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CHARACTERIZATION OF CROSS-SECTION CORRECTION TO CHARGE EXCHANGE RECOMBINATION SPECTROSCOPY ROTATION MEASUREMENTS USING CO+COUNTER NEUTRAL BEAM VIEWS

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Abstract

Measurements of rotation using charge exchange recombination (CER) spectroscopy can be affected by the energy dependence of the charge exchange cross-section. On DIII-D, the associated correction to the rotation can exceed 100 km/s at high temperatures. In reactor-relevant low rotation conditions, the correction can be several times larger than the actual plasma rotation and therefore must be carefully validated. New chords have been added to the DIII-D CER diagnostic to view the counter neutral beam (NB) line. The addition of these views allows determination of the toroidal rotation without depending on detailed atomic physics calculations, while also allowing experimental characterization of the atomic physics. A database of rotation comparisons from the two views shows that the calculated cross-section correction can adequately describe the measurements, although there is a tendency for “over-correction”. In cases where accuracy better than about 15% is desired, relying on calculation of the cross-section correction may be insufficient.

I. INTRODUCTION

Even though plasma rotation is widely acknowledged as playing a critical and beneficial role in fusion plasmas, the ability to make accurate and unbiased measurements of this important quantity in the core of high temperature plasmas has not been adequately validated. Rotation measurements are typically made by means of charge exchange recombination spectroscopy (CER) [1], and while the basic principle of determining velocity from the Doppler shift of a spectral line is relatively simple, the interpretation of this line-shift is complicated by atomic physics effects. In particular, the energy dependence of the charge exchange cross-section results in an apparent line-shift that is not directly related to plasma rotation [2-4]. Therefore, the measured line shift is a combination of the true plasma rotation plus some correction associated with the energy-dependent cross-section. The magnitude of the correction scales most directly with the ion temperature T_i, but other parameters also play a role, such as the plasma rotation and beam energy (which changes the "operating point" on the cross-section curve), and density and temperature (which alter the underlying cross-sections). In high temperature plasmas, corrections exceeding 100 km/s have been calculated (e.g. Refs [2,5]). However, such large corrections have invariably pertained to rapidly rotating plasmas, because the unidirectional neutral beam heating producing the large ion temperatures also deliver significant amounts of torque to the plasma. In such cases, the energy-dependent cross-section leads to corrections of typically 10%-20%. Necessarily, if the rotation is reduced while the temperature is kept high (as to be expected in future devices such as ITER), then these corrections become increasingly more important. Indeed, at low rotation speeds as attainable on DIII-D using balanced neutral beam (NB) injection, the apparent rotation can be completely dominated by the cross-section correction [6], and the true plasma rotation can easily be opposite to the apparent rotation. Therefore, a careful validation of the calculated cross-section correction is required in order to have confidence of the inferred rotation speed, especially for slowly rotating plasmas. Accordingly, a dedicated set of CER views have been installed on DIII-D to directly measure the magnitude of the cross-section correction applicable to rotation measurements.

In section II, we describe how one can isolate the cross-section correction using simultaneous views of co and counter (with respect to the plasma current I_p) injecting NBs, along with a discussion of how this technique is practically realized on the DIII-D CER system. Section III shows uncorrected and corrected velocities from the two views and compares with calculations based on the cross-section data. While the calculated velocities in many cases adequately reflect the true velocity, it is found that there tends to be a systematic error in these calculations compared with the inferred measurement. A discussion of the residual mismatch is given in section IV.

II. VIEWING GEOMETRY FOR CROSS-SECTION CORRECTION VALIDATION

As described in Ref. [4], the energy-dependent cross-section results in a velocity correction, $\vec{V}^{\mathrm{CX}}$, which is a vector pointed essentially along the direction neutral beam and whose magnitude depends on various atomic physics quantities, including the charge-exchange cross-section, population levels of excited energy states of the beam neutral [7,8], relative fractions of full-, half-, and third-energy components in the beam at the point in the plasma. The uncertainties in all of these can potentially lead to large systematic error in the determination of plasma velocity.

