Localized electron heating in merging spherical tokamaks

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Spherical tokamak (ST) is a low aspect ratio tokamak, which means that the ratio of the major radius to minor radius is less than two. ST could lead to a compact and economical fusion reactor if the central solenoid (CS) can be removed. Therefore, CS-less start-up and non-inductive plasma sustaining method are required for the ST research development. CS-less ST start-up is studied all over the world, such as, by using electron cyclotron waves [1], radio-frequency wave [2], coaxial helicity injection [3], and point-source dc helicity injection [4]. Here, we discuss one promising CS-less ST start-up method, that is, plasma merging start-up. When two initially created plasmas merge together to form a single plasma, magnetic field lines reconnect, and their energies are converted to the plasma kinetic or thermal energies during a very short period. On TS-3, two STs were merged to form a single ST having beta up to 50% in the cohelicity merging, and an oblate field-reversed configuration plasma formed by two spheromaks in the counter-helicity merging was transformed to an ST having ultra-high-beta up to 80% [5–7]. It has been reported that electrons are heated inside the current sheet during magnetic reconnection, while ions are heated at around the two downstream areas [8]. However, compared to the ion heating, the electron heating has not been clarified in detail, e.g., when and where in the current sheet electrons are heated. This work investigated and determined that electrons are locally heated at the merging X-point by using two ST devices; one is the Mega Ampere Spherical Tokamak (MAST) device, which is the world's largest plasma merging device, and the other is the University of Tokyo Spherical Tokamak (UTST) device, which uniquely demonstrates double null merging (DNM) by using out-vessel poloidal field coils.

MAST has the highest magnetic field (~0.6 T) and Lundquist number (10^6–10^8) among the merging laboratory plasma devices [9]. The plasma merging start-up method in MAST is called merging compression, which creates two initial plasmas around a pair of in-vessel poloidal field coils by its current ramping down and merges them at the mid-plane. In MAST, initial currents up to 500 kA and initial electron heating up to 1.2 keV were measured during the merging-compression plasma formation. Figure 1 shows the schematic cross view of the

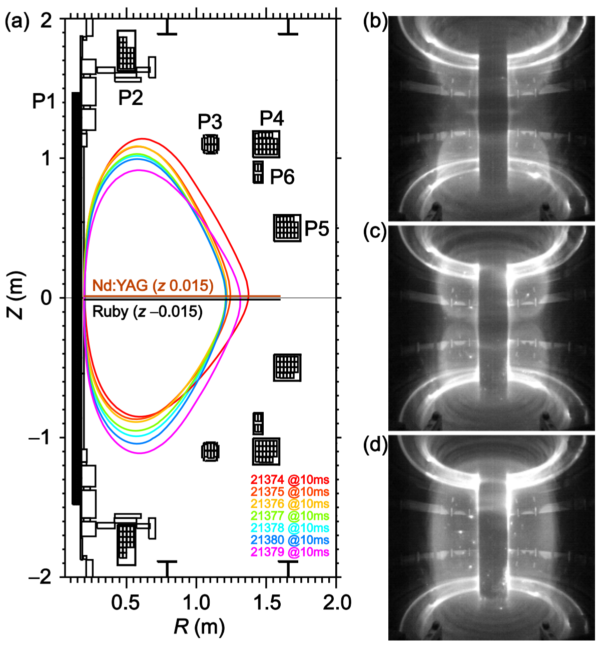

Fig. 1. (a) Schematic cross view of the MAST device. P1 is the central solenoid, P3 is used for merging compression, and P6 used for vertical positioning. Last closed flux surfaces of the vertically controlled plasmas are shown. (b)–(d) Fast camera images of the plasma merging compression.

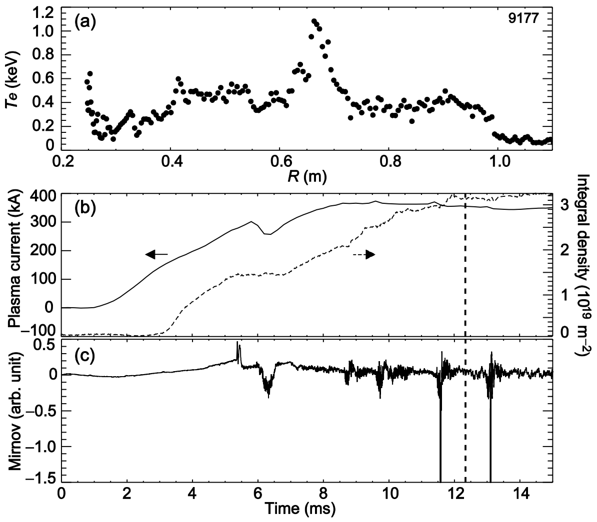

Fig. 2. (a) Radial electron temperature profile measured with ruby Thomson scattering. Time evolutions of (b) plasma current, line-integrated density, and (c) Mirnov coil signal. Dashed line indicates the timing of (a), which is 12.3 ms.

