Verification of Background Noise Estimation Method in W-Band Millimeter-Wave Back-Scattering System

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Millimeter-wave back-scattering (BS) system is a diagnostics system capable of measuring electron-scale turbulence, which is expected to have a large influence on future burning plasma confinement. The measured frequency band overlaps that of the electron cyclotron emission (ECE), resulting in comparable background noise. We have developed a method to estimate this background noise by implementing linear regression between the BS signal intensity and that of the ECE when the probing beam is turned off, and have verified the method in LHD experiments.

Keywords: millimeter-wave back-scattering, electron cyclotron emission, electron-scale turbulence, Large Helical Device

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Several simulation studies have pointed out that turbulence on the electron scale—that of the electron Larmor radius, may have a significant impact on heat transport in future burning plasmas. This is due to its interaction with larger ion-scale turbulence, at the scale of the ion Larmor radius, or meso-scale structures such as streamers [1, 2] although experimental research remains insufficient. It is necessary to measure fluctuations with higher wave numbers compared to conventional ion-scale turbulence diagnostics, which restrict the available measuring techniques. The W-band millimeter wave back-scattering (BS) system is one of the diagnostics capable of measuring such high wave number fluctuations and has been introduced for several magnetic confinement devices [3–5]. The utilized frequency band of the BS system overlaps with that of the Electron Cyclotron Emission (ECE). Hence, the BS signal contains background noises at comparable levels. However, the quantitative estimation of the background noise, based on ECE intensity, has not yet been verified. In this paper, we report on the results of developing and verifying a method for estimating background noise using a radiometer as ECE diagnostics introduced at the Large Helical Device (LHD).

The BS system observes the collective scattered wave of the probing beam. The scattered wave is generated by electron density perturbations following the Bragg relationship in which the perturbation wavenumber is certainly decided by the local wavenumber of the probing beam and the scattering angle. The signal intensity of the scattered wave, I_{BS}, therefore includes the intensity originating from the turbulence perturbation, I_{turb}, which is proportional to the electron density perturbation amplitude, $|\delta n_{\mathrm{e}}|$.

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However, I_{BS} also includes comparable background noise, n_{BS}. To measure n_{BS}, the probing beam is turned off for 2 ms every 100 ms in our BS system. This is because I_{turb} vanishes at these times due to absence of the probing wave (and accompanying scattered waves). Here, we particularly denote I_{BS} during this beam-off period as $I_{\mathrm{BS,off}}$ and the time as $t_{\mathrm{BS,off}}$. To estimate I_{turb}, the corresponding n_{BS} under beam-on conditions needs to be estimated. Here, n_{BS} is assumed to consist of the noise n_{EC} caused by ECE and the thermal noise n_{th} generated on the processing circuit of the BS system, etc. In other words, we assume $n_{\mathrm{BS}} = n_{\mathrm{EC}} + n_{\mathrm{th}}$. n_{EC} is reasonably able to be estimated by the ECE intensity, I_{EC}, from an ECE radiometer signal by a proportional relationship $n_{\mathrm{EC}} = \alpha I_{\mathrm{EC}}$, where α is a calibration coefficient from I_{EC} to n_{EC} [4, 6]. Therefore, n_{BS} can be estimated by $n_{\mathrm{BS}} = \alpha I_{\mathrm{EC}} + n_{\mathrm{th}}$. The contribution from electron temperature fluctuation δT_{e} to I_{BS} can be safely ignored because I_{turb} is comparable to n_{EC} as a result and therefore sufficiently larger than the δT_{e} originating intensity, which is usually a few % of n_{EC}.

Consequently, I_{BS} is described by Eq. (1). The signal intensity of the radiometer, I_{rad}, is offset by a processing circuit noise, n_{offset}, as shown in Eq. (2). n_{offset} is practically represented by an average of I_{rad} before the plasma generation.

$$\begin{aligned} I_{\mathrm{BS}}(t) &= I_{\mathrm{turb}}(t) + n_{\mathrm{BS}}(t) \\ &= I_{\mathrm{turb}}(t) + n_{\mathrm{EC}}(t) + n_{\mathrm{th}} \\ &= I_{\mathrm{turb}}(t) + \alpha I_{\mathrm{EC}}(t) + n_{\mathrm{th}}, \end{aligned} \tag{1}$$

$$I_{\mathrm{EC}}(t) = I_{\mathrm{rad}}(t) - n_{\mathrm{offset}}\,. \tag{2}$$

When the probing beam is turned off, since $I_{\mathrm{turb}} = 0$, the derived Eq. (1) yields $I_{\mathrm{BS,off}}(t) = \alpha I_{\mathrm{EC}}(t) + n_{\mathrm{th}}$. Therefore, we estimate α and n_{th} by linear regression between $I_{BS,off}$ and the linearly interpolated I_{EC} at $t_{BS,off}$ within the time of the analysis; then obtain n_{BS}.

