Measurements and Modeling of Plasma Flow Damping in the HSX Stellarator

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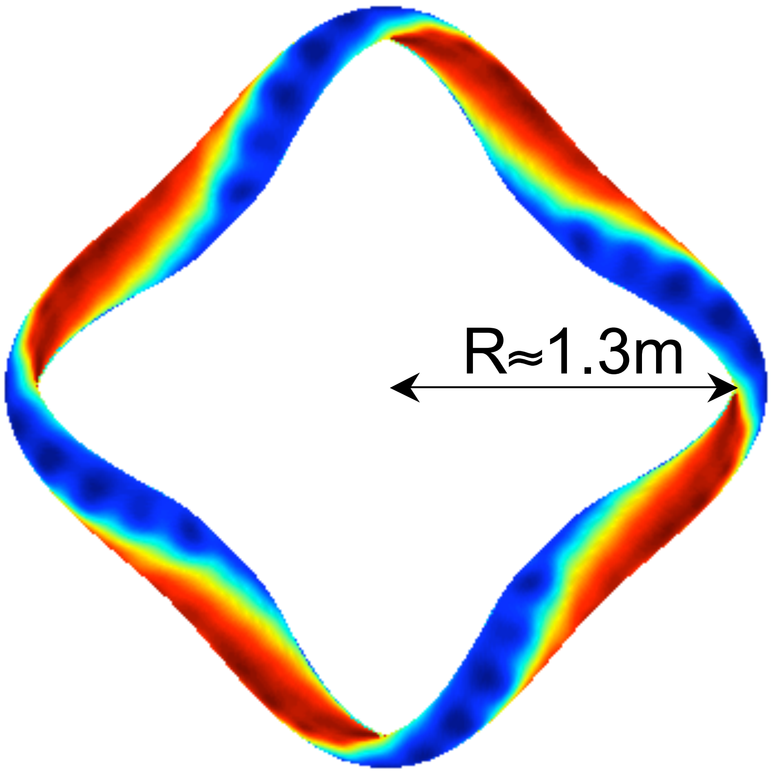
Outline

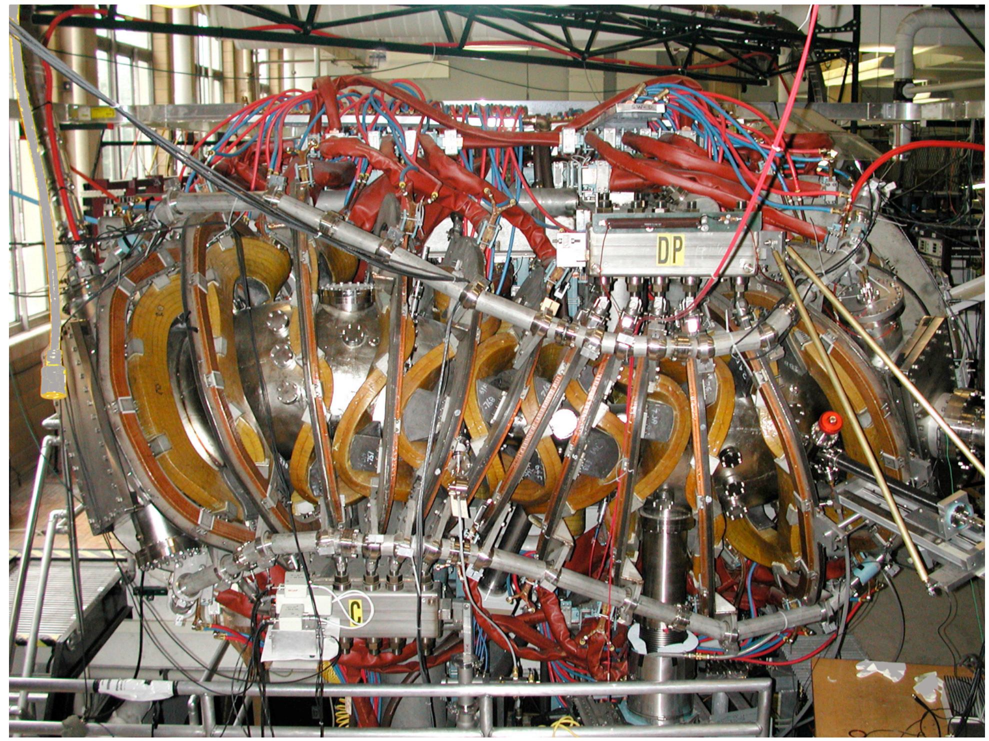
- Description of experiments and diagnostics
- Studies of flow and electric field evolution
  - Asymmetries between the spin-up and relaxation
  - Two time-scale flow evolution
  - Reduced damping with quasisymmetry
- Neoclassical modeling of flow damping
  - Original model for the spin-up
- Measurements/modeling comparison
  - Reduced flow damping in quasisymmetric configurations
  - Flow damping larger than the neoclassical prediction

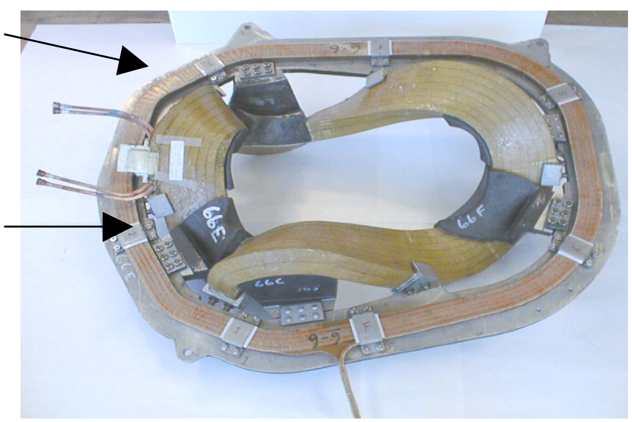
Modular Coils Lead to Experimental Flexibility

B=0.5T

P_{ECH}<200 kW @ 28 GHz



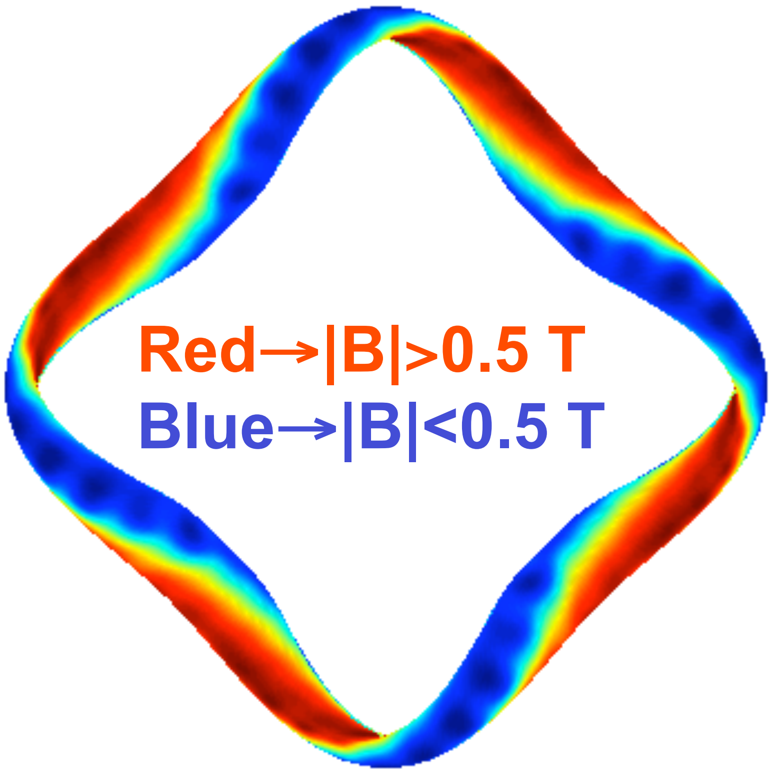




HSX is located at the University of Wisconsin-Madison

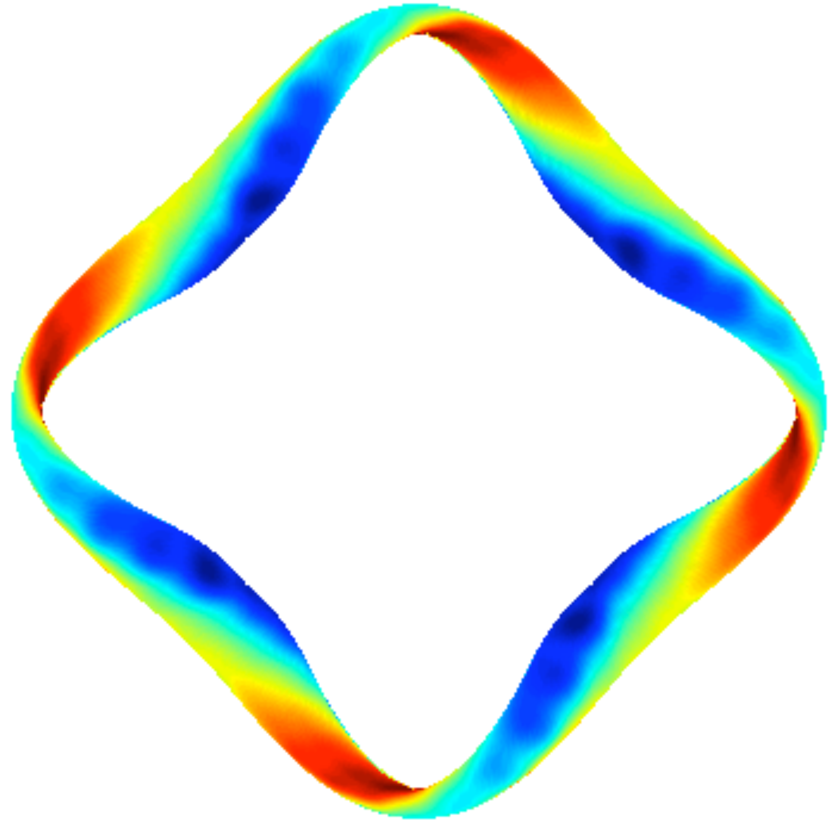
HSX Provides Access to Configurations With and Without Symmetry

