Studies of Bias Induced Plasma Flows in HSX

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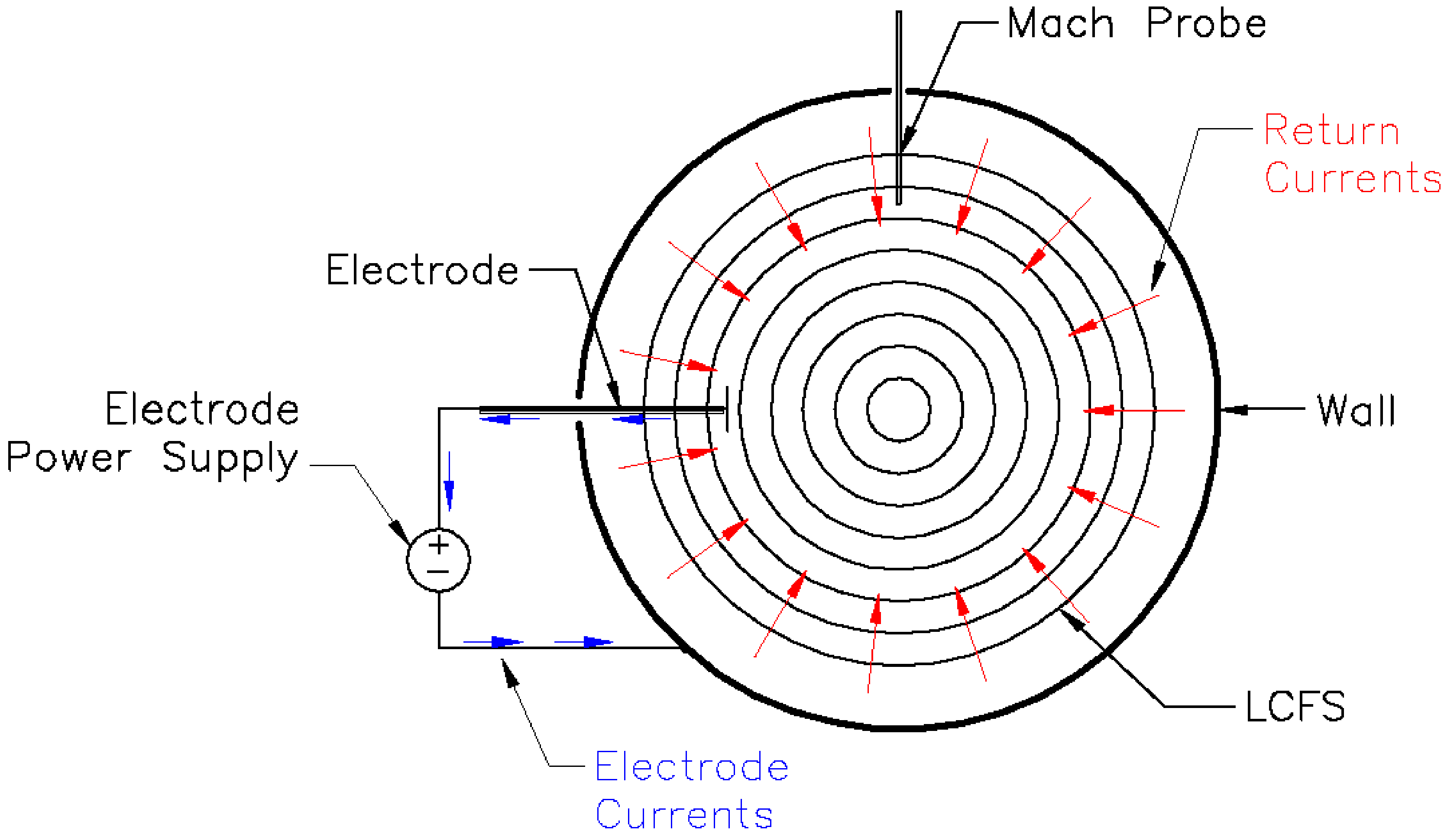
International Stellarator Workshop 2003

Outline

- Hardware and experimental setup
- Description of bias induced flows and evidence of two time scale flow damping.
- Neoclassical modeling of the plasma flows.
- Evidence of reduced damping in the quasi-symmetric configuration and comparison with modeling.

