Comparison of first-order neoclassical flow theory with CXRS measurements from Alcator C-Mod

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Abstract

First-order neoclassical theory describes flow on a flux surface as being composed of two parts. This theory is tested by using CXRS measurements at the low-field side (LFS) and the high-field side (HFS) of the plasma. [1,2]

- **If the density is a flux function the neoclassical theory does not satisfactorily relate the HFS and LFS velocities.**

Allowing the impurity density to vary poloidally leads us to calculate an expected impurity density at the HFS of the plasma. Similar experiments on MAST have also examined the effect of poloidal density variations. [3,4]

- **Relaxing the constraint of constant density on a flux surface allows us to relate the HFS and LFS measurements.**
- **The result is an in-out asymmetry in impurity density with the HFS having the higher density; the effect strongest in the steep gradient region.**

Neoclassical theory can also be used to directly calculate the flows at the LFS side of the plasma as another test of its validity. [3]

- **The theory is successful at predicting the shape and sign of the flow profiles but often underestimates the magnitude by a factor of 4-6.**

1. CXRS views of the plasma

High-Field Side

Inner Midplane Parallel Viewing Periscope for flows of B^{5+}

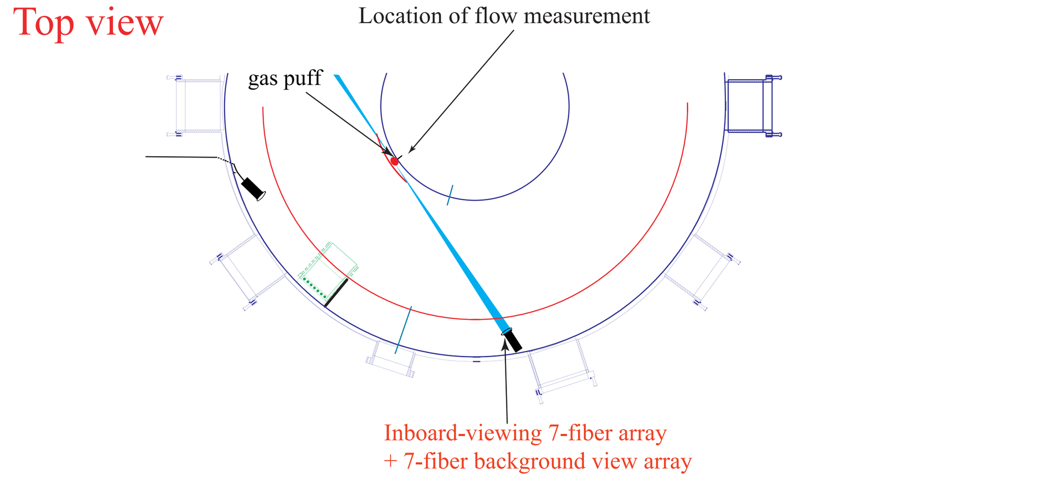

Figure 1. Top view looking down of the high-field side viewing periscope.

