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Plasma rotation measurement in small tokamaks using an optical spectrometer and a single photomultiplier as detector

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The method for plasma rotation measurement in the tokamak TCABR is reported in this article. During a discharge, an optical spectrometer is used to scan sequentially spectral lines of plasma impurities and spectral lines of a calibration lamp. Knowing the scanning velocity of the diffraction grating of the spectrometer with adequate precision, the Doppler shifts of impurity lines are determined. The photomultiplier output voltage signals are recorded with adequate sampling rate. With this method the residual poloidal and toroidal plasma rotation velocities were determined, assuming that they are the same as those of the impurity ions. The results show reasonable agreement with the neoclassical theory and with results from similar tokamaks. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2723749]

I. INTRODUCTION

The study of plasma rotation in tokamaks is important for the understanding of many physical phenomena in toroidal confinement systems. Plasma rotation is intimately connected with the existence of radial electric fields inside the plasma column. An approximate value of the radial electric field can be found from the ion momentum equation, neglecting the ion inertia, ion-electron friction, ion viscosity, and the radial component of external forces affecting the tokamak plasma,

$$E_r \approx \frac{1}{c}(-B_\zeta U_{i\theta} + B_\theta U_{i\zeta} + BU_{pi}), \qquad (1)$$

where

$$U_{pi} = \frac{c}{e_i n_0 B}\frac{\partial P_i}{\partial r},$$

and $U_{i\theta}$ and $U_{i\zeta}$ are the poloidal and toroidal "physical" components of the ion velocity V_i, respectively, P_i is the ion pressure, n_0 is the maximum line averaged plasma density. It follows from this equation that, in addition to direct measurements of E_r in tokamak experiments, the radial electric field can also be calculated by measuring $U_{i\theta}$, $U_{i\zeta}$, and the diamagnetic velocity U_{pi}.

It is well known that the poloidal velocity $U_{i\theta}$, given by $U_{i\theta}=(k/M_i\omega_{ci})\partial T_i \partial r$ (where k is a coefficient that depends on the tokamak regime, and is equal to -1.83 for the collisional regime; M_i is the ion mass; ω_{ci} is the ion cyclotron frequency, and T_i is the ion temperature) is of the order 10^5-10^6 cm/s. In most cases, experimental results are well described by neoclassical theory.[1–4] However, there are some experimental measurements performed on JT-60U, DIII-D, and JET that show disagreement with theory.[5–7] This disagreement is probably, related to turbulence and *L-H* transition. On the other hand, toroidal velocity $U_{i\zeta}$ is of the order 10^6-10^7 cm/s and the experimental results are in disagreement with the neoclassical theory.[1–3]

Rice and Marmar in[8] point out the fact that the toroidal velocity measured in several tokamaks differs not only in the magnitude but in the direction. In addition, plasma poloidal rotation in the edge of the plasma column plays an important role in the *L-H* transition[5,6,9] and toroidal momentum confinement is well correlated with energy confinement.[10] In this manner, the plasma rotation is an actual and important subject in the tokamak physical research.

There are several diagnostic systems designed to measure tokamak plasma rotation.[2,4,11–15] Bugarya *et al.*[3] measured poloidal and toroidal plasma rotation from the Doppler shift of impurities on a shot-to-shot basis. During one shot the monochromator was fixed at a wavelength and the intensities of the radiances of spectral lines were measured alternately from opposite directions. In the next shot the wavelength was then changed by the quantity $\Delta\lambda \ll \delta_D$, where δ_D is the Doppler half-width-half-maximum (HWHM) of the line profile. To have sufficiently wide line profile they worked in second and third-order dispersion, with very weak signals. Suckewer *et al.*[11] measured the temporal behavior and spatial profile of toroidal rotation of impurities from Doppler shift. In this work, as well as in Ref. 3, the authors obtained the radial profiles of the rotation by using impurities with different degrees of ionization located in different radial positions of the plasma column. To obtain the temporal be-

