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Comparison of measured poloidal rotation in MAST plasmas with neo-classical predictions

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Introduction:

Neo-classical tokamak plasma theory predicts bulk ion poloidal flows of order $v_\theta^i \sim v_{th,i}\,\rho_i / L_{T_i}$, which are driven by the temperature gradient of typically a few km/s. On JET and DIII-D, impurity poloidal flows measured using charge exchange recombination spectroscopy on C^{6+} ions have been observed to exceed the neo-classical predictions by up to an order of magnitude, particularly in the vicinity of internal transport barriers (ITBs), although agreement with neoclassical theory was recorded for poloidal flows on TEXT [1]. The apparent velocity determined from the Doppler shift can differ from the fluid velocity due to the energy dependence of the charge-exchange cross-section and the finite lifetime of the excited state. As this 'pseudo' velocity scales as $\Delta v_{cx} \propto T_i B$, these corrections are much smaller for measurements on low field Spherical Tokamaks (STs) and smaller machines than on the larger high field devices, where they can be comparable to the measured velocities. Here, the predictions of neoclassical theories from Newton and Helander [2], Kim [3] and the NCLASS code [4], are compared with one another and a comparison of measurements with the predictions of Kim [3] is presented. In L- and H-mode plasmas the measured poloidal velocities are found to be consistent with the neo-classical predictions within the uncertainties. Preliminary poloidal flow measurements on NSTX [5] also show agreement with the predictions of NCLASS.

Theory:

In neo-classical theory the poloidal flow of the bulk ions v_θ^i is heavily damped with a small residual flow driven by the ion temperature gradient. According to the theory of Kim [3], which is valid for a single impurity species in all collisionality regimes, v_θ^i is given by:

$$v_\theta^i = \frac{1}{2}\frac{v_{th,i}\rho_i}{L_T} K_1 \frac{BB_\phi}{\langle B^2 \rangle} \tag{1}$$

where $v_{th,i}$ is the ion thermal velocity, ρ_i the Larmor radius, L_T the temperature gradient and the brackets represent a flux surface average. Higher neo-classical poloidal flow contributions are thus predicted to occur on smaller tokamaks with short scale lengths, e.g. TEXT [1], and on low field machines with large Larmor orbits such as MAST and NSTX [5]. The numerical coefficient K_1 is of order unity and its sign depends on the collisionality. In order to maintain radial force balance for each ion species, the poloidal flow of the impurity ions v_θ^z differs from that of the bulk ions and is given by the expression:

$$v_\theta^z = \frac{1}{2} v_{th,i}\,\rho_i \left[\left(K_1 + \frac{3K_2}{2} \right) \frac{1}{L_T} - \frac{1}{L_{P_i}} + \frac{Z_i}{Z_z}\frac{T_z}{T_i}\frac{1}{L_{P_I}} \right] \frac{BB_\phi}{\langle B^2 \rangle} \tag{2}$$

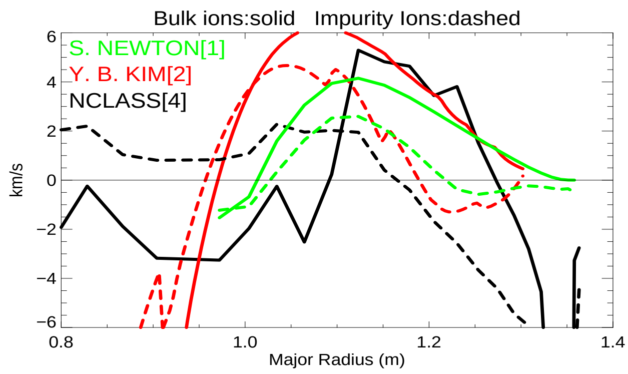


Fig. 1: Bulk (solid) and impurity (dashed) poloidal ion velocity profiles calculated by three different neo-classical theories for shot 12546 at 245ms.

where L_{P_i} and L_{P_I} are the scale lengths of the bulk and impurity ion pressures and K_2 is a numerical coefficient of order unity, which depends on the collisionality and represents inter-species frictional coupling. The second and third terms represent the diamagnetic flows of the bulk ions and impurities and the dimensionless factor $BB_\varphi/\langle B^2\rangle$ is of order unity. The more comprehensive theory of Newton and Helander [2] also takes account of the effect of strong sub-sonic toroidal rotation. In the case of C^{6+} ions in a deuterium plasma the contribution driven by the gradient in the rotation frequency is identically zero due to the fact that these ions have the same charge-mass ratio. In Fig.1 bulk and impurity ion poloidal velocity profiles calculated according to these two theories as well as by the NCLASS code are compared for a MAST discharge, where somewhat different input parameters have been used to calculate the values from the Kim theory, i.e. from the outboard profiles rather than in/out averaged values as for the other two cases. The results from the three theories are similar in magnitude, with reasonable agreement in the case of the impurities but a somewhat larger discrepancy between NCLASS and the other theories in the core and edge regions.

