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Density fluctuation measurements using beam emission spectroscopy on Heliotron J[a)]

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This paper describes the measurement of the density fluctuation using beam emission spectroscopy in Heliotron J, having the non-symmetrical helical-magnetic-axis configuration. In order to optimize the sightlines, the numerical calculations are carried out to estimate the spatial resolution and the observation location. When a tangential neutral beam is used as diagnostic one, suitable sightlines from the newly installed diagnostic port are selected whose spatial resolution $\Delta\rho$ is less than ± 0.07 over the entire plasma region. Modification of the interference filter and the detection systems enables us to measure the radial profile of the density fluctuation. Each of the three coherent modes due to the fast-ion-driven magnetohydrodynamic instabilities has different radial structure of the density fluctuation. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4734039]

I. INTRODUCTION

Plasma turbulence has long been an important subject in the confinement of particle, momentum, and energy in magnetically confinement fusion plasmas. The technique of beam emission spectroscopy (BES) has been developed in tokamak and helical devices.[1–4] The radial and/or the poloidal structure of the density fluctuation have been evaluated by the spectral measurement of the Doppler-shifted light emission followed by the collisional excitation process between the hydrogen or deuterium neutral beam atoms and plasmas. The BES measurements have greatly advanced our understanding of the physics of magnetohydrodynamic (MHD) activities and long-wavelength plasma turbulence. In particular, the radial structure of the density fluctuation and its phase difference provides important information for identifying MHD activity and for understanding the underlying physics.

In a previous study, in which BES was applied to Heliotron J,[5] we found that sightlines from a newly installed diagnostic port enabled us to estimate the density fluctuation over the entire plasma region with a good spatial resolution. In this study, we describe a recent development in the density fluctuation measurements using BES in Heliotron J. The upgraded BES system is explained including the objective optical and the detection systems. The radial structure of the density fluctuation is measured with regard to the fast-ion-driven MHD instabilities.

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II. BEAM EMISSION MEASUREMENT SYSTEM IN HELIOTRON J

Heliotron J is a medium sized (R/a = 1.2 m/0.2 m) helical-magnetic-axis heliotron device with $L/M = 1/4$ helical winding coil.[6] Two tangential beamlines of neutral beam injection (NBI, BL1:counter- and BL2:co-going directions) have been installed with a maximum acceleration voltage of 30 kV and a maximum power of 0.7 MW. Each beamline has two (upper and lower) bucket-type ion sources whose divergences were measured to be 1.2° in beam calibration experiments.

Beam emission spectroscopy observes Doppler-shifted H_α emission through the collisional excitation process between injected neutral beam atoms and background plasmas (electrons or ions). The intensity of the beam emission I_{BE} of the sightline l is given by[1,4,5,7]

$$I_{BE} = \int dl \frac{A_{32}}{A_{32}+A_{31}}(n_i\, n_{beam}\, \sigma_i\, v_{beam} + n_e\, n_{beam}\, \langle \sigma_e\, |v_{beam} - v_e| \rangle) h\nu S \Delta\Omega/4\pi, \quad (1)$$

where A_{nm} is the transition probability from the n to m state, n_i, n_e, and n_{beam} are, respectively, the ion, electron, and the neutral beam densities, and v_e and v_{beam} the electron thermal and the beam velocities. Under the typical experimental condition of the NBI heated plasmas in Heliotron J, the effect of the thermal velocity of bulk ions is negligible because the ion temperature ($T_i(0) < 0.3$ keV) is lower than the injected beam energy (E_b = 24–30 keV H^0 beam). For an electron temperature T_e of around 0.4 keV, the effective cross section of the electron impact excitation ($\langle \sigma_e\, |v_{beam} - v_e| \rangle / v_{beam} \approx 2.3 \times 10^{-17}$ cm^2) is in the same order of magnitude as that for the

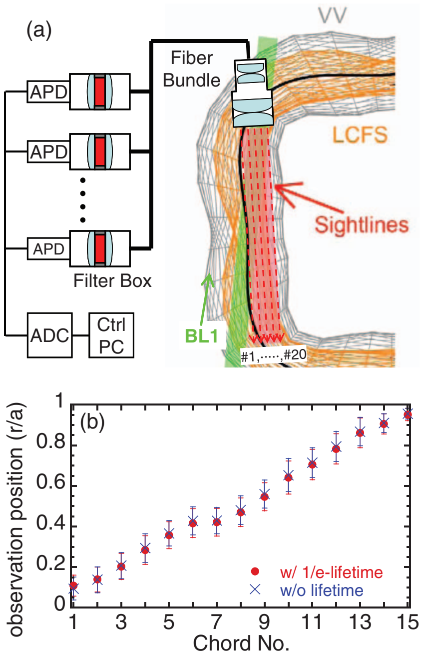

FIG. 1. (a) Top view of the Heliotron J device and BES sightlines. The chord numbers of the sightlines are denoted as #1 to #20. (b) Observation position and radial extent of the sightlines in the case of the standard configuration of Heliotron J.