QHS Configuration



QHS: Helical Bands of Constant |B|

Mirror Configuration

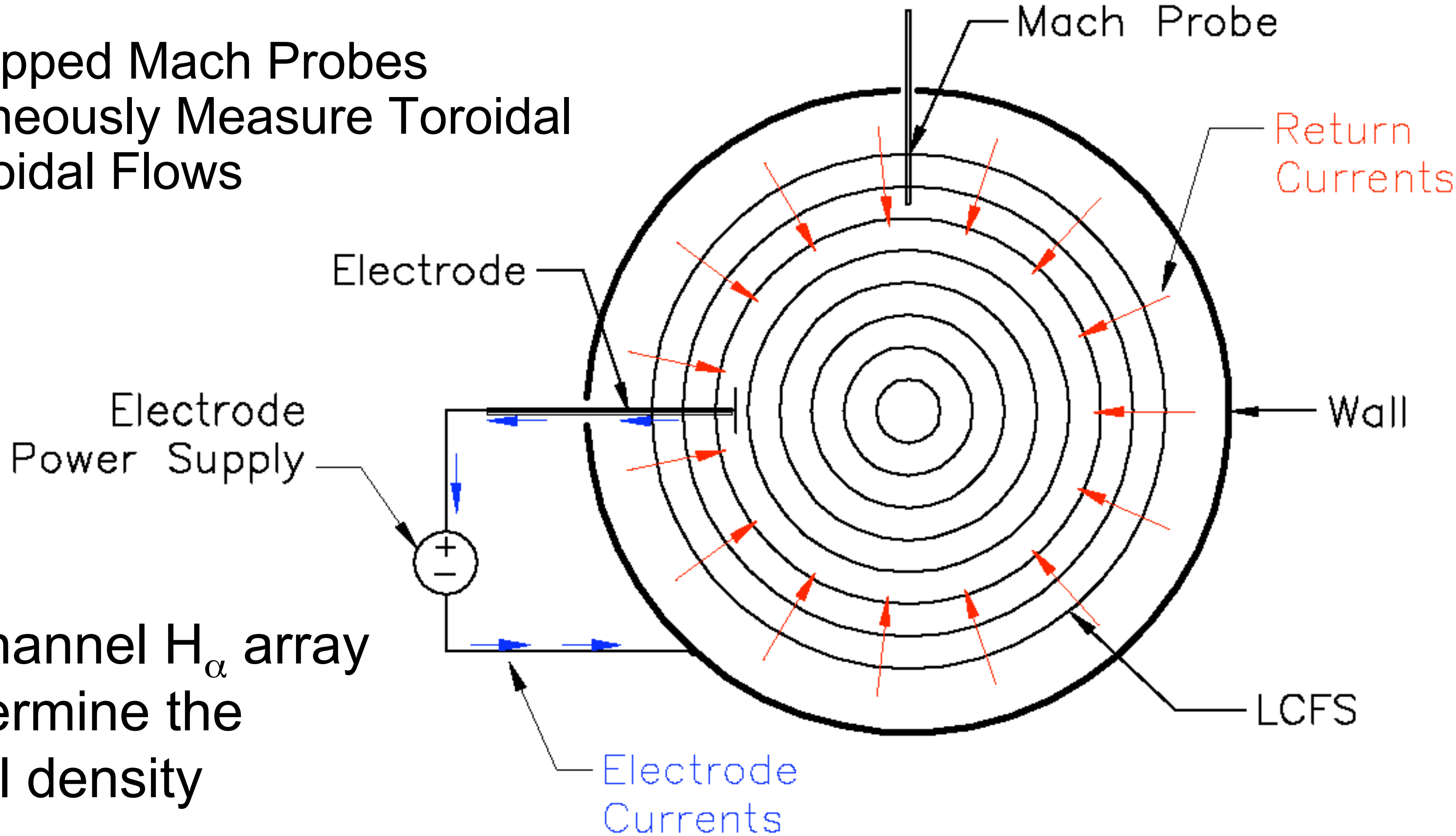


Mirror: Helical Bands are Broken

Probes and Electrodes Used to Study Flow Damping

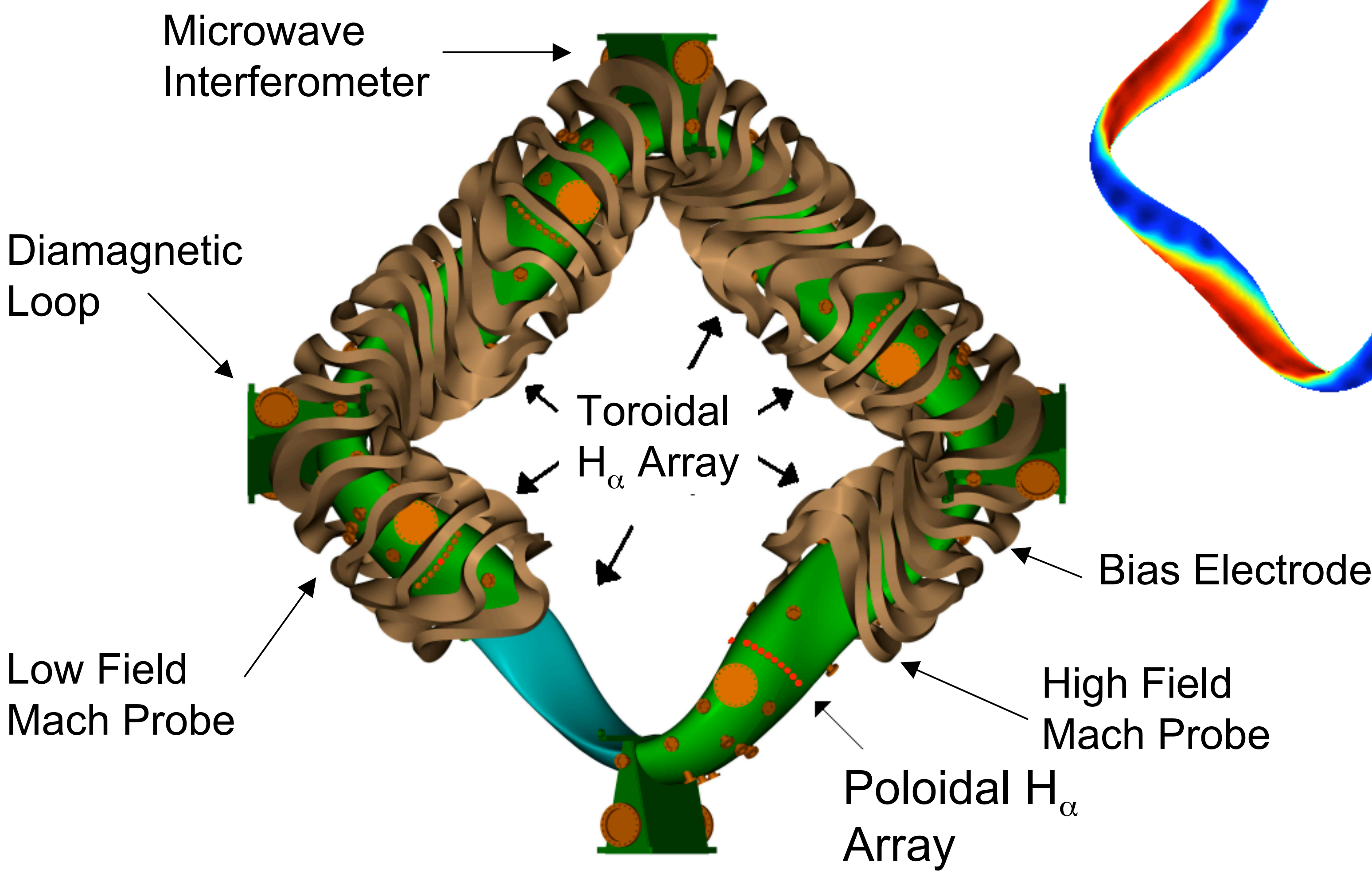
•Bias Electrode to Drive Flows

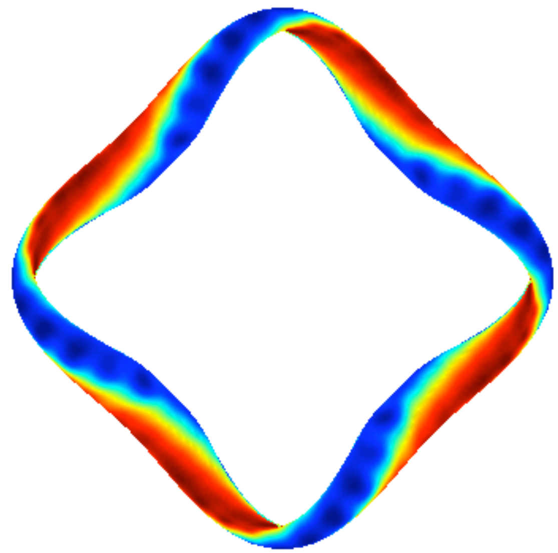
•Multi-Tipped Mach Probes Simultaneously Measure Toroidal and Poloidal Flows



• 16 channel H_{α} array to determine the neutral density

Comprehensive Diagnostics For Flow Damping Studies





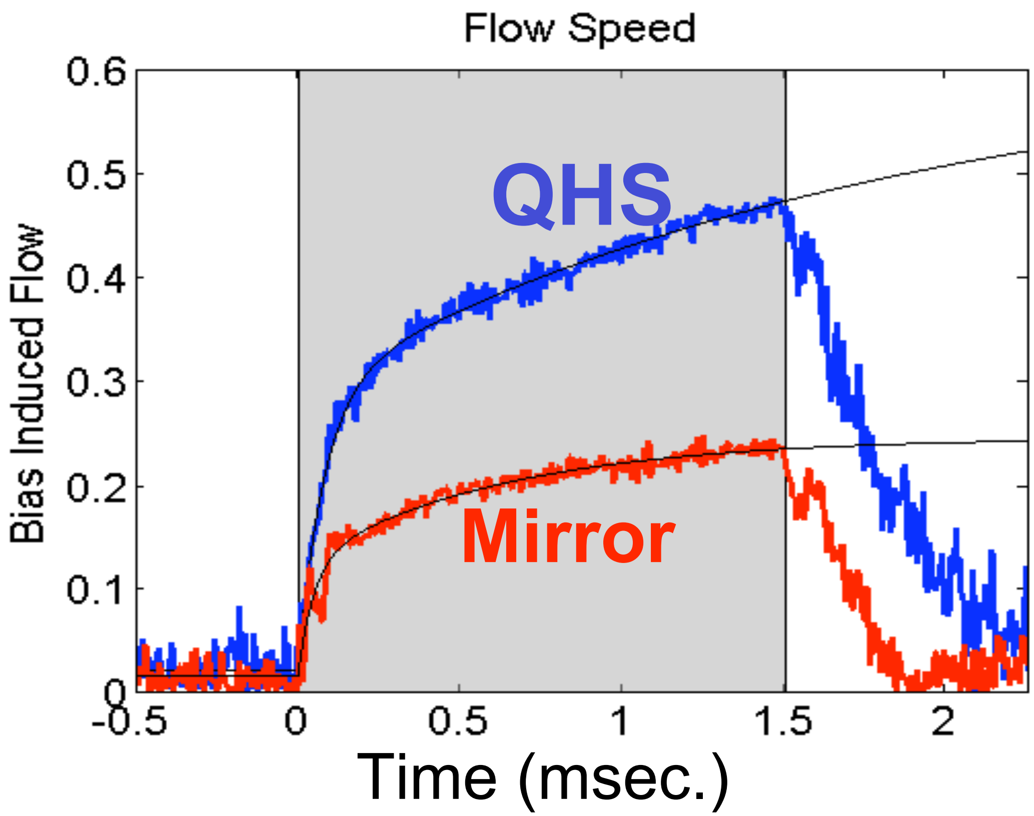
Biased Electrode Experiments

Demonstrate New Flow Phenomena:

1) Reduced Flow Damping with Quasisymmetry

2) Two Time-Scale Flow Evolution

Preview: QHS Flows Damp More Slowly, Goes Faster For Less Drive



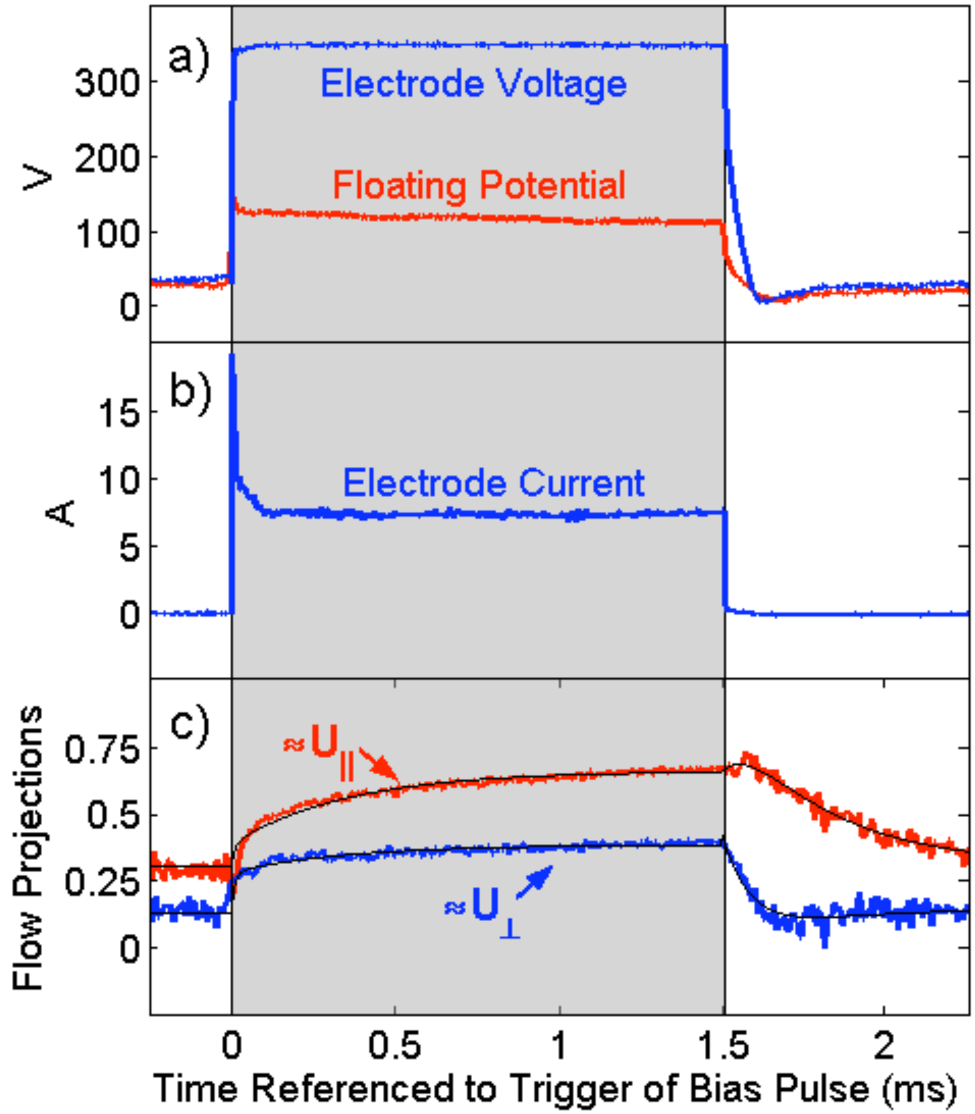
QHS: 8 A of electrode current

Mirror: 10 A of electrode current

All other parameters (n_e=1x10^{12}cm^{-3}, $n_n \approx$ 1x10^{10}cm^{-3} T_i ≈25eV, B=0.5T, P_{ECH}=50 kW) held constant.

