Measurements of Temporal Evolution of Plasma Rotation in the TCABR Tokamak

J.H.F. Severo 1), I.C. Nascimento 1), Yu.K Kuznetov 1), R.M.O. Galvão 1,2) and M. Tendler 3)

1) Institute of Physics, University of São Paulo, Rua do Matão, s/n, 05508-900 SP, Brasil
2) Brazilian Center for Physics Research, Rua Xavier Sigaud 150, Rio de Janeiro BR-22290180, Brazil
3) The Alfven Laboratory, EURATOM- Nuclear Fusion Research, Royal Institute of Technology 10044 Stockholm, Sweden

E-mail: jhsevero©if.usp.br

Abstract. A new method for determining the temporal evolution of plasma rotation is reported in this work. The method is based upon the detection of two different portions of the spectral profile of a plasma impurity line, using a monochromator with two photomultipliers installed at the exit slits. The plasma rotation velocity is determined by the ratio of the two detected signals. Preliminary results of poloidal and toroidal rotation velocities of CIII (4647.4 Å) and CVI (5290.6 Å), at different radial positions in TCABR discharges, show good agreement, within experimental uncertainty, with previous results.

1. Introduction

TCABR (Tokamak Chauffage Alfven Bresilien) is a machine with a broad research program in the physics of tokamaks: interaction of RF waves in the region of Alfvén frequencies [1], stochastic processes at the plasma edge [2], transport barriers created by external electrostatic polarization [3-4], and plasma rotation [5-6].

In particular, the rotation of the plasma column has been carefully measured and it has been shown that, in the collisional regime, the results agree reasonably well with the predictions of neoclassic transport theory [5-6].

Due to their relevance for the stabilization or excitation of wall modes, achievement of improved confinement regimes, transport of angular momentum and many other relevant physical mechanism, the profiles of poloidal and toroidal rotation are being intensively investigated in many experiments. One critical issue regarding the underlying mechanism associated with rotation is the damping rate. However, the diagnostic techniques used to measure temporal profiles (charge-exchange spectroscopy and multichannel diode array detector) do not have sufficient time resolution and in general are not available in small laboratories. Other methods, such as Mach probes, can be used, but only for edge measurements.

A new method for measuring the temporal evolution of plasma rotation in tokamaks is reported in this work. The method is based on the ratio of the signals corresponding to detection of two portions the same impurity emission line using two photomultipliers installed at the exit slits of a monochromator (Fig.1). The light from the plasma is collected and transmitted to the entrance slit of the monochromator through an optical fiber. Inside the monochromator, using a semi-transparent mirror, the light is divided

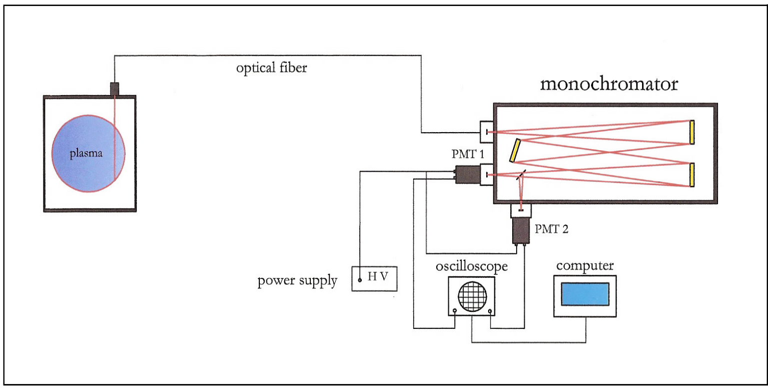

Fig.1 Experimental set up for temporal evolution of poloidal plasma rotation in the TCABR tokamak.

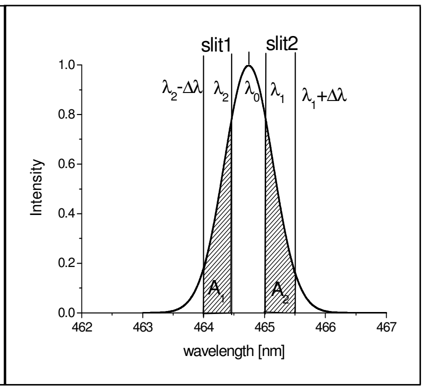

Fig.2 Schematic representation of Gaussian spectral profile.

