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Calculation of Impurity Poloidal Rotation from Measured Poloidal Asymmetries in the Toroidal Rotation of a Tokamak Plasma[a)]

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To improve poloidal rotation measurement capabilities on the DIII-D tokamak, new chords for the charge exchange recombination spectroscopy (CER) diagnostic have been installed. CER is a common method for measuring impurity rotation in tokamak plasmas. These new chords make measurements on the high-field side of the plasma. They are arranged in pairs that view co- and counter-neutral beams which allows them to measure toroidal rotation without the need for the calculation of atomic physics corrections. Asymmetry between toroidal rotation on the high- and low-field sides of the plasma is used to calculate poloidal rotation. Results for the main impurity in the plasma are shown and compared with a neoclassical calculation of poloidal rotation.

I. INTRODUCTION

This paper presents a new technique for measuring poloidal rotation in a tokamak. Rotation is an important component of tokamak plasma dynamics. Critical effects such as the suppression of turbulence through $\vec{E}\times\vec{B}$ shear,[1] the stabilization of the resistive wall mode and neoclassical tearing modes, and the formation of transport barriers are the result of rotation. Both the toroidal and poloidal rotation are important. Though poloidal rotation is typically smaller in magnitude, it can still play an important role in plasma dynamics, particularly in the edge of the plasma and when toroidal rotation is low. Charge exchange recombination spectroscopy (CER)[2] is typically used to measure rotation in tokamaks, but the measurement is complicated by the fact that the charge exchange cross section is energy dependent.[3-5] Toroidal rotation measurements can be made in such a way that the effect of the energy dependent cross section is directly measured,[6] but poloidal rotation measurements are typically made with vertical CER views that require atomic physics calculations to correct for the gyro-orbit coupling of the energy dependent cross section effect into the poloidal plane.[7] The ability to accurately measure poloidal rotation is necessary to develop a predictive understanding of rotation in tokamaks, but this task is complicated by the atomic physics effects that make up a significant portion of the measurement.

Neoclassical theory can predict rotation in tokamaks, but comparisons of neoclassical poloidal rotation to measurements have been mixed. In a high performance quiescent H-mode (QH-mode) plasma, the magnitude and direction of neoclassical predictions of poloidal rotation did not match measurements.[8] However, good agreement between theory and measurement has been seen in other conditions.[9] High quality poloidal rotation measurements are needed to further investigate the validity of the neoclassical formulation of rotation.

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The new method for measuring poloidal rotation presented in this paper is based on the functional form of the lowest order flow equations. For each plasma species, the flow equations are:[10]

$$\vec{V} = \omega(\rho)R\hat{\varphi} + K(\rho)\vec{B} \quad , \tag{1}$$

$$V_{\varphi} = \omega(\rho)R + K(\rho)B_{\varphi} \quad , \tag{2}$$

$$V_{\text{pol}} = K(\rho)B_{\text{pol}} \quad , \tag{3}$$

where ω and K are functions of the flux surface label ρ (the normalized square-root of the toroidal flux within a flux surface). Note that, in this formulation, density is also a flux function. Measurements of toroidal rotation at two different radii on the same flux surface allow ω and K to be calculated. Then, using Eq. (3), V_{pol} can be calculated. Because V_{pol} is not a flux function, the location where it is calculated needs to the specified. In this paper, V_{pol} is determined along the outboard midplane. At this location, a positive V_{pol} corresponds to moving in the $-z$ direction (i.e. the direction of gravity). The advantage of this new method is that only measurements of toroidal rotation are needed, and these can be made in such a way that the effect of the energy dependent cross section is directly measured.

II. EXPERIMENTAL APPARATUS

To make this new measurement, eight tangential chords were added to the CER diagnostic. These chords intersect neutral beams at positions near the plasma midplane with major radii that are smaller than the major radius of the magnetic axis. Four chords see a neutral beam that is injected co-parallel to the plasma current and four see a neutral beam that is injected counter-parallel to the plasma current such that the effect of the energy dependent cross section can be measured. Hardware upgrades were made to accommodate these new chords.

