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Spectroscopic Measurement to Study Two-Fluid Relaxation in an Internal Coil Device Mini-RT

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Abstract

Mahajan-Yoshida has developed a new relaxation theory, by taking two-fluid effect into account. This theory indicates that the plasma flow confines high beta plasma. We have constructed an internal coil device Mini-RT with high temperature superconductor (HTS) coil, and are expecting the high beta plasma with the fast toroidal plasma flow by inducing the radial electric field. In order to measure the radial profile of the plasma flow we introduced a spectroscopy. By setting up two cylindrical lenses between a monochromator and a charge-coupled device (CCD) detector, we could not only correct astigmatism of the monochromator but also increase the resolution of wavelength up to 2.55 pm/pixel which is equal to the measurement of the plasma flow up to 1.6×10^3 m/s. Additionally we are setting up an opposed fiber array for an accurate measurement. In the Mini-RT device the plasma was produced by 2.45 GHz ECH (Electron Cyclotron Heating) system with the power of 2.6 kW. Typical electron density and temperature are more than 10^{16} m^{-3} and 10–20 eV, respectively. The ion temperature measured by this spectroscopy system was 1.0 ± 0.3 eV and the plasma flow velocity was comparable to the resolution of this spectroscopic system. Although the plasma should flow to the toroidal direction by the ∇B/curvature drift in the internal coil device, the drift velocity of 1.3×10^3 m/s is not detectable with this spectroscopy. If the radial electric field of 160 V/m or more is induced in the plasma, the plasma flow due to the $\boldsymbol{E} \times \boldsymbol{B}$ drift could be measured with this system.

Keywords:

two-fluid relaxation theory, Mini-RT, spectroscopy, plasma flow, ion temperature

1. Introduction

Spectroscopy is generally used in plasma experiments as noncontact diagnostic instrument to measure plasma flow velocity and ion temperature and so on. This measurement is so important because plasma flow is playing an important role in plasma confinement properties. For example it is widely accepted in tokamak transport that the H-mode is strongly related to a shear of the electric field profile at the edge.

A two-fluid relaxation theory developed by Mahajan and Yoshida indicates that the fast plasma flow in the range of Alfvén velocity confines high beta plasma [1]. The Mini-RT device which has poloidal magnetic field is suitable to drive fast plasma flow in the toroidal direction, when the radial electric field is induced in the plasma. The electric field will be produced by inserting an electrode in the plasma directly or non-neutralizing with orbit loss of high-energy electron [2].

We introduced the spectroscopy to measure radial profile of the plasma flow velocity and ion temperature simultaneously. Since the spectroscopic measurement does not cool down the plasma, we consider that non-neutralizing by orbit loss of high-energy electron is easy to occur.

2. Spectroscopic measurement in the Mini-RT device

The spectroscopy in the Mini-RT device is set up for measurements of various plasma parameters as plasma flow velocity, ion temperature, electron density and electron temperature and so on. The schematic drawing of the spectroscopy in the Mini-RT device is shown in Fig. 1. The light from the plasma is collected to an optical fiber array seeing tangentially. In present experiments only one side optical fiber array is set up. Therefore an absolute wavelength is identified by standard source such as Ne lamp. The fiber array transmits light to an 1 m Czerny-Turner spectrometer. The basic parameters of the monochromator and the CCD detector are shown in Table 1.

In order to correct astigmatism, we set two cylindrical lenses between the monochromator and the CCD detector. The schematic figure of this cylindrical lens system is shown in Fig. 2. The difference of focal point between in the vertical (spatial) direction and in the horizontal (spectral) direction is 7 mm due to the astigmatism of spherical mirrors in the

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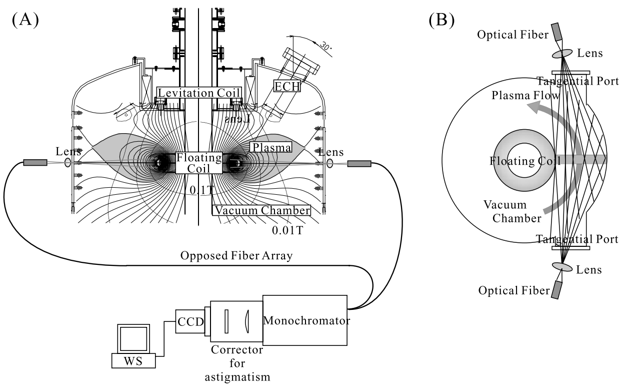

Fig. 1 (A) The schematic drawing of the spectroscopy. (B) Top view of the Mini-RT with optics collecting the light distributed radially.

Table 1 The list for basic parameters of the monochromator and the CCD detector.