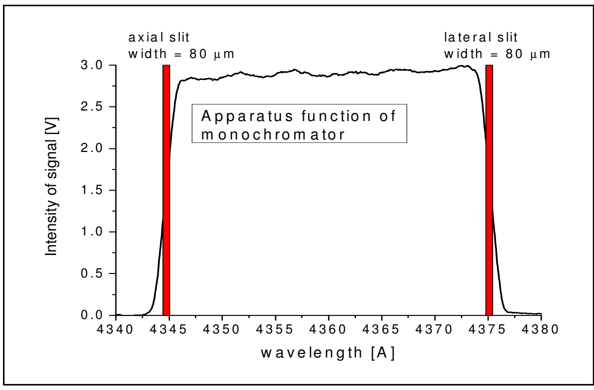

Fig.3 Trapezoidal contour used for plasma rotation measurements in the TCABR tokamak.

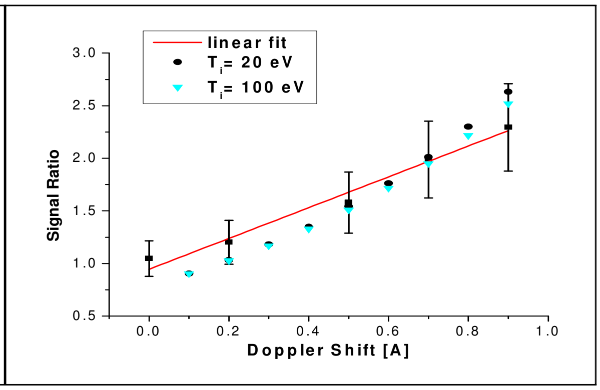

Fig.4 Dependence of signal ratio on the Doppler shift obtained experimentaly by scan of spectral line. The circles and triangules show this dependence for two different ion temperatures (20 and 200 eV).

into two parts and directed to the photomultipliers located at the exit slits. As the axial exit slit 1 integrates the left part (area A_1 in Fig.2) of the spectral line profile and the frontal slit 2 integrates its right part, when the plasma begins to move, the center of the spectral line will move to the right or left, changing the ratio $R = A_1/A_2 = R(\Delta\lambda_0)$, which is proportional to the plasma rotation. Here $\Delta\lambda_0$ is the Doppler shift of spectral line.

The signal ratio does not depend on detector or circuit parameters. Indeed, the possible differences related to detector sensitivity, amplifier gain, etc. can be removed by relative calibration and therefore the signal ratio depends just on the Doppler shift.

To obtain a linear dependence of signal ratio on the Doppler shift of the emission line, its Gaussian shape was changed to a trapezoidal contour through an increase of the width of the entrance slit. Figure 3 shows a new contour obtained with 2000 μm and 80 μm in the widths of the entrance and exit slits, respectively.

With this procedure, the shape of the recorded signal $f(\lambda)$, which is a convolution of two functions, $g(\lambda)$ (spectral profile of spectral line) and $a(\lambda)$ (apparatus function), has a trapezoidal form if the FWHM (full-width at half-maximum) of $g(\lambda)$ is much smaller $a(\lambda)$.

As can be seen from Fig.3, the convolution of these two functions yields trapezoidal contour and working with this new shape is more convenient because possible changes in the spectral profile of impurity does not affect the signal ratio and increases the sensibility of the diagnostic.

To properly calibrate the diagnostic, the line of sight of the detection system was placed at the position of magnetic axis and the signals adjusted to yield the expected zero poloidal rotation. Then the carbon lines CIII (4647.4 Å) and CVI (5290.6 Å) were scanned, in a shot-to-shot bases, and the dependence of the signal ratio on the Doppler shift was obtained for these lines (fig.4). The plasma rotation velocity was then calculated.

As can be inferred from Fig.2, if the ion temperature starts to increase, the shape of the recorded function changes and its variation can influence the dependence of signal ratio on the Doppler shift. To better investigate this effect, we computed the convolution of the apparatus function with the Gaussian function for different ion temperatures and took the ratio of the integrals of left and right sides as function of the Doppler shift. The results for two different ion temperatures, 20 and 200 eV, are shown in Fig.4. From this figure it can be seen that the influence of ion temperature is small and can be easily ignored for the TCABR parameters. Therefore this method for plasma rotation measurements is not sensitive to possible changes in the ion temperature during the experiment.

2. Doppler shift as a function of signal ratio

From Fig.2 we can see that the dependence of the signal ratio on the Doppler shift is directly connected with the shape of the recorded contour $f(\lambda)$. On the other hand, it is well known that the recorded contour $f(\lambda)$, which is a intensity distribution of a spectral line broadened by two effects, is expressed by the equation

$$f(\lambda) = \int_{-\infty}^{+\infty} g(\lambda')a(\lambda - \lambda')d\lambda', \tag{1}$$

where $g(\lambda)$ is contour of the spectral line that has, in most cases Gaussian profile, and $a(\lambda)$ is the apparatus function.

