# Poloidal Flow Velocity Measurement in High-Density NBI Plasmas of Heliotron J

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(Received 5 February 2018 / Accepted 19 March 2018)

A high-density experiment using a novel fueling technique–high-intensity gas puffing (HIGP)–has been performed in Heliotron J. Using the recently developed charge exchange recombination spectroscopy (CXRS), a poloidal flow shear is observed at the peripheral region of high-density NBI plasmas. The evaluation of radial electric field based on the experimental results of toroidal and poloidal rotation velocities shows the formation of a large $E_r$ shear in the peripheral region.



Keywords: CXRS system, Poloidal rotation, Er shear, High-density NBI plasma, Heliotron J

DOI: 10.1585/pfr.13.1202077

The radial electric field ($E_r$) and its associated shear can affect plasma transport and MHD activity [1, 2], which plays an important role in improving plasma confinement. A high-density NBI plasma experiment with a significant increase of plasma stored energy is performed using a high-intensity gas puffing (HIGP) method in Heliotron J [3]. Using a newly developed poloidal charge exchange recombination spectroscopy (CXRS) system [4], a large poloidal rotation velocity shear and radial electric field shear is observed in high-density NBI plasmas. In this study, the details of the high-density experiment and the poloidal rotation velocity data in high-density NBI plasmas are reported. The evaluation of radial electric field in such plasmas is also discussed.

The global behavior of the high-density experiment using HIGP is shown in Fig. 1. The plasma was started up by a 2.45-GHz microwave and sustained by balanced-NBI heating with a total of 600-kW port-through power. A high-density plasma is generated using the HIGP method starting at 230 ms. Both line averaged electron density ($\bar{n}_e$; $1.1 \times 10^{19}\,\mathrm{m}^{-3} \rightarrow 4.6 \times 10^{19}\,\mathrm{m}^{-3}$) and plasma stored energy ($W_p$; 1.1 kJ → 5.2 kJ) increased significantly after using HIGP (230 ms → 270 ms), indicating that high-performance plasma can be generated using the HIGP method.

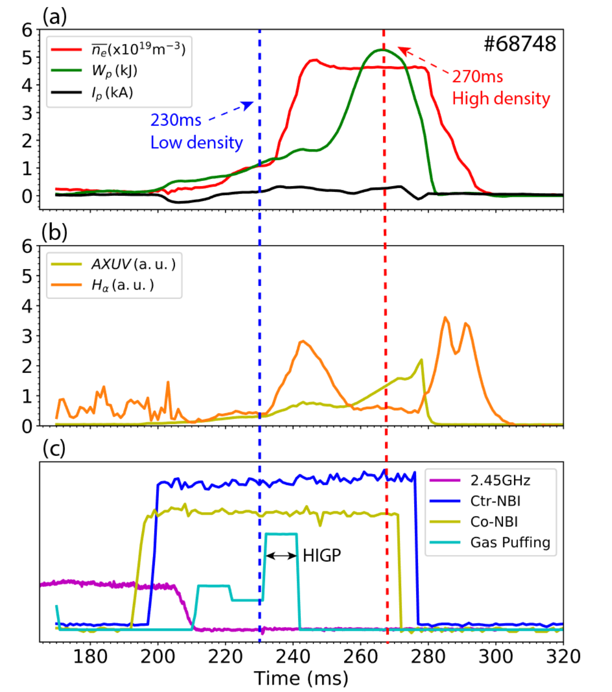


Fig. 1 Time evolution of (a) $\bar{n}_e$, $W_p$, $I_p$; (b) $AXUV$, $H_\alpha$; (c) NBI, microwave and gas puffing signal.

Figure 2 shows the profiles of electron density ($n_e$), parallel flow velocity ($V_\parallel$), and poloidal flow velocity ($V_\theta$) in the case of low-density (230 ms) and high-density (270 ms) plasmas. $V_\parallel$ is measured using a CXRS system in which the sightline is parallel to the magnetic field line [5]. Here, the radial resolution ($\Delta\langle r/a\rangle$) is in the range

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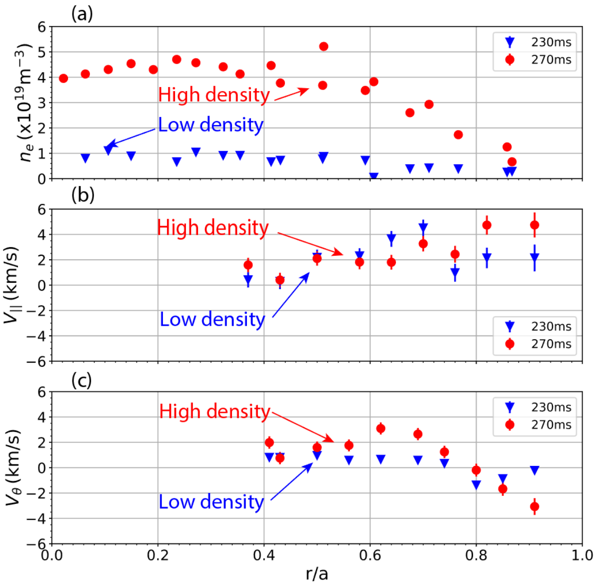


Fig. 2 Profiles of (a) $n_e$, (b) $V_\phi$, and (c) $V_\theta$ in the case of low-density (blue) and high-density plasmas (red).