Experimental Configuration

General Structure of Experiments



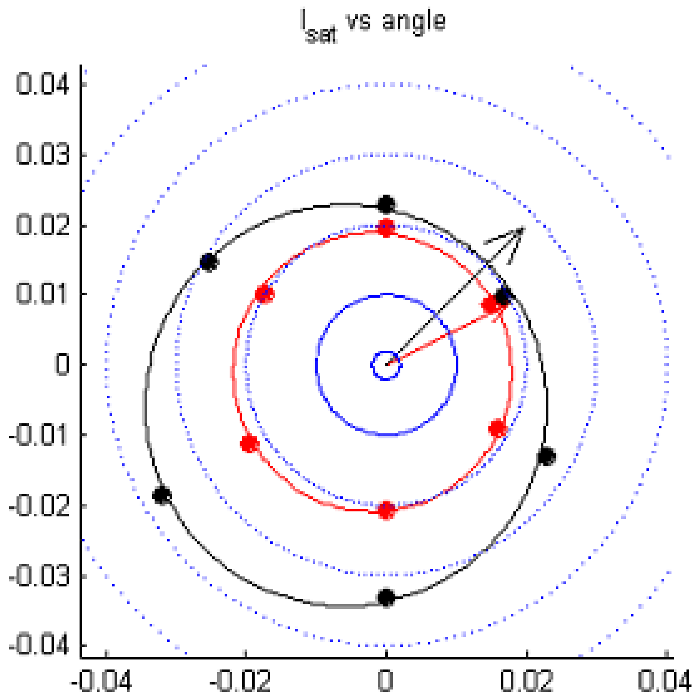
Mach Probes on HSX

- 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

Looking ⊥ To The Magnetic Surface

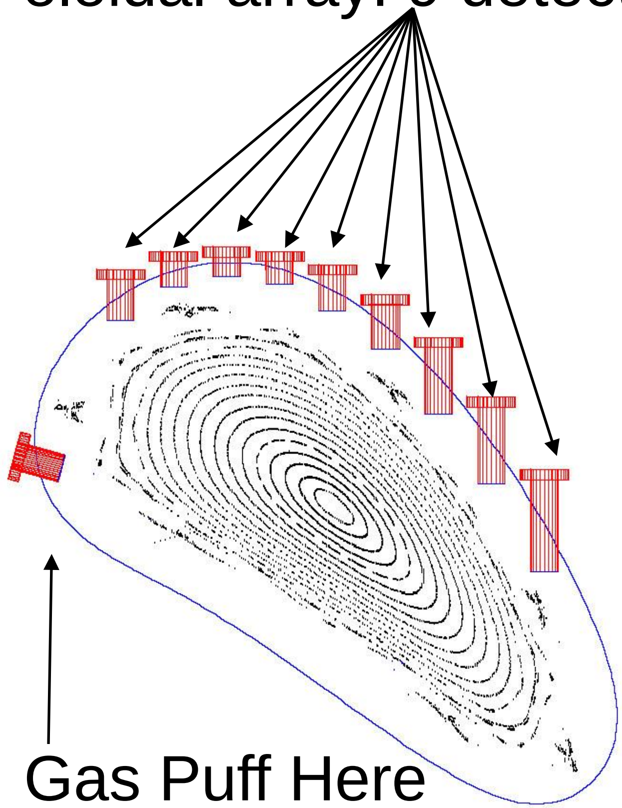


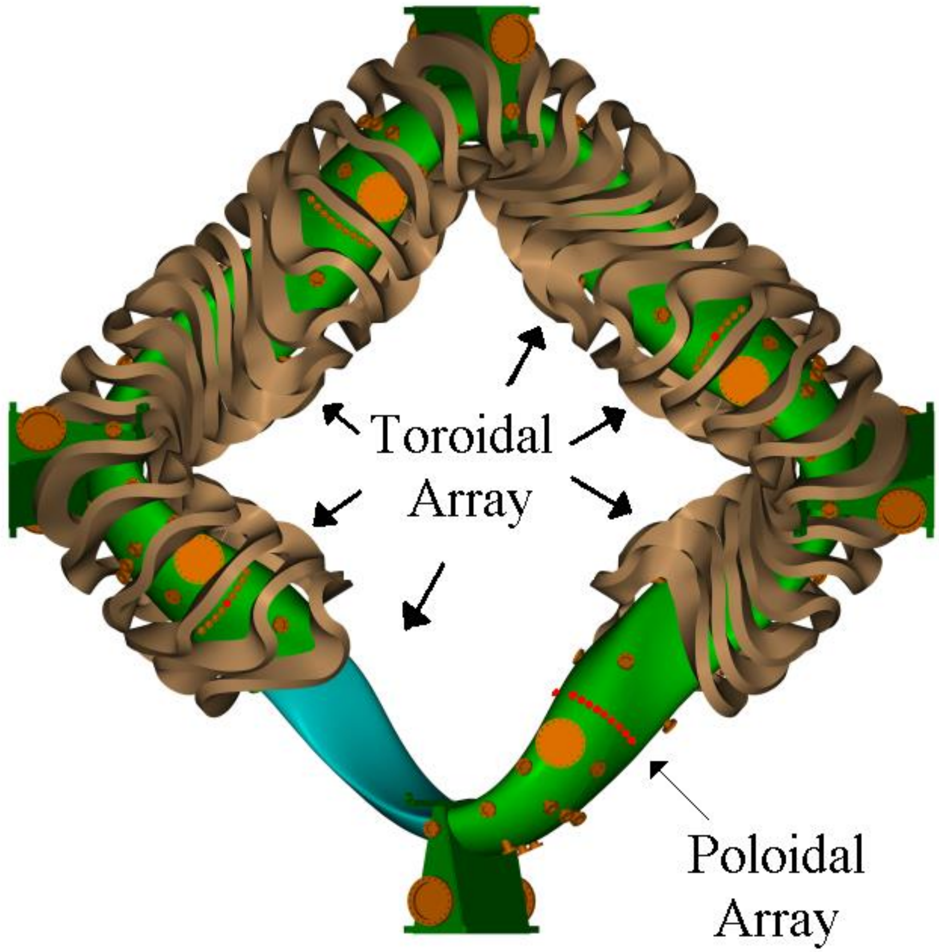
$$I_{sat}(\theta) = X_1 \exp\left(\left(\frac{X_2}{2}\right)\left[.64\left(1-\cos\left(\theta - X_3\right)\right) + .7\left(1+\cos\left(\theta - X_3\right)\right)\right]\right)$$

- Probe measures V_f with a proud pin.

HSX has a Comprehensive Set of H_α Detectors

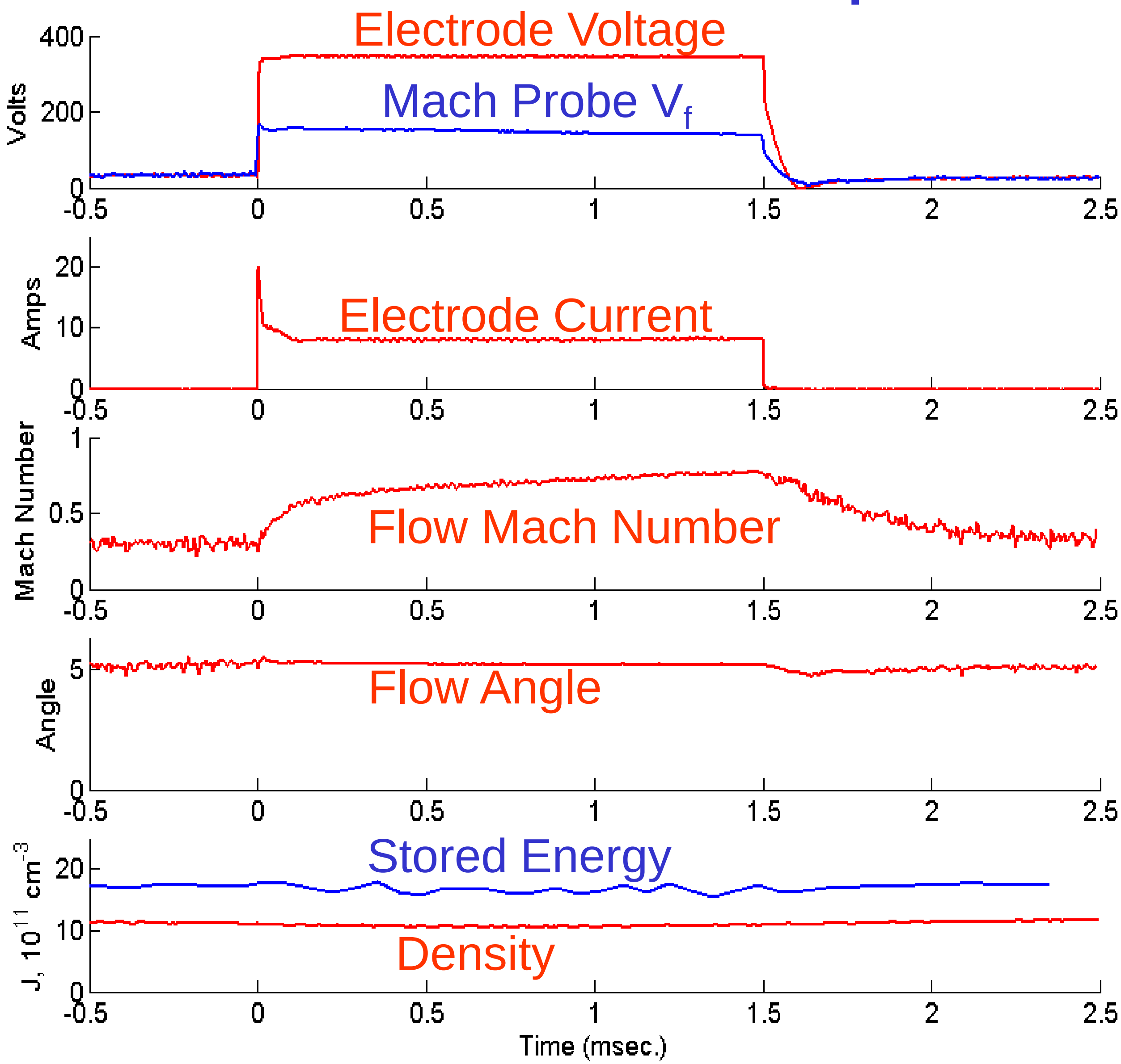
- Toroidal array: 7 detectors on magnetically equivalent ports
- Poloidal array: 9 detectors





•All detectors absolutely calibrated
•Analysis done by J. Canik using Degas code

Flows and Potential Respond to Bias



Flow Evolution and Two Time Scale Damping

Simple Flow Damping Example

- Take a simple 1D damping problem:

$$mn\frac{dU}{dt} = F - \mu U, \quad F = \begin{cases} 0 & t < 0 \\ jB & t > 0 \end{cases}$$

- Has solution

$$U = \begin{cases} 0 & t < 0 \\ \dfrac{jB}{\mu}\left(1 - \exp\left[-t\mu / nm\right]\right) & t > 0 \end{cases}$$

- As the damping μ is reduced, the flow rises more slowly, but to a higher value.
- Full problem involves two momentum equations on a flux surface→2 time scales & 2 directions.

