Merging Startup Experiments on the UTST Spherical Tokamak

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The University of Tokyo Spherical Tokamak (UTST) was constructed to explore the formation of ultrahigh-beta spherical tokamak (ST) plasmas using double null plasma merging. The main feature of the UTST is that the poloidal field coils are located outside the vacuum vessel to demonstrate startup in a reactor-relevant situation. Initial operations used partially completed power supplies to investigate the appropriate conditions for plasma merging. The plasma current of the merged ST reached 100 kA when the central solenoid coil was used to assist plasma formation. Merging of two ST plasmas through magnetic reconnection was successfully observed using two-dimensional pickup coil arrays, which directly measure the toroidal and axial magnetic fields inside the UTST vacuum vessel. The resistivity of the current sheet was found to be anomalously high during merging.

Keywords: spherical tokamak, merging startup, magnetic reconnection

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1. Introduction

A spherical tokamak (ST) is a low-aspect-ratio tokamak that supports a compact and economical fusion reactor. The study of central solenoid (CS)-less startup schemes is important in current ST research. One proposed CS-less ST startup scheme is the plasma merging method, which is expected to provide high-power initial heating to produce a high-beta ST plasma. When two plasmas merge to form a single plasma, magnetic field lines reconnect, and the magnetic field energy is converted to plasma kinetic or thermal energy, increasing the plasma beta to as high as 50% very quickly.

Merging startup has been demonstrated in the START/MAST (UKAEA) and TS-3/4 (University of Tokyo) devices. A merging-compression technique, pioneered on START, was employed on MAST to obtain ~ 0.5 MA initial plasma currents [1]. On TS-3, two STs were merged to form a single ST with a beta of up to 50% during cohelicity merging, and an oblate field-reversed configuration plasma formed by two spheromaks was transformed into an ultrahigh-beta (up to 80%) ST by applying an external toroidal field during counterhelicity merging [2–4]. However, in these experiments, the plasma merging startup used poloidal field (PF) coils inside the vacuum vessel. Using inner PF coils will not be suitable for a future fusion reactor.

To investigate the feasibility of merging startup for generating fusion ST plasmas, the University of Tokyo Spherical Tokamak (UTST) was constructed with all the PF coils outside the vacuum vessel, which provides more reactor-relevant conditions. The UTST plasma is generated using the double null merging (DNM) method with four external PF coils. The success of merging in the UTST will provide one of the key techniques for a CS-less startup scheme in high-beta ST research. Moreover, another purpose of the UTST experiment is to sustain the high-beta ST by employing external heating methods such as radio-frequency heating and neutral beam injection. These two heating methods have been prepared, and the heating experiments have just started. To obtain the plasma parameters over wide ranges of conditions, including those suitable for external heating, a CS coil has been installed on the UTST. This paper describes the UTST experiments demonstrated by the DNM method with CS coil support.

2. Double Null Merging Method

Figure 1 illustrates the DNM method using the PF coils of the UTST. The UTST has four PF coils, all located outside the vacuum vessel. Figure 1 (a) shows the PF coil currents. At the time shown in Fig. 1 (b), two magnetic null points are generated at the upper and lower regions inside

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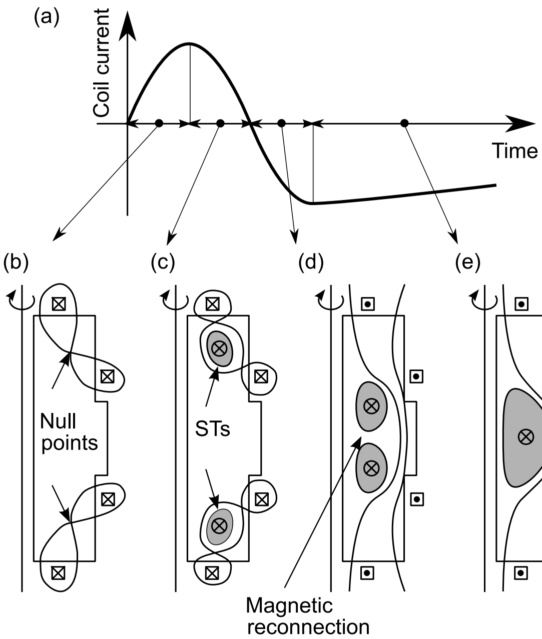