A general method to solve equation (1) consists in representing the functions $g(\lambda)$ and $a(\lambda)$ in the form of a Fourier integral

$$g(\lambda) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} G(\omega)e^{i\omega\lambda}d\omega; \qquad a(\lambda) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} A(\omega)e^{i\omega\lambda}d\omega \tag{2}$$

Then, the equation (1) can be rewritten as

$$f(\lambda) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} G(\omega) A(\omega) e^{i\omega\lambda} d\omega \tag{3}$$

where

$$A(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} a(\lambda) e^{-i\omega\lambda} d\lambda \tag{4}$$

is the Fourier transform of the slit function.

Equation (3) can be rewritten in the following way

$$f(\lambda) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left[G(\omega) - 1 + 1\right] A(\omega) e^{i\omega\lambda} d\omega \Rightarrow$$
$$f(\lambda) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left[G(\omega) - 1\right] A(\omega) e^{i\omega\lambda} d\omega + \frac{1}{2\pi} \int_{-\infty}^{+\infty} A(\omega) e^{i\omega\lambda} d\omega$$

Therefore, we have

$$f(\lambda) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \left[G(\omega) - 1\right] A(\omega) e^{i\omega\lambda} d\omega + a(\lambda) \tag{5}$$

The first term in equation (5), which will be called the correction term is, in our case ($FWHM_{monochr} \gg FWHM_{impurity}$), very small and vanishes in the ideal case of monochromatic illumination and the recorded contour $f(\lambda)$ will be equal to the apparatus function.

The correction term give small corrections connected with the dependence of the Gaussian profile on the ion plasma temperature.

To find the signal ratio dependence on the Doppler shift, we assume that the record function $f(\lambda)$ is a convolution of the trapezoidal function, taken in the form

$$a(\lambda) = \left\{ \begin{array}{ll} \frac{1}{S_1}; & S_1 > S_2; |\lambda| \leq \frac{S_1 - S_2}{2} \\ \frac{1}{S_1 S_2}\left(\frac{S_1+S_2}{2} - |\lambda|\right); & \frac{S_1-S_2}{2} \leq |\lambda| \leq \frac{S_1+S_2}{2} \\ 0; & \frac{S_1+S_2}{2} \leq |\lambda| \end{array} \right\} \tag{6}$$

and the Gaussian function.

Here $S_2 = b_{A,L} d_\lambda$ is the width of the exit slit and $S_1 = b_{A,L} d_\lambda$ is the width of the geometric image of the entrance slit, both multiplied by the inverse dispersion; $b_{A,L}$ is exit width of the lateral or axial slit; d_λ is the inverse dispersion and λ is wavelength of the impurity line.

Expanding the Fourier transform of Gaussian function in a Taylor series and substituting in (5) yields

$$f(\lambda) = \frac{-1}{2\pi} \int_{-\infty}^{+\infty} \sigma^2 \omega^2 A(\omega) e^{i\omega\lambda} d\omega + a(\lambda)$$

Where σ is FWHM of Gaussian function that is proportional to the square root of ion temperature T_i.

Taking into account (2), we can write

$$\frac{d^2 a\,(\lambda)}{d\lambda^2} = \frac{-1}{2\pi} \int_{-\infty}^{+\infty} \omega^2 A(\omega) e^{i\omega\lambda} d\omega$$

Therefore we have,

$$f(\lambda) = a(\lambda) + \sigma^2 \frac{d^2 a\,(\lambda)}{d\lambda^2} \tag{7}$$

Equation (7) give the record function $f(\lambda)$ as function of the apparatus function and its derivative. The second term in right side is a correction term that is proportional to the ion temperature.

To obtain a strong dependence of the signal ratio on the Doppler shift, the photomultipliers could integrate the recorded function where there is strong variations of its shape with wavelength, what means to integrate the function $f(\lambda)$ in the following two intervals: $\lambda_L - \Delta\lambda_L$ to $\lambda_L + \Delta\lambda_L$ and $\lambda_R - \Delta\lambda_R$ to $\lambda_R + \Delta\lambda_R$, where λ_L and λ_R are some points on left and right part of apparatus function where its height is one half of the maximum; $\Delta\lambda_L = b_L d_\lambda$ and $\Delta\lambda_R = b_R d_\lambda$ are limits of integration that are determined just by width of axial and lateral slits.