Asymmetries and Multiple Time-Scales Observed in Flow Evolution

- Potentials:
  Fast Rise and Slow Decay
- Electrode Current:
  Large Spike and Fast Termination
- Plasma Flows:
  Fast and Slow Time-Scales at Rise and Decay



Neoclassical Modeling

Goal: Assess the flow damping caused by

1) Symmetry breaking ripples

2) Ion-neutral friction

Solve the Momentum Equations on a Flux Surface

- Two time-scales/directions come from the coupled momentum equations on a surface

$$m_i N_i \frac{\partial}{\partial t} < \mathbf{B}_P \cdot \mathbf{U} > = -\frac{\sqrt{g} B^{\zeta} B^{\alpha}}{c} < \mathbf{J}_{plasma} \cdot \nabla\psi > - < \mathbf{B}_P \cdot \nabla \cdot \Pi > - m_i N_i < \nu_{in} \mathbf{B}_P \cdot \mathbf{U} >$$

$$m_i N_i \frac{\partial}{\partial t} < \mathbf{B} \cdot \mathbf{U} > = - < \mathbf{B} \cdot \nabla \cdot \Pi > - m_i N_i < \nu_{in} \mathbf{B} \cdot \mathbf{U} >$$

- Use Hamada coordinates, linear neoclassical viscosities, neglect heat fluxes

- Steady state solution yields radial conductivity

$$\left\langle \mathbf{J}_{plasma} \cdot \nabla\psi \right\rangle = \sigma_{\perp} \left(\left\langle \mathbf{E}_r \cdot \nabla\psi \right\rangle - \frac{\left\langle \nabla p_i \cdot \nabla\psi \right\rangle}{e N_i} \right)$$

Spin-Up and Spin-Down are Treated Differently in Modeling

- At bias turn-on, switches put voltage on the electrode (~1 μsec.).

- Measurements show electric field is established on the electrode voltage-rise time-scale.

- Spin-Up Model: Flows and radial current respond to the electrode potential rise.

- At bias turn-off, switches break the electrode current (~1 μsec.).

- Relaxation Model: Flows and electric field respond to the electrode current termination.

Flow Rise: Electric Field is Turned on Quickly

- Assume that the electric field, $d\Phi/d\psi$, is turned on quickly

$$\frac{\partial \Phi}{\partial \psi} = \begin{cases} E_{r0} & t < 0 \\ E_{r0} + \kappa_E\left(1 - e^{-t/\tau}\right) & t > 0 \end{cases}$$

- **ExB** flows and compensating Pfirsch-Schlueter flow grow on the electric field time-scale

- Parallel flow grows at a "Hybrid rate" ν_F determined by viscosity and ion-neutral friction

$$\nu_F = \iota\nu_\alpha + \nu_\zeta + \nu_{in}$$

Toroidal Damping (→ ν_ζ)

Poloidal Damping (→ $\iota\nu_\alpha$)

- Two time-scales/two direction flow evolution

$$\mathbf{U}(t) \approx U_E^\alpha\left(1 - e^{-t/\tau}\right)\mathbf{e}_\alpha + \mathbf{U}_\parallel\left(1 - e^{-\upsilon_F t}\right)$$

Flow Decay: External Radial Current is Quickly Turned Off

- $\gamma_f(\psi)$ (fast), and $\gamma_s(\psi)$ (slow rate) are flux surface quantities related to the geometry and ion-neutral collision frequency.

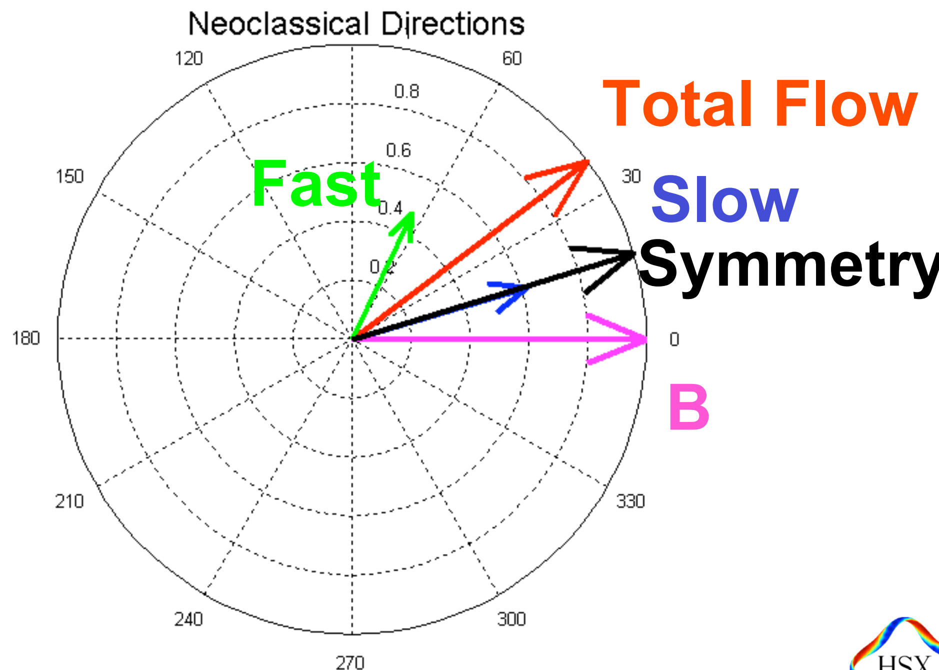
- Break the flow into parts damped on each time-scale:

$$\mathbf{U} = e^{-\gamma_f (t-t_0)}\mathbf{f} + e^{-\gamma_s (t-t_0)}\mathbf{s}$$

- Large neutral density (n_n=1x10^{12} cm^{-3}) in this calculation.

- Slow rate corresponds to flows in the direction of symmetry.

- Numerically calculated Hamada basis vectors used in this figure.



The Hybrid Rate is Intermediate to the Fast and Slow Rate

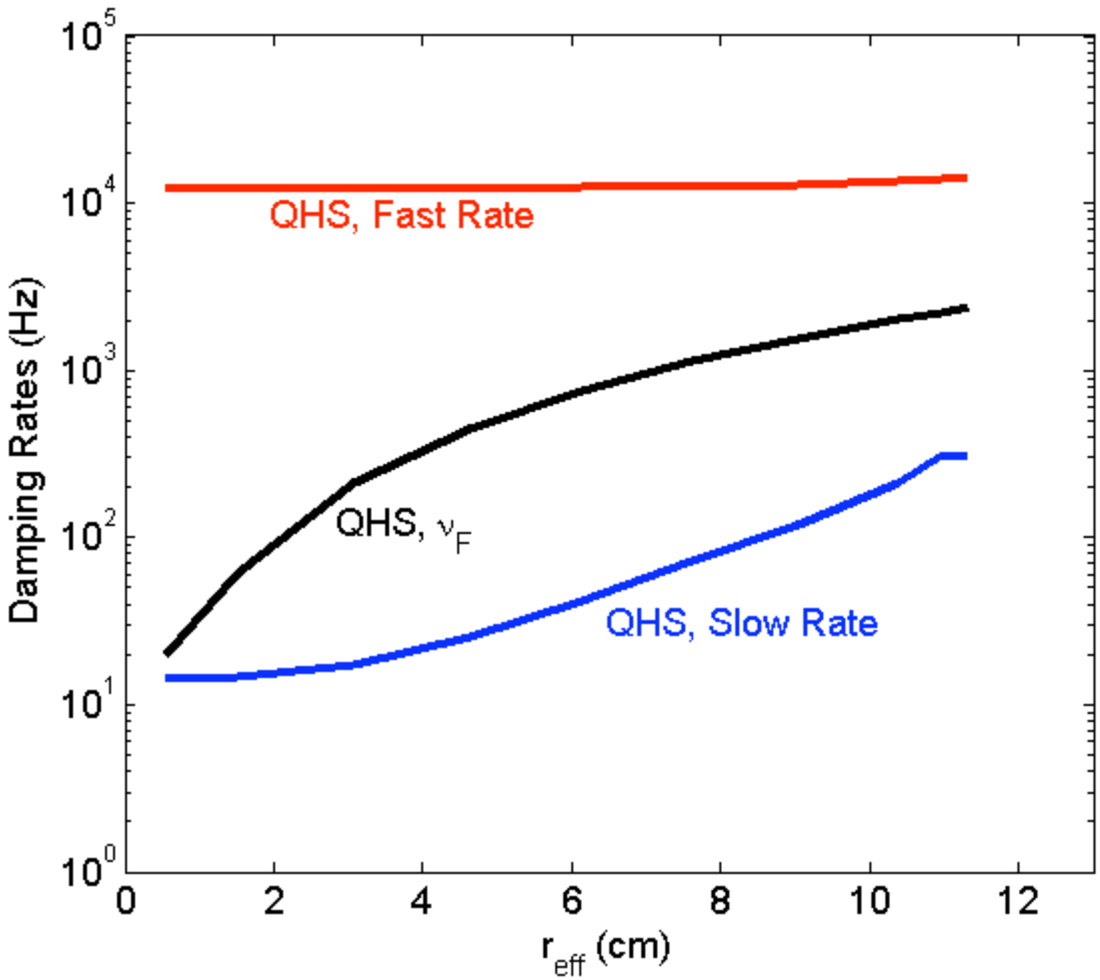
Fast Rate

is faster than

Hybrid Rate, ν_F

is faster than

Slow Rate



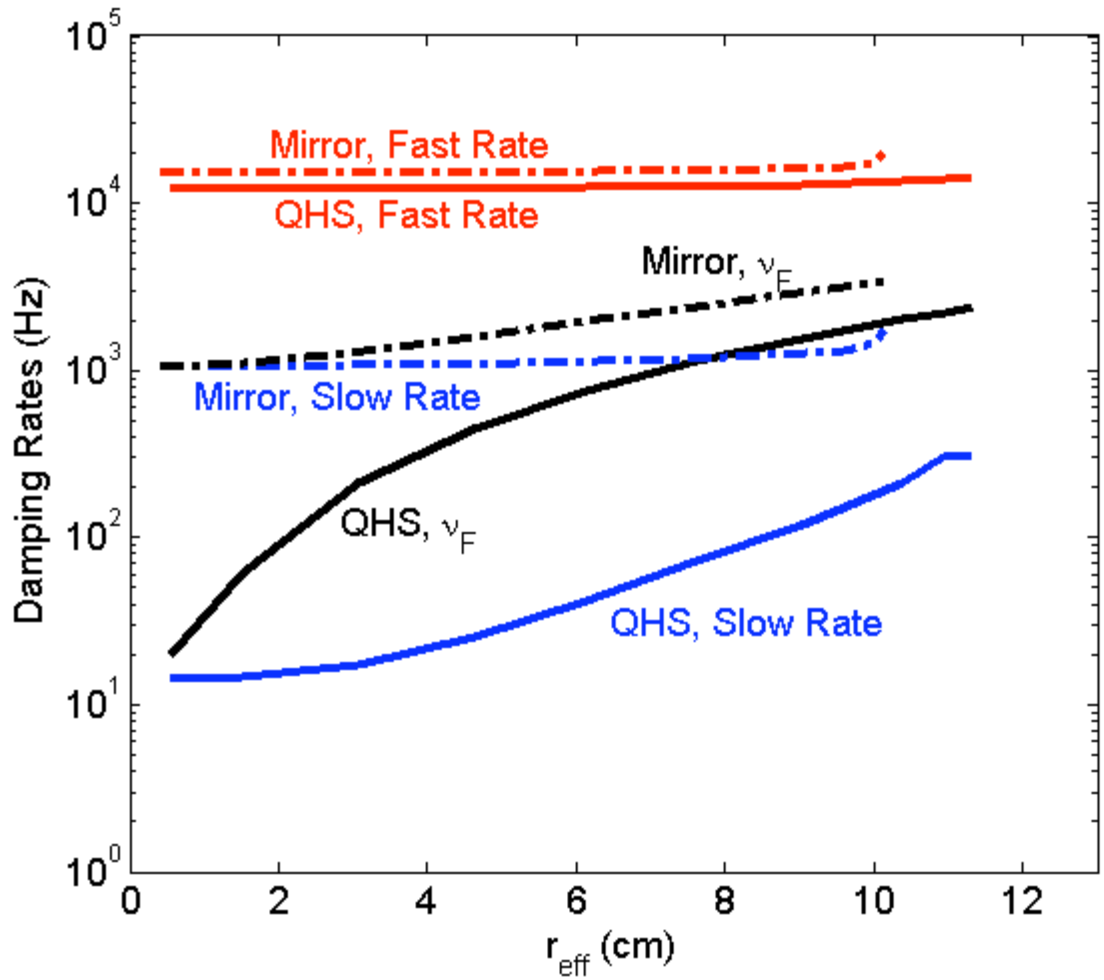
Mirror Shows Increased Neoclassical Damping Compared to QHS

