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X-ray Observations of Central Toroidal Rotation in Ohmic Alcator C-Mod Plasmas

J.E. Rice, E.S. Marmar, F. Bombarda[1], L. Qu

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[1]Associazione ENEA-Euratom per la Fusione, 00044 Frascati, Italy.

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J. E. Rice, E. S. Marmar, F. Bombarda[†] and L. Qu

Plasma Fusion Center, MIT

Cambridge, MA 02139-4307

[†] *Associazione ENEA-Euratom per la Fusione, 00044 Frascati, Italy*

Abstract

Impurity toroidal rotation has been observed in the center of Alcator C-Mod ohmic plasmas from the Doppler shifts of argon and molybdenum x-ray lines. The rotation is highest ($\sim 6 \times 10^6$ 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 $\leq 2 \times 10^6$ 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 neo-classical theory.

Introduction

While there have been several diagnostic systems designed to measure impurity toroidal rotation in tokamak plasmas [1-15], 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 UV observations of collisionally excited intrinsic impurities [1-8,10], or of visible lines populated by charge exchange recombination from a neutral beam [11,13,15]. There are x-ray measurements from intrinsic impurities [9,12], but since the viewing angles in these cases are close to radial, the lower limit for toroidal rotation measurements precludes observation during ohmic discharges. Typical values of the rotation velocity with neutral beam input are in the range of a few $\times$ 10^7 cm/s. Some toroidal rotation during purely ohmic plasmas has been observed [1,5,7,14], 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 10^6 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 from the formalism of Ref.[16]. Recently [17], the central toroidal neo-classical 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.

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

Experiment Description

The observations presented here were obtained from the Alcator C-Mod [18] tokamak, a compact (major radius R = 67 cm), high field device with molybdenum plasma facing components. During most operation, 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 [19], whose line of sight is tangent to the plasma major radius, pointing in the counter clockwise direction, as seen from above. Rotation velocities have been determined from the Doppler shifts of the argon Lyman α doublet [20] (1s $^1S_{\frac{1}{2}}$ - 2p $^2P_{\frac{3}{2}}$ at 3731.1 mÅ, and 1s $^1S_{\frac{1}{2}}$ - 2p $^2P_{\frac{1}{2}}$ at 3736.5 mÅ) and the $2p^6$ - $(2p^5)_{\frac{3}{2}}4d_{\frac{5}{2}}$ transition [21] in Mo^{32+} at 3739.8 mÅ. 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 [22]. Molybdenum is an intrinsic impurity, usually present in all Alcator C-Mod discharges. Absolute wavelength calibration was obtained from the potassium K_α lines generated from a KCl fluorescence x-ray source [20].

Observations of Toroidal Rotation

Shown in Fig.1 are x-ray spectra including the argon and molybdenum lines used for the rotation analysis. The thin vertical line indicates the rest wavelength for Ar^{17+} $Ly_{\alpha 1}$. The spectrum on the left (dash-dot-dot-dot line) 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 $\sim$.5 mÅ, which yields a toroidal rotation velocity of (.5 mÅ/3731.1 mÅ) $\times$ c = 4 $\times$ 10^6 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

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spectrum is red-shifted by about the same amount, and the impurities are rotating counter clockwise, again in the same direction as the electrons. Shown in Fig.2 are the time histories of several parameters of interest 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 counter clockwise direction, which increases to about 800 kA at the peak (here shown as negative current). In the next frame is the loop voltage, which peaks at −7 volts, then decays to around −2 volts. The central electron density [23] is shown in the middle frame by the solid curve. The dash-dot-dot-dot line in the same frame is the ion density, calculated from the electron density as $n_e(1 - (Z_{eff}-1)/8)$, where Z_{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 ECE [24] (solid curve) and the central ion temperature [22] (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 rotation of argon and molybdenum ions is 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 [25] 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

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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 curve 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 drop later on, as well as an apparent inverse relation with the density. However, in a plot similar to Fig.5 using these parameters as the variables, there is much more scatter than when using the loop voltage.

