§1. RF Plasma Generation and Current Ramp-up Experiments on Spherical Tokamaks

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High energy (>10 keV) electrons carry the plasma current in RF started plasmas in spherical tokamaks (STs)., Several tens of kA of plasma current have been achieved so far. For a further increase of the plasma current, it is necessary to reduce the orbit loss of high energy electrons. Unlike in conventional tokamaks, the plasma pressure is dominated by high energy electrons. It is worthwhile to investigate the basic characteristics of such plasmas. For example, the plasma potential could be highly positive due to the orbit loss, and large flows could be generated. The ion temperature is expected to be very low owing to the low density (~10^{17} m^{-3}) and low bulk electron temperature (tens of eV), but had not been measured accurately. Using a visible spectrometer, we measured the plasma flow and ion temperature using the CIII line emission (464.7 nm, C^{2+}) in LATE and TST-2 plasmas, which are sustained by the electron cyclotron wave (ECW) and the lower hybrid wave (LHW), respectively[1].

We used a Czerny–Turner spectrometer with 1 m focal length and an instrumental width of 0.03–0.04 nm. The plasma emission is focused using a collimator lens onto a fiber bundle (Fig. 1, left). The lines of sight can be selected by inserting the lens-fiber assembly into one of the holes on a shell-shaped holder (Fig. 1, right). By rotating the holder, we can lines of sight can be selected to measure the toroidal and poloidal flows. Symmetric lines of sight in toroidal and poloidal directions are used to determine the velocity. The temperature error depends mainly on the signal intensity. The flow error depends not only on the intensity but also on the wavelength shift of the spectrometer due to the ambient temperature variation. Typical errors of the temperature and the flow using the CIII line are ΔT_i ~2 eV and ΔV <1 km/s, respectively.

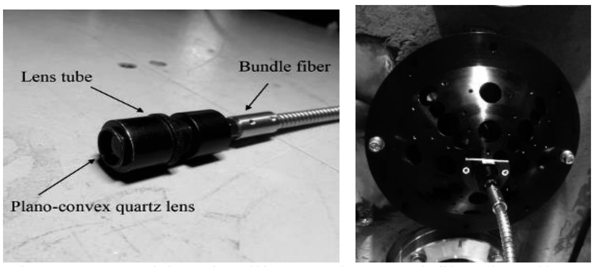

Fig. 1. Assembly of collimator lens and fiber bundle (left). Rotatable shell-shaped holder (right).

Figure 2 shows typical waveforms obtained in TST-2 (left) and LATE (right). During the current flat top phase, the plasma current is I_p ~9 kA, the line averaged density is n_e ~1 x 10^{17} m^{-3}, and the ion temperature is T_i ~3–5 eV. Figure 2 (d) shows the toroidal flow. The measured flow is shifted by a constant value, so that the radial flow (black curve) becomes nearly zero. The velocities of the two symmetric lines of sight are opposite to each other, ensuring the accuracy of the measurement. The toroidal flow is V_ϕ ~1 ± 0.5 km/s in the co direction to the plasma current. The ion temperature and the poloidal flow are T_i ~3 ± 1 eV and V_θ ~±0.5 km/s, respectively.

Using the same visible spectrometer system, similar measurements were performed on LATE. The plasma current is I_p ~8 kA, the line averaged density is n_e ~1.4 x 10^{17} m^{-3}, and the ion temperature is T_i ~10 eV. The toroidal flow is V_ϕ ~4 ± 0.5 km/s in the co direction to the plasma current. The ion temperature and the poloidal are T_i ~12 ± 7 eV (large error because of the up–down asymmetry) and V_θ ~5 ± 1 km/s in the diamagnetic direction, respectively.

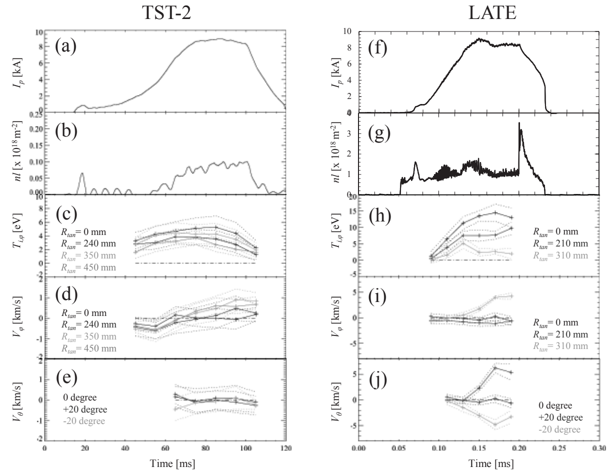

Fig. 2. Typical waveforms of plasmas in TST-2 (left) and LATE (right): plasma current (a, f), line integrated density (b, g), ion temperatures (toroidal sight lines) (c, h), toroidal flows (d, i), and poloidal flows (e, j). Typical error bars are shown in (c), (d), (e), (h), (i), (j).

Using the radial force balance equation for the C^{2+} ion, the estimated radial electric fields in TST-2 and LATE are $|E_r|$ < 50 V/m and E_r ~+290 ± 60 V/m, respectively. Compared with the equilibrium described in Ref. (2), the toroidal flow velocity and the centrifugal force are very small in TST-2 and LATE, whereas the electric field in LATE is similar in order whereas that in TST-2 is small. The ion temperature is high in these two devices. For example, the poloidal Larmor radius for a 5 eV C^{2+} ion is 50 mm and that of a 100 keV electron is 90 mm at the edge of a TST-2 plasma. Since these energies are typical in TST-2 and LATE, the large poloidal Larmor radii imply that not only high energy electrons but also thermal ions suffer orbit losses, and must be considered for the formation of the radial electric field.

1) S. Tsuda, et al., Plasma Fusion Res. **10** (2015) (in press).
2) Y.-K. M. Peng, et al., Plasma Fusion Res. **9**, 3403146 (2014).