Flow Analysis Method

- Convert flow magnitude and angle into flow in two directions:

$$U_{1,\exp}(t) = X_2(t)\cos(X_3(t))$$
$$U_{2,\exp}(t) = X_2(t)\sin(X_3(t))$$

- Predicted form of flow rise from modeling:

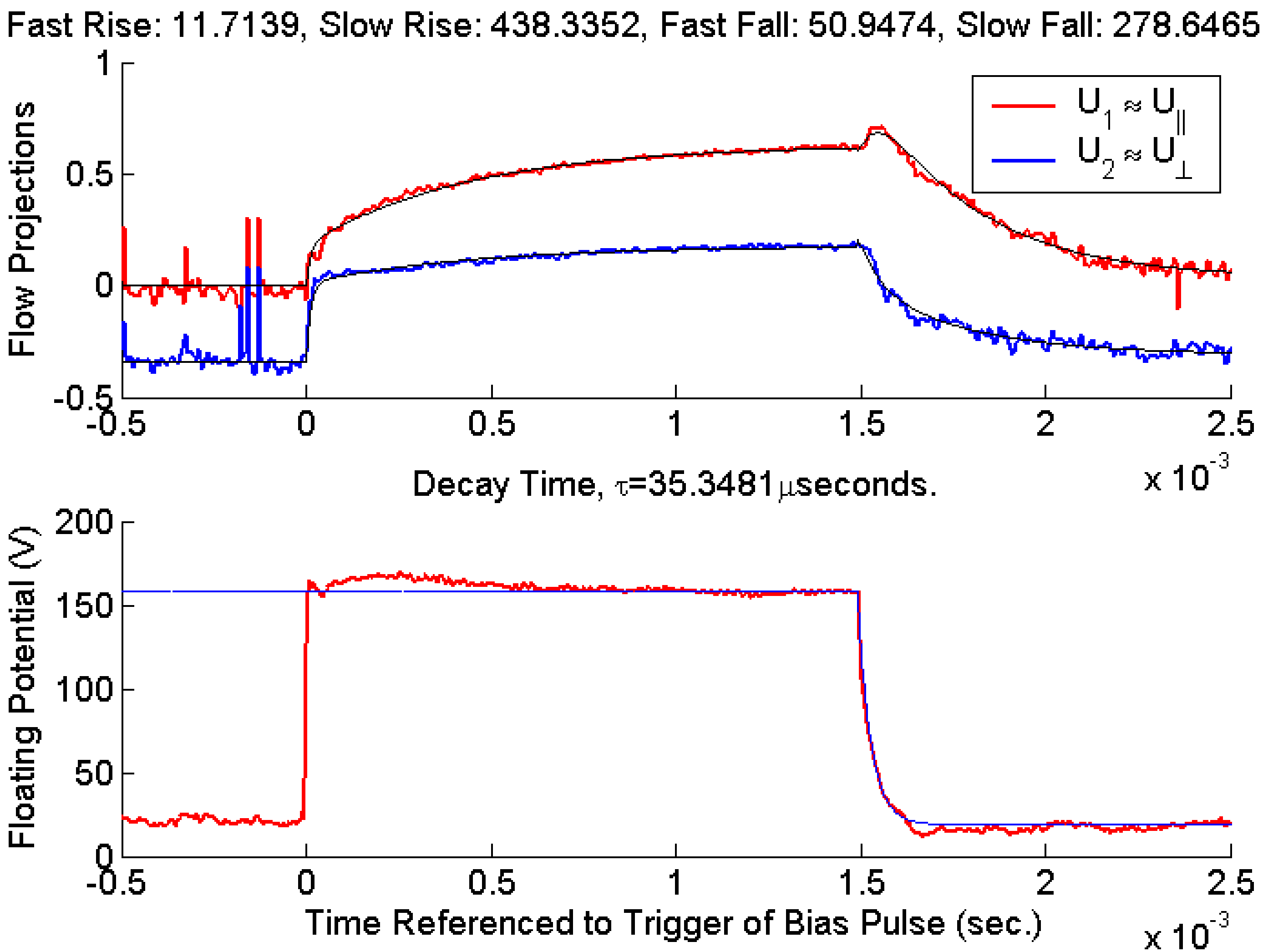
$$U(t) = C_f\left(1-\exp\left(-t/\tau_f\right)\right)\hat{f} + C_s\left(1-\exp\left(-t/\tau_s\right)\right)\hat{s}$$

- Fit flows to models

$$U_{1,fit}(t) = C_f\left(1-\exp\left(-t/\tau_f\right)\right)\cos(\alpha_f) + C_s\left(1-\exp\left(-t/\tau_s\right)\right)\cos(\alpha_s) + U_{1SS}$$
$$U_{2,fit}(t) = C_f\left(1-\exp\left(-t/\tau_f\right)\right)\sin(\alpha_f) + C_s\left(1-\exp\left(-t/\tau_s\right)\right)\sin(\alpha_s) + U_{2SS}$$

- Similar model 2 time scale / 2 direction fit is used to fit the flow decay.

Two Time Scale Model Fits Flow Rise Well



Similar time scales measured by LFS and HFS probes

Neoclassical Modeling

Solve the Momentum Equations on a Flux Surface

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

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

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

- Solve these with Ampere's Law

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

- Use Hamada coordinates, using linear neoclassical viscosities.
- No perpendicular viscosity included.

Formulation #1: The External Radial Current is Quickly Turned On.

- After solving the coupled ODEs, the contravariant components of the flow are given by:

$$U^{\alpha} = \left(1 - e^{-t/\tau_1}\right) S_1 + \left(1 - e^{-t/\tau_2}\right) S_2$$

$$U^{\zeta} = \left(1 - e^{-t/\tau_1}\right) S_3 + \left(1 - e^{-t/\tau_2}\right) S_4$$

- $S_1 \ldots S_4$, τ_1 (slow rate), and τ_2 (fast rate) are flux surface quantities related to the geometry.
- Break the flow into parts damped on each time scale:

$$\vec{U} = \left(1 - e^{-t/\tau_1}\right)\left(S_1 \vec{e}_{\alpha} + S_3 \vec{e}_{\zeta}\right) + \left(1 - e^{-t/\tau_2}\right)\left(S_2 \vec{e}_{\alpha} + S_4 \vec{e}_{\zeta}\right)$$

- This allows the calculation of the radial electric field evolution:

$$\frac{d\Phi}{d\psi}(t) = \frac{d\Phi}{d\psi}(t=0) + F_1\left(1 - e^{-t/\tau_1}\right) + F_2\left(1 - e^{-t/\tau_2}\right)$$

Formulation #2: The Electric Field is Quickly Turned On.

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

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

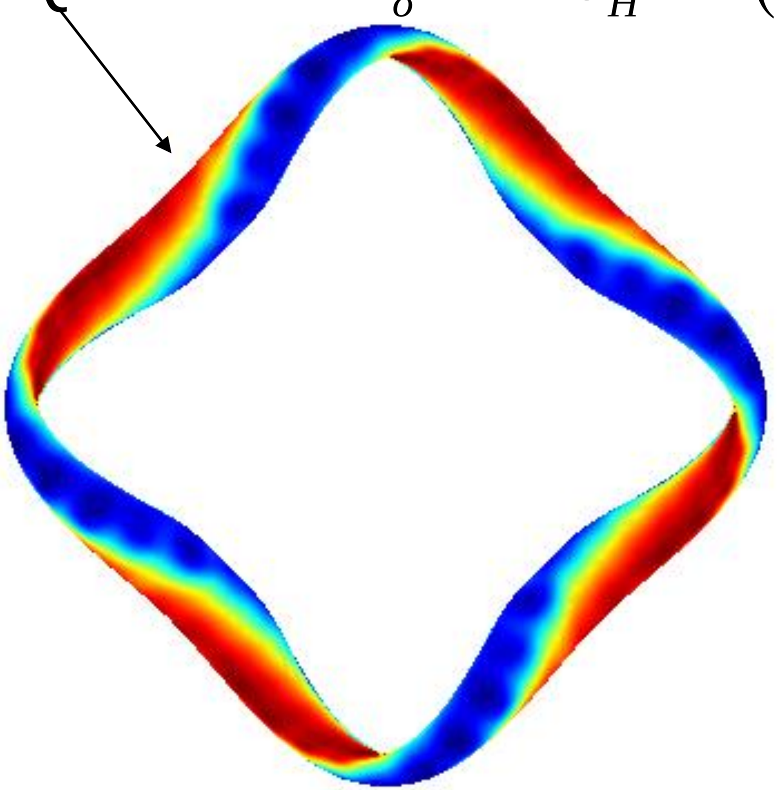
- ExB flows and compensating Pfirsch-Schlueter flow will grow on the same time scale as the electric field.
- Parallel flow grows with a time constant τ_F determined by viscosity and ion-neutral friction.

