Measurements and Modeling of Biased Electrode Discharges in HSX

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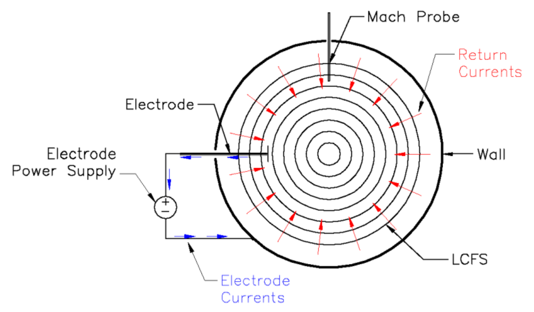
Key Points

- •IV Characteristics of the Biased Electrode.
- •Evidence of Two Time Scale Damping in HSX.
- •Neoclassical Modeling of Plasma Flows.
- •Experimental Verification of Reduced Viscous Damping with Quasi-Symmetry
- •Computational Study of Different Configurations

1. Structure of the Experiments

General Structure of Experiments



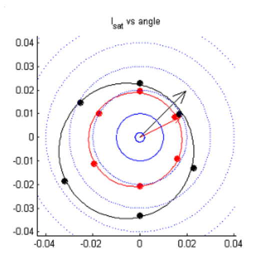
Mach Probes in HSX

- 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.

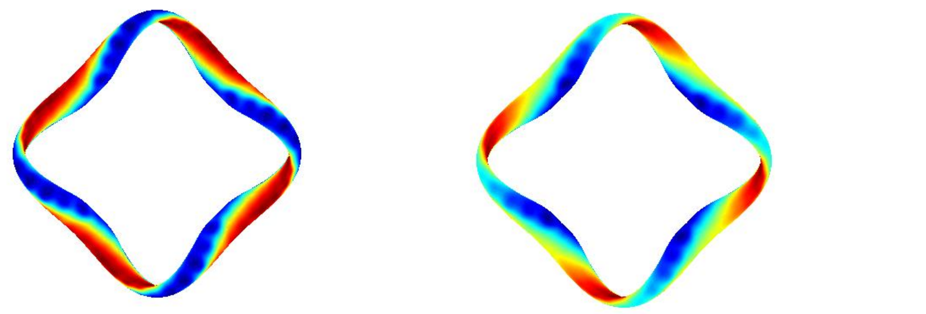
Looking ⊥ To The Magnetic Surface



Symmetry Can be Intentionally Broken with Auxiliary Coils

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

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



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

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

- 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

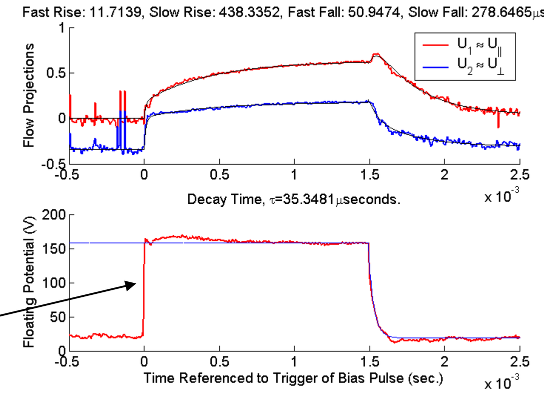
- Convert flow magnitude and angle into flow in two directions:

$U_{Long}(t)=X_2(t)\cos(X_3(t))$

$U_{\perp}(t)=X_2(t)\sin(X_3(t))$

- Predicted form of flow rise from modeling:
- Fit flows to models
- Similar model 2 time scale / 2 direction fit is used to fit the flow decay.

Model Fits Flow Rise Well



Note: Floating Potential Rises Much Faster Than the Flows.

