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LETTERS

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Experimental test of the radial force balance equation in the compact helical system

K. Ida, A. Fujisawa, H. Iguchi, Y. Yoshimura, T. Minami, S. Okamura, S. Nishimura, M. Isobe, S. Kado,^{a)} Y. Liang, I. Nomura, K. Tanaka, M. Osakabe, C. Takahashi, and K. Matsuoka

National Institute for Fusion Science, Toki 509-5292, Japan

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Experimental test of the radial force balance equation was done in the Compact Helical System Heliotron/Torsatron [S. Okamura *et al.* Nucl. Fusion **39**, 1337 (1999)]. A radial electric field is measured with a heavy ion beam probe, while plasma rotation and drift velocity of fully ionized carbon are measured with charge exchange spectroscopy. The two measurements agree with each other to within 10% of the radial electric field in a wide range of electron densities of $0.3\text{--}2.0 \times 10^{19} \text{ m}^{-3}$. © 2001 American Institute of Physics. [DOI: 10.1063/1.1331097]

The radial force balance equation has been widely used to derive radial electric field profiles from measurements of plasma rotation velocities with charge exchange spectroscopy (CXS).^{1–5} The preliminary study was done in Impurity Studies Experiment-B (ISX-B)⁶ tokamak by using a heavy ion beam probe (HIBP) and passive spectroscopic measurements.⁷ Although the radial profiles of space potential were measured precisely, there was no radial profile of poloidal or toroidal rotation velocity because of the lack of charge exchange spectroscopy. Only the central toroidal rotation velocity was measured and the test of the radial force balance equation was crude. The measurements of the poloidal and toroidal flow of bulk and impurity ions in Doublet-IIID (D-IIID)⁸ show that the deduced radial electric field derived from bulk ions using a radial force balance equation agrees well with that from impurity ions.⁹ Although the agreement observed suggests the validity of the radial force balance equation, it was not conclusive because there was no direct measurement of the radial electric field with HIBP.

The radial electric field profiles measured with charge exchange spectroscopy (CXS) are compared with those measured with the HIBP in the Compact Helical System (CHS).¹⁰ The comparison of the two radial electric fields measured with CXS and HIBP is considered to be a test of the radial force balance equation (1),

$$en_i Z_i E_r = - \frac{\partial p_i}{\partial \psi / (RB_\theta)} - en_i Z_i (v_\theta B_\phi - v_\phi B_\theta). \quad (1)$$

^{a)}Present address: High temperature Plasma Center, University of Tokyo, Tokyo, 113-8656, Japan.

In CHS, both poloidal and toroidal rotation velocity profiles as well as the ion temperature of fully ionized carbon are measured with charge exchange spectroscopy by using the heating neutral beam (NB) at the midplane of the vertically elongated poloidal cross section. The charge exchange spectroscopy consists of two sets of 30 channel poloidal array viewing the same plasma radii vertically with the opposite direction (viewing downward and viewing upward) in order to determine the Doppler shift precisely. The toroidal charge exchange spectroscopy system has a 16 channel toroidal array viewing the poloidal cross section same as that of the poloidal arrays. The time resolution of the CXS is 20 ms, which is determined by the frame rate of the intensified charge coupled device (ICCD) camera used as a detector. The space potential profiles are measured with a heavy ion beam probe (HIBP) along the beam path at a different poloidal cross section. The beam energy of the HIBP is 75 kV. The radial profiles of the space potential are obtained by scanning the heavy ion beam. Because space potential is constant on a magnetic flux surface,¹¹ the radial electric field profiles $E_r(\rho)$, are obtained from the derivative of space potential along the CXS measurement points. The magnetic flux surface is calculated with a finite-beta three-dimension equilibrium code VMEC¹² based on the radial profiles of electron density temperature and ion temperature. The electron density and its profiles are measured with a scanning 3 chord far infrared (FIR) interferometer and a 24 point YAG Thomson scattering system.

The plasma flow velocities and radial electric fields between CXS and HIBP measurements are compared in the

FIG. 1. Radial profiles of (a) electron density, (b) electron temperature, (c) carbon density, and (d) ion temperature.

plasma heated by neutral beam injection (NBI) and electron cyclotron heating (ECH) with a relatively low density of $0.3\text{--}2.5 \times 10^{19} \text{ m}^{-3}$, where the beam attenuation of the HIBP is small enough to make measurements possible. The neutral beam is injected from 40 ms to 160 ms. The ECH pulse with the second harmonic frequency (53 GHz) of electron cyclotron resonance is overlapped on the NBI pulse for $t=60\text{--}100$ ms. The central electron temperature jumps to 1–1.5 keV from 0.2–0.3 keV after the onset of the ECH pulse, while the central electron density drops to $0.3\text{--}0.5 \times 10^{19} \text{ m}^{-3}$ due to the pump out effect. The central ion temperature also increases to: 0.3–0.4 keV after the ECH pulse.

