Development of ultra-fast charge exchange recombination spectroscopy for temperature and flow velocity fluctuation measurements in Heliotron J

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1. Introduction

For magnetically confined fusion plasmas, many diagnostic techniques to measure fluctuations in density/temperature/flow have been demonstrated to understand fast time-scale phenomena and heat/particle/momentum transports due to turbulent fluctuations. For many years, several types of diagnostics with high time-resolution have been developed for the measurement of the ion temperature and the flow velocity by using technique of charge exchange recombination spectroscopy (CXRS). A combination of Fabry–Pérot interferometer and photodiode array has been used in JIPP TII-U to obtain the ion temperature and flow velocity measurements with the sampling speed of 8 kHz [1]. In JT-60U, a polychromator system equipped with photomultiplier tube was used to measure the rapid change in the ion temperature and the flow velocity at the sampling speed of 1.3 kHz [2]. This system was also used for real-time control of the ion temperature or temperature gradient [3]. In DIII-D, a combination system of volume-phase-holographic transmission grating and avalanche photodiode detectors enables to record the CXR emission at 1 MHz sampling [4].

From the view of the study on intrinsic toroidal rotation, the residual Reynolds stress in parallel direction to the magnetic field line has been proposed as the source of the intrinsic flow [5]. In order to obtain the parallel Reynolds stress experimentally, it is required to measure the parallel and radial flow-velocity fluctuations. Recently, we have started to develop a fast sampling CXRS system aiming at measuring the residual parallel Reynolds stress in Heliotron J [6]. This paper describes the current status of the development in the new CXRS system. In Section 2, the component of the fast CXRS system is explained in detail. Section 3 reports the calibration experiments to investigate the feasibility of fluctuated spectrum measurement. The fluctuated CXR spectrum is simulated experimentally using two sets of monochromator and LED lamp. The dispersion of the monochromator and the measurement of the flow velocity fluctuation are tested using the calibration system.

2. Ultra-fast CXRS system

The CXRS diagnoses the spectrum of an impurity line by the charge-exchange recombination reaction between the fully ionized impurities and the neutral beam particles. In this study, the ultra-fast CXRS system is designed to measure the fluctuations of the carbon (CVI, 529.05 nm) or He impurity (HeII, 468.57nm) lines. The target of the frequency range for the ion temperature (T_i) and the parallel flow velocity ($v_{\parallel}$) is several kHz to 100 kHz with the resolution of $\delta T_i/\langle T_i \rangle \sim 1$ % and $\delta v_{\parallel} \sim 1$ km/s. Figure 1 shows the schematic view of the ultra-fast CXRS, which consists of a fiber bundle, a high dispersion and high throughput photographic-lens monochromator with Echelle grating, one set of imaging lens and a fast framing camera with an array of avalanche photodiodes (APD). The photographic lens monochromator, being based on the poloidal CXRS system developed in Heliotron J [7], has the focal length of 200 mm, the effective F number of 2.9 and the dispersion of 0.173 nm/mm for the HeII line (468.5 nm) at the exit slit. The spectrum image is expanded by 2.7 times using the imaging optics. The fast framing camera (APDCAM, Fusion Instrum.) has a 4×8 APD array element, which is commonly used for the 2D fluctuation imaging diagnostics such as beam emission spectroscopy. Each APD element has a quantum efficiency more than 80 % at the wavelength range of 500-800 nm. The cut-off frequency of the pre-amplifier in the camera is set to be 220 kHz. The ADC in the camera has sampling frequency up to 1 MHz, which is controlled by a Python based software [6].

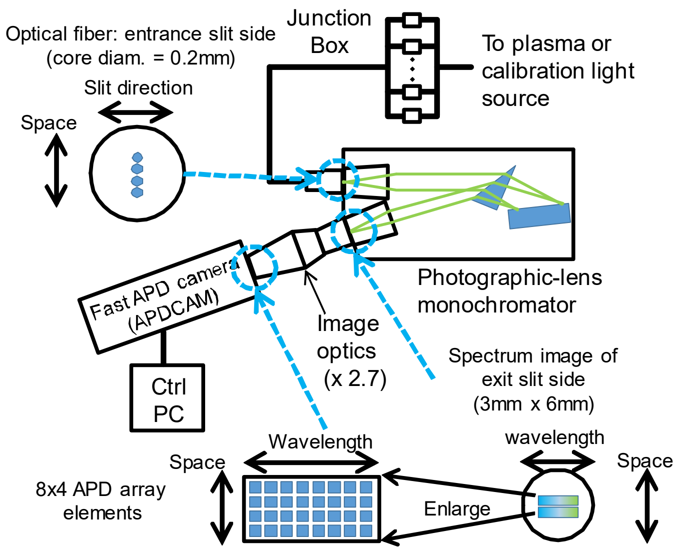

Fig. 1. Schematic view of ultra-fast CXRS system.

