Double Null Merging Start-up Experiments in the University of Tokyo Spherical Tokamak

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Abstract. University of Tokyo Spherical Tokamak (UTST) is a unique device that demonstrates merging start-up of the spherical tokamak (ST) plasma using two pairs of poloidal field (PF) coils outside the vacuum vessel. In this double null merging (DNM) method, two initial STs are formed at two null-points generated by two pairs of PF coils, and are merged to form a single ST. Without using the central solenoid (CS), the plasma current of 40 kA and the pulse width of 0.6 ms were obtained only by the DNM method. After the completion of the plasma merging, the thermal energy reached 80 J, and the heating power of reconnection was as high as 1.7 MW. Using CS in addition to the DNM discharge, the plasma current and discharge time increased to 100 kA and 1.2 ms, respectively. The thermal energy reached 230 J after the completion of the merging, and the heating power was as high as 4.5 MW. The DNM method is more reactor-relevant plasma heating method as well as one of CS-less start-up schemes world-widely studied.

1. Introduction

A spherical tokamak (ST) is a low-aspect-ratio tokamak that supports a compact and economical fusion reactor. If the central solenoid (CS) can be removed, the aspect ratio will be reduced and simpler and more economical ST can be obtained. Therefore, study of CS-less start-up scheme is important in current ST research. The CS-less ST start-up has been widely studied in the ST devices by using electron cyclotron waves [1–3], a radio-frequency wave [4], coaxial helicity injection [5], and point-source dc helicity injection [6].

One proposed CS-less ST startup scheme is the plasma merging method whose advantage is high-power initial heating to produce a high-beta ST plasma. When two ST plasmas merge together to form a single ST, magnetic field lines reconnect, and the magnetic field energy is converted to the plasma kinetic and thermal energy, increasing the plasma beta up to 50% within the short reconnection period. The ST merging experiments have been demonstrated in the START and MAST (Culham Centre for Fusion Energy) and TS-3 and TS-4 (Univ. Tokyo) devices, by using the PF coils located inside the vacuum vessels. A merging-compression technique, pioneered on START, was employed on MAST to obtain 0.5 MA initial plasma currents [7]. The double null merging (DNM) start-up was demonstrated in TS-3, TS-4, START, and MAST by using PF coils inside the vacuum vessel [8]. The TS-3 experiment merged two STs to form a single ST with higher beta of up to 50%. An oblate field-reversed configuration plasma formed by two spheromaks with counterhelicity was transformed into an ultrahigh-beta (up to 80%) ST by applying an external toroidal field [9–11]. A remain problem for these experiments is to demonstrate the merging start-up not by PF coils inside the vacuum vessel, which are not suitable for a future fusion reactor, but by those outside the vessel.

