

Measurement of Radial Electric Field Using Doppler Reflectometer in High-Density Plasma of Heliotron J^{*})

Yasuto KONDO, Takeshi FUKUDA, Kazunobu NAGASAKI¹⁾, Hiroyuki OKADA¹⁾, Takashi MINAMI¹⁾, Shinichiro KADO¹⁾, Shinji KOBAYASHI¹⁾, Satoshi YAMAMOTO²⁾, Shinsuke OHSHIMA¹⁾, Tohru MIZUUCHI¹⁾ and Takeshi TOMITA³⁾

Graduate School of Engineering, Osaka University, Suita 565-0871, Japan

¹⁾*Institute of Advanced Energy, Kyoto University, Uji 611-0011, Japan*

²⁾*National Institutes for Quantum and Radiological Science and Technology, Naka 311-0193, Japan*

³⁾*Graduate School of Energy Science, Kyoto University, Uji 611-0011, Japan*

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In this study, the radial electric field, E_r , has been measured using a two-channel Doppler microwave reflectometer at high-density plasmas of the Heliotron J helical device. The experimental results show that E_r grows negatively as the energy confinement is improved and the stored energy, W_p , is increased in a high-density plasma produced by neutral beam injection heating and high-intensity gas-puffing (HIGP). In a high-density plasma without HIGP, the E_r radial structure in which the direction of the E_r changes is measured.

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1. Introduction

In magnetically confined fusion plasmas, it is believed that plasma confinement is governed by turbulence and the radial electric field, E_r , can affect plasma transport and confinement [1,2]. Measuring and the controlling E_r structure greatly contributes to an understanding of high performance plasmas. A Doppler reflectometer is a diagnostic tool to measure density fluctuation, \tilde{n}_e , and poloidal rotation velocity, v_θ , with high temporal and spatial resolution and is used for E_r measurement by measuring v_θ and \tilde{n}_e measurement in a number of fusion plasma devices [3–6].

In this study, we introduce a two-channel Doppler microwave reflectometer system in the Heliotron J helical device to measure E_r and \tilde{n}_e . In general, v_θ can be approximated by the $E \times B$ drift velocity, $v_{E \times B}$, in the peripheral region, and with knowledge of the toroidal magnetic field B_t , E_r can be calculated as $E_r = v_\theta B_t$.

In this paper, we show the measurement results for E_r using the Doppler reflectometer system in Heliotron J for the first time. We describe the Doppler reflectometer system in Sec. 2, and show the plasma experimental results in Sec. 3. These include the temporal relationship between E_r and the stored energy, W_p , at transition phenomena observed in a high density plasma using the high-intensity gas-puffing (HIGP) [7] and the time evolution of E_r structure in the NBI plasma without HIGP. The conclusion is given in Sec. 4.

2. Doppler Reflectometer Systems for Heliotron J

Heliotron J is a medium-sized plasma experimental stellarator/heliotron device [8, 9]. Its main parameters are the plasma major radius, $R = 1.2$ m, averaged minor radius, $a = 0.1 - 0.2$ m, rotational transform $\iota/2\pi = 0.3 - 0.8$, and maximum magnetic field strength on the magnetic axis, $B = 1.5$ T. The coil system comprises an $L = 1$, $M = 4$ helical coil, two types of toroidal coils A and B, and three pairs of vertical coils. Here, L and M denote the poloidal and toroidal pitch numbers, respectively. In Heliotron J, the magnetic configuration can be scanned by varying the current ratios in each coil.

In Heliotron J, we designed and constructed a two-channel O-mode Doppler reflectometer system. Figure 1 (a) shows the schematic of the Ka-band (26 - 40 GHz) microwave Doppler reflectometer system. In a frequency-scannable reflectometer referred to as ‘‘Reflectometer 1,’’ a voltage-controlled oscillator (VCO) is used as a frequency source, which generates a microwave of 12.82 - 19.99 GHz, corresponding to bias voltage applied using a function generator (FG). The microwave is upconverted using a 100 MHz wave generated by a RF source and doubled in frequency to 25.84 - 40.18 GHz using a multiplier. These frequencies correspond to the O-mode cut-off density of $0.85 \times 10^{19} - 2.00 \times 10^{19} \text{ m}^{-3}$. The reflected wave is mixed with the reference wave, amplified, filtered using a band-pass filter (BPF), and then detected by I/Q detector.

