Characteristics of Biased Electrode Discharges in HSX

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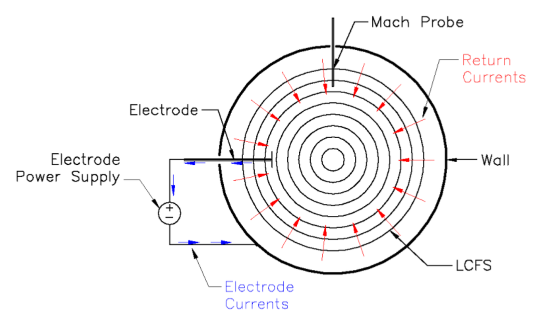
1. Structure of the Experiments

General Structure of Experiments



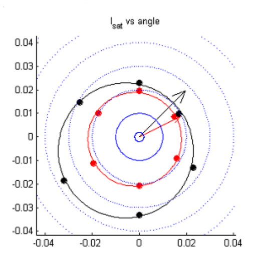
Mach Probes in HSX

- 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.

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

- Probe measures V_f with a proud pin.

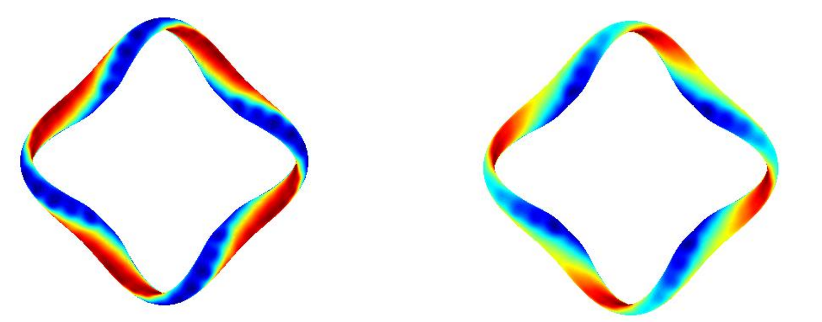
Looking ⊥ To The Magnetic Surface



Symmetry Can be Intentionally Broken with Trim Coils

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

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

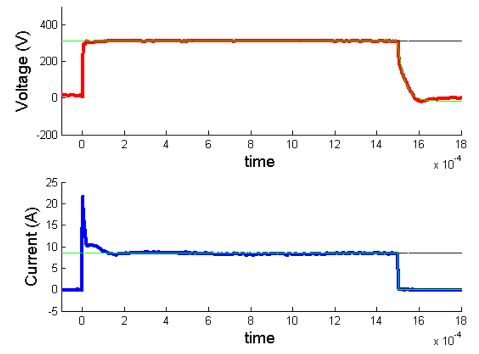


2. The Biased Plasma as a Capacitor

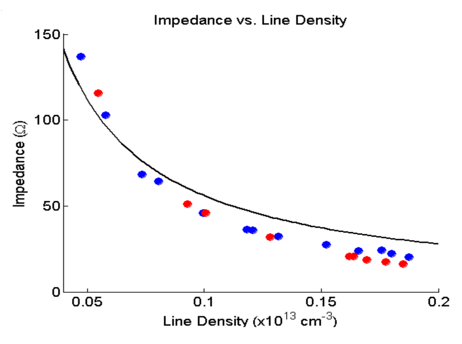
Bias Waveforms Indicate a "Capacitance" and an Impedance

Decay Time:
$\tau=33\times10^{-6}$ seconds
Impedance: $R=V/I=36\ \Omega$
$C=\tau/R=8.9\times10^{-7}$F

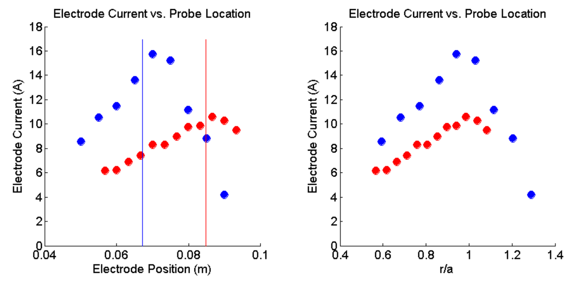
Acumulated Charge from "Charging Current":
Q=2.33 Coulombs
Voltage: V=310 Volts
$C=Q/V=7.5\times10^{-7}$F



- Impedance∝1/n consistent with radial conductivity scaling like n.
- Consistent with both neoclassical modeling by Coronado and Talmadge or anomalous modeling by,for instance, Rozhansky and Tendler.

