Measurements and Modeling of Plasma Flow Damping in the HSX Stellarator

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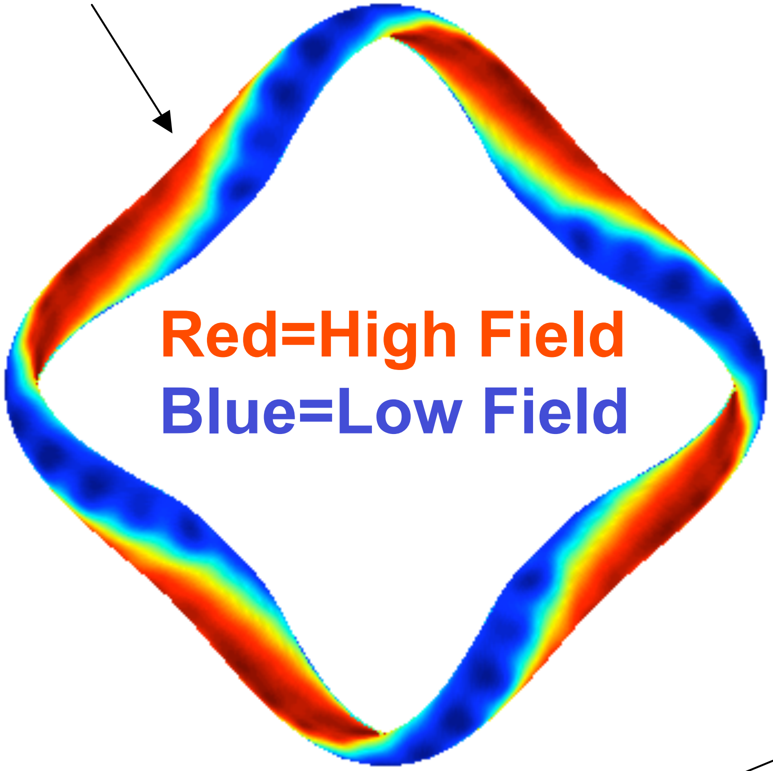
Outline of Talk

- Description of experiments and diagnostics
- Description of flow and electric field evolution.
  - **Asymmetries between the spin-up and relaxation.**
  - **Two time-scale flow evolution.**
- Neoclassical modeling techniques developed for these studies
  - **Original model for the spin-up**
  - **Calculation of the Hamada basis vectors**
- Comparison between measurements and modeling in QHS and Mirror discharges
  - **Increased flow damping in symmetry-broken configurations**
  - **Viscous damping is larger than the neoclassical prediction.**

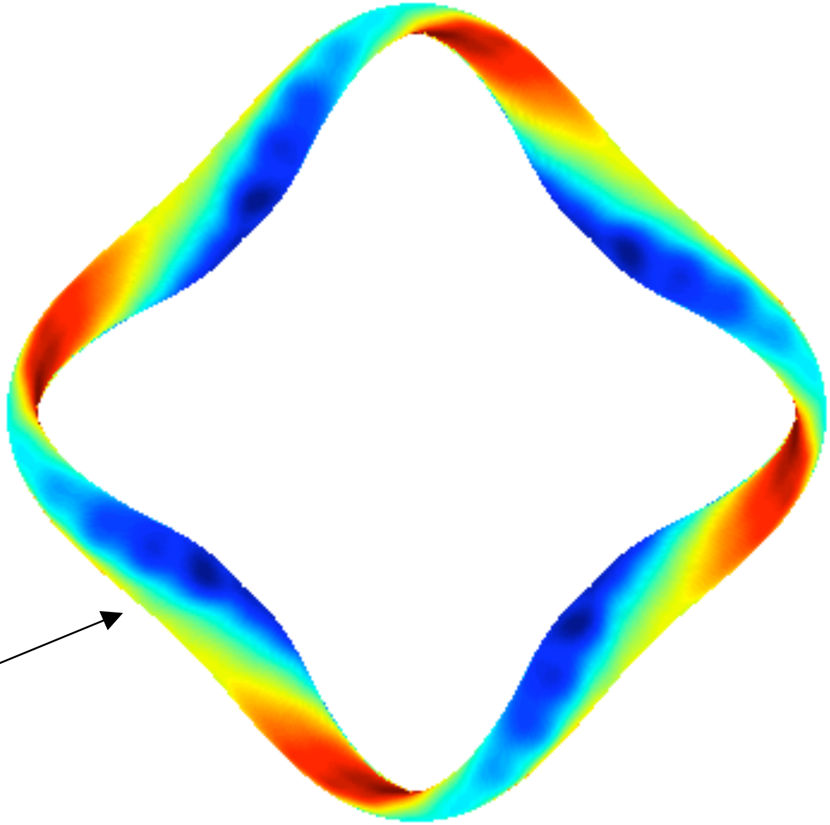
HSX Provides Access to Configurations With and Without Symmetry

$$\text{QHS}: \quad B/B_o \approx 1 + \varepsilon_H \,\mathbf{cos}(4\varphi - \theta)$$



Red=High Field

Blue=Low Field

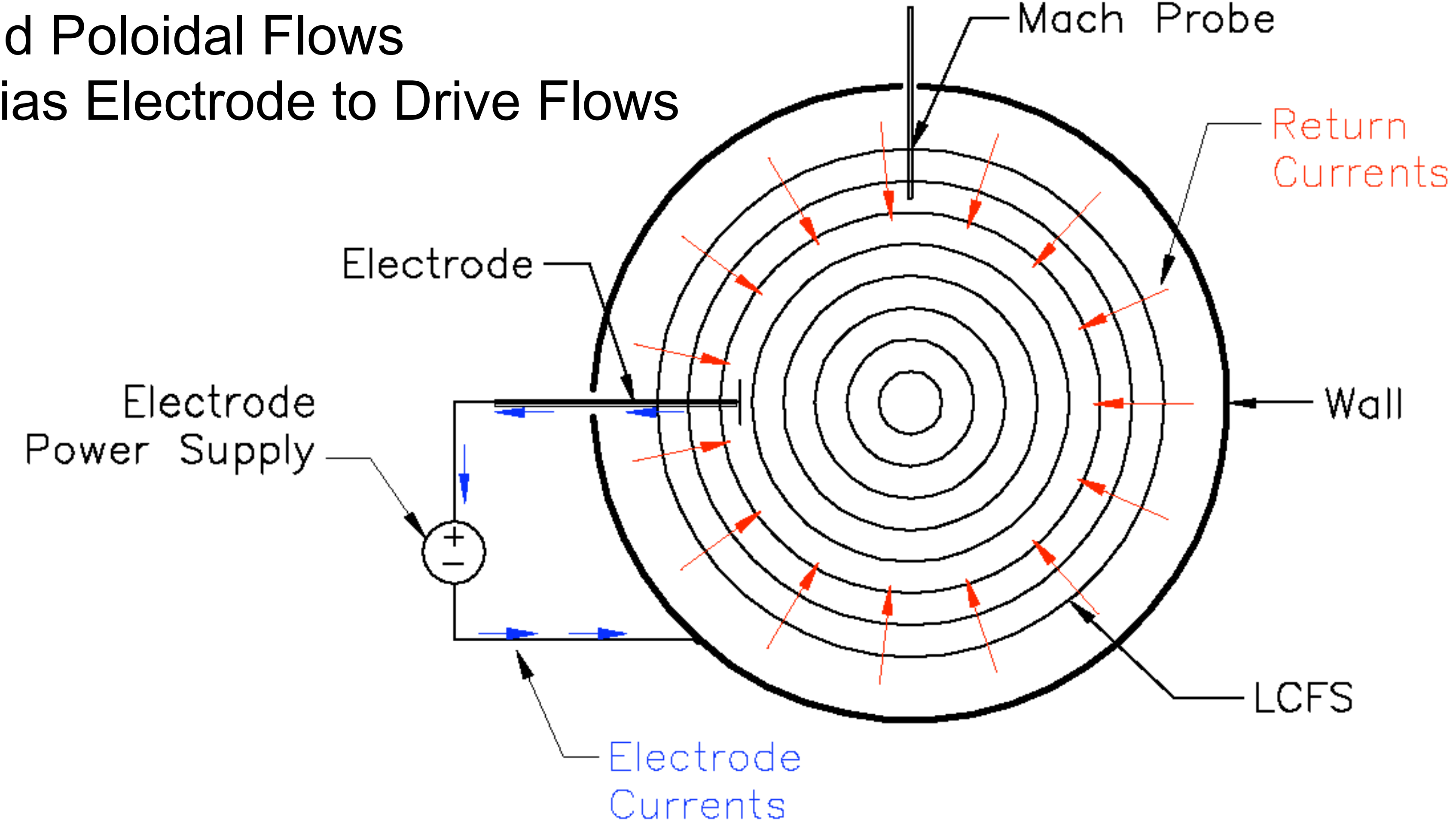


$$\text{Mirror}: \quad B/B_o \approx 1 + \varepsilon_H \,\mathbf{cos}(4\varphi - \theta) + \varepsilon_M \,\mathbf{cos}(4\varphi)$$

Structure of Experiments

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

•Bias Electrode to Drive Flows



Biased Electrode Experiments

Demonstrate New Flow Phenomena:

1) 2 Time-Scale Flow Evolution

2) Reduced Flow Damping with Quasisymmetry

Multiple Time Scales Observed in Flow Evolution

- Electrode Voltage and Floating Potential:

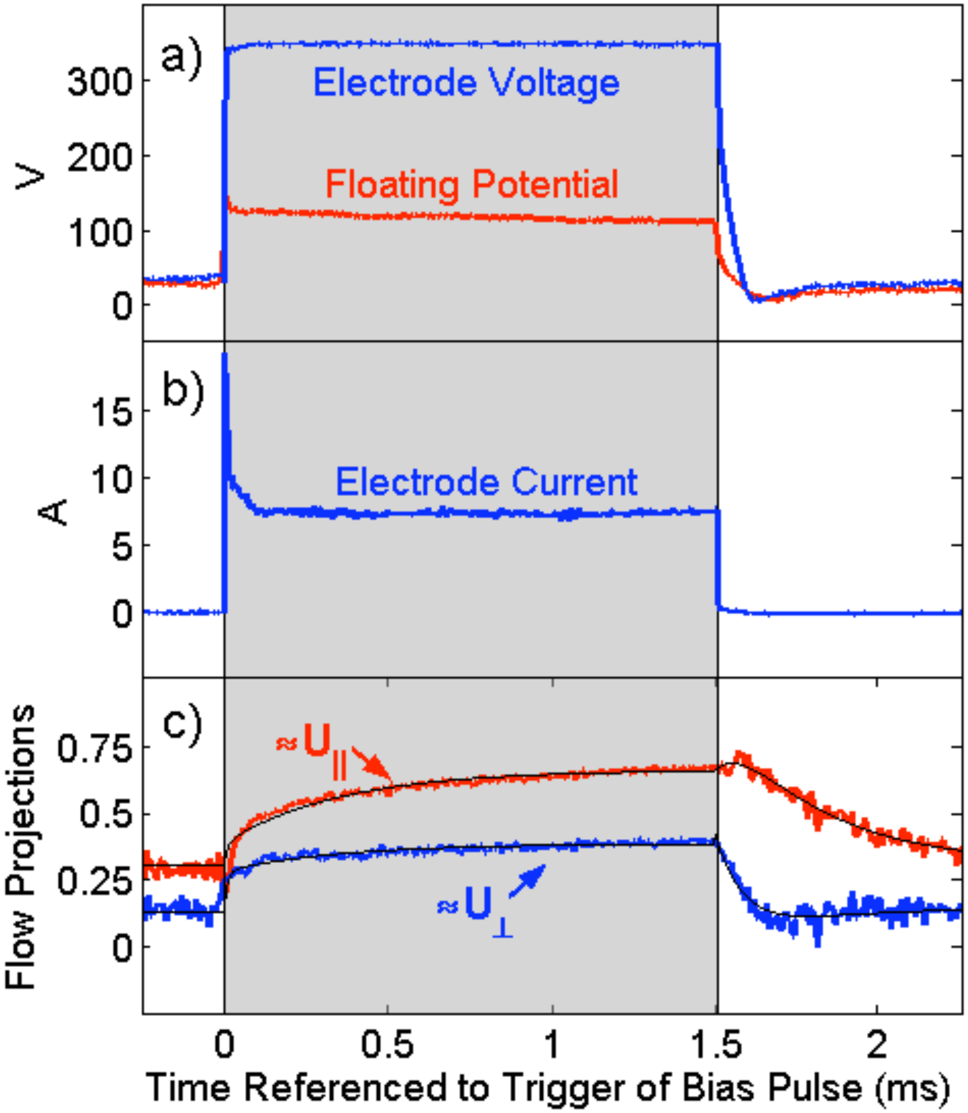
  Quick Rise and Slow Delay

- Electrode Current:

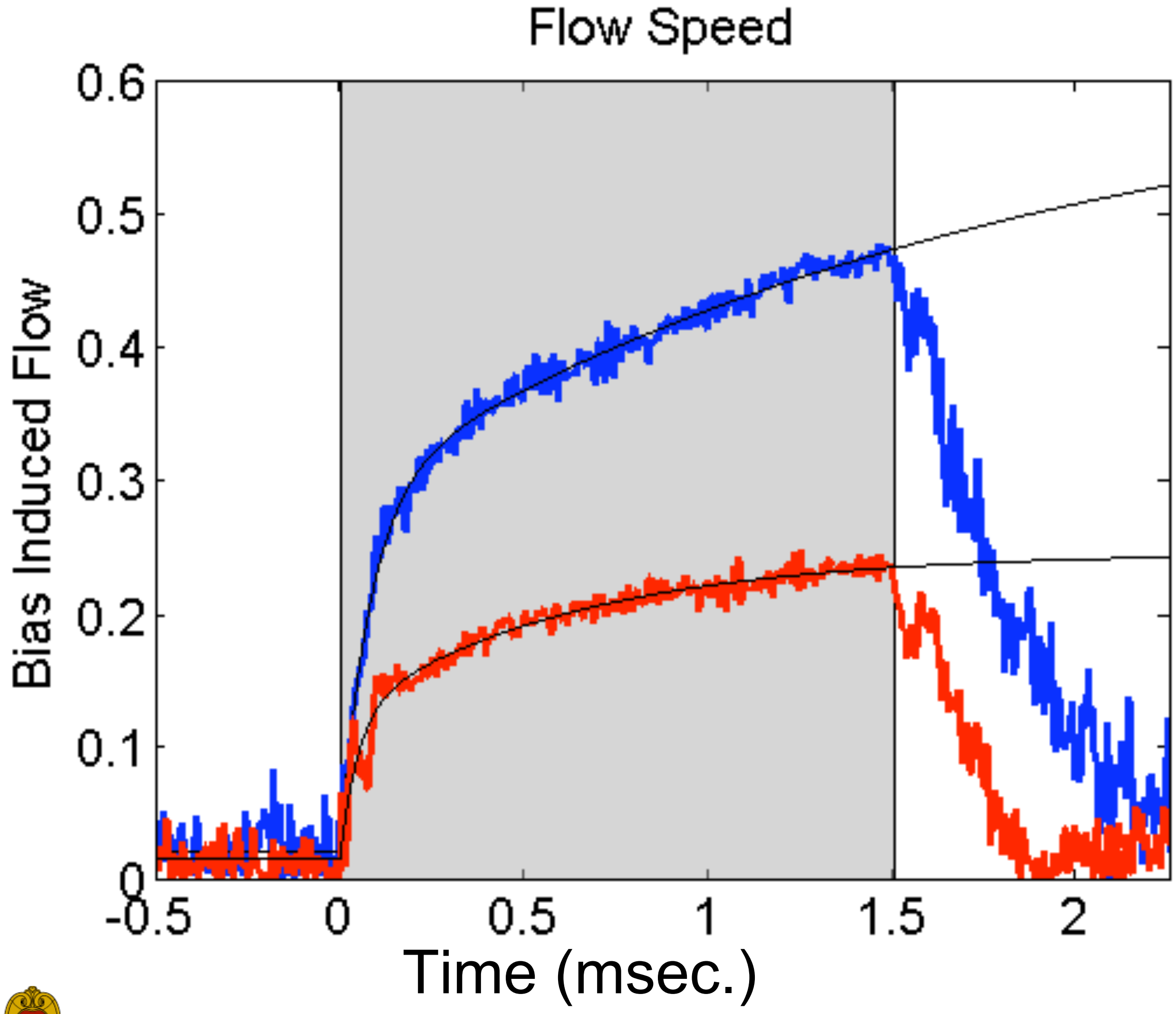
  Large Spike and Fast Termination

- Plasma Flows:

  Fast and Slow Time Scales at Rise and Decay.



Preview: QHS Flow Damps Slower, Goes Faster For Less Drive.



QHS: 8 A of electrode current

Mirror: 10 A of electrode current

More QHS/Mirror comparisons after discussion of neoclassical modeling.

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.

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

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

- Solve these with Ampere’s Law

$$-\frac{\partial}{\partial t} \frac{\partial \Phi}{\partial \psi} \langle \nabla\psi \cdot \nabla\psi \rangle = -4\pi \left(< \mathbf{J}_{plasma} \cdot \nabla\psi > + < \mathbf{J}_{ext} \cdot \nabla\psi > \right)$$

- Use Hamada coordinates, linear neoclassical viscosities, neglect heat fluxes.
- Steady state solution yields radial conductivity.

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

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

- At bias turn on, IGBT switches put voltage on the electrode (~1 μsec.).
- Measurements show steady 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, IGBT 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 will grow on the same time scale as the electric field.
- Parallel flow grows at a “Hybrid rate” ν_F determined by viscosity and ion-neutral friction.

Toroidal Damping

$$\upsilon_F = \text{ƚ}\upsilon_\alpha + \upsilon_\zeta + \upsilon_{in}$$

Poloidal Damping

- Two time scales/two direction flow evolution.

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

- Model developed in the course of this research.

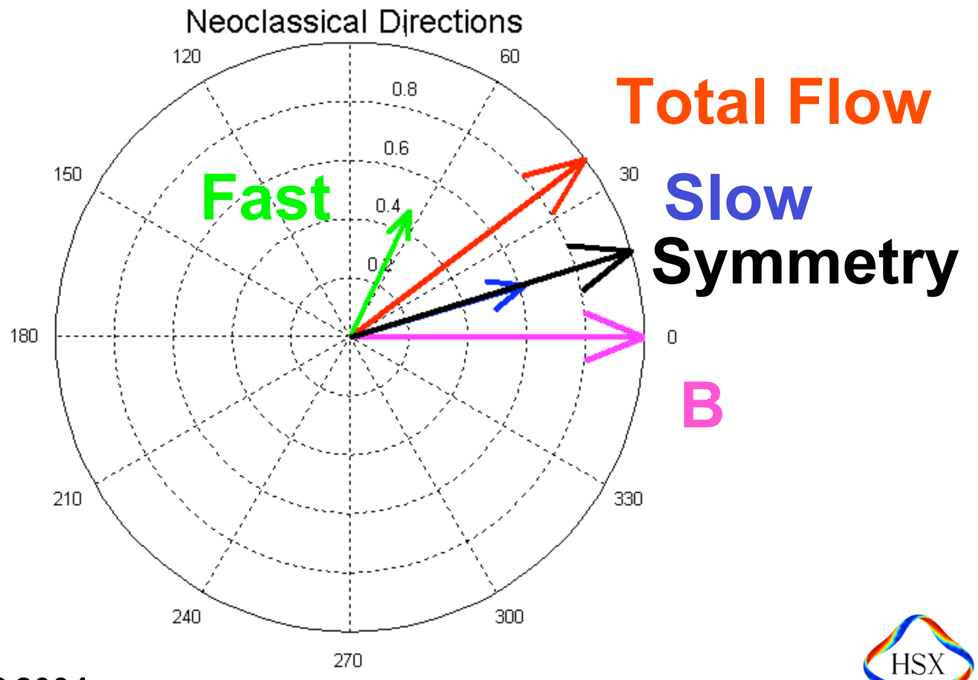
Flow Decay: External Radial Current is Quickly Turned Off.