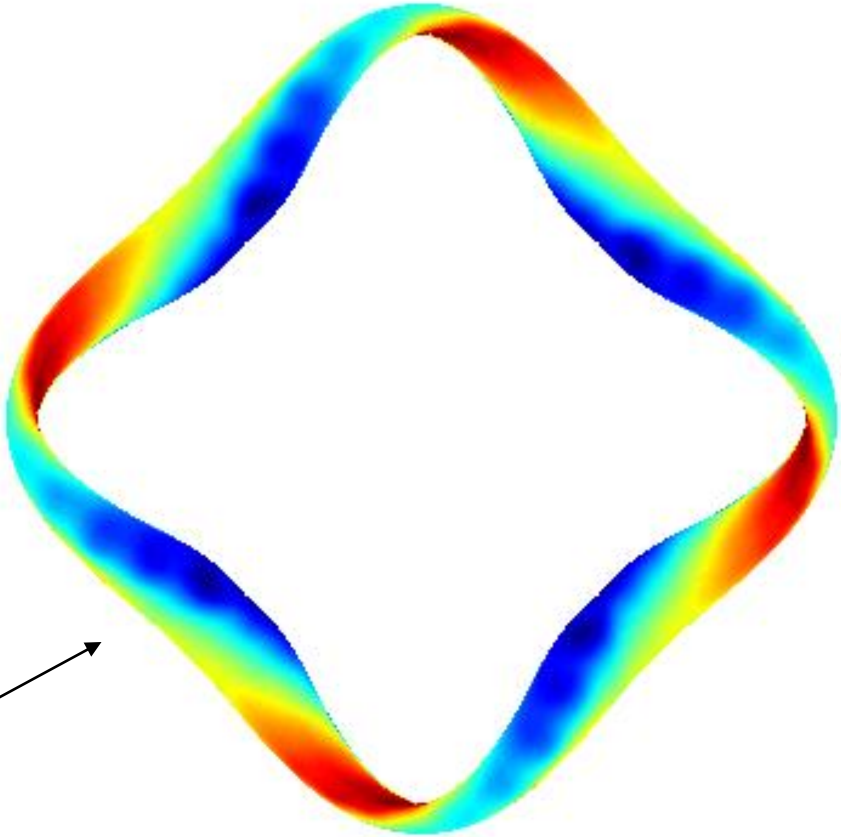
$$\vec{U}(t) = U_E^{\alpha}\left(1 - e^{-t/\tau}\right)\vec{e}_{\alpha} + \vec{B} Q_1 \kappa_E \left(1 - \left(1 + Q_2\right) e^{-\upsilon_F t} + Q_2 e^{-t/\tau}\right)$$

- Two time scales/two direction flow evolution.

Symmetry Can be Intentionally Broken with Trim Coils

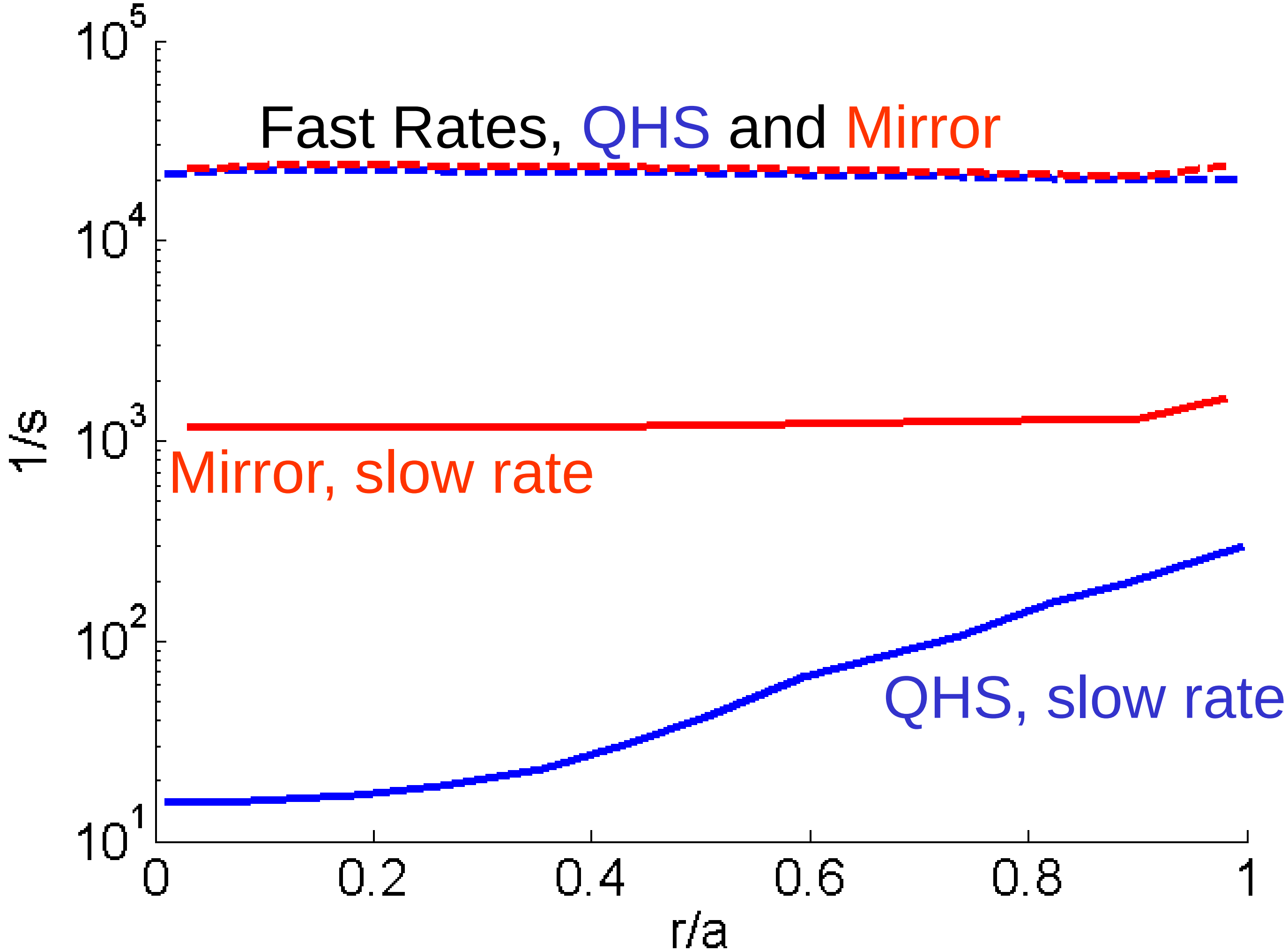
QHS: $B/B_o \approx 1+\varepsilon_H \cos(4\phi-\theta)$



