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Cite as: Rev. Sci. Instrum. **89**, 10H118 (2018); <https://doi.org/10.1063/1.5035118>

Submitted: 13 April 2018 • Accepted: 25 June 2018 • Published Online: 05 October 2018

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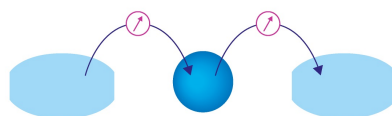
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# Microwave frequency comb Doppler reflectometer applying fast digital data acquisition system in LHD

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(Presented 17 April 2018; received 13 April 2018; accepted 25 June 2018;  
published online 5 October 2018)

We succeeded in increasing the radial observation points of the microwave frequency comb Doppler reflectometer system from 8 to 20 (or especially up to 45) using the high sampling rate of 40 GS/s digital signal processing. For a new acquisition system, the estimation scheme of the Doppler shifted frequency is constructed and compared with the conventional technique. Also, the fine radial profile of perpendicular velocity is obtained, and it is found that the perpendicular velocity profile is consistent with the  $E \times B$  drift velocity one. *Published by AIP Publishing.* <https://doi.org/10.1063/1.5035118>

## I. INTRODUCTION

Regarding the study of the behavior of the turbulence affecting transport, the multi-scale interaction of turbulence between macro-, meso-, and micro-scale structures is receiving much attention at present. For this aim, higher spatial and temporal resolution diagnostics have been developed and applied in several devices.<sup>1</sup> Microwave Doppler reflectometry (also called Doppler back-scattering: DBS) has the capability to measure the perpendicular velocity  $v_{\perp}$  of electron density fluctuations, the radial electric field  $E_r$ , and the perpendicular wavenumber spectrum  $S(k_{\perp})$  in magnetized confinement plasmas, using its unique advantage, that is, the combination with the back-scattering method (which provides a wavenumber resolution) and reflectometry (which provides a high-spatial resolution).<sup>2</sup> As a result, a number of systems have been used in worldwide fusion plasma devices, such as tokamaks (Tuman-3M,<sup>3</sup> ASDEX Upgrade,<sup>4,6,7</sup> Tore Supra,<sup>8,9</sup> DIII-D,<sup>10</sup> JT-60U,<sup>11</sup> MAST,<sup>12</sup> and JET<sup>13</sup>) and helical/stellarators (Wendelstein 7-AS,<sup>2,14</sup> TJ-II,<sup>15</sup> and LHD<sup>16,17</sup>).

The principle of Doppler reflectometry is explained simply as follows. When a probing microwave beam is injected into a plasma and approaches a cutoff layer with an oblique angle to the cutoff surface, a backscattering occurs caused by the density fluctuations which matches the Bragg condition, i.e.,  $k = -2k_i$  (where  $k_i$  is the local wave vector of the probing beam). For example in the Large Helical Device (LHD),<sup>18</sup> the range of the fluctuation wavenumber of around  $2\text{--}15\text{ cm}^{-1}$  is

designed to correspond to the ion temperature gradient (ITG) mode and/or the trapped electron mode (TEM) turbulence.<sup>19,20</sup> The detected power of the backscattered radiation is proportional to the density fluctuation amplitude, and the scattered signal frequency is Doppler shifted by the propagation velocity of the density fluctuations. The Doppler shift is given by  $\omega_D = vk \approx v_{\perp}k_{\perp} = k_{\perp}(v_{E \times B} + v_{ph})$ , where  $v_{E \times B}$  is a composition of the plasma background  $E \times B$  drift velocity and  $v_{ph}$  is the intrinsic phase velocity of the density fluctuations. If  $v_{ph}$  is known or  $v_{ph} \ll v_{E \times B}$  (which is usually satisfied at the plasma edge in magnetically confined devices and shown later in the LHD's results), the radial electric field  $E_r$  can be extracted from the measurement of the perpendicular velocity through  $E_r = v_{\perp}B$ , where  $B$  is the absolute local value of the magnetic field.