- γ_1 (fast), and γ_2 (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:

$$\mathbf{U} = e^{-\gamma_1 (t-t_0)} \underline{\left(N_4 \mathbf{B} + \frac{cN_1}{B^\zeta \sqrt{g}} \mathbf{e}_\alpha \right)} + e^{-\gamma_2 (t-t_0)} \underline{\left(N_5 \mathbf{B} + \frac{cN_2}{B^\zeta \sqrt{g}} \mathbf{e}_\alpha \right)}$$

$$+$$

- Very large neutral density ($n_n = 1\text{x}10^{12}$ cm^{-3}) in this calculation.
- Slow rate corresponds to flows in the direction of symmetry
- Numerically calculated Hamada basis vectors used in this figure.
- This follows development by Coronado and Talmadge.



The Hybrid Rate is Intermediate to the Fast and Slow Rate

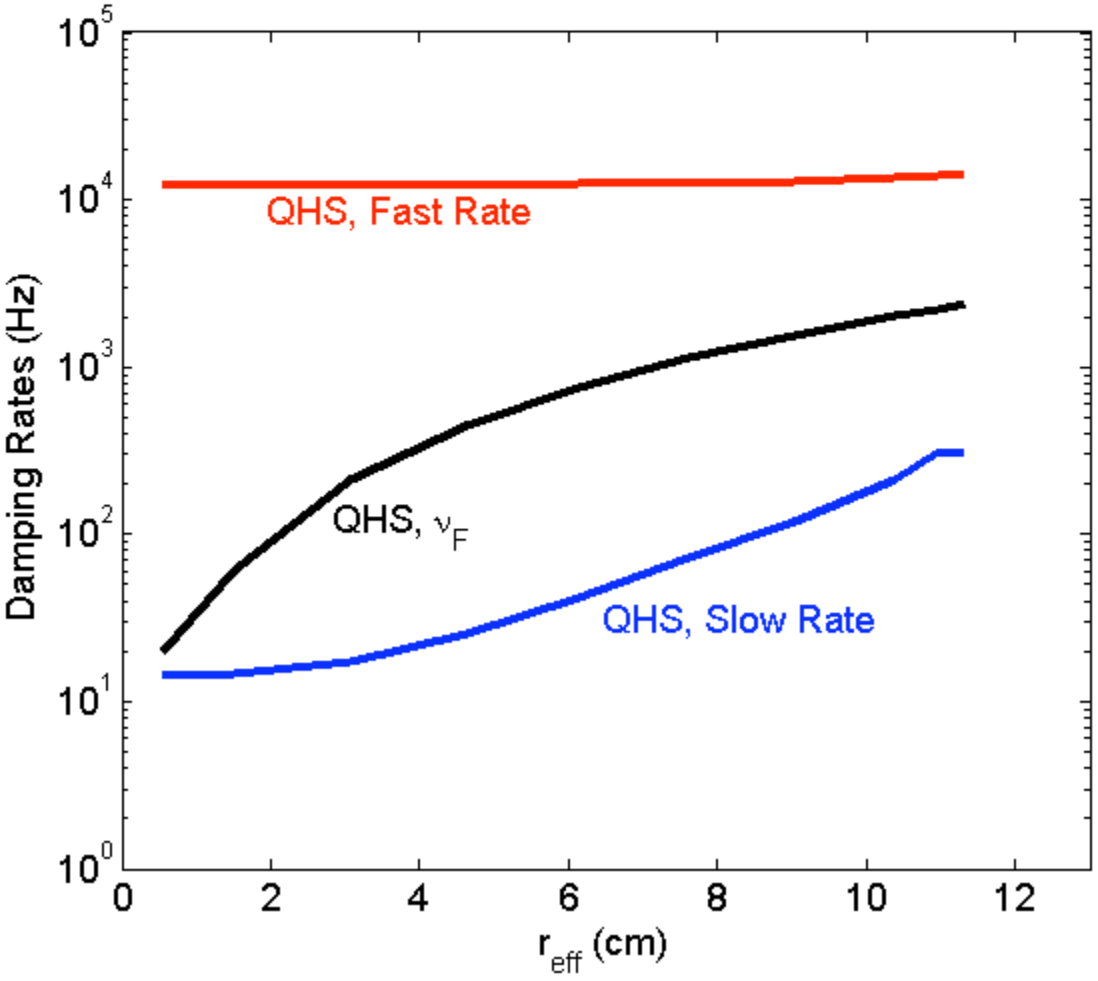
Fast Rate

is faster than

Hybrid Rate, ν_F

is faster than

Slow Rate



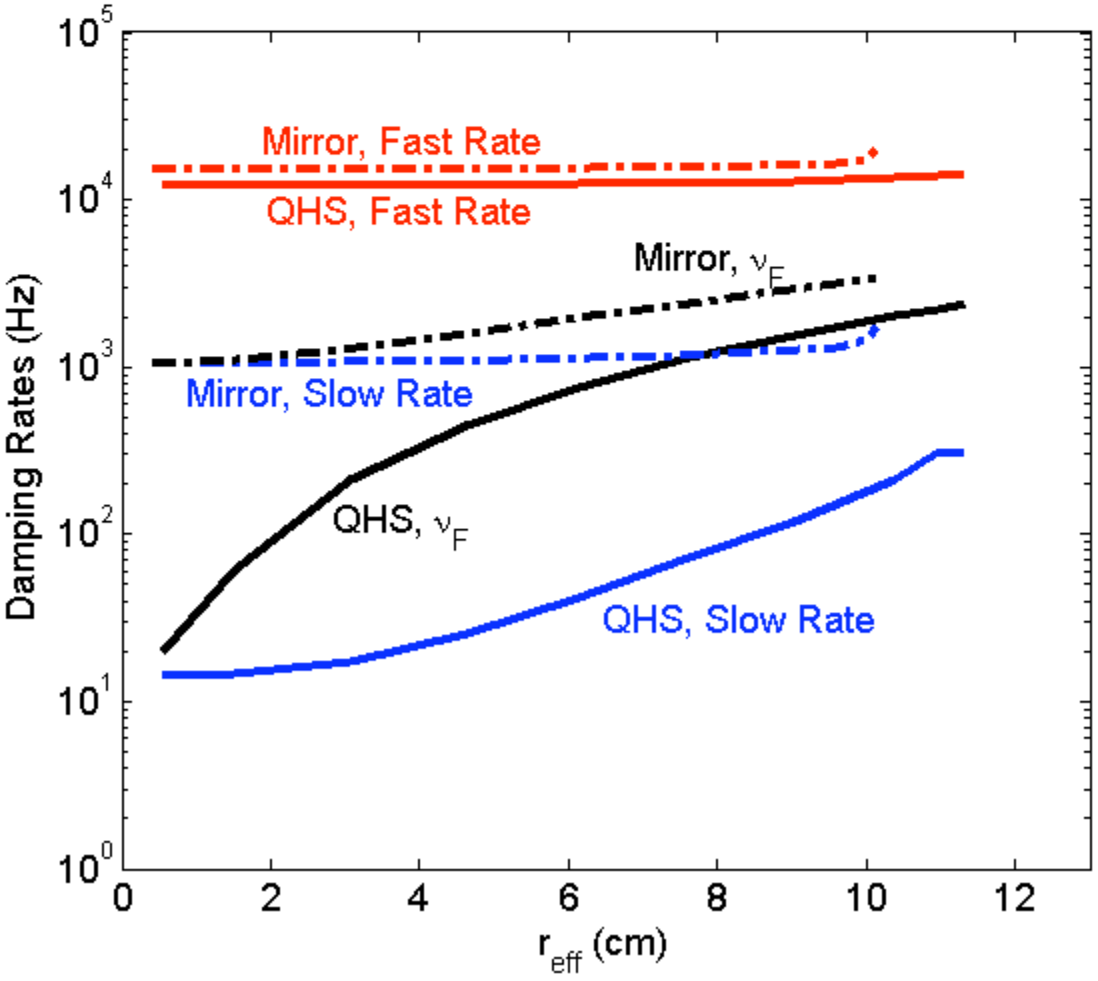
Mirror Shows Increased Neoclassical Damping Compared to QHS

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.