Fig. 1 Drawings illustrating DNM as used in the UTST. (a) Current of the PF coils used for DNM. (b) Outer PF coils generate two null points inside the vacuum vessel. (c) Two STs are generated at the null points. (d) When the PF coil current is reversed, the STs are pushed toward the midplane. (e) STs merge to form a single high-beta ST.

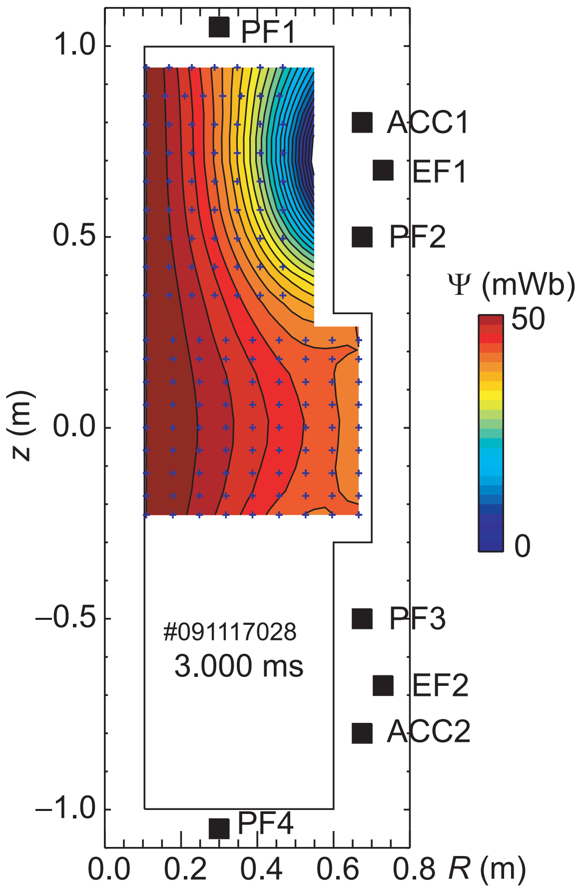

Fig. 2 Schematic of the UTST plasma merging device. Locations of EF1 and 2, PF1–4, and ACC1 and 2 coils are illustrated. Crosses indicate the positions of the B_z and B_t pickup coils. Plot shows the contours of the poloidal magnetic flux generated by the EF coils.

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 midplane 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. The initial heating of STs using merging has been successfully demonstrated in the TS-3 and TS-4 devices with internal PF coils [2–4]; however, DNM using PF coils outside the vacuum vessel has never been performed before.

3. The UTST Plasma Merging Device

The UTST plasma merging device is located at the Kashiwa campus of the University of Tokyo. The designed plasma parameters for its full operation are a plasma current of 200 kA, density of 5×10^{19} m^{-3}, and temperature of 200 eV. 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). The locations of the coils are illustrated in Fig. 2. The TF, EF1 and 2 (parallel), PF1 and 2 (parallel), PF3 and 4 (parallel), CS, and ACC1 and 2 (parallel) coils are supplied with powers of 200, 27, 110, 110, 45, and 27 kJ, respectively. The CS coil is used for plasma startup assistance, although the goal of the UTST experiment is CS-less plasma startup. The ACC coils are used to increase the plasma merging speed. Preionization for generating the seed plasma is performed by two washer guns inside the vacuum vessel, one at the bottom and the other at the low-field-side wall ($z \sim 0.3$ m) [5]. The gas resource is hydrogen, and the filling pressure is about 0.02 Pa. Each washer gun is supplied with a power of 7 kJ.