Low-Field Side

Outer Midplane Viewing Periscopes for flows of B^{5+}

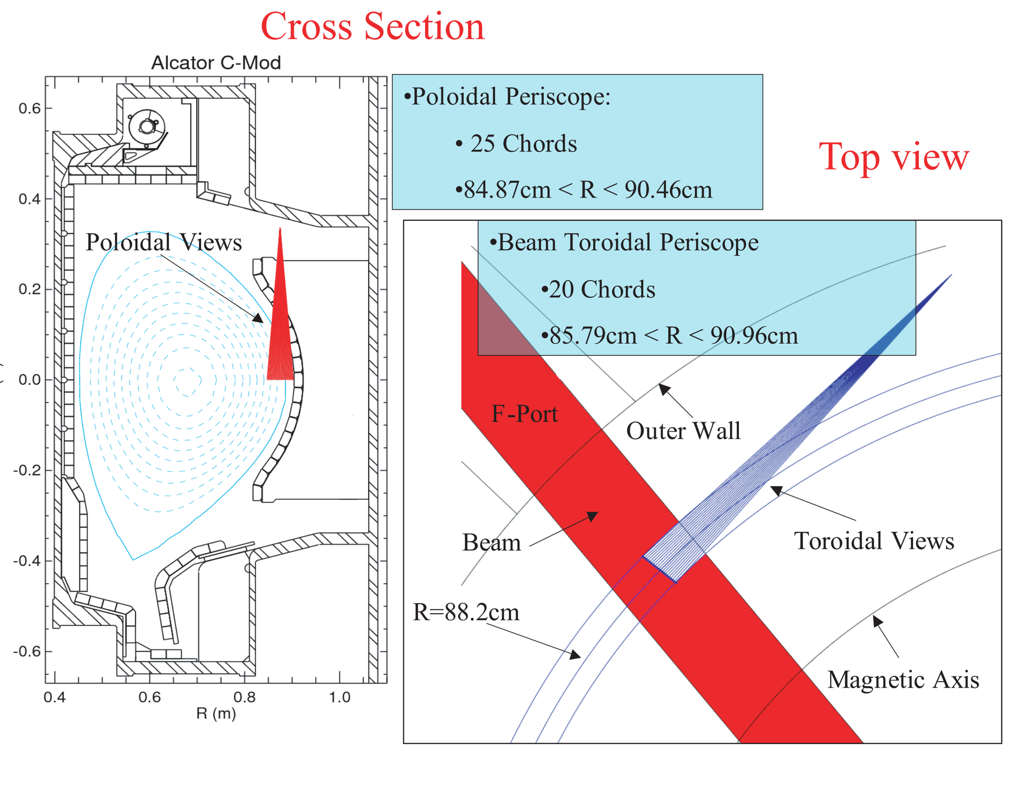

Figure 2. Top view and cross section of the low-field side periscopes views.

2. First-order neoclassical predictions for velocity on a flux surface

With poloidal and toroidal views of the DNB at the low-field side (LFS) and a view parallel to **B** at the HFS of Alcator C-Mod we can provide some comparison of flows and flow profiles on both sides of the plasma.

First order neoclassical theory (divergence-free, i.e. $\nabla\cdot(nV)=0$) predicts that on a flux surface, particle flow, *V*, can be decomposed into two terms; 1) flow along the field and 2) strictly toroidal flow (rigid rotation):

$$V = k(\psi)\mathbf{B} + \omega(\psi)R\hat{\phi} \qquad (1)$$

where k and ω are constants on a flux surface. Typically, this equation is further simplified by the assumption that k=0 as seen in Eq. 2. This implies rigid body rotation of the plasma.

$$V = \omega(\psi)R\hat{\phi} \quad (k=0) \qquad (2)$$

Using the HFS and LFS CXRS measurements we can test these models for *V* on a flux surface. We do this by solving for k and ω at the LFS. We then use these parameters to calculate the expected velocity at the HFS and compare with measurements there. Figure 5 shows this result for an EDA H-mode.

