Electron Density Measurements of Non-Inductive Start-Up Plasmas in the TST-2 Spherical Tokamak

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A new 50 GHz microwave interferometer was installed, and non-inductively sustained spherical tokamak plasmas in the TST-2 device were measured. The line integrated electron densities ($n_e l$s) on five chords were compared with visible CCD camera image and equilibrium analysis. It is concluded that the high-density region has a C-like shape along the outboard boundary. This shape suggests that the electron density is not constant on the magnetic flux surface.

Keywords: spherical tokamak, electron cyclotron heating, plasma start-up, electron density, microwave interferometer

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Non-inductive plasma current start-up by electron cyclotron heating (ECH) was performed on the TST-2 spherical tokamak device. Key issues in spherical tokamak (ST) research are plasma current start-up and formation of the ST configuration without using the central solenoid (ohmic coil). A spontaneous current jump resulting in the formation of closed magnetic flux surfaces was observed in ECH start-up plasmas [1–3]. In this study, line integrated electron densities ($n_e l$s) on five chords were measured by a microwave interferometer to clarify the features of the sustained ST configuration. In general, a poloidal density profile can be obtained from the $n_e l$ by the slice-and-stack method or by fitting to a parameterized function for a given magnetic flux surfaces [4–6]. However, when the plasma has anisotropic pressure or open field lines, density is not a flux function and the measurement of the poloidal density profile becomes difficult. Thus, we emphasize obtaining the shape of the high-density region.

The following are the plasma parameters of TST-2: major radius $R \leq 0.38$ m, minor radius $a \leq 0.25$ m, aspect ratio $A = R/a \geq 1.5$, toroidal magnetic field $B_t \leq 0.3$ T and plasma current $I_p \leq 150$ kA (inductive operation), and ≤ 1.6 kA (non-inductive operation). EC power (2.45 GHz, up to 5 kW) was injected in X-mode polarization from the weak magnetic field side. A new heterodyne interferometer was built to measure the low density ($\sim 1 \times 10^{17}$ m^{-3}) ECH start-up plasmas. The oscillator frequency is 50 GHz, and the intermediate frequency is 1.2 GHz. A typical phase shift is 50 degrees. We also tested the systems with microwave frequencies of 104 GHz and 140 GHz, but the 50 GHz system was the best from the viewpoint of ECH noise and mechanical vibration effect in the measurement. One of the five measurement chords (Fig. 1) can be measured during a single discharge. Therefore, more than five reproducible discharges are necessary to measure the plasma shape. Each chord has U-band conical horn antennas for launching and receiving the microwaves. In the horizontal chords, convex lenses made of Teflon were used, and as a result the beam width was about 100 mm at the center wall.

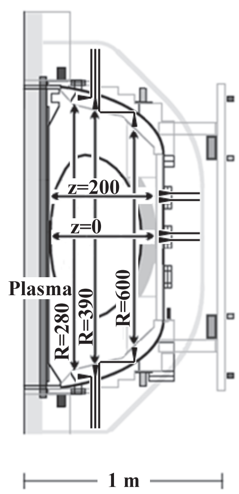

Fig. 1 Measurement chords of the interferometer (R = 280, 390, 600 mm, Z = 200, 0 mm).

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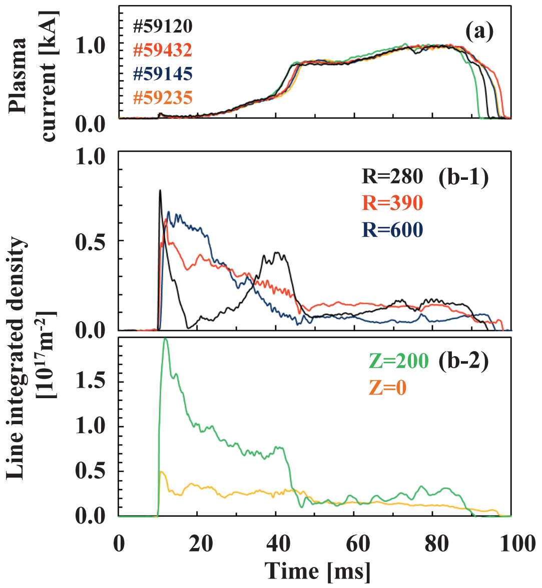

Fig. 2 Time evolutions of the plasma current (a) and line integrated densities (b-1, b-2) for five discharges.