To observe the plasma merging, two-dimensional (axial, z and radial, R) pickup coil arrays are located inside the vacuum vessel to measure the axial and toroidal magnetic fields (B_z and B_t) directly at the plasma. The locations of the pickup coil arrays are shown in Fig. 2. The pickup coil array in the upper region of the vacuum vessel (0.35 m $\leq z \leq$ 0.95 m) has 64 channels of B_z coils and 64 channels of B_t coils. The array in the middle region (−0.23 m $\leq z \leq$ 0.23 m) has 81 channels of B_z coils and 81 channels of B_t coils. Each pickup coil has windings of 300 turns and outer and inner diameters of 5.0 mm and 3.5 mm, respectively. The pickup coils are covered by glass tubes. The pickup coil arrays degrade the plasma parameters only by

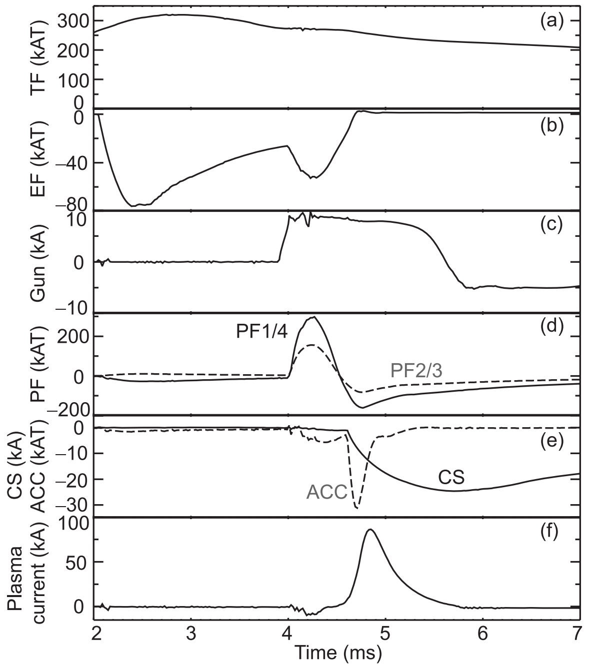

Fig. 3 Typical discharge of UTST plasma by DNM assisted by the CS coil. Time evolutions of the currents of the (a) TF coil, (b) EF coils, (c) washer guns, (d) PF coils, (e) CS coil/ACC coils, and (f) plasma. Positive direction is counterclockwise.

