A new Method for Absolute Measurements of the Toroidal Plasma Rotation Velocity at TEXTOR-94

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I. Introduction.

Toroidal rotation plays an important role in tokamak experiments. First studies of the correlation between momentum and energy confinement were performed at TFTR in high power neutral beam heating experiments and in adiabatic compression experiments [1,2]. More recently, Rice et al. determined the toroidal rotation in plasmas with ohmic and ICRF heating using a X-ray crystal spectrometer with an absolute wavelength calibration [3,4]. Due to the lack of appropriate high-precision wavelength standards in the X-ray region, such a calibration is an extremely difficult task. In this paper, we discuss a new method, which circumvents this problem by using the Doppler shift of two spectral lines.

II. Experimental Arrangement.

Experimental studies were performed at TEXTOR-94 with a Johann curved X-ray crystal spectrometer, which records spectra of heliumlike argon, ArXVII [5]. The most prominent features in the spectrum of ArXVII are the resonance line **w:** $1s^2\ {}^1S_0 – 1s2p\ {}^1P_1$ and the forbidden line **z:** $1s^2\ {}^1S_0 – 1s2s\ {}^3S_1$ at wavelengths of 3.9494 to 3.9944 Å, respectively. These lines were used for Doppler measurements of the toroidal plasma rotation velocity v_t. The experimental arrangement is shown in Fig. 1. A cylindrically bent 110-quartz crystal with a 2d spacing of 4.913 Å and a radius of curvature of 380 cm was placed at a distance x_c = 604.3 cm from the center of the tokamak. The central line of sight from the crystal to the plasma included an angle $\alpha_0 = 10^o$ with a major radius vector at R_p = 175 cm and the orientation of the crystal was such that the Bragg angle for the central line of sight was $\theta_0 = (\theta_w + \theta_z)/2$, where $\theta_w = 53.50^o$ and $\theta_z = 54.39\ ^o$ are the Bragg angles for the lines **w** and **z**, respectively. Therefore, a Bragg angle θ is associated with an angle α through the following equation

$$\sin(\alpha) = 1/(1+m^2)[A\text{-}m\ (1 + m^2 – A^2)^{1/2}] \qquad (1)$$

where $A = \sin(\alpha_0) + m\ x_c/R_p$ and $m = \tan(\theta_0 - \theta)$. It then follows from Bragg's law and Doppler's law that there is a unique correspondence between an angle α, a wavelength λ, and an ion velocity v, so that each wavelength λ and each velocity v are observed from a different position in the plasma. Similarly each point on the detector is associated with certain values for λ and v. The relation between v and λ is given by equation (2)

$$v = c(1 - \lambda/\lambda_{w,z}) = v_r + v_t \sin[\alpha(\lambda) + \theta_0 - \theta] \quad (2)$$

where v_r and v_t are the random ion velocity and toroidal plasma rotation velocity, respectively, and where $\lambda_{w,z}$ assumes the values of λ_w and λ_z. In the case of a non-rotating plasma, $v_t = 0$, the relation between v_r and λ is linear, so that the observed line profile is Gaussian for a Maxwellian ion velocity distribution. The fact that each value of λ is observed from a different point in the torus has, in this case, no consequences for the observed line profiles, since the ion velocity distribution is invariant in the toroidal direction. In the case of a rotating plasma, the observed line profile is both Doppler shifted *and* deformed, since the relation between v_r and λ is nonlinear. The degree of distortion depends on the magnitude of v_t, α, and θ as well as on the instrumental dispersion. The distortion is negligible for the conditions at TEXTOR-94. The Doppler shift of the line profile is obtained by solving equation (2) for $v_r = 0$, which corresponds to the maximum of the thermal ion velocity distribution. We note that the Doppler shifts for the lines **w** and **z** are different so that - depending on the direction of the plasma rotation - the wavelength separation between these lines is either compressed or expanded. The magnitude and direction of the toroidal rotation velocity v_t can therefore be determined from the separation between **w** and **z** by comparing the experimental value to a reference value, which can be taken from theory or an independent measurement. Theoretical and experimental values for the relative wavelengths of **w** and **z** are, in general, very accurate and more reliable than absolute wavelength values.