We verified the above n_{BS} estimation method from an actual LHD experiment of a standard configuration. Figure 1(a) shows the heating pattern. This plasma was generated at 3.3 s by Electron Cyclotron resonance Heating (ECH) and then heated by both ECH and Neutral Beam Injection (NBI). The ECH power was scanned from 4.2 s to monitor the variation in the I_{EC}. Here, we chose the 86.5 GHz channel for I_{EC}, which is the closest frequency channel to 90 GHz, the same frequency as the BS system. Both are operated by O-mode. We used a notch filter in the BS system to reduce gyrotron noise. The ECE signals and noise obtained from the ECE radiometer and the BS system, respectively, are assumed to be generated at a similar peripheral region although the optical thickness is lower than 1 at this location. The measured I_{EC} alters according to ECH and NBI power changes. Figure 1(b) shows some types of intensities regarding the BS signal. I_{BS} is defined as an amplitude of the BS signal throughout and after a high pass filter cut-off at 150 kHz. This is to avoid lower frequency fluctuation noises e.g. MHD fluctuations. $I_{BS,off}$ changes temporarily in a different trend from I_{BS}. Before the plasma generation, $I_{BS,off}$ and the estimated n_{BS} are constant at the estimated n_{th} level. As shown in Fig. 2, n_{BS} agrees very well with $I_{BS,off}$, with quite a high correlation coefficient of 0.99. As a result, the accurate trend of I_{turb} is successfully calculated by employing the ECE signal.

We have developed and verified a method for calculating background noise in the BS system, n_{BS}. n_{BS} is expected to be dominated by steady-state thermal noise originating from the circuit and noise caused by ECE. Our method implements linear regression between the BS signal obtained when the probing beam is turned off to observe the background noise, $I_{BS,off}$, and the ECE intensity measured by the radiometer. When this method was applied to an actual LHD experiment in which ECH power was scanned, we successfully estimated n_{BS} following the heating power change. The estimated n_{BS} agrees very well with $I_{BS,off}$, with quite a high correlation coefficient of 0.99. This method enables for us measurement of more accurate electron-scale fluctuation intensity by the BS system.

The data supporting the findings of this study are available in the LHD experiment data repository at https://doi.org/10.57451/lhd.analyzed-data. This study was supported in part by the Japan Society for the Promotion of Science KAKENHI (Grant Nos. 19H01880, 21H04973, 23H01161, and 23K25858).

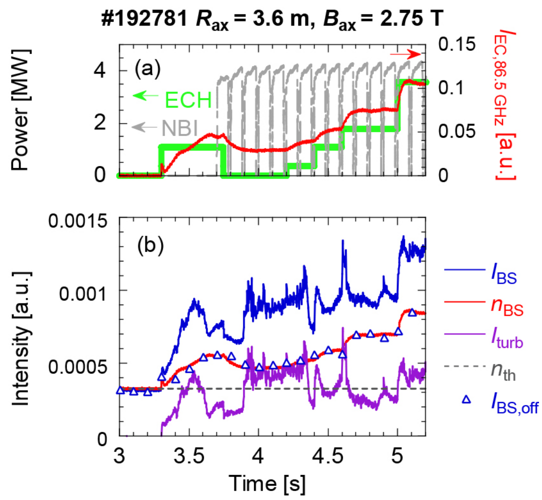

Fig. 1. Time traces of (a) ECH power (green line), NBI power (grey dotted line), and I_{EC} (red line), and (b) I_{BS} (blue line), n_{BS} (red line), I_{turb} (purple line), $I_{BS,off}$ (blue triangle), and n_{th} (grey dotted line).

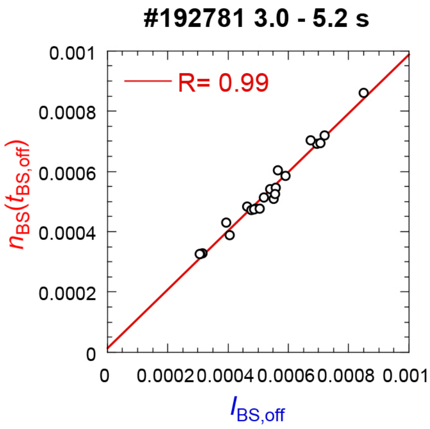

Fig. 2. Parity plot between estimated n_{BS} at $t_{BS,off}$ and observed $I_{BS,off}$. Red line and R stand for a regression line and its correlation coefficient.

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