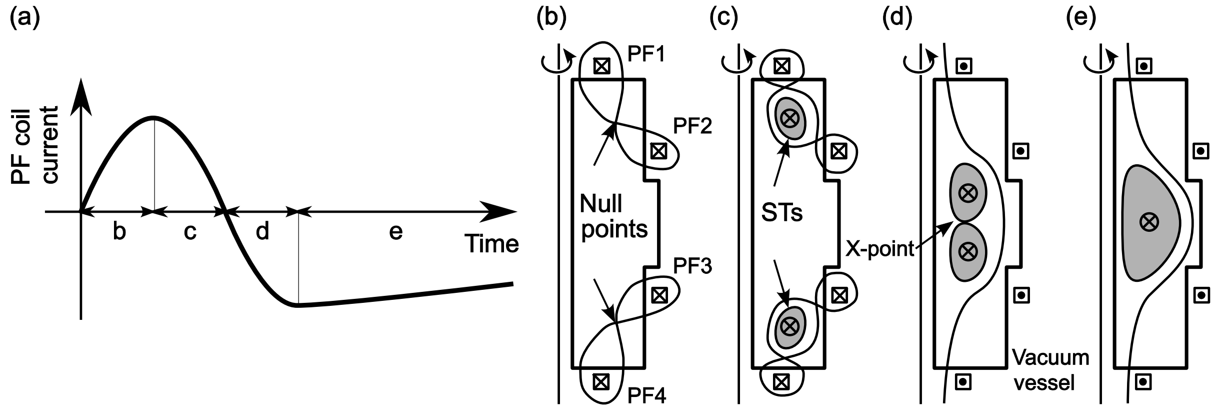

FIG. 1. The DNM scheme used in the UTST: (a) Current of the PF coils used for the DNM method. (b) Outer PF coils generate two null points inside the vacuum vessel. (c) Two STs are generated at two null points. (d) When the PF coil current is reversed, the STs are pushed toward the mid-plane. (e) Two STs merge to form a single ST.

University of Tokyo Spherical Tokamak (UTST, Univ. Tokyo) was constructed for the purpose of demonstrating the reactor-relevant plasma merging start-up by using the outer PF coils, which would be more reactor-relevant condition. Figure 1 illustrates the DNM method using the PF coils located outside of the UTST vacuum vessel. Figure 1(a) shows the waveform of the PF coil current. At the time shown in Fig. 1(b), two magnetic null points are generated at the upper and lower regions inside the vacuum vessel. In Fig. 1(c), two STs are generated at the null points by ramping down of the PF coil currents. In Fig. 1(d), the STs are pushed toward the mid-plane by the reversed PF coil currents. In Fig. 1(e), the two STs merge to form a single ST. The beta value of the merged ST is expected to be quite high because the magnetic field energy is converted to plasma kinetic energy by magnetic reconnection. Here, we present the successful start-up of the spherical tokamak by using the external PF coils outside the vacuum vessel. The UTST experiment provides a useful technique for the CS-less start-up scheme.

2. The UTST Plasma Merging Device

The UTST ST merging device was designed to form ultra high-beta ST plasmas whose plasma current, density, and temperature are about 200 kA, 5×10^{19} m^{-3}, and 200 eV, respectively. The vacuum vessel has an axial (z) length of about 2 m and a major radius (R) of about 0.7 m. The UTST has a toroidal field (TF) coil with 8 turns, two equilibrium field (EF) coils (8 turns each), four PF coils (PF1 and 4: 8 turns; PF2 and 3: 3 turns), a CS coil with 95 turns, and two acceleration (ACC) coils (4 turns each) as shown in Fig. 2(a). The TF, EF1 and 2 (in parallel), PF1 and 2 (in parallel), PF3 and 4 (in parallel), CS, and ACC1 and 2 (in parallel) coils are connected to capacitor banks whose energy are 200 kJ, 27 kJ, 110 kJ, 110 kJ, 45 kJ, and 27 kJ, respectively. The CS coil is used to compare the CS-less start-up and CS start-up. It is used to improve the target plasma for neutral beam (NB) injection and radio-frequency heating. The ACC coils are used to increase the plasma merging speed. Pre-ionization for generating the seed plasma is performed by two washer guns inside the vacuum vessel. The gas resource is hydrogen, and the filling pressure is about 0.02 Pa. Each washer gun is energized by a 7 kJ capacitor bank.