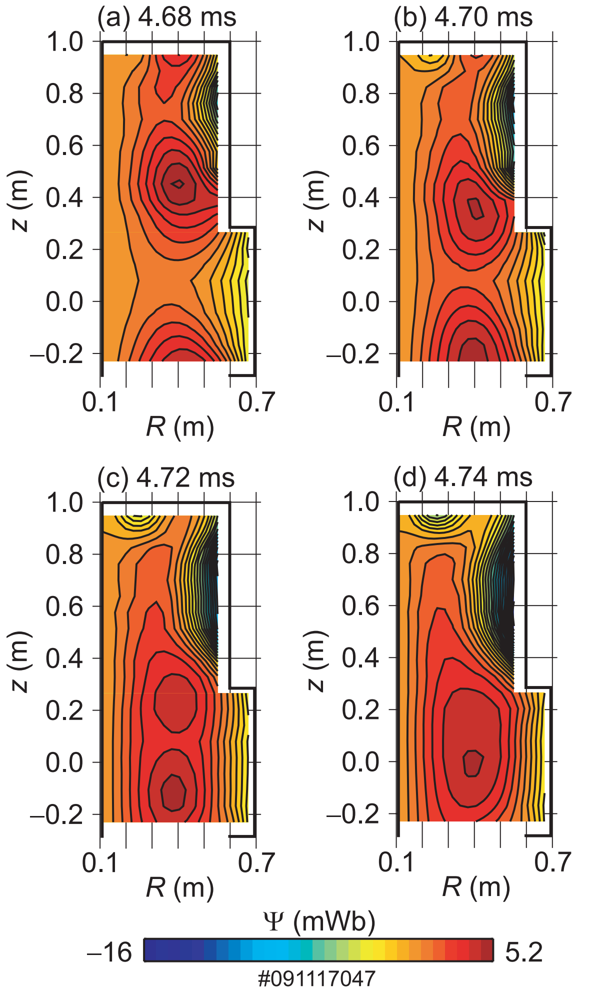

Fig. 4 Time evolution of poloidal magnetic flux contours during the PF + CS discharge at (a) 4.68 ms, (b) 4.70 ms, (c) 4.72 ms, and (d) 4.74 ms. Reconnection of the magnetic surface is clearly observed by poloidal magnetic flux measurement.

about 5%. All 290 channels are simultaneously measured with digitizers (sampling frequency of 0.5 MHz). An example of the measured poloidal magnetic flux contour for the vacuum EF is shown in Fig. 2. The poloidal magnetic flux Ψ is calculated from B_z by $\Psi = 2\pi \int B_z R \, dR$. The shape of the poloidal magnetic flux produced by the EF coils is precisely reconstructed by the B_z measurement.

4. Experimental Results

Figure 3 shows the typical discharge of the UTST plasma, which was generated by PF coils using DNM with CS coil support. The time evolutions of the currents of the TF coil, EF coils, washer guns, PF coils, CS coil, ACC coils, and plasma are shown. The TF coil, EF coils, washer guns, and PF coils start at 1, 2, 3.9, and 4 ms, respectively. During the current startup phase of the PF coils, plasma current in the negative (clockwise) direction (opposite to the desired direction) up to −10 kA is induced. After the PF coil currents reverse, plasma current is induced in the positive (counterclockwise) direction. Without the CS coil, the plasma current is no more than 50 kA, and its pulse width is less than 0.6 ms [6]. With the assistance of the CS coil, the plasma current reaches a value as high as 100 kA for a pulse width for time of about 1.2 ms. ACC coils support the plasma merging movement. Both the CS and ACC coils are started at 4.6 ms. However, the plasma current is still much smaller and the discharge duration is much shorter than those expected in the UTST's full potential discharge because the power supplies are only partially operated. In this initial run, the feasibility of plasma merging using external PF coils has been investigated intensively.

The two-dimensional poloidal magnetic flux profile during the PF + CS discharge was calculated from the pickup coil array measurements. From 4.64 to 4.74 ms, reconnection of the magnetic surface was clearly observed. Formation of an ST at the upper region was observed, and the ST was pushed toward the midplane to merge with another ST moved from the lower region. Figure 4 shows the time evolution of the contour map of the poloidal magnetic flux. The timings of the contours are 4.68, 4.70, 4.72, and 4.74 ms. The two magnetic surfaces of the STs approach from both the upper and lower regions and reconnect at the midplane area. At 4.74 ms, merging is complete and a single ST is created. Although the CS coil was used to assist in plasma generation, magnetic reconnection due to PF coils outside the vacuum vessel was observed for the first time. Plasma merging startup without the use of the

