



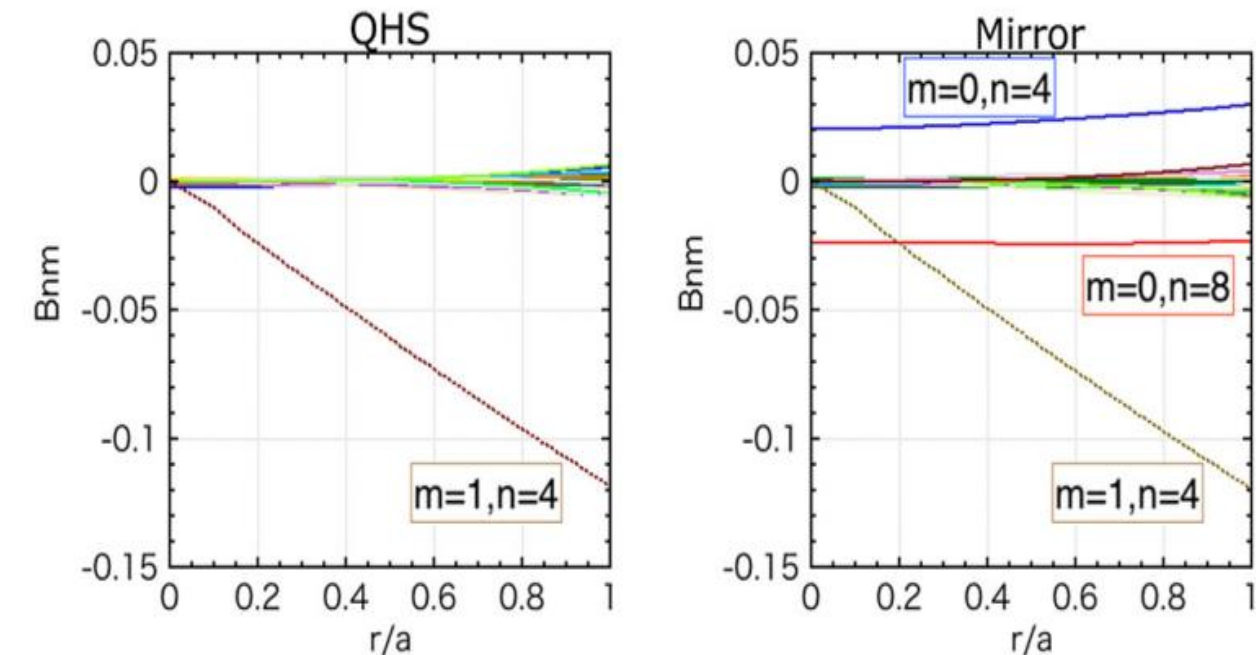
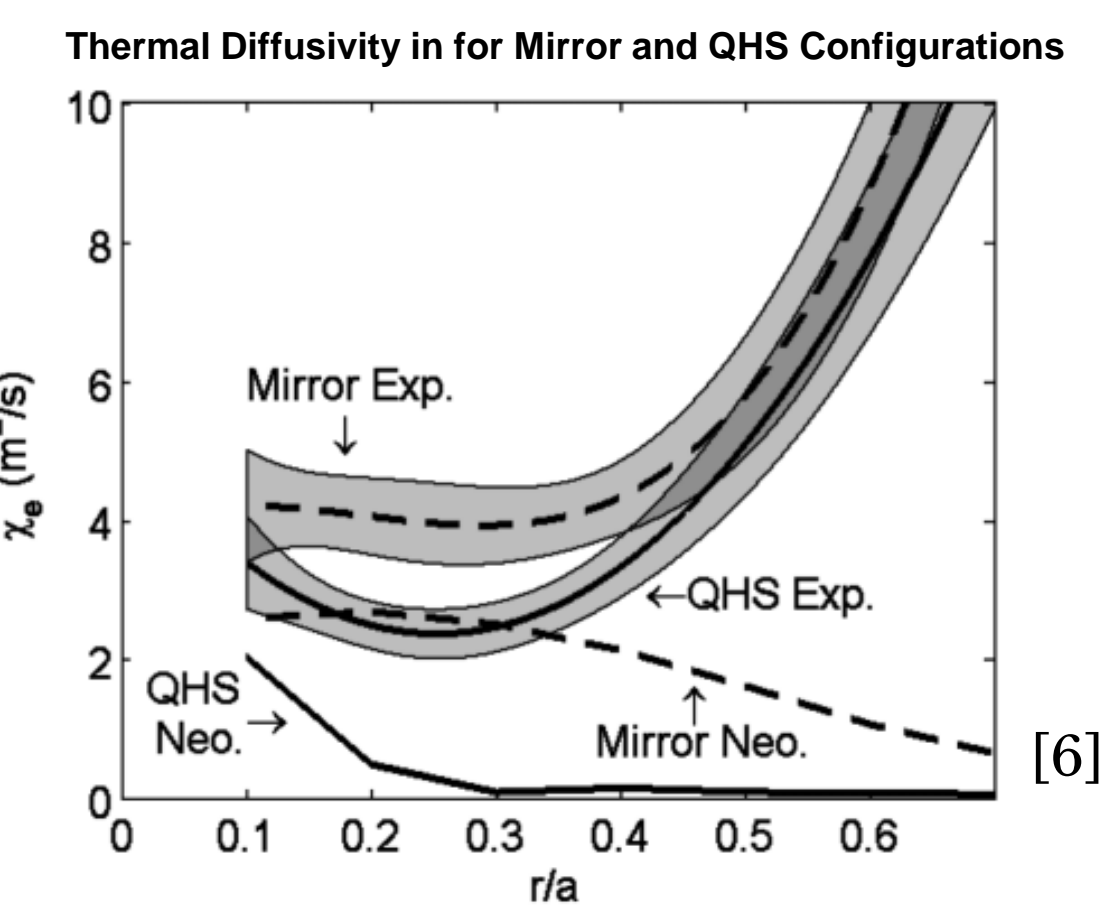
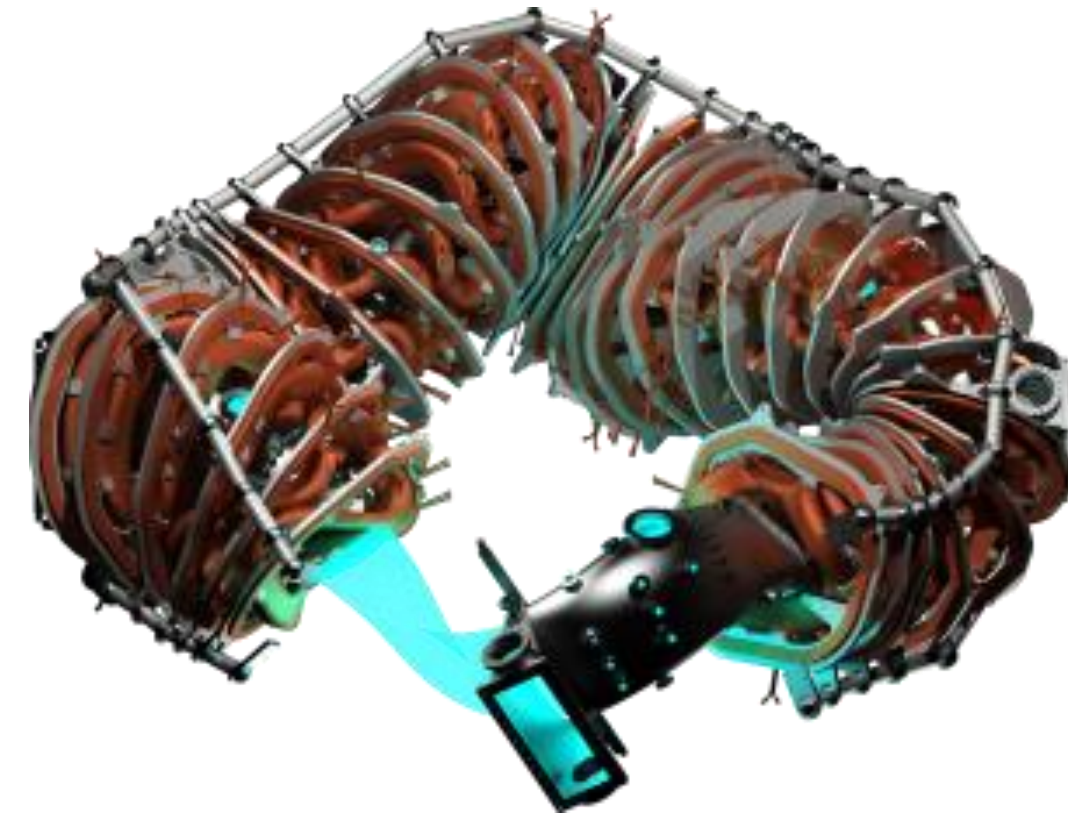
Active Charge Exchange Spectroscopy of Helium Ions for Momentum Transport Studies in HSX Stellarator

