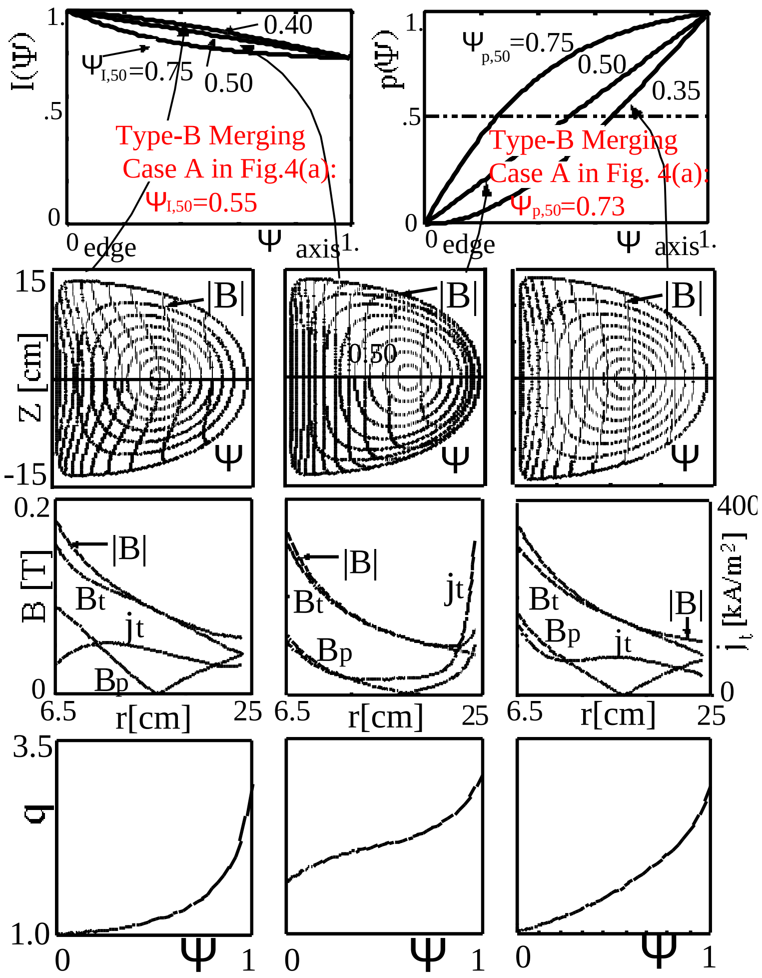


FIG. 5. High-ß ST equilibria with three current profiles I and thermal pressure profiles p: poloidal flux and |B| contours, radial profiles of |B|, B_t, B_p and j_t and q profiles.

Those high-ß equilibria were analyzed by the BALLOO equilibrium/ stability code[4] to study the first and second stable regimes of high-ß ST. Figure 5 shows how the current and pressure profiles (I, p) change the high-ß ST equilibrium of case A in Fig. 3 (by Type-B merging). Its magnetic well was observed to increase, as p and I became broad and hollow, respectively. The absolute minimum-B profile observed in case A (Fig.3) was formed under the condition of $\Psi_{p,50}>0.7$ and $\Psi_{I,50}>0.5$ (half-widths of p and q profiles).

Figures 6(a)(b) show the q_Ψ-p_Ψ diagrams of the high-ß ST (case A: $\Psi_{p,50}=0.73$, $\Psi_{I,50}=0.55$) and the medium-ß ST (case B: $\Psi_{p,50}=0.4$, $\Psi_{I,50}=0.55$) produced by Type-B merging and those of the medium-ß and low-ß STs produced by Type-A merging. Based on the BALLOO code analyses, typical ballooning-unstable regimes (together with their reference points) are also shown in Fig. 6. The high-ß ST: case A had the maximum pressure gradient and magnetic shear at the edge and was maintained stably over 200µsec. The stability analysis indicates that its whole flux surfaces were located in the second stability regime. The medium-ß ST: case B was produced by degraded Type-B merging and was found to locate in the unstable regime. In agreement with this result, the ST was observed to collapse

