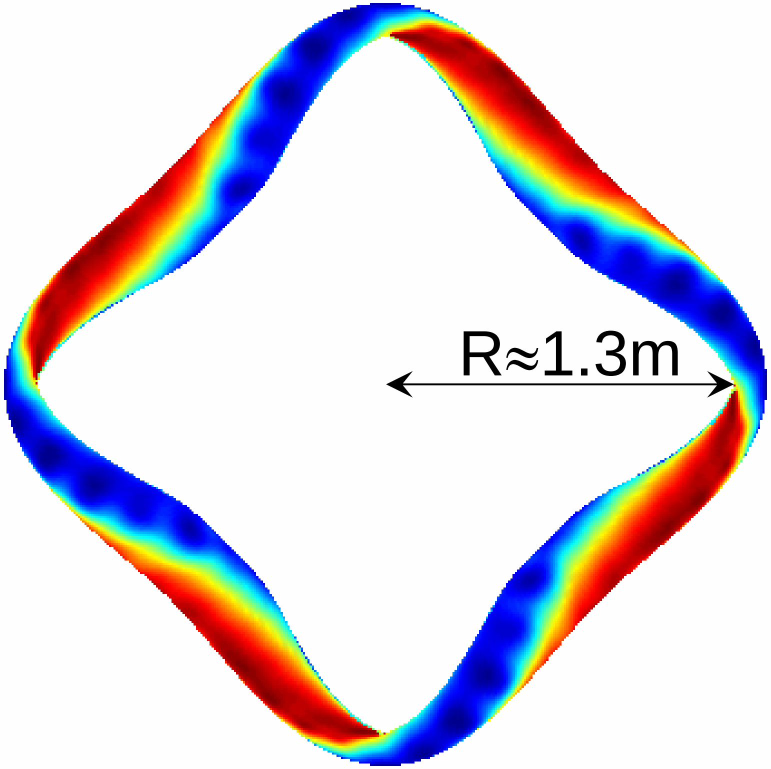
Measurements and Modeling of Plasma Flow Damping in the HSX Stellarator

S.P. Gerhardt, A.F. Almagri, D.T. Anderson, F.S.B. Anderson, D. Brower, J.M. Canik, C. Deng, W. Guttenfelder, K.M. Likin, V. Sakaguchi, J.N. Talmadge, and K. Zhai

