# Measurement of Ion Temperature and Flow in RF Start-Up Plasmas in TST-2 and LATE

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The ion temperature and flow of RF start-up plasmas in TST-2 and LATE were measured using a visible spectrometer. The plasma currents were 9 kA and 8 kA, respectively. The typical ion temperatures $T_\mathrm{i}$ and toroidal flow $V_\phi$ were 4 eV and 1 km/s, respectively, in the TST-2 plasma sustained by the lower hybrid wave (20 kW) and $T_\mathrm{i}$ ~10 eV and $V_\phi$ ~5 km/s in the LATE plasma sustained by the electron cyclotron wave (50 kW). The poloidal flow velocities were comparable to the toroidal velocities. The ion temperatures were relatively high and the ion orbit loss can be significant.



Keywords: lower hybrid wave, electron cyclotron resonance wave, spectrometer, flow, rotation, ion temperature, spherical tokamak, TST-2, LATE

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High-energy (>10 keV) electrons carry the plasma current in RF start-up plasmas in spherical tokamaks (STs). Because of significant orbit loss in the high-energy electrons, the plasma potential can be highly positive and large flows (e.g., several tens of km/s) can be generated. In such a situation, two-fluid equilibrium model must be used [1, 2], and it is important to confirm whether the plasma has substantial flows. In addition, it is also interesting to measure the ion temperature, which is expected to be very low owing to the low density (~$10^{17}$ m$^{-3}$) and low bulk electron temperature (several tens of eV). Using a visible spectrometer, we measured the plasma flow and ion temperature of CIII (464.7 nm, $C^{2+}$) in the LATE and TST-2 plasmas, which are sustained by the electron cyclotron wave (ECW) [3, 4] and lower hybrid wave (LHW) [5, 6], respectively. We also estimated the radial electric fields.

We use a Czerny–Turner spectrometer with 1 m focal length. The exit image is expanded by a cylindrical lens and detected by an 11-channel photomultiplier tube array. The typical width of the entrance slit is 150 µm, the instrumental width is $\Delta\lambda_\mathrm{FWHM}$ ~0.03 - 0.04 nm, and the wavelength difference between the adjacent channels is $\Delta\lambda_\mathrm{ch}$ 0.020 - 0.025 nm. The plasma emission is focused using a collimator lens on a fiber bundle with 40 fiber cores, whose diameter is 230 µm. The typical beam radius of the lines of sight is 20 mm in the plasma. The lines of sight can be selected by inserting the lens and fiber bundle into one of the holes on a shell–shaped holder. Figure 1 shows the lines of sight in TST-2 and LATE. By rotating the holder we can flip the lines of sight and measure the toroidal and poloidal flows. Consequently, symmetrical lines of sight becomes available in toroidal and poloidal flow measurements, and we compare them to confirm the origin of velocity.

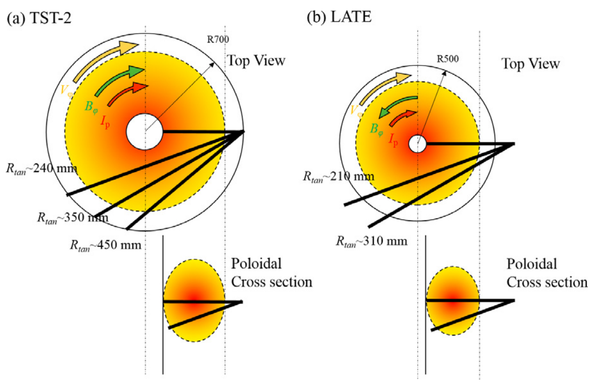


Fig. 1 Black lines show the line of sights on the midplane and poloidal cross section on TST-2 (a) and LATE (b). The red, green, and yellow arrows show the direction of plasma current, toroidal magnetic field, and flow, respectively.

