High-speed imaging spectroscopy for pellet plasmoid observation in LHD

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Abstract

To investigate the physics of pellet plasmoid dynamics, internal distribution measurements in pellet plasmoid by high-speed imaging spectroscopy have been demonstrated successfully in the Large Helical Device (LHD). In this spectroscopic system, a five-branch fiberscope is used. Each objective lens has a different narrow-band optical filter for the hydrogen Balmer lines and background continuum radiation. The electron density and temperature in a plasmoid can be obtained from the intensity ratio measured with these filters. The electron density distribution in the range of $10^{22} - 10^{24}$ m^{-3} and the temperature distribution in around 1 eV are observed, indicating that weakly-ionized plasmoid is spectroscopically measured. The electron density distribution of 0.1 m in size expands across the magnetic field line. The time dependence of electron density distribution is investigated. The different electron density distribution is confirmed at each time slice.

1. Introduction

Solid hydrogen pellet injection is a primary technique for efficient core plasma fuelling in magnetic fusion devices. The pellet ablation and subsequent behavior of the dense plasmoid which is the pellet ablatant ionized by heat flux of the background plasma are key elements to determine the characteristics of pellet refuelling, and especially the behavior of the plasmoid has an important role as a density redistribution effect by grad B drift. To understand these behaviors, well diagnosed experiments which enable the quantification of internal distribution in the plasmoid are required. In LHD, the density distribution of the plasmoid was obtained by imaging measurements using a bifurcated fiberscope[1]. Here, it was assumed that the temperature of the plasmoid is in the limited narrow range. However, it is essential for the deeper understanding of ionized state of the plasmoid to identify the electron temperature of the plasmoid. The objective of this study is to evaluate the two-dimensional electron density and temperature distribution in the plasmoid quantitatively by imaging measurements with high-speed spectroscopic diagnostics.

2. Experimental setup

The spectra of hydrogen Balmer-lines and background continuum radiation are determined by the electron density and temperature of the plasmoid. Here, the emission from the background plasma can be ignored, because the density of the plasmoid is several hundred times greater than that of the background plasma. In this study, it should be noted that the spectra are estimated from the fitting with the theoretical data. In the theoretical data, the intensity of the spectra is calculated on the assumption of local thermodynamic equilibrium. The broadening profile of the spectra is calculated using Ref. [2]. We concentrate on the Balmer-β line (wavelength: 486.1 nm) and continuum (wavelength: 576.8 nm) to evaluate the density and temperature of the plasmoid, because the influence of the self-absorption effect on the Balmer-β line profile is negligible while the Balmer-α line profile is affected by it and the Balmer-γ line intensity is relatively small. However, the Balmer-α line is measured as a reference and the plasma thickness can be probably obtained by evaluation of the effect of self-absorption in Balmer-α line. The filter parameters suitable for various presumed densities and temperatures in a plasmoid are selected on the basis of the spectra estimated from the theoretical data: (i) filter for Balmer-β line with full width at half maximum (FWHM) of 5 nm, (ii) filter for Balmer-β line with FWHM of 20 nm and (iii) filter for continuum radiation with FWHM of 50 nm.

Figure 1 shows the contour plot of intensity ratio as a function of electron temperature and density. Figure 1(a) is the ratio of the intensities obtained with two filters having different FWHM for the Balmer-β line and (b) is the ratio of continuum to Balmer-β line. In Fig. 1(a), intensity ratio depends strongly on electron density in the range between 0.8-1.3 eV of electron temperature. Whereas, in Fig. 1(b), the intensity ratio has a different dependence on both electron density and temperature. If these intensity ratios are proven experimentally, we can determine the parameters which give the best consisting with theoretical data.

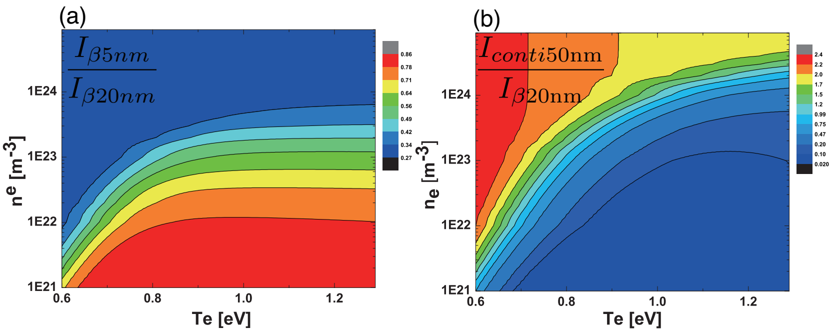

Figure 1: Contour plot of (a) intensity ratio obtained with two filters having different FWHM for the Balmer-β line and (b) the ratio of continuum to Balmer-β line. Presumed density is in the range between $10^{21} - 10^{24}\mathrm{m}^{-3}$ and temperature is in the range between 0.6-1.3 eV in a plasmoid.