Since we are analyzing the ideal case where apparatus function is described by (6), the second term on the right side of (7) is equal to zero, so we can write

$$A_L = \int_{\lambda_L+\Delta\lambda_0-\Delta\lambda_L}^{\lambda_L+\Delta\lambda_0+\Delta\lambda_L} f(\lambda) d\lambda = \int_{\lambda_L+\Delta\lambda_0-\Delta\lambda_L}^{\lambda_L+\Delta\lambda_0+\Delta\lambda_L} a(\lambda) d\lambda$$

and

$$A_R = \int_{\lambda_R+\Delta\lambda_0-\Delta\lambda_R}^{\lambda_R+\Delta\lambda_0+\Delta\lambda_R} f(\lambda) d\lambda = \int_{\lambda_R+\Delta\lambda_0-\Delta\lambda_R}^{\lambda_R+\Delta\lambda_0+\Delta\lambda_R} a(\lambda) d\lambda$$

The above equation describes the areas A_L and A_R as function of the Doppler shift $\Delta\lambda_0$. To find the signal ratio dependence on the Doppler shift, we take the ratio between A_L and A_R so

$$A_L = \frac{\Delta\lambda_L}{2S_1S_{2L}} \left(S_{2L} + 2.\Delta\lambda_0\right) \text{ and } A_R = \frac{\Delta\lambda_R}{2S_1S_{2R}} \left(S_{2R} - 2.\Delta\lambda_0\right)$$

Then, the ratio between A_L and A_R is equal to

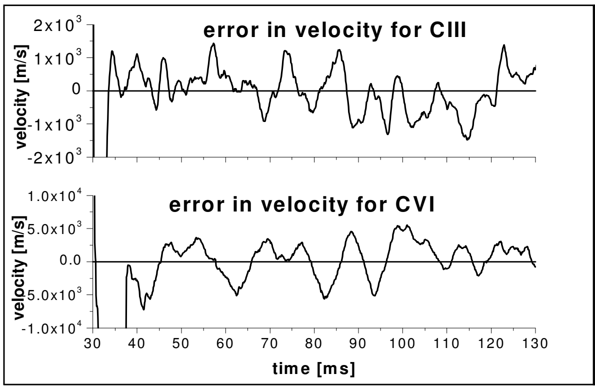

Fig.5 Experimental uncertainty for rotation velocities of CIII (4647.4 Å) and CVI (5290.6 Å).

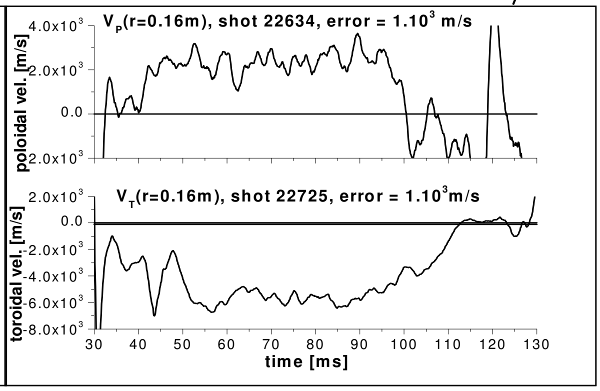

Fig.6 Temporal evolution of poloidal and toroidal rotation velocities of CIII (4647.4 Å) at $r = 0.16m$ radial position.

$$R = \frac{(S_{2L} + 2.\Delta\lambda_0)}{(S_{2R} - 2.\Delta\lambda_0)} \Rightarrow \Delta\lambda_0 = \frac{1}{2}\left(\frac{RS_{2R} - S_{2L}}{R+1}\right) \tag{8}$$

Here S_{2L} and S_{2R} are the width of the lateral and axial exit slits which are equal to the integration limits $\Delta\lambda_L$ and $\Delta\lambda_R$ respectively.

3. Error analysis

The error in measuring rotation velocity, can be obtained from the derivative of equation (8),

$$\begin{aligned}
\sigma^2_{\Delta\lambda_0} &= \left(\frac{\partial\Delta\lambda_0}{\partial R}\right)^2 \sigma_R^2 + \left(\frac{\partial\Delta\lambda_0}{\partial S_{2L}}\right)^2 \sigma^2_{S_{2L}} + \left(\frac{\partial\Delta\lambda_0}{\partial S_{2R}}\right)^2 \sigma^2_{S_{2R}} \simeq \\
&\simeq \left(\frac{\partial\Delta\lambda_0}{\partial R}\right)^2 \sigma_R^2 + 2\left(\frac{\partial\Delta\lambda_0}{\partial S_2}\right)^2 \sigma^2_{S_2} = \\
&= \left[\frac{2S_2}{(R+1)^2}\right]^2 \sigma_R^2 + \left(\frac{R-1}{R+1}\right)^2 \sigma^2_{S_2} \simeq \left(\frac{2S_2}{R+1}\right)^2 \sigma_R^2 \Rightarrow \\
\sigma_{\Delta\lambda_0} &= \left[\frac{2S_2}{(R+1)^2}\right] \sigma_R \simeq \frac{\sigma_R}{4}
\end{aligned} \tag{9}$$