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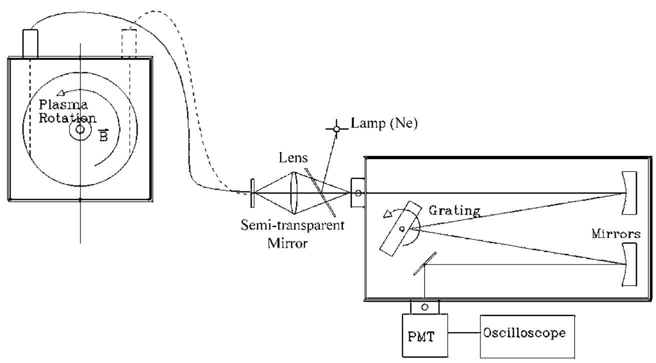

FIG. 1. Experimental setup used for poloidal rotation measurements.

havior, Suckewer *et al.* installed in the monochromator a vibrating mirror near the exit slit which repeatedly scanned the observed spectral line in time intervals of $10^{-3}-10^{-2}$ s. With the advent of multichannel diode arrays detectors, plasma rotation began to be measured with higher precision. An example of this can be seen in Ref. 12, where Duval *et al.*, using a 1024 blue-enhanced multichannel diode array detector, measured the poloidal and toroidal rotations with high precision $(\sigma < 0.12) \times 10^3$ m/s. Other methods, such as Mach probes[13] and measurements of spectral lines excited from charge exchange by neutral beam plasma interaction are also frequently used in the plasma rotation measurements.[4] Neutral beams are a very powerful diagnostic allowing measurement of density of impurities, ion temperature, and plasma rotation with high space resolution, but have the disadvantage of being very expensive for small tokamak laboratories. A new possibility to measure the temporal behavior of plasma rotation, proposed in Ref. 14, is based on the use of two interference filters to detect the light intensities, the Doppler shift being determined from the ratio of the intensities.

Here, we present a new method used in the tokamak TCABR.[15] During a discharge, an optical spectrometer is used to scan sequentially spectral lines of plasma impurities and of a calibration lamp by a rotation of diffraction grating. Knowing the scanning velocity of the diffraction grating with adequate precision, the Doppler shift of impurity lines are obtained in the oscilloscope. This article, which presents this method, is divided in the following way: in Sec. II the apparatus and methodology are described; in Sec. III the error analysis is discussed; Sec. IV is dedicated to showing illustrative results of the application of the method; discussions and conclusions are given in Sec. V.

II. APPARATUS AND METHODOLOGY

The radial profiles of the toroidal and poloidal velocities were measured using a 1 m Czerny-Turner optical spectrometer (Jobin-Yvon, THR 1000), which is equipped with a 1200 g/mm grating and R943–2 (Hamamatsu) photomultiplier installed in the exit slit. The spectrometer has the following specifications: Focal length 1000 mm; aperture $f/8.4$; geometric spread per bandwidth unit 0.0014 Sr/Å; spectral range order zero at 15 000 Å with a 1200 line/mm; inverse dispersion 8 Å/mm. The spectrometer has a stepping motor with 0.01 Å per step with a 1200 line/mm grating; grating velocity is about 70 Å/s and repeatability ±0.2 Å.

The optical measurement system is shown in Figs. 1 and 2 The semitransparent mirror M1 was used to collect the light from the neon or xenon lamp. The light from the plasma is collected and transmitted to the entrance slit of the spectrometer through an optical fiber of 1 mm diameter and two lens with aperture of $f/4$ and $f/8$, respectively. To register the signals of the photomultiplier a two-channel oscilloscope with sampling rate of 1 GS/s and 60 MHz of bandwidth was used.

The rotation of the diffraction grating was triggered by a pulse from the master pulser of the tokamak and adjusted to measure the impurity spectral line during the flat top of the plasma current and density. These lines were CIII (4647.4 Å) and CVI (5290.2 Å) and were chosen after a calculation of the respective radial distribution. To determine the positions of maximum emission of these lines, a corona equilibrium calculation was used, and fractional abundance ($f_Z = n_Z/n_{\mathrm{imp}}$) was obtained. We used the standard procedure, starting from the balance equation

$$\alpha_{Z+1}(T_e)n_{Z+1} = S_Z(T_e)n_Z, \tag{2}$$

where S_Z is the ionization rate coefficient of an ion of charge Z in $\mathrm{cm}^3\ \mathrm{s}^{-1}$, α_{Z+1} is the radiative recombination rate coefficient of an ion of charge $Z+1$ in $\mathrm{cm}^3\mathrm{s}^{-1}$, n_Z and n_{Z+1} are the density of impurity of an ion of charge Z and $Z+1$, respectively. On the other hand it is also known that the corona model works better for the central plasma than for the periphery. To avoid these problems, the position $r_{\max\ \exp}$ of the