The amount of cross-section correction observed by a given CER channel is dependent on the relationship between the viewing geometry and the beam geometry. For unit viewing vector, $\hat{s}$, a chord will pick up an apparent velocity contribution $\left(\hat{s}\cdot\vec{V}^{\mathrm{CX}}\right)$. Thus, changing either the viewing geometry or the beam injection geometry will alter the fraction of cross-section correction that is measured. Evidence of the existence of the cross-section correction has been demonstrated using this principle [2,5]. As an aside, views perpendicular to the beam would see no direct cross-section effect. However, further complications arising from the gyro-motion of the ions come into play [4,9], but these are not particularly important for toroidal rotation measurements.

On DIII-D, we have exploited the geometry dependence to maximize our sensitivity to the cross-section effect and enable us to experimentally separate the cross-section effects from the true plasma velocity. In particular, we have installed seven new CER chords viewing the counter NB line as shown in figure 1. The different directions in beam injection result in the two complementary views observing cross-section corrections of the opposite *sign*. In practice, for the C VI ($n = 8 \rightarrow 7$) transition at $\lambda = 529.05$ nm used to measure the impurity carbon velocity, the charge exchange cross-section with deuterium beam neutrals with 80 kV injection energy is such that the co-views tend to underestimate the true rotation when the rotation is in the positive toroidal direction (counter-clockwise in figure 1), while the counter-views overestimate it. With two measurements and two unknowns, the true plasma velocity and cross-section correction can be solved analytically and determined experimentally, avoiding the uncertainties associated with calculating the cross-section effect.

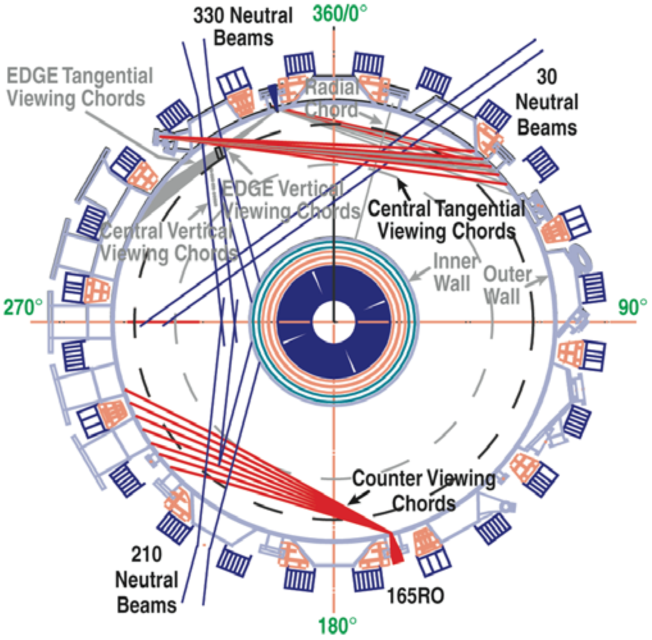

Fig. 1. Geometry of the DIII-D CER diagnostic and neutral beam arrangement, showing all present chords. Matching chords viewing the co and counter beams shown in red for clarity.

Specifically, if the beam makes an angle γ to the toroidal direction at the point of intersection with view chord, then the beam unit vector is simply $\hat{V}_b = \sin\gamma \hat{e}_R + \cos\gamma \hat{e}_\phi$ where $\hat{e}_R$ and $\hat{e}_\phi$ are the radial and toroidal unit vectors. Assuming that the beam velocity is much greater than the plasma velocity, then the apparent velocity including cross-section correction is simply $\vec{V}' = \vec{V} + \alpha \hat{V}_b$, where α is a scalar dependent on the atomic physics as described in Ref. [4]. For a chord with unit vector $\hat{s} = s_R \hat{e}_R + s_\phi \hat{e}_\phi + s_z \hat{e}_z$ (where $\hat{e}_z$ is the vertical unit vector), the measured velocity including the cross-section effect is $V = \hat{s} \cdot \vec{V}' = -\alpha s_R \sin\gamma + s_\phi \left(V_\phi + \alpha \cos\gamma \right)$, neglecting poloidal velocity, $V_z = 0$. With two velocity measurements V_1 and V_2 with viewing geometry $\hat{s}_1$ and $\hat{s}_2$ viewing separate beams with toroidal angles γ_1 and γ_2, one can uniquely determine the toroidal velocity and cross-section correction:

$$\alpha = \frac{s_{2\phi} V - s_{1\phi} V_2}{s_{2R} s_{1\phi} \sin\gamma_2 - s_{1R} s_{2\phi} \sin\gamma_1 + s_{1\phi} s_{2\phi} \left(\cos\gamma_1 - \cos\gamma_2 \right)}$$

$$V_\phi = \frac{V_1 + \alpha s_{1R} \sin\gamma_1}{s_{1\phi}} - \alpha \cos\gamma_1 \tag{1}$$

$$= \frac{V_2 + \alpha s_{2R} \sin\gamma_2}{s_{2\phi}} - \alpha \cos\gamma_2 \quad .$$

III. MEASUREMENT OF TOROIDAL ROTATION FROM CO AND COUNTER VIEWS

In the discharge presented in figure 2, measurement of the central toroidal velocity ($R \sim 1.77$ m, $\rho < 0.05$) has been made by two CER channels viewing a co and counter beam respectively. This particular discharge was selected simply because it spans a broad space in rotation and temperature, which are of primary interest in this study. The rotation is initially in the negative toroidal direction and ramps to the positive direction, and the ion temperature is initially relatively low, $T_\mathrm{i} < 3$ keV increasing to $T_\mathrm{i} > 6$ keV by 2000 ms. The uncorrected velocities show clear evidence of the cross-section correction, with the measurements differing by up to 40 km/s later in the discharge. Using the complete beam and viewing geometry, the two measurements are combined and the cross-section correction and the toroidal velocity are determined. For comparison, the correction is calculated using cross-sections from the Atomic Data and Analysis Structure (ADAS) database, including up to the $n = 2$ excited energy state for the deuterium neutral. Early in time, the calculated cross-section correction for the two chords closely matches the experimentally determined quantity, but after approximately 1000 ms, the calculation results in an “over-correction'” of the measurement.

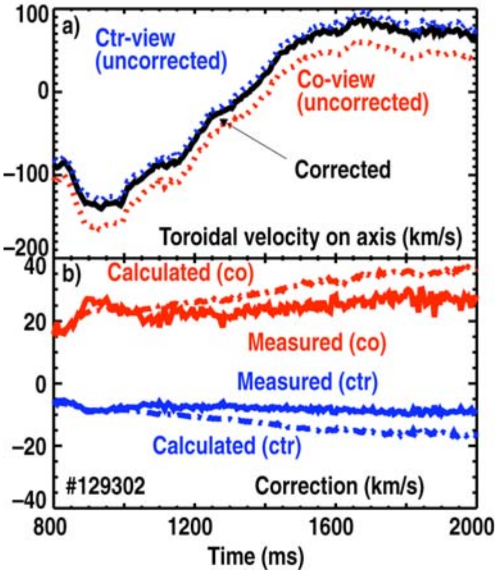

Fig. 2. (a) Toroidal velocity inferred from simultaneous measurement from co and counter viewing CER chords at $R \sim 1.77$ m ($\rho < 0.05$). The uncorrected velocities (dotted) show significant difference, due to cross-section effects. (b) Comparison of measured and calculated cross-section correction for the two chords. Calculation of the correction results in significant over-correction.

The accuracy of calculating the cross-section correction depends on the specifics of the plasma parameters. Figure 3 shows a comparison of rotation profiles acquired from the co and counter view CER chords in both rapidly and slowly rotating plasmas. In this discharge, the neutral beam injection is initially counter dominated, switching to balanced later in time. For the slowly rotating plasma, the uncorrected velocities from the two views do not even agree on the direction of rotation, and the difference between the central values is more than a factor of five greater than the actual rotation speed. In this particular case, calculating and applying the cross-section correction brings the two views into acceptable agreement for both the high and low rotation cases. Note that at the earlier time, both the beams in the counter beam line were being modulated out of phase, and since the radial position of the chords shifts depending on which beam it is viewing, we have effectively twice the number of radial positions from the counter view.