ion ($\sigma_i \approx 1.7 \times 10^{-17}$ cm^2). S is the observation area along the sightline element dl and $\Delta\Omega/4\pi$ is the solid angle.

Figure 1(a) shows the schematic view of the BES system in Heliotron J. The BL1 neutral beam path is imaged onto a 20-channel fiber bundle using a vacuum compatible mirror and a set of lenses mounted in the newly installed viewing port. Because the heating neutral beam is used as a diagnostic beam and the Heliotron J magnetic configuration has a complicated three-dimensional shape, the numerical calculations were carried out to optimize the sightlines.[5,8] Briefly, the spatial resolution can be minimized when the sightlines are almost aligned with a magnetic field line in the beam intersection region. In the standard configuration of Heliotron J, the length of the beam intersection region is about 0.5 m long. The detector system is modified to obtain a significant signal-to-noise ratio. It consists of a set of relay lenses, an interference filter and an avalanche photodiode (APD). The center wavelength (656.1–656.2 nm) and the passband (1–2 nm) of the interference filter, mounted between the relay lenses, are selected to admit the full and half components of the Doppler shifted beam emission. To reduce the losses due to the lens aberration and transmission, the filtered beam emission is directly focused on the active photosensitive area of the APD whose diameter is ϕ3 mm. The cutoff frequency of the pre-amplifier of the APD is set to be 200 kHz. A 1 MHz digitizer is used to acquire the APD signal. In this study, four detector systems were used and their locations were changed shot-by-shot to obtain the entire plasma distribution of the beam emission intensity.

Each optical sightline has a solid angle of $\Delta\Omega = 5.7 \times 10^{-5}$ sr and an observation volume of $\int S\, dl = 60$ cm^3, respectively. In the standard configuration of Heliotron J, 15 sightlines are available for the radial profile measurements of the beam emission. Figure 1(b) shows the observation position and the radial extent of each channel determined by calculations based on Eq. (1). The plasma density and the temperature profiles are assumed to be parabolic having core values of $n_e(0) = n_i(0) = 3 \times 10^{19}$ m^{-3} and $T_e(0) = 0.3$ keV, respectively, which are typical conditions obtained in the NBI plasmas of Heliotron J. The beam density was determined by a Monte-Carlo simulation[9] with taking beam absorption effects into account. The effect of the lifetime of the excited-state beam atom was also investigated by the model calculations. For the proton-impact excitation, the population of the excited-state beam atom will decay with a characteristic time $\tau_j = 1/A_j\ 1/(1 + n_p D_j/A_j)$, where A_j is the total radiative decay rate and $n_p D_j$ is the total depopulation rate.[1] For the standard plasma parameters of Heliotron J, the beam atoms can travel along the beam (nearly tangential) direction for less than 1 cm before radiative decay occurs. Even when the 1/e beam travel length is taken to be 1 cm, the radial displacement due to the lifetime of the excited beam is negligible, as shown in Fig. 1(b). A good spatial resolution ($\Delta r/a \approx \pm 0.07$) is achieved from the plasma core to the edge region ($0.1 < r/a < 1$). The measurable wavenumber range $k_N\ \rho_i$ is estimated to be smaller than 0.7 in the case that the ion Lamor radius ρ_i is 0.2 cm for the standard parameters of the Heliotron J plasmas (i.e., the ion temperature of 0.3 keV and the magnetic field strength of 1.25 T).