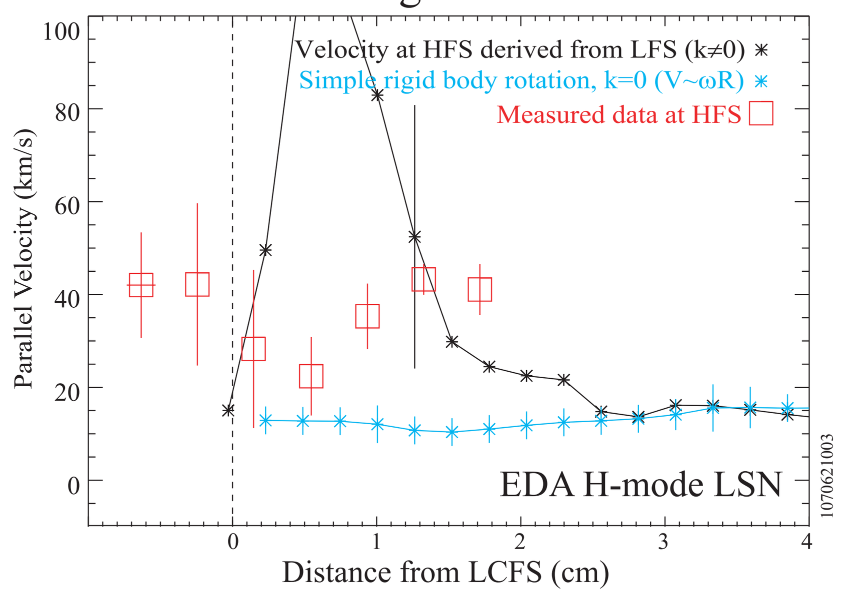

Figure 3. Parallel flow comparisons between the first-order neoclassical theories and CXRS measurements at the HFS show a distinct difference in profile shape and magnitude.

3. Poloidal variation of n_I

- Allowing the impurity density to vary poloidally leads to:

$$V = (k(\psi)/n_I(\psi,\theta))\mathbf{B} + \omega(\psi)R\hat{\phi} \qquad (3)$$

where k and ω are constants on a flux surface and n_I is the impurity density. [3]

- Relate the measured parallel impurity flow at the HFS to the flows at the LFS
- Calculate the expected impurity density at the HFS that satisfies Eq. 3. This process is shown in Figure 4a-f. Also shown are two alternate calculations for small, arbitrary changes to v_{pol}.