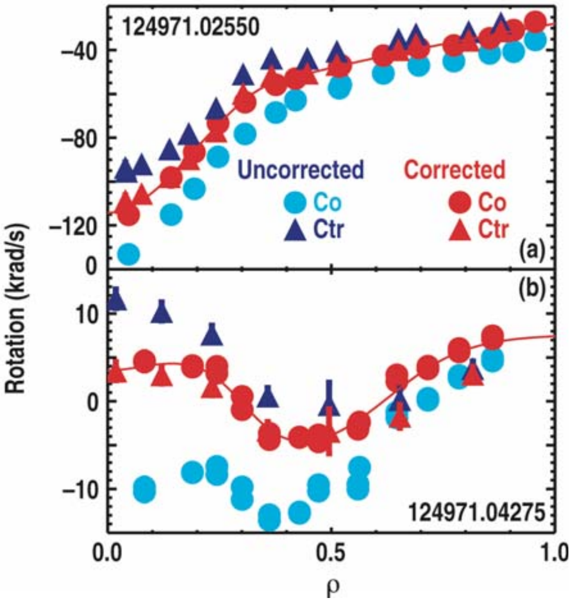

Fig. 3. Comparison of rotation profiles with and without calculated atomic physics correction at (a) t = 2550 ms with large rotation and (b) t = 4275 ms with very low rotation. Without the correction, measurements from the co NB form a separate profile than those measured from the counter NB.

A broad database has been built up from discharges taken since the installation of the new views, using automated CER analysis (CERQUICK). This database includes plasmas from a wide range of conditions, including ion temperatures ranging from 300 eV up to 15 keV and toroidal velocities from 0 km/s to over 300 km/s. From this data, the statistical performance of the calculated cross-section correction has been investigated for the central-most matched co/counter CER views. Overall, there is a tendency to over-correct, and the median difference between the corrected velocities is found to be approximately 15%. In absolute terms, the two corrected measurements are found to be within 10 km/s of each other at least 73% of the time.

IV. DISCUSSION

Several possibilities exist to explain the systematic difference observed between the calculated corrected toroidal velocities. By far, the most trivial possibility is that there is simply a systematic error in the determination of the zero of rotation between the two systems. However, the velocities tend to match well at early times when the ion temperature is very low (and therefore the cross-section correction is small) suggesting that the issue is not related to a fiducial issue.

Although a geometry error in the chords' viewing location might in principle result in a systematic error in the measured velocity, the fact that the rotation profile is generally pretty flat in the plasma center makes this an unlikely reason for the observed differences. In addition, the good agreement of the temperature between the matched pairs of chords also argues that the geometry is not the issue.

The most likely problem is related to the calculation of the cross-section correction itself. We have investigated the details of this over-correction in discharges with optimal beam modulation for the best quality CER data. In these cases, again a systematic over-correction was observed. In order to bring the inferred rotations into agreement, one needs a mechanism to reduce the amount of cross-section correction. One such possibility involves tweaking the population level for the $n = 2$ excited energy state of the deuterium beam. The cross-section for $n = 2$ excited energy state is peaked at low energies [7,8], and even for low excited state populations (a fraction of a percent), results in an effective cross-section that reduces the total cross-section correction. In this discharge, it requires an artificial enhancement of the $n = 2$ fraction by a factor of three from the calculated value (which was approximately 0.25% at the third energy) to bring these two measured quantities into agreement. Error in the calculated cross-section could presumably also arise by including higher excited states above $n = 2$, having inaccurate half and third energy fractions (including effects of beam attenuation) or even errors in the underlying cross-section data. Fundamentally, if better than approximately 15% accuracy is desired for rotation measurements, then relying on calculations of the cross-section correction may be inadequate. Simultaneous CER measurements of co and counter neutral beams offers the possibility of avoiding the systematic uncertainties in such calculations.

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Acknowledgments

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