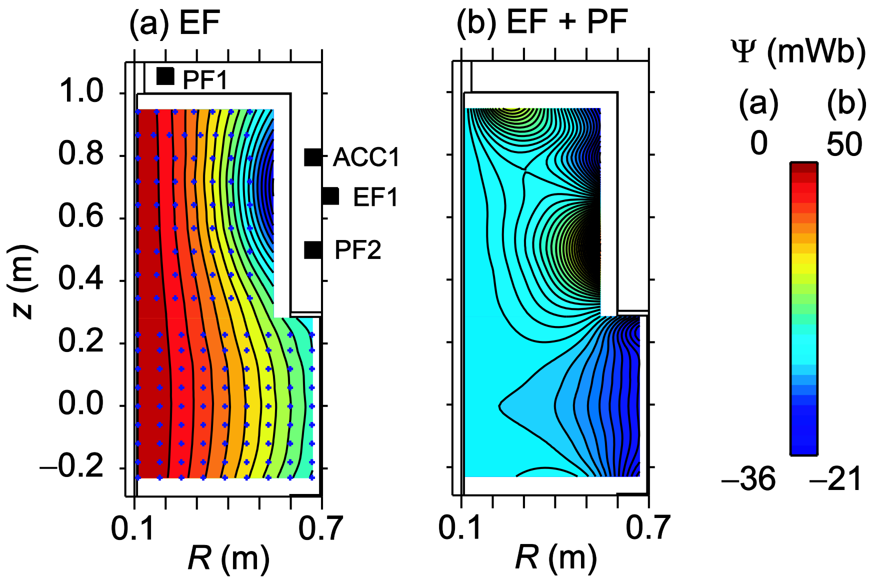

FIG. 2. Poloidal magnetic flux contours generated by (a) the EF coils and (b) the EF and PF coils. Positions of the magnetic pickup coils and locations of the magnetic coils are illustrated in (a). Null point at the upper region is observed in (b).

Two-dimensional (axial, z and radial, R) pickup coil array is located inside the vacuum vessel to measure the axial and toroidal magnetic fields (B_z and B_t) directly at the plasma existing region. As shown in Fig. 2(a), the pickup coil array is composed of two parts. The upper part of array ($0.35\ \mathrm{m} \le z \le 0.95\ \mathrm{m}$) has 64 channels of B_z coils and 64 channels of B_t coils, and the middle part ($-0.23\ \mathrm{m} \le z \le 0.23\ \mathrm{m}$) has 81 channels of B_z coils and 81 channels of B_t coils. The pickup coil arrays degrade the plasma parameters only by about 5%. All 290 channels are simultaneously measured with digitizers (sampling frequency of 1 MHz). The poloidal magnetic flux, Ψ, is calculated from B_z using $\Psi = 2\pi\int B_z R\, \mathrm{d}R$. Examples of the measured poloidal magnetic flux contour for the vacuum EF coil current and vacuum EF plus PF coil currents are shown in Fig. 2. The shape of the poloidal magnetic flux produced by the EF coils is precisely measured by the B_z measurement, and also a null point is clearly observed in the EF plus PF case. Radial magnetic field, B_R, toroidal current density, j_t, and toroidal electric field, E_t, are calculated by

$$B_R = -\frac{1}{2\pi R}\frac{\partial \psi}{\partial z},$$

$$j_t = \frac{1}{\mu_0}\left(\frac{\partial B_R}{\partial z} - \frac{\partial B_z}{\partial R}\right),$$

$$E_t = -\frac{1}{2\pi R}\frac{\mathrm{d}\psi}{\mathrm{d}t},$$

respectively. The pressure, p, is derived from the equation $\nabla p = \boldsymbol{j} \times \boldsymbol{B}$, and the thermal energy, W, is calculated from integrating p.

3. Experimental Results

For the past three years, the DNM start-up has been successfully performed in UTST. Figure 3(a) shows the time evolutions of the poloidal magnetic flux contours with toroidal current density, which were measured by the two-dimensional pickup coil array. One initial ST with aspect ratio of 2.4 was formed at the null-point in the upper region and was pushed toward the mid-plane to merge with another ST moving from the lower region. Figure 3(b) shows the fast camera images, which also show the merging formation of a single ST with aspect ratio of 1.5. The plasma current of 40 kA and the pulse width of 0.6 ms were obtained as shown in Fig. 4(a). The acceleration coils were used to increase the plasma merging speed. During the merging period, a current sheet, which is the toroidal current density anti-parallel to the plasma current density, was clearly observed at around the merging X-point as shown in Fig. 3(a). As shown in Fig. 4(b), the effective resistivity of the current sheet calculated from E_t/j_t at X-point was observed to be as small as 1 mΩ·m (ten times larger than classical resistivity) during the initial reconnection phase but to increase significantly just before the merging completion. After the completion of the plasma merging, the thermal energy, W, reached 80 J (central pressure of 200 Pa), and the heating power of reconnection, dW/dt, was as high as 1.7 MW [Fig. 4(c)] under the present magnetic field condition.