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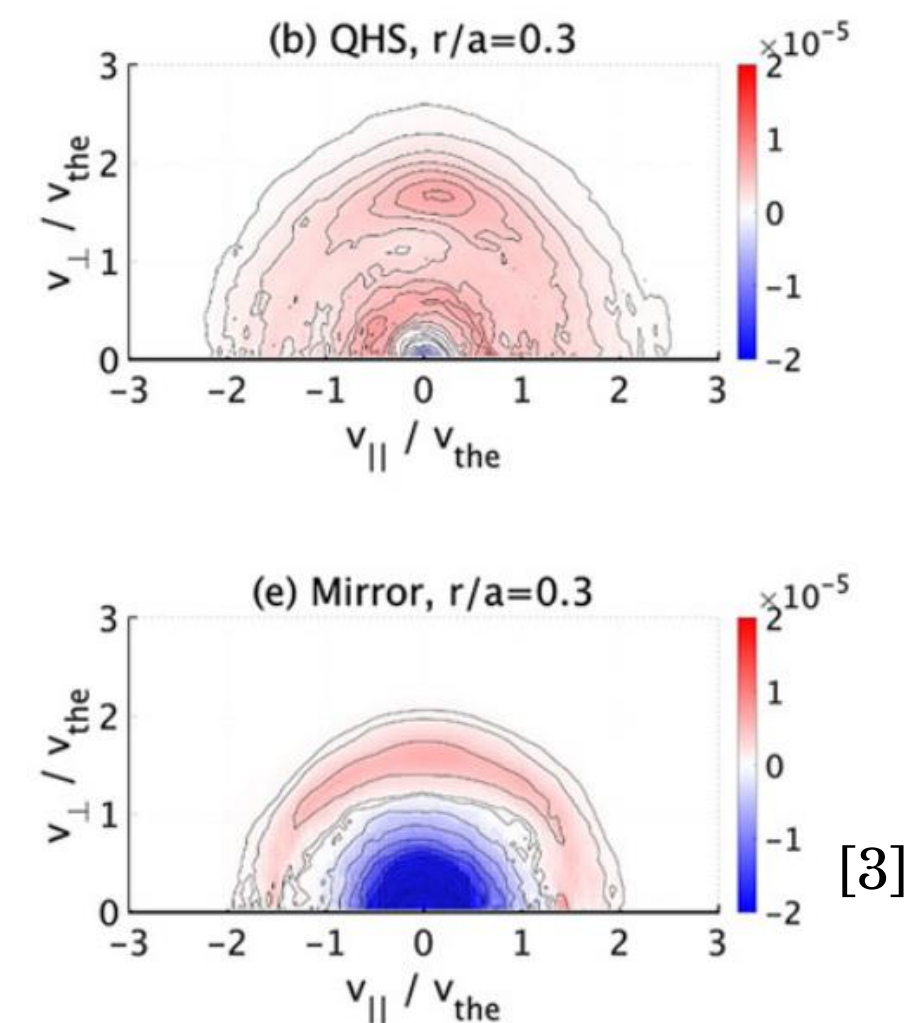
Flows and Quasisymmetry