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.
- Solve these with Ampere's Law
- 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:

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

- 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

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

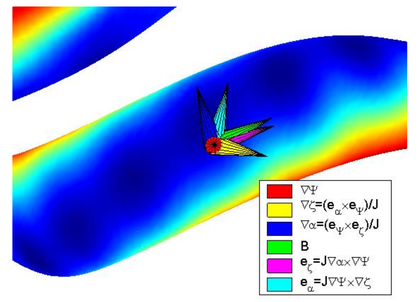
- ExB flows and compensating Pfirsch-Schlueter flow will grow on the same time scale as the electric field.
- Parallel flow grows with a time constant τ_F determined by viscosity and ion-neutral friction.

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

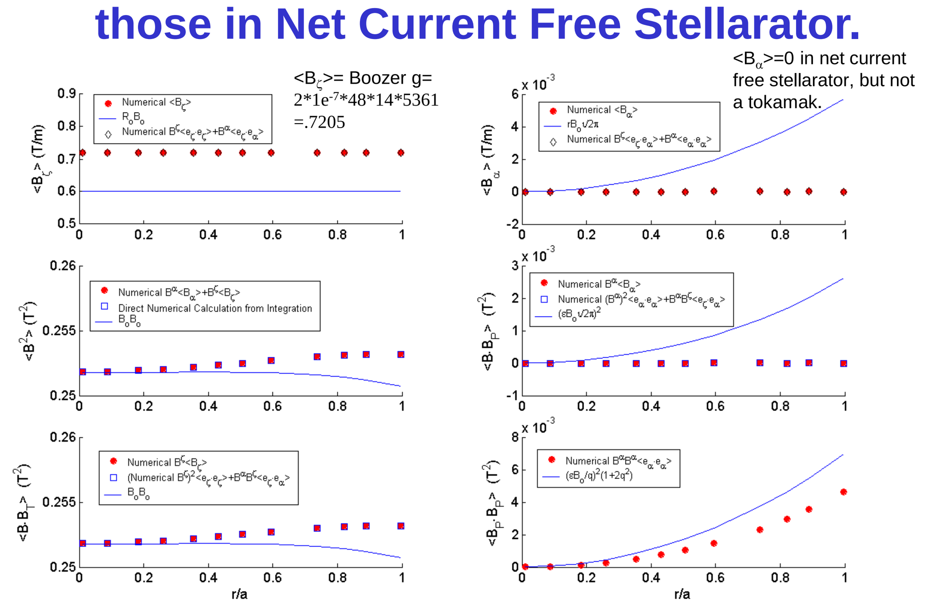
- Two time scales/two direction flow evolution.

We Have Developed a Method to Calculate the Hamada Basis Vectors

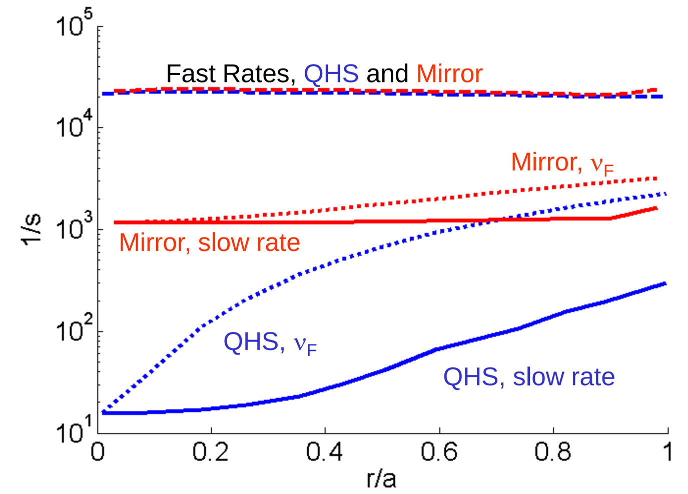
- Need quantities like $\langle e_{\alpha}\cdot e_{\zeta}\rangle$, $\langle e_{\alpha}\cdot e_{\zeta}\rangle$, $\langle e_{\alpha}\cdot e_{\zeta}\rangle$, $\langle|\nabla\psi|\rangle$, $\langle|\nabla\psi\cdot\nabla\psi|\rangle$.
- Previous calculation used large aspect ratio tokamak approximations.
- 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.



