Poloidal Flows and In-Out Impurity Density Asymmetries in the Pedestal Region

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Simultaneous CXRS measurements of boron density, velocity, and temperature in the pedestal region ($0.8 < r/a < 1.05$) at the low- and high-field sides (LFS and HFS) of Alcator C-Mod allow studies of variations in boron density and total velocity on a flux surface. As is well known, in strong temperature and density gradient H-mode plasmas, the poloidal velocity peaks in the pedestal region, travelling in the electron diamagnetic direction (EDD). This is true at both the LFS and HFS, however the HFS poloidal velocity is anomalously small in the pedestal region, based on the divergence-free flow equation. This indicates an in/out boron density asymmetry with a build-up on the HFS, in agreement with previous results which compared HFS parallel velocity with LFS poloidal and toroidal velocities. In contrast, in I-mode plasmas, which have no density pedestal but a strong temperature pedestal, the poloidal velocity peak in the pedestal region travels in the ion diamagnetic direction (IDD), and the poloidal velocities at the LFS and HF are at similar values.

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Motivation: Understanding Pedestal Physics

- Ability to predict pedestal characteristics important, as it will set overall plasma performance in ITER

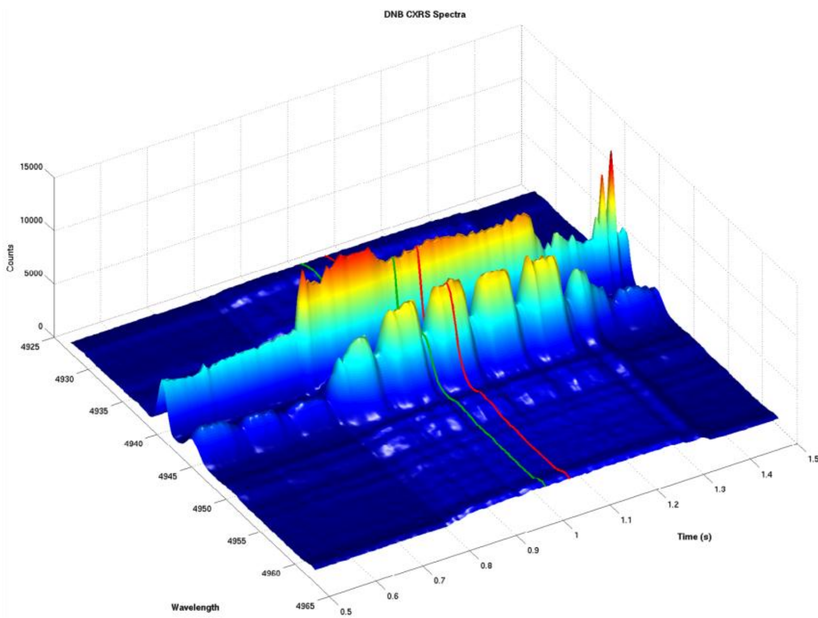
- Pedestal transport still not well understood

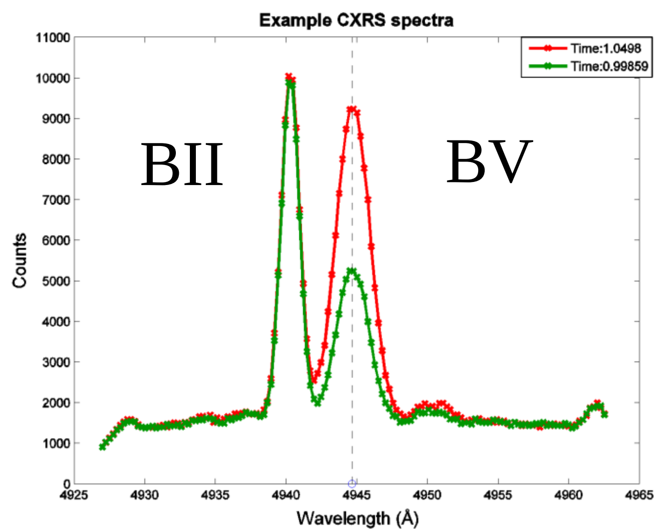
- Flows in the pedestal and edge set boundary conditions for the core rotation

- Impurity flows in and through the pedestal important for controlling core impurity levels