- Tokamaks and perfect quasisymmetric stellarators have low flow damping in the direction of symmetry
- HSX is a quasihelically symmetric stellarator with 48 main coils and 48 auxiliary coils that allow for different configurations to be studied
- QHS configuration of HSX should have less flow damping than its broken symmetry Mirror configuration [6], but measurements show larger flow in the latter [7]



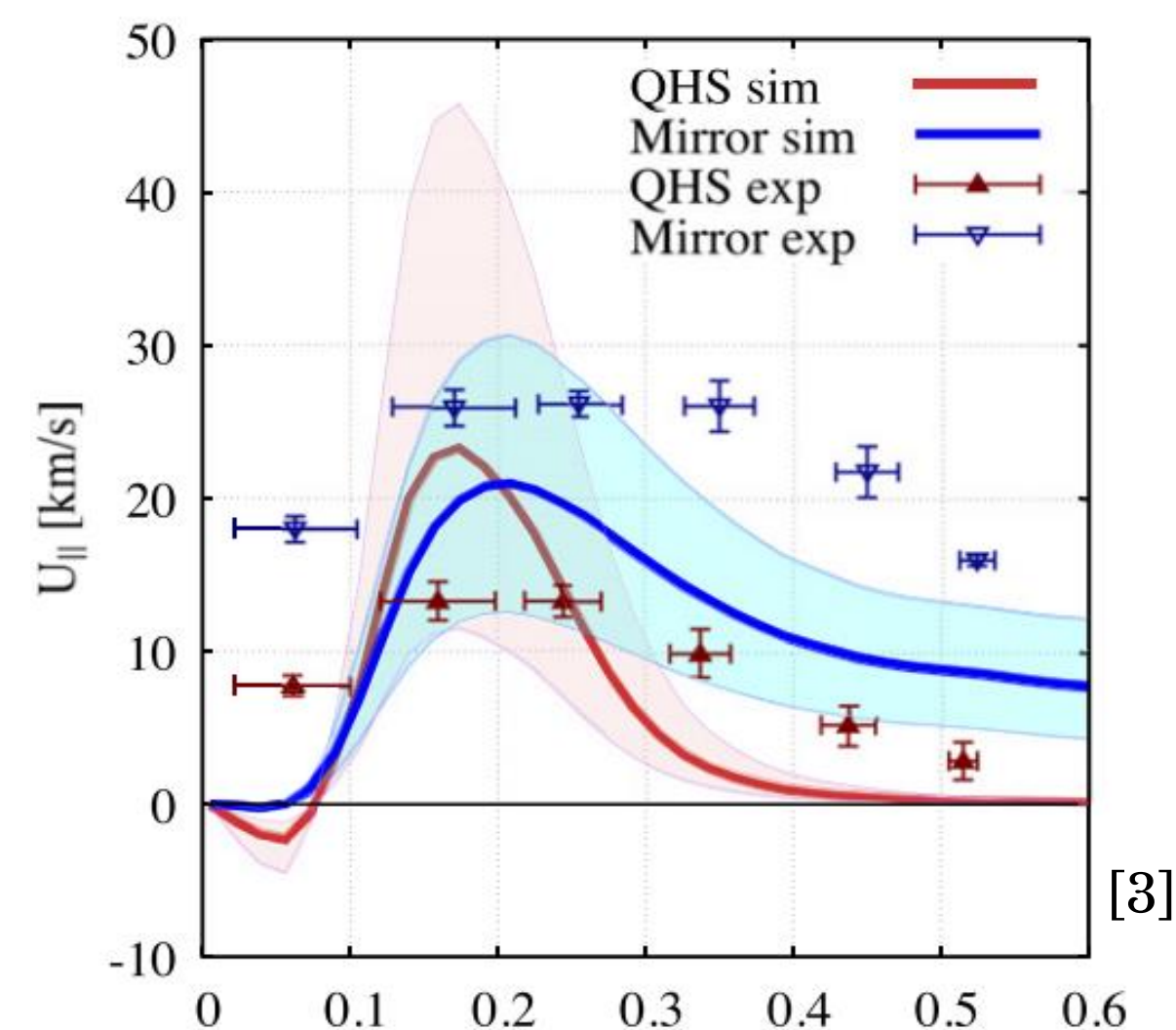
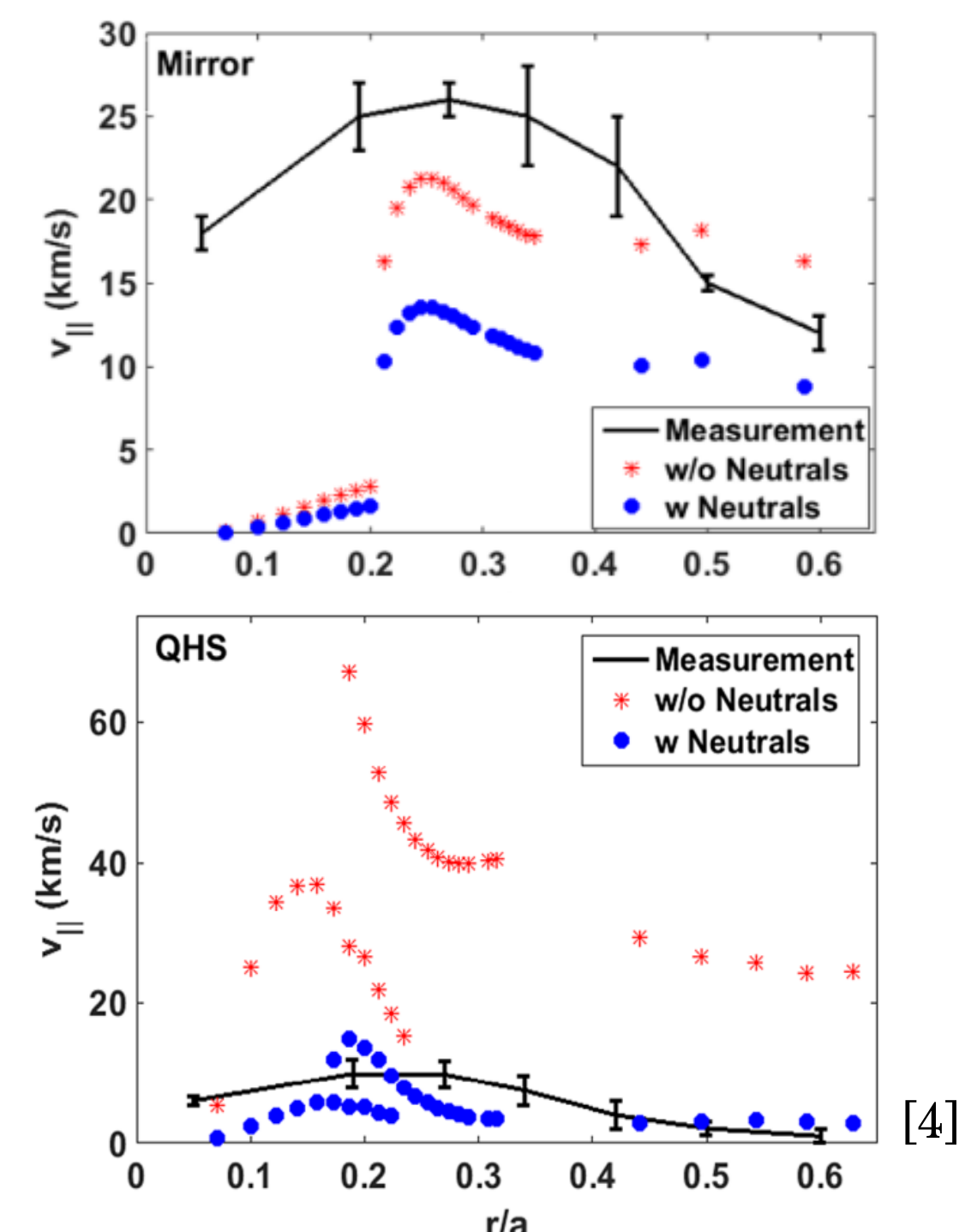
Flow Drive by Supra-thermal Electrons