The temperature error mainly depends on the signal intensity. The flow error depends not only on the intensity but also on the wavelength shift of the spectrometer owing to the ambient temperature variation, and it is typically 0.2 km/s between succeeding discharges. The wavelength shift due to the different incident angles on the collimator lens was found negligible. The temperature and flow errors are calculated from the fitting error of the Doppler broadening. The typical error of the CIII temperature and flow is $\Delta T_\mathrm{i}$ ~2 eV and $\Delta V$ < 1 km/s, respectively. Figure 2 shows examples of the PMT signals and fits to the Gaussian shapes.

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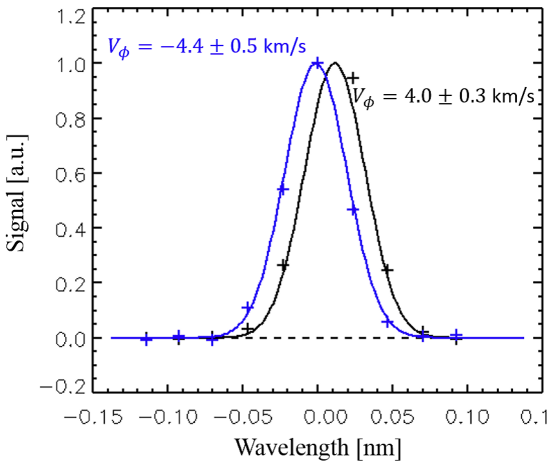


Fig. 2 Wavelength spectra for the two symmetrical lines of sight (black and blue) at $R_{\text{tan}}$ = 310 mm. Crosses denote the measured signals for each PMT channel and the curves are fits to the Gaussian shapes. The target plasmas are those of LATE and the measured time $t$ = 160 - 180 ms.

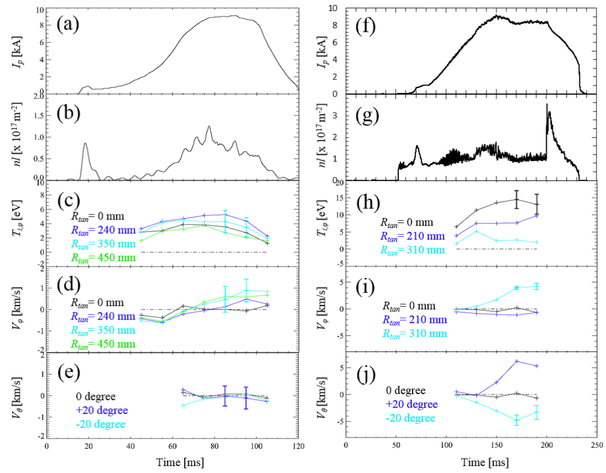


Fig. 3 Typical waveforms of the target plasma in TST-2 (left) and LATE (right): plasma current (a, f), line integrated density (b, g), ion temperature (toroidal measurement) (c, h), toroidal flow (d, i), and poloidal flow (e, j). Typical error bars are shown in (c), (d), (e), (h), (i), and (j).

The target plasmas of TST-2 have major and minor radii of $R_0$ ~360 mm and $a$ ~ 230 mm, respectively, aspect ratio $A = R_0/a$ ~1.6, toroidal magnetic field $B_\phi$ ~0.09 T, and LHW power $P_{\text{LH}}$ ~20 kW. Figure 3 shows typical waveforms. At the current flat top phase, the plasma current is $I_\text{p}$ ~9 kA, the line averaged density is $n_\text{e}$ ~$1 \times 10^{17}$ m$^{-3}$, and the ion temperature is $T_\text{i}$ ~3 - 5 eV. Figure 3 (d) shows the toroidal flows measured at the tangent radius $R_{\text{tan}}$ ~240, 350, and 450 mm and at the radial (i.e., perpendicular) line of sight. The measured flow is shifted by a constant value so that the radial flow (black curve) is close to zero. The velocities of the two symmetrical lines of sight flip each other and their average at the same time is zero within error. The toroidal flow is $V_\phi$ ~1 ± 0.5 km/s and codirectional to the plasma current. The ion temperature and flow in the poloidal measurements are $T_\text{i}$ ~3±1 eV and $V_\theta$ ~±0.5 km/s, respectively.