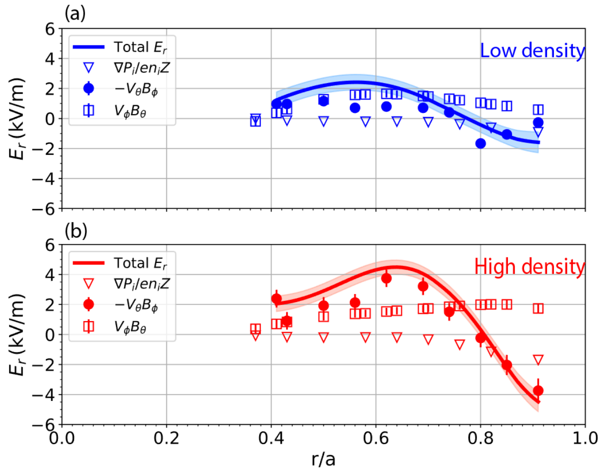


Fig. 3 Profiles of $V_\phi B_\theta$ (circle), $-V_\theta B_\phi$ (square), pressure contributed $E_r$ (triangle), and total $E_r$ (solid line), in the case of low-density (blue) and high-density plasmas (red).

of $0.02 < \Delta\langle r/a\rangle < 0.1$. The error bar in the radial direction is not shown to keep the plasma profile clear. The co-direction of parallel flow is defined as the direction of plasma current, which increases the rotational transform. For poloidal flow, the positive direction is defined as the ion diamagnetic direction. Since the plasma is heated by balanced NBI, the external momentum input from the NBI is expected to be extremely small. In the case of low-density plasma, the parallel flow is in co-direction and the poloidal flow velocity is small at the region wherein $0.4 < r/a < 0.9$. In the case of high-density plasma, a poloidal flow velocity shear is observed at the peripheral region ($0.7 < r/a < 0.9$). In contrast, no significant difference is observed in the parallel flow. In Heliotron J, the $E_r$ is dominated by $V_\theta \times B_\phi$ because $V_\phi \times B_\theta$ is relatively small owing to the large parallel viscosity and the significant change observed in $V_\theta$ indicates a large variation of $E_r$.

Considering the momentum force balance equation [6], the radial electric field ($E_r$) is evaluated by the following equation [7]:

$$E_r = \nabla P_i/en_iZ - \left(V_\theta B_\phi - V_\phi B_\theta\right), \quad (1)$$

where $\nabla P_i$ is the pressure gradient, $Z$ is the charge number, $V_\theta$ and $V_\phi$ are the poloidal and toroidal flow velocities, respectively, and $B_\theta$ and $B_\phi$ are the magnetic field strengths in the poloidal and toroidal directions, respectively. In this case, the fully ionized carbon ion is treated. The toroidal flow ($V_\phi$) is evaluated from the parallel and poloidal data, where $V_\phi = (V_{||} - V_\theta \sin\alpha) / \cos\alpha$; ($\alpha$: pitch angle). Figure 3 shows the $E_r$ components of $V_\phi B_\theta$, $-V_\theta B_\phi$ and $\nabla P_i/en_iZ$ in the case of low-density and high-density plasmas, respectively. Here, the radial electric field is dominated by the poloidal flow ($-V_\theta B_\phi$) component because the toroidal flow ($V_\phi B_\theta$) and pressure components ($\nabla P_i/en_iZ$) are relatively smaller than the poloidal flow component. In the case of low-density plasma (Fig. 3 (a)), the $E_r$ at the region of $0.4 < r/a < 0.9$ is weak. In the case of high-density plasma (Fig. 3 (b)), a strong negative $E_r$ with a large shear, contributed by the poloidal flow, is observed at the peripheral region ($0.7 < r/a < 0.9$). The value of $E_r$ in the high-density plasma is consistent with the probe data of a previous high-density experiment [8]. Here, the $E_r$ shear in high-density plasma ($\mathrm{d}E_r/\mathrm{d}r = -650\,\mathrm{kV/m^2}$; $r/a = 0.8$) is much larger than that of low-density plasma ($-210\,\mathrm{kV/m^2}$). We observed an increase in the global energy confinement time from 8 to 17 ms, which indicates that the formation of the $E_r$ shear contributes to the improvement of energy confinement due to the HIGP method.

In summary, a high-density plasma experiment is performed in Heliotron J using the HIGP method. Using a newly developed poloidal CXRS system, a large poloidal flow shear is observed in the peripheral region of high-density plasmas. The evaluation of the radial electric field ($E_r$) based on the momentum force balance equation shows that a large $E_r$ shear ($-650\,\mathrm{kV/m^2}$) is formed at the peripheral region ($r/a = 0.8$). This indicates that the large improvement on $W_p$ and $\tau_E$ due to the HIGP method is related to the formation of the large $E_r$ shear in the peripheral region.

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