3. Calibration experiments

To discuss the feasibility of the fluctuated spectrum measurement, it is required to calibrate the CXRS system using simulation experiments of the CXR spectrum with a modulation of Doppler-shift or Doppler-broadening. To simulate the fluctuated spectrum, two sets of monochromator (P250, Nikon) are set to make a calibration light. As shown in Fig. 2, one of the monochromator is used for a stationary spectrum component with a center wavelength of around 468.5 nm. The other simulates a fluctuated spectrum component using a LED lamp with the operation frequency of 10 Hz-10 kHz. Here, the central wavelength of the fluctuated component is slightly shifted to the stationary one, then the merged spectrum modulates its central gravity and the dispersion at the frequency. Moreover, although the difference of the central wavelength between the two spectra is fixed, the amount of the fluctuation component of the central gravity and the dispersion can be varied by changing the amplitude of $\delta I_{\rm fluc}$. Then, this technique enables us to simulate the oscillations of Doppler-shift and Doppler-broadening. The spectrum from the fast framing APD camera is compared with that from a CCD camera (DV897, Andor, 512×512 pixels). Figure 3 shows the comparison of the spectrum profile of the stationary component between the fast framing APD and the CCD cameras. The dispersion at the sensor of the fast framing camera is calculated to be 0.064 nm/mm, which is consistent with the result obtained by the CCD measurement.

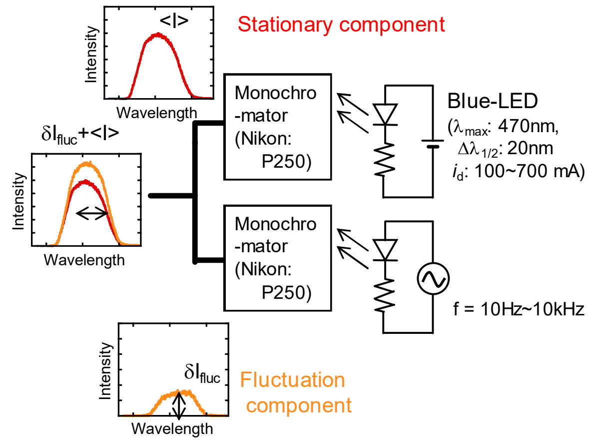

Fig. 2. Schematic view of the experimental setup of calibration light source. Two sets of monochromator are used to simulate fluctuated CXR spectrum experimentally.

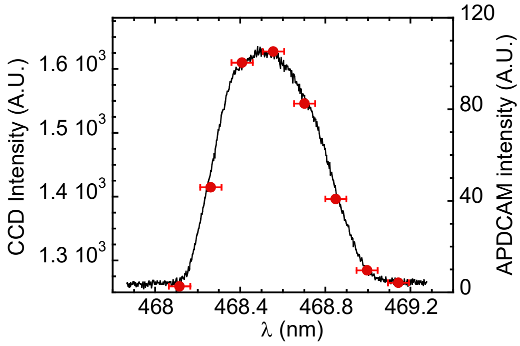

Fig. 3. Comparison of the spectrum profile measured by fast framing camera and CCD camera.

In the case that the fluctuation intensity of the CXR spectrum is weak, it is concerned that the accuracy in estimating the temperature/flow velocity fluctuations becomes worse when the Gaussian fitting is applied to the spectrum profile. In this case, a calculation scheme using frequency domain analysis has a benefit to reduce the fitting error, because the information of fluctuation component appears on the phase difference and the amplitude among each APD signal. In this study, FFT analysis is adopted to obtain the phase difference and the amplitude. After that, the spectrum is reconstructed at each frequency. The calculation of the fluctuation of the flow velocity is tested, which is compared to the CCD measurement. Figure 4 shows the change in

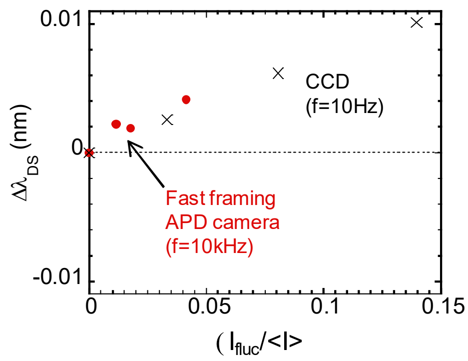

Fig. 4. Fluctuation component of Doppler-shift as a function of fluctuation intensity. Since the CCD framing rate was 400Hz, the LED modulated at f = 10Hz for the CCD measurement and that is 10 kHz for the measurement with the fast framing APD camera.

the Doppler-shift ($\Delta\lambda_{DS}$) at the frequency of interest as a function of the fluctuation intensity at the peak value (δI_{fluc}). The change in the Doppler-shift measured by the fast framing APD camera is consistent with that measured by CCD. Even in the case that the fluctuation amplitude of 1 %, a small amplitude of the Doppler-shift change (0.002 nm) is detectable, which corresponds to the fluctuation of the He impurity flow velocity around 1 km/s.

4. Discussions and Summary

From the calibration experiment, the required CXR intensity to obtain the fluctuation components of the ion temperature and flow velocity is estimated to be several-tens to 100 times higher than that measured by the conventional CXRS in Heliotron J. The enlargement of the optical fiber core (0.2mm to 0.6mm) is planning in conjunction with the improvement in the reflectance of the mirror inside the vacuum vessel by applying dielectric coating. Additional gas puffing by He or Methane will improve the signal-to-noise ratio.

In summary, we are developing the ultra-fast CXRS system for the temperature and flow velocity fluctuation measurements. To calibrate the system, the experimental simulation of the fluctuated CXR spectrum was carried out. The dispersion at the sensor surface of the fast framing APD camera is consistent with the estimation from the CCD camera images. The calibration experiments show that this system has an ability to measure the Doppler-shift fluctuation about 1 km/s.

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