- Measured flow is larger in Mirror configuration than QHS configuration – likely due to changes in the loss of supra-thermal electrons driven by Electron Cyclotron Heating (ECH) [3]
- Supra-thermal electrons are lost more quickly in the Mirror configuration than in the QHS configuration because of symmetry breaking terms
- This supra-thermal electron drift creates a radial current, j_{se} , for which the plasma develops a return current, j_{return} , to maintain quasi-neutrality. This results in a $j_{return} \times B$ force that drives plasma flow



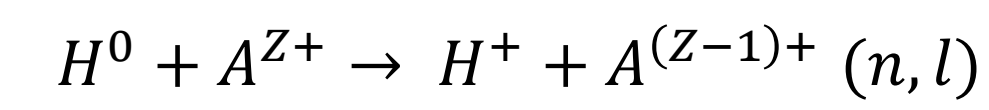
$$m_i N_i \frac{\partial}{\partial t} (\mathbf{B}_p \cdot \mathbf{U}_i) = \underbrace{-B^{\theta} B^z (j_{return} \cdot \nabla V)}_{j_{return} \times B} - \underbrace{(\mathbf{B}_p \cdot \nabla \cdot \boldsymbol{\pi}_i)}_{viscosity} - \underbrace{m_i N_i v_{in} (\mathbf{B}_p \cdot \mathbf{U}_i)}_{neutral flow damping term}$$

- Simulations containing both supra-thermal electrons and neutral damping (right) more closely match measured flow compared to simulations with just neutral damping (left) for both the QHS and Mirror configurations



Measuring CHERS Data

- Charge Exchange Recombination Spectroscopy (CHERS) is used to measure ion temperature, velocity, and density [1]