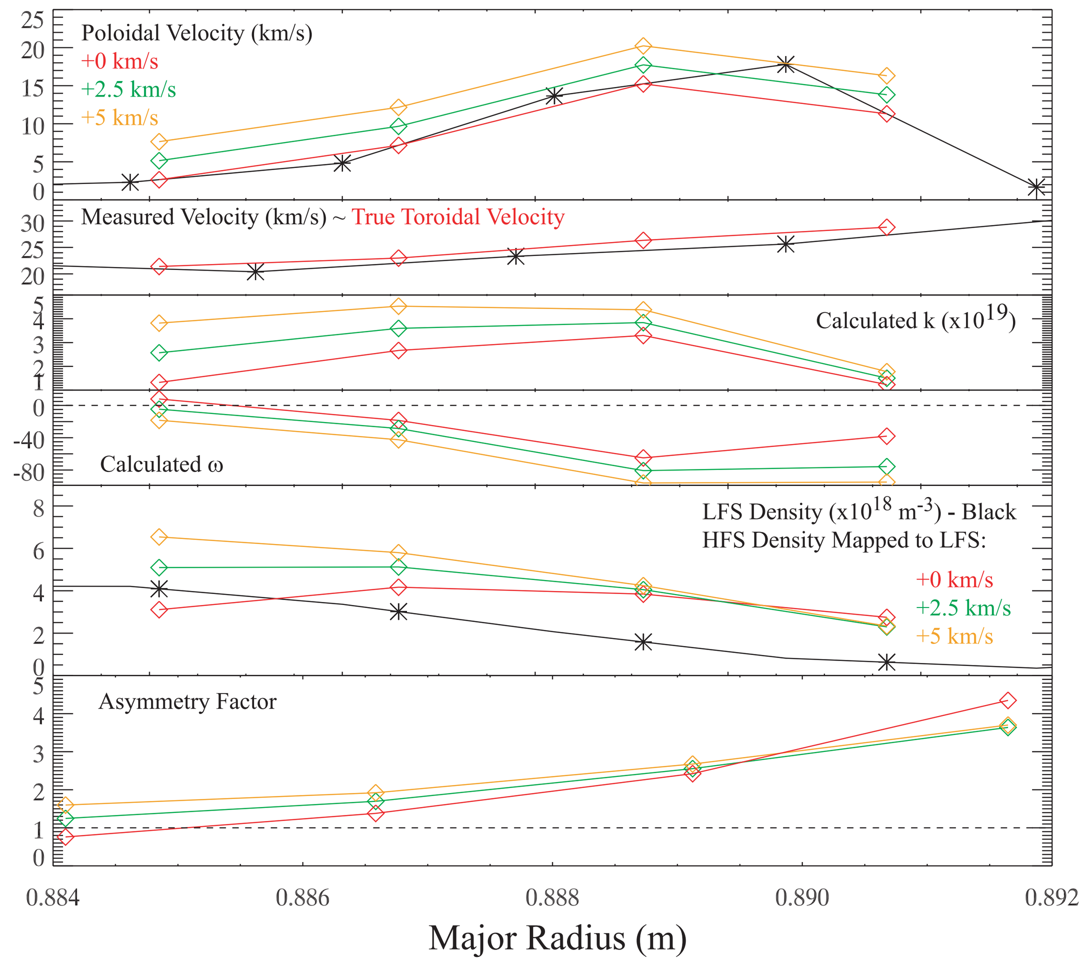

Figure 4. Traces showing the relevant profiles in the HFS density calculation.

- **The HFS poloidal velocity exhibits a strongly peaked non-zero flow less than 1cm inside the separatrix (right edge of Figure 4), but quickly returns to near zero beyond this region.**
- The HFS density as measured is usually higher than its counterpart at the LFS just inside the separatrix.
- At 1-2cm into the plasma the HFS density often drops below the LFS density and at times is calculated to be negative.
- **The HFS density calculation is very sensitive to small changes in v_{pol} in the region where v_{pol} nears zero.**

- Because the *k* and ω constants are mapped to the HFS, small variations in the mapping can change the calculated density at the HFS. **The HFS density has a weak dependence on mapping changes.**
- Figure 5 shows the a diagram of the flow vectors:

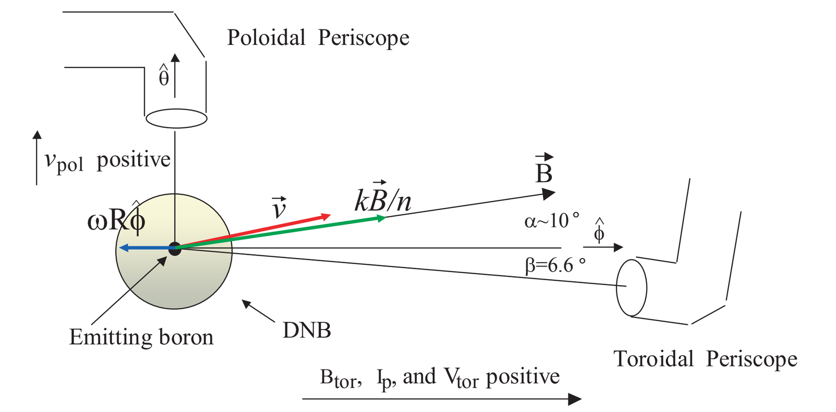

Figure 5. A diagram showing the relative directions of flows and the magnetic field at the LFS (looking at the outerwall from inside the plasma).