The radial electric field near the plasma center ($\rho=0.18$) also jumps to positive (10–15 kV/m) during the ECH pulse, while it has small negative values during the phase when there is no ECH applied.

As shown in Fig. 1, the electron temperature profile becomes peaked at the plasma center during the ECH ($t=90$ ms) because of the localized heating of the ECH, while it becomes relatively flat after the ECH pulse is turned off ($t=110$ ms). The ion temperature profiles also become slightly peaked during the ECH pulse. The energy transfer from electrons to ions increases because of a large difference of temperature between electrons and ions. The energy deposition of the neutral beam to ions also increases as the electron temperature is increased. The radial profile of electron density becomes more flattened during the ECH pulse and this flattening of the electron density is due to the outward directed thermodiffusion driven by a sharp electron temperature gradient.¹³ On the other hand, the radial profile of carbon is even more hollow during the ECH pulse and more peaked than that of electron density after the ECH pulse. These results show that the accumulation (exhaust) of carbon impurity during the NBI (NBI+ECH) phase is more significant than that of the bulk ions. In general, the particle transport both of bulk ions and carbon impurity is affected by the sign of the radial electric field.¹⁴ These data show that the particle transport of the carbon impurity is more sensitive to the radial electric field than that of bulk ions. The poloidal rotation velocity increases to 12 km/s in the ion diamagnetic direction at the plasma core ($\rho=0.3$) with ECH, while it is almost zero in the NBI phase, which shows that a large positive radial electric field appears associated with the ECH as shown in Fig. 2. In the CXS measurements the radial electric field is derived from the poloidal rotation velocity as well as the toroidal rotation velocity and pressure gradient. The contribution of the toroidal rotation velocity is small (less than 1 kV/m) and the contribution of the poloidal rotation velocity to the radial electric field is dominant, because the poloidal magnetic field is much smaller than the toroidal magnetic field. The diamagnetic drift term always contributes a negative radial electric field and it also has a small contribution to the radial electric field. The error bar of the radial electric field for CXS is mainly due to the error of the poloidal rotation velocity measurements. The error bar of the HIBP is much smaller than that of the CXS. The error of the potential measured with HIBP depends on the beam current and it is typically 5–10 V, which gives the error in the radial electric field of 0.5–1 kV/m. Although the offset of the potential has a large uncertainty, the offset does not cause the error in the radial electric field, because it is canceled out when we take the derivative of potential. The systematic error of the radial electric field is determined by the accuracy of energy calibration of the beam and it is on the order of 1%.

As seen in Figs. 2(c) and 2(d), the radial electric field is positive during the ECH pulse, while it is negative after the ECH pulse in the whole region of the plasma. During the ECH pulse, the radial electric field profile has a peak at $\rho=0.3$ and the positive electric field is localized at the plasma core ($\rho<0.5$) where the electron temperature gradient is large. On the other hand, the radial electric field is negative

FIG. 2. Radial profiles of (a), (b) $v_\theta \times B_\phi$, $v_\phi \times B_\theta$ ($1/6en_i$) $\partial p_i/\partial R$ and (c), (d) radial electric field during ECH heating ($t=90$ ms) and after ECH heating ($t=110$ ms). The open and closed circles are the radial electric field measured with CXS, while the solid lines are that measured with HIBP.

and is almost flat at the plasma core and becomes more negative towards the plasma edge during the NBI phase.

The comparison of the radial electric field estimated from CXS and measured with HIBP was done in a wide range of electron density of $0.3\text{--}2.0 \times 10^{19} \text{ m}^{-3}$, where the plasma parameter changes from electron root to ion root. When the plasma is heated with NBI and there is no ECH, the sign of the electric field is always negative regardless of the electron density. However, when the ECH is overlapped to the NBI heating, the electric field jumps from negative to positive values at the low density of $0.5 \times 10^{19} \text{ m}^{-3}$ as shown

FIG. 3. (a) Radial electric field at $\rho=0.25$ as a function of the central electron density for NBI+ECH heated plasmas (closed circles and solid line) and NBI plasmas (open circles and dashed line), and radial profiles of the radial electric field for NBI+ECH heated plasma for the central electron densities of (b) 0.34, (c) 0.47, (d) $0.96 \times 10^{19} \text{ cm}^{-3}$.