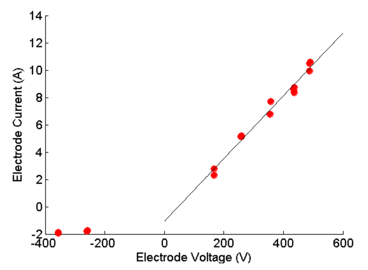


Impedance in Smaller in the Mirror Configuration



- Current peaks at the calculated separatrix.
- Electrode Current Profile does not follow the density profile⇒Electrode is not simply drawing electron saturation current.

- Linear I-V relationship
- Consistent with linear viscosity assumption.
- Very little current drawn when collection ions ⇒ collect electrons in all experiments in this poster.



3. Two Time Scales Observed in Flow 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 $U=\begin{cases}0 & t<0\\ \frac{jB}{\mu}(1-\exp[-t\mu/nm]) & t>0\end{cases}$
- 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:

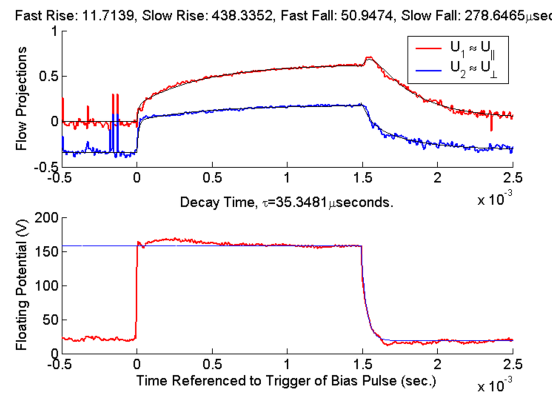
$$U(t)=C_1(1-\exp(-t/\tau_1))\hat{f}+C_2(1-\exp(-t/\tau_2))\hat{s}$$

- Fit flows to models

$$U_{2,fit}(t)=C_1(1-\exp(-t/\tau_1))\sin(\alpha_1)+C_2(1-\exp(-t/\tau_2))\sin(\alpha_2)+U_{2ss}$$
$$U_{1,fit}(t)=C_1(1-\exp(-t/\tau_1))\cos(\alpha_1)+C_2(1-\exp(-t/\tau_2))\cos(\alpha_2)+U_{1ss}$$

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

Model Fits Flow Rise Well



4. Neoclassical Modeling of Plasma Flows

Solve the Momentum Equations on a Flux Surface

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

$$m_iN_i\frac{\partial}{\partial t}\langle B_p\cdot U\rangle=-\frac{c}{\sqrt{g}B_\zeta B_\alpha}\langle J\cdot\nabla\psi\rangle-\langle B_p\cdot\nabla\cdot\Pi\rangle-m_iN_i\nu_{in}\langle B_p\cdot U\rangle$$
$$m_iN_i\frac{\partial}{\partial t}\langle B\cdot U\rangle=-\langle B\cdot\nabla\cdot\Pi\rangle-m_iN_i\nu_{in}\langle B\cdot U\rangle$$

- Solve these with Ampere's Law

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

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

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

- Original calculation by Coronado and Talmadge
- 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

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

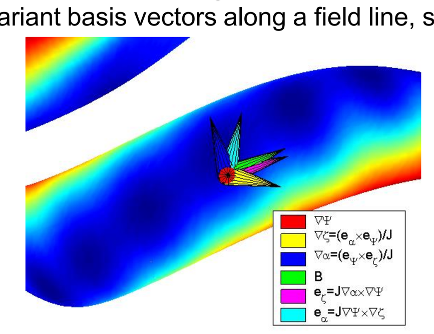
- ExB flows and compensating Pfirsch-Schlueter flow will grow on the same time scale as the electric field.
- Parallel flow grows with a time constant τ_F determined by viscosity and ion-neutral friction.

$$\vec{U}(t)=U_E^\alpha\left(1-e^{-t/\tau}\right)\vec{e}_\alpha+\vec{B}Q_1\kappa_E\left(1-(1+Q_2)e^{-\upsilon_F t}+Q_2e^{-t/\tau}\right)$$

- Two time scales/two direction flow evolution.