Experimental Measurement:

The poloidal CXRS system on MAST [6, 7] has two overlapping arrays of 32 chords with a spatial resolution of 1 cm. The velocity and temperature of C^{6+} ions in the plasma core is determined from the Doppler shift and broadening of the n=8-7 transition at 529.05 nm of C^{5+} ions that have undergone charge-exchange with a deuterium atom from the neutral beam.

The lines of sight also pass through the plasma edge where charge exchange also occurs with thermal neutrals. The final spectra consist of a superposition of edge and core CX emission along with bremsstrahlung. The 'passive' background emission spectrum is measured during the integration period, usually 5 ms in duration, immediately following a fast cut-off of the neutral beam. This can then be subtracted by the spectrum from the integration period immediately before the cut-off to obtain the 'active' CX spectrum. These active spectra are well represented by a Gaussian profile convolved with the instrument function. Empirically the subtraction [7] of adjacent passive and active timeslices of the same chord at cut off was found to be the only means of obtaining high enough quality spectra for meaningful poloidal flow analysis. This technique only produces a few poloidal velocity profiles per pulse.

By illuminating the spectrometer with a Ne^{1+} n =6-3 transition at 529.82 nm from a spectral lamp, the instrument function and also the absolute wavelength of the CXRS spectra can be determined. Most errors are due to shot and readout noise from the finite photon number of each spectrum. Drifts in the absolute wavelength can also occur after the calibration due to various causes, including barometric variations on the refractive index of air and mechanical disturbance. Its influence was minimized by calibrating the system a few days prior to the measurements and by monitoring the wavelength of a line from a calibration lamp connected to a dedicated chord and recorded during each discharge. The magnitude of this drift was hence determined to be about 1km/s.

Because the measured toroidal velocities v_φ^z are a factor of 10-100 times larger than the poloidal velocities, accurate alignment of the viewing chords to a plane of constant toroidal azimuth is critical if a significant component of the toroidal velocity is not to be detected by the poloidal views. It is estimated that when these chords were installed they were aligned to an accuracy of 7 arc minutes. For a maximum toroidal velocity of 300 km/s this results in an uncertainty in the poloidal velocities of 0.6 km/s, which is smaller than the statistical errors.

Pseudo-velocity correction:

The cross-section for charge-exchange is dependent on the relative velocities of the beam atoms and the C^{6+} ions. This can cause the velocity inferred from the Doppler shift of the excited spectral line to differ from the fluid velocity by a pseudo-velocity offset, Δv_{CX}. If the beam is injected perpendicularly to the field, i.e. in the plane of the Larmor orbit, this is given by the following simplified expression:

$$\Delta v_{cx} = \frac{v_{th,i}^2}{2} \frac{\sqrt{2eE_b m_i}}{\sigma_{cx}^k} \frac{d\sigma_{cx}^k}{dE} \frac{1}{1+\omega_g^2 \tau_k^2} \left(\omega_g \tau_k + \cos\alpha \right) \tag{3}$$

where e is electron charge, m_i is ion mass, E_b is beam injection energy, σ_{cx}^k is the cross-section for excitation of the k^{th} level and α is the angle between the line of sight and the field. Even when viewing poloidally ($\alpha = \pi/2$) the gyration of the excited ions into the poloidal direction within the finite lifetime of the excited state τ_k can produce a finite poloidal pseudo-velocity component, which scales as $T_i B$. On an ST operating at lower B_t and T_i the poloidal pseudo velocities are thus much smaller than for a conventional tokamak, these scaling as B^{-2} relative to the neo-classical poloidal velocity.