QHS/Mirror Comparison

Fast rates are comparable

Mirror ν_F is larger by a factor of 2-3

Mirror slow rate is larger by 1-2 orders of magnitude

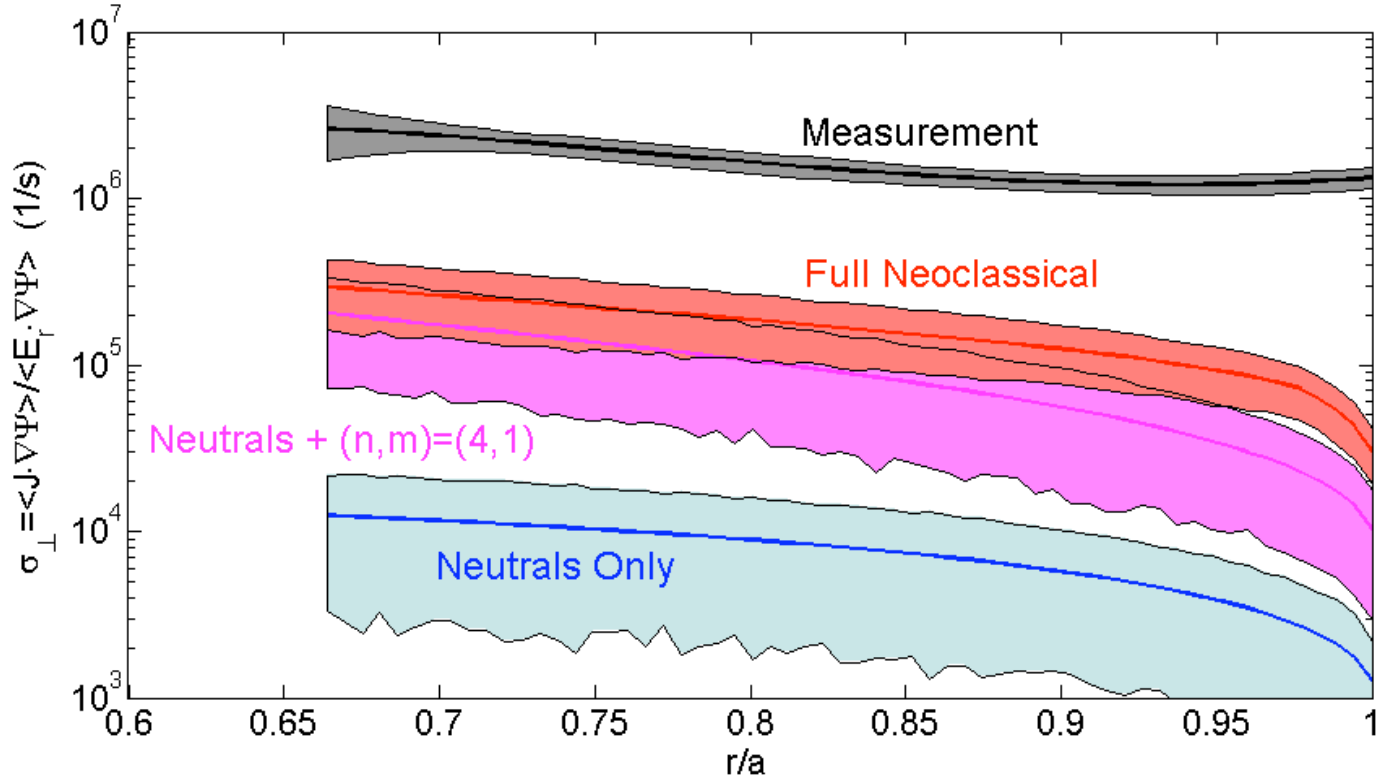


Comparison of Neoclassical Theory with Measurements

1) Reduced Flow Damping with Quasisymmetry

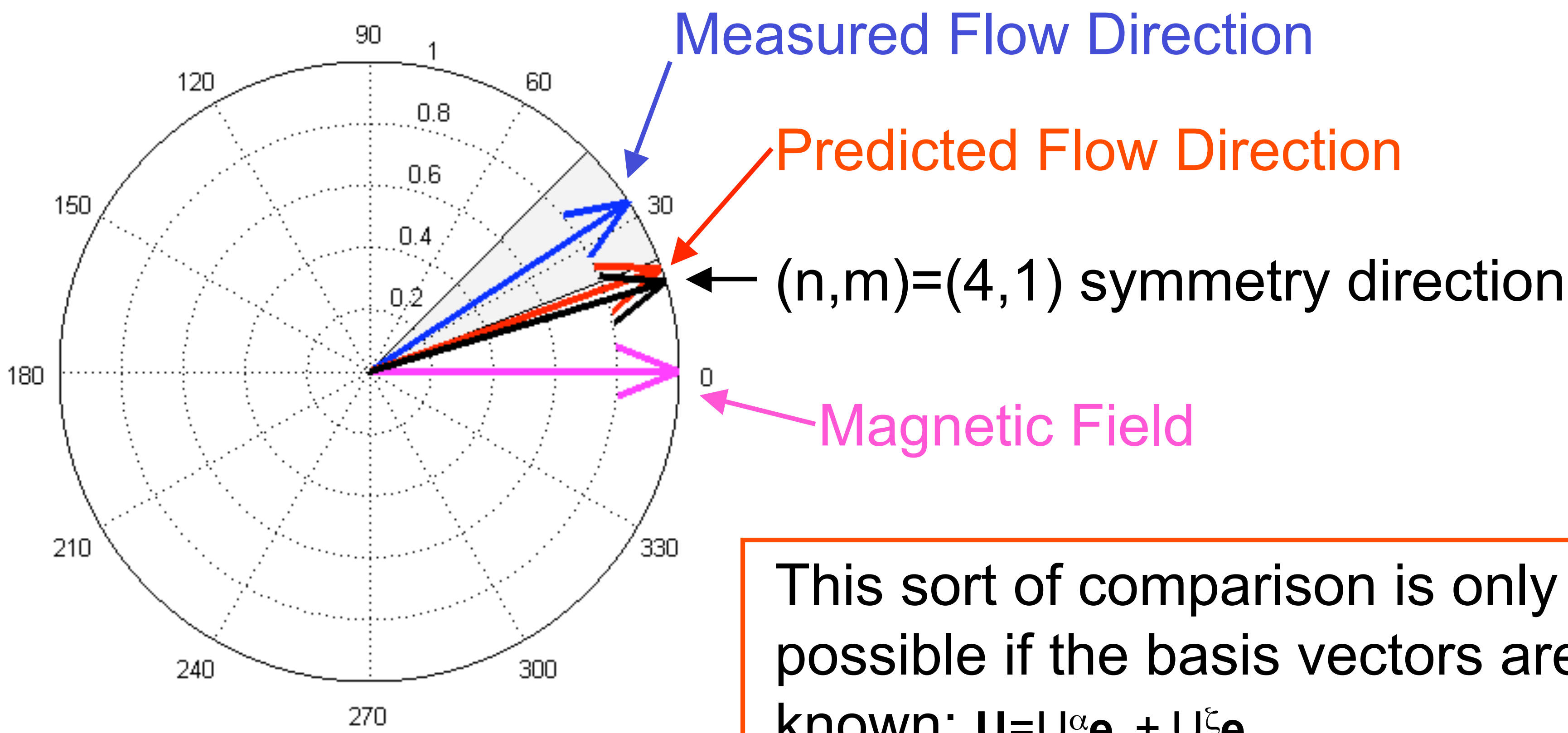
2) Evidence of Anomalous Flow Damping

QHS Radial Conductivity is Larger than the Neoclassical Prediction



$$\left\langle \vec{J}_{plasma} \cdot \vec{\nabla}\psi \right\rangle = \sigma_{\perp}\left(\left\langle \vec{E}_r \cdot \vec{\nabla}\psi \right\rangle - \frac{\left\langle \vec{\nabla}p_i \cdot \vec{\nabla}\psi \right\rangle}{eN_i} \right)$$

Steady State Flow Direction Differs Somewhat from Neoclassical Prediction

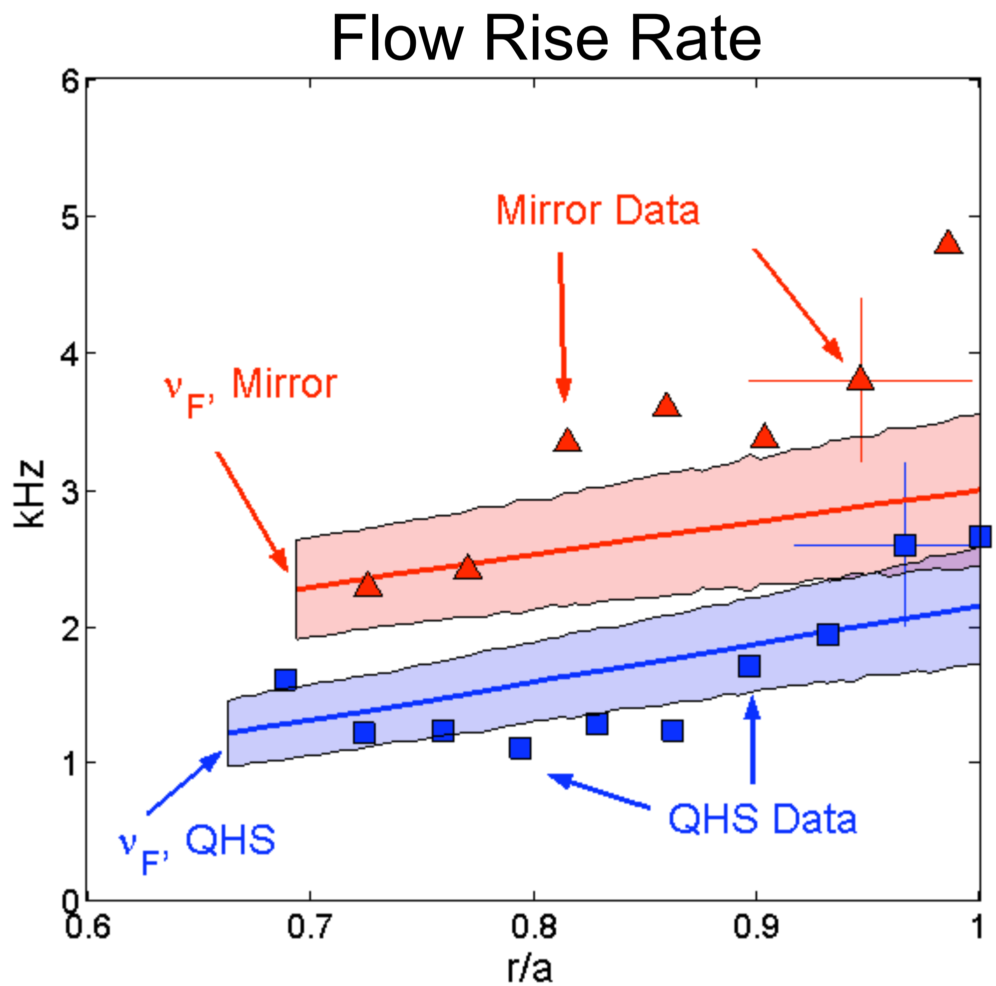


This sort of comparison is only possible if the basis vectors are known: $\mathbf{U}=U^{\alpha}\mathbf{e}_{\alpha}+U^{\zeta}\mathbf{e}_{\zeta}$

Modeling Predicts the Difference in the QHS and Mirror Slow Rise Rates

➢ Mirror flows rise more quickly than QHS.