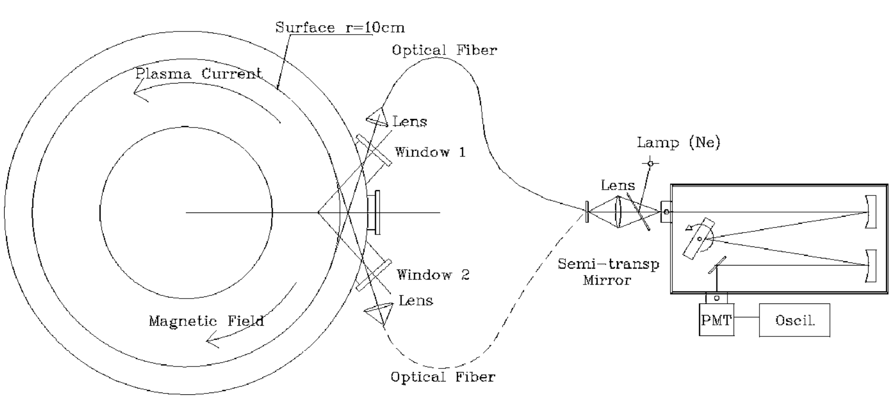

FIG. 2. Experimental setup used for toroidal rotation measurements.

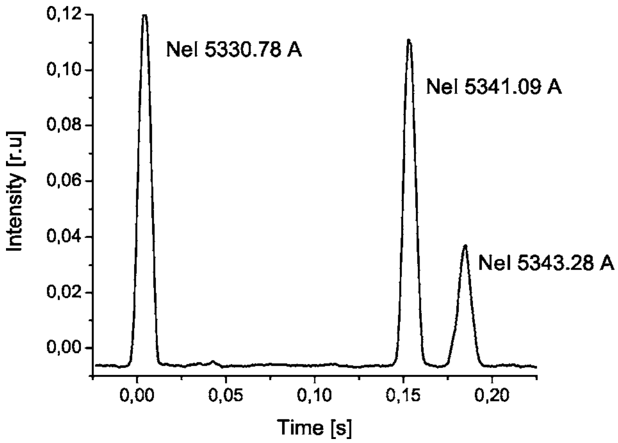

FIG. 3. Time evolution of spectral lines of NeI (5330.78, 5341.09, and 5343.28 Å) used in the rotation calibration of diffraction grating.

maximum emissivity of the carbon CIII (4647.4 Å) spectral line was obtained by Abel inversion of the measured radial intensity profile. For the CVI we used the corona model.

The plasma rotation velocities were obtained from the measurement of Doppler shifts of spectral lines of carbon impurities, CIII (4647.4 Å) and CVI (5290.2 Å). The values of the shifted wavelengths of the spectral lines of these impurities, measured by rotation of the diffraction grating, are compared to the spectral profiles of neon or xenon spectral lines, obtained in the same scan. In other words, in the beginning of the discharge, a pulse from the TCABR master pulser triggers the rotation of the diffraction grating. This rotation scans the impurity line and the calibration line. If the scanning velocity of the grating is known with the necessary accuracy and precision, the shift of the impurity spectral line can be obtained; then, the plasma rotation velocity can be calculated.