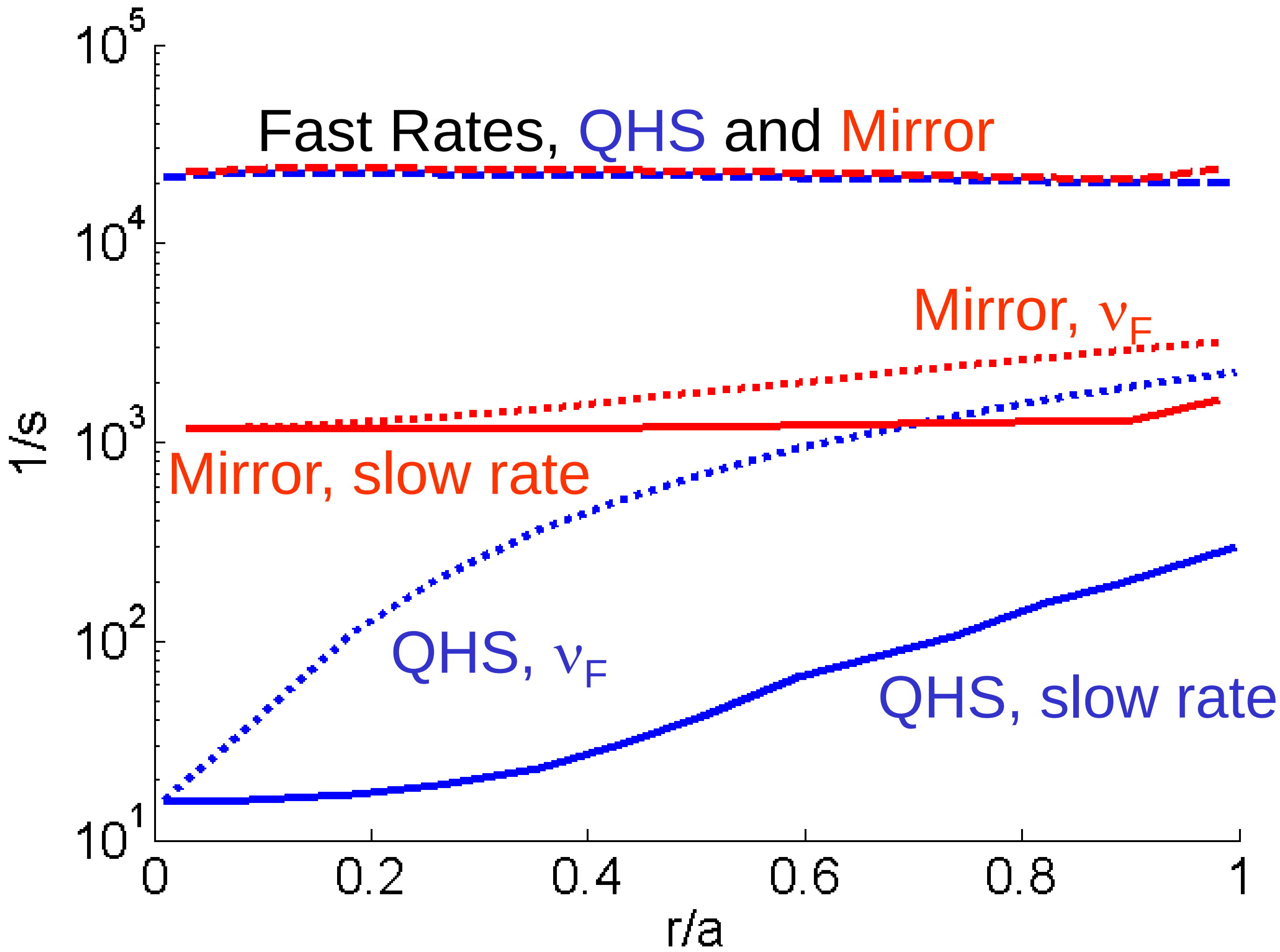


Mirror: $B/B_o \approx 1+\varepsilon_H \cos(4\phi-\theta)+\varepsilon_M \cos(4\phi)$

Modeling Shows Reduced Viscous Damping in the QHS Configuration



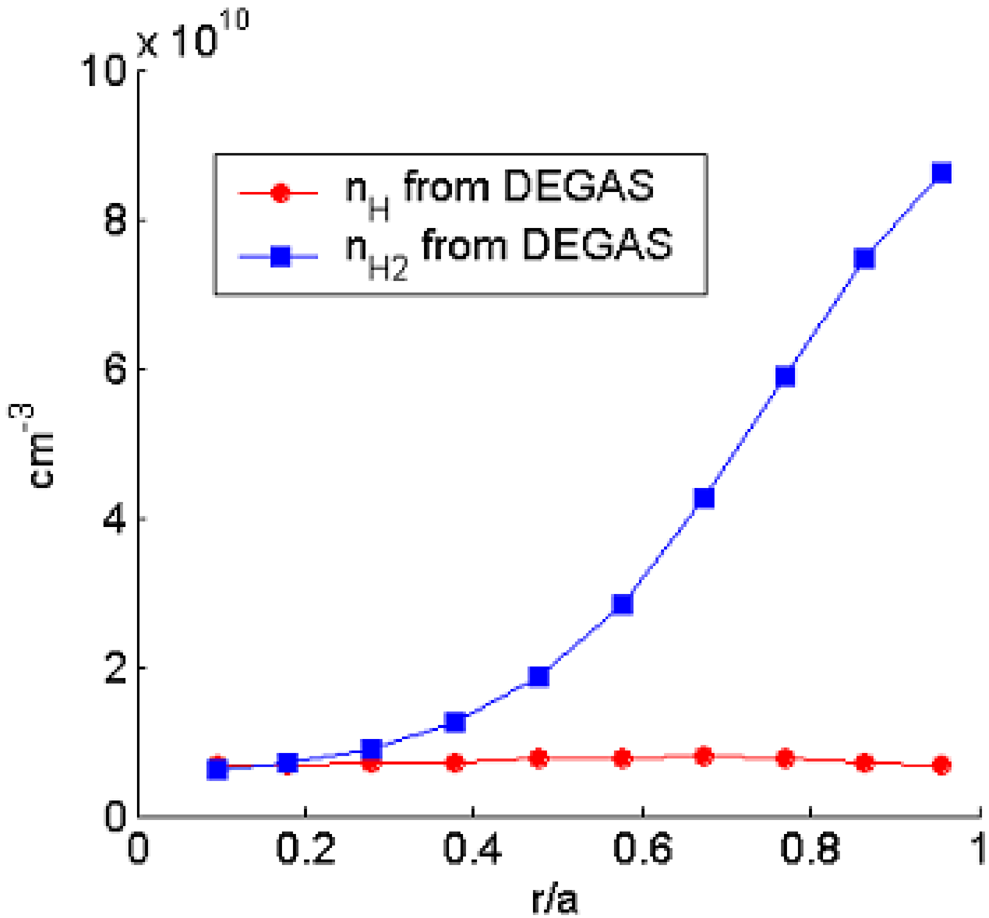
"Forced E_r" Plasma Response Rate is Between the Slow and Fast Rates.



Neutral Density Profiles Computed with DEGAS Code

- DEGAS simulation of unbiased discharge, puff only.