Figure 1 (b) shows the schematic of a frequency-fixed microwave Doppler reflectometer system referred to as

author's e-mail: kondo.yasuto@eb.see.eng.osaka-u.ac.jp

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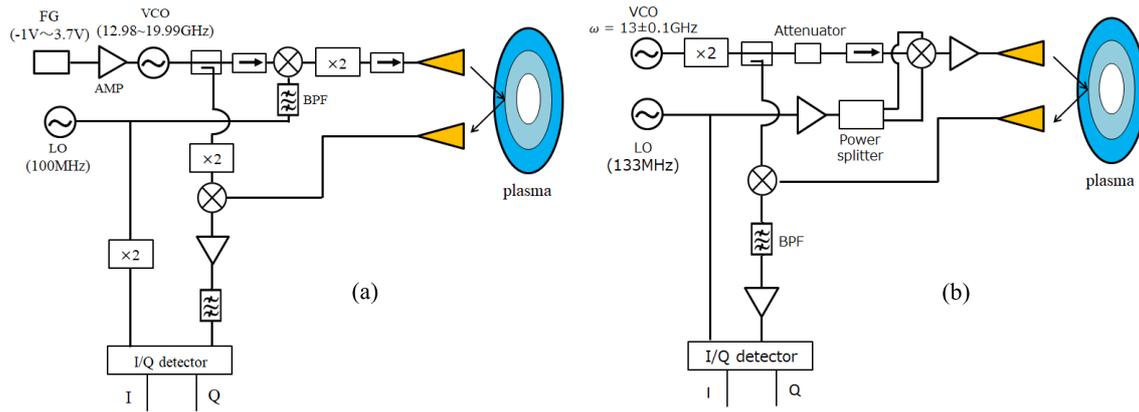


Fig. 1 The schematic of (a) Ka-band; (b) frequency-fixed microwave circuit for the Doppler reflectometer.

“Reflectometer 2.” In Reflectometer 2, a VCO is also used as a frequency source, which generates a microwave of 13 ± 0.1 GHz. The microwave is doubled in frequency to 26 ± 0.2 GHz using a multiplier, attenuated to the input signal amplitude of an upconverter and then upconverted using a 133 MHz wave generated by a RF. The intermediate frequency (IF) input of the upconverter used in Reflectometer 2 must have two types of input waves: a wave generated by a RF and a wave that is 90 degrees out of phase. Therefore, the phase of the intermediate wave is shifted 90 degrees using a power splitter. Finally, the microwave frequency is 26.13 ± 0.2 GHz and the corresponding cut-off density is $0.85 \pm 0.01 \times 10^{19} \text{ m}^{-3}$. The reflected wave is mixed with the reference wave, filtered using a BPF, amplified and then detected using an I/Q detector.

We use rectangular waveguide transmission lines and incident and receiving rectangular horn antennas for the microwaves from these two circuits. The antenna is tilted approximately 10 degrees with respect to the poloidal cross-section, and approximately 7 degrees in the toroidal direction to be incident perpendicular to the three-dimensional magnetic axis.

This two-channel Doppler reflectometer system can estimate E_r structure and the radial correlation length by simultaneously measuring two radial points in the plasma.

3. Experimental Results

3.1 Radial electric field in NBI plasma with HIGP

The time evolution of an NBI plasma discharge with HIGP is shown in Fig. 2. The plasma is generated using a 2.45 GHz microwave and sustained by NBI heating. The high-density plasma is generated by applying the HIGP at 230 ms. After the HIGP, the average electron density, \bar{n}_e , increased, H_α decreased rapidly, and W_p increased 10 ms after the HIGP. The achieved stored energy was higher than the conventional gas-puffing case. These results suggest that a transition occurred by using the HIGP method and that energy confinement was improved.