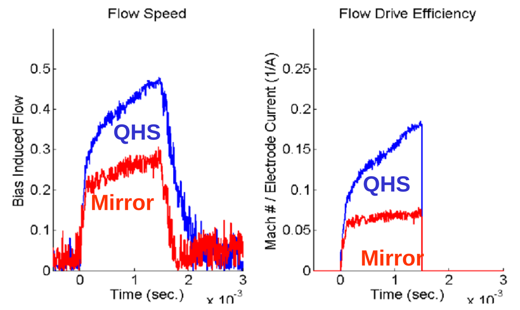
"Forced E_r" Plasma Response Rate is Between the Slow and Fast Rates.



5. Comparisons Between QHS and Mirror Configurations of HSX and with Modeling

QHS Flow Damps Slower, Goes Faster For Less Drive.

- •QHS Flow Rises and Damps More Slowly
- •Flow Goes Faster For Per Unit Drive

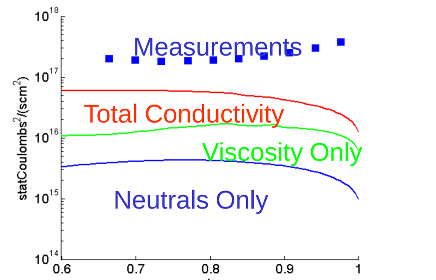


QHS Modeled Radial Conductivity agrees to a Factor of ≈3-4

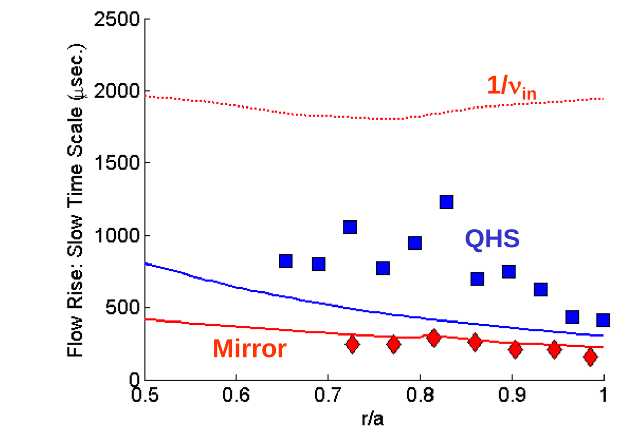
- Define the radial conductivity as

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

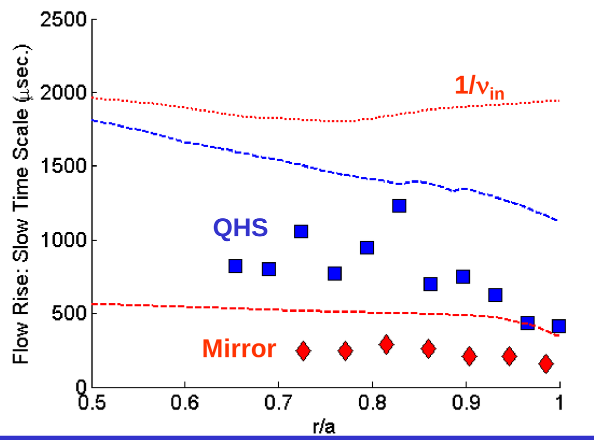
- Combination of neutral friction and viscosity determines radial conductivity.
- Mirror agreement is somewhat better.



