Plasma Residual Poloidal Rotation in TCABR Tokamak

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Abstract. This paper reports the first measurement of the radial profiles of plasma poloidal and toroidal rotation performed on the TCABR tokamak for a collisional plasma (Pfirsch-Schluter regime), using Doppler shift of carbon spectral lines, measured with a high precision optical spectrometer. The results for poloidal rotation show a maximum velocity of $(4.5 \pm 1.0) \cdot 10^3$ m/s at $r \approx 2/3a$, (a - limiter radius), in the direction of the diamagnetic electron drift. Within the error limits, reasonable agreement is obtained with calculations using the neoclassical theory for a collisional plasma, except near the plasma edge, as expected. For toroidal rotation, the radial profile shows that the velocity decreases from a counter-current value of $(20 \pm 1) \cdot 10^3$ m/s for the plasma core to a co-current value of $(2.0 \pm 1.0) \cdot 10^3$ m/s near the limiter. An agreement within a factor 2, for the plasma core rotation, is obtained with calculations using the model proposed by Kim, Diamond and Groebner [5].

1. Introduction

The TCABR tokamak is a machine with a broad program of plasma physics investigation in small tokamaks: interaction of RF waves in the region of Alfvén frequencies, stochastic processes in plasma edge, transport barriers created by Alfvén waves, physical processes underlying transport barriers, residual and induced plasma rotation in plasmas. The study of plasma rotation in tokamaks is important for many reasons. It is well-known that the sheared radial electric field E_r plays an important role in tokamak plasmas, being responsible, first, for the creation of transport barriers and, second, for squeezing particle banana orbits in the core of large tokamaks [1]. In the first case, simple estimates to find the required radial electric field shear give $(cB_\theta R/B)\partial E_r/\partial(RB_\theta) \geq \gamma_{\max}$, where c is the light speed, r, R, B and B_θ are respectively minor and major torus radius and total and poloidal magnetic fields, $\gamma_{\max}$ is the growth-rate of the most dangerous instability in edge tokamak plasmas. In the second case, there is the so-called squeezing parameter S, $S = 1 - e_i B_\zeta^2/(M_i \omega_{ci}^2 B_\theta^2) dE_r/dr$. Here, B_ζ is the toroidal component of the magnetic field, e_i and M_i are the ion charge and mass, respectively, and $\omega_{ci} = e_i B/(cM_i)$ is the ion cyclotron frequency. The approximate value of the radial electric field E_r can be found from the radial projection of the ion momentum equation, and is given by

$$E_r \approx \frac{1}{c}\left(-B_\zeta U_{i\theta} + B_\theta U_{i\zeta} + BU_{pi}\right), \quad U_{pi} = \frac{c}{e_i n_0 B}\frac{\partial p_i}{\partial r}, \tag{1}$$

where $U_{i\theta}$ and $U_{i\zeta}$ are the poloidal and toroidal "physical" components of the ion velocity $\mathbf{V}_i$ respectively, p_i is the ion pressure, and n_0 is the maximum line averaged plasma density. It follows from Eq. (1) that, in addition to direct measurements of E_r in tokamak experiments, the radial electric field can also be calculated from $U_{i\theta}$ and $U_{i\zeta}$ and the diamagnetic velocity U_{pi}, obtained experimentally. This shows the importance of studying plasma rotation in tokamaks. From another side, there is a well-elaborated neoclassical theory of plasma rotation (the so-called residual rotation) in tokamaks [2]. The main result of this theory is that $U_{i\theta}$ is proportional to the gradient of ion temperature,

$$U_{i\theta} = kU_{Ti}, \qquad U_{Ti} = \frac{1}{M_i\omega_{ci}}\frac{\partial T_i}{\partial r}, \tag{2}$$

where the coefficient k depends on tokamak regime, and is equal to -1.83 in the collisional regime [2, 3].