The scanning velocity of the grating was measured from the well-known wavelengths of three neon lines (NeI =5330.78 Å, NeI=5341.09 Å, NeI=5343.28 Å) and of two xenon lines (XeI=4624.28 Å and XeI=4671.23 Å), which are shown in Figs. 3 and 4. After scanning these lines, the experimental points of their profiles were best fitted by a Gaussian function, using the least-squares method, and the

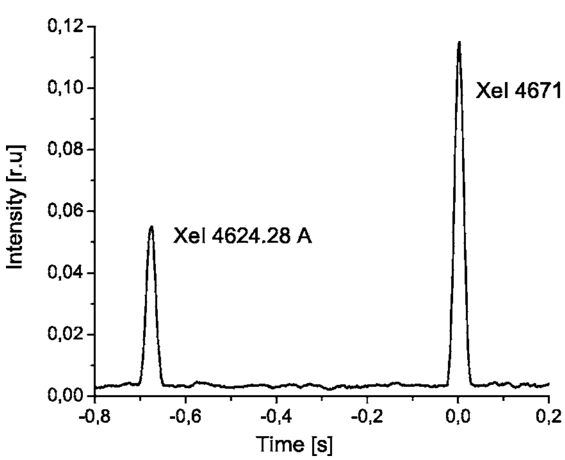

FIG. 4. Time evolution of spectral lines of XeI (4624.28 and 4671.23 Å) used in the rotation calibration of diffraction grating.

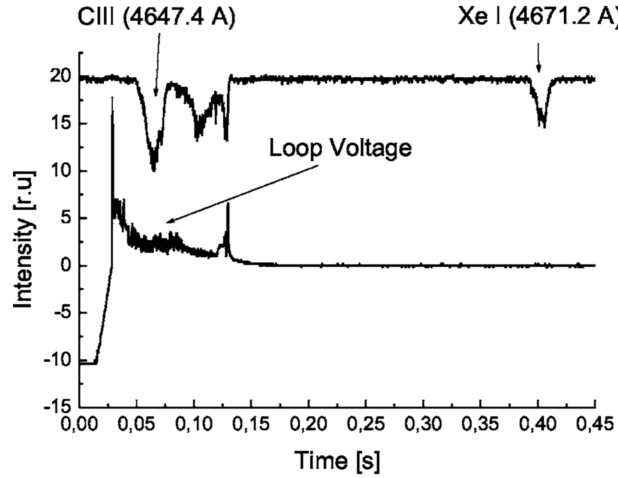

FIG. 5. Time profile of the CIII and XeI spectral lines used in the measurements of ion velocities and loop voltage.

time elapsed between the lines were determined. If the wavelengths of the three neon lines and the time elapsed between them are known with the necessary precision, the scanning velocity of the grating can be calculated. A time evolution of the CIII and XeI spectral lines used in the measurements of ion velocities is shown in Fig. 5. In Fig. 6 is shown the same lines after fitting by a Gaussian function, using the least-squares method. These lines were obtained when the optical system was collecting light from the positions 1 (periphery) and 2 (central); (see Fig. 1). The respective temporal displacement between them was calculated and from the velocity of the diffraction grating, which in this case is 69.2 Å/s, it was possible to calculate the spectral displacement between these lines, which in this case was 0.06 Å.

A small dependence of the grating velocity with the wavelength was found in this experiment. For the neon lines, the velocity is 69.16±0.01 Å/s, which represents the average velocity in the range 5341.09 to 5330.78 Å, while for the xenon lines this velocity is 69.20±0.01 Å/s, representing the average velocity between the lines XeI (4671.23 Å) and XeI

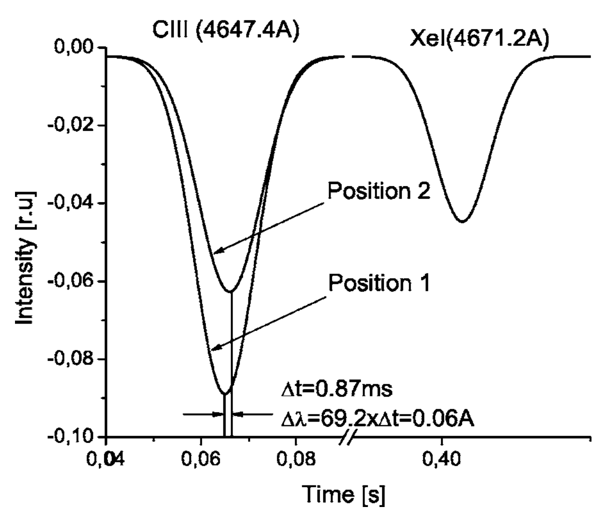

FIG. 6. Time profile of the CIIIand XeI spectral lines used in the measurements of ion velocities after fitting by a Gaussian function, using the least-squares method.

