X RAY OBSERVATIONS OF CENTRAL TOROIDAL ROTATION IN OHMIC ALCATOR C-MOD PLASMAS

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ABSTRACT. Impurity toroidal rotation has been observed in the centre of ohmic plasmas in the Alcator C-Mod tokamak from the Doppler shifts of argon and molybdenum X ray lines. The rotation is highest (~6 x 10^6 cm/s) in the early portion of the discharges, when the loop voltage is highest and the electron density is lowest, and then typically settles to values ≤ 2 x 10^6 cm/s during the steady state period. The impurity rotation is in the same direction as the electron toroidal drift, opposite to the plasma current, and reverses direction when the plasma current direction is reversed. Molybdenum and argon ions rotate with the same velocity. These observations are in qualitative agreement with neoclassical theory.

1. INTRODUCTION

While there have been several diagnostic systems designed to measure impurity toroidal rotation in tokamak plasmas [1–19], most of the observations have been made in plasmas with an external momentum source, usually provided by neutral beams. These techniques mostly rely on visible and near ultraviolet observations of collisionally excited intrinsic impurities [1–8, 10, 18], or of visible lines populated by charge exchange recombination from a neutral beam [11, 13, 15, 17, 19]. There are X ray measurements from intrinsic impurities [9, 12, 16]; for the Tokamak Fusion Test Reactor (TFTR) measurements, there was no wavelength calibration and the rotation during the ohmic phase was assumed to be zero, to provide a reference for the rotation during neutral beam injection. Typical values of the rotation velocity with neutral beam input are in the range of a few units of 10^7 cm/s. Some toroidal rotation during purely ohmic plasmas has been observed [1, 5, 7, 14, 18], and there have been some ancillary measurements of toroidal rotation during the ohmic phase of neutral beam plasmas [2, 3, 4, 6, 10]. The ohmic results are summarized in Table I. Values of the rotation velocity for ohmic plasmas are of order 10^8 cm/s, more than an order of magnitude lower than the neutral beam injection results. Here, negative values indicate rotation in the direction opposite to the plasma current. There is a wide range of velocities (in magnitude and direction) in this table, so further study is warranted. To date there has been little systematic analysis of these ohmic results, other than to deduce values for the radial electric field [20] from the formalism of Ref. [21]. Recently [22], the central toroidal neoclassical impurity rotation velocity in ohmic discharges has been derived from the parallel momentum and heat flow balance equations. The toroidal rotation velocity is given in terms of routinely measured plasma parameters, and will be compared with observations below.

Table I. Central Toroidal Rotation during Ohmic Discharges

| Device     | $V_{tor}$ (cm/s) | Ref. |
|------------|-----------------|-----|
| LT-3       | +5 x 10^6       | [1] |
| PLT        | -1.5 x 10^6     | [2] |
| JFT-2      | -1.3 x 10^6     | [3] |
| Torus II   | +1.6 x 10^6     | [5] |
| PDX        | ≤3 x 10^6       | [6] |
| TM-4       | -7 x 10^5       | [7] |
| ISX        | ~0              | [10]|
| DIII-D     | -2.5 x 10^6     | [14]|
| TCA        | ±4 x 10^6       | [18]|

The organization of this paper is as follows: a description of the experimental set-up is given, followed by a presentation of the toroidal rotation observations and a comparison with the predictions of neoclassical theory.

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2. EXPERIMENT DESCRIPTION

The observations presented here were obtained from the Alcator C-Mod [23] tokamak, a compact (major radius \( R = 67 \) cm), high field device with molybdenum plasma facing components. During most operations, the plasma current is in the counter-clockwise direction as viewed from the top of the machine. X ray spectra were recorded with a von Hamos type X ray spectrometer [24], whose line of sight is tangential to the plasma axis, pointing in the counter-clockwise direction, as viewed from above. Rotation velocities have been determined from the Doppler shifts of the argon Lyman \( \alpha \) (Ly\( \alpha \)) doublet [25] (1s \( ^1S \rightarrow 2p \) \( ^2P \) at 3731.1 mA and 1s \( ^1S \rightarrow 2p \) \( ^2P \) at 3736.5 mA) and the 2p\(^0\)→(2p\(^0\))\(_4\)4d\(_4\) transition [26] in Mo\(^{32+}\) at 3739.8 mA. The emissivities from these ions are very centrally peaked in minor radius, so variations with plasma major radius are negligible. Spectra are typically collected every 50 ms during plasma discharges. Argon is routinely injected into Alcator C-Mod plasmas through a piezoelectric valve, to provide X ray transitions for Doppler width ion temperature measurements [27]. Molybdenum is an intrinsic impurity, usually present in all Alcator C-Mod discharges. Absolute wavelength calibration was obtained from the potassium K\( \alpha \) lines generated from a KCl fluorescence X ray source [25], and was reproducible over time.