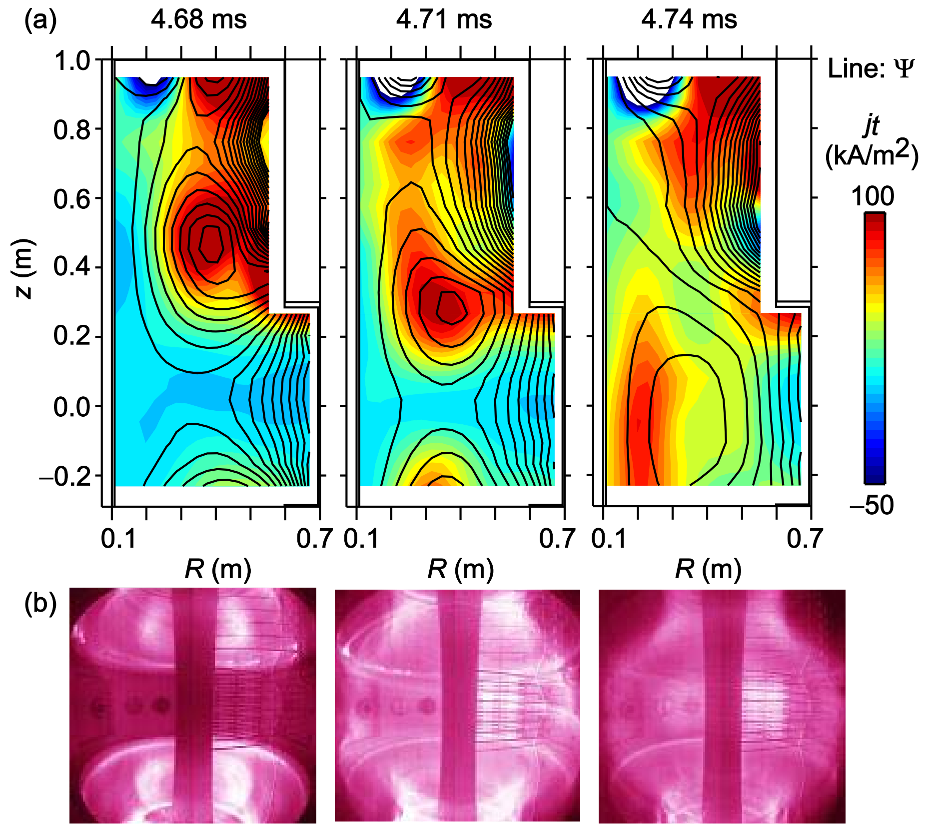

FIG. 3. (a) Time evolution of poloidal magnetic flux contour with toroidal current density (by color) during the two ST merging discharge and (b) fast camera images of this process.

When we use CS coil in addition to the DNM discharge, better initial plasmas were formed and merged together as the CS-less discharge. The measured plasma current and discharge time increased to 100 kA and 1.2 ms, respectively as shown in Fig. 4(a). The current sheet and its anomalous resistivity (2.5 times larger than CS-less) were also observed in the CS-assisted discharge as shown in Fig. 4(b). The thermal energy reached 230 J (central pressure of 400 Pa) after the completion of the merging, and the heating power was as high as 4.5 MW. Note that the effect of CS is included in this power. After the merging completion, the thermal energy continued to increase and reached 650 J (central pressure of 1000 Pa). Figure 5 shows the time evolution of the poloidal magnetic flux contours at t = 4.70 ms, 4.71 ms, 4.72 ms, and 4.74 ms. The toroidal current density contours at t = 4.71 ms is plotted by color. Formation of current sheet around the X-point is also clearly seen as the CS-less discharge.