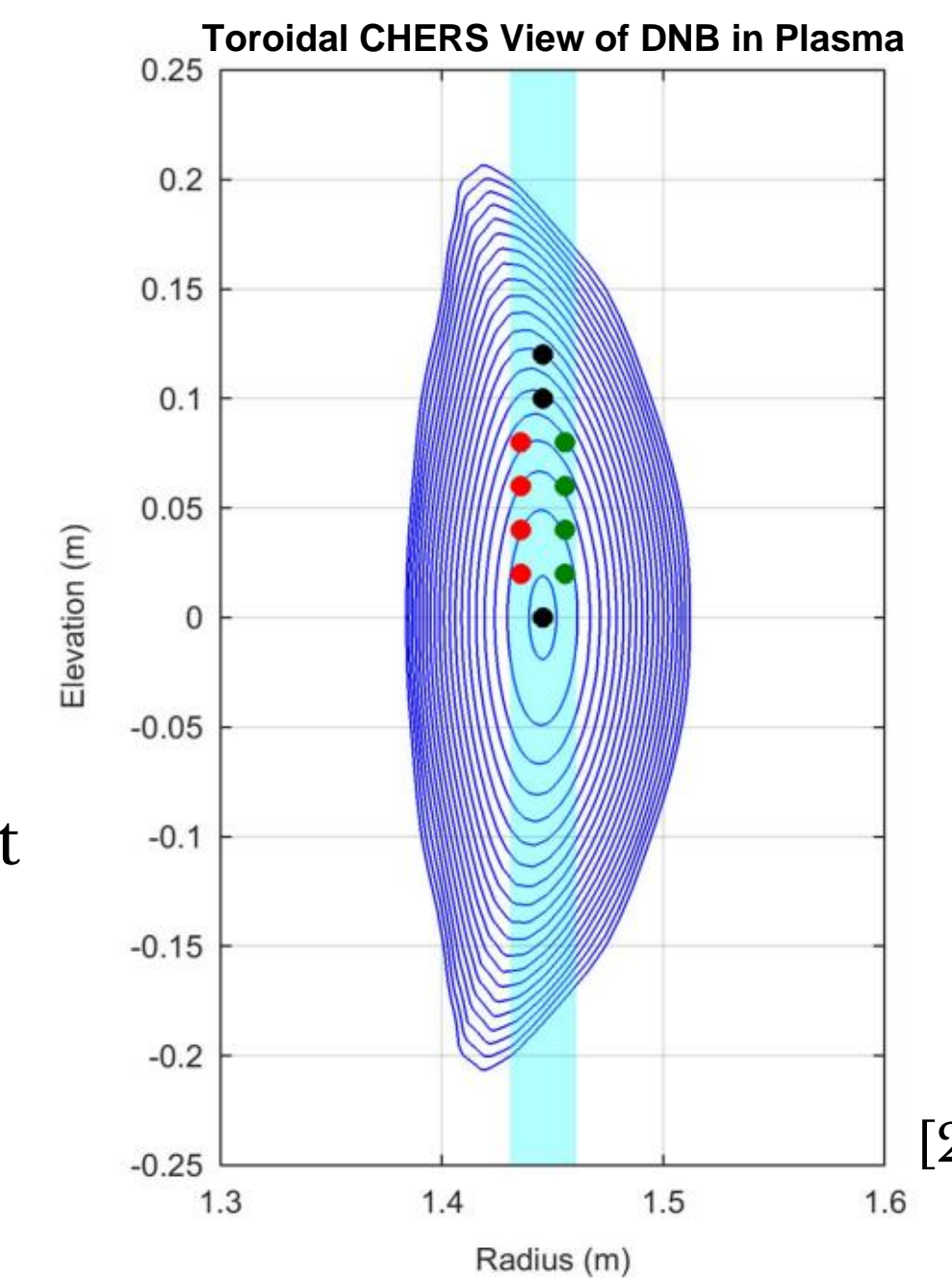
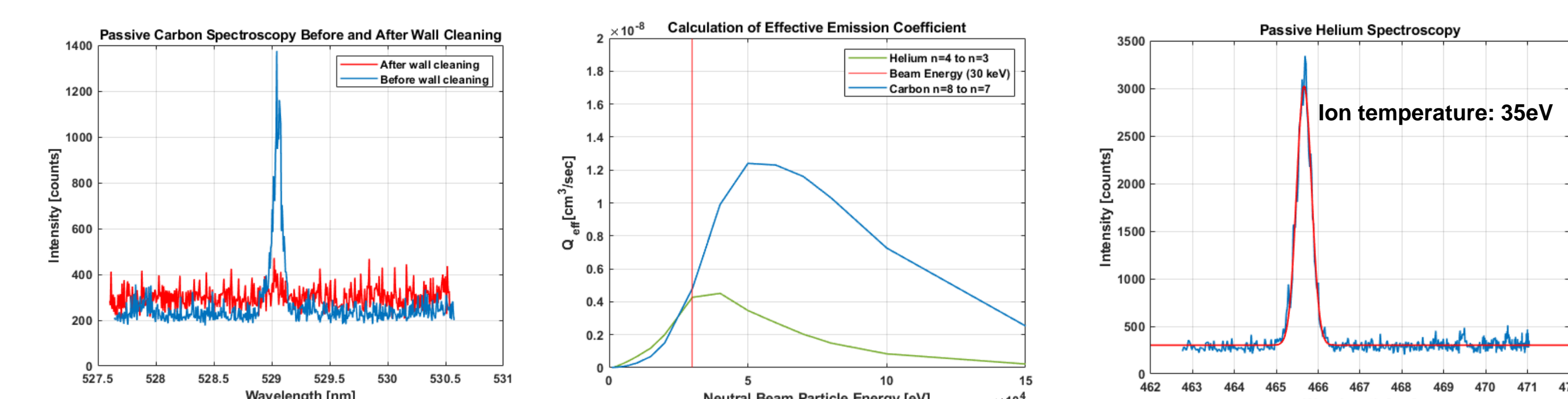


- Historically, in HSX, an emission line at of C^{5+} 529 nm from transitions $n = 8$ to $n = 7$ was measured. Now, with a newly cleaned metal wall, a shift towards a He^+ emission line at 468nm from transitions $n = 4$ to $n = 3$ will be made

- A 30keV, 3ms, 4A hydrogen Diagnostic Neutral Beam (DNB) is injected radially into the plasma

- Calculations for photon emission coefficient, Q_{eff} , at the Diagnostic Neutral Beam (DNB) energy are comparable between C^{5+} and He^+

$$\text{Photons emitted} = \int_{\text{BeamStart}}^{\text{BeamEnd}} \iiint Q_{eff} n_{ion} n_{beam} dV dt$$