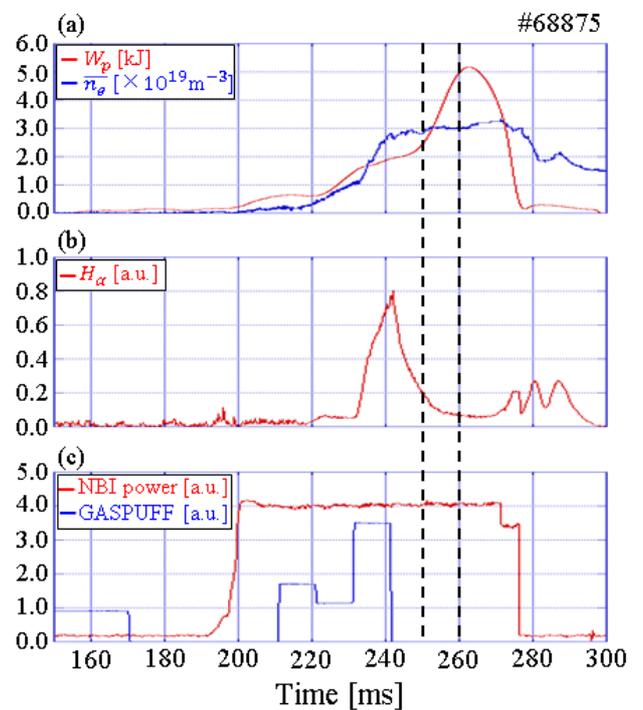


Fig. 2 Time evolution of (a) W_p , \bar{n}_e ; (b) H_α ; (c) NBI and gas puffing signals.

Figure 3 shows the complex Fourier spectrum obtained from I/Q signals from Reflectometer 1. The cut-off density is $0.84 \times 10^{19} \text{ m}^{-3}$. Although the electron density profile could not be measured, according to the density profile obtained from a similar experiment in a previous study [10], the cut-off layer may be formed at the peripheral region around $r/a = 0.9$. Between 250 ms and 260 ms (inside of dashed lines in Fig. 2), the energy confinement is improved and the density fluctuation at frequencies < 100 kHz is suppressed, whereas the density fluctuation at high frequencies (> 100 kHz) is enhanced, and negative Doppler shift appears.

Figure 4 shows the relationship between E_r and W_p during the improved phase obtained from Reflectometer 1.

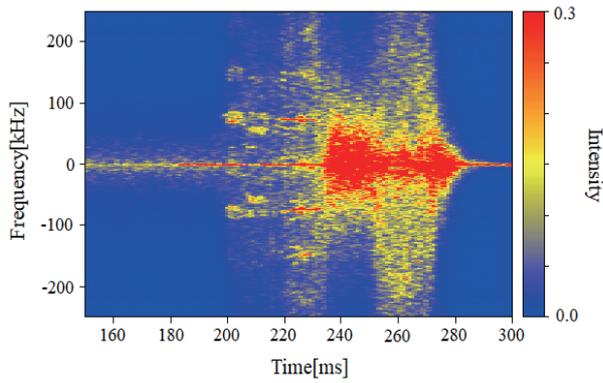


Fig. 3 Time evolution of Fast Fourier Transformed (FFT) I/Q signal of Reflectometer 1.

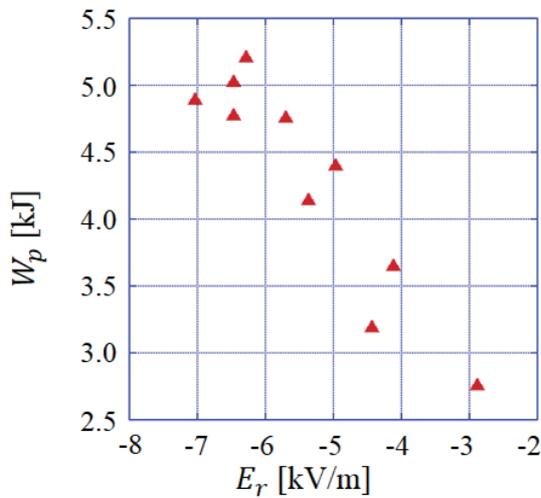


Fig. 4 Relationship between W_p and E_r from Reflectometer 1.

As the absolute value of E_r increases, W_p increases monotonically. We confirmed that E_r obtained from Reflectometer 2 (cut-off density of $0.85 \times 10^{19} \text{ m}^{-3}$) had the same tendency as that obtained from Reflectometer 1, with the same intensity and sign. This shows that the two Doppler reflectometer systems are consistent with each other, their intensity and sign of E_r is consistent with the E_r distribution estimated from charge exchange recombination spectroscopy [10].

When W_p increases, \tilde{n}_e is almost constant. However the electron density profile changes, that is, the measured radial location might have moved. In contrast, because the cut-off layer is located at the peripheral region, changes in radial location are not expected to be large. In future, we will measure the change in electron density profile with high temporal resolution using an AM reflectometer.