➢Neoclassical hybrid time ν_F shows good agreement with the measurements.

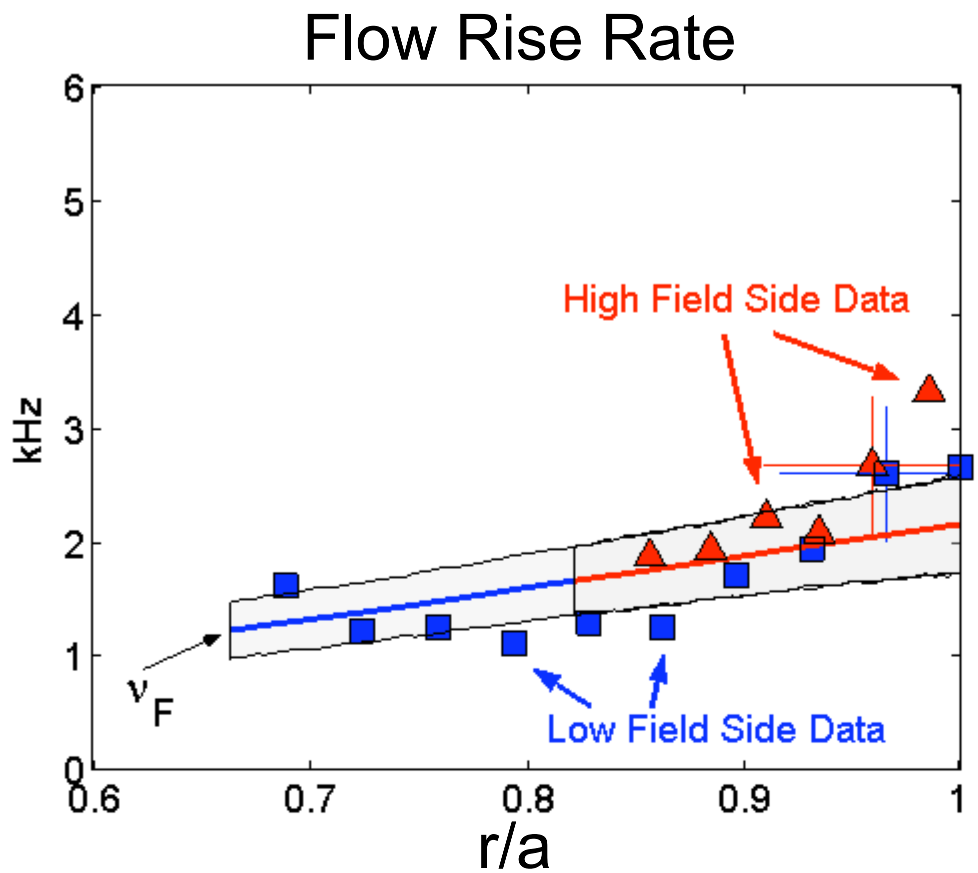


Similar Flow Rise Rates Simultaneously Measured at High and Low Field Locations

All relevant time-scales are similar on high and low field sides

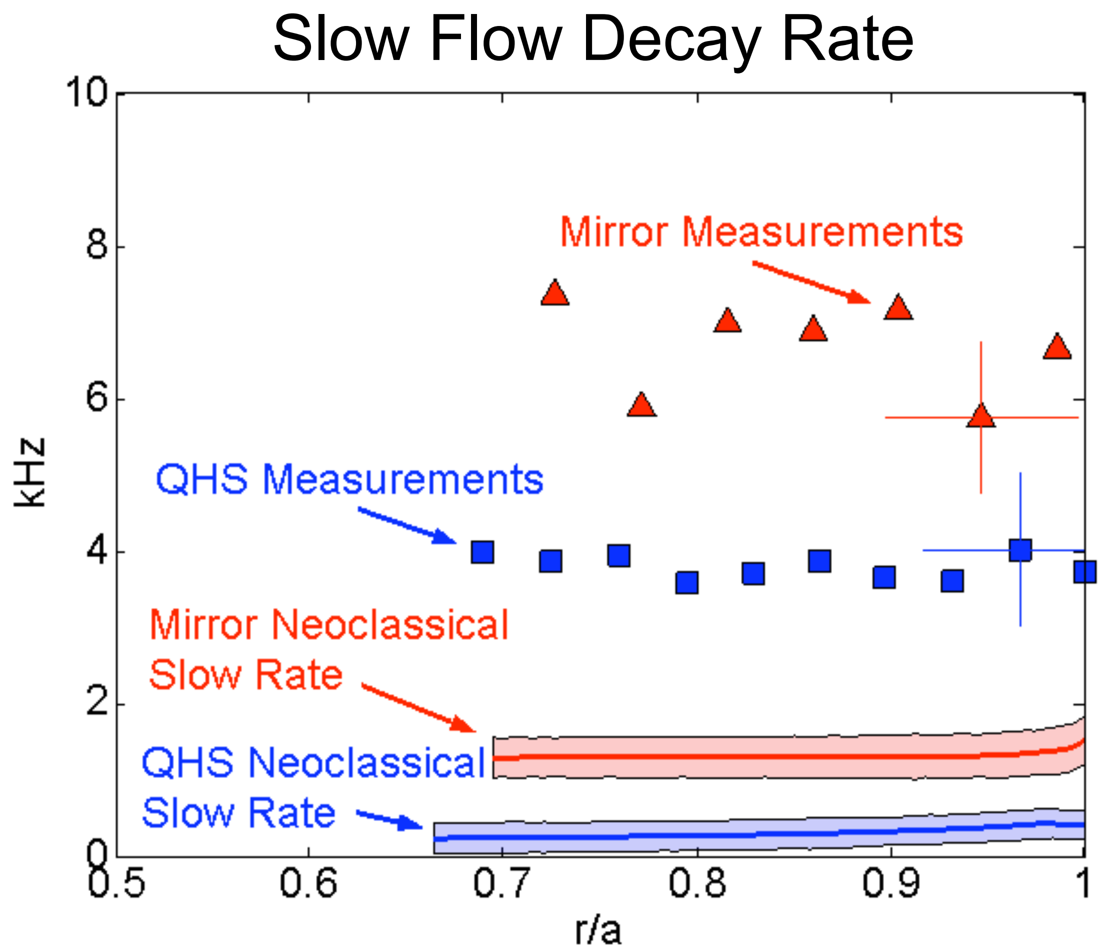
- **Slow Flow Rise Time**
- **Floating Potential Decay Time**
- **Fast Flow Decay Time**
- **Slow Flow Decay Time**

Floating Potential and J_{sat} profiles similar as well.



Flow Decay Rates Show Reduced Damping with Quasisymmetry

- Neoclassical model predicts a much slower decay than the measurements (Factor of 10 in QHS, factor of 3-5 in Mirror).
- *Difference* between measurements is comparable to the *difference* between the models.



<u>Conclusion</u>

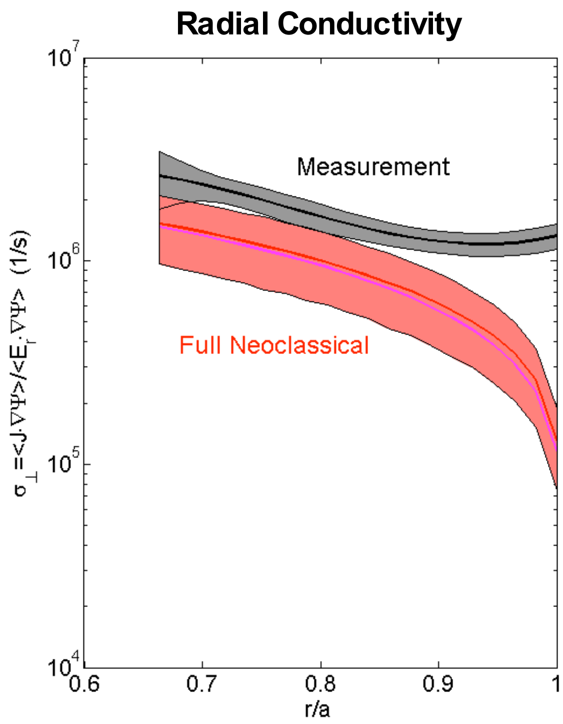
Quasisymmetry reduces flow damping, even in the presence of some anomalous damping.

Artificially Increased Damping Improves Theory/Experiment Comparison

Increase the neutral density to *simulate* extra damping.

$$\upsilon_{in} \rightarrow \upsilon_{eff} \approx 3.6\text{kHz}$$

$$\frac{a^2}{4\tau} \approx \frac{3600\left(0.11^2\right)}{4} \approx 10\,\frac{m^2}{s}$$



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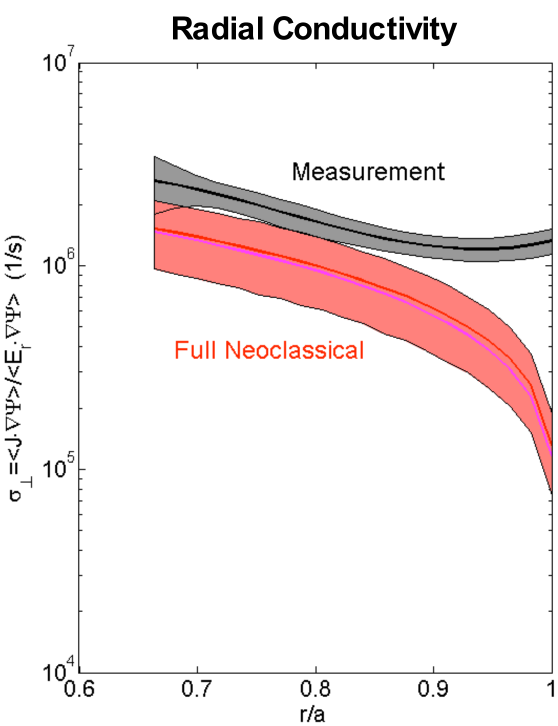