Background: edge CXRS Diagnostic

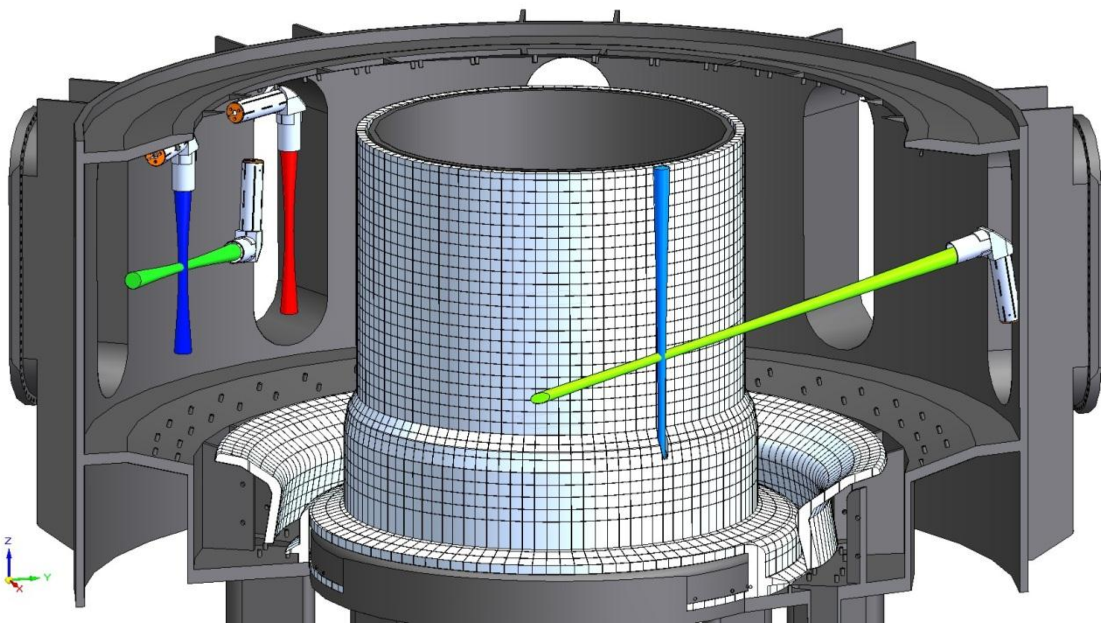
- Charge Exchange Recombination Spectroscopy (CXRS) measures impurity density, temperature, and rotation
- Neutral source spatially localizes emission ("active" CXRS)
- C-Mod edge CXRS uses exclusively the boron BV line (λ=494.467 [nm])

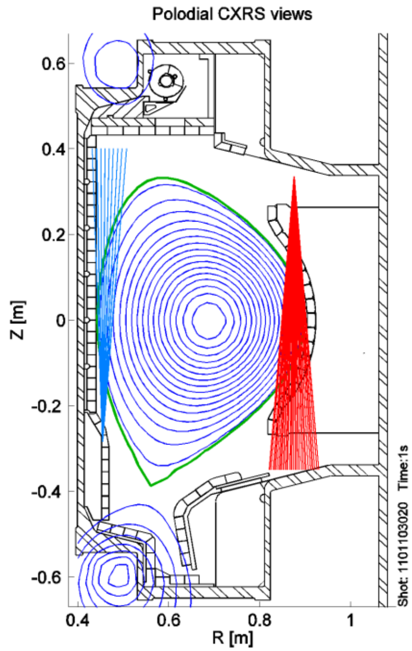




Background: Diagnostics

- C-Mod edge CXRS uses in-vessel collection optics to image the low-field side (LFS) and high-field side (HFS) mid-planes
- LFS uses for neutral source
  - Diagnostic neutral beam (50keV)
  - D2 gas puff (4 torr/L)
- HFS uses exclusively a D2 gas puff





Impurity Flows in a Tokamak

- In a tokamak the lowest order, divergence-free flow on a flux surface for any species is characterized by flux functions *u* and ω

$$\vec{V} = u(\psi)\vec{B} + \omega(\psi)R\hat{\phi}$$

- edge CXRS systems on C-Mod can validate these flux functions with HFS and LFS mid-plane measurements

- Previous studies[3] showed *u* from LFS DNB in reasonable agreement with neoclassical theory; also studied whether impurity density constant on a flux surface

[3] K D Marr et al 2010 PPCF 52 055010

H-mode vs. I-mode

- H-mode characterized (simply) by Te pedestal
  ne pedestal
- I-mode characterized (simply) by Te pedestal
  no ne pedestal

- Both modes characterized by reduction in typical broadband fluctuations found in L-mode