Monochromator	
Focal length	1 m
Grating	1800 grooves/mm
Instrumental width (at 50 μm slit width)	0.0397 nm
astigmatism	7 mm
CCD detector	
Wave length	250 nm ~ 950 nm
The number of pixel	256 (vertical) × 1024 (horizontal) pixel
Pixel size	26 μm
Dark current	2.8 e/pixel/hr at –80°C

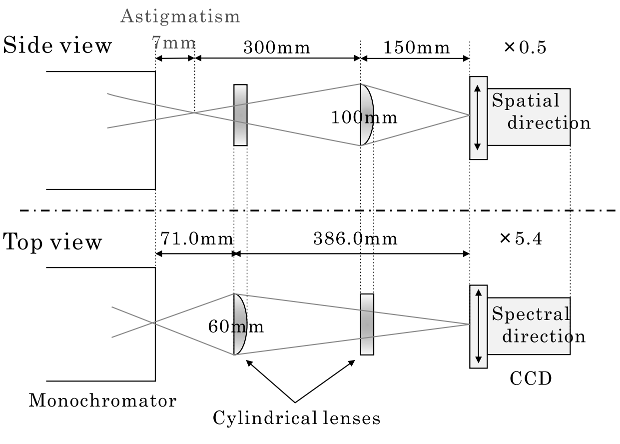

Fig. 2 The cylindrical lens system compensating for astigmatism and expanding spectrum.

monochromator. The two cylindrical lenses focusing light on different point in the each direction correct this astigmatism. With length between image and lens a and b, focal length of lens f, magnification of image m, and a corrected thin lens equation $1/a + 1/b = 1/f$, vertical and horizontal optics can be

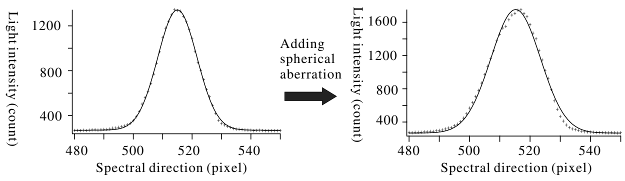

Fig. 3 Broadened spectrum due to the spherical aberration of the monochromator, measured line profile (dot) and multi-gaussian fitting curve (line).

determined as (a, b, f, $a + b$, m) = (300 mm, 150 mm, 100 mm, 450 mm, 0.5) and (71 mm, 386 mm, 60 mm, 457 mm, 5.4), respectively. The astigmatism is corrected by this 7 mm difference of $a + b$ in this calculation. At the same time, we get high resolution in the spectral direction by magnification of image m. Therefore we can measure the plasma flow velocity up to 1.6×10^3 m/s. Furthermore we obtain several magnifications of image by changing focal length of the lens. So when we measure the slow plasma flow, we use large magnification of this lens system and in the case of the fast flow we use low magnification of the lens.

Image from the monochromator is distorted by spherical mirrors in the monochromator. This distortion is called spherical aberration. Broadened spectrum caused by influence of spherical aberration is shown in Fig. 3, where a background of this spectrum is a lead noise of the CCD detector. In this experiment we put the light intensity ahead of the effect of spherical aberration. Because we integrated the data in the spatial direction on the CCD detector for strong light intensity, measured spectrum included the aberration. The effect of the aberration in full width at half maximum (FWHM) is 0.029 nm corresponding to temperature 2.6 eV, and the instrumental width is 0.0397 nm (slit width: 50 μm) corresponding to temperature 4.9 eV.

3. Experimetal results

The Mini-RT device consists of the vacuum chamber (diameter: 1.0 m, height: 0.7 m), the HTS floating coil (major/minor radius: 150 mm /28 mm, total coil current: 50 kAT, total weight: 20 kg), a levitation coil, cooling and exciting instruments. The floating coil produces the dipole magnetic field and the typical field strength is 0.1 T near the floating coil. In the Mini-RT device the plasma is produced by 2.45 GHz ECH and operated for over ten seconds normally. In this experiment the floating coil is supported by posts, not levitating. The plasma parameters of Mini-RT are that electron density and temperature are more than 10^{16} m^{-3} and 10–20 eV, respectively.

The measured line profile at He II around 468.57 nm and fitting curve is shown in Fig. 4. We obtained fitting curve by using multi-gaussian fitting (We used 4 lines 468.538 nm, 468.541 nm, 468.570 nm, 468.580 nm out of 13 lines of He: n = 3–4) [3]. Ion temperature is estimated to be 1.0 ± 0.3 eV, where we deducted the effect of aberration and instrument width from measurement value. Plasma flow velocity

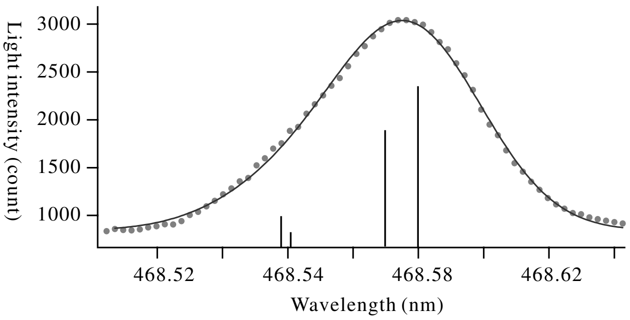

Fig. 4 Multi-gaussian fitting curve (line) and measured line profile (dot).