- Ion temperatures are calculated from the width of beam data fit: $T_i = \frac{mc^2 \sigma^2}{\lambda_0}$
- DNB fires during CHERS acquisition, and the raw data is extracted by subtracting out the background light

CHERS System Specifications

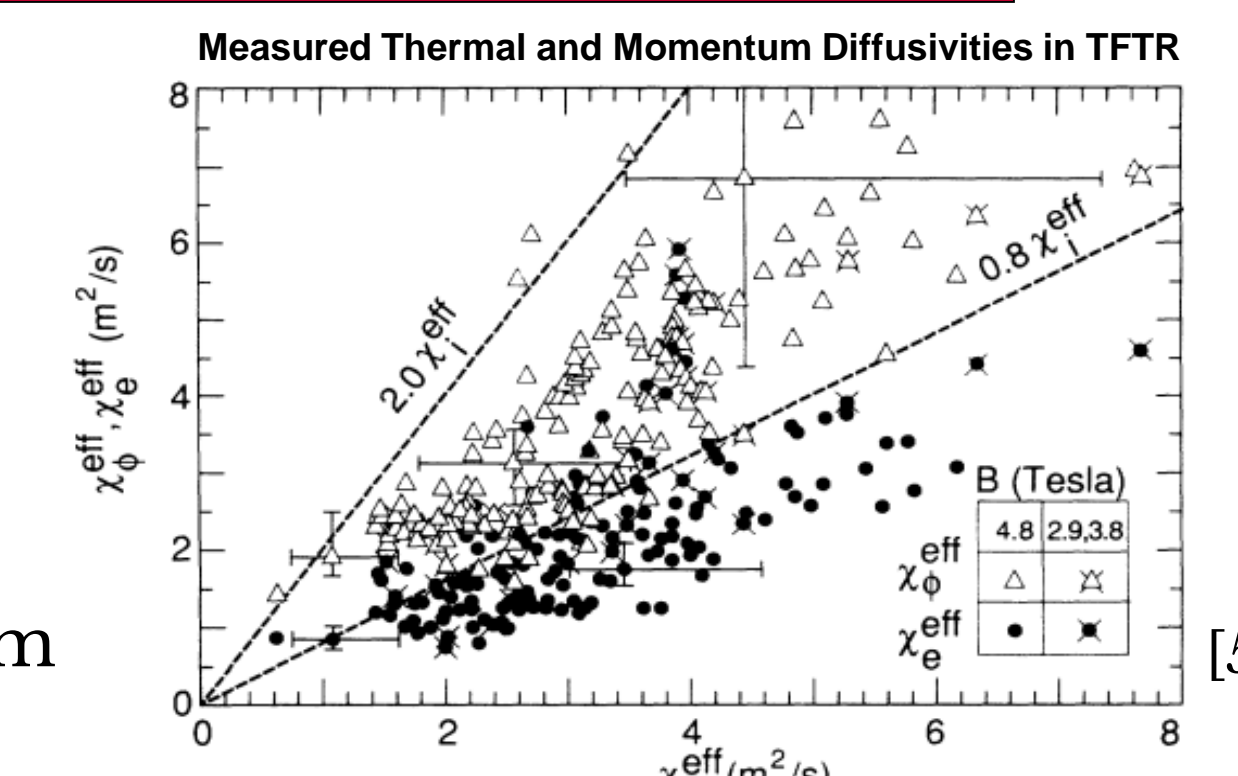
- Spectrometer:** Acton SpectraPro 750 **Camera:** Andor iXon Ultra
- Spectrometer Specifications:** **Camera Specifications:**
- Focal length: 0.75 m
 - Active Pixels: 512x512
 - Aperture ratio: f/6.5
 - Pixel Size: 16x16 μm
 - Grating: 2400 G/mm
 - Readout Rate: 17 MHz at 16-bit
 - Wavelength range: 0-600 nm
 - EM Amplifier: 17, 10, 5, & 1 MHz
- Fibers:** 12 fibers per camera, 600mm diameter core, 400-800nm wavelength

Momentum Transport

- The Prandtl number (P_r) gives the ratio of momentum diffusivity (χ_ϕ) to the ion thermal conductivity (χ_i). It is related to energy confinement time (τ_E)