Outline

B=0.5T

P_{ECH}<200 kW @ 28 GHz

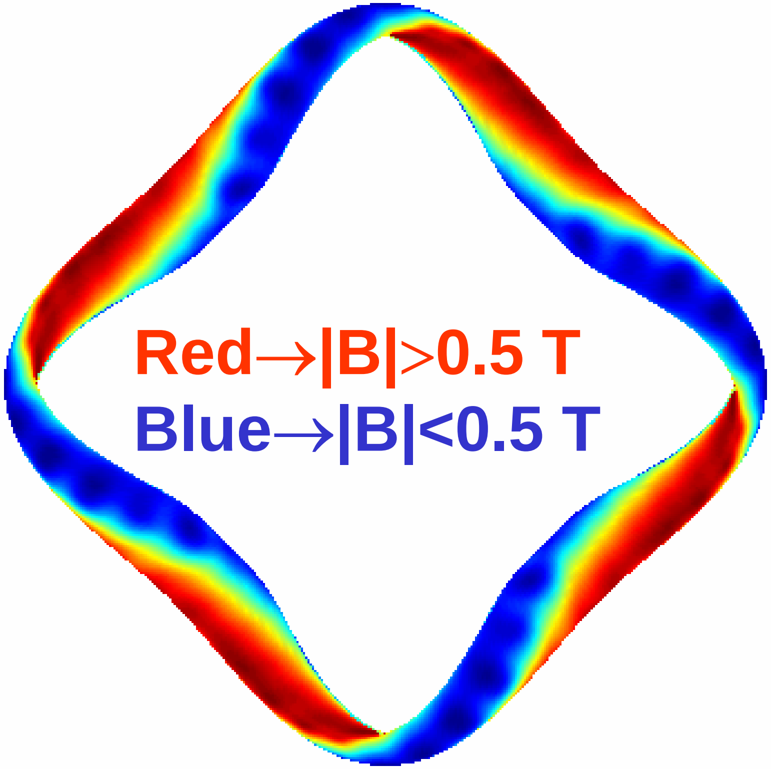


HSX is located at the University of Wisconsin-Madison

- 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

HSX Provides Access to Configurations With and Without Symmetry

QHS Configuration

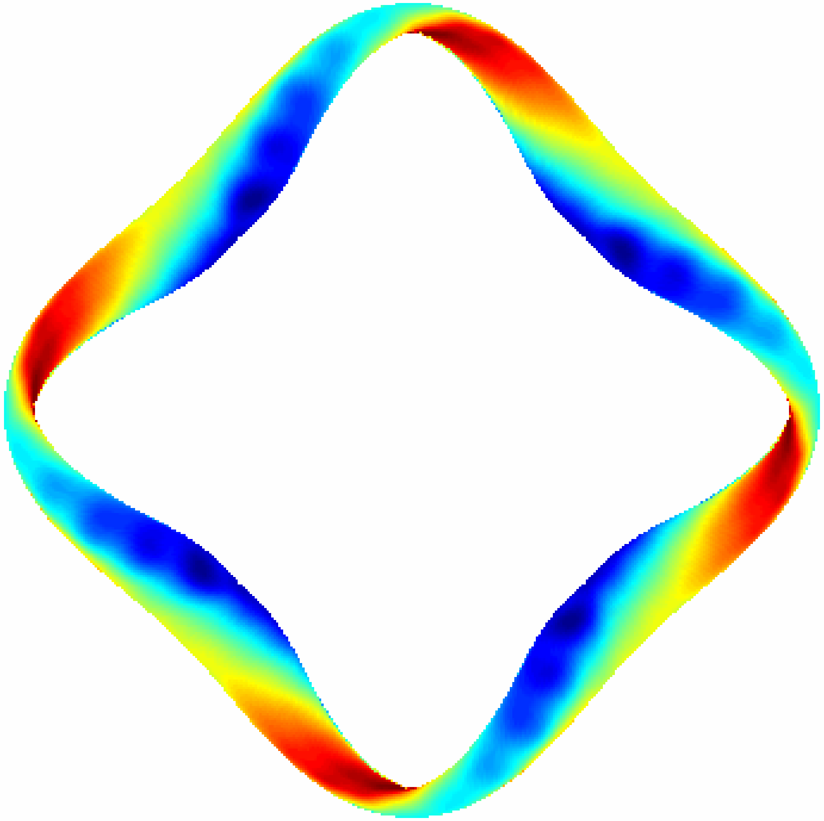


Red→|B|>0.5 T

Blue→|B|<0.5 T

QHS: Helical Bands of Constant |B|

Mirror Configuration

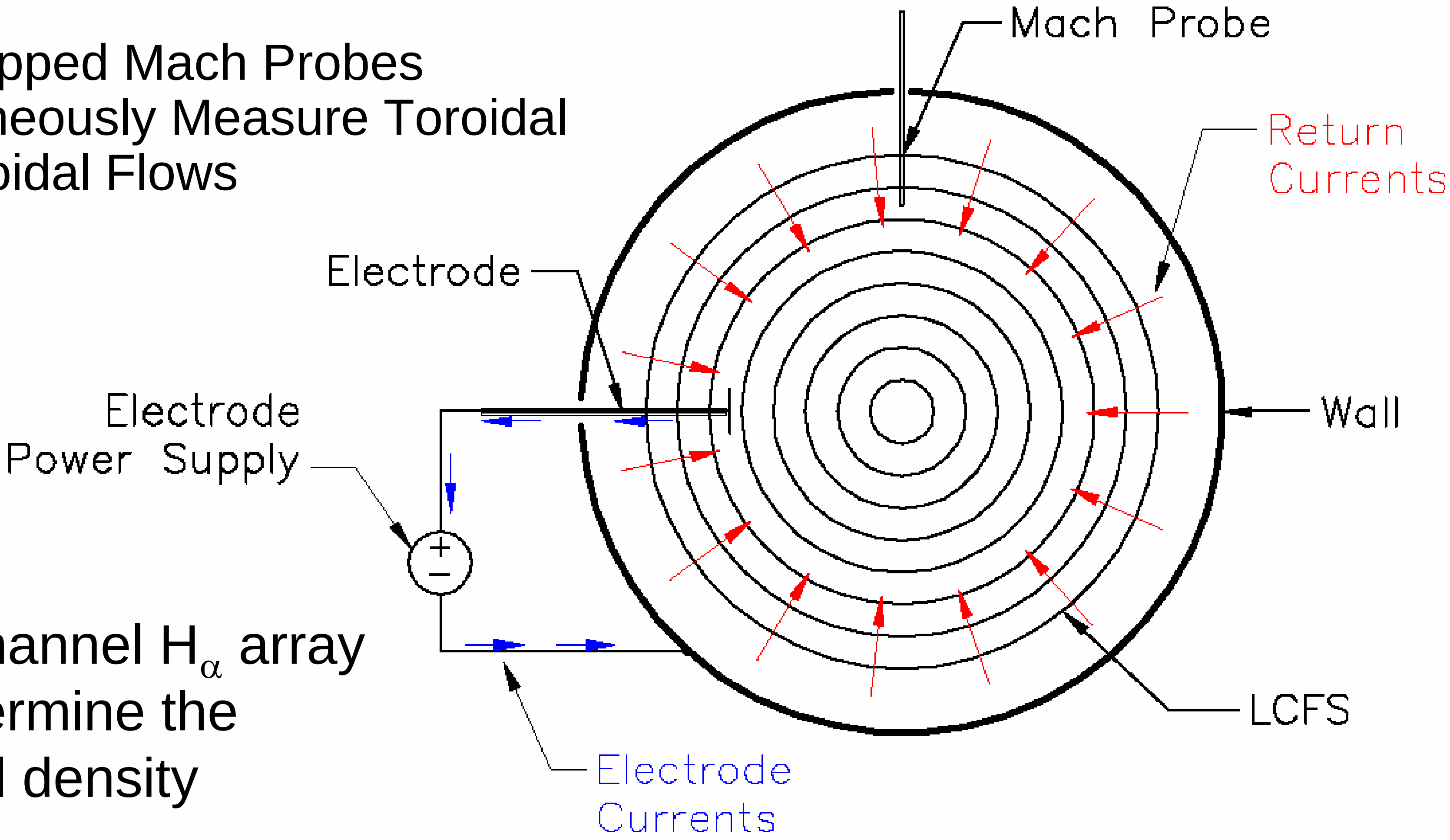


Mirror: Helical Bands are Broken

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

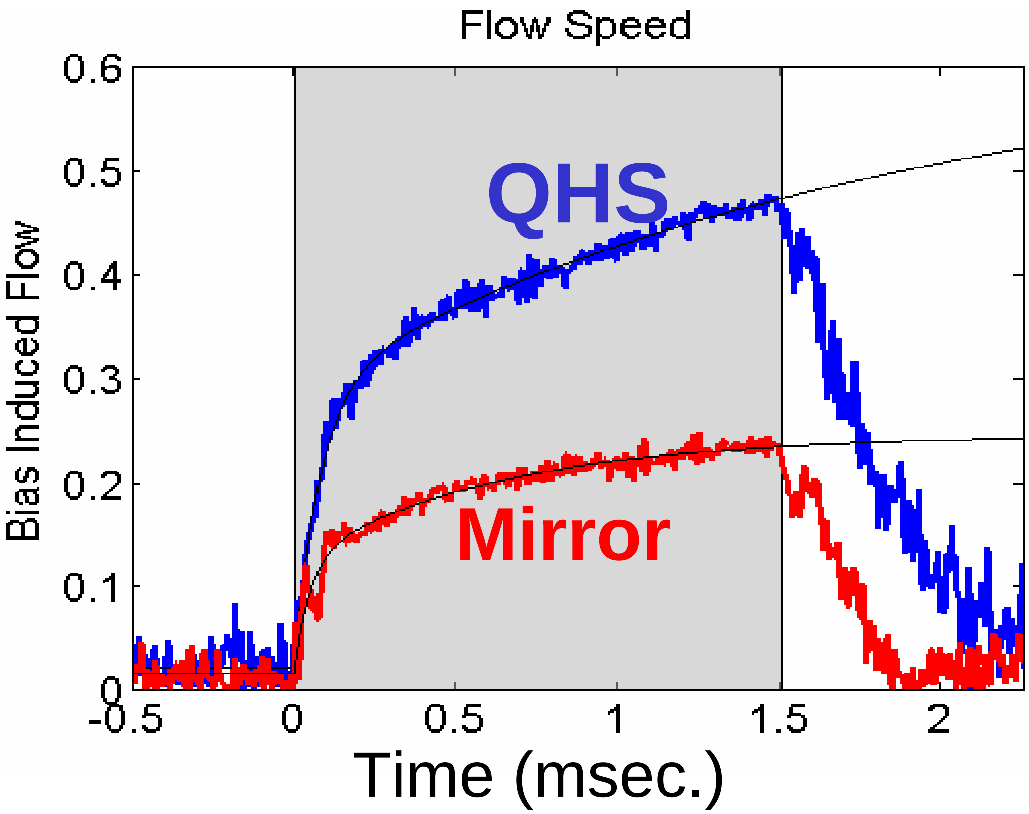
Biased Electrode Experiments

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 \approx$25eV, B=0.5T, P_{ECH}=50 kW) held constant.

Asymmetries and Multiple Time-Scales Observed in Flow Evolution

- Potentials:

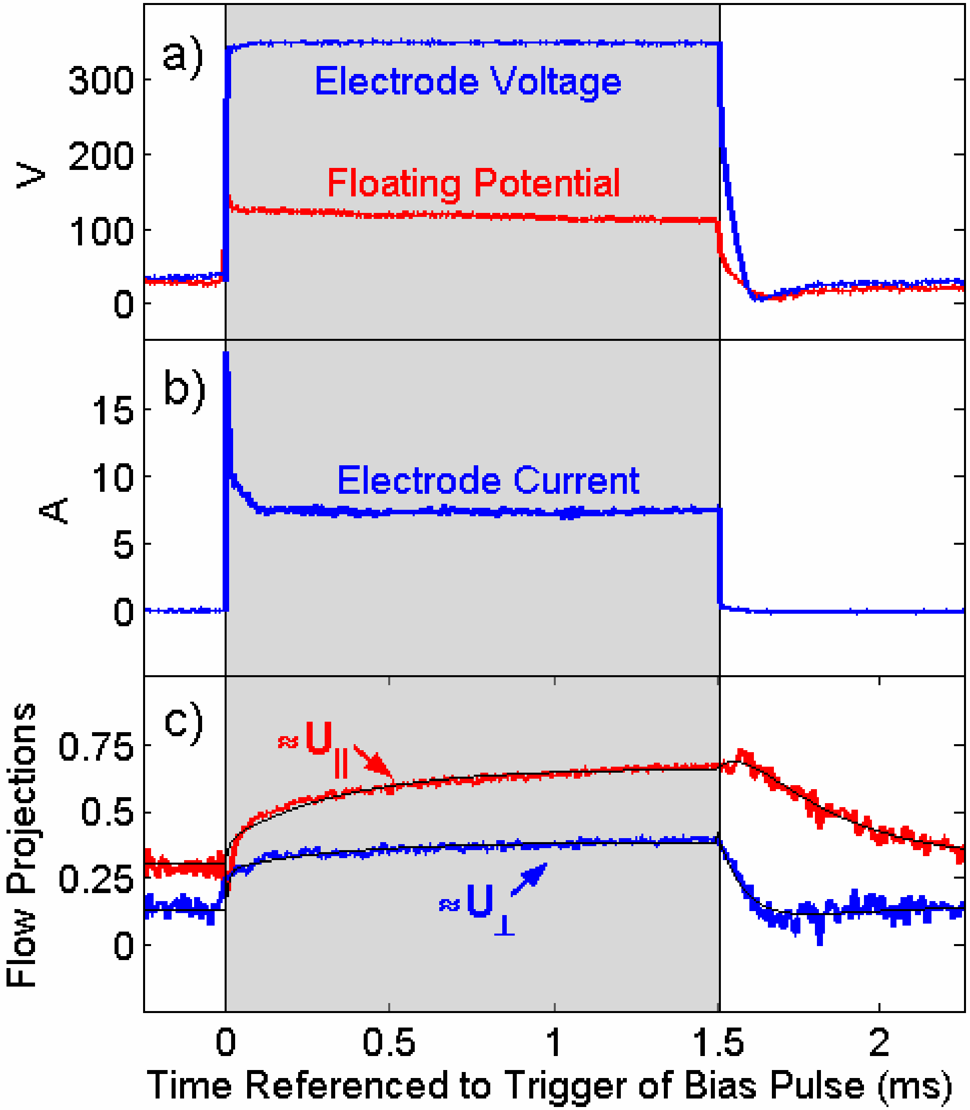
  Fast Rise and Slow Decay

- 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

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

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

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

- **E**x**B** 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

Toroidal Damping

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

Poloidal Damping

- Two time-scales/two direction flow evolution

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

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:

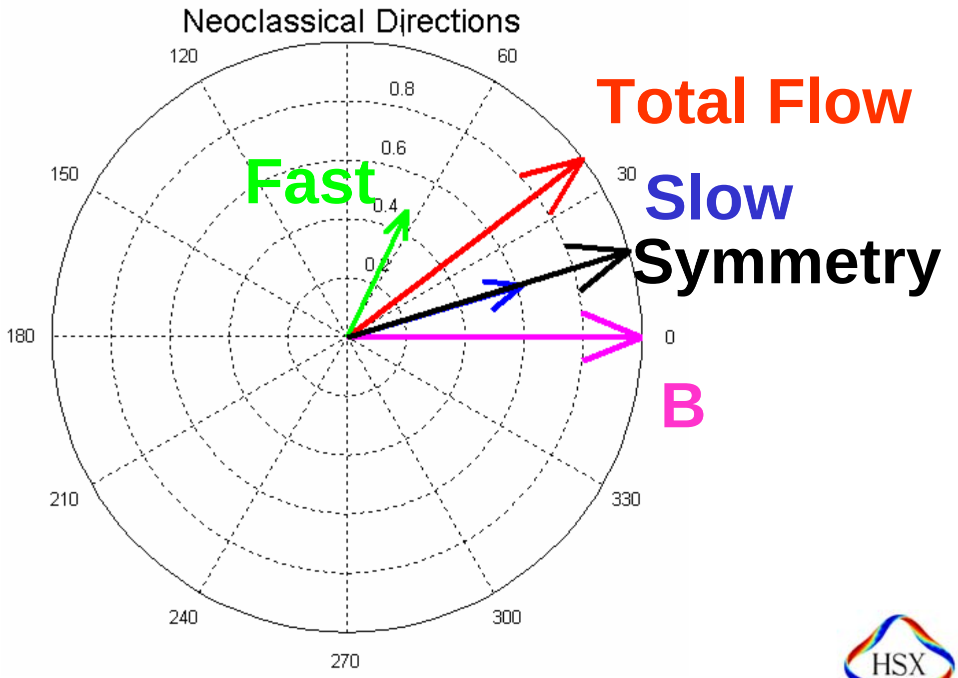
$$\mathbf{U} = e^{-\gamma_f (t-t_0)}\mathbf{f} + e^{-\gamma_s (t-t_0)}\mathbf{s}$$