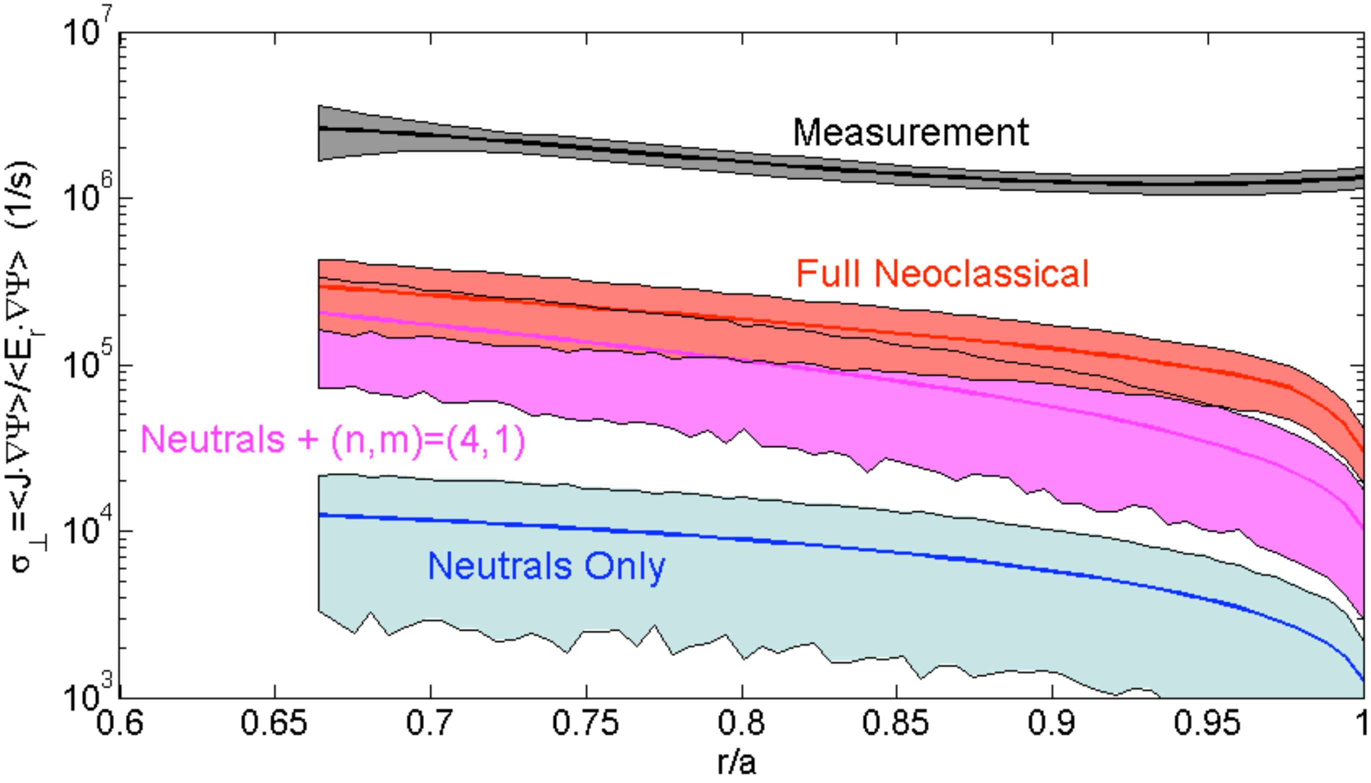


Comparison of Neoclassical Theory with QHS and Mirror Configuration Measurements

1) Reduced Flow Damping with Quasisymmetry

2) Evidence of Anamalous Flow Damping.

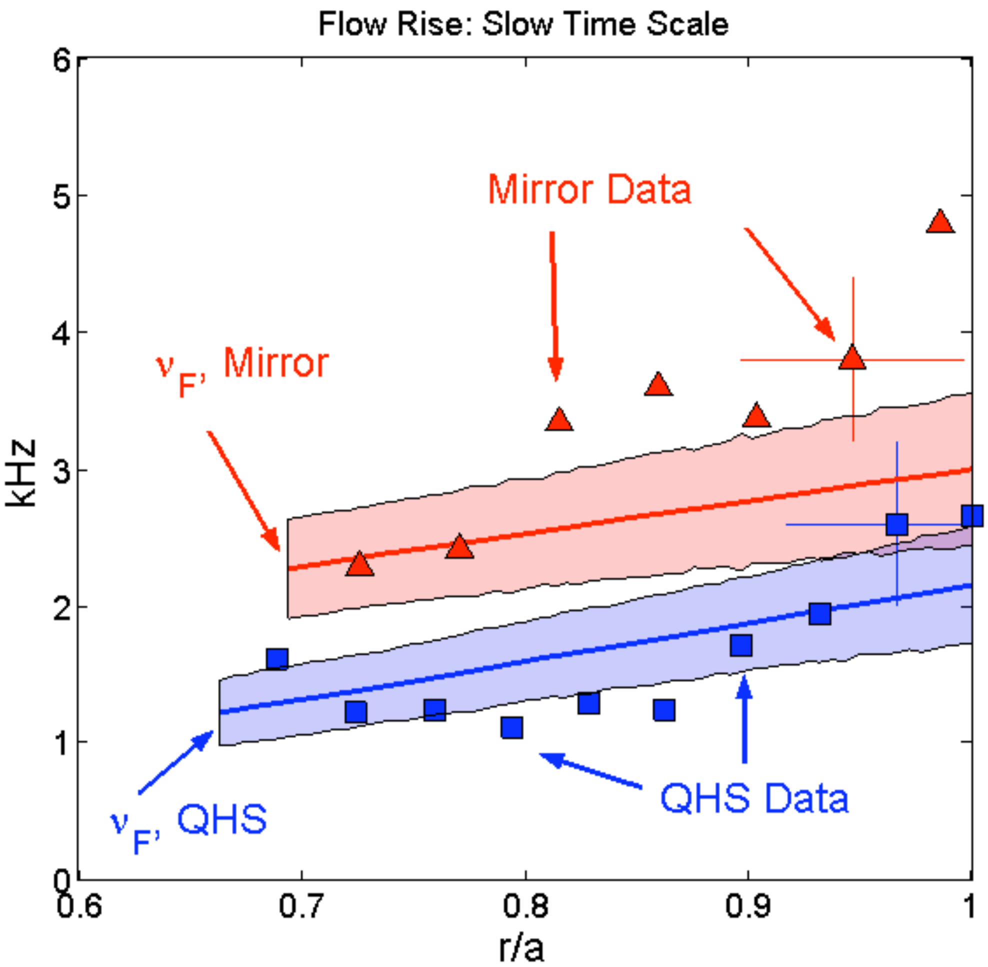
QHS Radial Conductivity is Larger than the Neoclassical Prediction



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

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

- Measurements from the low field side.
- Mirror flows rise more quickly than QHS
- Neoclassical hybrid time ν_F shows good agreement with the measurements.
- Both modeling and data show a weak scaling with density, as expected in the Plateau regime.

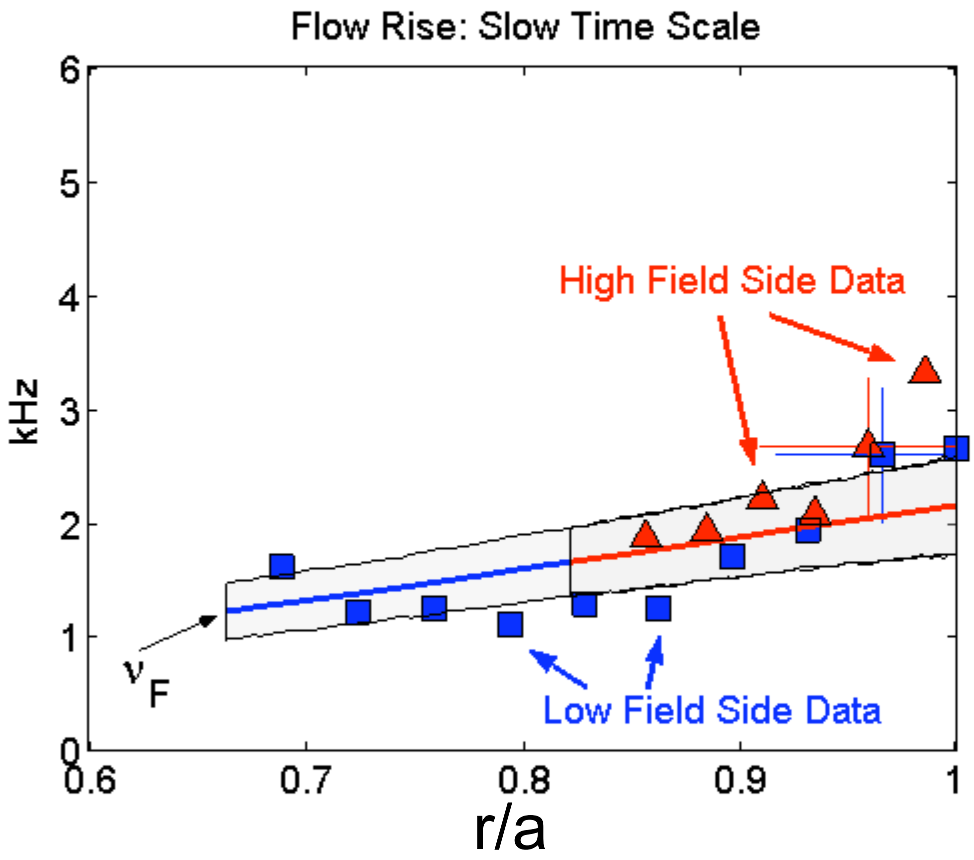


Similar Flow Rise Times Simultaneously Measured at High and Low Field Locations

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**

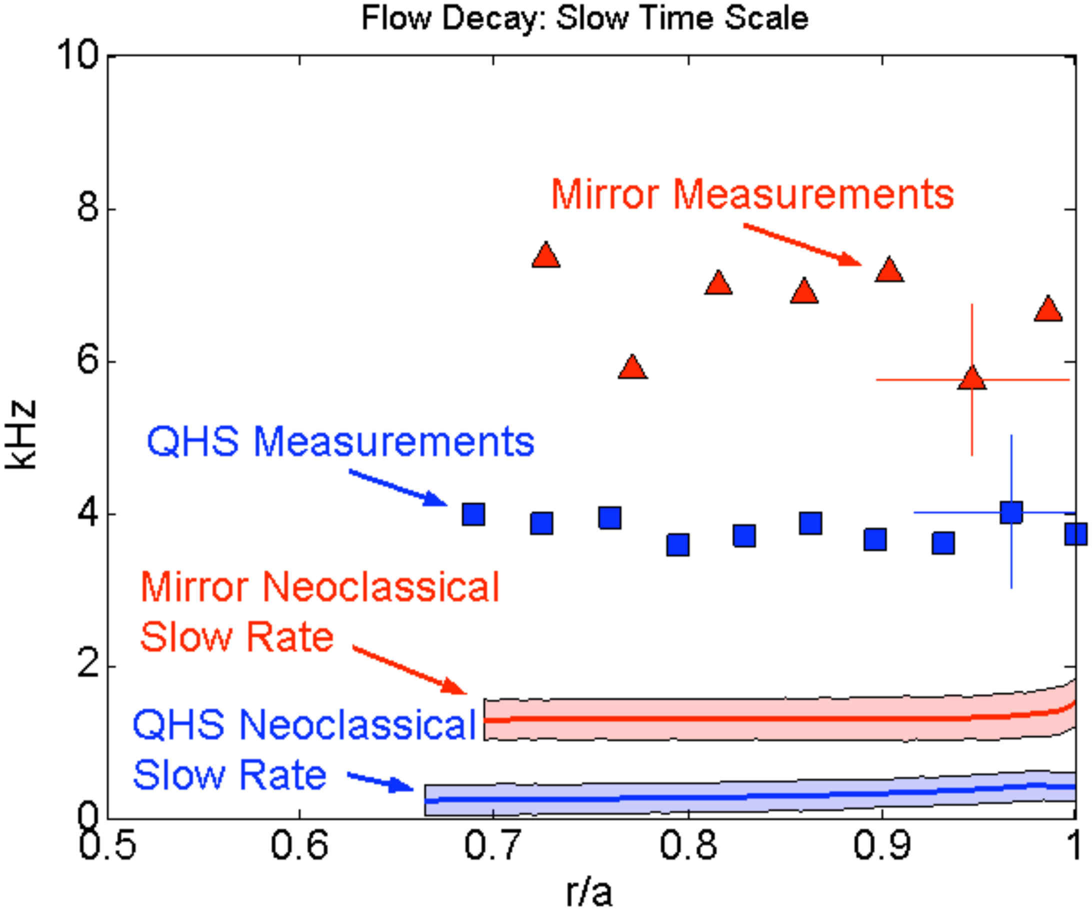
Floating Potential and J_{sat} profiles are similar at both locations as well.