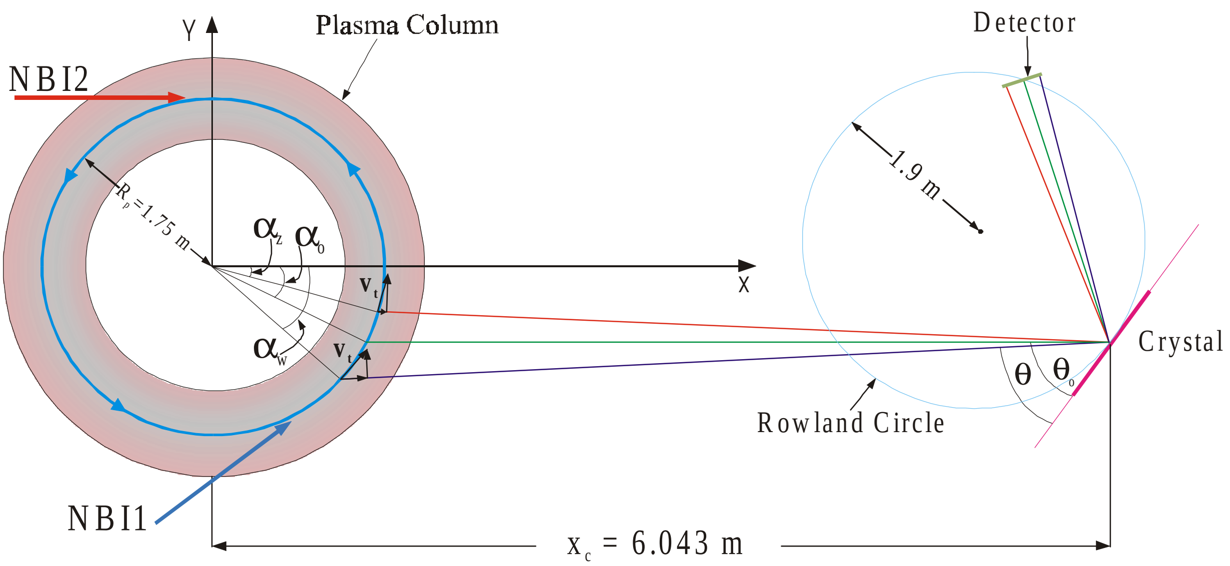

Figure 1: Experimental arrangement

III. Experimental Results

Experimental data have been obtained from a series of discharges with ohmic and neutral-beam heating. The experiments were performed with the plasma current I_p and toroidal magnetic field B_t in the *standard* (counter-clockwise) direction and injection of neutral beam NBI1, and with I_p and B_t in the *reverse* (clockwise) direction and injection of neutral beam NBI2 (see Fig. 1). The plasma densities were in the range 2 to 5 x 10^{13} cm^{-3}. A typical spectrum of ArXVII which was recorded in these experiments is shown in Fig. 2. The horizontal arrows show qualitatively the different magnitudes of Doppler shifts for **w** and **z**.

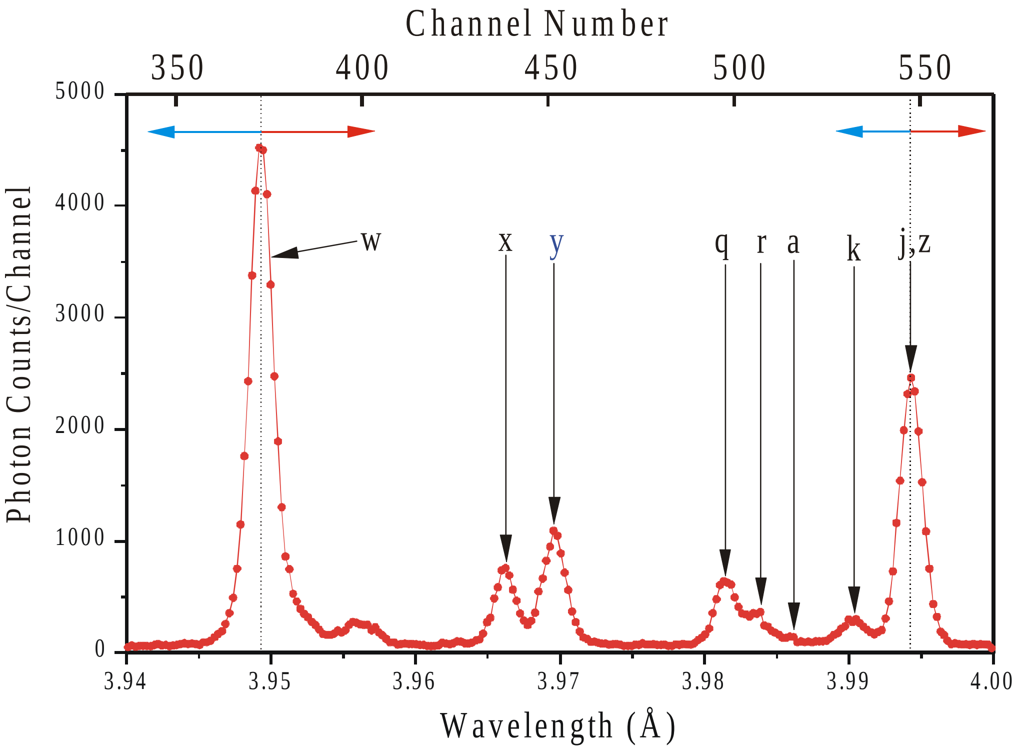

Figure 2: Dielectronic satellite spectrum of ArXVII.