In LHD, a multi frequency channel Doppler reflectometer system has been developed.<sup>17</sup> The system, which uses a frequency comb generator as a source and is constructed using a filter bank IQ detection for the Doppler shifted frequency calculation, is utilized for measuring not only the spatial structure of the parameters but also the temporal relationship between two (or many) points in space. These measurements are quite helpful for evaluating plasma turbulence, transport, and confinement phenomena. Recently, the fast digital data acquisition system including a high sampling rate oscilloscope is installed for this reflectometer in order to increase the spatial resolution (radial observation points).

In this paper, we describe the improved system and its characteristics in Sec. II. Section III presents some plasma experimental data, which is used to demonstrate successful implementation and to validate the cross-diagnostic comparisons of velocity measurements. Finally, in Sec. IV, we provide the summary.

Note: Paper published as part of the Proceedings of the 22nd Topical Conference on High-Temperature Plasma Diagnostics, San Diego, California, April 2018.

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## II. DIAGNOSTIC DESCRIPTION

### A. Microwave frequency comb Doppler reflectometer system

Figure 1 shows the schematic of the current Ka-band microwave frequency comb Doppler reflectometer system. This microwave system is described in detail in Ref. 17. The frequency comb source, which is a passive, nonlinear transmission line (PSPL model 7112), can generate an array of equally spaced frequencies, which are controlled by the frequency of the stable synthesized signal generator (SG). The frequency range of the output is initially up to 20 GHz. After the amplifier and the frequency doubler, a Ka-band (26–40 GHz) microwave comb is provided. A local oscillator (LO) is used for the heterodyne detection. The power and frequencies of SG and LO can be controlled remotely between the plasma discharges. Two intermediate frequency (IF) components, which are indicated as “Reference” and “Signal” are generated in each Mixer. In order to estimate the Doppler shifted frequency  $f_{\text{Doppler}}$  during the whole plasma discharge time, the filter bank system that comprises eight band pass filters is utilized for the in/quadrature (IQ) phase detection. The output of the IQ detection signal is led to the analog to digital convertors (ADCs) with the sampling rate of 1 and 10 MHz. Especially, a part of *Signal* is fed to an electro-optical converter set (E/O and O/E, whose frequency range is 0.1–12 GHz) and transmitted via a 100 m optical fiber directly to the oscilloscope in the diagnostic room. The specifications of the oscilloscope (Teledyne LeCroy model WaveMaster 820Zi-B) are as follows: The sampling rate is 40 GS/s at 4 channel operation, the bandwidth is 20 GHz,

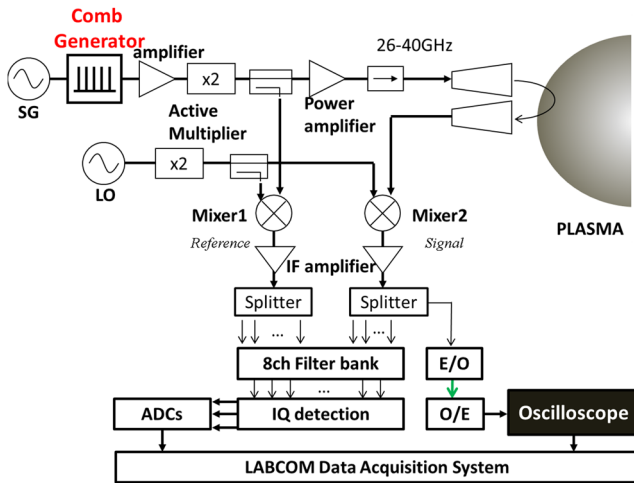


FIG. 1. Schematic of the Ka-band microwave circuit for the Doppler reflectometer comprising a comb generator. A synthesized signal generator (SG) is used as a modulator. A 30 dB amplifier and an active multiplier provide the ka-band probe wave. A local oscillator (LO) is used for heterodyne detection. Two intermediate frequency (IF) components, which are indicated as “Reference” and “Signal,” are generated in each Mixer. Each IF signal is divided in the splitter. The filter bank system comprises eight band pass filters for quadrature signal detection. The output of IQ detection is fed to the 1 MHz/10 MHz data acquisition system. Also, a portion of the splitter output is fed to an electro-optical converter set (E/O and O/E) and transmitted via an optical fiber directly to the diagnostic room for the direct signal acquisition of the wideband oscilloscope. The LABCOM data acquisition system collects all of the acquired signal on the real-time and also controls the acquisition setting via the web site.

and the memory size is 256 M Words/channel. The LABCOM data acquisition system<sup>21–23</sup> collects all of the acquired signals on the real-time and also controls the acquisition setting via their web site.