Measurements and Modeling Show Reduced Damping in QHS Compared to Mirror

- 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 in the model.



Conclusion/Hypothesis

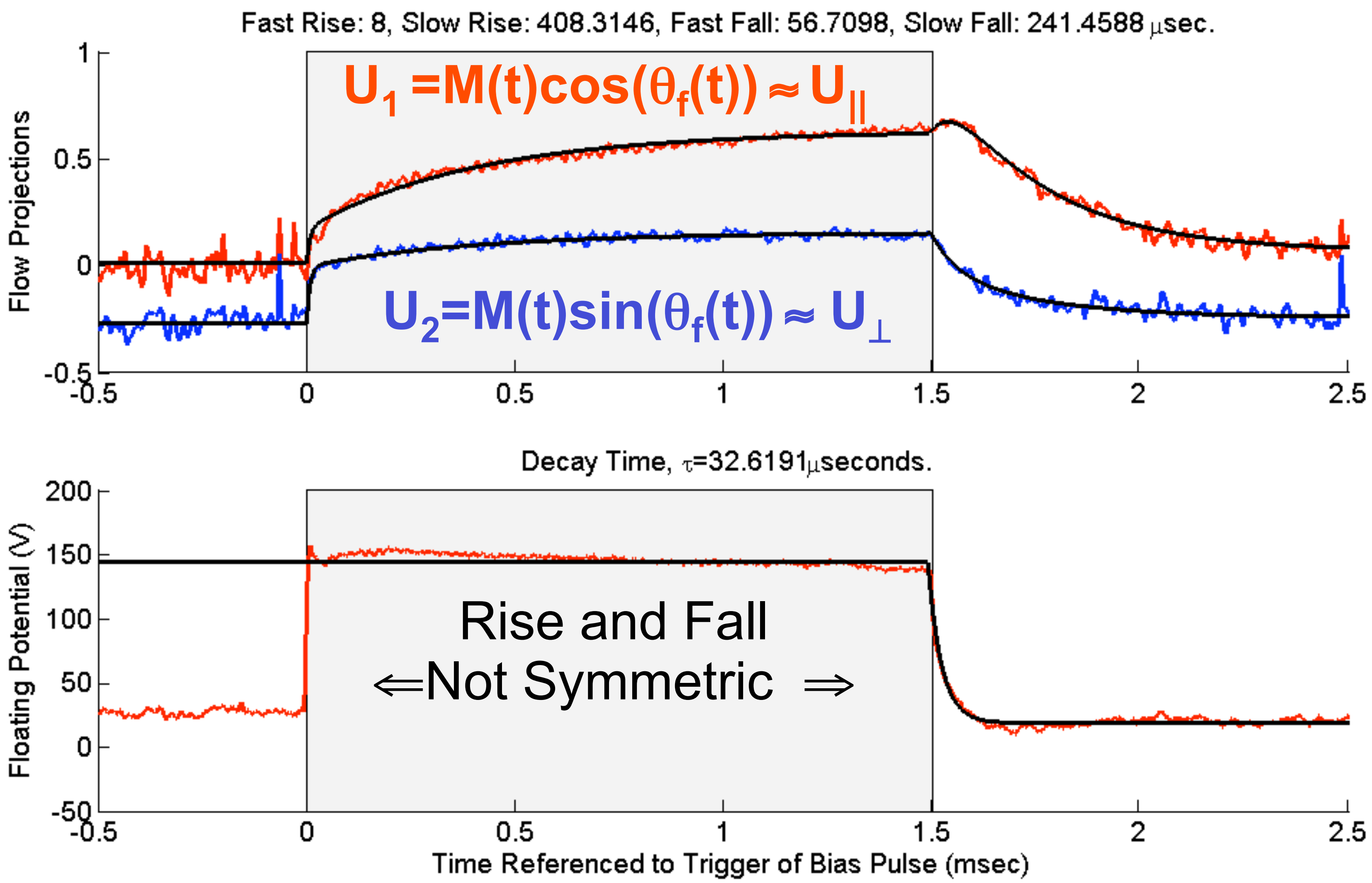
Some non-neoclassical damping mechanism obscures most, but not all, of the difference between the configurations.

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 QHS configuration exhibits reduced damping compared to a configuration with the symmetry broken.
- The damping in the symmetry direction appears to be larger than the neoclassical prediction with neutrals.

The End

Two Time Scale Model Fits Flow Evolution



Fast Rise: 8, Slow Rise: 408.3146, Fast Fall: 56.7098, Slow Fall: 241.4588 μsec.

$U_1 = M(t)\cos(\theta_f(t)) \approx U_{||}$

$U_2 = M(t)\sin(\theta_f(t)) \approx U_{\perp}$

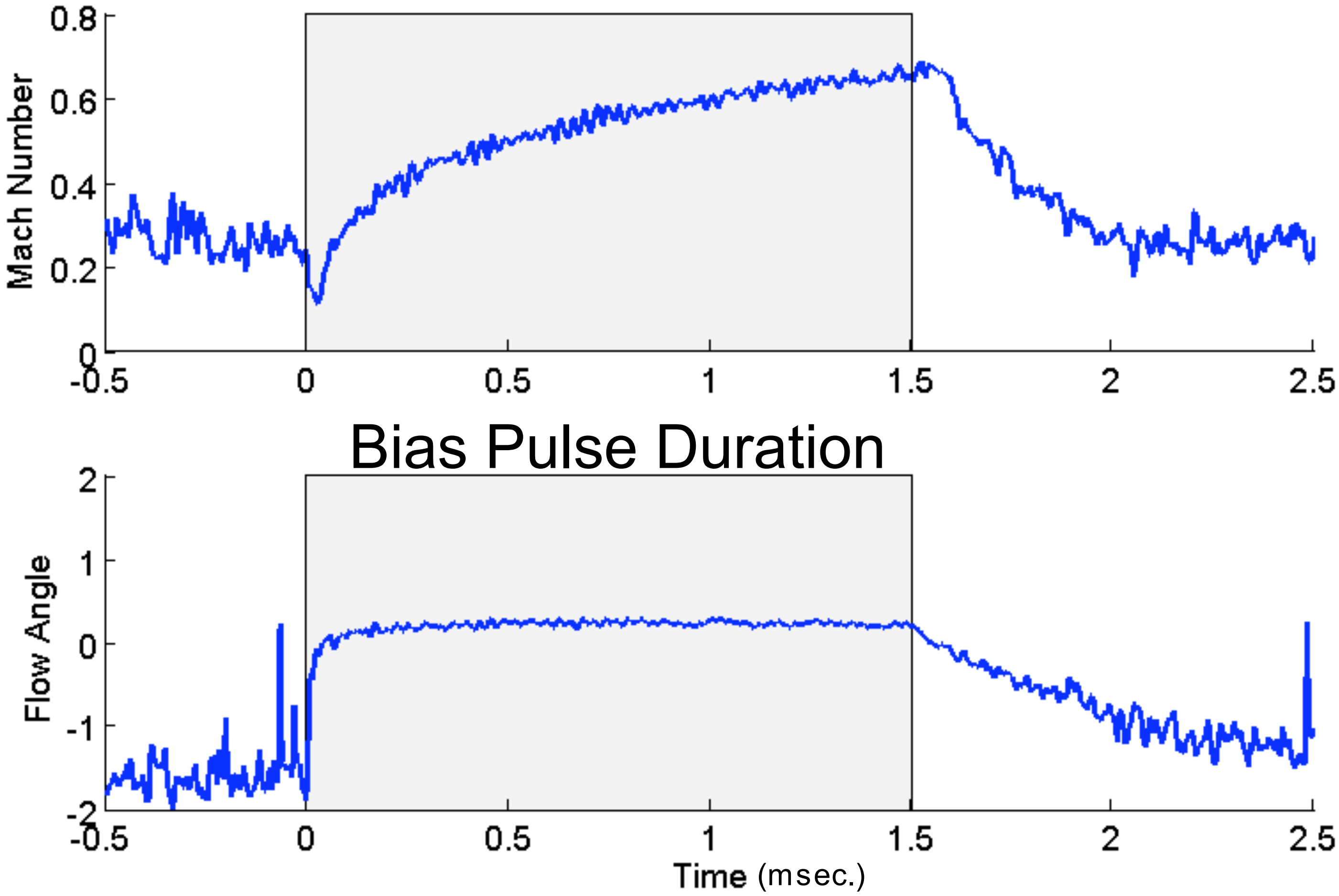
Decay Time, τ=32.6191μseconds.