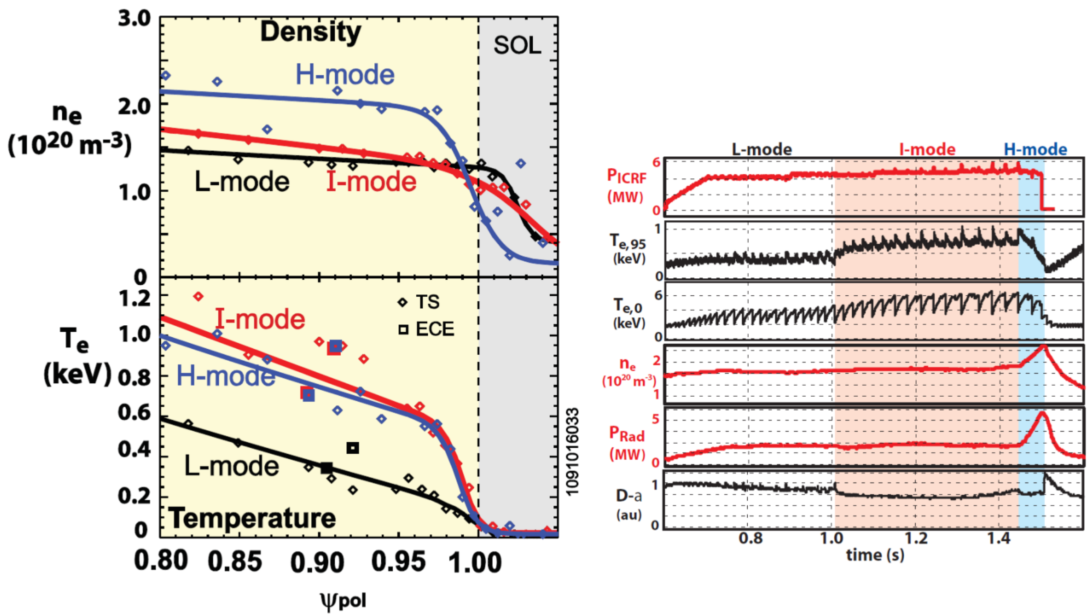
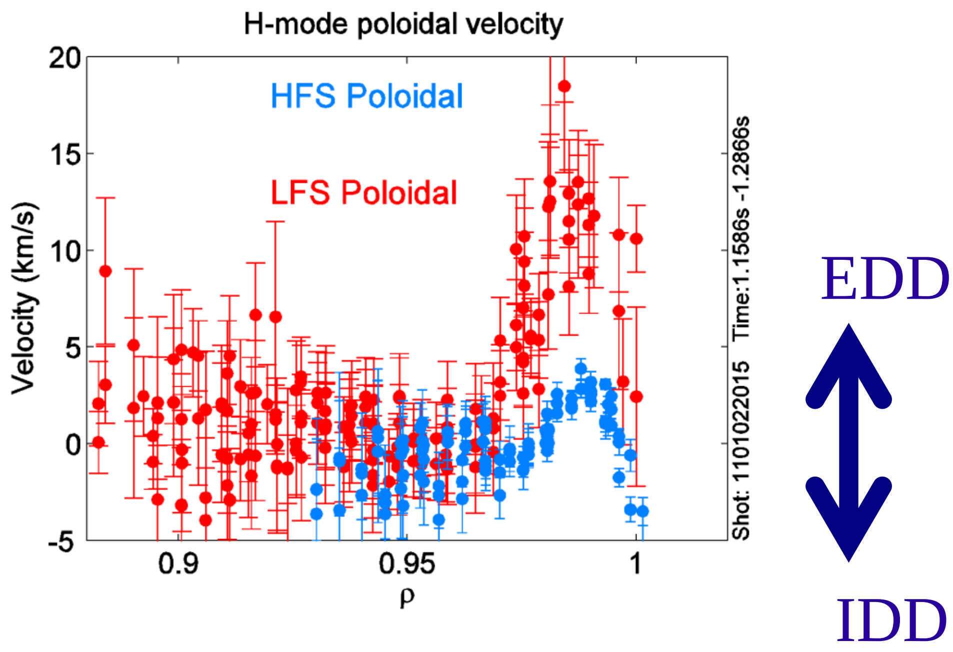


Figure from A. Hubbard, et.al, Phys. Plasmas 18, 056115 (2011)

H-mode poloidal velocity in **Electron** Diamagnetic Drift Direction (EDD)

- In H-mode, poloidal velocity in C-Mod sets Er “well” depth[2]