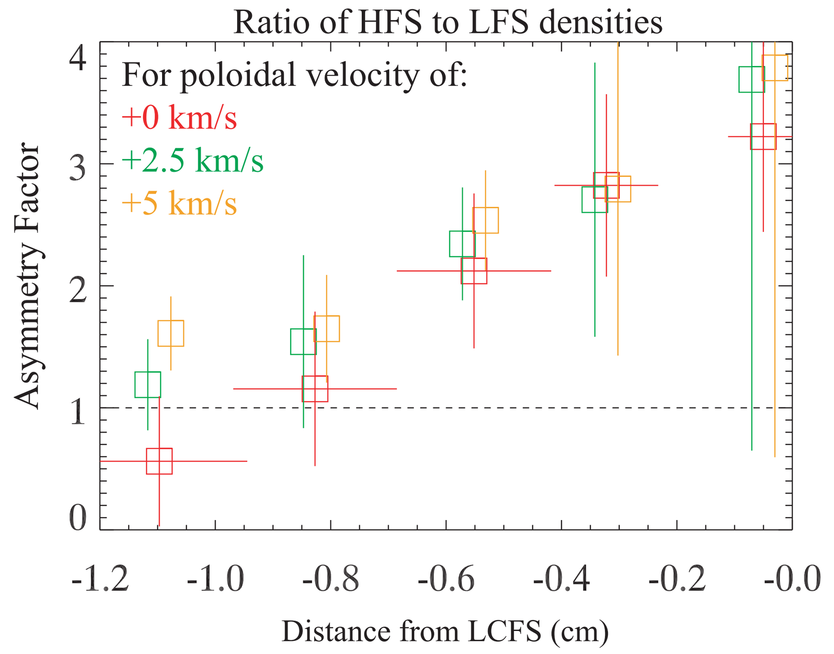

Figure 6. Asymmetry between HFS and LFS densities for 48 frames spanning four EDA H-mode shots. Horizontal shift is arbitrary for viewing purposes only.

- The asymmetry seen in Figure 6 is common to all discharges with the greatest effect being seen in the steep gradient region.
- The magnitude of the asymmetry is sensitive to the changes in poloidal velocity where the poloidal velocity is near zero.
- **This leads to large uncertainties in asymmetry away from the steep gradient region.**

4. Comparison of neoclassically calculated LFS flows with CXRS measurements

As the impurities and main ions are sufficiently collisional (i.e. in the Phirsch-Schluter regime) we can utilize neoclassical theory to calculate the flows at the LFS directly. [3]

- The poloidal velocity is calculated using the ion and impurity density and temperature profiles and their derivatives:

$$V_\theta = -cI/\langle B^2\rangle\left(1/n_i \, dp_i/d\psi + 1.8\, dT_i/d\psi - 1/Zn_z \, dp_z/d\psi\right)B_\theta \qquad (4)$$

where *i* is for main ion and *z* is for impurity. Here we assume $T_i = T_z$ and $n_i = n_e$.

- E_r is required to calculate the toroidal velocity:

$$V_\phi = cE_r/B_\theta - cR/eZn_z \, dp_z/d\psi - cI^2/R\langle B^2\rangle\left(1/n_i \, dp_i/d\psi + 1.8\, dT_i/d\psi - 1/Zn_z \, dp_z/d\psi\right) \qquad (5)$$

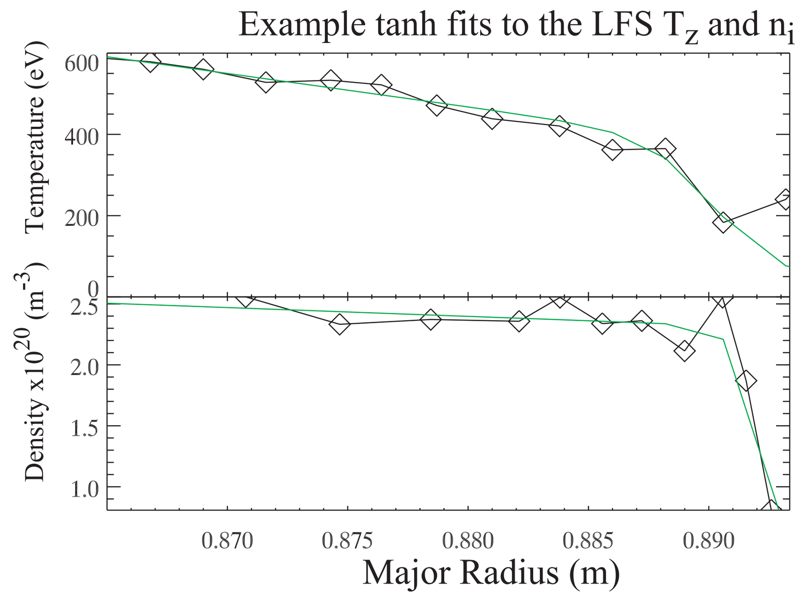

Figure 7. The main ion and impurity density and temperature profiles are fit with tanh functions.