### B. Characteristics of frequency comb signal through a fast digital data acquisition

The number of frequency combs can be controlled by the base SG frequency  $f_{\text{base}}$ . Figure 2 shows the frequency spectrum of *Signal*. The original designed  $f_{\text{base}}$  is 710 MHz (we call this *normal* mode operation). The number of combs is around 20 in Ka-band. However, the number of band pass filters in filter bank limits the radial observation points to eight. If we acquire the whole *signal* waveform, the observation points can be increased. Furthermore, in smaller  $f_{\text{base}}$ , more detailed radial profiles would be obtained. For example, when  $f_{\text{base}}$  is 310 MHz (*hyper* mode operation), more than 45 comb components are available, as shown in Fig. 2(b).

In order to lower the IF, the LO frequency is set approximately to the center frequency of the Ka-band, and it is necessary to pay attention to overlapping IFs especially when changing the operation mode  $f_{\text{base}}$ . Comparing the characteristics in both modes of operation, the IF frequency and

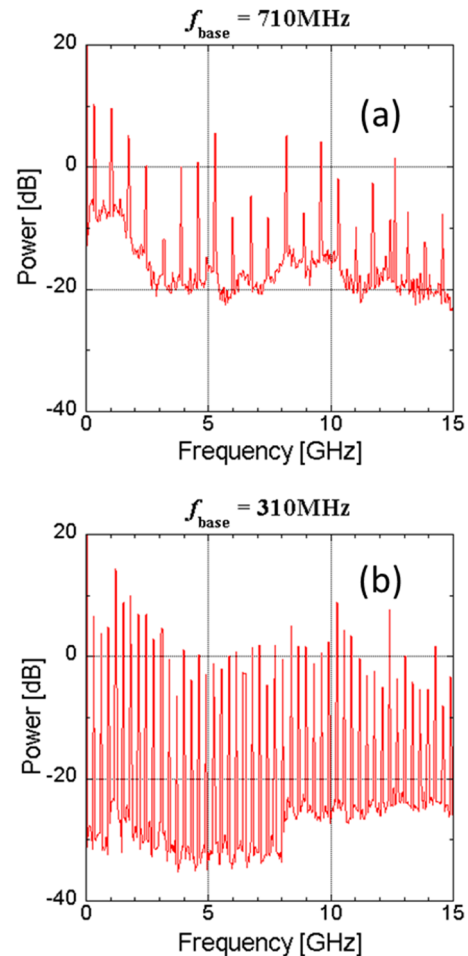


FIG. 2. Examples of frequency spectrum of Mixer 1 output (*Signal*) in two cases of base frequency. Base frequency is (a) 710 MHz and (b) 310 MHz.

the signal power are found to be different even if they have the same probe frequencies. This is because when the LO frequency is changed, the characteristics of the IF amplifier are not flat in the frequency domain. Figure 3 shows the Doppler shifted frequency spectra around the (carrier) probing microwave frequency of 31 GHz in two different operations. In the *normal* mode operation ( $f_{\text{base}} = 710$  MHz), the peak amplitude of the scattered signal is more than 35 dB larger than the noise floor. On the other hand, in the *hyper* mode operation ( $f_{\text{base}} = 310$  MHz), the amplitude decreases, but it is still more than 23 dB larger than the noise floor and the  $f_{\text{Doppler}}$  can be estimated. Therefore, usually we use the *normal* mode because the band pass filters are designed for this mode of operation and are out of range in the *hyper* mode of operation.