$$+$$

- 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

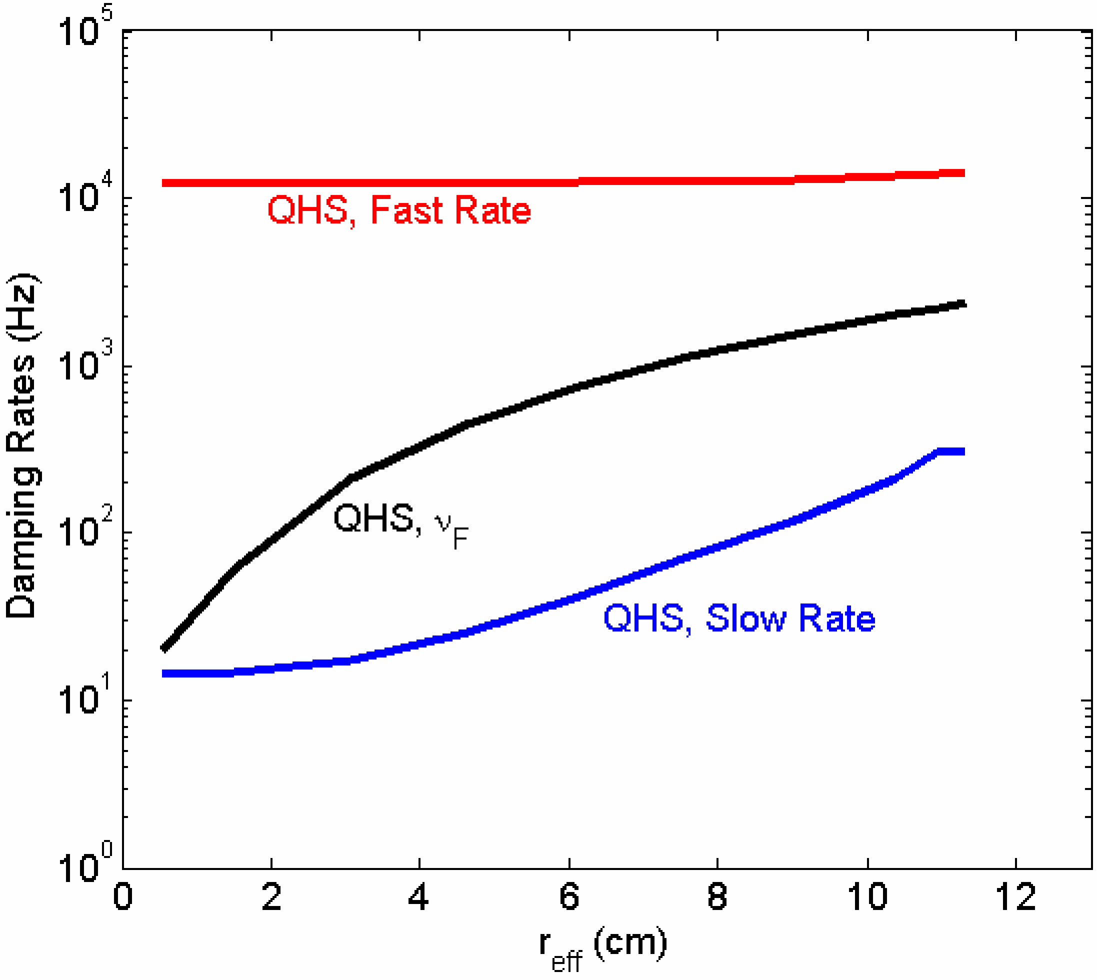
Fast Rate

is faster than

Hybrid Rate, ν_F

is faster than

Slow Rate



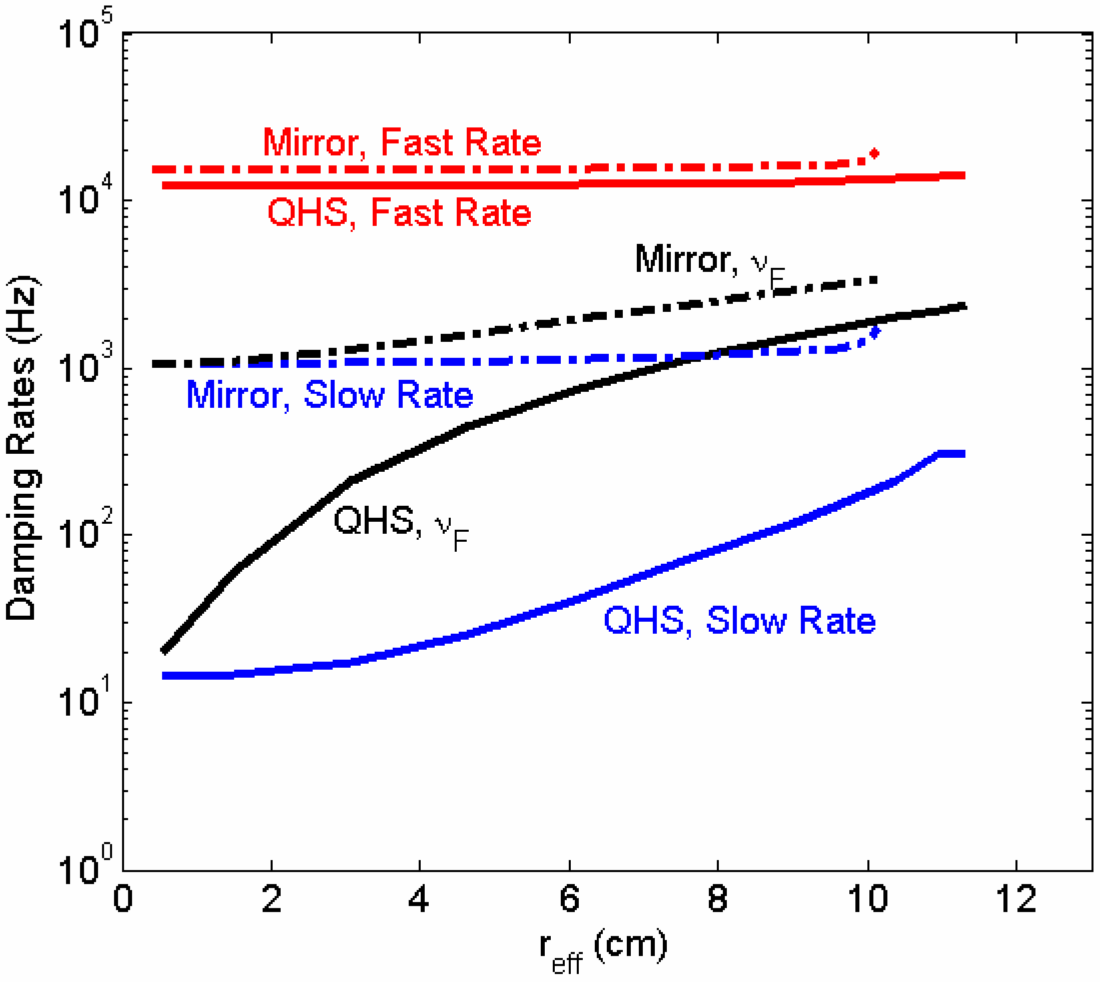
Mirror Shows Increased Neoclassical Damping Compared to QHS