III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The beam emission was measured in the NBI (BL1 and BL2) heated plasmas, in which fast-ion-driven MHD instabilities were observed. We obtained an intense beam emission that was more than 50 times higher than that of the previous prototype BES system.[5] Power spectra of the beam emission fluctuations are shown in Fig. 2. These are obtained from $r/a = 0.20$ to 0.95. The line-averaged electron density was around 1–1.5 $\times 10^{19}$ m^{-3}. The power spectrum of the dark current component is also shown in the figure. A significant signal intensity was achieved relative to the dark current spectrum. Note that, relatively strong peaks at $f = 15$ and 50 kHz, being due to the noise from the pre-amplifier, should be eliminated in the analysis. Three intense modes (denoted A, B,

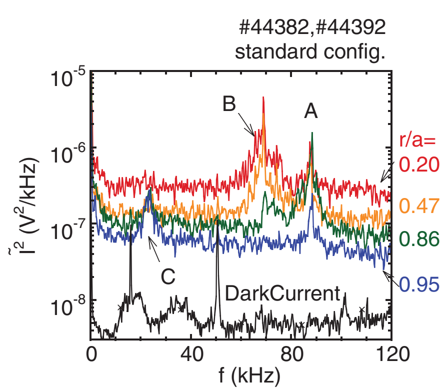

FIG. 2. Power spectra of the beam emission at $r/a = 0.20$, 0.47, 0.86, and 0.95 obtained in the NBI heated plasmas of Heliotron J.

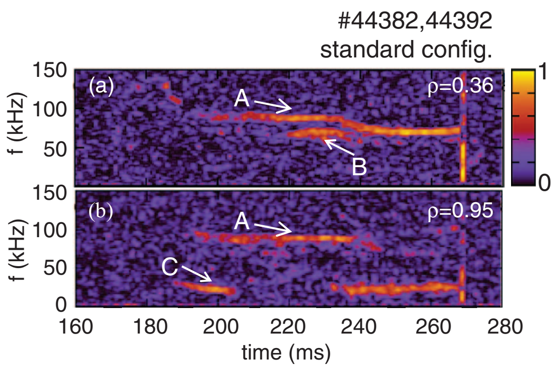

FIG. 3. Temporal and spectral evolution of coherence to Mirnov coil signal at $r/a = 0.36$ and 0.95.

and C) were clearly observed in the frequency range of 25–90 kHz. Mode B ($f = 62$–70 kHz) was observed strongly at the sightlines inside $r/a < 0.5$, however, the peripheral chords observed a lower frequency mode (C, $f = 21$–25 kHz).

Figures 3(a) and 3(b) shows the temporal and spectrally resolved coherences at $r/a = 0.36$ and 0.95 to the Mirnov coil signal mounted on the vacuum vessel. The high coherence region has a radial structure as well. From a toroidal array of Mirnov coils, the toroidal mode numbers were estimated to be $n = 1$ for modes A and B and $n = 2$ form mode C. The fluctuation level of the beam emission is plotted in Fig. 4 as a function of the normalized minor radius ρ. These are normalized to the dc component of the beam emission intensity, i.e., $\tilde{I}_{BE}/\langle I_{BE}\rangle$ which is proportional to the density fluctuation ($\tilde{n}(\rho)/n(\rho)$) at the local position. If the density profile is assumed to be parabolic, the radial profile of the density fluctuation (i.e., $\tilde{n}(\rho)$) for mode B will have a peaked one and will be higher in the core region ($\rho < 0.6$). The density fluctuation for mode A spreads over the whole region, while the C is localized at the edge region.

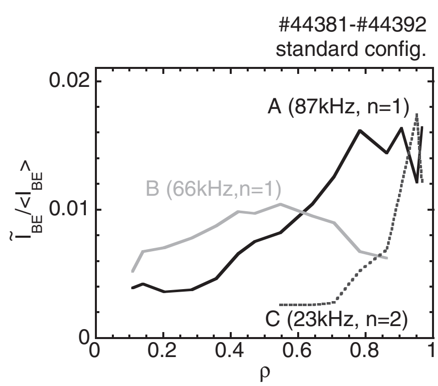

FIG. 4. Radial profile of the fluctuation strength of beam emission normalized by the dc component of the beam emission ($\tilde{I}_{BE}/\langle I_{BE}\rangle$).

Heliotron J has a low magnetic shear configuration. For example, the magnetic shear ($s = (r/q)(dq/dr)$) is less than 0.02 on average in the standard configuration. In such the case, the MHD stability analysis has showed that global Alfvén eigenmode (GAE) has been a candidate of most unstable mode, rather than gap modes such as toroidicity induced Alfvén eigenmode.[10] Although the observed frequency and the toroidal mode number for mode A are consistent with the analytical results for GAE, the radial structure of the density fluctuation and the phase difference will be compared by the stability analysis. To obtain the beam emission over the entire plasma region by a single shot, 12 sets of the detector systems are being installed. This will enable us to measure the radial structure for the density fluctuation for frequently occurring phenomena such as the bursting mode of the fast-ion-driven MHD activity.

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