2. Theoretical results

The study of physical processes in non-circular cross-section plasma could be performed in many tokamaks, and also in TCABR if additional magnetic poloidal coils are installed. In addition, interaction of AW with the tokamak plasma could produce toroidal rotation on the level of sound velocities. Taking this into account, we found it useful to generalize the theoretical expressions for plasma poloidal velocity to plasma shapes of arbitrary cross-sections.

Using toroidal coordinates r, θ, ζ, where r is the arbitrary magnetic surface function, and θ and ζ are poloidal and toroidal angles, respectively, we assume axial symmetry, i.e., $\partial/\partial\zeta = 0$, large aspect ratio, and smooth profiles of the macroscopic plasma quantities. The θ-contravariant velocity component V_i^θ can be found from the magnetic surface averaging of the parallel component of the momentum equation with the weight B

$$\int_0^{2\pi} d\theta \left(M_i n \frac{\mathbf{B}}{B^\theta} \cdot \frac{d_i \mathbf{V}_i}{dt} - \frac{3}{2}\pi_\parallel \frac{\partial \ln B}{\partial \theta} \right) = 0. \tag{3}$$

Here the parallel ion viscosity $\pi_\parallel$ is defined by [3] $\tilde{\pi}_\parallel = -2p_i\,(0.96\beta - 0.59\gamma)\,/\,(3\nu_i)$, where

$$\beta = 3\left\{ -V_i^\theta \frac{\partial}{\partial\theta} \ln\left(\sqrt{g}n^{2/3}B\right) + \frac{B^{\theta 2}}{B^2} V_i^\theta \frac{\partial g_{22}}{\partial \theta} + V_{Ti}\frac{\partial}{\partial\theta}\ln\frac{B}{n} \right\}, \tag{4}$$

$$\gamma = -3\left\{ 0.34 V_i^\theta \frac{\partial}{\partial\theta}\ln n + V_{Ti}\left(1.36\frac{\partial}{\partial\theta}\ln B - 0.84\frac{\partial}{\partial\theta}\ln n \right) \right\}, \tag{5}$$

$V_{Ti} = c\,[\mathbf{B}\times\boldsymbol{\nabla}T_i]^\theta\,/\,(e_iB^2)$, g_{ik} are the metric tensor components and g is its determinant.

We see from Eq. (3) that, in order to find V_i^θ, we need to calculate $\tilde{n}$ and $\widetilde{T}_i$. The equation for $\widetilde{T}_i$ follows from the ion heat transport equation

$$-T_iV_i^\theta \frac{\partial \tilde{n}}{\partial \theta} + \frac{B^\theta}{B}\frac{\partial q_{i\parallel}}{\partial\theta} + \boldsymbol{\nabla}\cdot\mathbf{q}_{i\perp} + \frac{3M_en\nu_e}{M_i}\widetilde{T}_i = 0, \tag{6}$$

where V_i^θ is the θ-contravariant component of the ion velocity $\mathbf{V}_i$, and

$$q_{i\parallel} = -3.91\frac{nT_iB^\theta}{M_i\nu_iB}\frac{\partial T_i}{\partial\theta}, \qquad \mathbf{q}_{i\perp} = \frac{5}{2}\frac{cnT_i}{e_iB^2}\left[\mathbf{B}\times\boldsymbol{\nabla}T_i\right]. \tag{7}$$

To find $\tilde{n}$ one can employ the parallel component of the plasma one-fluid momentum equation

$$\frac{\partial\left(p+\pi_{\|}\right)}{\partial\theta}+M_i n\frac{\mathbf{B}}{B^\theta}\cdot\frac{d_i\mathbf{V}_i}{dt}=0, \tag{8}$$

where $p=p_i+p_e=n_0\left(T_i+T_e\right)$.