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

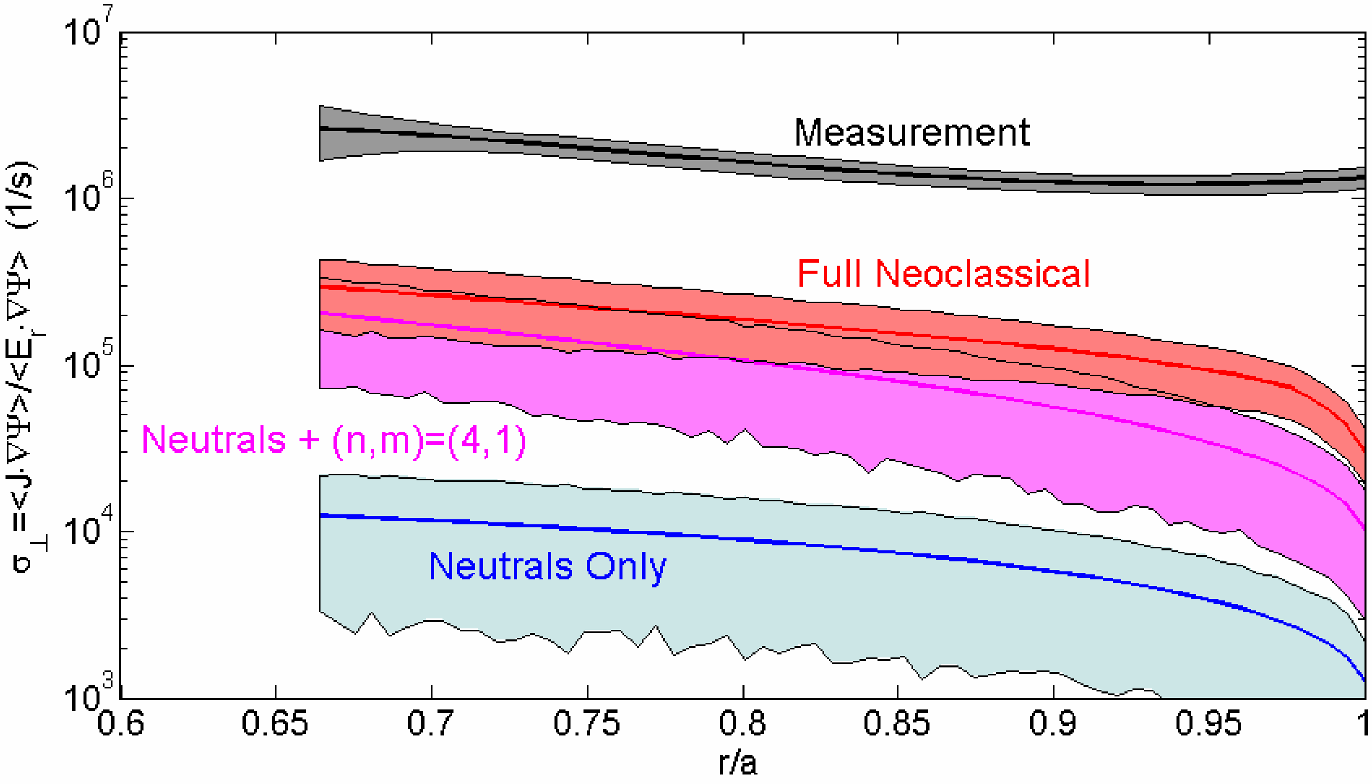


Comparison of Neoclassical Theory with Measurements

1) Reduced Flow Damping with Quasisymmetry

2) Evidence of Anomalous Flow Damping

QHS Radial Conductivity is Larger than the Neoclassical Prediction

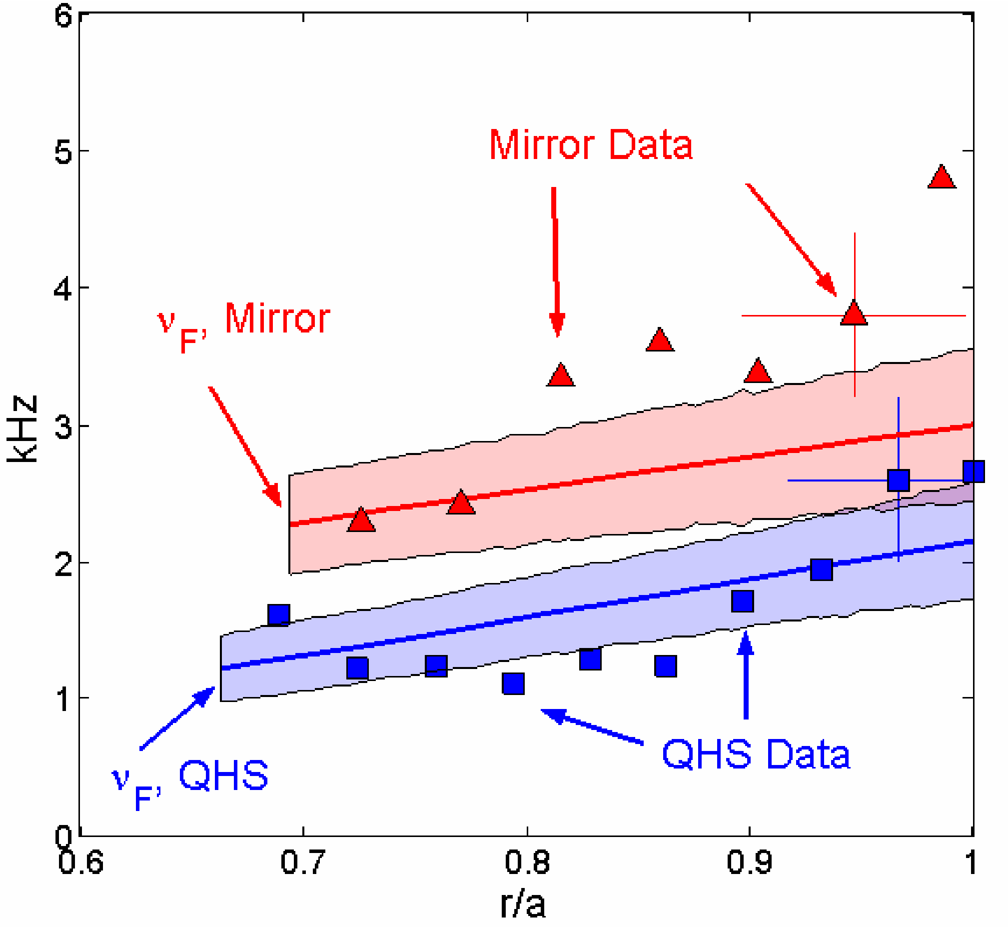


$$\left\langle \vec{J}_{plasma}\cdot\vec{\nabla}\psi\right\rangle = \sigma_\perp\left(\left\langle \vec{E}_r\cdot\vec{\nabla}\psi\right\rangle - \frac{\left\langle \vec{\nabla}p_i\cdot\vec{\nabla}\psi\right\rangle}{eN_i}\right)$$

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.

Flow Rise Rate

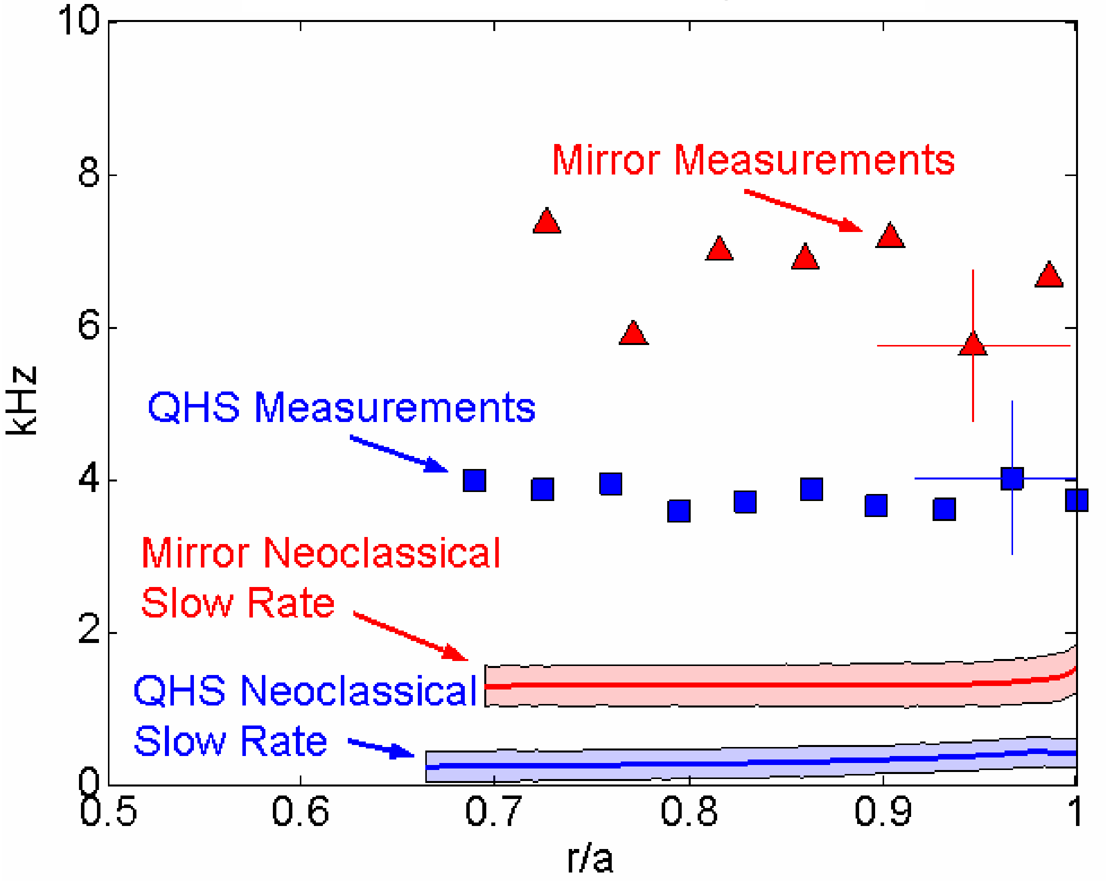


Flow Decay Rates Show Reduced Damping with Quasisymmetry

- ➢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.

Slow Flow Decay Rate



Conclusion

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

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.