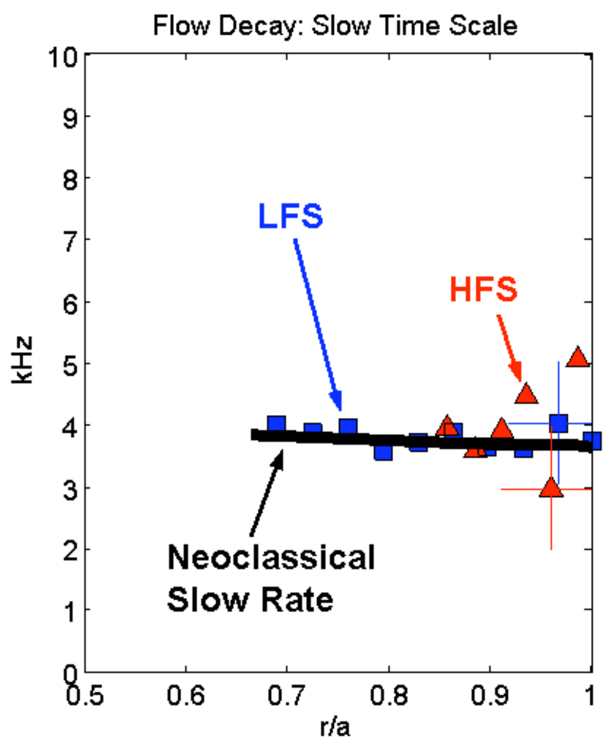

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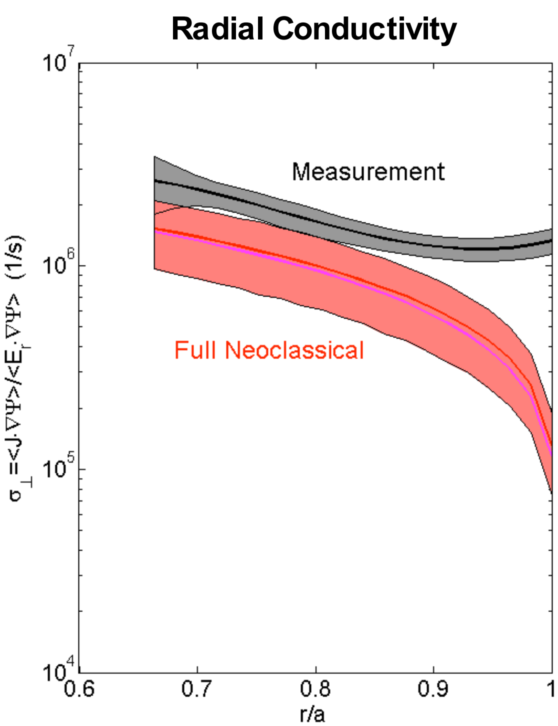
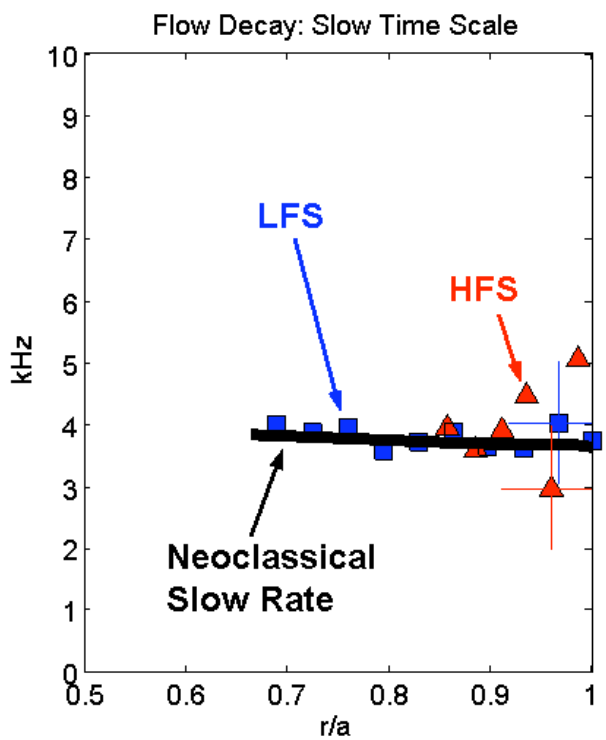
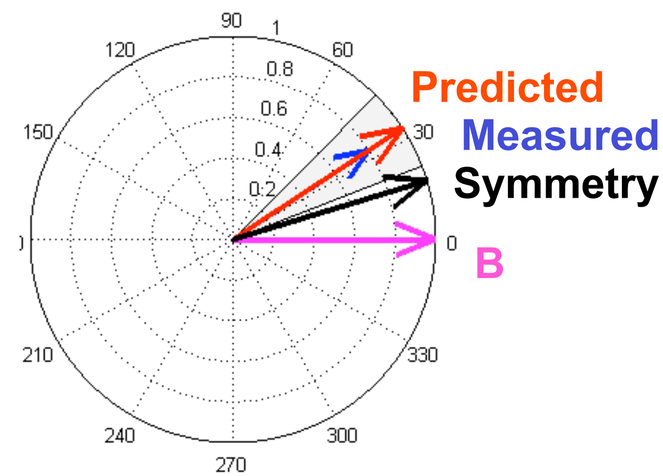




Steady State Bias Induced Flows Agree Better



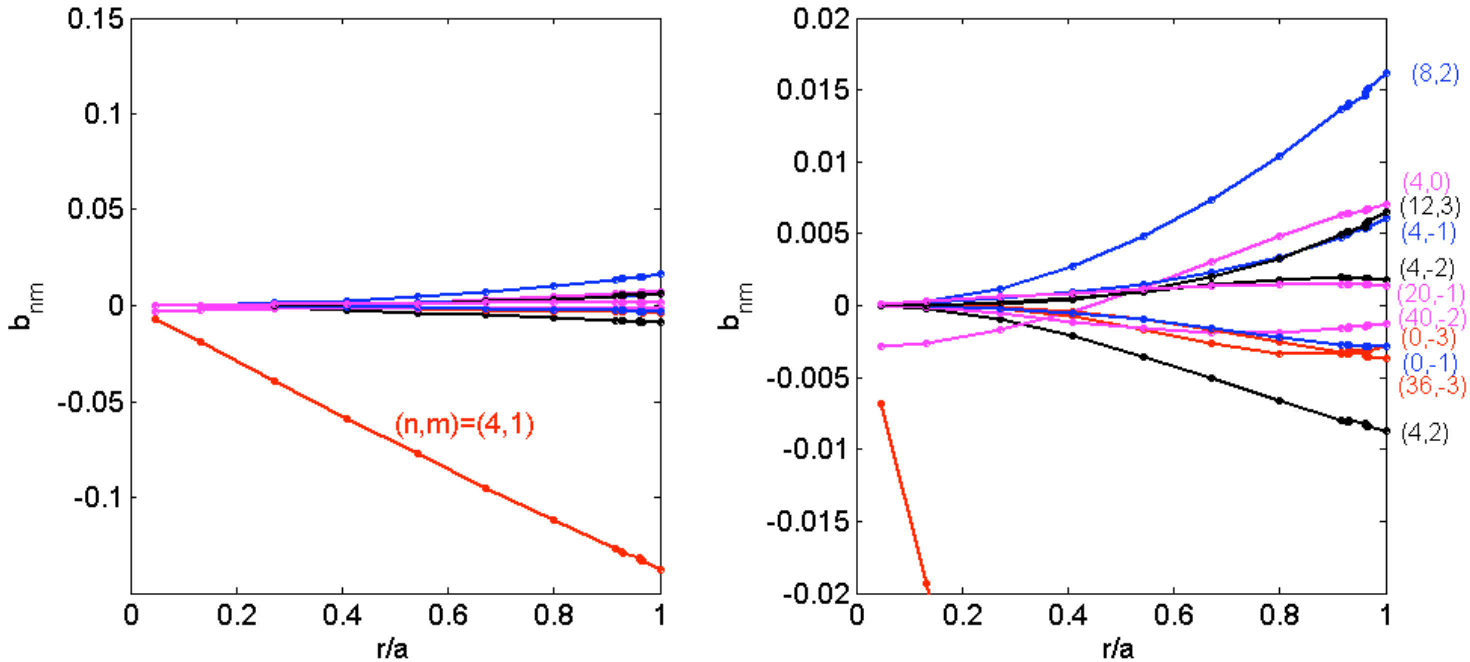
Summary

- We have observed 2 time-scale flow evolution in HSX.
- An original model for the spin-up reproduces many of the features in the measurement.
- The damping in the symmetry direction appears to be larger than the neoclassical prediction with neutrals.
- The QHS configuration exhibits reduced damping compared to a configuration with the symmetry broken.

The End

Neoclassical Theory, Including Neutrals, is a Candidate to Explain Flow Damping in HSX

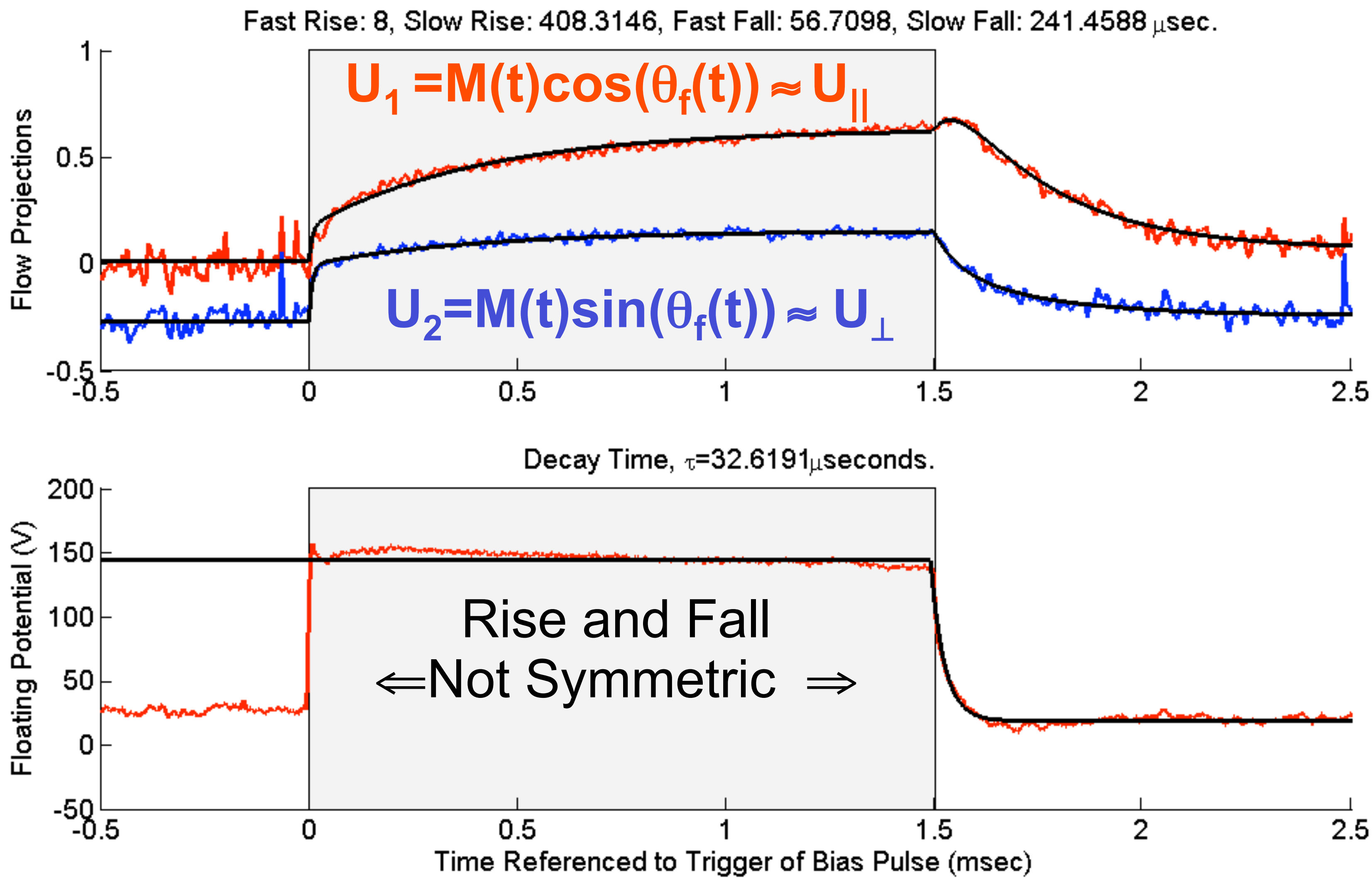
- Near the edge, there are a number of growing symmetry breaking terms in the Hamada spectrum.



- Low density plasma allows significant neutral penetration.