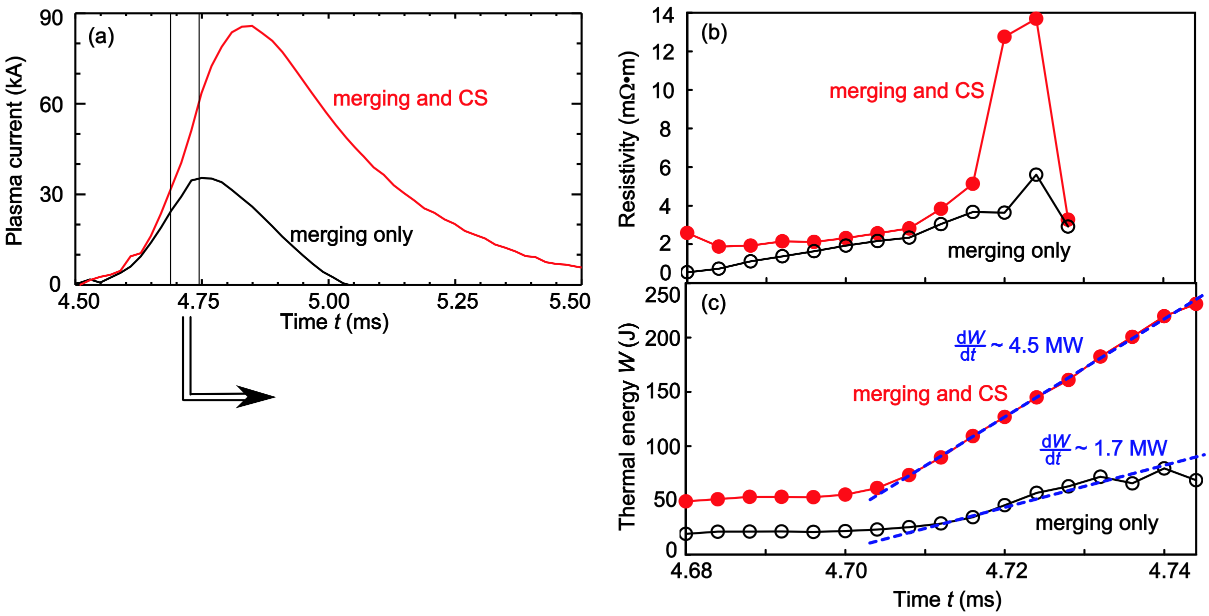

FIG. 4. Time evolutions of (a) plasma current, (b) resistivity at current sheet, and (c) thermal energy. Black and open circles represent the merging discharge, and red and closed circles do the merging and CS discharge.

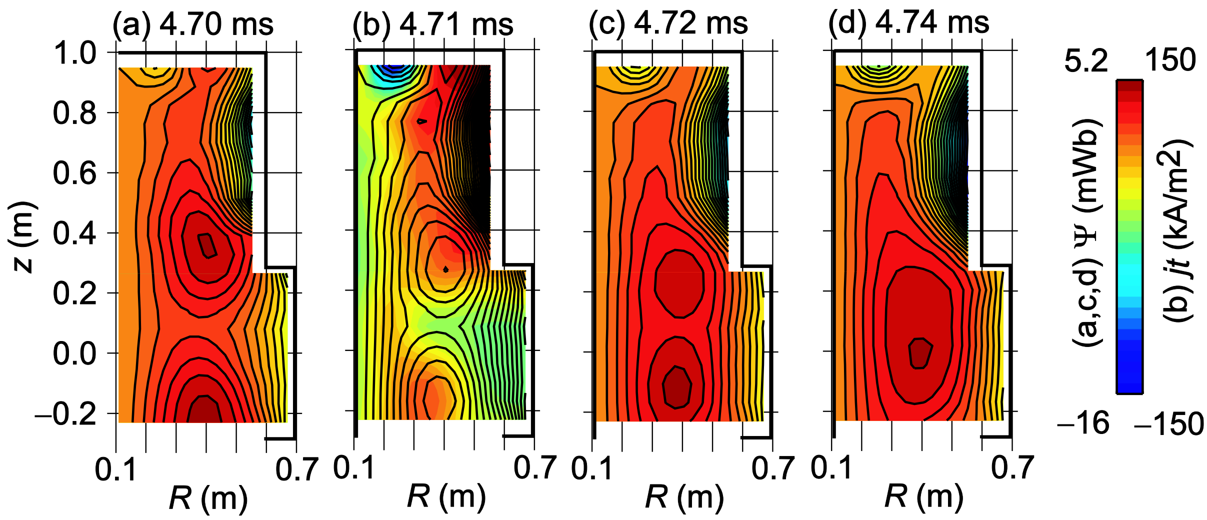

FIG. 5. Time evolution of poloidal magnetic flux contour for the merging and CS discharge. For (b), toroidal current density is superposed by color.

