Observation of Electron Temperature and Density Gradients in Volumetric Recombining Plasma Using ECR Linear Plasma Experimental Device NUMBER

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Spatial gradients of electron temperature and density along the magnetic field line are directly measured in helium recombining plasma using the linear plasma device NUMBER. In a specific neutral gas pressure range, a steep temperature gradient is observed, with a scale length shorter than the device length. At higher pressures, the sign of electron density gradient reversed from positive to negative, indicating existence of a spatial density peak. Reconstruction of spatial temperature and density profiles indicates that monotonically decreasing temperature and the spatial peak of density along the magnetic field line.

Keywords: detached divertor, volumetric recombining plasma, electrostatic probe, electron temperature, electron density, distribution along the magnetic field line, rollover

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In future fusion reactors, detached divertor is employed to reduce heat flux entering the divertor plate by cooling and neutralizing the plasma in the scrape-off layer (SOL). As a result, the dominant atomic process along the magnetic field line transitions from ionization to recombination. Numerical simulations have shown that the electron temperature T_e decreases monotonically, and the electron density n_e exhibits a rollover behavior along the field line [1]. The location where volumetric recombination occurs most actively is referred to as the recombination front. As well as the location, the scale length of this front is critical for its control.

In many linear plasma devices, measurements of T_e and n_e are performed at fixed points by systematically varying the neutral gas pressure p in the vacuum chamber [2, 3]. Measurements at downstream and upstream ports have suggested a decrease in temperature and/or density along the field line [4]. However, direct measurements of the gradient scale length were difficult due to restriction of measurement port accessibility. We developed a local two-point measurement probe called a forked probe to evaluate the scale lengths of electron temperature and density. This paper presents initial results of the forked probe, which suggest that the electron temperature gradient becomes steep near the pressure at which the density peaks.

The experiment was conducted in the electron cyclotron resonance (ECR) linear plasma device NUMBER [5], which consists of a cylindrical vacuum chamber with its axis defined as the z-axis. Helium plasma was produced between the microwave injection window at z = 0 m and an endplate at z = 1.98 m. Although the magnetic field B in downstream test region varies with time, this study focuses on the range B = 0.1–0.3 T. Feeding additional helium gas into the downstream region, we obtained volumetric recombining plasma as previously reported [6].

We developed a forked probe, and its conceptual diagram is illustrated in Fig. 1. It has electrostatic probes capable of simultaneous measurements at two points with a spatial resolution of Δz = 40 mm apart. The upstream and downstream electrodes are referred to as UE and DE, respectively. Using the single-probe method, we evaluate T_e and n_e. We also evaluate the inverse scale length of T_e and n_e gradients along the field line: $1/L_{T_e}$ is defined as

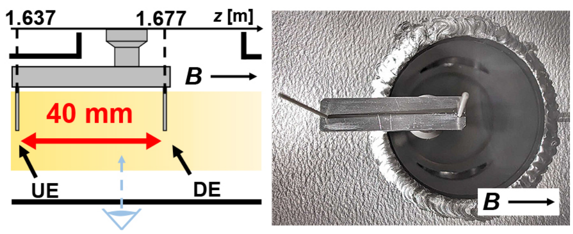

Fig. 1. Schematic diagram of the forked probe (left) and a corresponding photograph (right) taken from below, showing the actual probe configuration.

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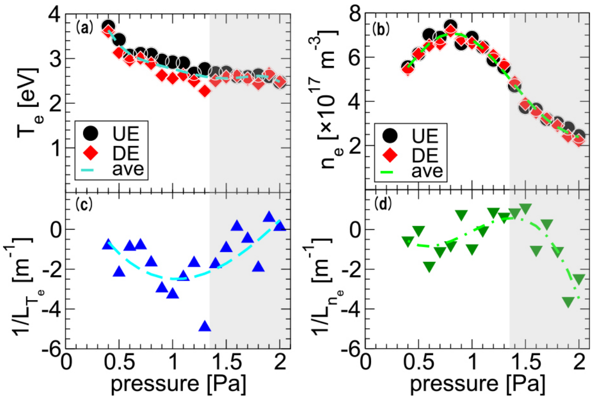

Fig. 2. Pressure dependence of (a) the electron temperature T_e, (b) the electron density n_e, (c) the inverse scale length of T_e, and (d) that of n_e. In (a) and (b), circles and diamonds represent measurements from the upstream electrode (UE) and downstream electrode (DE) of the forked probe, respectively. Dashed curves show polynomial fits. Hatched areas, corresponding T_e overestimation, are omitted from Fig. 3.

$$\frac{1}{L_{T_e}} = \frac{1}{\bar{T}_e}\frac{T_{e,DE} - T_{e,UE}}{\Delta z}, \tag{1}$$

where $\bar{T}_e$ represents the average temperature between UE and DE. $1/L_{n_e}$ is also defined using a similar equation. The forked probe was positioned at z = 1.66 m, and the pressure dependence of these parameters was measured.