In general, the ambiguity at the estimation process of  $f_{\text{Doppler}}$  from the frequency spectra of the scattered wave signal is reduced by the ensemble average. If we use the large number of the ensemble, however, the temporal resolution becomes

worse. The frequency spectrum is calculated by the fast Fourier transform (FFT). The number of data samples for one FFT calculation is 4 194 304 ( $=2^{22}$ ) in this study. In this case, the frequency resolution of  $f_{\text{Doppler}}$  estimation is 4.7 kHz. The ambiguity is evaluated by the standard error  $\sigma$  of the Gaussian fitting process. In the LHD plasma experiment, the scattered frequency spectra of 32 GHz probing microwave component are shown in Fig. 4(a). The component of 890 MHz (black vertical line) is the carrier frequency of the IF signal and has the bandwidth of 0.1 MHz around the center frequency is eliminated in the  $f_{\text{Doppler}}$  estimation process. The increasing ensemble case ( $N = 20$ ) looks much smoother than the case of  $N = 2$ . The standard error  $\sigma$  is plotted as a function of the number of the ensemble, as shown in Fig. 4(b). It is clear that the increasing number ( $N \rightarrow \infty$ ) leads the unambiguity. In addition, 10 kHz ambiguity means almost 0.1 km/s in velocity measurement. Therefore,  $N = 10$  is selected for the  $f_{\text{Doppler}}$  estimation in this direct digital data acquisition system. This selection of  $N = 10$  is sufficient to reduce the ambiguity and has the temporal resolution of 0.1 ms.

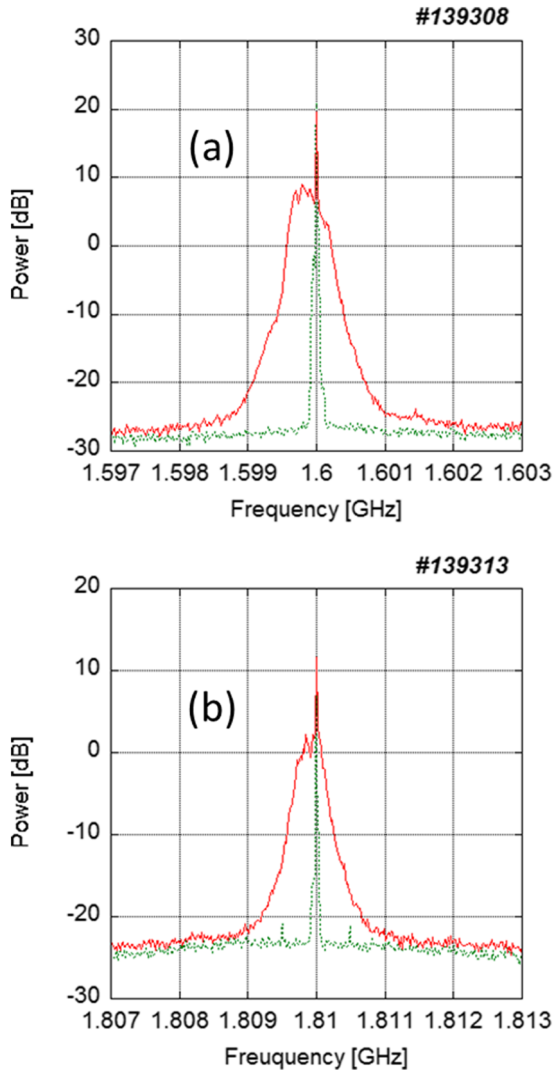


FIG. 3. Examples of Doppler shifted frequency spectra around the (carrier) probing microwave frequency of 31 GHz in two different modulation operations. Each base frequency is (a) 710 MHz and (b) 310 MHz. Here, the green dotted lines show the carrier frequency spectra.