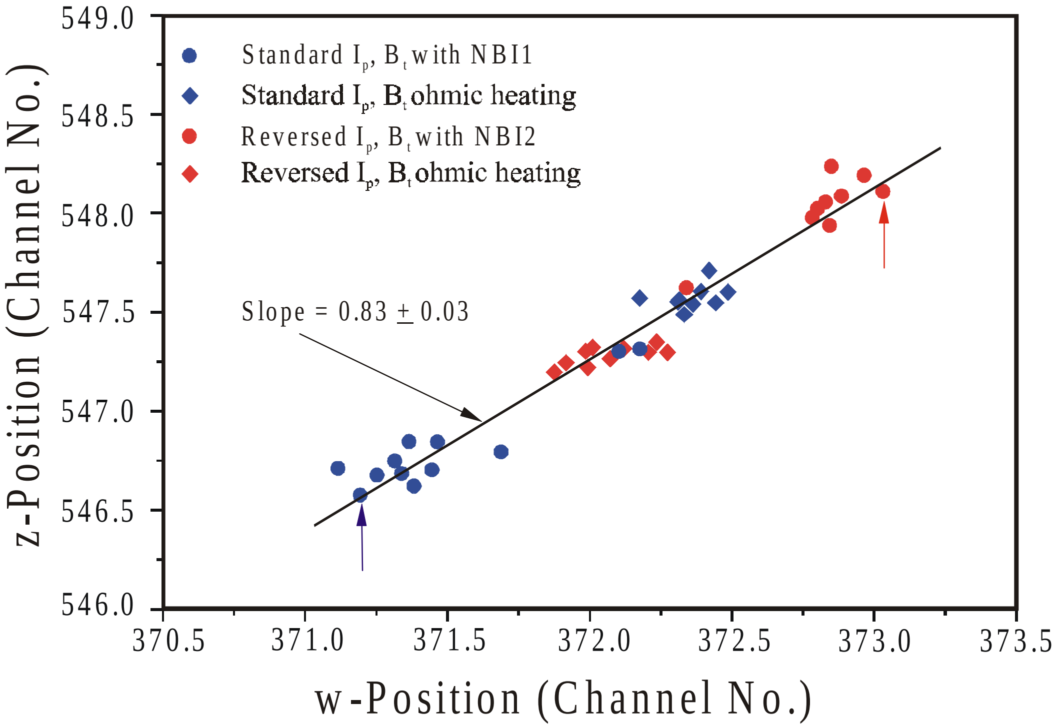

Figure 3: Center position of line z versus center position of line w

Fig. 3 shows a plot of the observed center positions of the line **z** versus the center positions of the line **w**. The blue and red data points were obtained for *standard* and *reverse* conditions, respectively. Ohmic and beam conditions are distinguished by diamonds and circles, respectively. The straight line represents a linear least-squares fit to all the experimental data. The resultant slope of 0.83 is somewhat larger than the value of 0.74, which is expected for our experimental arrangement. For the data points obtained with *standard* conditions one expects a blue shift and a dilation of the separation between the lines **w** and **z**, whereas for the data points obtained with reversed condition one expects a red shift and a compression of the separation between **w** and **z**. These expectations are confirmed by the experimental data. For instance the channel separation between **z** and **w** is 175.39 and 175.08 for the far points, which are marked by the blue and red arrows. These data points correspond to toroidal rotation velocities of 103 and 86 km/s in the co- and counter directions, respectively.

We note that the ohmic data points for the *standard* and *reversed* conditions are separated. This suggests that there is a rotation even in the absence of neutral beam injection and that the sense of the rotation is reversed with the reversal of I_p and B_t. It is evident from Fig. 3 that the rotation in the ohmic discharges is in the direction of electron current. The toroidal rotation velocities in ohmic discharges are in the range from 0 to 30 km/s, which is consistent with the observations of Rice *et. al.* [3,4]. The three neutral-beam data points, which are intermingled with the ohmic data points, were obtained from high density discharges, for which small rotation velocities are expected.

We point out that the spectrometer was not optimized for rotation velocity measurements, since the choice of α and θ was dictated by constraints with respect to the available diagnostic space at TEXTOR-94. The observed Doppler shifts are therefore small and at the limit of detectability of the multi-wire proportional counter. We note that one channel corresponds to a wavelength shift of 2.55×10^{-4} Å or a displacement on the detector of 0.268 mm and that the observed effects are only a few tenths of a channel. Statistical deviations are therefore not small so that the applicability of the here-discussed method has been demonstrated only for the statistical average of the experimental data. The experimental conditions can be substantially improved by increasing α and θ. With an appropriate crystal, which allows for a Bragg angle of e.g. $\theta = 70^o$, and with an appropriate layout of the spectrometer as in reference [2] one can obtain sufficient dispersion, so that statistical deviations of few tenths of a channel will be negligible.

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