Rise and Fall

⇐Not Symmetric ⇒

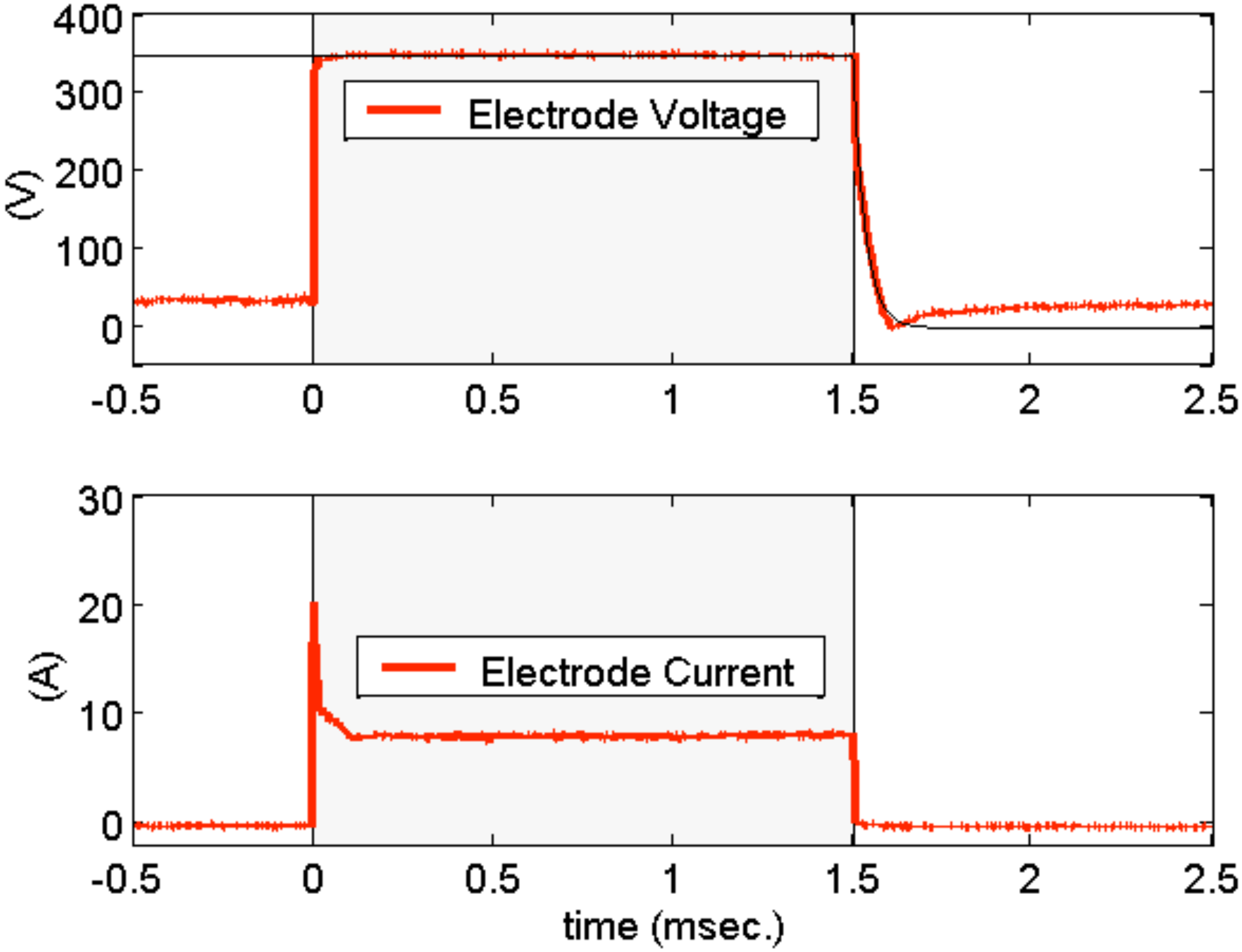
Similar time scales measured by LFS and HFS probes.

Both Flow Speed and Direction Evolve over the Electrode Pulse



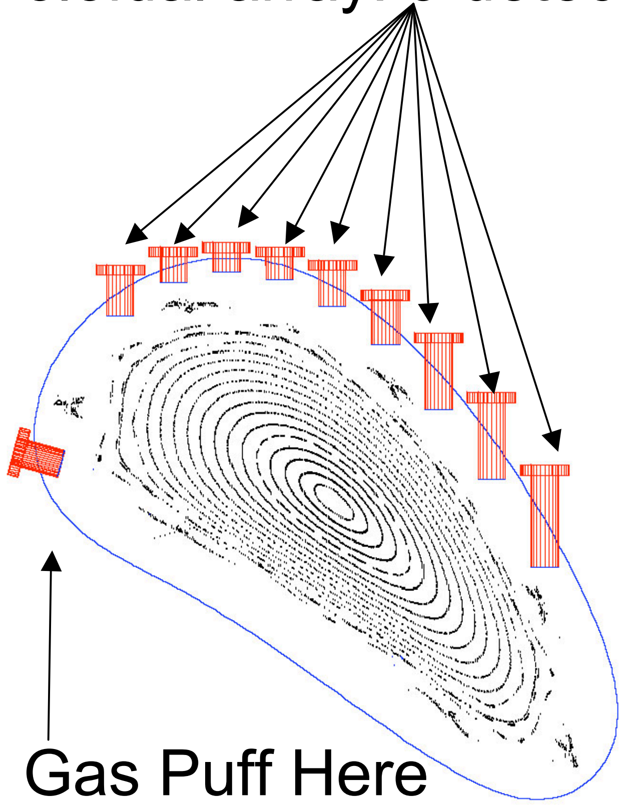
Need to extract the time scales and directions.

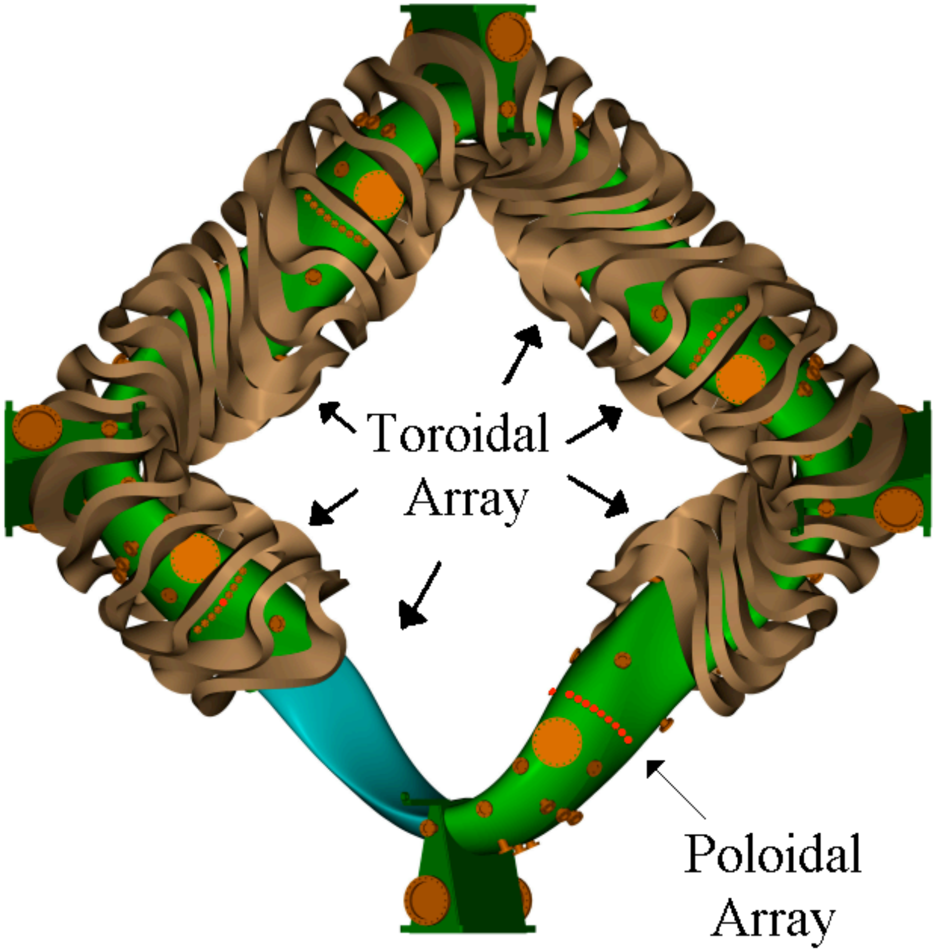
Voltage Application Initiates the Rise, Current Termination Initiates the Decay.



Developed a Comprehensive Set of H_α Detectors for Neutral Density Measurements

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



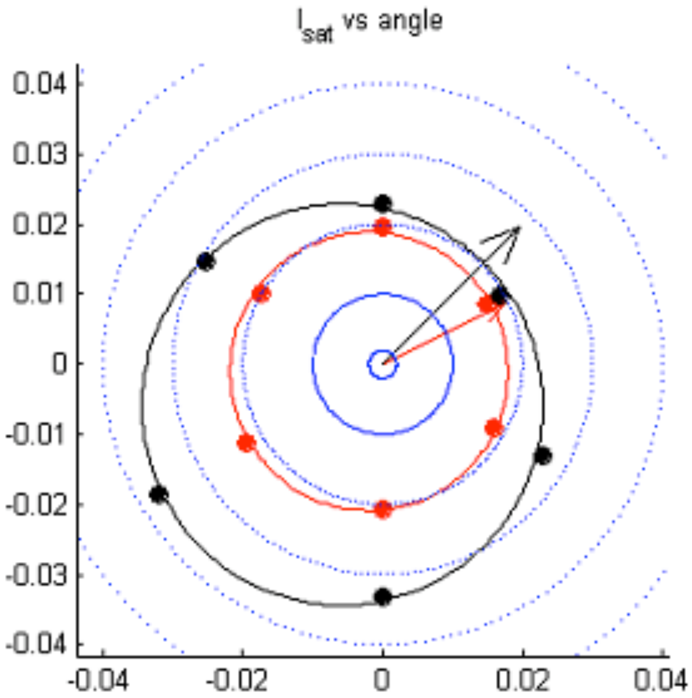


- All detectors absolutely calibrated
- Analysis done by J. Canik using DEGAS code