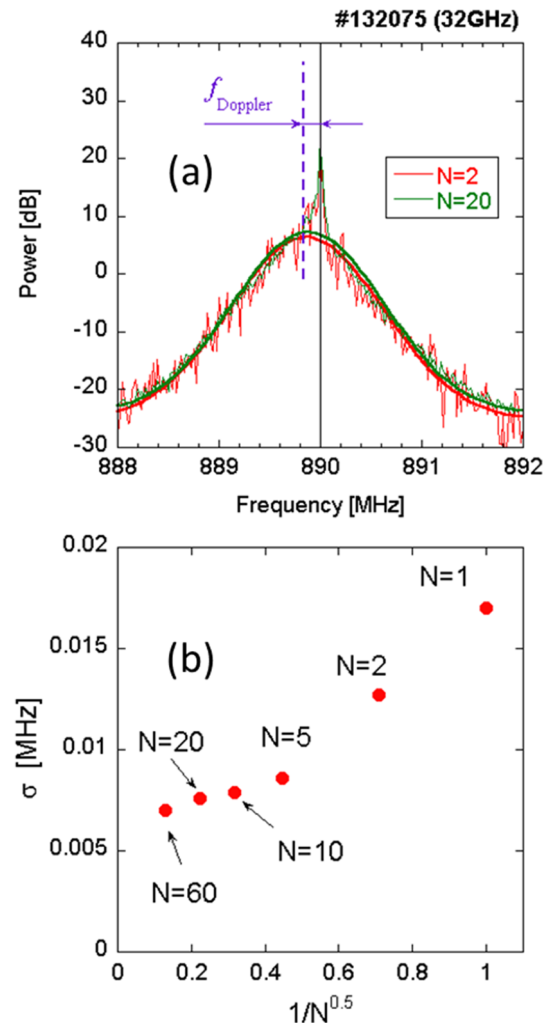


FIG. 4. Estimation accuracy of the Doppler shifted frequency. (a) 2 (red) and 20 (green) sample averaging frequency spectra. Here, each thick solid line shows the Gaussian fitting result. (b) The standard error  $\sigma$  as a function of the number of ensemble  $N$ .



### III. PLASMA MEASUREMENTS

#### A. Comparison with filter bank system

The obtained value of  $f_{\text{Doppler}}$  in the new acquisition system is compared with the estimated value utilized in the conventional filter bank IQ detection system in the LHD plasma discharge. The experiment is carried out under the condition that the magnetic axis position in the vacuum field is  $R_{\text{ax}} = 3.60$  m, the magnetic field strength is  $B_t = 1.375$  T, the helical coil pitch parameter  $\gamma = 1.2538$ , and the ratio of the quadrature field  $B_q = 100\%$ . The Doppler shifted frequencies  $f_{\text{Doppler}}$  of 33 GHz are obtained, as shown in Fig. 5(c). During the continuous neutral beam injection (NBI) heating, the electron density increases and, after around  $t = 3.4$  s, the cutoff surface appears in the plasma. The IQ detection system can give us the estimated  $f_{\text{Doppler}}$  value during the whole plasma discharge every  $10 \mu\text{s}$ . On the other hand, because of the limitation of the memory size of the oscilloscope, we apply two types of operation for the data acquisition. One is the batch operation. In this operation, we use whole memory continuously in 6.4 ms and the temporal resolution of the estimated  $f_{\text{Doppler}}$  is  $100 \mu\text{s}$ . Another case is the burst-like sequence operation. In this operation, total memory is divided into 60 segments during the whole plasma discharge and the data are acquired every 30 ms. The latter operation is used for this comparison. As shown in Fig. 5(c), both estimated

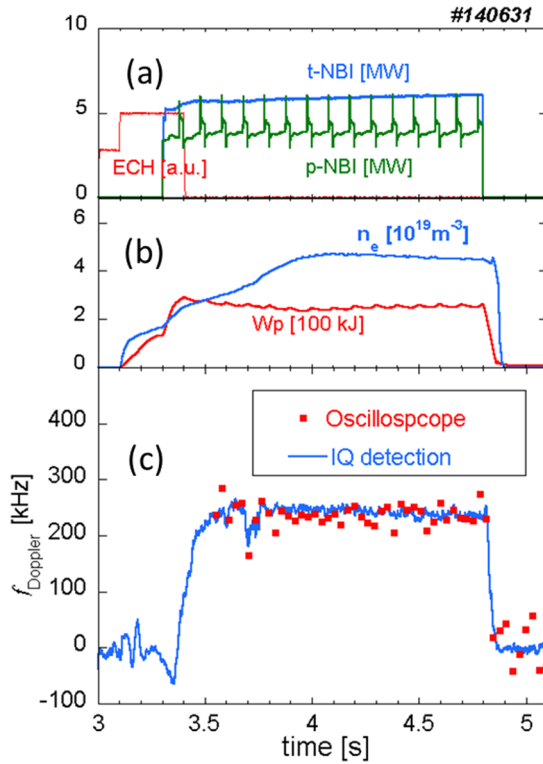


FIG. 5. Temporal behavior of (a) the electron cyclotron heating (ECH), tangential neutral NBI (t-NBI), and perpendicular NBI (p-NBI), (b) the line-averaged electron density  $n_e$  and the stored energy  $W_p$ , and (c) the Doppler shifted frequency of 33 GHz. Here, the blue solid line shows the extraction from the IQ signal using the filter bank system. Red dots show the extraction from the fast oscilloscope acquisition system (trigger time is  $t = 3.5$  s). After  $t > 4.8$  s, the data scattering of the oscilloscope extracted  $f_{\text{Doppler}}$  is caused by the termination of the plasma.