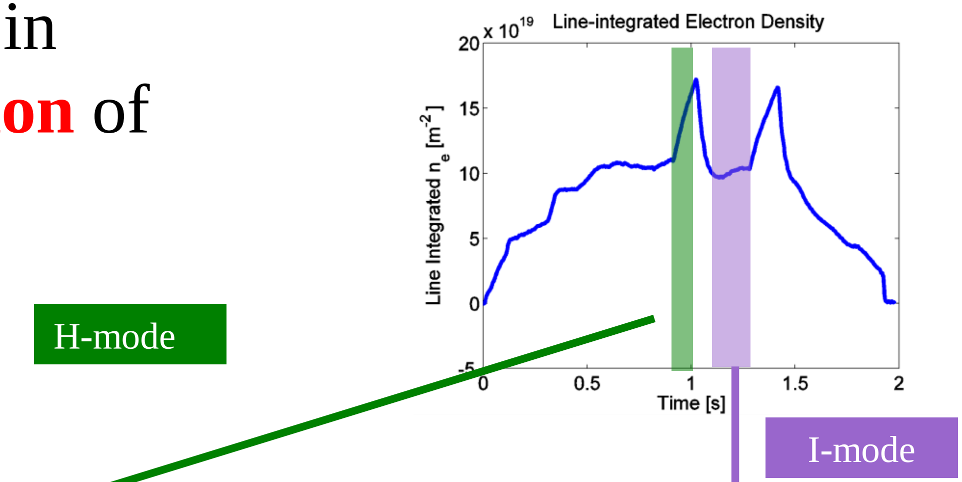
- LFS poloidal velocity **~2-3x higher** than HFS poloidal velocity

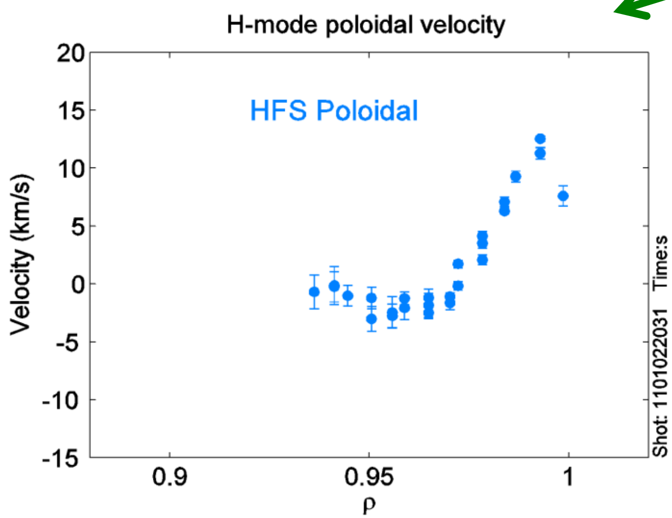


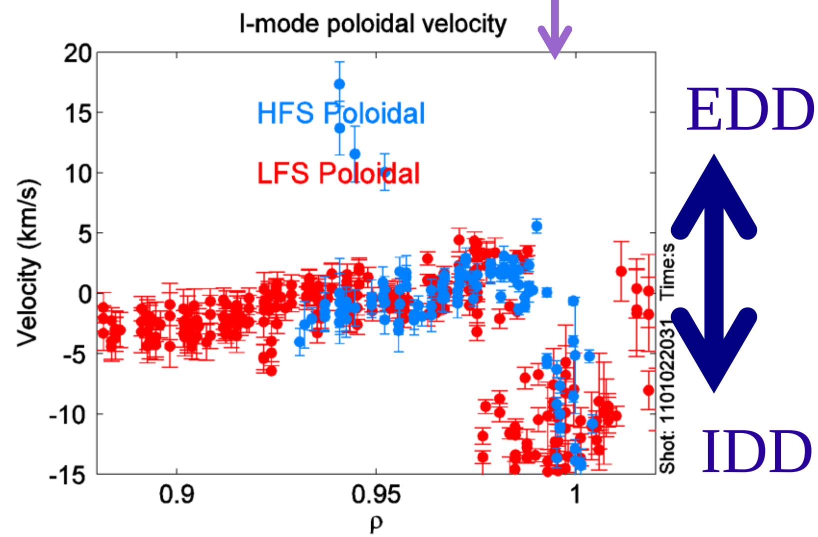
[2] R.M McDermott, Phys. Plasmas 16, 056103 (2009)

I-mode poloidal velocity in **Ion** Diamagnetic Drift Direction (IDD)

- I-mode poloidal velocity in pedestal **opposite direction** of H-mode
- Reduces Er "well"
- HFS and LFS poloidal velocities match