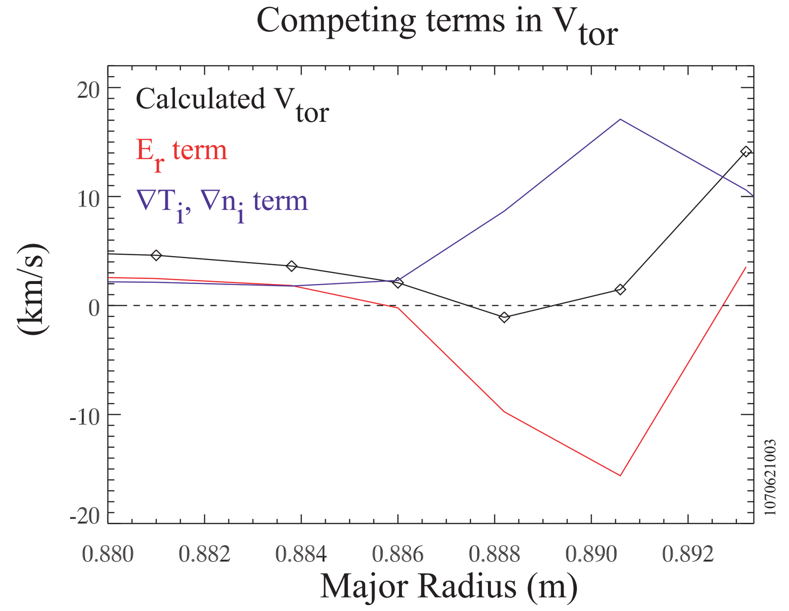

Figure 8. The toroidal velocity has two competing terms which tend to counter-balance in the strong gradient region.