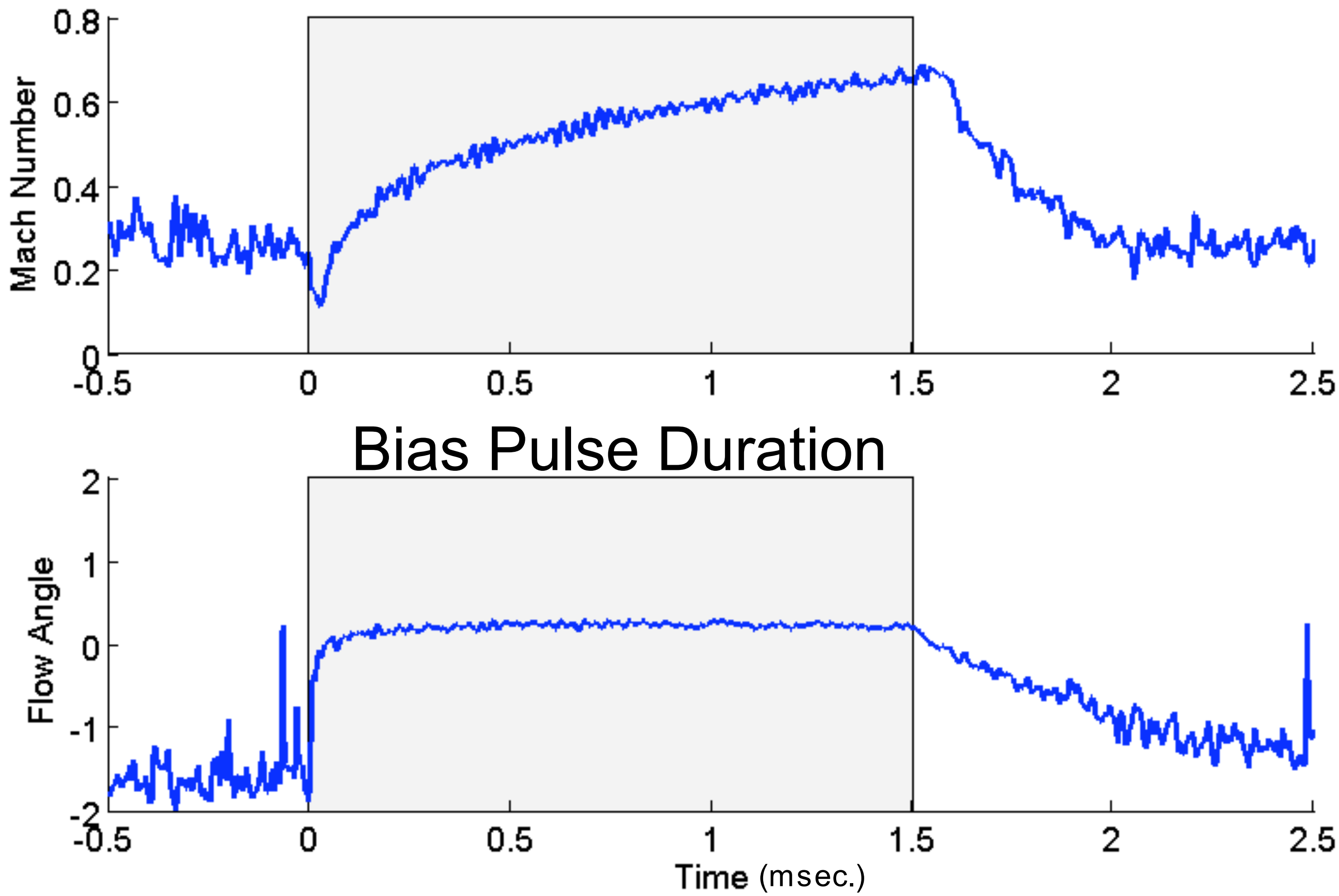
$$\lambda_{mfp,H} = \frac{\sqrt{\frac{2E_H}{m}}}{n_e \langle \sigma v \rangle_{H+e\rightarrow p+2e}} = \frac{\sqrt{\frac{2\cdot 3\cdot 1.6\times 10^{-19}}{1.67\times 10^{-27}}}\left(\frac{m}{s}\right)}{10^{12}\left(cm^{-3}\right)\cdot 2.5\times 10^{-8}\left(cm^3 s^{-1}\right)} \approx 1m$$

Two Time-Scale Model Fits Flow Evolution



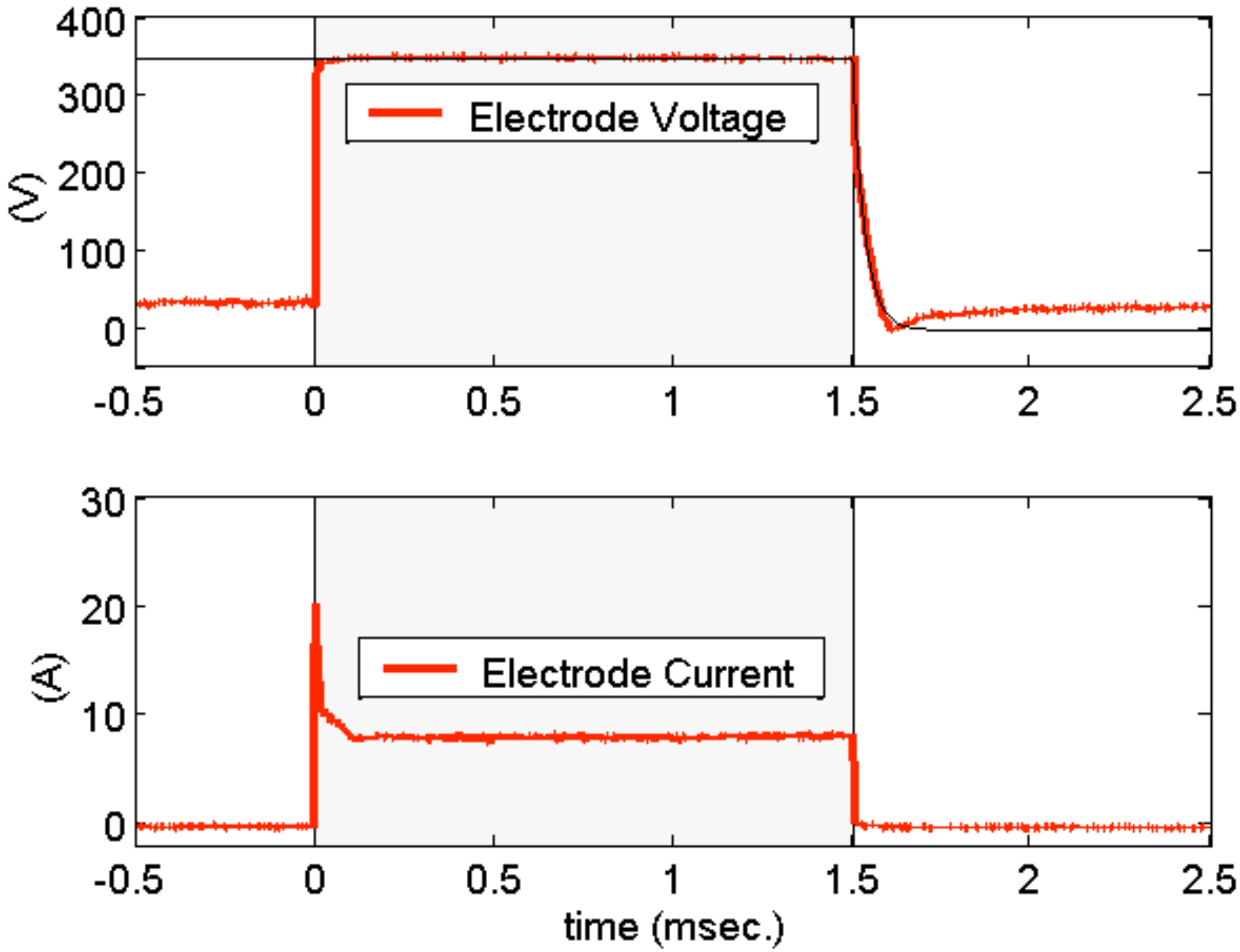
Similar time-scales measured by LFS and HFS probes.

Both Flow Speed and Direction Evolve over the Electrode Pulse



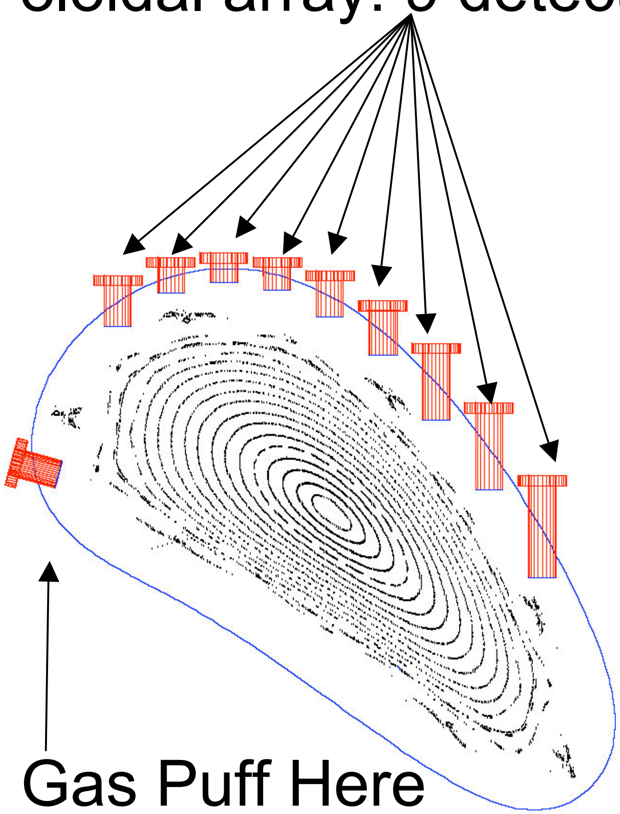
Need to extract the time-scales and directions.

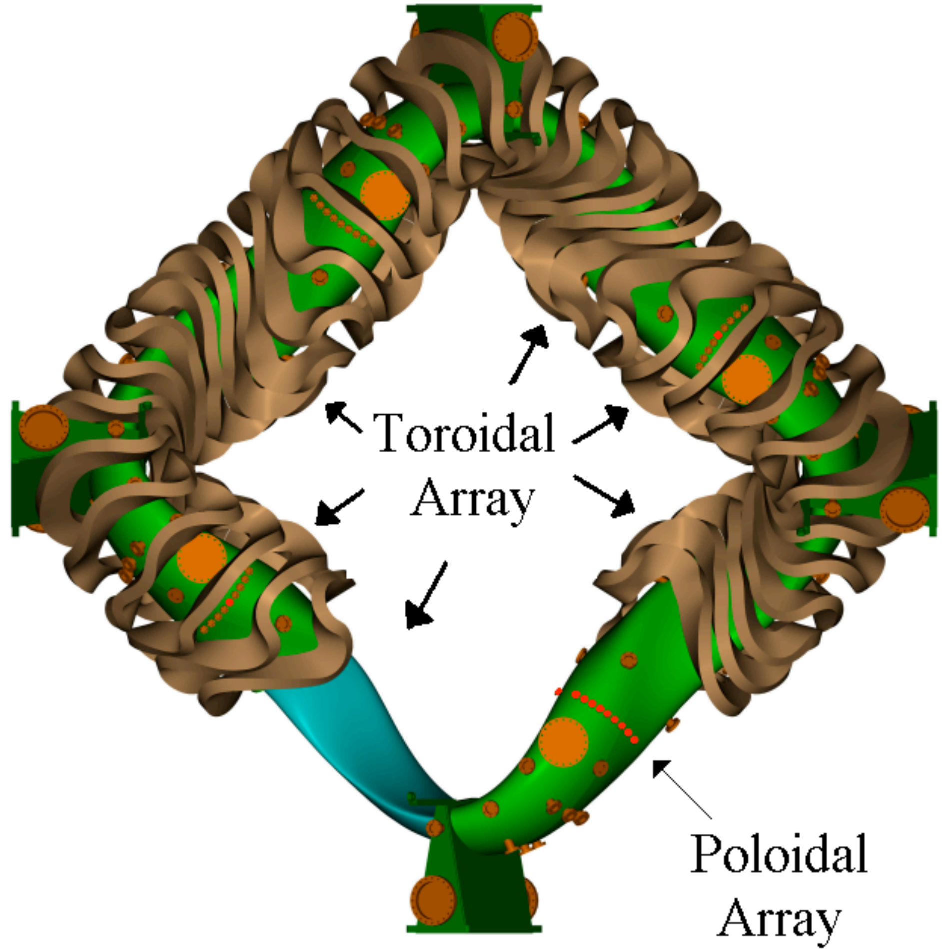
Voltage Application Initiates the Rise, Current Termination Initiates the Decay



Developed a Comprehensive Set of H_α Detectors for Neutral Density Measurements

- Toroidal array: 7 detectors on magnetically equivalent ports
- Poloidal array: 9 detectors





- All detectors absolutely calibrated
- Analysis done by J. Canik using DEGAS code

Mach Probes Used to Measure Time-Dependent Plasma Flows

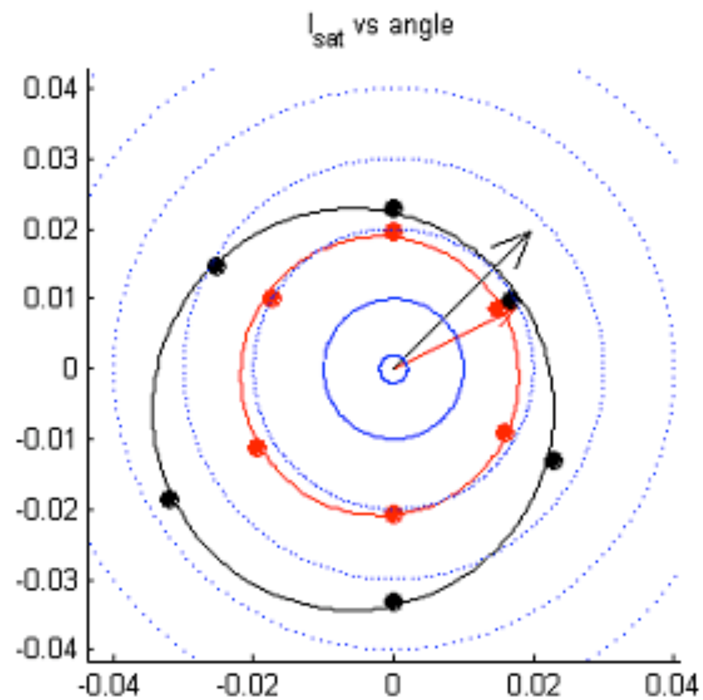
- 6 tip mach probes measure plasma flow speed and direction on a magnetic surface.