Figure 2 shows the measured pressure dependence of T_e, n_e, $1/L_{T_e}$, and $1/L_{n_e}$. As neutral pressure increases, T_e decreases monotonically. At pressures $p \geq 1.4$ Pa, T_e measurements by the single-probe method may be overestimated [7]. Consequently, since n_e is derived from the probe current using T_e, it may be underestimated in the same pressure region. For n_e, a rollover (referred to as a n_e-p rollover) is observed, where n_e increases up to 7×10^{17} m^{-3} at p = 0.8 Pa and then monotonically decreases.

Figures 2(c) and (d) present $1/L_{T_e}$ and $1/L_{n_e}$ with third-order polynomial fits, denoted as $g_{T_e}(p)$ and $g_{n_e}(p)$. Negative values of the inverse scale lengths in Figs. 2(c) and (d) correspond to decreasing temperature and/or density in a downstream direction. The inverse scale lengths for both temperature and density are on the order of 1 m throughout the experimental pressure range. The spatial temperature gradient exhibits distinct behavior across different pressure regimes. In the low-pressure regime $p \leq 0.7$ Pa, the T_e decreases toward downstream but moderately, where the scale length of the temperature gradient is about $|L_{T_e}| \sim 1$ m, comparable to device scale. In the high-pressure regime $p > 0.7$ Pa, a steep temperature gradient is observed at the probe position, where the scale length reaches $|L_{T_e}| \simeq 0.3$ m, much shorter than the device scale. The average temperature in the steep temperature gradient is $T_e < 3$ eV, lower than in the low-pressure region, as shown in Fig. 2(a). Notably, the pressure range exhibiting the steep temperature gradient in Fig. 2(c) corresponds closely to the region of the n_e-p rollover. $1/L_{n_e}$ gradually increases up to approximately p = 1.5 Pa. The data reveal that $1/L_{n_e}$ exhibits a weak decreasing gradient or remains nearly uniform in the low-pressure region while showing a weak increasing gradient in the intermediate-pressure region. The pressure-dependent sign change of $1/L_{n_e}$ indicates the existence of a spatial density peak that moves upstream with increasing pressure.

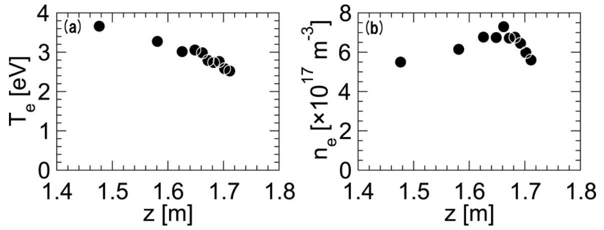

Fig. 3. Reconstructed spatial profiles of (a) T_e and (b) n_e along the magnetic field line at a gas pressure of p = 1.0 Pa.

In order to reconstruct the spatial profiles of $T_e(z)$ and $n_e(z)$ along the magnetic field line, the experimentally obtained pressure dependences of $T_e(p)$ and $n_e(p)$ are converted to their z-dependence. In the following discussion, we assume that the z-profiles of T_e and n_e maintain their shape but shift spatially with pressure changes along the field line. An equivalent change in z-direction is obtained from the difference in pressures:

$$z(p_{i+1}) = z(p_i) + (p_{i+1} - p_i)\left.\frac{dz}{dp}\right|_{p_{i+1/2}}, \tag{2}$$

where i represents the index of pressure ascending, $p_{i+1/2} \equiv (p_{i+1} + p_i)/2$ is the average of neighbouring pressures. The boundary condition for $z(p_1)$ is set such that the pressure at the measurement port, z = 1.66 m, corresponds to pressure of interest. The derivative dz/dp is determined as follows:

$$\frac{dz}{dp} = \frac{dT_e(p)}{dp} \Big/ \frac{dT_e}{dz}(p). \tag{3}$$

In the right hand side of Eq. (3), the pressure derivative is obtained from the smoothed curve in Fig. 2(a), and the local gradient is taken from Fig. 2(c). Substituting Eq. (3) to Eq. (2) yields the equivalent position z for each pressure p_i. The reconstructed z-profiles of $T_e(z)$ and $n_e(z)$ are presented in Figs. 3(a) and (b). To avoid the overestimation of T_e, as mentioned earlier, the reconstruction is carried out in the pressure range $p < 1.4$ Pa. Fig. 3(a) demonstrates that T_e decreases monotonically with increasing z. For n_e, a rollover in the z-direction (n_e-z rollover) is observed in Fig. 3(b). Specifically, the density gradually increases up to z = 1.66 m, then decreases sharply around z = 1.70 m.

In summary, direct measurements of T_e and n_e gradients along the magnetic field line were performed in helium recombining plasma using the linear plasma device NUMBER. The neutral gas pressure dependence reveals a steep temperature gradient, the scale length of which is shorter than the device length, for a certain pressure range. The density gradient reverses signs from positive to negative in high-pressure region indicating existence of a spatial density peak. The reconstruction of spatial T_e and n_e profiles demonstrates monotonically decreasing temperature and a spatially localized density peak, consistent with expectations from numerical simulations.

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