3.2 Radial electric field structure in NBI plasma without HIGP

We measured the E_r structure in NBI plasmas without HIGP by changing the carrier microwave frequency

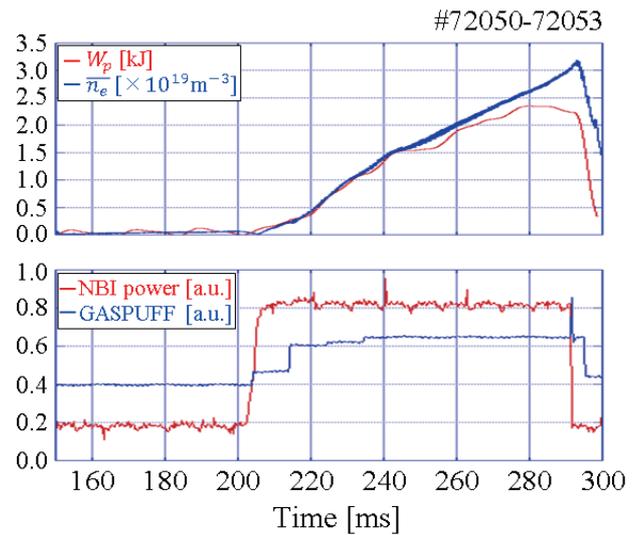


Fig. 5 Time evolution of (a) W_p , \tilde{n}_e ; (b) NBI and gas-puffing signals.

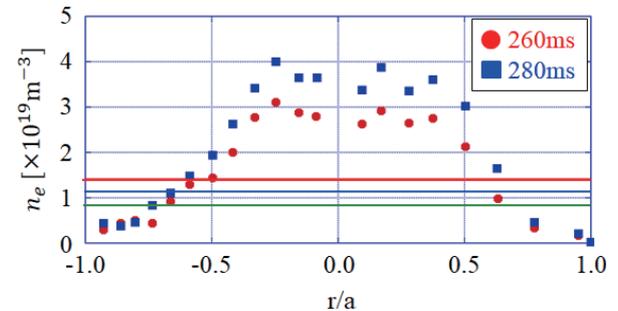


Fig. 6 Profiles at 260 ms (red) and 280 ms (blue).

shot-by-shot in fixed plasma conditions. The time evolution of plasma discharge is shown in Fig. 5. The E_r estimation is performed at 260 ms and 280 ms (broken line in Fig. 5). Figure 6 shows the density profiles at 260 ms and 280 ms. In this plasma discharge, the density is centrally peaked. The microwave cut-off density is $1.42 \times 10^{19} \text{ m}^{-3}$, $1.15 \times 10^{19} \text{ m}^{-3}$, $0.839 \times 10^{19} \text{ m}^{-3}$; the red, blue, and green lines in Fig. 6 show the respective cut-off density. The cut-off layer is formed at a location where the density gradient is large, that is, at the peripheral region.

The E_r structure at 260 ms and 280 ms is shown in Fig. 7. The change in sign of E_r is observed in the radial direction. With an increase in the electron density and stored energy, the absolute value of E_r increases and this structure moves outward. In future, we will measure detailed radial E_r structure by finely scanning the microwave frequency.

4. Conclusion

We have reported the measurement results for the radial electric field of high-density NBI plasmas in Heliotron J using a two-channel Doppler reflectometer for the first time.

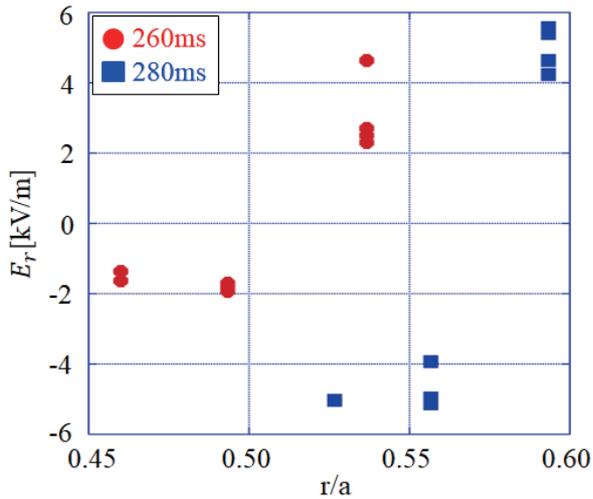


Fig. 7 Profiles at 260 ms (red) and 280 ms (blue) in non-HIGP plasma.

In the NBI plasma with HIGP, W_p increases after HIGP and energy confinement is improved. The increase in W_p is correlated with the increase in E_r magnitude at the peripheral region, indicating that the radial electric field has an important role in the improvement.

In non-HIGP NBI plasma, we measured the time evo-

lution of E_r structure. The sign of E_r changed in the radial direction, and the structure shifted as the density profile evolved. Detailed studies on E_r structure will be performed in the future.

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