MAST plasma device. There exist the P1 coil, which is the CS coil, and pairs of in-vessel coils, P2–P6. A pair of PF3 coils is used for the plasma merging compression start-up, and a pair of PF6 coils is used for plasma vertical positioning. Several last closed surfaces of vertically positioned plasmas are plotted in the figure. By using the P6 coils, two-dimensional electron temperature and density profiles are measurable with the Thomson scattering systems, which measure profiles at the mid-plane. Fast camera images during the plasma merging compression are also shown in Fig. 1.

Figure 2 shows the radial electron temperature profile at 12.3 ms measured with the ruby Thomson scattering. Time evolutions of the plasma current, line-integrated density, and Mirnov coil signal are also plotted. A spike at 5.5 ms in the Mirnov coils signal indicates the time when merging compression ends. Therefore, such a high electron temperature peak up to 1.2 keV was observed about 7 ms after the merging completion. And also, the peak in the temperature profile is very narrow in the radial direction, indicating that the electron heating has only occurred close to the merging X-point. However, the vertical structure of the electron temperature profile was not investigated in this case. Several shots which were vertically controlled by the P6 coils were used to reconstruct the two-dimensional electron temperature profile. The last closed flux surfaces of these shots are plotted in Fig. 1. Here, we calculated the

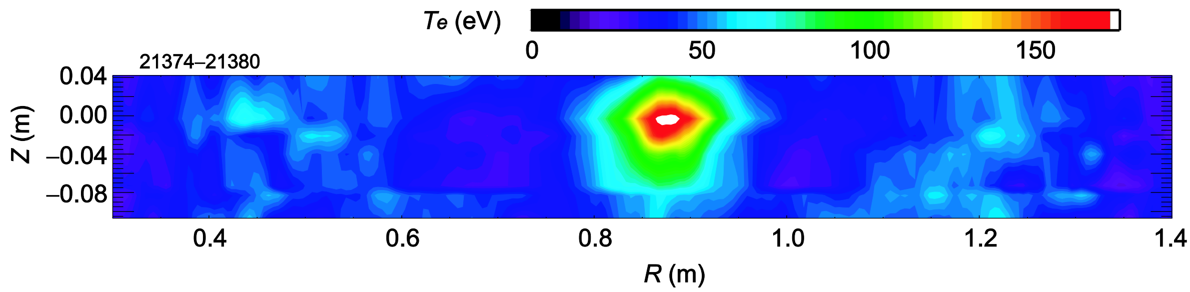

Fig. 3. Two-dimensional electron temperature profile at 10 ms measured with ruby Thomson scattering. Several vertically controlled shots were used. Almost circular narrow peak at the X-point and a structure like an outer rim surrounding the central peak were observed.

two-dimensional electron temperature profile at 10 ms, which was about 5 ms after the merging, as shown in Fig. 3. The narrow central electron temperature peak is approximately circular, having almost the same width in the radial and vertical directions. In addition, there is a structure surrounding the central peak like an outer rim. However, the vertical range was not enough in this figure to determine whether the structure had a circular or oblate shape. Data from a different series of shots with larger outer rim structure, in which the filling gas pressure was lower than those in the shots of Fig. 3, make it clear that the outer rim structure also had a circular shape. The origins of these structures are considered to be as follows. As mentioned in Ref. [8], the electrons are heated inside the current sheet by the toroidal electric field produced by reconnection via Joule heating. This expectation is supported by the fact that the electron heating was observed both with the CS and without the CS. However, most of the heated electrons flow to the downstream and only a narrow peak at the X-point region remains. Hot electrons flowed into the downstream areas and/or the relaxation from the hot ions, which were heated by reconnection in the downstream areas, make another electron temperature peaks in the plasma edge. After the plasma merges and forms closed surfaces, the temperature peaks at the edge create an outer rim structure surrounding the central peak.

A similar phenomenon was observed in preliminary results from the UTST plasma. Electron temperature measurements using a triple Langmuir probe indicate electron heating only at around the X-point. The electron temperature rapidly rose from 5 eV to 15 eV in a very short time of 0.01 ms order and soon disappeared. This result supports the conclusion that the electrons are heated in the current sheet by Joule heating to create a two-dimensionally narrow electron temperature peak. This effective temperature heating verifies not only that the plasma merging start-up is a promising CS-less start-up method for ST plasma formation but also gives us a clue for understanding the dynamic astrophysical phenomena, such as solar flares, solar winds, and auroras.

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