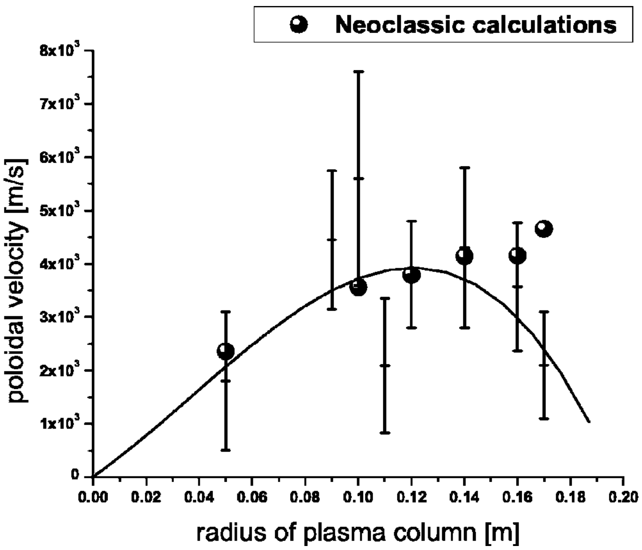

FIG. 7. Radial profile of the poloidal velocity.

(4624.28 Å). Therefore, the values of the grating velocity were used in accordance with the wavelength values of the CIII and CVI spectral lines values.

The small difference in the grating velocities for the neon and xenon lines can generate an error in the measurements of plasma rotation of approximately 1 km/s. However, the assumption that the grating velocities are constant in the above-referred intervals is not necessarily true. To avoid systematic errors related to this fact and possible variations in the grating velocity, the plasma rotation was measured in the following way: after some number of shots (usually 10), the average Doppler displacement between the spectral line of the impurity and spectral line of the calibration lamp was obtained. After this, the optical system was moved from position 1, at the plasma periphery, to position 2, at the plasma center where the Doppler shift is supposed to be zero (see Fig. 1), and the same procedure was repeated. From the difference between the Doppler displacements obtained for positions 1 and 2, the plasma rotation velocity was calculated for position 1.

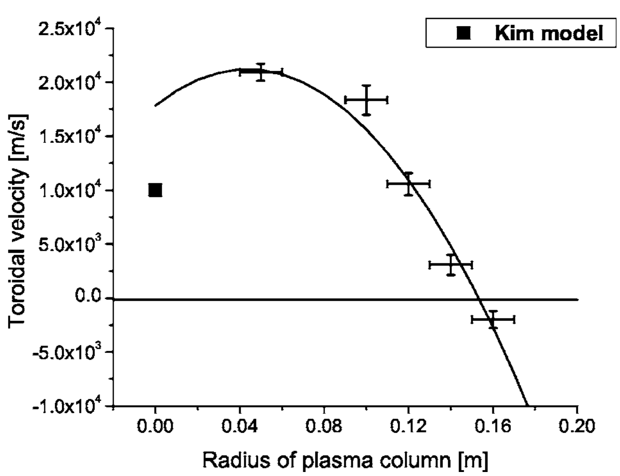

FIG. 8. Radial profile of the toroidal velocity.

TABLE I. Poloidal rotation.

Impurity	Chord position [m]	Doppler shift [Å]
CIII	0.17	0.03±0.02
CIII	0.16	0.06±0.02
CVI	0.14	0.08±0.03
CVI	0.12	0.07±0.02
CVI	0.11	0.04±0.02
CVI	0.10	0.10±0.04
CVI	0.09	0.08±0.02
CVI	0.05	0.03±0.02

III. ERROR ANALYSIS

By careful error analysis, it was obtained that the characteristic errors in the determination of radial position in plasma column are approximately 0.005 and 0.010 m (horizontal error bar) for poloidal and toroidal measurements, respectively. These characteristic errors are related, at first, with displacements of the plasma column during discharge, which for TCABR, during the stationary phase, are smaller than 0.005 m. The second is related to the plasma light-emitting volume accepted by the optical system, which is an approximate cylinder of 0.005 m diameter. To measure the plasma toroidal rotation, the same optical system was moved to another tokamak port located in the equatorial plane but making an angle of 45° with the plasma minor radius, which generated a larger uncertainty in the radial position of the plasma column (approximately 0.01 m).