in Fig. 3. In NBI plasmas, the electron temperature is only 0.2–0.3 keV and not high enough to bring the plasma into the electron root. However, when the ECH pulse is applied, the electron temperature increases to above 1 keV and the transition from ion root ($E_r \approx -1 \text{ kV/m}$) to electron root ($E_r \approx 10 \text{ kV/m}$) is observed. The radial electric field has a peak of 15 kV/m (positive E_r) at $\rho=0.3$ in the electron root at the low density of $0.34 \times 10^{19} \text{ m}^{-3}$, while it is negative (-4 kV/m) near the plasma edge ($\rho=0.8$) in the ion root at the higher electron density of $0.96 \times 10^{19} \text{ m}^{-3}$. At the elec-

FIG. 4. A comparison of the radial electric field measured with CXS and HIBP.

tron density in between ($0.47 \times 10^{19} \text{ m}^{-3}$), the radial electric field has only a small peak of 4 kV/m near the plasma center ($\rho=0.2$), and it is considered to be in the transition regime from electron root to ion root. The agreement of the two measurements HIBP and CXS shows that the radial friction force is relatively small for the wide range of electron density of 0.3 to $1.0 \times 10^{19} \text{ m}^{-3}$ and the radial electric field of (-4 to 15 kV/m).

The comparison of the radial electric field estimated from CXS and measured with HIBP is plotted in Fig. 4. The data for all radii and in all density regimes available are plotted. The relation of the two radial electric fields measured with CXS and HIBP is $E_r^*(\text{CXS}) = (0.89 \pm 0.03) \times E_r(\text{HIBP}) - (0.19 \pm 0.08) \text{ kV/m}$, which is given by the unweighted least squares fit. If we take the ratio of radial electric field measured with CXS to that measured with HIBP by ignoring the offset, the coefficient is 0.9 ± 0.03 . The radial electric field measured with CXS is smaller than that with HIBP by 10%. The discrepancy between the two measurements exceeds the statistical scatter of the measurements. As seen in Fig. 2(c) and Fig. 3(b), the discrepancy between the two measurements appears when the radial electric field and its shear become large. The discrepancy would be due to the poor spatial resolution of CXS measurements. The spatial resolution of the CXS is relatively poor near the plasma center because of the finite width (180 mm) of the heating neutral beam. Therefore the peak values of the positive radial electric field near the plasma measured with CXS tend to be underestimated because of poor spatial resolution ($\Delta\rho = \pm 0.3$). Although the spatial resolution due to the finite beam width is most poor at the plasma center, the effect of smoothing depends on the second derivative of the radial electric field not the first derivative of the radial electric field. (If the change of the radial electric field is linear, the smoothed value is identical to the local value.) The underestimation of the local value due to the radial smoothing increases as the second derivative of the radial electric field is increased. Therefore the effect of radial smoothing due to poor spatial resolution is largest at $\rho=0.3$, where the second

derivative of the radial electric field has a maximum. On the other hand, the spatial resolution of the HIBP is much better than that of CXS because the heavy ion beam is less than 1 cm in diameter and has good spatial resolution ($\Delta\rho = < 0.05$). Therefore the radial electric field measured with CXS is considered to be slightly underestimated because of smoothing, when the strong radial electric field is localized as seen in Fig. 3(b). The offset of (0.19 ± 0.08) is due to the uncertainty in determining the wavelength for zero poloidal rotation velocity. The accuracy of zero wavelength determined by using the two viewing array with the opposite direction is 1 pm, which gives the error in poloidal rotation velocity of 0.6 km/s and the radial electric field of 0.5 kV/m. The zero wavelength of the toroidal system is measured by adding the optical fiber viewing the plasma center from poloidal array to toroidal optical fibers. Because there should be no Doppler shift of the spectrum viewing the plasma center poloidally, the center of the spectrum can be taken as a reference of the zero wavelength. The offset due to the toroidal rotation velocity is negligible, because the contribution of toroidal rotation to the radial electric field is very small ($B_\theta/B_\phi = 0.1$ at $\rho=0.5$).

These observations show that the radial electric field measured with CXS measurements agrees with the E_r measured with HIBP within the margins of error. Agreement between the two measurements is observed in the absolute values of E_r as well as in the radial profiles. These observations confirm the validity of radial force balance equation with the accuracy of below 10%. Because of the error bar of the CXS measurements, it is difficult to rule out the other terms, which is not included in the standard radial force balance equation, such as a radial frictional force due to the differences in radial velocity between bulk and impurities.

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