- 2 similar probes are used to simultaneously measure the flow at high and low field locations, both on the outboard side of the torus.

- Data is analyzed using the unmagnetized model by Hutchinson.

- Time response of ~10-20μs

Looking ⊥ To The Magnetic Surface



$$I_{sat}(\theta) = A\,\mathbf{exp}\left(\left(\frac{M}{2}\right)\left[.64\left(1 - \mathbf{cos}(\theta - \theta_F)\right) + .7\left(1 + \mathbf{cos}(\theta - \theta_F)\right)\right]\right)$$

- Probe measures V_f with a proud pin.

We Have Developed a Method to Calculate the Hamada Basis Vectors

- Method involves calculating the lab frame components of the contravariant basis vectors along a field line, similar to that by V.V. Nemov.

$$B^{\Psi} = \vec{B}\cdot\vec{\nabla}\Psi = 0$$ ← **Radial Basis Vector**

$$B^{\varsigma} = \vec{B}\cdot\vec{\nabla}\zeta = \frac{1}{2\pi\sqrt{g}}$$ ← **Toroidal Basis Vector**

$$B^{\alpha} = \vec{B}\cdot\vec{\nabla}\alpha = \frac{\iota}{2\pi\sqrt{g}}$$ ← **Poloidal Basis Vector**

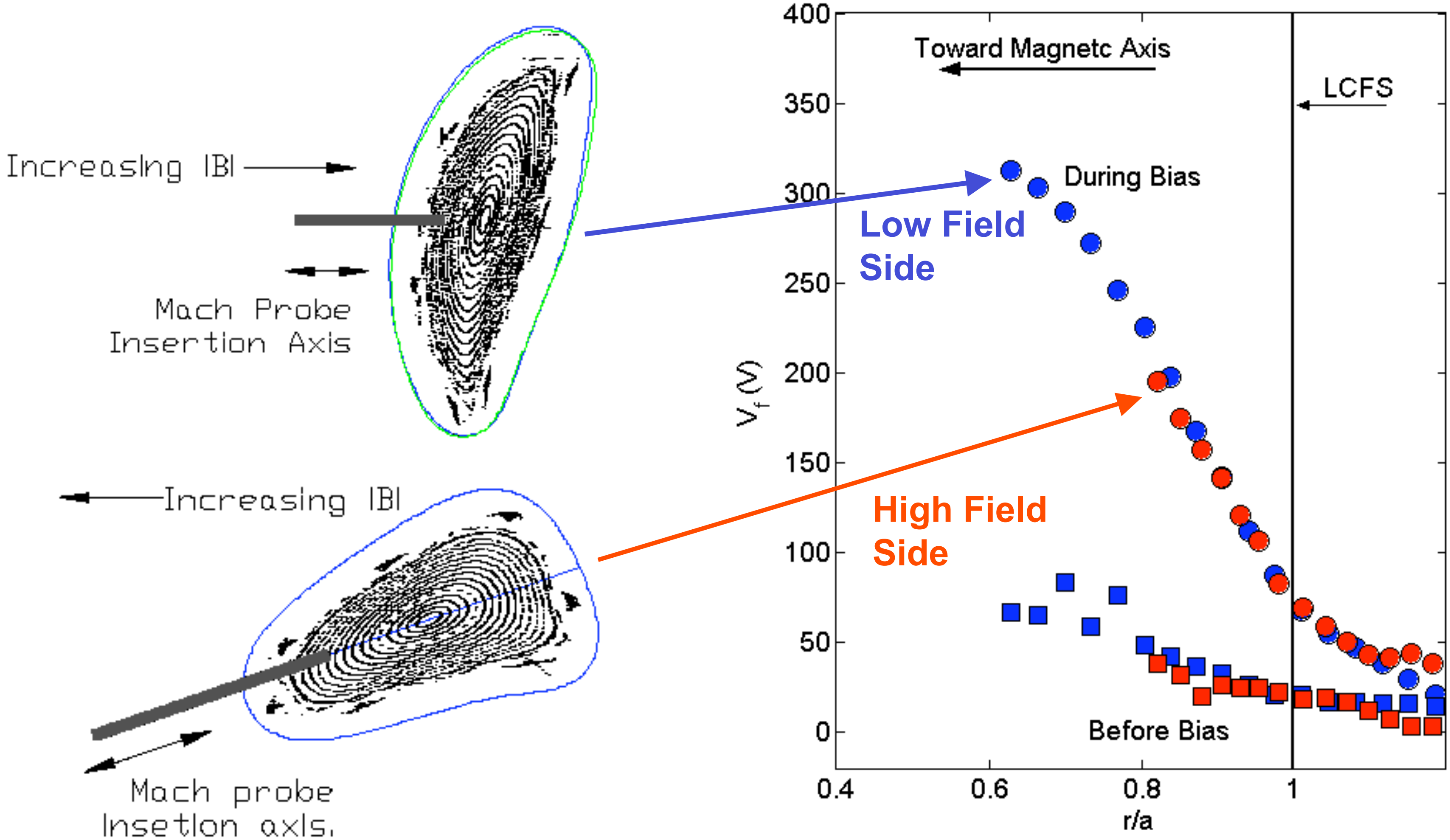
- Need initial condition on the basis vectors to complete this integration.
- Knowing $(\sqrt{g}, \iota, B_{\alpha})$ at outboard symmetry plane is sufficient for calculating the initial conditions.
- Use two methods of computing the Pfirsch-Schlueter current to derive initial condition...

$$\mathbf{J}_{||} = h\frac{\partial p}{\partial \psi}\mathbf{B}$$ Method by Nemov[1], h is numerically calculated

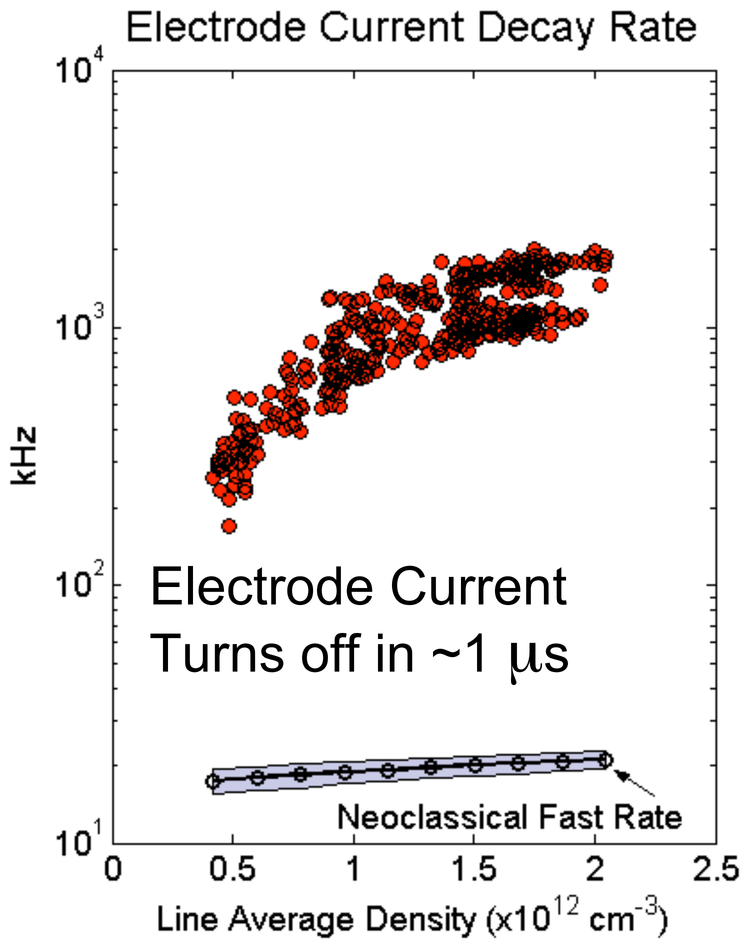
$$\mathbf{J}_{||} = -\frac{B_{\alpha}}{B^2 B^{\zeta}\sqrt{g}}\frac{\partial p}{\partial \psi}\mathbf{B}$$ Method by Coronado and Wobig[2], B_{α} is the desired quantity

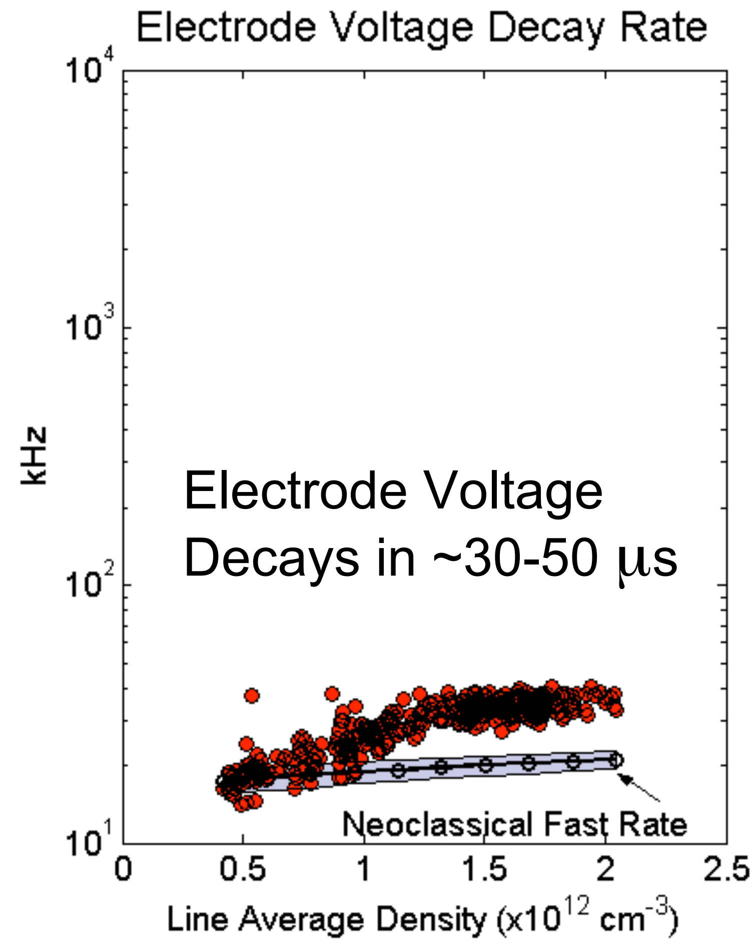
1) V.V. Nemov, Nuclear Fusion **30**, 927 (1990), 2) M. Coronado and H. Wobig Phys Fluids B **4**, 1294 (1992)

Floating Potential is a Flux Surface Quantity



Electrode Characteristics at Turn Off Fit the Decay Model





Floating potential and fast component of flow decay on same time-scale as electrode voltage, in agreement with neoclassical fast rate.