Four spectrometers were upgraded to have multiple slits and masked charge-coupled device (CCD) detectors which allowed light from more chords to be acquired by a CCD without sacrificing any fast acquisition abilities.[11] The spectrometers used for the CER diagnostic are Czerny-Turner type spectrometers,[12] and generally suffer from spherical aberration. Two of the previously mentioned spectrometers possess toroidal collimating mirrors which correct this aberration. The other two had their aberration corrected through the addition of thin glass plates at the spectrometer entrance slits.[13]

New chords that view the counter-injected beam were designed so that they matched the major radius of the new chords that view the co-injected beam. Each neutral beam on DIII-D has two ion sources, one which points more tangential to the toroidal direction, and one which points more perpendicular. The new views were designed to have matched major radii on the perpendicular source because this source is less attenuated at low major radii. For most experiments, the amount of charge exchange signal acquired by the new chords is sufficient for analysis.

Since temperature is expected to be constant on flux-surfaces, when CER data from inside and outside the magnetic axis is plotted versus a flux-surface label like ρ, the two profiles should be closely matched. Such profiles for a QH-mode plasma are shown in Fig. 1. Ten data points were acquired for tangential CER chords throughout a 100 ms window of stationary operation, and the measurement errors shown are the standard deviation of the data. This result suggests that the position of the new views is accurately known. For typical plasma shapes, CER data inside the magnetic axis can be acquired up to $\rho \approx 0.6$.

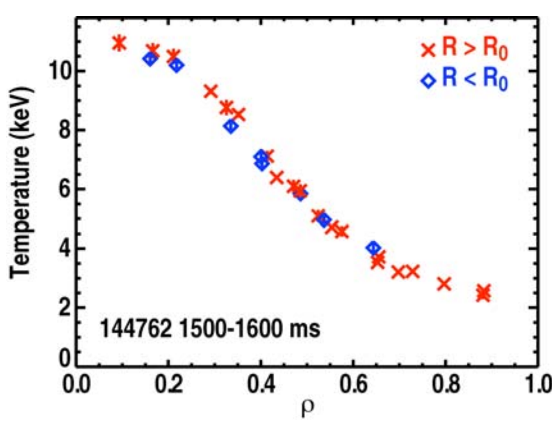

FIG. 1. Measured temperature as a function of ρ, showing how measurements from inside the magnetic axis ($R < R_o$) compare with measurements from outside the magnetic axis ($R > R_o$). Error bars are sometimes smaller than the symbol size.

III. RESULTS

In order to relate the toroidal rotation of Eq. (2) to tangential CER measurements, the rotation must be projected onto the CER sightlines, and a term must be added which accounts for the effect of the energy dependent cross section. Here, the effect of the energy dependent cross section is formulated the same as in Ref. 5: $\vec{V}_{\rm app} = \vec{V} + \alpha\hat{V}_{\rm b}$, where $\alpha\hat{V}_{\rm b}$ represents the effect on the measured plasma velocity and is aligned with the velocity of the beam neutrals. Taking a CER sightline to be $\hat{s} = s_R\hat{e}_R + s_\varphi\hat{e}_\varphi + s_z\hat{e}_z$, and β to be the angle between $\hat{V}_{\rm b}$ and $\hat{s}$, the line-of-sight velocity is:

$$V_{\rm los} = (\omega R + KB_\varphi)s_\varphi + \alpha\cos\beta \quad . \tag{4}$$

R, s_φ, and β are known for each chord based on calibrations with physical targets and B_φ is determined from a plasma equilibrium reconstruction from EFIT.[14] Spline functions are simultaneously generated for ω, K, and α to get a best fit to the line-of-sight data. The spline for α is well constrained by matched co- and counter-views. Because $B_\varphi \propto R^{-1}$, the terms involving ω and K have different dependence on major radius and therefore they make different relative contributions to $V_{\rm los}$ on the low and high major radius sides of the magnetic axis. This allows information about each term to be extracted from CER data that spans the magnetic axis and views both the co- and counter-injected neutral beams. With $B_{\rm pol}$ from the equilibrium reconstruction and the result of the fit, $V_{\rm pol}$ is calculated.

Analysis of C VI for one discharge is presented. In this discharge the plasma is heated primarily with electron cyclotron heating. At the time analyzed, central ion temperature was ≈ 1.2 keV and central electron density was $\approx 2.5\times10^{-19}$ m^{-3}. This time is after a transition to H-mode but before the first edge-localized mode. Neutral beams were only used briefly to generate CER data so that no fast-ion population could be sustained. This scenario is ideal for making comparisons to neoclassical theory.