Since the plasma rotation can be different in the regions of low field side and high field side, the optical system for collecting the light emitted by the plasma, in both poloidal and toroidal measurements, was assembled to detect, approximately, only tangentially emitted light.

The method for determining the plasma rotation velocities was the following. For each tokamak shot, temporal profiles of the impurity spectral and calibration lines were measured; Gaussian least-square fits were performed giving the time values t_D and t_C of the peaks of the Gaussian profiles, respectively. From the known scanning velocity of the diffraction grating, the Doppler displaced wavelength λ_D of the impurity line was obtained,

$$\lambda_{D,r,i} = \lambda_C - V_G(t_C - t_{D,r,i}); \quad \text{for } \lambda_C > \lambda_{D,r,i}, \tag{3}$$

where λ_C is the wavelength of the calibration line, V_G is the grating velocity, r is the radial position of the measurement, and i is the ith measurement. Working with discharges with good reproducibility, the measurement was repeated not less than 10 times, and an average value $\langle \lambda_{D,r} \rangle$ was obtained. After this, the optical system was moved to position 2, at $r = 0$ where the rotation velocity is assumed to be zero and

TABLE II. Toroidal rotation.

Impurity	Chord position [m]	Doppler shift [Å]
CIII	0.16	0.03±0.01
CVI	0.14	0.05±0.02
CVI	0.12	0.19±0.02
CVI	0.10	0.32±0.02
CVI	0.05	0.37±0.01

taken as reference. Again, the same procedure was performed, and the final value of the Doppler displacement, $\lambda_{D,r,f}$, for the position r is

$$\langle\lambda_{D,r}\rangle - \langle\lambda_{D,0}\rangle = \lambda_{D,r,f}. \tag{4}$$

For the poloidal velocity at a radial position, the standard deviation is $\sim 10^3$ m/s, except for the position $r=0.10$ m, where the deviation was $\sim 2\times 10^3$ m/s (vertical error bar). This fact is related, as can be seen in Ref. 16, to the presence of magnetic islands.

In our experience, to obtain the plasma rotation velocity we did 10 measurements so that the standard deviation was smaller than 0.01 Å.

IV. EXPERIMENTAL PLASMA ROTATION RESULTS

Plasma poloidal and toroidal residual rotation measurements were performed on the TCABR tokamak. This machine has the following parameters: minor radius $a=0.18$ m, major radius $R=0.61$ m, toroidal magnetic field $B_T=1.1$ T, discharge current $I_P=100$ kA, maximum average density $n_e \simeq (1-4.5)\times 10^{13}$ cm^{-3}, $T_e(0)\simeq 600$ eV, $T_i(0)\simeq 200$ eV, duration of the stationary phase of the discharge 60 ms. The measurements were carried out in the collisional regime (Pfirsch-Schlūter), using Doppler shift of carbon lines, CIII (4647.4 Å) and CVI (5290.2 Å). Figures 7 and 8 show the radial profile of the poloidal and toroidal velocities measurements, respectively. The Doppler shifts for different positions of plasma column are shown in Tables I and II.

V. DISCUSSION

Assuming that plasma impurities rotate together with the plasma, poloidal and toroidal plasma rotations were measured in the TCABR tokamak using the method described in this article. The results show that:

(a) The direction of poloidal velocity in the TCABR coincides with the diamagnetic electron drift and there is a reasonable agreement between experimental and theoretical neoclassical values of poloidal velocity except in the periphery ($r=16-17$ cm), which is probably related to poor information on plasma parameters in this region.

(b) The toroidal velocity of the plasma core is opposite to the direction of the plasma current, while near the plasma edge ($r>0.16$ m), plasma rotates in the opposite direction. This effect was already observed in other tokamaks, for example in Ref. 3.

(c) The toroidal rotation in the core region of the plasma column, which is approximately 20 km/s, is in a reasonable agreement with the model proposed by Kim *et al.*,[17] which gives 10 km/s for TCABR.

(d) Our experimental results are in good agreement with the results obtained in other small tokamaks experiments,[1–3] which indicates that this method can be used for plasma rotation measures.

ACKNOWLEDGMENT

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