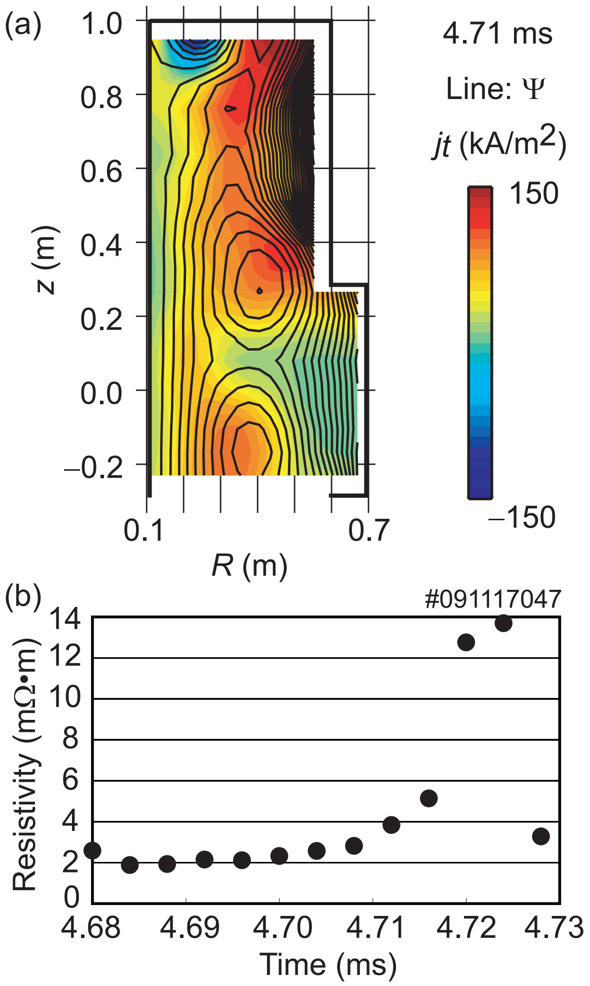

Fig. 5 (a) Poloidal magnetic flux contours with toroidal current density (by color) during PF + CS discharge at 4.71 ms. (b) Time evolution of the effective resistivity at the current sheet.

CS coil will be reported in Ref. [6].

The ACC coils enhance the plasma merging speed. The ACC coil currents are in the same direction as the reversed PF coil currents, so they support the plasma pushing force. Figure 5 (a) shows the contours of the poloidal magnetic flux Ψ and toroidal current density j_t, which is calculated by

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

$$j_t = \frac{1}{\mu_0}\left(\frac{\partial B_R}{\partial z} - \frac{\partial B_z}{\partial R}\right). \tag{2}$$

The discharge is the same as in Fig. 4. In Fig. 5 (a), a current sheet [2], which is the toroidal current density against the plasma current density, is observed at around the merging X-point. The current density at the X-point is about $-10\,\mathrm{kA/m^2}$ (in the negative direction with respect to the plasma current). Thus, the current sheet is successfully observed in the UTST experiment. Although the UTST has outer PF coils, the result is the same as in previous studies in which current sheets were observed with strong outer forces in high-safety-factor plasmas [2]. Figure 5 (b) is the time evolution of the effective resistivity η at the X-point, calculated by

$$E_t = -\frac{1}{2\pi R}\frac{\mathrm{d}\Psi}{\mathrm{d}t}, \tag{3}$$

$$\eta = E_t / j_t, \tag{4}$$

where E_t is the toroidal electric field at the X-point. The resistivity of the current sheet is clearly observed to increase significantly to more than one hundred times larger than the Spitzer resistivity just before plasma is completely merged.

5. Summary

The successful initial operation of a UTST plasma merging experiment was demonstrated. The UTST's PF coils are located outside the vacuum vessel to demonstrate the DNM startup method in a reactor-relevant situation. By means of plasma generation by the PF and CS coils, the magnetic surfaces of two STs were successfully observed to merge based on two-dimensional pickup coil measurements. The maximum plasma current was 100 kA and the pulse width was about 1.2 ms, which were larger and longer than those without the CS current ramp-up (50 kA and 0.6 ms, respectively). A current sheet at the X-point and anomalous resistivity over one hundred times larger than the Spitzer resistivity at the current sheet during merging were observed. In the future, the power supplies to the coils will be increased to discharge the UTST plasma at its full specification. Radio-frequency heating and neutral beam injection are under preparation.

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