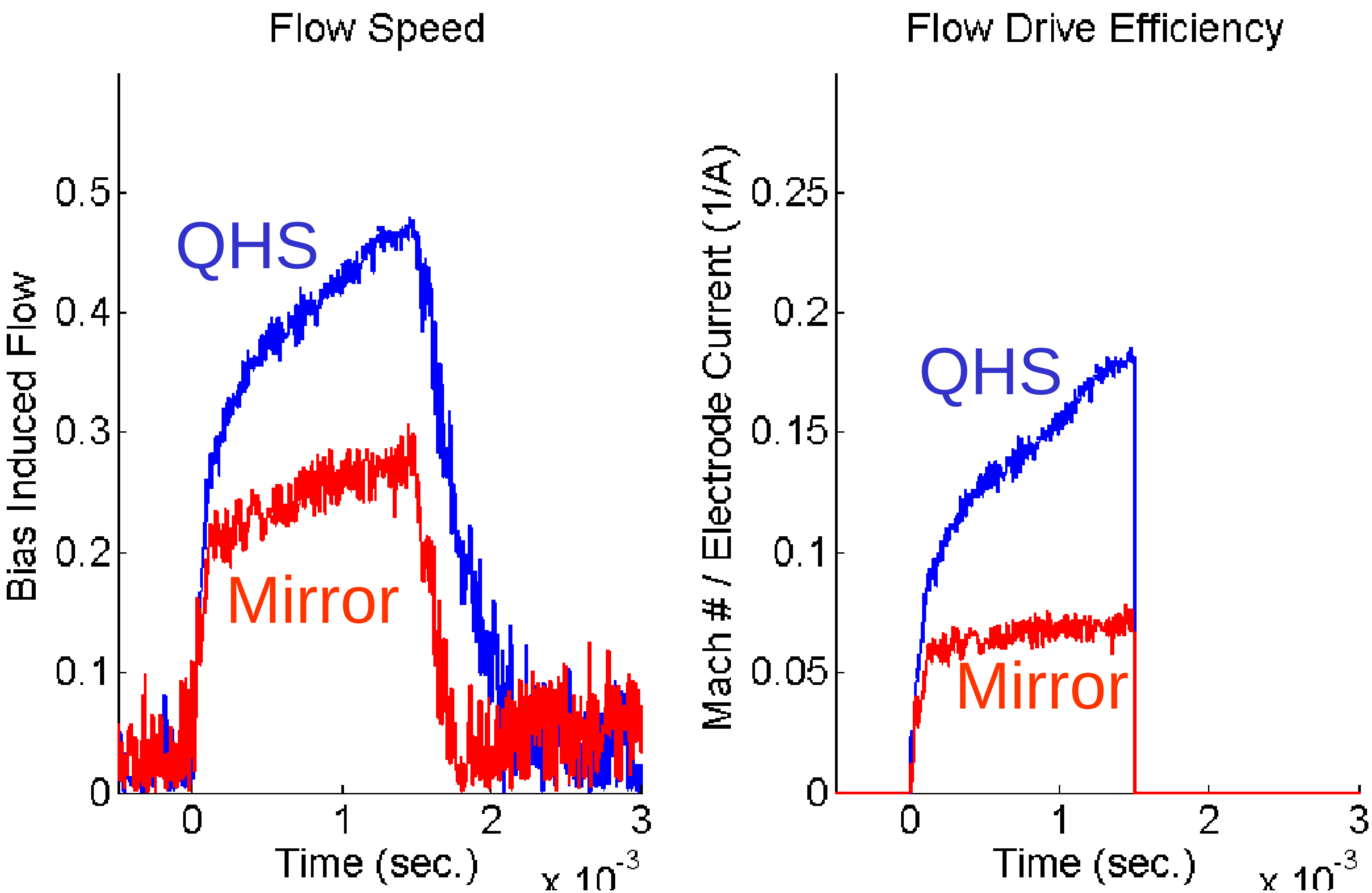
- Wall and electrode recycling not included $\Rightarrow$ Double these profiles for calculating ion-neutral damping.



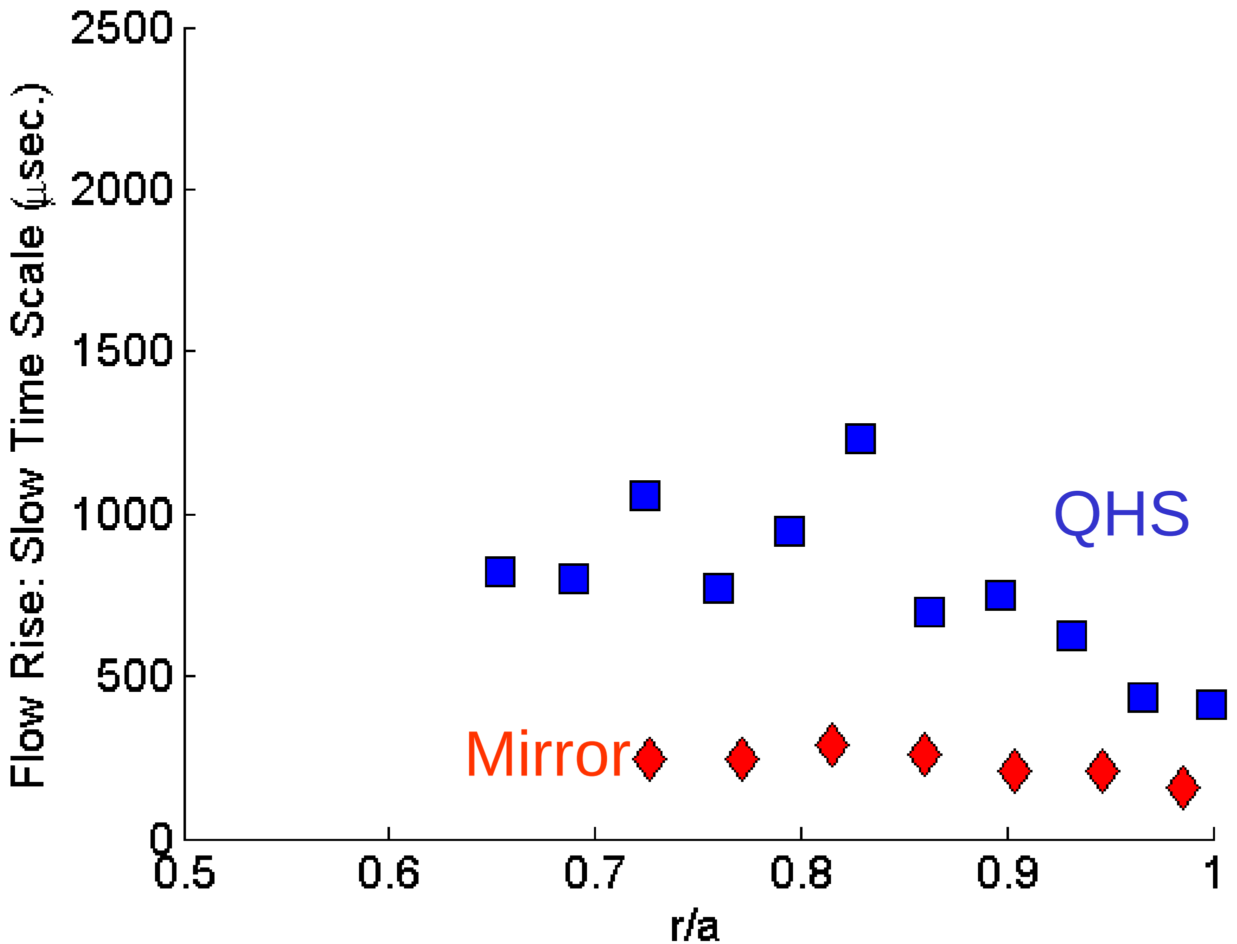
- See poster by J. Canik this afternoon for more details.