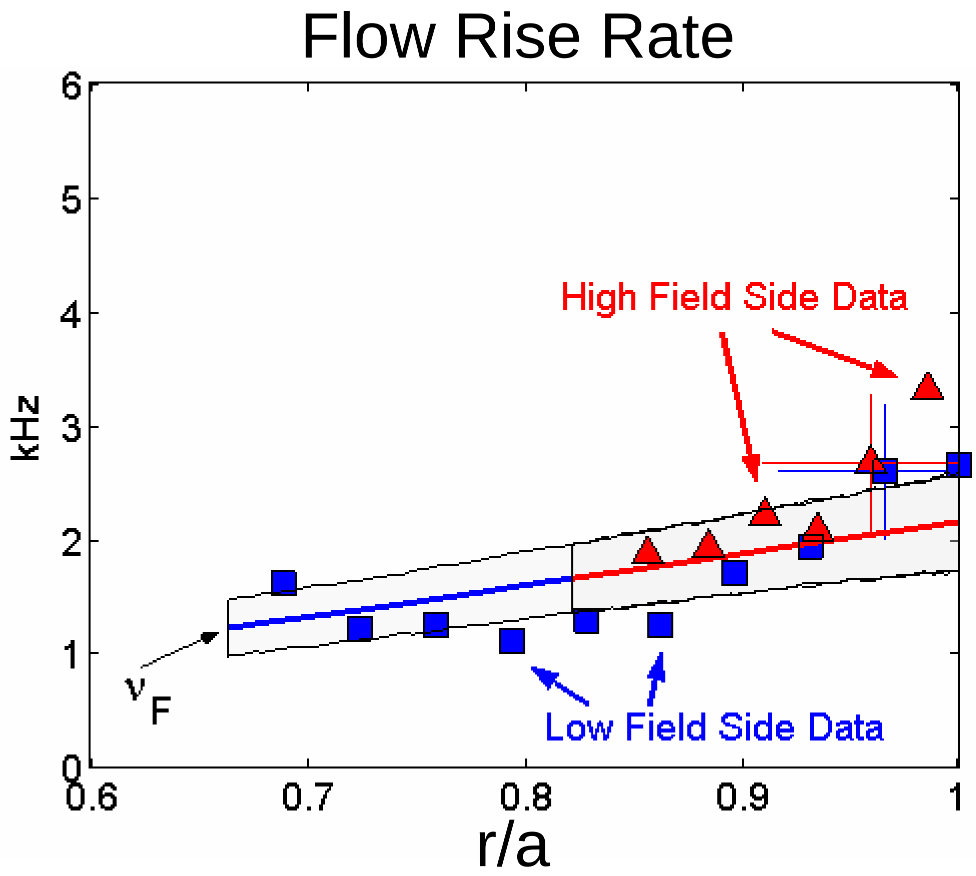
The End

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

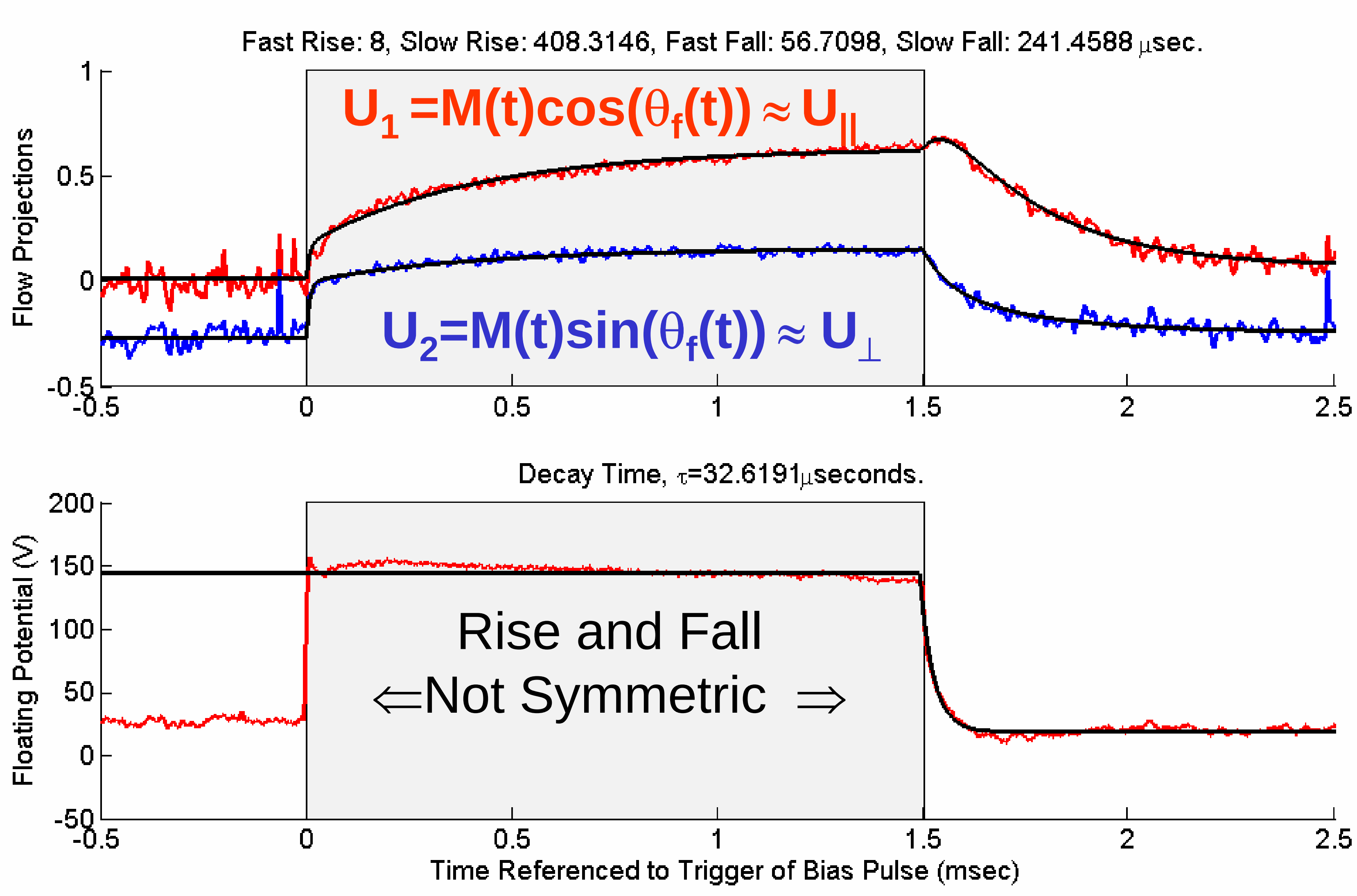
All relevant time-scales are similar on high and low field sides

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

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



Two Time-Scale Model Fits Flow Evolution



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

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

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

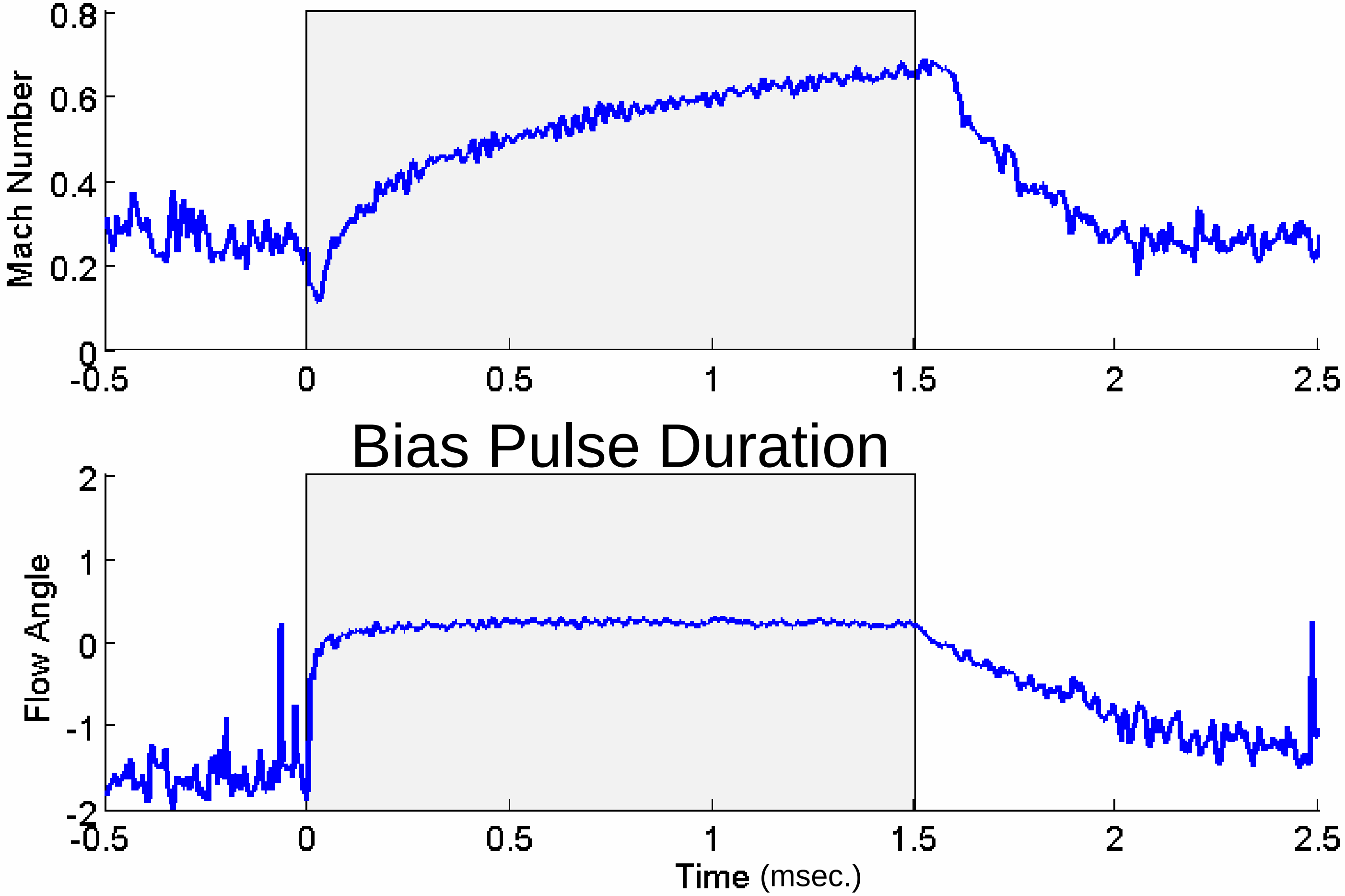
Decay Time, τ=32.6191μseconds.