The "Forced E_r" Model Underestimates the QHS time

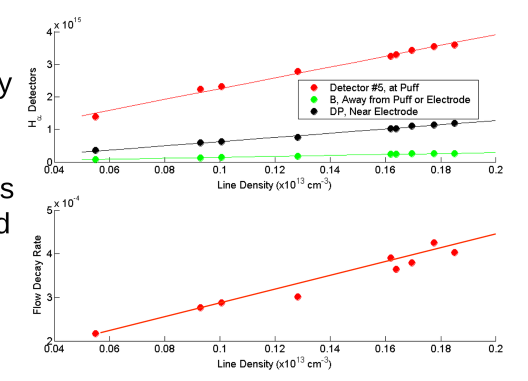


Coronado and Talmadge Model Overestimates the Rise Times



QHS Damping Does Not Appear to Scale with the Neutrals

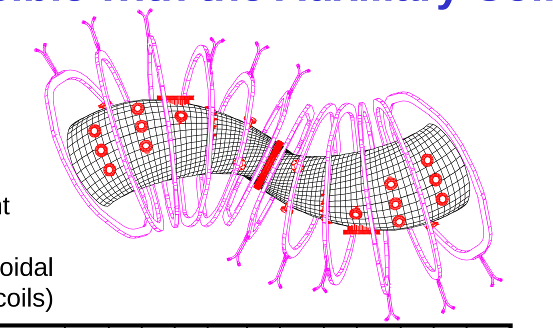
- H_α signal is linear in the density⇒neutral density approximately constant.
- See Poster by J. Canik for more details on the H_α system and interpretation.
- Flow decay time becomes longer as density increases.



QHS Damps Less Than Mirror; Some Physics Besides Neoclassical and Neutral Damping Appears to be Necessary to Explain the QHS Data.

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

Many Different Configurations are Accessible with the Auxiliary Coils

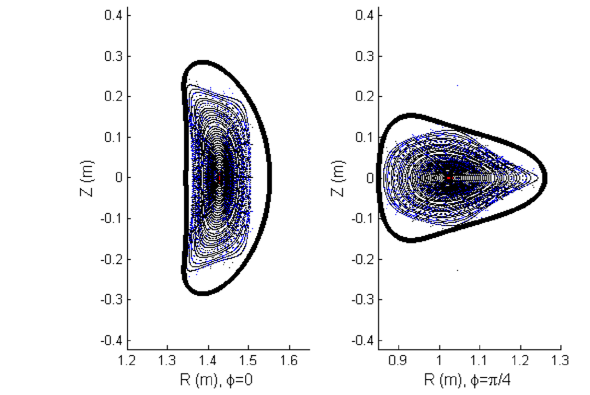


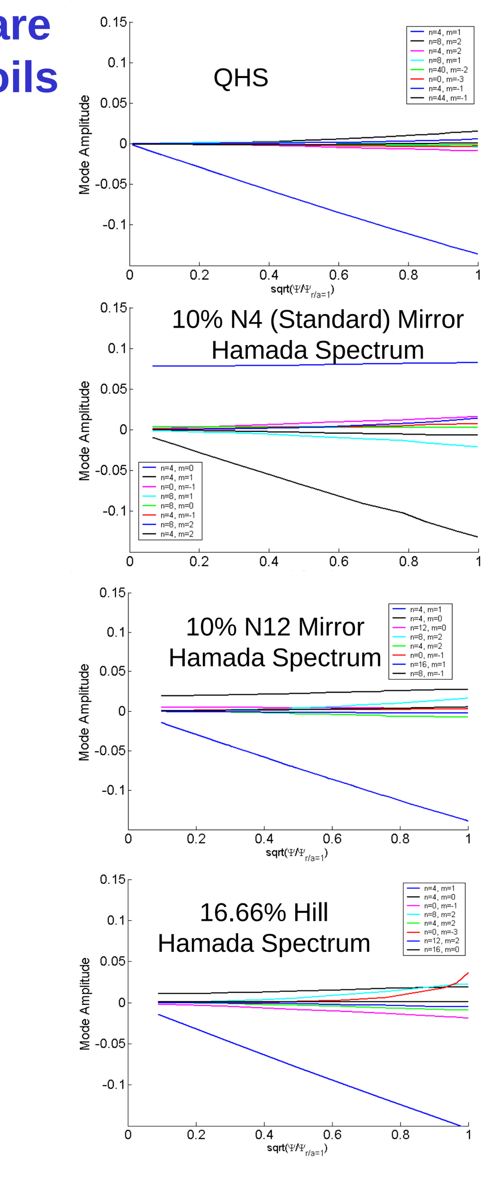
Aux. Coil Current Direction (+ for adding to the toroidal field of the main coils)