Comparison Between the QHS and Mirror Configurations

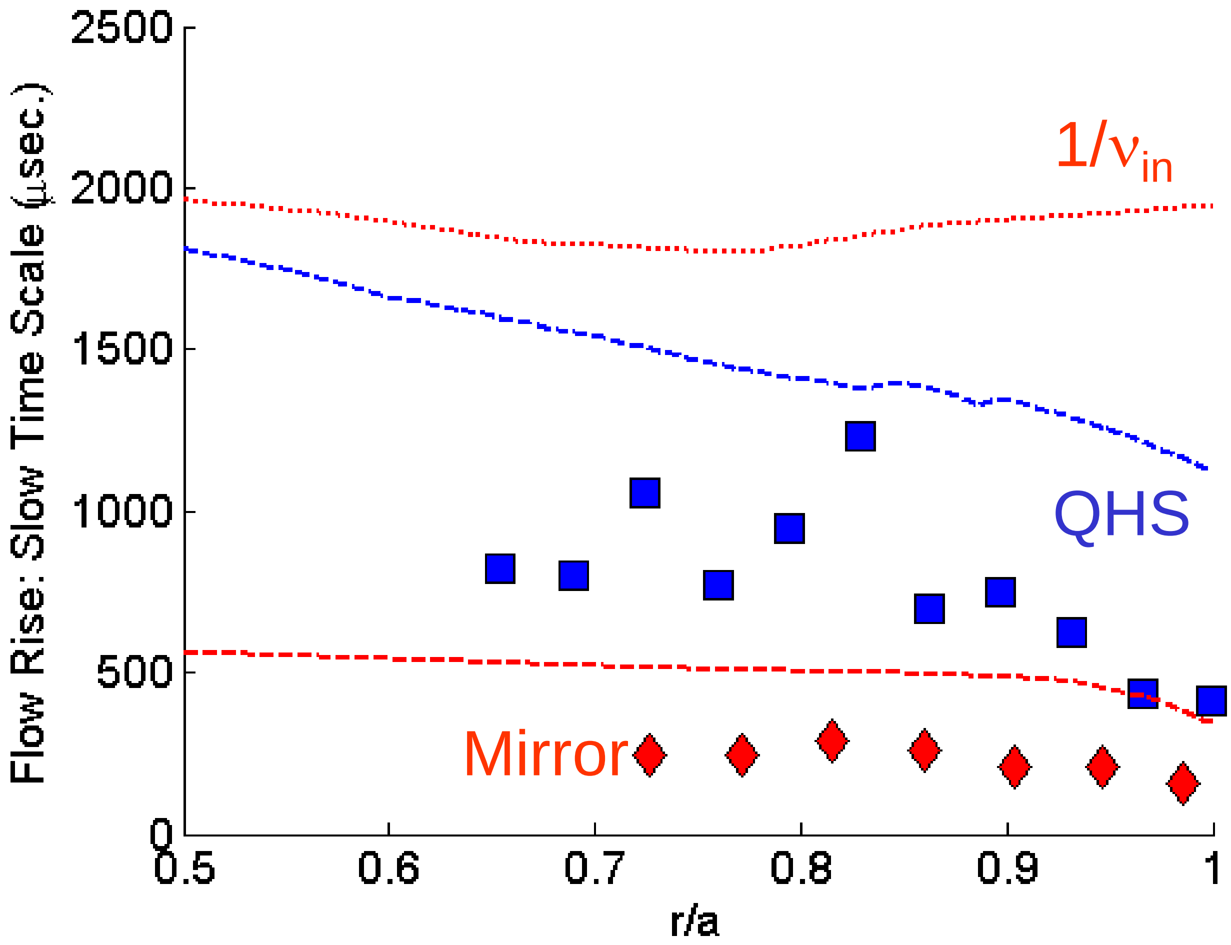
QHS Flow Damps Slower, Goes Faster For Less Drive.



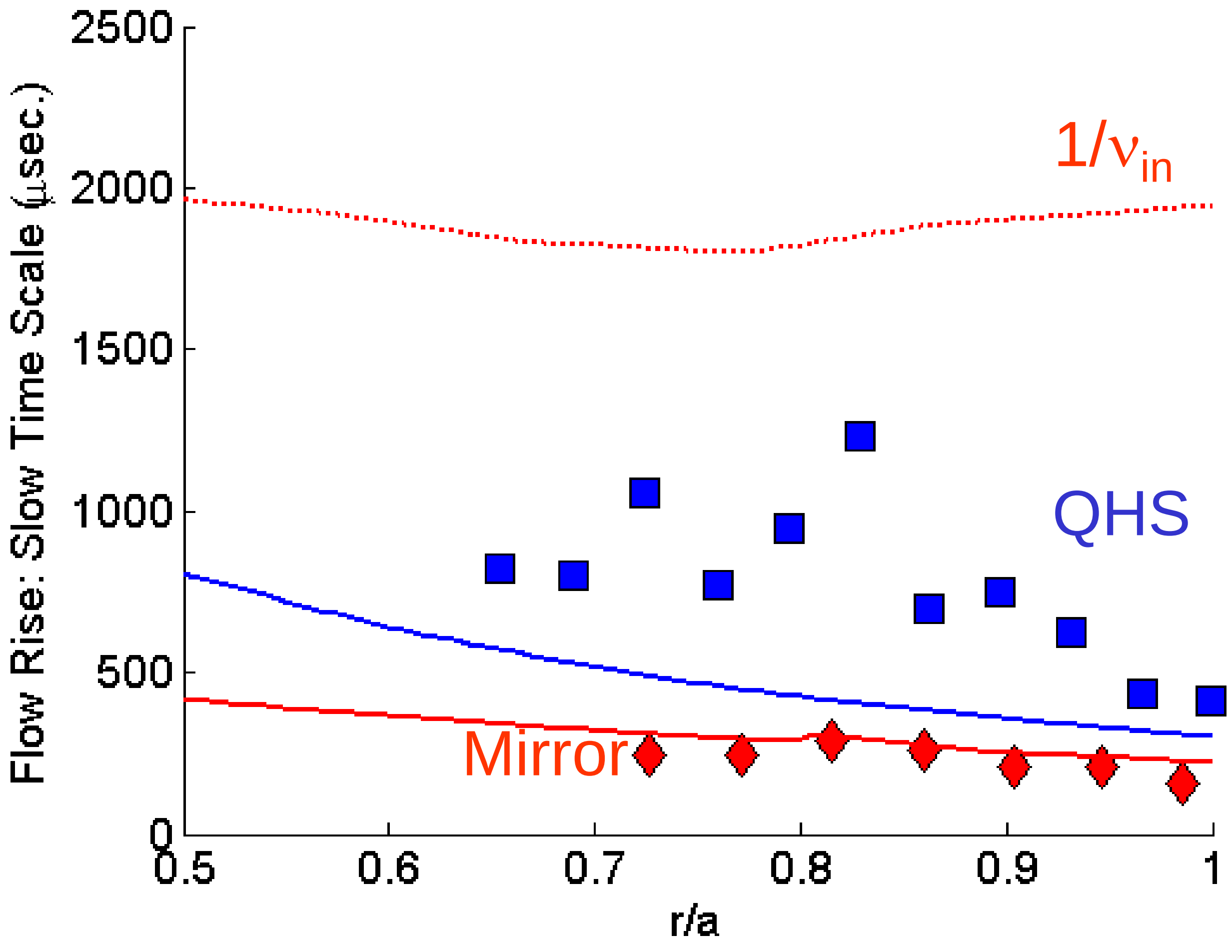
QHS Damps more Slowly Across the Entire Minor Radius