In this spectroscopic system, a five-branch fiberscope is used as shown in Fig. 2. The scope is composed of 15,000×5 quartz fiber elements packed in a flexible protective tube made of stainless-steel. The total length is 15 m. Each objective lens, which has a field of view of 15 degrees, has a different narrow-band optical filter for the Balmer lines and continuum radiation. The five images are focused onto a single fast camera so that the simultaneity is ensured. The fast camera is equipped with a 12-bit SR-CMOS sensor. The selected frame rate and exposure time with a resolution of 35,000 pixels (One pixel corresponds to about 7 mm, which is enough to reveal the density distribution in the plasmoid of several dozen cm in size) are 20,000 fps and 2 μs, respectively. Here, wavelength dependence of filters are negligible in this study because the field of view in the observed area of plasmoid is about 4 degrees which lead to blue shift of about 1.2 nm at 486.1 nm. The pellet moves 2 mm during the exposure time. However, the movement is within 1 pixel, which does not affect the measurement. The plasmoid can be observed close behind the pellet injection port. The pellet is injected into the NBI plasma. The nominal pellet size is 3.4 mm $\phi \times$ 3.4 mm ℓ. The typical pellet speed is 1000 m/s. Doppler shift can be neglected because the shift is only 10^{-3} nm at 486.1 nm.

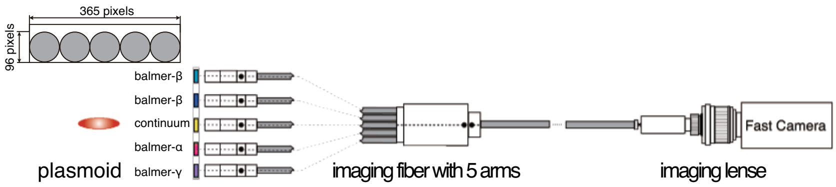

Figure 2: Schematic drawing of a five-branch fiberscope.

3. Results

The large-scale electron density and temperature in the plasmoid have been already measured by the global spectroscopy in LHD[3]. The electron density of the order of 10^{23} m^{-3} and the electron temperature of around 1 eV are determined. When the electron temperature is about 1 eV, theoretical calculation predicts that the continuum radiation is dominated by the radiative recombination and the radiative electron attachment, the latter of which yields negative ions. Due to the effect of radiative electron attachment, the spatial extent of ions may play an important role in the continuum emission.

Figure 3 shows typical images of the plasmoid through each filter. Not only Balmer-β emission but also the continuum radiation expand in a direction parallel to the magnetic field line, suggesting that the electron temperature of the plasmoid exists in the range of about 1 eV in which radiative electron attachment is dominant. The electron density and temperature distributions are obtained by comparing the intensities measured with the filters as shown in Sec.2.

We confirmed that the density distribution is in the range between 10^{22} and 10^{24} m^{-3} and the temperature distribution is about 1 eV, indicating that weakly-ionized plasmoid can be spectroscopically measured(See Fig. 3(d),(e)). These results are in agreement with the global spectroscopic measurement. The time dependence of electron density distribution is investigated. As shown in Fig. 4, the different electron density distribution is confirmed at each time slice. Roughly speaking, the electron density is gradually decreased. The density distribution of 0.1 m in size expands to one direction at a certain angle. The angle gradually changes as the pellet penetration deepens, suggesting that the plasmoid location is estimated from these angles. Thereby, we identified the plasmoid location at each time slice and confirmed that the pellet moves at the constant speed of about 990 m/s. The relationship between electron density distribution and plasmoid location will be studied as a future work.

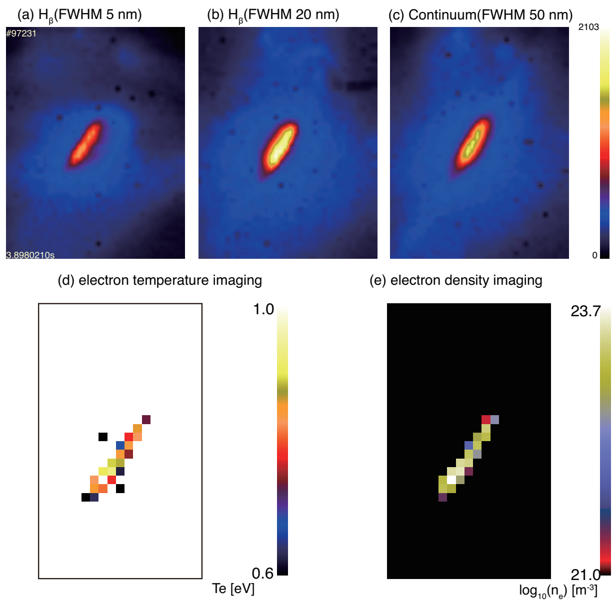

Figure 3: Typical images of the plasmoid with the filters of (a) H_β of FWHM 5 nm, (b) H_β of FWHM 20 nm and (c) Continuum of FWHM 50 nm. (d)Electron temperature imaging and (e)density imaging are also shown.

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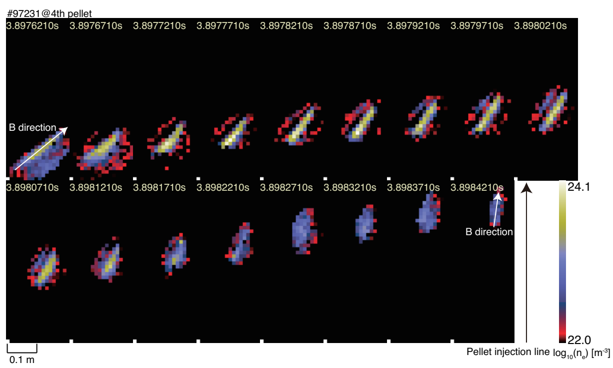

Figure 4: Time dependence of electron density distribution.

References

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