4. Pre-ionization by NBI

Though the DNM start-up has been successfully demonstrated, the plasma parameters still does not reach the expected value for the UTST full-power operation, because of the partial operation of the power supplies. In the near future, UTST will be fully operated to produce a suitable target plasma for NB injection. In the present situation, the NB system is tested mostly for the purpose of pre-ionization of the UTST plasma now. The accelerating voltage of NB is 25 kV and the beam duration is 15 ms. Figure 6 shows the time evolutions of the beam power and those of the plasma currents when the injected NB were co and counter with respect to the plasma current direction. The NB power was increased successfully up to 0.5 MW. The plasma current induced by the CS ramp-up (~1 ms) in the NB co-injection case was found to be 5–6 times larger than that in the NB counter-injection case, indicating that the ions produced by the NB mainly contributed to the plasma formation.

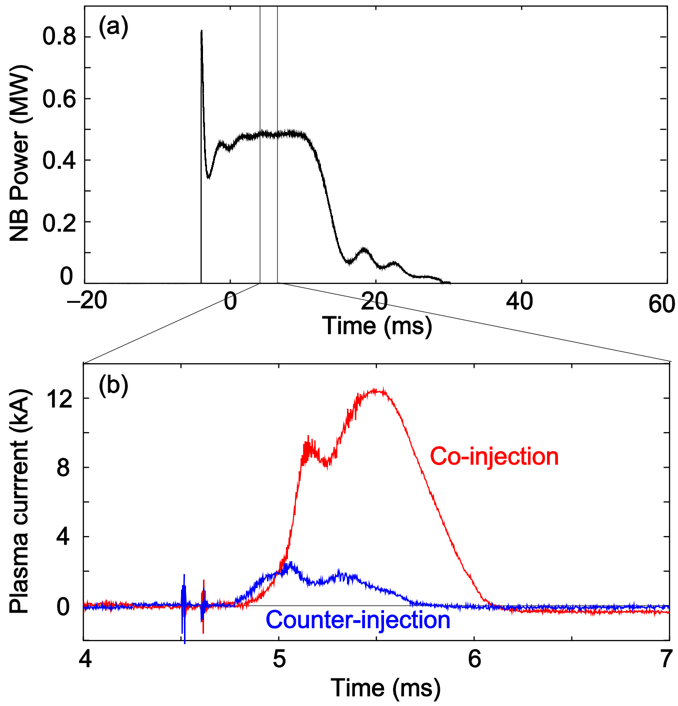

FIG. 5. Time evolutions of the (a) neutral beam power and (b) plasma currents for the NB injections with co and counter polarities.

5. Summary

We successfully demonstrated the double null merging start-up scheme using the UTST merging device. Its PF coils are located outside the vacuum vessel to demonstrate a reactor-relevant merging start-up for the first time. The two-dimensional pickup coil measurement indicates that the magnetic surfaces of two STs were merged together by means of plasma generation by the PF and CS coils. The maximum plasma current 40 kA and the pulse width about 0.6 ms were obtained without using the CS coil. After the completion of the plasma merging, the thermal energy reached 80 J, the central pressure reached 200 Pa, and the heating power of reconnection was as high as 1.7 MW. With using CS as an assistance, the maximum plasma current was 100 kA and the pulse width was about 1.2 ms. After the completion of the plasma merging, the thermal energy reached 230 J, the central pressure reached 400 Pa, and they still increased to 650 J and 1000 Pa after plasma merging, respectively. The heating power was as high as 4.5 MW. In both cases, we measured a current sheet at the X-point and anomalous resistivity over one hundred times larger than the Spitzer resistivity. In the future, the power supplies to the coils will be increased for full operation of UTST and for NB injection experiments.

Acknowledgement

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