Poloidal Velocity in H-mode and I-mode Qualitatively matches Neoclassical Prediction

Alcator C-Mod

Courtesy of M. Landreman

- Neoclassical predicted poloidal impurity velocity[2]

$$\mathbf{V}_{Z,\theta} = \frac{cI}{e\langle B^2\rangle}\left[\frac{1}{Zn_Z}\frac{dp_Z}{d\psi} - \frac{T_i}{n_i}\frac{dn_i}{d\psi} + (\gamma - 1)\frac{dT_i}{d\psi}\right]\nabla\zeta\times\nabla\psi$$

- Collisionality:

H-mode pedestal in Pfirsch-Schluter regime
I-mode pedestal in bananna regime

$$\gamma_{PS} = -1.69$$
$$\gamma_{ban} = +1.37$$

- Ignoring impurity pressure gradient and main ion density gradient, predicted poloidal flow in observed directions:

$$\text{Direction of } \mathbf{V}_{Z,\theta} = \begin{cases} -\mathbf{B_{tor}}\times\nabla T_i & \text{EDD in H-mode} \\ +\mathbf{B_{tor}}\times\nabla T_i & \text{IDD in I-mode}\end{cases}$$

- More detailed analysis can be done with neoclassical codes though validity questionable as transport becomes non-local in steep gradient regions

[2] Catto & Simakov, PoP (2006)

Theoretical Poloidal Velocity Suggests HFS poloidal velocity larger than LFS

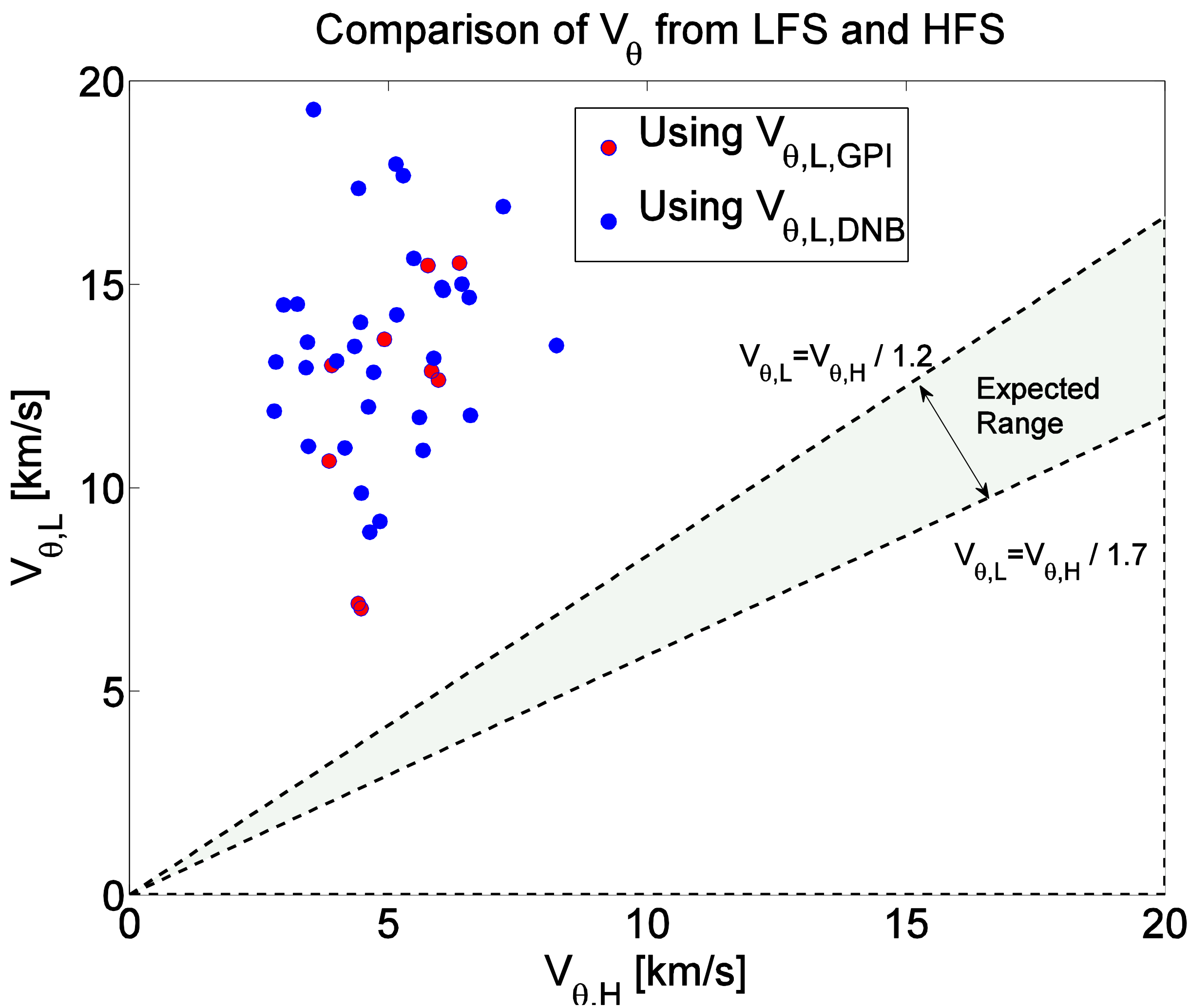
- LFS and HFS poloidal velocites derived using the *u* constant:

$$V_{\theta,HFS} = V_{\theta,LFS}\frac{B_{\theta,HFS}}{B_{\theta,LFS}}$$

- In the edge region on C-Mod, $\frac{B_{\theta,HFS}}{B_{\theta,LFS}} \sim 1.5$, so we expect

$$V_{\theta,HFS} \sim 1.5 \cdot V_{\theta,LFS}$$

H-mode HFS poloidal velocities consistently lower than LFS



$$u = \frac{V_\theta}{B_\theta}$$

u taken at peak of poloidal velocity

In-Out Density Asymmetry in the Pedestal Can Explain Poloidal Velocity Discrepancy

- Previously, in-out density asymmetry inferred from combination of HFS toroidal velocity and LFS poloidal and toroidal velocities[3]

- If impurity density allowed to vary on a flux surface:

$$\vec{V} = \frac{k(\psi)}{n}\vec{B} + \omega(\psi)R\hat{\phi}$$

- In terms of poloidal velocities then:

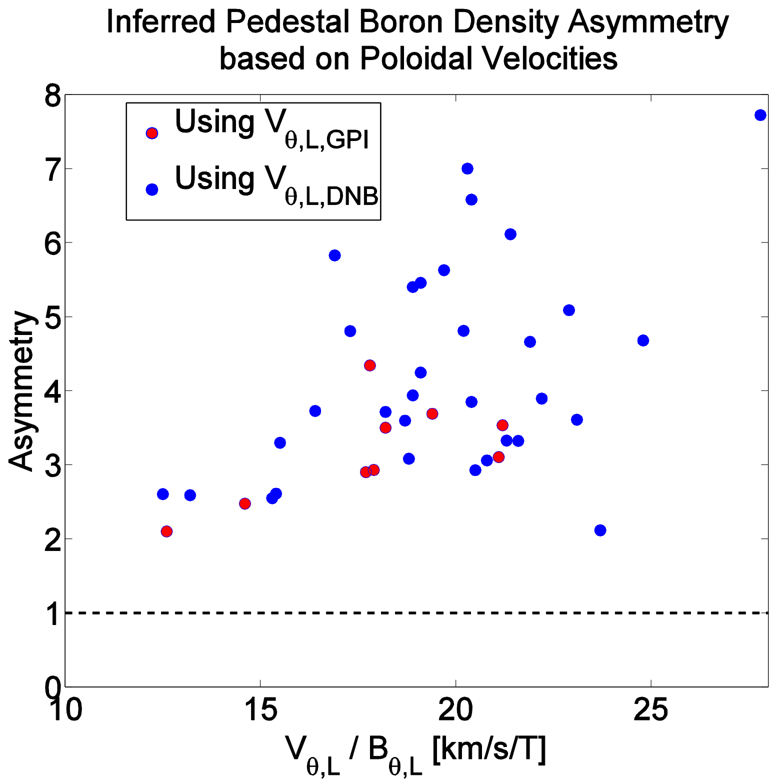
$$\frac{n_{HFS}}{n_{LFS}} = \frac{V_{\theta,LFS}}{V_{\theta,HFS}}\frac{B_{\theta,HFS}}{B_{\theta,LFS}} = \frac{u_{LFS}}{u_{HFS}}$$

[3] K D Marr et al 2010 PPCF 52 055010

In-Out Boron Density Asymmetry Can Explain Poloidal Velocity Discrepancy

- In-out density asymmetry of 2-7x can explain pedestal poloidal velocity discrepancy

- Initial LFS to HFS boron density comparison[4] using KN1D simulations for the HFS gas puff showed shift of density pedestal, leading to in-out asymmetry of ~2-3x