Solutions to Eqs. (6) and (8) in the form of Fourier series and their substitution into Eq. (3) lead to the poloidal velocity V_i^θ

$$V_i^\theta=-1.83V_{Ti}f_2\left(\alpha,b,A,D\right)/f_1\left(\alpha,b,A,D\right), \tag{9}$$

where $f_1\left(\alpha\right)=\left(1+2\alpha/3\right)\left(1+0.46\alpha\right)A_{33}+A_{22}-\left(2+1.13\alpha\right)A_{23}+0.36\alpha^2bD_{33}$, $f_2\left(\alpha\right)=\left(1+2\alpha/3\right)\left(1+0.83\alpha\right)A_{33}+A_{22}-\left(2+1.5\alpha\right)A_{23}-0.48\alpha b\left[\left(1+\frac{\alpha}{2}\right)D_{33}-D_{23}\right]$,

$$A_{33}=\int_0^{2\pi}d\theta\left(\frac{\partial\ln g_{33}}{\partial\theta}\right)^2,\qquad A_{22}=\frac{1}{q^4R^4}\int_0^{2\pi}d\theta\left(\frac{\partial g_{22}}{\partial\theta}\right)^2, \tag{10}$$

$$A_{23}=\frac{1}{q^2R^2}\int_0^{2\pi}d\theta\frac{\partial\ln g_{33}}{\partial\theta}\frac{\partial g_{22}}{\partial\theta},\qquad D_{33}=\sum_{s=1}^{\infty}\frac{1}{d_s\left(b\right)}\left(\int_0^{2\pi}d\theta\sin s\theta\frac{\partial\ln g_{33}}{\partial\theta}\right)^2, \tag{11}$$

$$D_{23}=\frac{1}{q^2R^2}\sum_{s=1}^{\infty}\frac{1}{d_s\left(b\right)}\int_0^{2\pi}d\theta\sin s\theta\frac{\partial\ln g_{33}}{\partial\theta}\int_0^{2\pi}d\theta\sin s\theta\frac{\partial g_{22}}{\partial\theta}, \tag{12}$$

$\alpha=M_iU_{\zeta i}^2/\left(T_i+T_e\right)$, $d_s\left(b\right)=s^2+2.17b\sqrt{M_e/M_i}$, $b=B^2/\lambda_i^2B^{\theta 2}$, and $\lambda_i=\sqrt{2T_i/M_i}/\nu_i$ is the ion mean free path.

Let us analyze the expressions for ion poloidal velocity Eq. (9) in a general case. When the squared Mach number α vanishes, $\alpha=0$, we obtain from Eq. (9)

$$V_i^\theta=-1.83V_{Ti}, \tag{13}$$

which agrees with results of [3, 4]. Estimates show that parameters A_{23} and D_{23} are negative, $A_{23}<0$ and $D_{23}<0$. Hence, the denominator in Eq. (9) is positive and has no roots as a function of α. A remarkable property of the poloidal velocity V_i^θ is the change of sign at a value α_0 of the parameter α. This results for taking into account inertial forces in the starting equations. Assuming that the poloidal velocity changes sign at $\alpha<1$, we find from Eq. (9) $\alpha_0\approx 2.1\left(A_{33}+A_{22}-2A_{23}\right)/\left[b\left(D_{33}-D_{23}\right)\right]$.

From the approximate equation,

$$V_i^\theta\approx 0.88V_{Ti}\alpha b\left(D_{33}-D_{23}\right)/\left(A_{33}+A_{22}-2A_{23}+0.36\alpha^2bD_{33}\right), \tag{14}$$

one finds the critical quantity $\alpha_k\approx 1.67\sqrt{\left(A_{33}+A_{22}-2A_{23}\right)/\left(bD_{33}\right)}$, corresponding to the maximum of the poloidal velocity $V_{i(\max)}^\theta$,

$$V_{i(\max)}^\theta\approx 0.73V_{Ti}\sqrt{b}\left(D_{33}-D_{23}\right)/\sqrt{D_{33}\left(A_{33}+A_{22}-2A_{23}\right)}. \tag{15}$$