In our calculations we have taken into account that, for small Doppler shift that was measured in the TCABR, $R \simeq 1$ and the axial and lateral slits give approximately the same experimental uncertainty.

Equation (9) shows that the error in the Doppler shift measurements is equal to one fourth of the error in the signal ratio measurements. In our measurements of rotation velocity, the error in signal ratio was approximately equal to 5% for CIII (4647.4 Å) and 35% for CVI (5290.6 Å); that means that the error in velocity is approximately 1 km/s for CIII and 5 km/s for CVI (Fig.5).

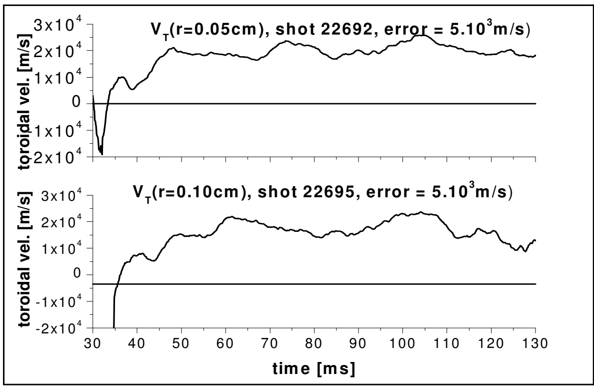

Fig.7 Temporal evolution of toroidal rotation velocity of CVI (5290.6 Å) for $r = 0.05$ and $r = 0.10m$ radial positions.

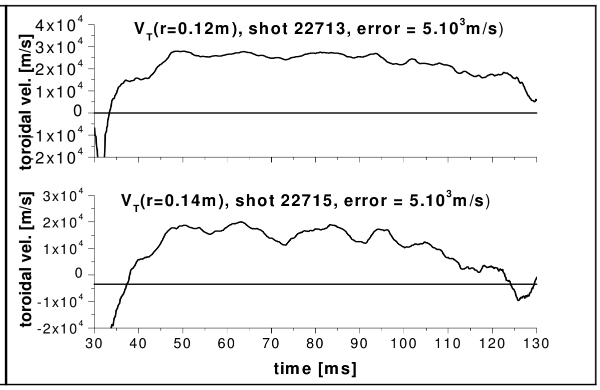

Fig.8 Temporal evolution of toroidal rotation velocity of CVI (5290.6 Å) for $r = 0.12$ and $r = 0.14m$ radial positions.

4. Experimental results of poloidal and toroidal rotation

Here we present the preliminary results of poloidal and toroidal rotation velocities at different radial positions using this technique.

The measurements were carried out in the collisional regime (Pfirsch-Schlūter) using the Doppler shift of the carbon lines, CIII (4647.4 Å) and CVI (5290.6 Å).

The parameters of TCABR are the following: 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 $n_e \simeq (1 - 4.5) \cdot 10^{13}$ cm^{-3}, $T_e(0) \simeq 600$ eV, $T_i(0) \simeq 200$ eV, duration of the stationary phase of the discharge $60ms$.

The temporal evolution of the poloidal and toroidal rotation velocities are shown in Figs. 6, 7 & 8, for CIII (4647.4 Å) and and CVI (5290.6 Å), at $r = 0.05$, $r = 0.10$, $r = 0.12$, $r = 0.14$ and $r = 0.16m$ for different shots. These measurements show that the direction of poloidal velocity coincides with the diamagnetic electron drift. The toroidal velocity of the plasma core is opposite to the direction of the plasma current and its change signs at the plasma edge at $r \geq 0.16m$.

5. Discussions and Conclusions

The first successful results of a temporal evolution of plasma rotation in TCABR tokamak were determined. The experimental results are in well agreement with the results obtained in [5-6] and other small tokamaks experiments, what indicates that this method can be used for temporal evolution of plasma rotation measurements.

These results support the continuation and simultaneously measurements of poloidal and toroidal evolution of plasma rotation are being planed.

Acknowledgments
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