The radial electric field is derived by using the following equation:

$$E_r = -\frac{1}{e n_s Z_s}\frac{\partial p_s}{\partial r} - (V_\theta B_\phi - V_\phi B_\theta), \quad (1)$$

where $Z_s(= 2)$ is the charge number of $C^{2+}$, $V$ and $B$ correspond to the flow and magnetic field, respectively, and the subscripts $\phi$ and $\theta$ denote the toroidal and poloidal components, respectively. Note that the centrifugal forces, which may appear in Eq. (1), are negligible owing to the small flow velocities. When we consider the errors, the electric field is dominated by the error of $V_\theta$ and the estimated radial electric field is $|E_r| < 50$ V/m.

The target plasmas of LATE have $R_0$ ~230 mm and $a$ ~170 mm, $A = R_0/a > 1.35$, $B_\phi$ ~0.07 T, and ECW power of $P_{\text{EC}}$ ~50 kW. Here we consider the current area to estimate the plasma size. Figure 3 shows the typical waveforms. At the current flat top phase, the plasma current is $I_\text{p}$ ~8 kA, the line averaged density is $n_\text{e}$ ~$1.4 \times 10^{17}$ m$^{-3}$, and the ion temperature is $T_\text{i}$ ~10 eV. Figure 3 (i) shows the toroidal flows $V_\phi$ ~4 ± 0.5 km/s at $R_{\text{tan}}$ ~210 and 310 mm and at the radial line of sight. The flow direction was codirectional to the plasma current. At $R_{\text{tam}}$ ~210 mm (ECW resonance layer), the flow velocity is small but opposite to the direction at $R_{\text{tan}}$ ~310 mm. The ion temperature and flow in the poloidal measurements is $T_\text{i}$ ~12 ± 7 eV (large error because of the up-down asymmetry) and $V_\theta$ ~5 ± 1 km/s, respectively, and the poloidal flow direction is the diamagnetic direction.

The radial electric field of the LATE plasma is calculated with Eq. (1). The dominant term in Eq. (1) is $V_\theta B_\phi$, the estimated radial electric field is $E_r$ ~+290 ± 60 V/m, and the direction is outward. Note that the electric field direction near the center may change its polarity if the poloidal flow changes its direction as the toroidal flow does.

Compared with the equilibrium in Ref. 1, the toroidal flow velocity and centrifugal force are very small in TST-2 and LATE, whereas the electric field of LATE is similar in order and that of TST-2 is small. The ratio of poloidal flow to toroidal flow is relatively large in LATE.

The ion temperature is high in these two devices. For example, the poloidal Larmor radius for a carbon ion ($C^{2+}$) of 5 eV is 50 mm at the edge of the TST-2 plasma. The radius of the high-energy electrons of 100 keV is 90 mm. Because these energies are typical of TST-2 and LATE, the large poloidal Larmor radii imply that not only the high-energy electrons but also the thermal ions suffer from the orbit loss, and these losses may contribute to the formation of the radial electric field.

In conclusion, measurements of ion temperature and flow in the RF start-up plasmas in TST-2 and LATE were performed for the first time. The toroidal flows are much smaller than the values in Ref. 1 and the centrifugal forces are negligible. The ion temperature is low but the ion orbit loss can be significant.

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[1] Y.-K.M. Peng *et al.*, Plasma Fusion Res. **9**, 3403146 (2014).
[2] A. Ishida *et al.*, Phys. Plasmas **19**, 102512 (2012).
[3] T. Maekawa *et al.*, Proceedings of 19th IAEA Fusion Energy Conference, Lyon, France (2002).
[4] T. Maekawa *et al.*, Nucl. Fusion **45**, 1439 (2005).
[5] Y. Takase *et al.*, Nucl. Fusion **41**, 1543 (2001).
[6] Y. Takase *et al.*, Nucl. Fusion **53**, 063006 (2013).