3. Experimental results and theoretical estimates

Recently, as a first step of the experimental program on the investigation of H mode physics, plasma poloidal and toroidal residual rotation measurements were performed on TCABR tokamak, which has the following parameters: minor radius $a = 0.18$ m, major radius $R = 0.61$ m, toroidal magnetic field $B_T = 1.13$ T, discharge current $I_P = 100$ kA, average density $n_e \simeq (1-3)\cdot 10^{19}$ m^{-3}, $T_i(0) \simeq 200$ eV, duration of the stationary phase of the discharge 60 ms. These preliminary measurements were fulfilled in the collisional regime (Pfirsch-Schlūter regime), using the Doppler shift of carbon spectral lines, $CIII$ (464.74 nm) and CVI (529, 02 nm). The set ups of the optical measurement system are shown in Figs.1 and 2. Radiation from the plasma column was focused on the spectrometer using lenses and an optical fiber. A semi-transparent mirror placed between the second lens and the spectrometer slit was used to collect the light from a neon lamp for calibration purposes, in order to achieve the high precision needed in the Doppler shift measurements ($\lambda \simeq 0.002$ nm). The intensities of the spectral lines were detected by a R943-2 (Hamamatsu) photomultiplier, and the signals recorded by an oscilloscope triggered by the loop voltage. A pulse from the TCABR master pulser triggers rotation of the diffraction grating of the spectrometer. Its velocity was measured from the known wavelengths of three neon lines and the elapsed times between them were measured on the oscilloscope, without plasma, just prior to the tokamak discharge. Then, during a TCABR discharge, the monochromator scanned the impurity spectral line followed by the calibration line. Using the calibration values and the measured profiles, the shift and broadening of the impurity spectral lines were obtained, and the plasma rotation and ion temperature calculated. The radial profile of the poloidal and toroidal velocities of the impurities are shown in Figs.3 and 4.

The experimental results for the poloidal velocity were compared with values calculates using the neoclassical theory obtained using Eq.(1) for the proton and for the carbon impurity in collisional regimes. Assuming $U_{i\zeta} \approx U_{I\zeta}$ [5] and $B_\zeta \approx B$, we obtain:

$$U_{\theta Z}^{neo} = -\frac{cT_i}{eB_\zeta}\left[\frac{\partial}{\partial r}\ln n_i - \frac{1}{Z}\frac{\partial}{\partial r}\ln n_Z + \left(1 - k - \frac{1}{Z}\right)\frac{\partial}{\partial r}\ln T_i\right], \tag{16}$$

where Z is the ion charge. The neoclassical poloidal velocity is shown in Fig.3 curve 2, showing reasonable agreements except near the limiter, as expected.

The radial profile of the toroidal velocity of $CIII$ and CVI impurities in TCABR, seen in Fig.4, shows that the toroidal velocity is counter-current and has a maximum of $(20 \pm 1)\cdot 10^3$ m/s for the plasma current core and decreases quickly towards the edge, reaching a co-current value of approximately $(2 \pm 1)\cdot 10^3$ m/s for $r = 0.16m$, at $0.02m$ from the limiter.

The radial electric field values, calculated for different minor radius of the plasma column, are in good agreement with analogous results obtained on similar small tokamaks (see, e.g. [4]). The obtained values are: $-3.9\cdot 10^3$ V/m for $r = 0.05m$; $-6.6\cdot 10^3$ V/m for $r = 0.10m$; $-6.5\cdot 10^3$ V/m for $r = 0.12m$; $-5.4\cdot 10^3$ V/m for $r = 0.14m$ and $-3.6\cdot 10^3$ V/m for $r = 0.16m$. The uncertainties in these values are $\sim 50\%$.