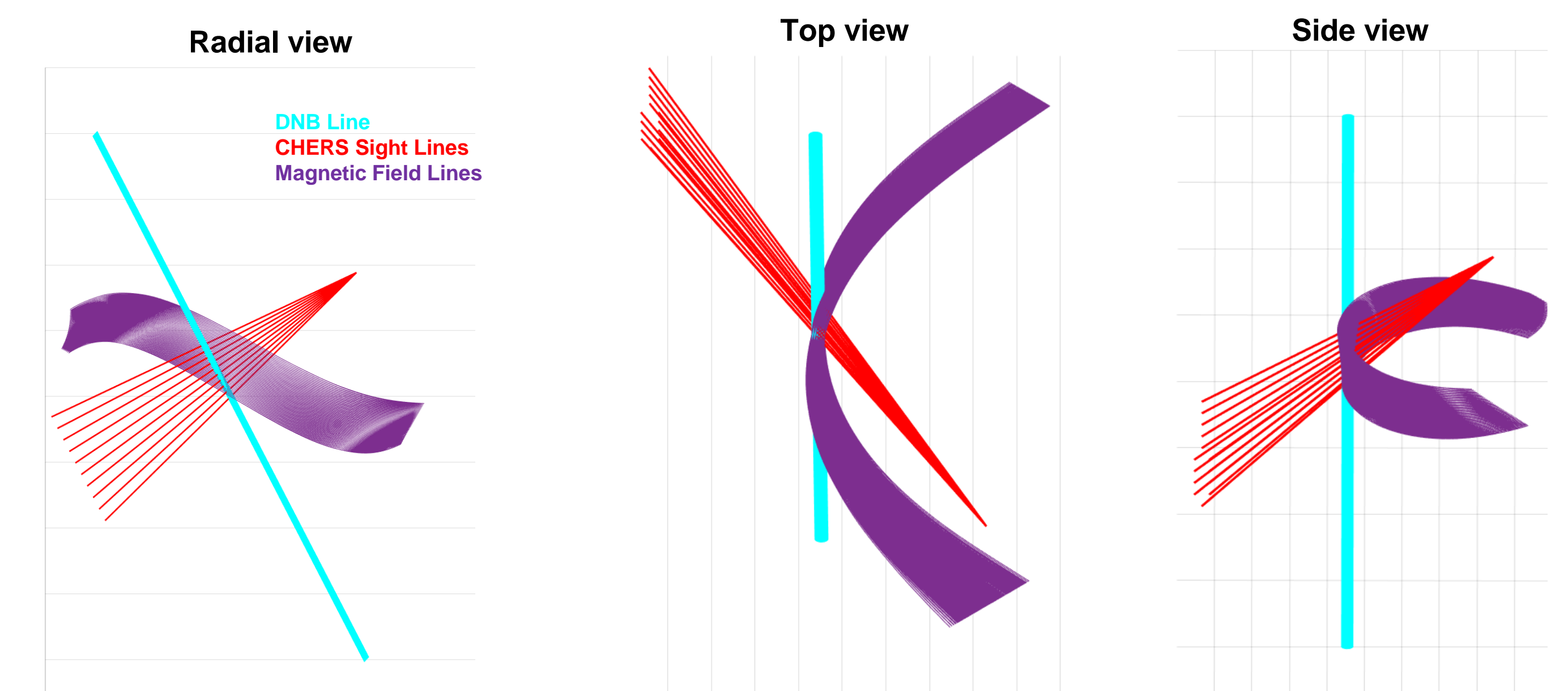
$$P_r = \frac{\chi_\phi}{\chi_i} \sim \frac{\tau_E}{\tau_\phi}$$

- Studies on TFTR show heat and momentum transport scale with each other [5]
- In many tokamaks, $P_r \sim 0.8 - 2$ which shows a close relation between momentum and energy confinement time ($\tau_E = 3-5$ ms in HSX) [8]
- A bias electrode will be used for momentum injection experiments. Momentum transport measurements will be conducted by observing how quickly the bias reaches the plasma core



Helium Plume Mitigated by HSX Geometry

- The plume effect occurs when a particle that has already emitted a photon undergoes electron-impact excitation outside the beam intersection region and emits another photon in the line of sight
- The plume effect is more common in Helium than Carbon, because electron impact ionization is larger in Carbon than Helium, making it harder for an electron to jump from $n = 7$ to $n = 8$ (529nm C emission lines) than from $n = 3$ to $n = 4$ (468nm He emission lines)
- HSX geometry allows particles following field lines to move out of CHERS line of sight regardless of if they emit more photons



Future Work

- Reconditioning of the DNB is in progress
- Upgrade in progress for poloidal CHERS views which will allow for better time resolution of momentum transport measurements
- Since 0.5T ECH (X-mode, 28GHz) heating produces more supra-thermal electrons than 1T ECH (O-mode, 28GHz) heating, measurements of flow in Mirror and QHS configurations at both field strengths will be made and used to further verify and explore trends and predicted scaling
- Bias electrode studies will be used to understand the relationship of momentum transport and energy confinement time

References

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- [3] Y. Yamamoto *et al.*, Nucl. Fusion **62** 064004 (2022)
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- [7] A.R. Briesemeister, Ph.D. Thesis, University of Wisconsin - Madison, 2013
- [8] J. Rice, Driven Rotation, Self-generated Flow, and Momentum Transport in Tokamak Plasmas (Springer, 2022)