3. OBSERVATIONS OF TOROIDAL ROTATION

In Fig. 1 X ray spectra are shown, including the argon and molybdenum lines used for the rotation analysis. The thin vertical line indicates the wavelength for Ar\(^{17+}\) Ly\( \alpha \) at rest. The spectrum on the left (the chain curve) is from a plasma with the current in the counter-clockwise direction. Since the spectrometer is viewing counter-clockwise, and the spectrum is blue shifted, the impurities (argon and molybdenum) are rotating clockwise, in the same direction as the electrons, opposite to the plasma current. The magnitude of the shift is \(-0.5\) mA, which yields a toroidal rotation velocity of \((0.5 \text{ mA}/3731.1 \text{ mA}) \times c = 4 \times 10^6 \text{ cm/s}, in what will be defined in this paper to be the negative direction. The spectrum on the right (shown by the solid curve) is from a reversed (clockwise) current plasma; the spectrum is red shifted by about the same amount, and the impurities are rotating counter-clockwise, again in the same direction as the electrons. In Fig. 2 the time histories of several parameters of interest are shown for a discharge similar to the one for which the blue shifted spectrum of Fig. 1 was obtained. In the top frame is the plasma current, in the counterclockwise direction, which increases to about 800 kA at the peak (here shown as a negative current). In the next frame is the loop voltage, which peaks at \(-7\) V, then decays to around \(-2\) V. The central electron density [28] is shown in the middle frame by the solid curve. The chain curve in the same frame is the ion density, calculated from the electron density as \( n_e \frac{1 - (Z_{\text{eff}} - 1) / 8}{Z_{\text{eff}}} \), where \( Z_{\text{eff}} \) is measured, and the average \( Z \) of all impurities is taken to be 8. In the next frame is the central electron temperature from electron cyclotron emission (ECE) [29] (solid curve) and the central ion temperature [27] (asterisks) from X ray Doppler widths. In the bottom frame is the central toroidal rotation velocity from the X ray Doppler shift of the Ar\(^{17+}\) lines. The rotation is highest at the beginning of the discharge, and slows down during the steady state portion. The rotations of argon and molybdenum ions are very similar, which is demonstrated in Fig. 3, where the rotation velocity deduced from Ar\(^{17+}\) and Mo\(^{32+}\) is shown as a function of time. The line brightness time histories for these two lines are very different. The molybdenum signal is strongest in the early portion of the
discharge [30] around 100 ms, when the plasma is in contact with the molybdenum walls and before the plasma is diverted, and drops substantially during the high density portion of the discharge when the electron temperature is lowest. In contrast, argon is usually injected at 300 ms into the discharge, so the signal before that time is very low, and then increases and holds steady at an ample level for the remainder of the discharge. The rotation velocity time histories for these two ions, however, are nearly the same.

As was shown in Fig. 1, when the current is in the counter-clockwise direction, the impurities (and electrons) rotate in the clockwise (negative) direction, and when the current is in the clockwise direction, the impurities (and electrons) rotate in the counter-clockwise (positive) direction. The complete rotation time histories for two such cases are shown in Fig. 4. In both cases, the magnitude of the rotation is largest at the beginning of the discharge when the loop voltage is highest and the density is low, and then decreases as the discharge develops. In order to demonstrate the apparent correlation between the rotation velocity and the loop voltage, these two quantities are plotted in Fig. 5 for the two discharges shown in Fig. 4, where the variable time has been eliminated. The solid line represents the best fit to the points. While there is considerable scatter, the data reflect the general trend. There is also an apparent relation between the rotation velocity and the temperature, in that these two are highest at the beginning of the discharges and fall later on, as well as an apparent inverse relation with the density. However,
FIG. 3. Rotation velocity time histories for molybdenum (solid curve) and argon (chain curve) ions.

in a plot similar to Fig. 5 using these parameters as the variables, there is much more scatter than when using the loop voltage.