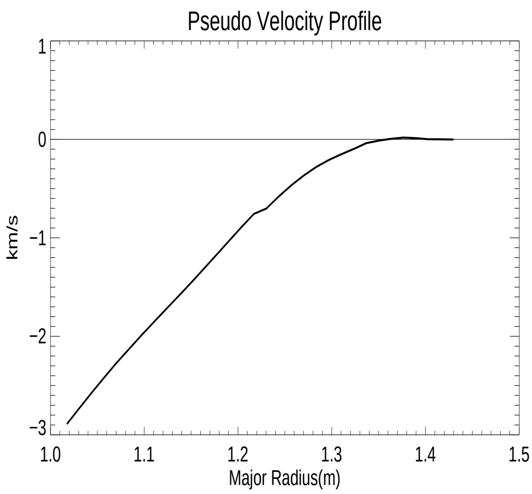
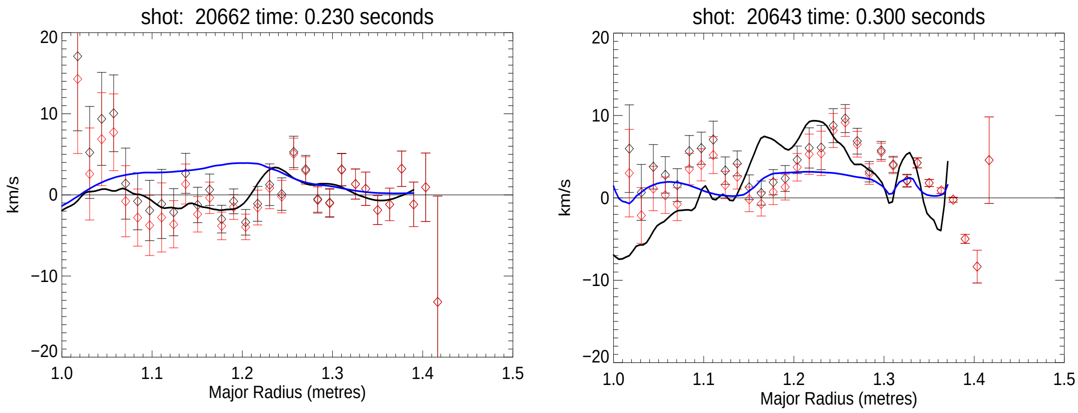


Fig. 2 The poloidal pseudo velocity profile calculated for #20643 at 0.3s.

On MAST the main contribution to the poloidal pseudo velocities is from a component of the radial pseudo velocity arising from a finite radial component from the lines of sight which are not precisely vertical, that increases with decreasing major radius. The beams are also injected tangentially in the horizontal mid-plane, i.e. out of the plane of the Larmor orbits. The pseudo velocities must therefore be calculated from a full integration over the 3D velocity distribution [8], rather than from the simplified expression (3). The resulting pseudo-velocity profile is shown in Fig. 2, which can be seen to increase in significance towards the plasma core.

Results:

Poloidal velocity profiles measured during L- and H-mode phases are compared with the neo-classical values calculated according to Ref. 3 are shown in Figs. 3 and 4 respectively, where positive values are in the ion diamagnetic direction. The typical measurement uncertainties are ~ ±2 km/s over most of the radius and, as discussed above, systematic uncertainties are



Figs. 3 (left) and 4 (right): Bulk ion (Blue line) and impurity (Black line) velocities as predicted by [3]. Dots with error bars are measurements from CXRS corrected (black) and uncorrected (red) for pseudo-velocity. Fig 3(left) gives profile measured for L-mode while Fig. 4 (right) gives profiles measured in H-mode.

estimated to be smaller than this. The predicted and measured C^{6+} poloidal velocities are of similar magnitude (≤ 10 km/s), except in the core of the discharge where the CX signal was weak and the errors correspondingly larger. The change of sign of both the observed and predicted impurity velocity the L-mode discharge #20662 inside 1.2 m can be explained by the contribution from the second term in Eq. 2, which dominates in the mid-radius region where the ion pressure gradient peaks. The negative velocities observed in the edge of the H-mode plasma are due to the negative E-field within the pedestal region of the edge transport barrier.

Discussion:

Reasonable agreement between measured poloidal velocities and the predictions of neo-classical theory is observed in MAST L- and H-mode plasmas. That similar observations have been made on NSTX supports the view that poloidal velocities on existing STs are well described by this theory. No large discrepancies like those observed on JET and DIII-D have yet been observed on STs, albeit the data set on such comparisons is currently limited. One explanation could be that the high values of the variable $\rho^* \sim \rho/L_T$ featured in equation (1) and (2) and present on MAST, NSTX[5] and TEXT[1] supports a higher neo-classical contribution to poloidal flow, this might exceed the turbulent poloidal velocity contribution for low field machines, but may not be the case for large high field devices.

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