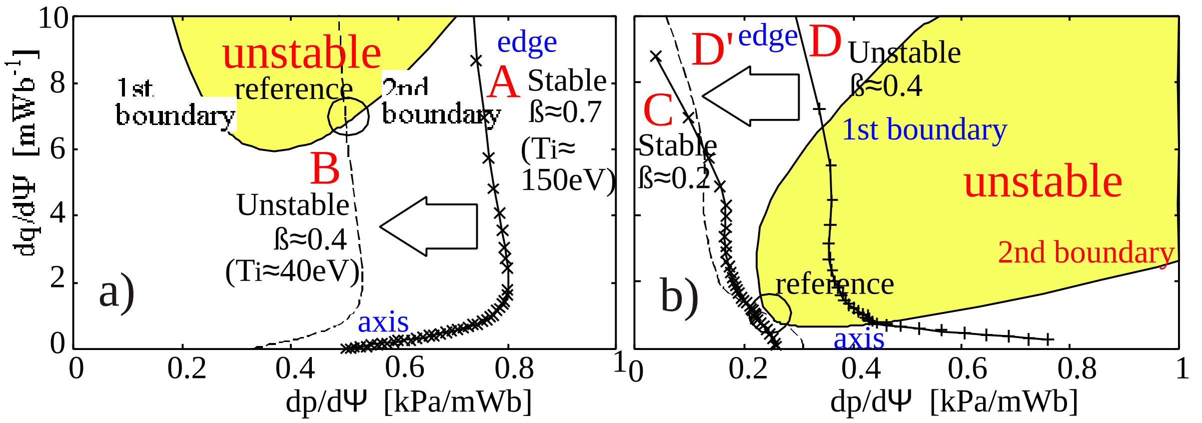


FIG. 6. (a) q_Ψ-p_Ψ profiles of high-ß ST (stable: case A) and medium-ß ST (unstable: case B) by Type-B merging, (b) those of low-ß ST (stable: case C) and medium-ß ST (unstable: case D) by Type-A merging.

due to high-n (n>8) modes. In Fig. 6(b), the low-ß ST: case C had maximum pressure gradient in the core and was maintained stably for 200-300µsec. The medium-ß ST: case D which had higher p_Ψ but similar q_Ψ profiles, collapsed due to edge-localized high-n modes. The stability analysis indicates that the low-ß ST was located in the first stability regime and that the core surfaces of the medium-ß ST were located in the ballooning unstable regime.

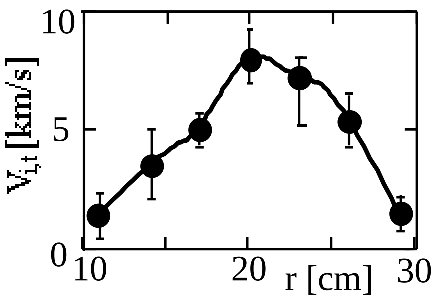


FIG. 7. Radial profile of toroidal ion velocity after Type-B merging.

An important finding is that the window between the first and second stability regimes becomes markedly wider as I and p profiles are set more hollow and broad, respectively. The hollow I and broad p profiles are essential to stable sustainment of the second stable ST, suggesting the importance of profile control for the future ultra-high-ß ST experiment.

A final question is how those high-ß STs were stable for current driven modes caused by the hollow current profile. We detected high-n fluctuations consistent with the ballooning mode but have not detected any large low-n kink mode. It is possibly due to mode stabilization effect of ion flow shear. As shown in Fig. 7, the fast sheared flow was directly measured in the high-ß ST/FRC produced by Type-B merging.

4. Summary and Conclusions

In summary, we formed the first and second-stable STs and unstable STs for ballooning mode, using two types of ST and spheromak mergings without use of center solenoid. Their stability analyses indicate that the hollow current and broad pressure profiles are essential to stable formation and sustainment of the second stable STs. The ultra-high-ß STs produced from FRC had ß$_N$≈15-20 much higher than the conventional STs, while other high-ß STs produced by ST merging had ß$_N$≈5-10. The ST merging was found to be a promising profile control method for the high-ß ST. This merging scheme is also suitable for their current drive, as shown in Fig. 8. During intermittent mergings, two STs will be produced only when the PF coil currents have the same polarity as the plasma current. The produced plasma toroids are considered to disappear if the PF coil currents are opposite to the plasma current. Based on the B^2 scaling of T_i, the upscaled experiment TS-4 with B≈2kG is expected to demonstrate merging startup of second stable ST with T_i over 0.5keV.

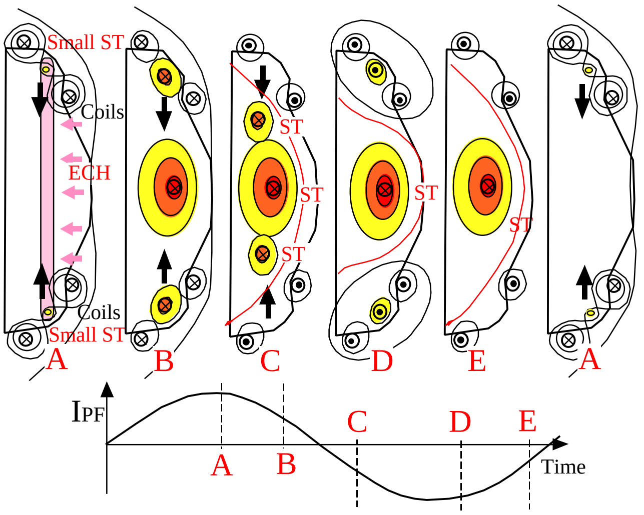


FIG. 8. Mechanisms for startup and current drive of ST by the Type-A merging in FIG. 1(c).

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