Comparison with Neo-Classical Theory

Neo-classical toroidal rotation has been calculated [17] from the electron, ion and impurity parallel momentum and heat flow balance equations [26], 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.[17])

$$V_{Tor}^I \quad = \quad 4.19 \times 10^7 \quad f \quad \frac{Z_i}{\sqrt{\mu}} \quad \frac{V_l}{R} \quad \frac{T_i^{3/2}}{n_i} \quad (cm/s). \tag{1}$$

Z_i is the charge of the background ion, μ is the mass of the background ion in amu, V_l is the loop voltage in volts, R is the major radius in cm, T_i is the ion temperature in keV, n_i is the ion density in $10^{14} cm^{-3}$ and

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

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 2×10^{-4} (α=0.2) for molybdenum [25] and 3×10^{-4} (α=.09) for argon. In any case the difference in toroidal rotation between these ions is only a few percent, well within the scatter shown in Fig.3.

In Eq.1, the impurity rotation direction is in the same direction as the electrons. The observed rotation direction is the same as that predicted in the calculation of Ref.17.

For the deuterium discharge shown in Fig.2, the loop voltage was 2.5 V, the ion density was 1.0×10^{14} cm^{-3} and the ion temperature was 1.36 keV at 400 ms. Eq.1 predicts a toroidal rotation velocity of 1.7×10^{6} cm/s, which is close to the observed value of 3.9×10^{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.

There are no dynamics in the predictions of Eq.1, so it's not surprising that there are large discrepencies 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 haven't 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

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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 μ, 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 μ is hidden.

In the derivation of the impurity toroidal rotation velocity in Ref.[17], 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 are ignored. These last two assumptions probably don't affect the rotation calculation on the magnetic axis.

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 ($\sim 6 \times 10^6$ cm/s) at the beginning of the discharges, and settles to less than 2×10^6 cm/s during the steady state portion. The direction of the rotation is in the same direction as the electrons, opposite to the plasma current, and switches direction when the plasma current is reversed. The rotation velocity is 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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Table I. Central Toroidal Rotation during Ohmic Discharges

Device	V_{Tor} (cm/s)	reference
LT-3	$+5 \times 10^5$	1
PLT	-1.5×10^6	2
JFT-2	-1.3×10^6	3
Torus II	$+1.6 \times 10^6$	5
PDX	$\leq 3 \times 10^5$	6
TM-4	-7×10^5	7
ISX	~ 0	10
DIII-D	-2.5×10^6	14

Figure Captions

Fig. 1   X-ray spectra of the Ar^{17+} Ly_α doublet and the $2p^6$ - $(2p^5)_{\frac{3}{2}}4d_{\frac{5}{2}}$ transition in Mo^{32+} for CCW I_P (dash-dot-dot-dot) and CW I_P (solid) discharges. The $Ly_{\alpha1}$ rest wavelength of 3731.1 mÅ is shown by the thin vertical line.

Fig. 2   The time histories of several parameters for a 5.3 T, deuterium discharge. In the top frame is the plasma current, where the negative sense indicates counter clockwise current. In the second frame is the loop voltage. In the middle frame is the central electron density (solid) and the central ion density (dash-dot-dot-dot). In the fourth frame is the central electron temperature (solid) and the central ion temperature (asterisks). In the bottom frame is the central toroidal rotation velocity of Ar^{17+}, where the negative sense indicates clockwise rotating impurities.

Fig. 3   The rotation velocity time histories for molybdenum (solid) and argon (dash-dot-dot-dot) ions.

Fig. 4   The toroidal rotation velocity time histories for clockwise (solid) and counter clockwise (dash-dot-dot-dot) plasma current.

Fig. 5   The toroidal rotation velocity as a function of loop voltage for the two discharges shown in Fig.4. The solid curve is the best linear fit to the data.

Fig. 6   The quantity f (Eq.2) as a function of relative impurity concentration for Mo^{32+} and Ar^{17+} ions in hydrogen and deuterium plasmas.

Fig. 7   The calculated rotation velocity (solid curves) time histories (from Eq.1) compared to the measured (asterisks) values from Fig.4.