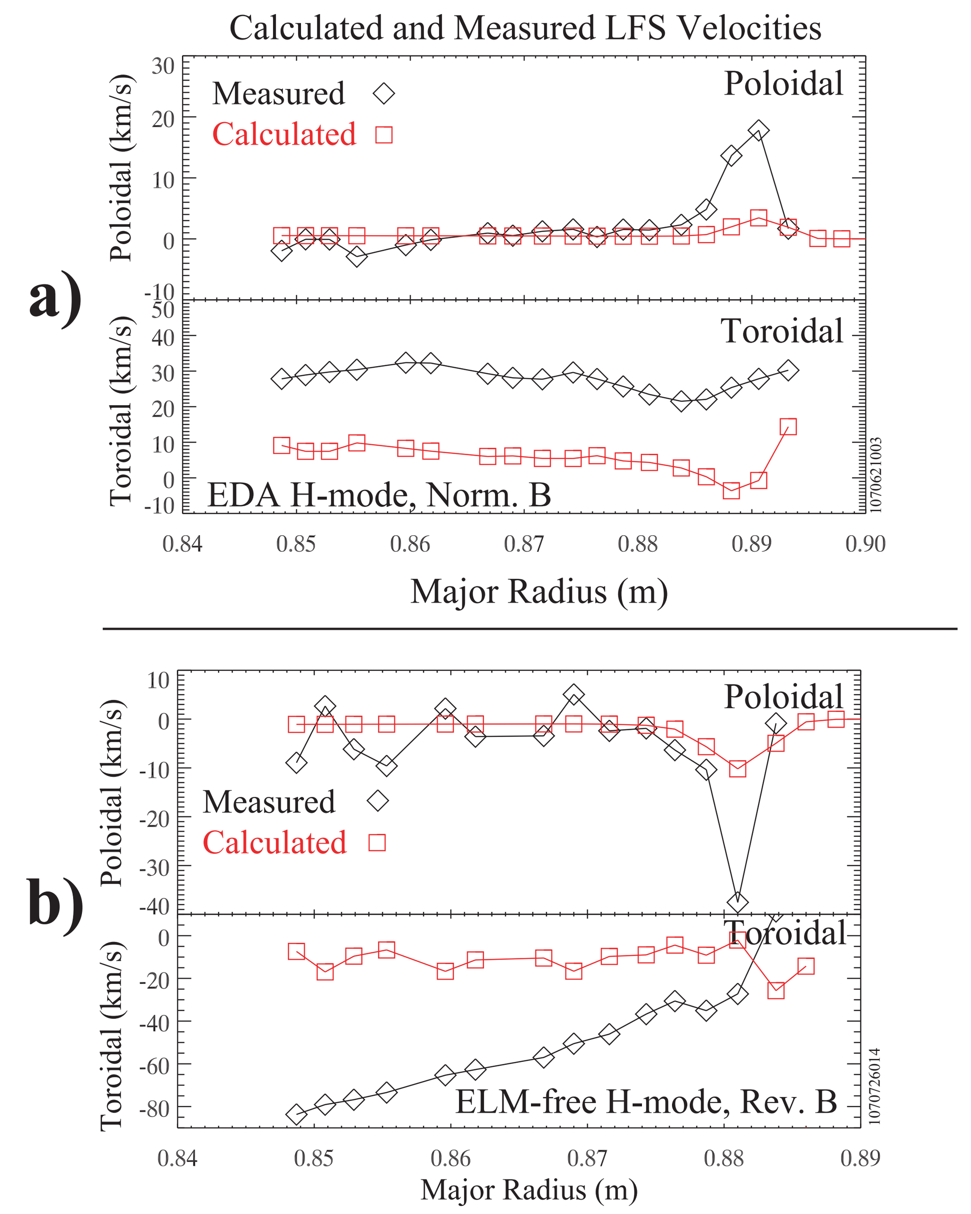

Figure 9. Calculated poloidal and toroidal velocity at the LFS (red) and the measured flows from CXRS (black) for an a) EDA H-mode and b) ELM-free H-mode in reversed field.

- For EDA H-modes, the calculated velocities match the measured velocties in shape and sign. They tend to differ in magnitude by a factor of 4-6.
- Similar trends are seen for the ELM-free H-mode in Figure 9b. The flows are reversed because they are from a shot during a reversed magnetic field run.
- Further work is required to gather more statistics in both EDA and ELM-free H-modes. Also we would like to see if the theory reproduces the expected change in the peak poloidal velocity during the evolution of the ELM-free H-mode. [5]

Summary and Conclusions

A poloidal variation of the impurity density is required to reconcile the impurity flow at the HFS to the flow at the LFS using first-order neoclassical flow theory.

- **The HFS density is greater than the LFS density.**
- **The peak of the HFS density corresponds to the steep gradient region that creates the E_r well.**

Direct calculation of the LFS impurity flows from neoclassical theory is made using the measured temperature and density profiles.

- **The calculated flows correlate with the measured flows in direction and shape, and have similar magnitudes to within a factor of 4-6.**

References

1. Y. Kim, P. Diamond, R. Groebner. Neoclassical poloidal and toroidal roation in tokamaks. Phys. Fluids B. 3 (8). (1991)
2. W. Solomon et. al. Experimental test of the neoclassical theory of impurity poloidal rotation in tokamaks. Phys. of Plasmas. 13, 056116 (2006)
3. P. Catto, A. Simakov. Magnetic topology effects on Alcator C-Mod flows. Phys. of Plasmas. 13, 052507 (2006)
4. T. Fülöp, P. Helander. Nonlinear neoclassical transport in toroidal edge plasmas. Phys. of Plasmas 8 (2001)
5. R. McDermott talk; this conference.