[4] Churchill, *et al.* APS 2010 http://meetings.aps.org/link/BAPS.2010.DPP.TP9.65

B5+ Source Term

- Flow equation derived from steady-state, **divergence-free** continuity equation

$$\nabla \cdot (n\mathbf{V}) = 0 \Rightarrow \vec{V} = u(\psi)\vec{B} + \omega(\psi)R\hat{\phi}$$

- If significant source of n_{B5+} present, introduces a source term to the continuity equation

- For pedestal region, ionization source could be important

- Further work needed to quantify magnitude of ionization source to determine importance

Impurity Density Measurements from CXRS

- Four quantities required to calculate boron density:
  - CX radiance [photons/s/m^2/ster]
  - Optics line-of-sight geometry
  - CX rate coefficient (for each neutral quantum state, *i*) [m^3/s]
  - Donor neutral density (for each neutral quantum state, *i*) [m^{-3}]

$$n_{B^{5+}} = \frac{4\pi I_{CX}^{\lambda}}{\sum_i \int_{LOS} dl \, \langle \sigma v \rangle_i^{\lambda} \, n_{D,i}}$$

- DNB neutral density calculated by pencil-beam code[1]
- Gas puff neutral density requires neutral transport codes (KN1D, OSM-EIRENE, DEGAS2)

[1] R.M McDermott, Doctoral Dissertation, 2009

Impurity Density Measurements from Gas Puff CXRS using Dα measurements

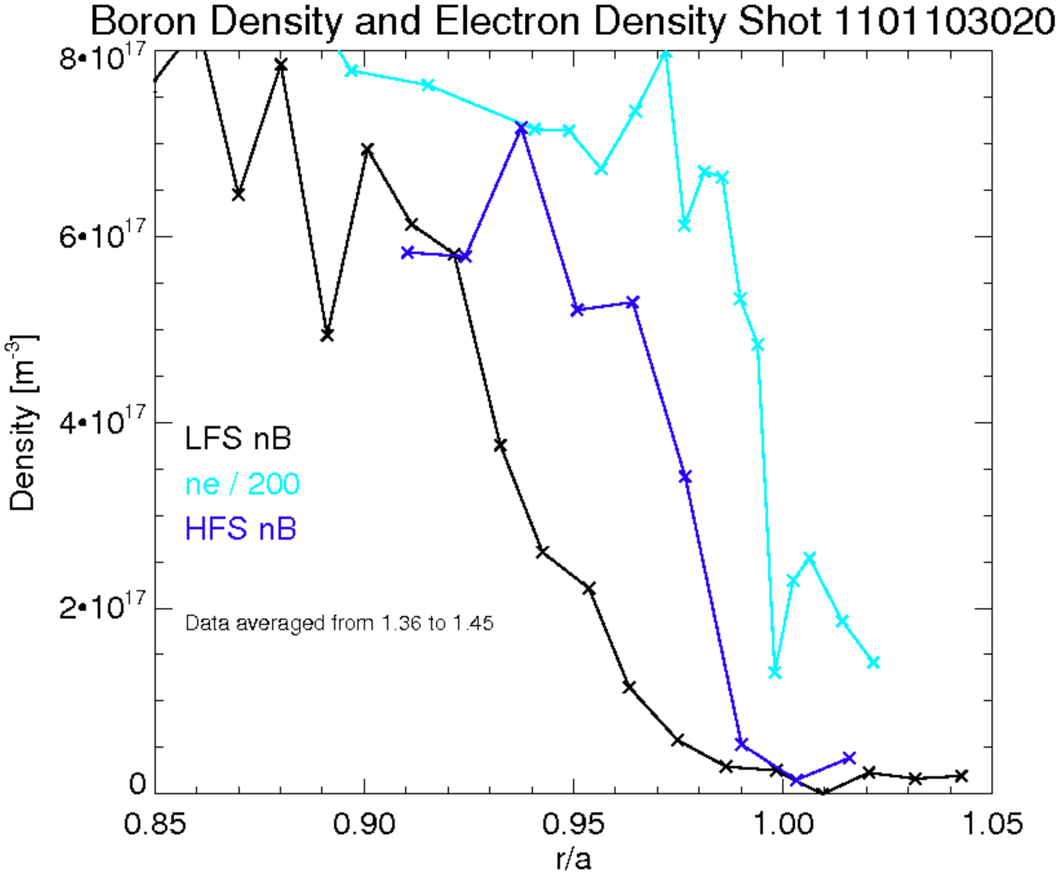
- For neutral beam based CXRS, impurity density derived from pencil-beam code
- Gas puff based CXRS more difficult to calculate impurity density, need full 3D neutral modeling codes to calculate $n_{D,i}$ (OSM-EIRENE or DEGAS2)
- If Dα measured along CXRS optical path, can calculate impurity density directly:

$$n_{B^{5+}} = \frac{1}{\langle \sigma v \rangle_2} E_{32} A_{21} \frac{PEC_{32}^{EXC}}{PEC_{21}^{EXC}} \frac{I_{CX}}{I_{D_\alpha}}$$

where PEC are ADAS Photon Emissivity Coefficients
I_{D_α} Dalpha brightness

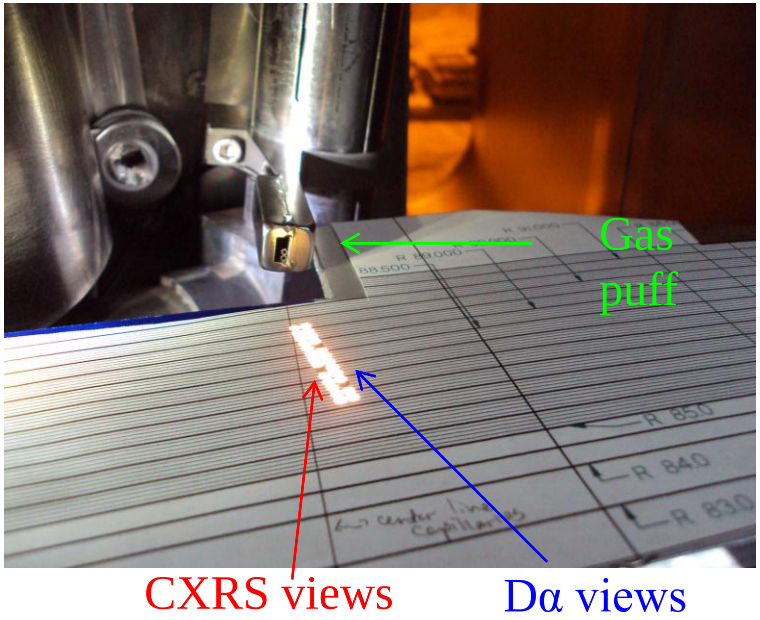
Measured Impurity Boron Density

- Actual density measurements show in-out boron density asymmetry, with buildup on the HFS, as predicted by poloidal velocities



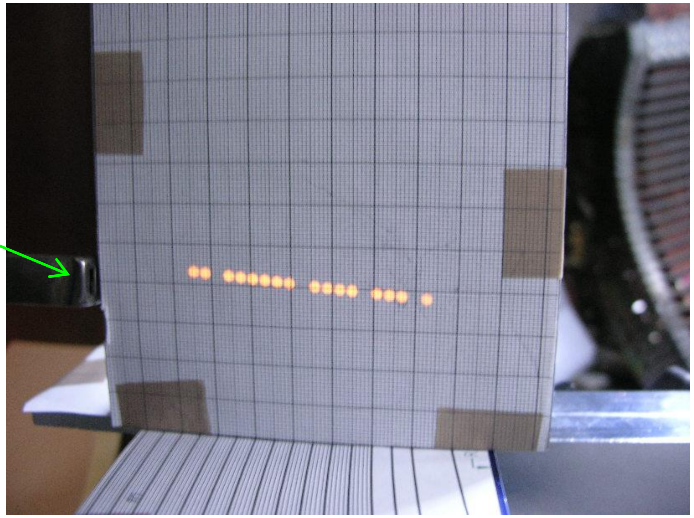
Future Work

- Second row of side-by-side fibers added to LFS gas puff periscope (similar to HFS gas puff system) for FY2012
- Measure Dα (λ=656.3nm) emission using Hamamatsu PMTs and photodiodes (H10722-01 and S8736)
- Dα measurement allows direct calculation of the boron density from gas puff CXRS



Future Work

- LFS parallel viewing gas puff periscope installed for FY2012



- Will allow accurate, high signal-background CXRS measurements of the full velocity vector at both the LFS and HFS

Summary

- Poloidal impurity flow observed to change direction when:
  - H-mode flow in electron diamagnetic drift direction (EDD)
  - I-mode flow in ion diamagnetic drift direction (IDD)

- HFS poloidal velocities are consistently lower than LFS poloidal velocities in H-mode plasmas, opposite theoretical predictions

- An in-out pedestal density asymmetry of the order 2-7x can explain the poloidal velocity discrepancy