$f_{\text{Doppler}}$  values are in quite good agreement in the stationary plasma.

Another example of dynamic experiment is shown in Fig. 6. In this discharge, the power of perpendicular NBI (p-NBI) is modulated. It is found that the stored energy  $W_p$  and the estimated  $f_{\text{Doppler}}$  also oscillate with NBI modulation period, as shown in Figs. 6(b) and 6(c). Just after the p-NBI injects, the stored energy increases and the estimated  $f_{\text{Doppler}}$  decreases. In addition, it is known that the flow velocity varies with the modulated tangential NBI.<sup>10,17</sup> In this time, it is found that the p-NBI can also affect the flow velocity. The estimated  $f_{\text{Doppler}}$  values are sometimes slightly different in this observation. One of the reasons of this discrepancy might be caused by the sequential data acquisition, and the acquired timing may sometimes match the switching time of NBI modulation.

#### B. Radial profile of $V_{\perp}$

The Doppler reflectometer is expected to measure the radial profile of perpendicular velocity  $v_{\perp}$ . For this aim, the radial observation position and the wavenumber  $k_{\perp}$  is calculated by the ray tracing code LHDGAUSS<sup>24,25</sup> which uses the radial profile of electron density and temperature measured by the Thomson scattering method.<sup>26</sup> Figure 7 shows the radial profile of  $v_{\perp}$  in the *hyper* mode operation as the comb output and batch operation as the data acquisition. Here,  $r_{\text{eff}}$  is the effective minor radius and  $a_{99}$  is the effective minor radius of

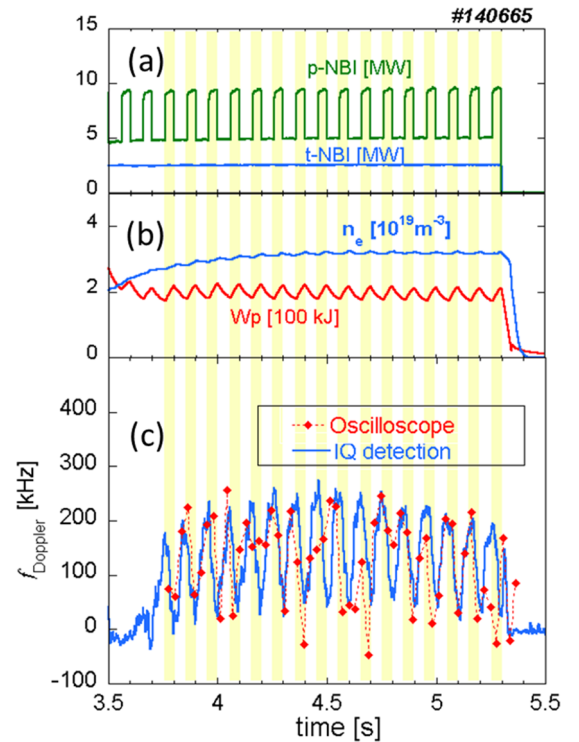


FIG. 6. Temporal behavior of (a) continuous tangential t-NBI and modulated perpendicular p-NBI, (b) the line-averaged electron density and the stored energy  $W_p$ , and (c) the Doppler shifted frequency of 33 GHz. The blue solid line shows the extraction from the IQ signal using the filter bank system. Red dots show the extraction from the fast oscilloscope direct acquired system (trigger time is  $t = 3.75$  s).