Rise and Fall

⇐Not Symmetric ⇒

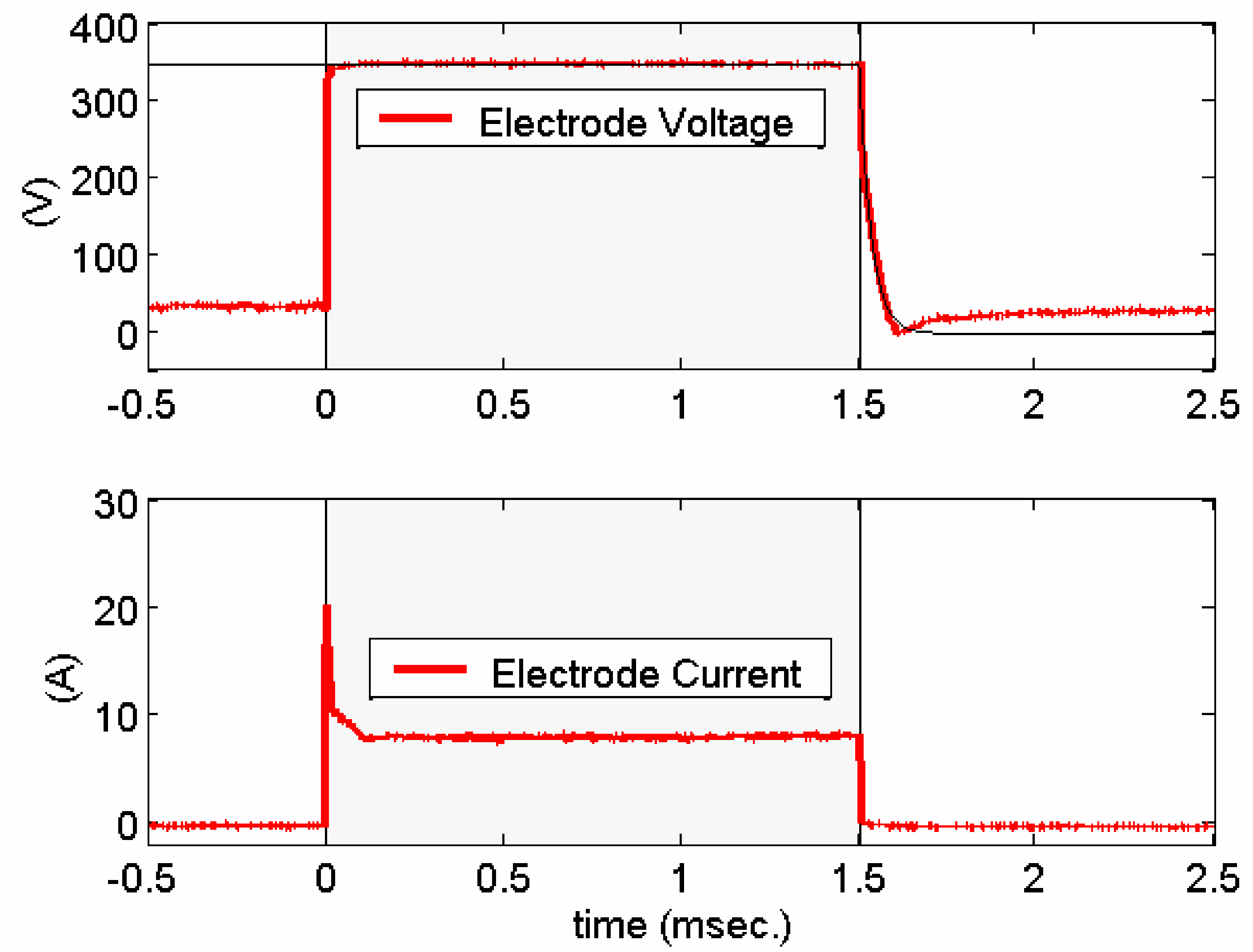
Similar time-scales measured by LFS and HFS probes.

Both Flow Speed and Direction Evolve over the Electrode Pulse



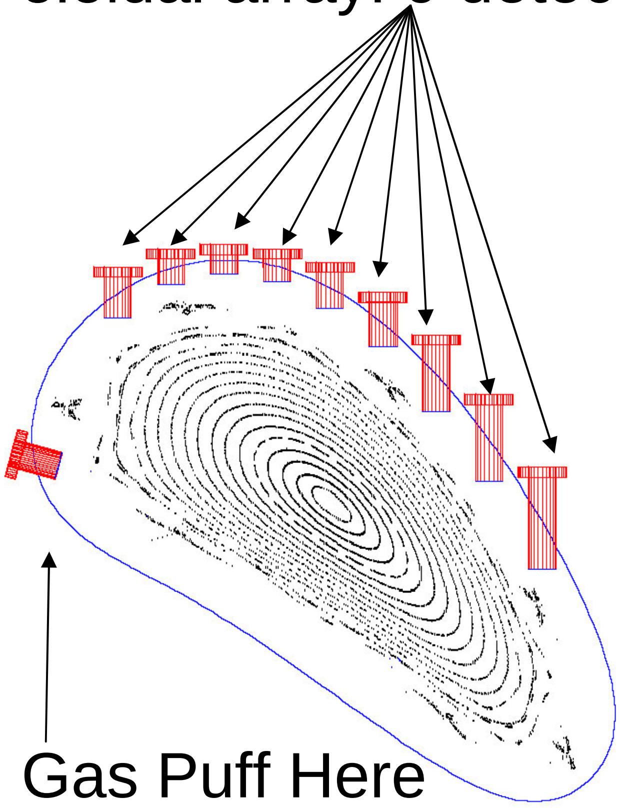
Need to extract the time-scales and directions.

Voltage Application Initiates the Rise, Current Termination Initiates the Decay

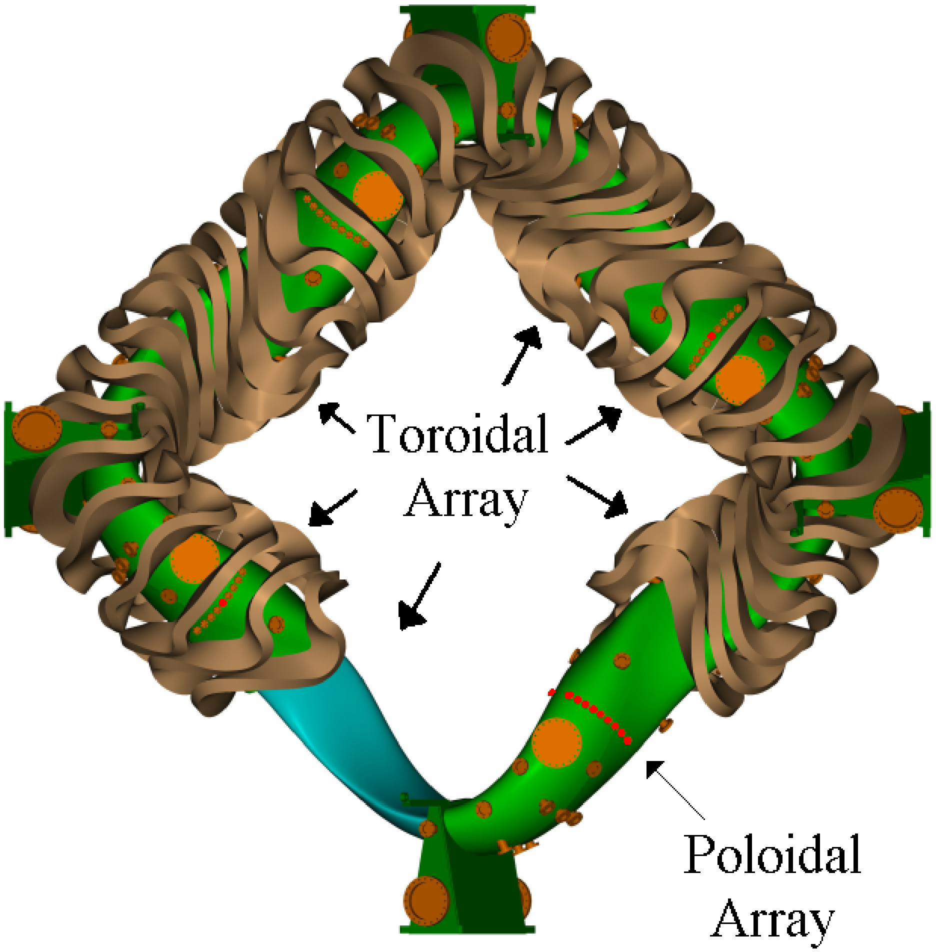


Developed a Comprehensive Set of H_α Detectors for Neutral Density Measurements

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



Gas Puff Here



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

Mach Probes Used to Measure Time-Dependent Plasma Flows

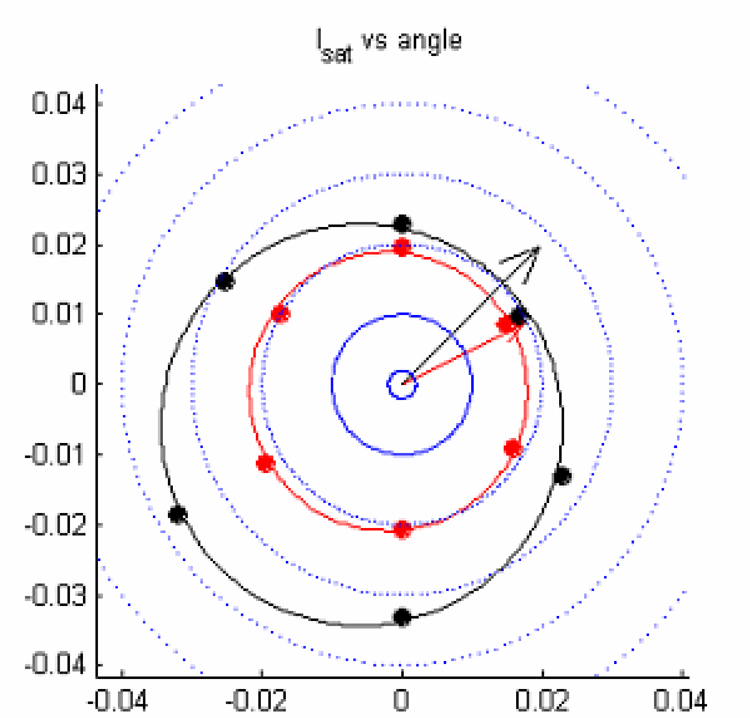
- 6 tip mach probes measure plasma flow speed and direction on a magnetic surface.