4. COMPARISON WITH NEOCLASSICAL THEORY

Neoclassical toroidal rotation has been calculated [22] from the electron, ion and impurity parallel momentum and heat flow balance equations [31], under the assumption of no net momentum input, appropriate for ohmic discharges. The expression for the toroidal impurity rotation velocity is given as (from Eq. (56), Ref. [22])

$$V_{	ext{tor}}^2 = 4.19 \times 10^7 f Z_i V_i T_i^{3/2} \frac{\sqrt{\mu}}{R} \frac{n_i}{n_i} \quad (\text{cm/s}).$$

Here, $Z_i$ is the charge of the background ions, $\mu$ is the mass of the background ions in amu, $V_i$ is the loop voltage in volts, $R$ is the major radius in centimetres, $T_i$ is the ion temperature in kiloelectronvolts, $n_i$ is the ion density in $10^{14}$ cm$^{-3}$ and

$$f = \frac{Z_i - Z_i}{Z_i} \frac{\sqrt{2} + 13 \alpha/4}{(1 + \alpha)(\sqrt{2} + \alpha)} \frac{n_i m_i}{n_i m_i + n_i m_i}.$$  

(2)

Here, $Z_i$ is the charge of the impurity ion, $n_i$ is the impurity ion density, $m_i$ is the impurity ion mass, $m_i$ is the background ion mass and $\alpha \equiv n_i Z_i^2 / n_i Z_i^2$. $f$ is of order 1 for typical Alcator C-Mod conditions, and is plotted in Fig. 6 as a function of $n_i/n_i$. Four cases are shown, Mo$^{32+}$ and Ar$^{17+}$ in hydrogen and deuterium plasmas. Alcator C-Mod is usually operated with deuterium as the majority ion, and nominal maximum values for the impurity concentration $n_i/n_i$ are $2 \times 10^{-4}$ ($\alpha = 0.2$) for molybdenum [30] and $3 \times 10^{-4}$ ($\alpha = 0.09$) for argon. In any case, the
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FIG. 6. The quantity $f$ (Eq. (2)) as a function of relative impurity concentration for Mo$^{2+}$ and Ar$^{17+}$ ions in hydrogen and deuterium plasmas.

difference in toroidal rotation between these ions is only a few per cent, well within the scatter shown in Fig. 3.

In Eq. (1), the impurity rotation direction is the same as that of the electrons. The observed rotation direction is the same as that predicted in the calculation of Ref. [22].

For the deuterium discharge shown in Fig. 2, the loop voltage was 2.5 V, the ion density was $1.0 \times 10^{14}$ cm$^{-3}$ and the ion temperature was 1.36 keV at 400 ms. Equation (1) predicts a toroidal rotation velocity of $1.7 \times 10^6$ cm/s, which is close to the observed value of $3.9 \times 10^6$ cm/s. The complete time histories of the calculated (from Eq. (1)) rotation velocities for the discharges of Fig. 4 (and Fig. 2) are shown in Fig. 7. The predicted values are in good qualitative agreement with the observed velocities, and are everywhere within a factor of 3 of each other. The calculation only extends to 0.9 s, since in both cases there was ion cyclotron resonance frequency (ICRF) power injected and the discharges are no longer purely ohmic.

There are no dynamics in the predictions of Eq. (1), so it is not surprising that there are large discrepancies in the early part of the discharge, when parameters are changing rapidly ($t \leq 50$ ms), and the predicted velocities are much larger than the observed ones. The impurities must be ionized and accelerated in a low density plasma, from their initial rest velocity at breakdown. Also early in the discharge, the loop voltage can be larger than the calculated voltage on the magnetic axis. During the steady state portion of these discharges, the predictions underestimate the measured velocities, because the impurities have not completely slowed down from the large rotation they obtained earlier, when the voltage was high and the density was low.

The only true externally controlled variable in Eq. (1) is the electron (ion) density, which is determined by gas puffing rates. The loop voltage is influenced by the time history of the plasma current and the electron density, and is not independently set. The ion temperature is also not set in ohmic discharges, but is determined by the electron density and temperature. It is possible to vary $\mu$, by running in hydrogen gas, which would change Eq. (1) by $\sqrt{2}$. However, when operating at the same electron (ion) density, the ion temperature and loop voltage are different in hydrogen working gas (by more than a factor of $\sqrt{2}$), so the effect of changing $\mu$ is hidden.

In the derivation of the impurity toroidal rotation velocity in Ref. [22], it was assumed that the impurity collisionality is in the Pfirsch–Schlüter regime (which is well satisfied for argon and molybdenum throughout Alcator C-Mod plasmas), that $\epsilon = 0$ and viscous forces were ignored. These last two assumptions
probably do not affect the rotation calculation on the magnetic axis.

5. CONCLUSIONS

The central impurity toroidal rotation has been measured from the Doppler shift of X-ray lines from argon and molybdenum in ohmic Alcator C-Mod plasmas. The magnitude of the rotation is largest (~6 x 10^6 cm/s) at the beginning of the discharges, and settles to less than 2 x 10^6 cm/s during the steady state portion. The direction of the rotation is the same as that of the electrons, opposite to the plasma current, and reverses when the plasma current is reversed. The rotation velocities are the same for Ar^{17+} and Mo^{32+}. The rotation time histories qualitatively follow the loop voltage time evolution. These observations are in good qualitative agreement with neoclassical theory.

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