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**

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

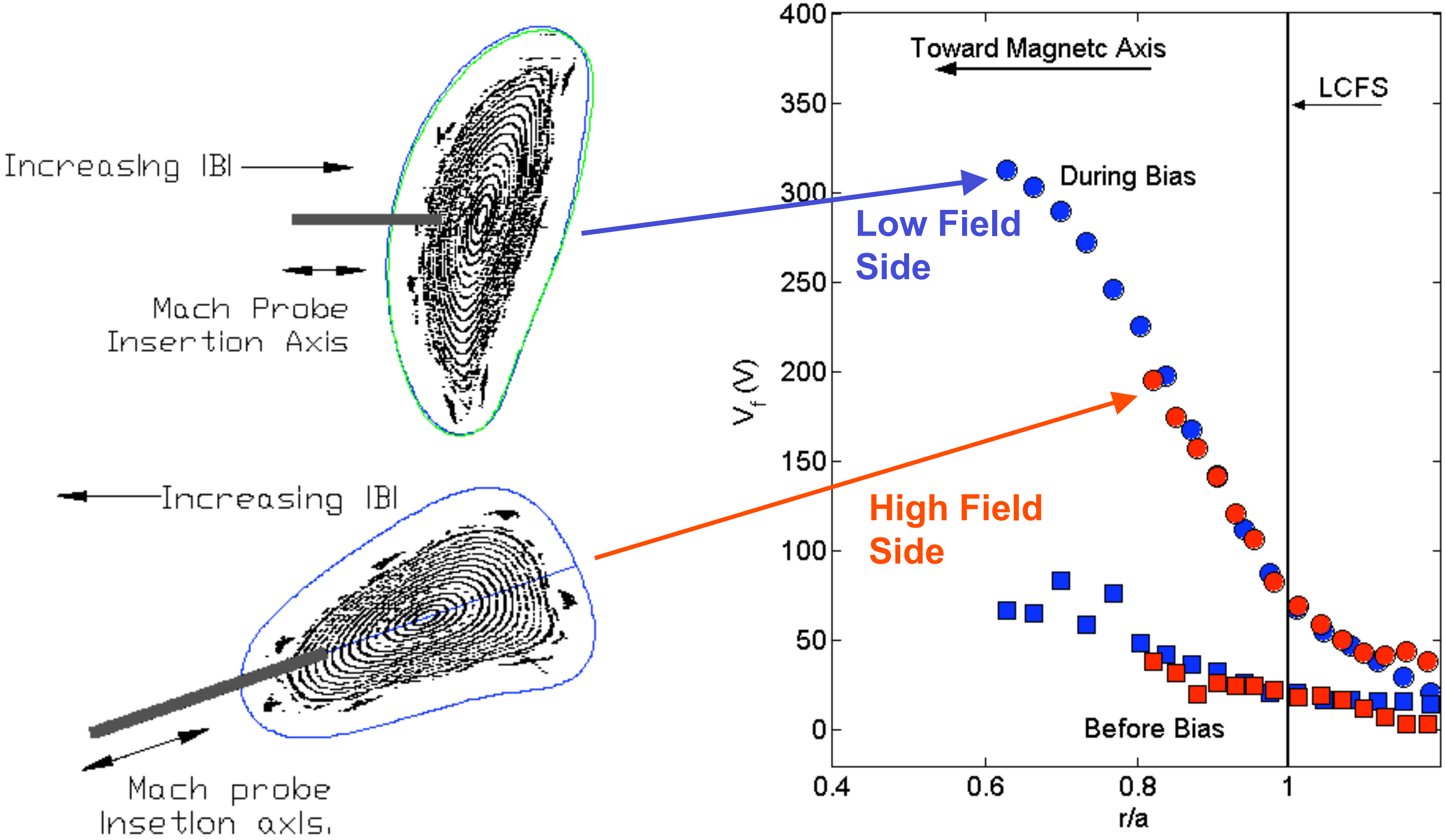
$$B^{\alpha} = \vec{B}\cdot\vec{\nabla}\alpha = \frac{\iota\!\!\!-}{2\pi\sqrt{g}}$$ ← **Poloidal Basis Vector**

- Need initial condition on the basis vectors to complete this integration.
- Knowing $\left(\sqrt{g}, \iota\!\!\!-, B_{\alpha}\right)$ 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, 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, B_{α} is the desired quantity

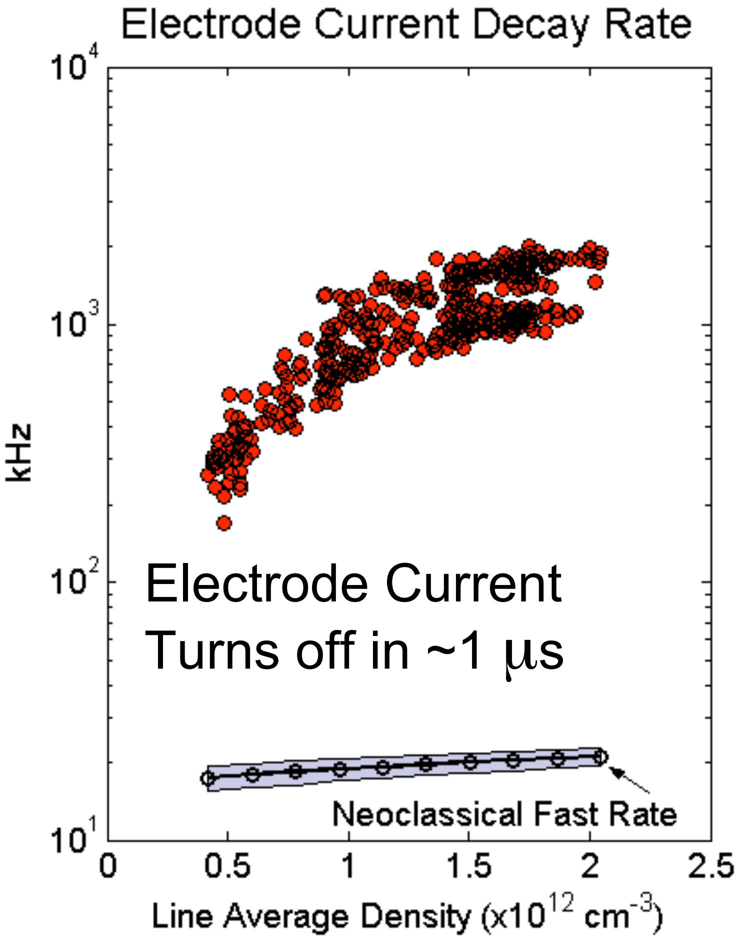
Floating Potential is a Flux Surface Quantity



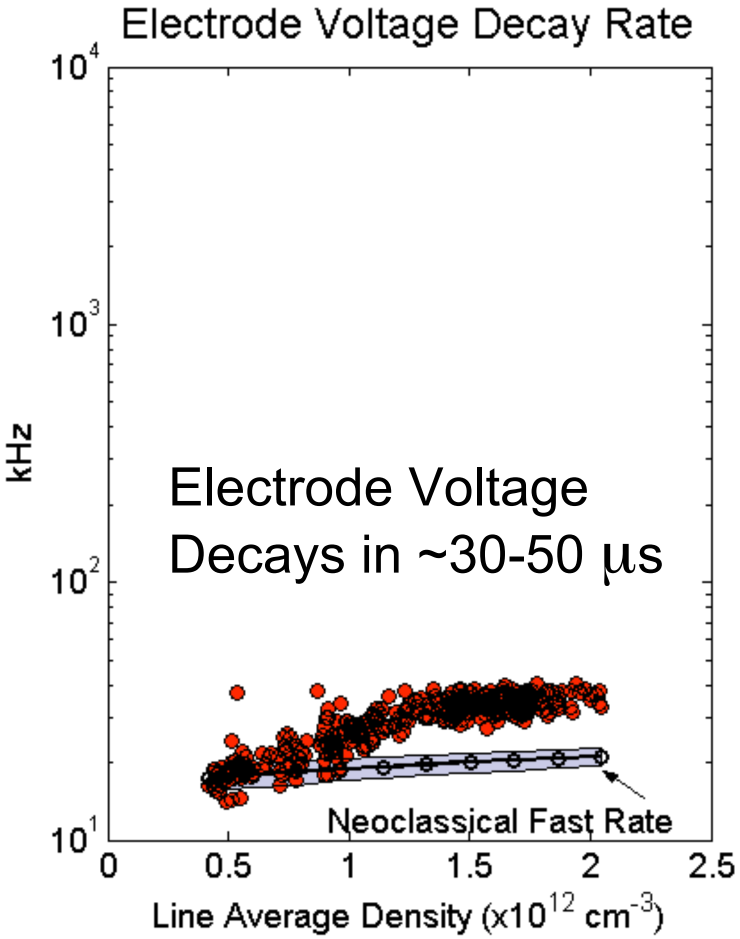
Low Field Side

High Field Side

Electrode Characteristics at Turn Off Fit the Decay Model


Electrode Current Decay Rate

Electrode Current Turns off in ~1 µs


Electrode Voltage Decay Rate

Electrode Voltage Decays in ~30-50 µs

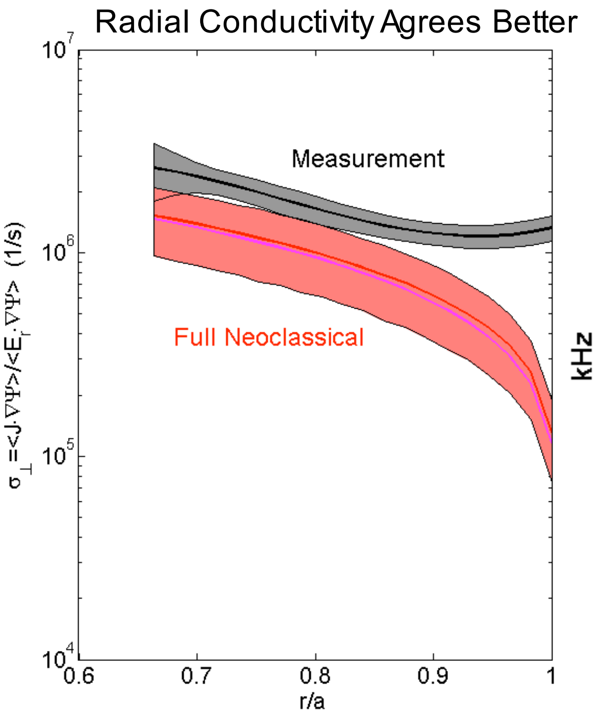
Floating potential and fast component of flow decay on same time scale as electrode voltage, in agreement with neoclassical fast rate.