The Coronado and Talmadge Model Overestimates the Rise Times By 2



The "Forced E_r" model Underestimates the QHS time

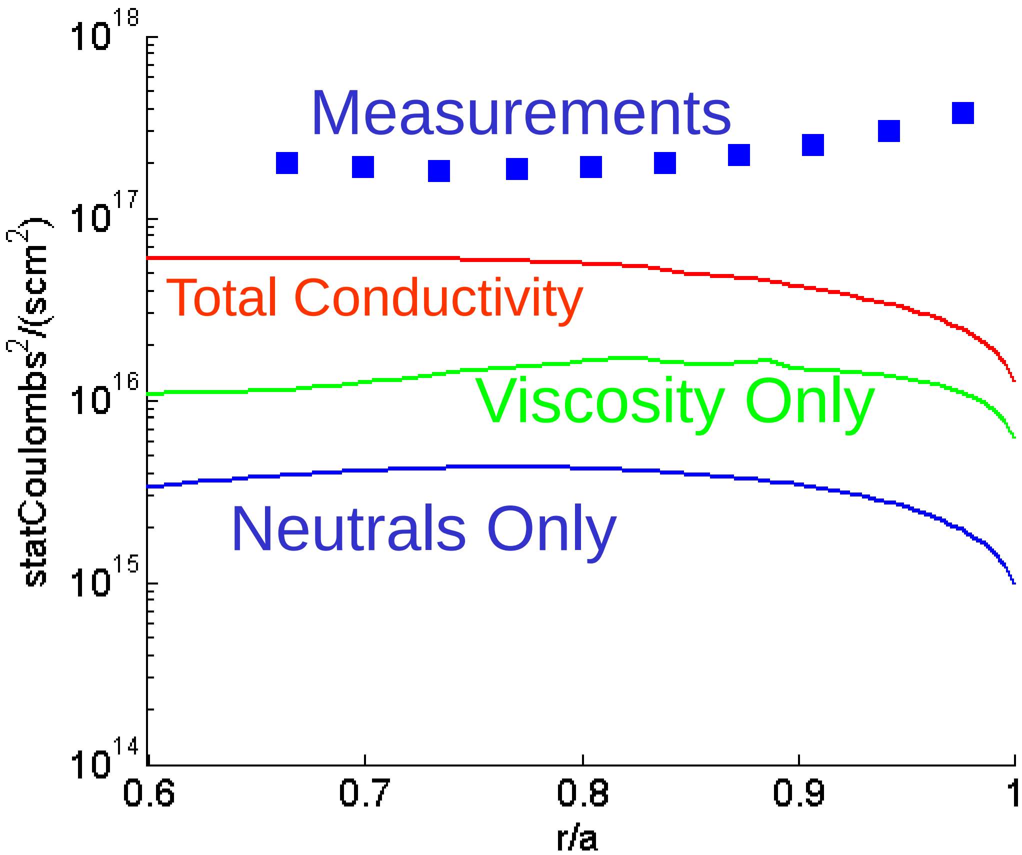


QHS Modeled Radial Conductivity agrees to a Factor of ≈3-4

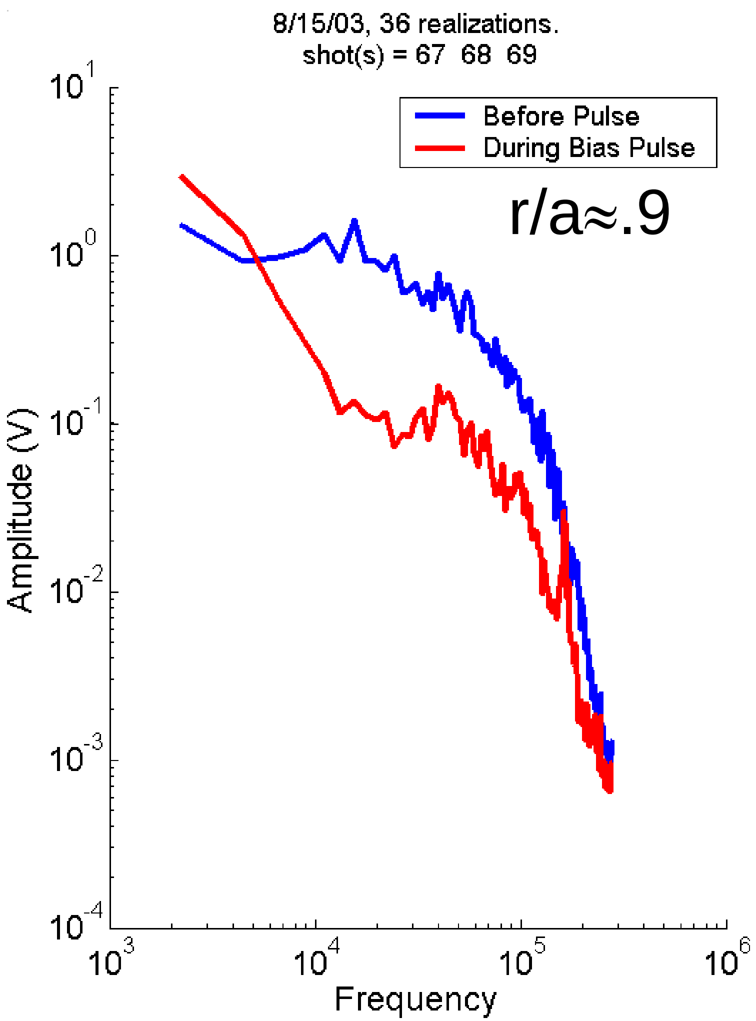
- Define the radial conductivity as

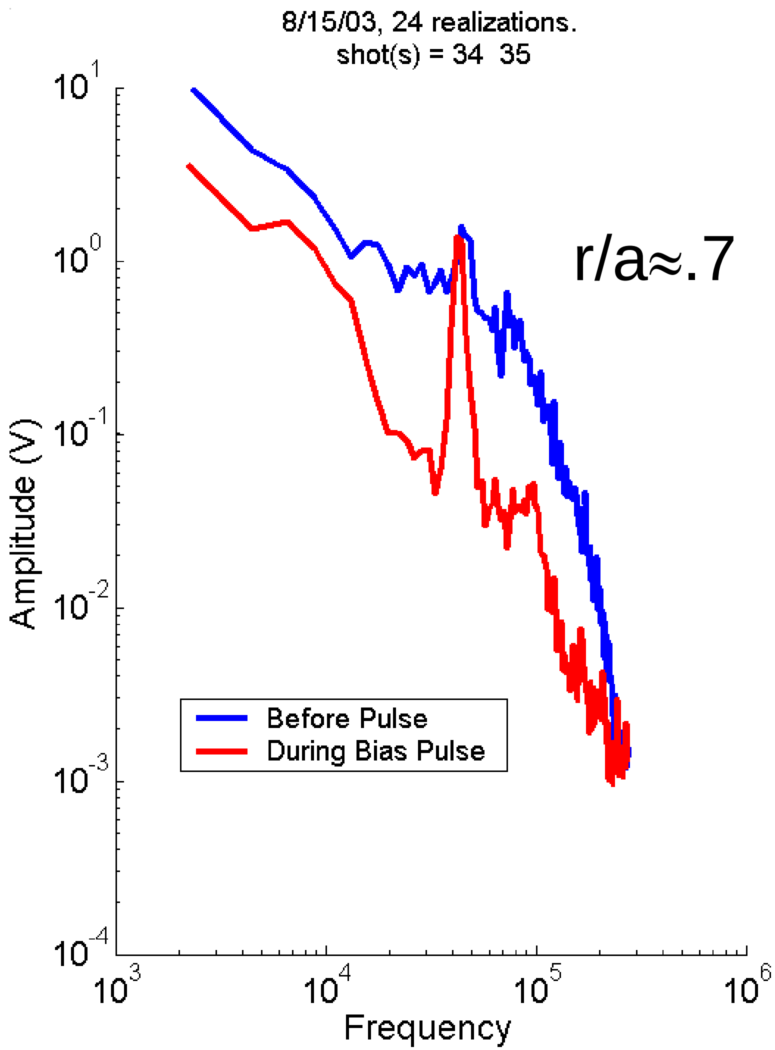
$$R = \frac{\left\langle \vec{J} \cdot \vec{\nabla} \psi \right\rangle}{d\Phi / d\psi}$$

- Combination of neutral friction and viscosity determines radial conductivity.
- Mirror agreement is somewhat better.



V_f Turbulence Reduction with Bias





- 50 kHz mode remains unsuppressed by bias.
- Electrostatic transport measurements soon.

Conclusions

- We have observed 2 time scale flow damping in HSX.
- The QHS damping rate is lower than the Mirror.
- The damping rates are consistent with neoclassical theory, though the radial conductivity appears to be too high.
- Significant reduction in V_f turbulence with bias.