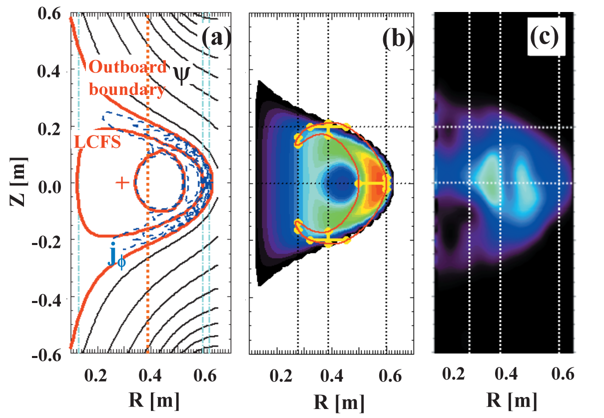

Fig. 3 The magnetic flux surfaces obtained from the equilibrium analysis (a), the shape of the high-density region (red) and colored equilibrium pressure contour (b), and the visible emission profile (c) after the current jump. The EC resonance layer is shown by the orange dotted line in (a). The yellow line segments in (b) indicate the line integrated densities and the white dotted line in (c) indicates the interferometer chords.

Figure 2 shows the typical waveforms of the plasma current I_p and $n_e l$. A current jump occurred around 45 ms. Significant decreases in $n_e l$ for all chords is observed after the current jump. The ratios of $n_e l$ for different chords are extremely different from what we had expected for an elliptic center peaked density profile. For example, the line integrated density of $Z = 0$ mm is less than $Z = 200$ mm during the discharge period, except for the short period after the current jump. Comparing different discharges with the same plasma current and the same external poloidal field strength, the line integrated density of $Z = 200$ mm was very small for certain discharges, and the line integrated density of $R = 280$ mm was very small for other discharges. In addition, the line integrated density of $Z = 200$ mm often shows large fluctuations. These results suggest that a steep density gradient region and/or boundary are located around those chords (i.e., $Z \sim 200$ mm and $R \sim 280$ mm).

In order to extract the poloidal shape of the high-density region from the five line integrated densities, we assume that the density inside the shape is constant and negligible outside the shape. Under these assumptions, each line integrated density corresponds to a line segment whose length is proportional to the measured value ($n_e l$). The shape of the high-density region is represented by a loop passing both ends of the line segment. By adjusting the scale factor and the location of the segment on each measurement chord, we obtain a smooth shape. We also assume that the shape has an up–down symmetry, because no clear up–down asymmetry was observed in the various measurements.

Figure 3 shows the magnetic flux surfaces and pressure profile obtained from the equilibrium analysis, the shape of the high-density region, and the visible emissivity profile after the current jump. The shape of the high-density region resembles the letter "C". An equilibrium solution that has a similar C-like pressure profile and is consistent with magnetic measurements was found when we introduced anisotropic pressure. The high-density region is located just inside the outboard boundary of the equilibrium solution. The inboard boundary is close to the chord $R = 280$ mm, and the top boundary is close to the chord $Z = 200$ mm. It should be noted that the shape is similar to the banana orbits trapped at the weak-field region. The banana orbits can contribute to the perpendicular pressure, and the net plasma current through the toroidal precession of the orbits. The line averaged density for the shape (of the high-density region) shown in Fig. 3 (b) is about 1.6×10^{17} m^{-3}, while the O-mode cutoff density for the EC wave is 7.3×10^{16} m^{-3}. This C-shaped high-density region might reflect and refract the EC waves, leading to poor accessibility to the central region.

In summary, the line integrated electron densities of ECH plasmas were measured by a five-chord 50 GHz microwave interferometer. The measurement results imply that a C-shaped high-density region is located along the outboard boundary. Although the shape is qualitatively consistent with the equilibrium with anisotropic pressure, we would like to point out another scenario where a large magnetic island with isotropic pressure forms the C-shaped region.

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