We Have Developed a Method to Calculate the Hamada Basis Vectors

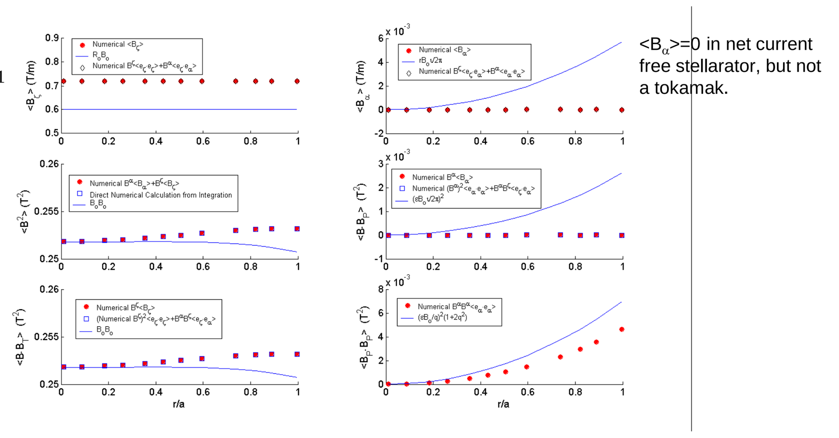
- Need quantities like $\langle e_\alpha\cdot e_\zeta\rangle$, $\langle e_\alpha\cdot e_\zeta\rangle$, $\langle e_\alpha\cdot e_\zeta\rangle$, $\langle|\nabla\psi|\rangle$, $\langle|\nabla\psi\cdot\nabla\psi|\rangle$.
- Previous calculation used large aspect ratio tokamak approximations.
- Method involves calculating the lab frame components of the contravariant basis vectors along a field line, similar to Nemov.



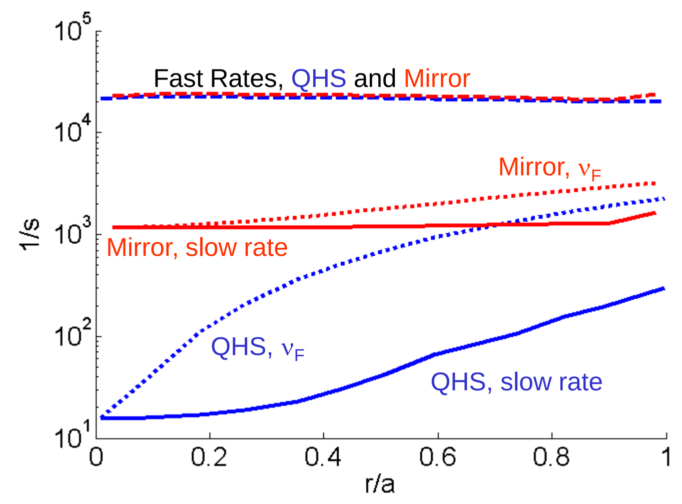
Tokamak Basis Vectors Can Differ from those in Net Current Free Stellarator.

$\langle B_\zeta\rangle$= Boozer g= $2*1e^{-7}*48*14*5361$ =.7205

$\langle B_\zeta\rangle$=0 in net current free stellarator, but not a tokamak.

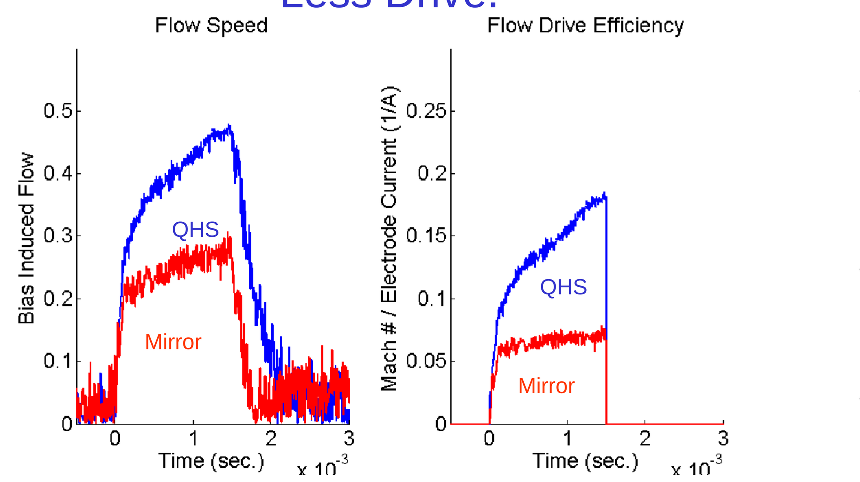


"Forced E_r" Plasma Response Rate is Between the Slow and Fast Rates.



5. Comparisons Between QHS and Mirror Configurations of HSX

QHS Flow Damps Slower, Goes Faster For Less Drive.