- 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.

$$B^{\Psi} = \vec{B}\cdot\vec{\nabla}\Psi = 0 \quad \longleftarrow \text{Radial Basis Vector}$$

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

$$B^{\alpha} = \vec{B}\cdot\vec{\nabla}\alpha = \frac{\bar{\iota}}{2\pi\sqrt{g}} \quad \longleftarrow \text{Poloidal Basis Vector}$$

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

$$\mathbf{J}_{||} = h\frac{\partial p}{\partial \psi}\mathbf{B}$$

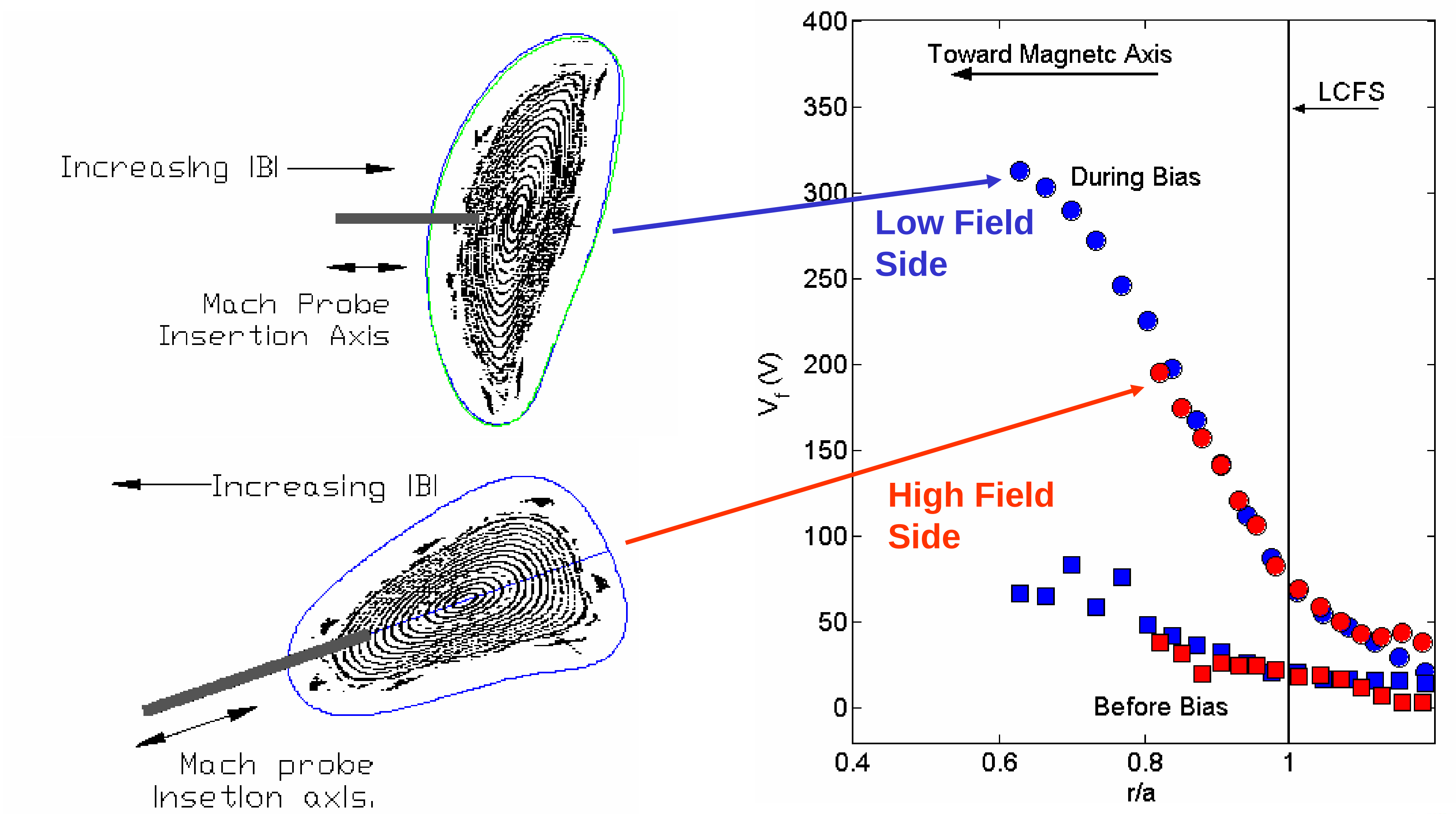
Method by Nemov[1], h is numerically calculated

$$\mathbf{J}_{||} = -\frac{B_{\alpha}}{B^{2}B^{\zeta}\sqrt{g}}\frac{\partial p}{\partial \psi}\mathbf{B}$$

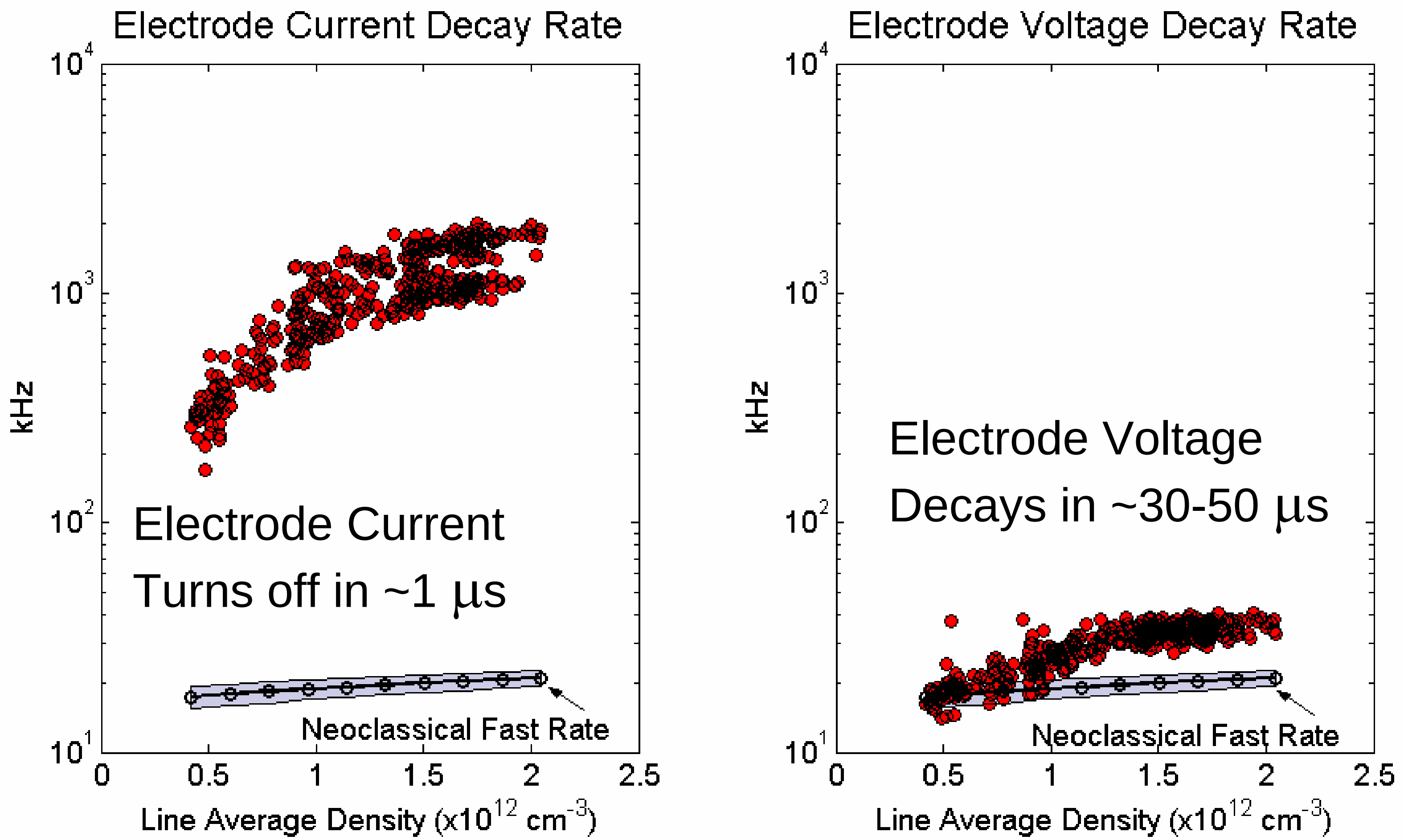
Method by Coronado and Wobig[2], B_{α} is the desired quantity

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



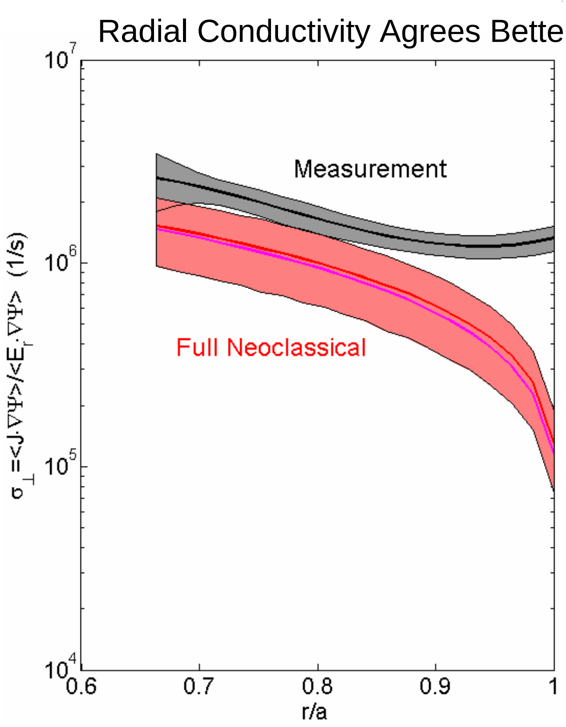
Floating potential and fast component of flow decay on same time-scale as electrode voltage, in agreement with neoclassical fast rate.