Shown in Fig. 2(a) is the measured $V_{\rm los}$ for 20 CER chords taken during a 20 ms window and the $V_{\rm los}$ result from the fit. It can be seen that the fit has nearly replicated the measurements. The measurement errors are equal to the standard deviation of the four data points made in the time window. Figure 2(b) shows the splines that have been fit for ω and K. Given the limited number of measurements of rotation inside the magnetic axis, it is important that minimizing the errors between the fit and the data does not cause these splines to possess more detail than is justifiable. Figure 2(c) shows the $V_{\rm pol}$ that is calculated from the value of K in the fit, and a neoclassical prediction of $V_{\rm pol}$ from NCLASS[15] via the front-end code FORCEBALL.[16] Error bars in this figure are generated by a Monte Carlo method. This result shows qualitative agreement between the theory and the measurements. The measurements show poloidal rotation in the same direction as the theory, with a broad maximum in the magnitude of $V_{\rm pol}$ near $\rho \approx 0.3$, but the measurement shows lower magnitude $V_{\rm pol}$ throughout.

IV. DISCUSSION

Poloidal rotation of an impurity ion has been determined from measurements of tangential rotation on the high and low major radius side of the magnetic axis. The use of views of co- and counter-injected neutral beams has eliminated the need for atomic physics calculations. In the case presented, $V_{\rm pol}$ was found with an error of ≈ 0.5 km/s. Note that while this amount of error is relatively small for a rotation measurement, it is much larger than the amount of multiplicative error that can be introduced by inaccuracies in the value of $B_{\rm pol}$ from EFIT. The measurements made showed carbon poloidal rotation to be more ion-diamagnetic than the prediction from a neoclassical calculation of rotation.

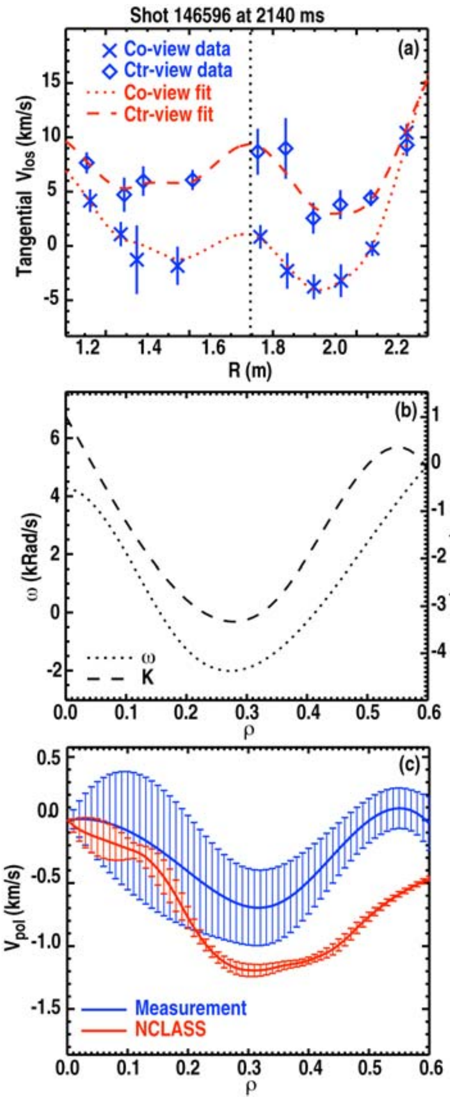

FIG. 2. (a) Measured V_{los} data and results from a fit of Eq. (4) to the data, showing good agreement, the separation between the co- and counter-viewing measurements shows the cross section effect, the vertical dotted line represents the location of the magnetic axis. (b) Spline fits for ω and K. (c) Calculated V_{pol} from the fit to the data and a NCLASS calculation.

This method of finding the poloidal rotation through measurements of tangential rotation depends on the functional form of Eq. (1). This functional form comes from the same type of derivation that leads to the current density used in the Grad-Shafranov equation. Results of solving the Grad-Shafranov equation are routinely used to control plasma equilibrium, and the success of these control algorithms suggests that the plasma rotation will be well described by Eq. (1).

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