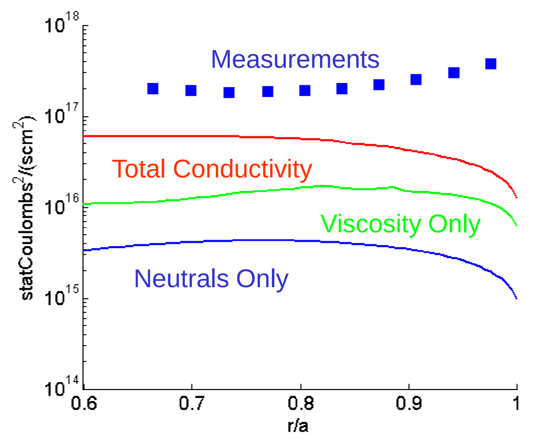


QHS Modeled Radial Conductivity agrees to a Factor of ≈3-4

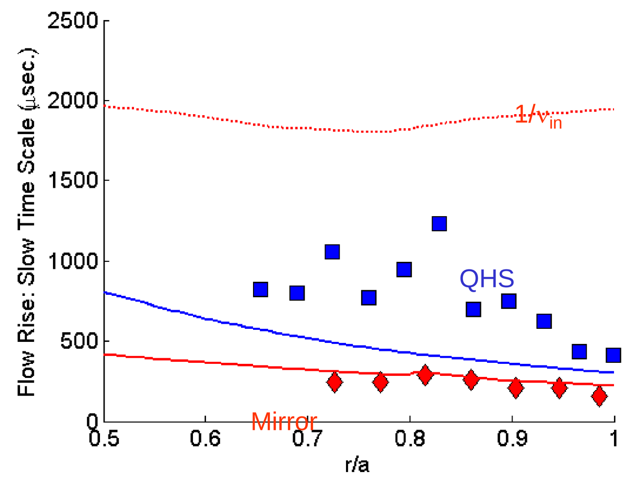
- Define the radial conductivity as

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

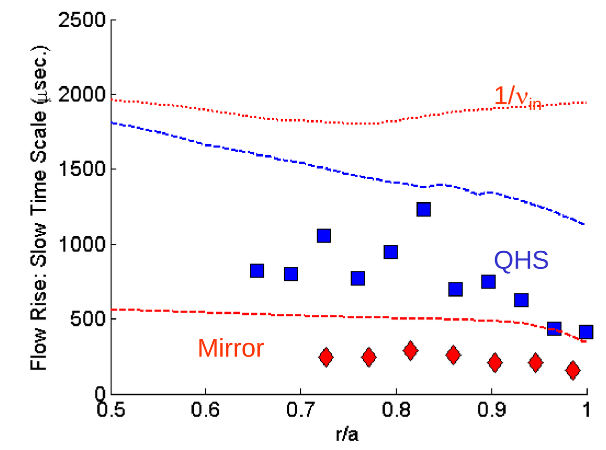
- Combination of neutral friction and viscosity determines radial conductivity.
- Mirror agreement is somewhat better.



The "Forced E_r" model Underestimates the QHS time

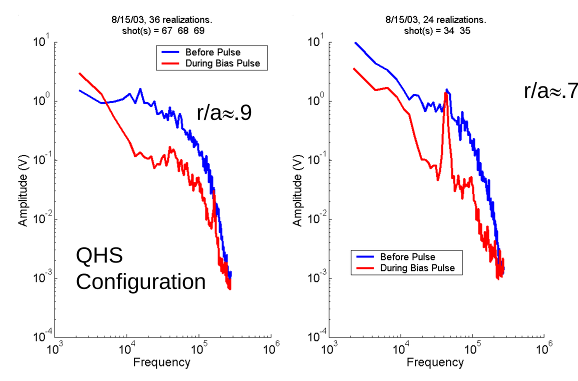


The Coronado and Talmadge Model Overestimates the Rise Times By 2



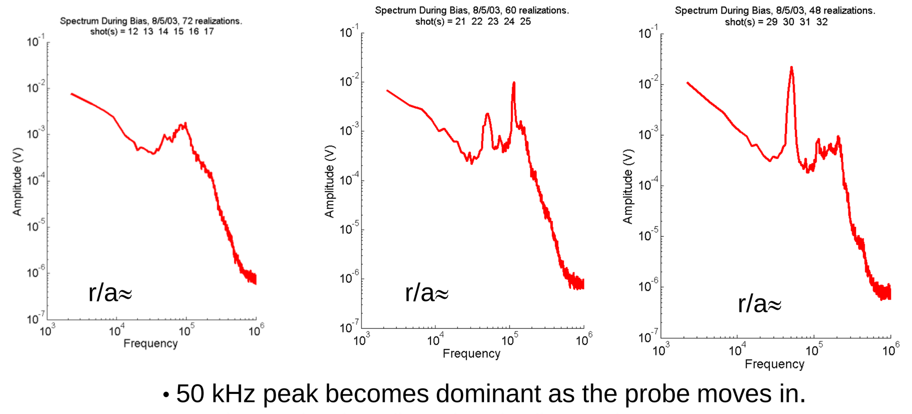
6. Observations of and Reductions in Turbulence With Electrode Bias.

V_f Fluctuation Reduction with Bias



- 50 kHz mode remains unsuppressed by bias. See Poster by C. Deng
- Electrostatic transport measurements soon. See Poster by W. Guttenfelder

Distinct Spectral Peaks in the Electrode Current



- 50 kHz peak becomes dominant as the probe moves in.
- Do these simply reflect density fluctuations?

7. Computational Study: Viscous Damping in Different Configurations of HSX