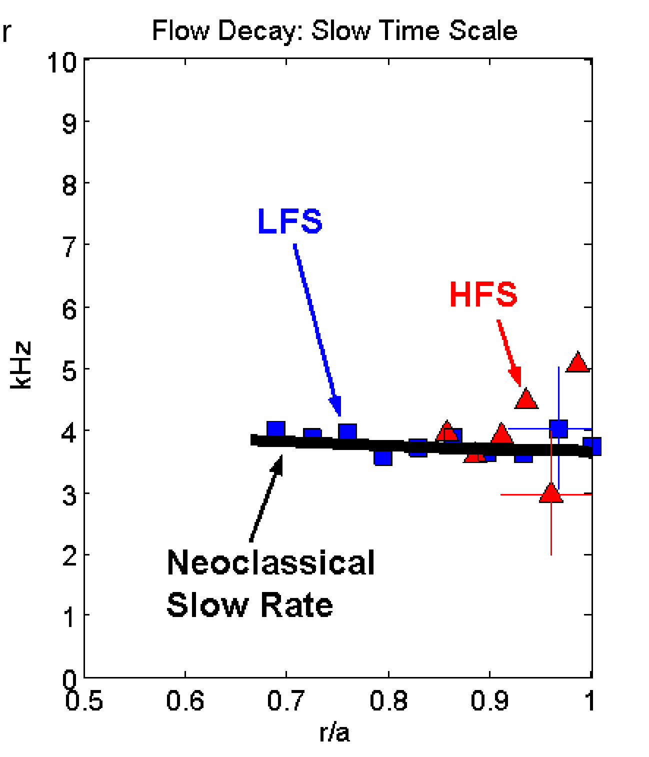
Artificially Increasing the Damping Improves Theory/Experiment Comparison

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

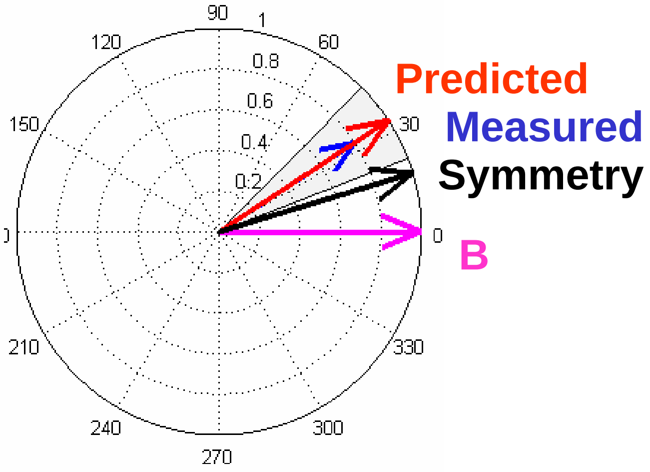
Increase the neutral density to *simulate* extra damping.

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


Radial Conductivity Agrees Better

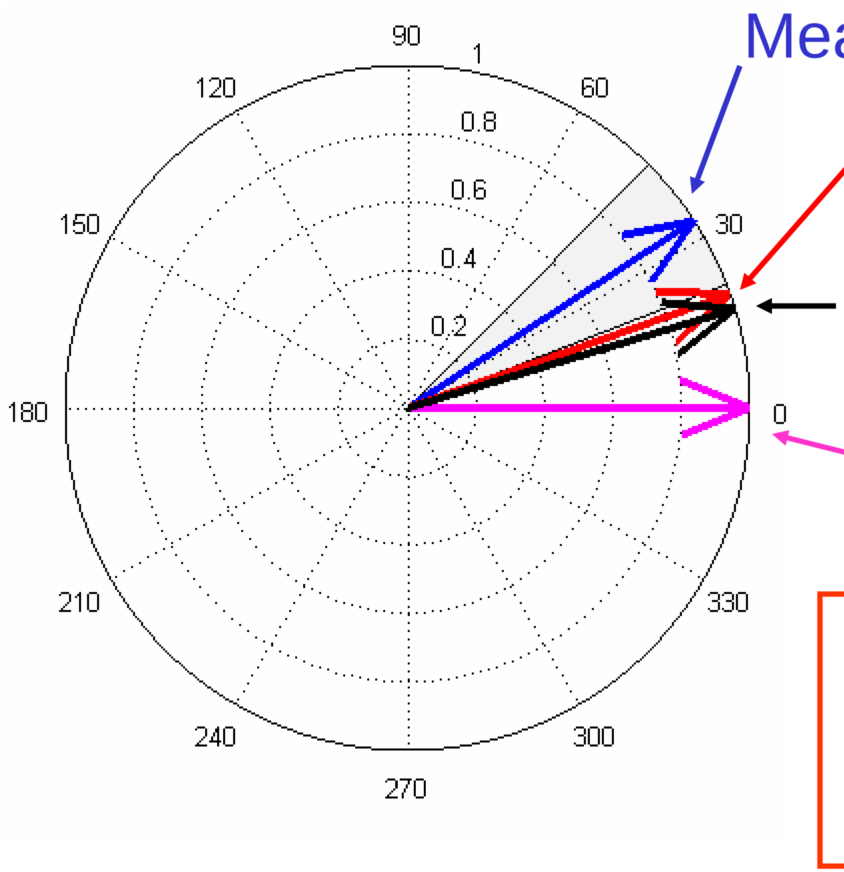

Flow Decay: Slow Time Scale

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

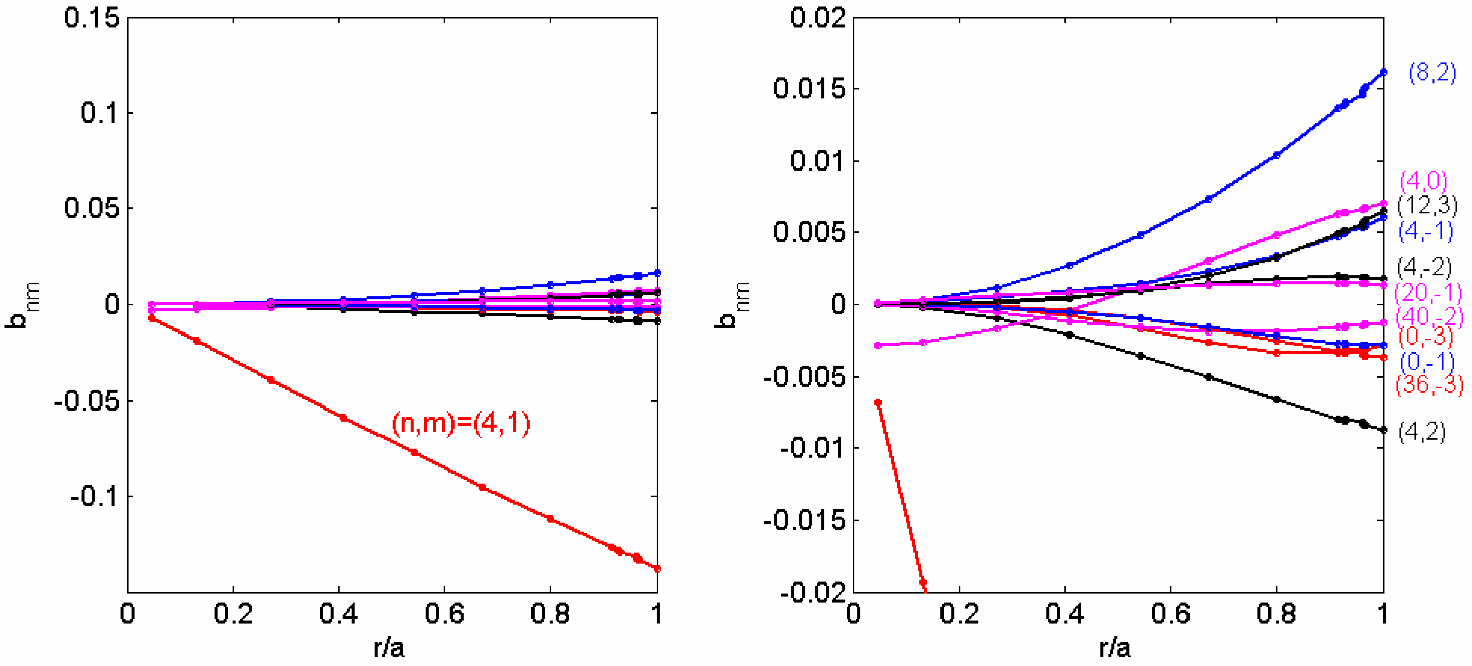
(n,m)=(4,1) symmetry direction

Magnetic Field

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

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.

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

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