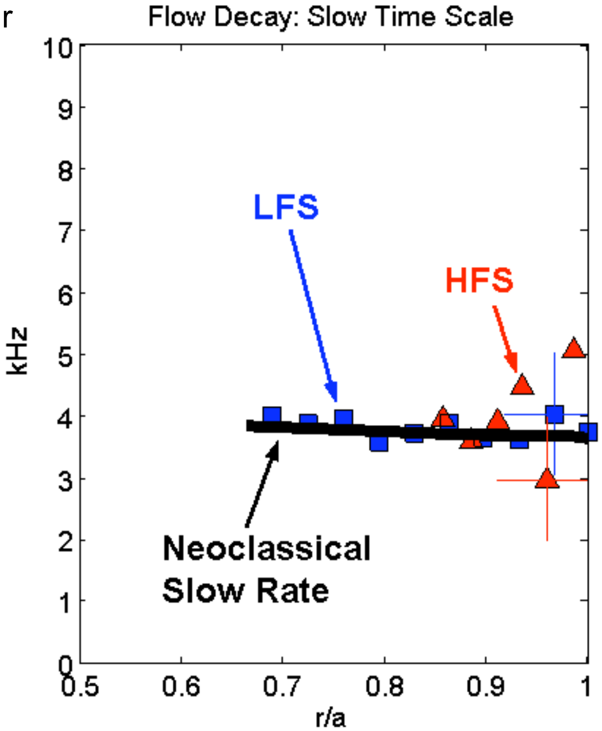
Artificially Increasing the Damping Improves Theory/Experiment Comparison

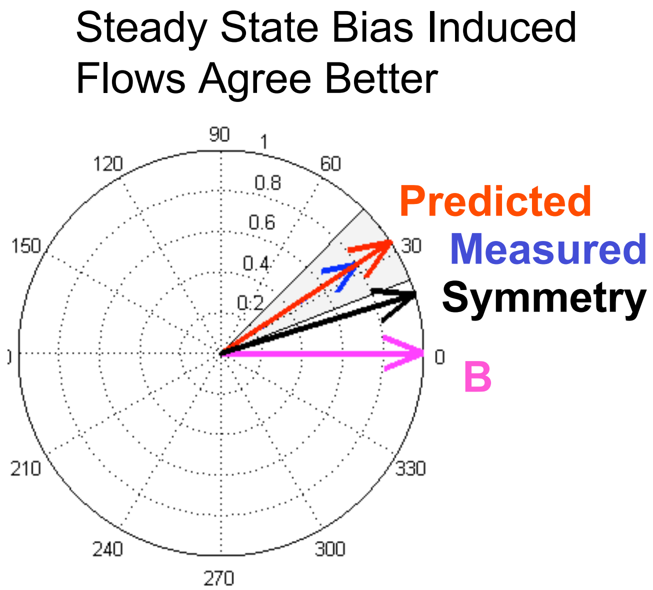
Increase the neutral density to *simulate* extra damping.

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

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

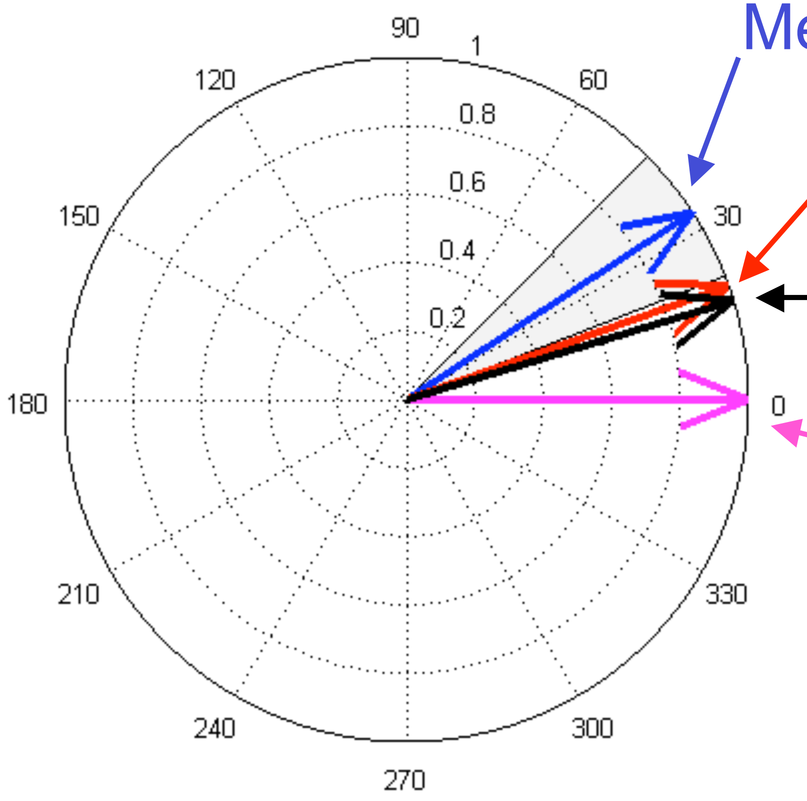

Radial Conductivity Agrees Better


Flow Decay: Slow Time Scale


Steady State Bias Induced Flows Agree Better

- ➢ This agreement comes at the cost of the rise model agreement.
- ➢ Need a better model for the enhanced damping.

Steady State Flow Direction Differs Somewhat from Neoclassical Prediction.



Measured Flow Direction

Predicted Flow Direction

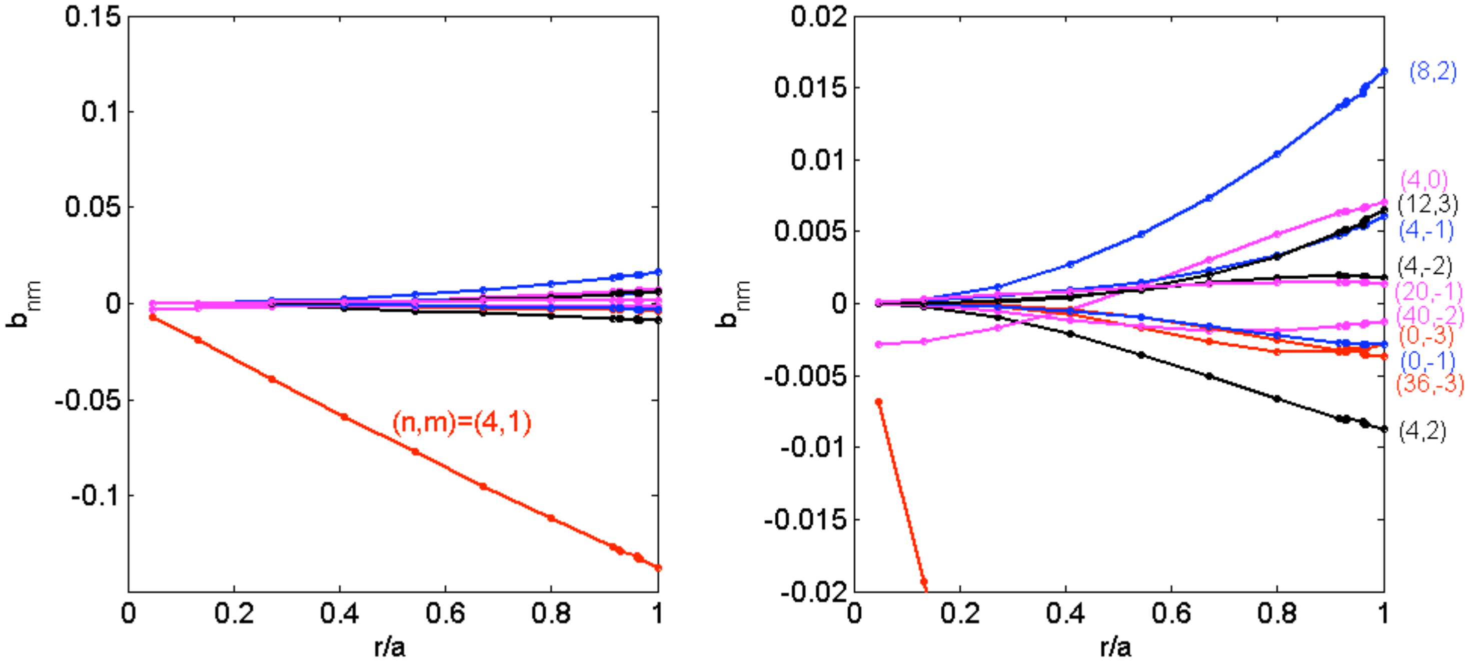
(n,m)=(4,1) symmetry direction

Magnetic Field

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

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.

$$\lambda_{mfp,H} = \frac{\sqrt{\frac{2E_H}{m}}}{n_e\langle\sigma v\rangle_{H+e\to p+2e}} = \frac{\sqrt{\frac{2\cdot 3\cdot 1.6\times10^{-19}}{1.67\times10^{-27}}}\left(\frac{m}{s}\right)}{10^{12}\left(cm^{-3}\right)\cdot 2.5\times10^{-8}\left(cm^{3}s^{-1}\right)} \approx 1m$$

Synthesis of These Comparisons

- Measured fast time scales match the neoclassical predictions.
- Slow time scale is significantly faster than the neoclassical prediction.
- Appears that the damping in the direction of symmetry is faster than neoclassical.
- Large tokamaks have usually seen anomalous toroidal flow damping (DITE, ISX-B, PLT,PDX, ASDEX, TFTR, DIII-D, JET, C-MOD…)
- Smaller tokamak biased electrode experiments show anomalously large radial conductivity (barring neutrals, any radial current is anomalous!)
- HSX is quite similar to the tokamak results in this sense.

The End