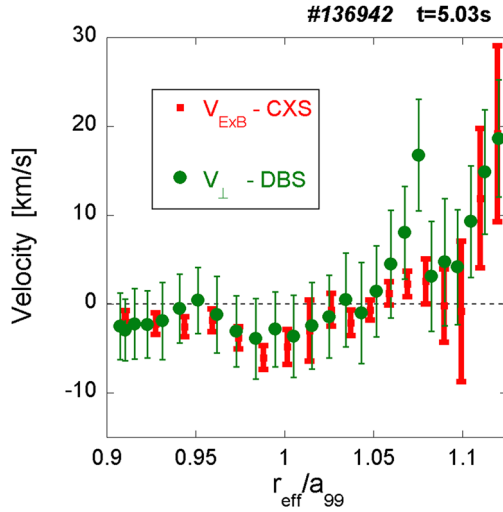


FIG. 7. Radial profiles of perpendicular velocity obtained by the Doppler reflectometer (green circles) and the  $E_r \times B$  velocity obtained by CXS (red squares).

which encloses 99% of the total electron pressure.<sup>27</sup> These results are obtained under the experimental condition that  $R_{ax} = 3.60$  m,  $B_t = 2.75$  T,  $\gamma = 1.2538$ , and  $B_q = 100\%$ . By heating with the electron cyclotron heating (ECH) and NBI, the central electron density, electron temperature, and ion temperature are  $2.5 \times 10^{19} \text{ m}^{-3}$ , 3 keV, and 1.5 keV, respectively. The error bars of DBS data are estimated by the deviation in the 60 time slices between 6.4 ms. The calculated  $E \times B$  drift velocity  $v_{ExB}$ , which is obtained by the charge exchange spectroscopy (CXS),<sup>28,29</sup> and plasma pressure profile data, is also plotted. It is found that they are nearly in agreement, that is,  $v_{\perp} (= v_{ExB} + v_{ph}) \sim v_{ExB}$ . This result means that  $v_{ph}$  is not effectively large rather than  $v_{ExB}$  in the LHD plasma edge region at least at this time. In addition, it can be seen that only a few data points at  $r_{eff}/a_{99} \sim 1.07$  are different. This location is close to the rational surface of  $\iota/2\pi = 2$  in vacuum condition, and it might be some effect of the magnetic island<sup>30,31</sup> because both diagnostics are separated in toroidally as shown in Fig. 8 and

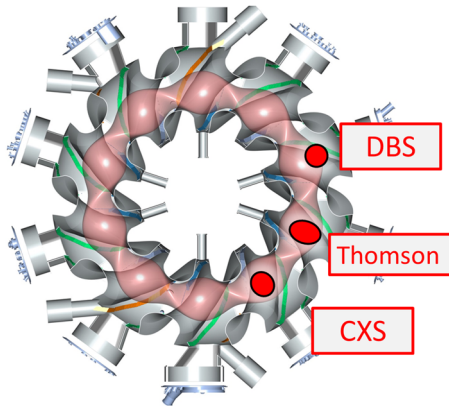


FIG. 8. Schematic drawing of toroidal locations of the Doppler reflectometer DBS, the Thomson scattering, and the charge exchange spectroscopy CXS.

the phase of the magnetic island follows the toroidal location. The future research with MSE measurement is necessary for this understanding. Therefore, the fine  $v_{\perp}$  profile observed by the direct signal acquisition is utilized.

#### IV. SUMMARY

The fast data acquisition system consisting of the wide-band oscilloscope is applied to the microwave frequency comb Doppler reflectometer in LHD. The  $f_{Doppler}$  estimation scheme for this system is constructed, and the temporal behavior of  $f_{Doppler}$  is confirmed to be in agreement with the  $f_{Doppler}$  value obtained by the conventional IQ detection system. Also, the fine radial profile of  $v_{\perp}$  is obtained and its result is verified with other diagnostics.

#### ACKNOWLEDGMENTS

The authors would like to thank the technical staff of LHD for their support of these experiments. The authors also would like to thank Mrs. Y. Tsuji and T. Uto of Teledyne LeCroy Japan Corporation for their support of the fast digital data acquisition system. The present study was supported in part by KAKENHI (Nos. 17K18773, 17H01368, 15H02335, and 15H02336), by a budgetary Grant-in-Aid from the NIFS LHD project under the auspices of the NIFS Collaboration Research Program, and by the Collaborative Research Program of Research Institute for Applied Mechanics, Kyushu University. Additional support was provided by Japan/U.S. Cooperation in Fusion Research and Development.

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