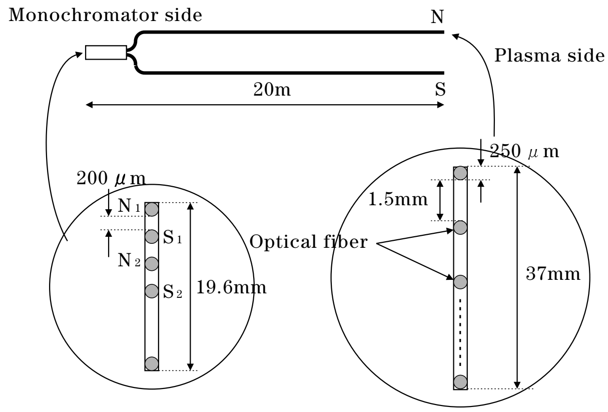

Fig. 5 The schematic of the opposed fiber array.

calculated from Doppler shift has margin of error which is comparable to measurement value. So we obtained that plasma flow velocity is less than 1.6×10^3 m/s.

∇B drift and curvature drift are considered as toroidal plasma flow in the Mini-RT device with the dipole magnetic field. ∇B drift and curvature drift are expressed as follows:

$$\boldsymbol{v}_{\nabla B} + \boldsymbol{v}_R = \frac{m}{q}\frac{\boldsymbol{R}\times\boldsymbol{B}}{R^2B^2}\left(\frac{1}{2}v_\perp^2 + v_{||}^2\right), \qquad (1)$$

where $v_{\nabla B}$ and v_R are ∇B drift and curvature drift velocity respectively, R is curvature radius of poloidal magnetic field, m and q are ion mass and quantum of electricity, $\perp$ and $||$ indicate perpendicular and parallel to poloidal magnetic field, respectively. We obtain that this drift velocity is up to 1.3×10^3 m/s with magnetic field 0.003 T and ion temperature 1.0 eV in the Mini-RT device. Because of these drift speeds, it is reasonable that Doppler shift is comparable to the maximum spectral resolution of this spectroscopy system.

We consider the $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity expressed $\boldsymbol{v}_{E\times B} = \boldsymbol{E}/\boldsymbol{B}$ from radial electric field and magnetic field. The radial profile of the plasma potential from probe measurements is that the potential is flat at about 60 V from the coil to the chamber wall. It is due to the support interrupting to produce the high-energy electron. Therefore we regarded that the radial electric field is too small to generate measurable $\boldsymbol{E} \times \boldsymbol{B}$ drift.

4. Discussion and summary

We are installing the opposed optical fiber array shown in Fig. 5.

By using this fiber array we can eliminate the error of spectral identification of standard source and improve the resolution of the spectroscopy system. The space between the optical fibers on the plasma side is designed for measuring the radial distribution of plasma parameters all at once. Also the space on the monochromator side is made for decreasing a cross-talk between optical fibers. The optical fibers of different view side are alternately arranged on the monochromator side for correcting the spherical aberration. By changing the focal length of lens we can measure the plasma flow velocity up to 6.0×10^2 m/s. So we will be able to obtain ∇B and curvature drift velocity.

We have to apply an electric field to plasma more than 160 V/m to measure $\boldsymbol{E} \times \boldsymbol{B}$ drift. Additionally in order to drive plasma up to Alfvén velocity, we need to charge up plasma to 260 kV which is equivalent to electric field 860 kV/m, where the electron density is 4.2×10^{16} m^{-3} and poloidal magnetic field is 0.09 T. When we measure the plasma flow velocity up to Alfvén velocity, Doppler shift is too large to detect to the contrary. Hence, we have to change the magnification of image in the cylindrical lens system to 0.3 times for exposing the shifted spectrum on the acceptance surface of the CCD detector.

Since the line-integrated emission is measured in the spectroscopy except for active diagnostics such as charge-exchange spectroscopy, some techniques might be required. Especially, we cannot apply the Abel inversion on the flow velocity measurements, because the velocity component of the line-of-sight in the toroidal flow velocity is measured. We need to use a parameter-fitting technique due to necessity for compensation of the flow direction at the non-focal point.

We could measure the plasma flow velocity up to 1.6×10^3 m/s by using the expander optics which consists of two cylindrical lenses. We obtained that ion temperature is 1.0 ± 0.3 eV and the flow velocity is comparable to maximum resolution of spectroscopy in the Mini-RT plasma. We are setting up the opposed optical fiber array which could eliminate the error of spectral identification and increase the resolution of the spectroscopy system. Accordingly we can measure the plasma flow velocity up to 6.0×10^2 m/s.

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