4. **Conclusions**

a) The plasma poloidal velocity is in the direction of the diamagnetic electron drift (see Fig.1), in agreement with results from other tokamaks. Comparison with values got using the neoclassical theory shows reasonable agreement for r between 0.05 and 0.14 m. For $r > 0.14m$ the experimental values decrease as expected due to the presence of the limiter, while the neoclassical theoretical values increase.

b) The measured TCABR plasma toroidal rotation velocity has a direction opposite to the plasma current, i.e., counter-current, decreases for increasing values of r, changing to co-current direction near the limiter. The values are $(20 \pm 1) \cdot 10^3$ m/s for the plasma core and $(2 \pm 1) \cdot 10^3$ for the co-current at $r = 0.16m$, $0.02m$ from the limiter. Calculations using the model proposed by Kim, Diamond and Groebner [5] give for TCABR a value of 10^4 m/s, showing an agreement within a factor 2 with experimental values for the plasma core. These findings are in agreement with results for similar tokamaks and operation regimes.

This first successful experiment on the study of plasma rotation in TCABR tokamak supports the continuation of the study of more complicated dependences of the proportionality coefficient k, Eq. (2), on macroscopic plasma parameters [3].

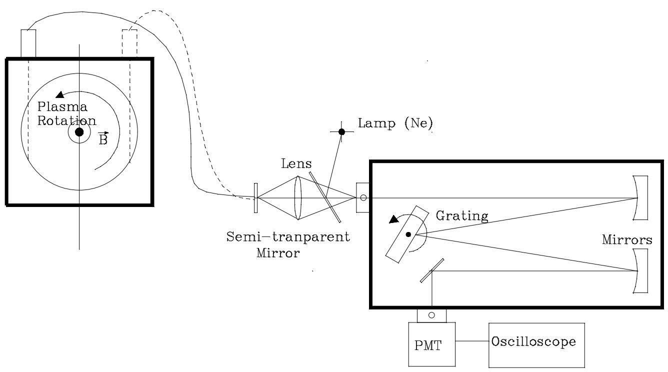

FIG. 1. Experimental set up for poloidal rotation

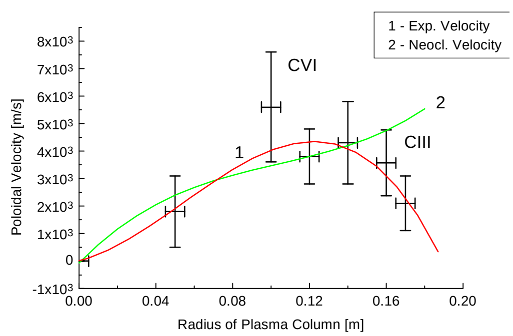

FIG. 3. Profile of the poloidal velocity

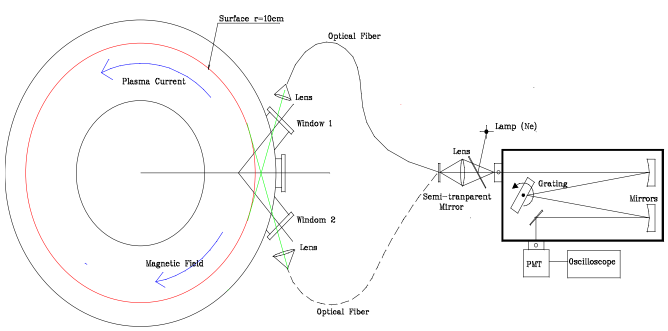

FIG. 2. Experimental set up for toroidal rotation

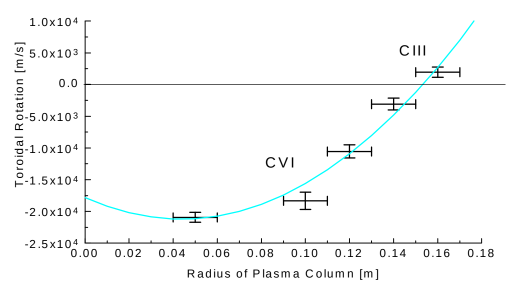

FIG. 4. Profile of the toroidal velocity

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