N4 Mirror (Standard)	+	+	+	-	-	-	-	-	-	-	+	+	+	+
N12 Mirror	+	-	-	+	+	-	-	+	+	-	-	+		
Broad N Mirror	+	-	+	-	+	-	+	-	+	-	+	-	+	
Hill	+	+	+	+	+	+	+	+	+	+	+	+	+	+

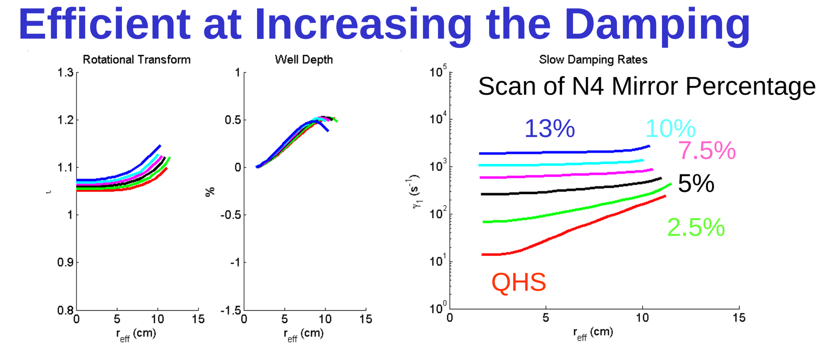
Percentage indicates the ratio of amp-turns in the two coil sets.

Large Change in Surface Shape for Deep Hill Configuration

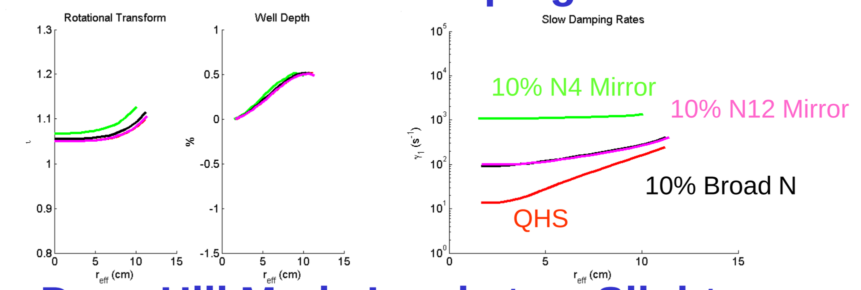




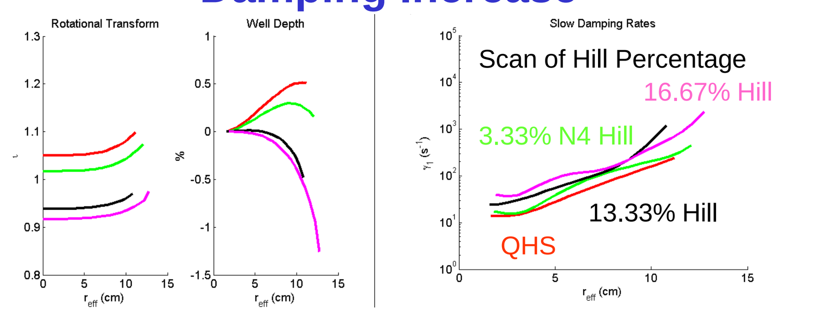
Increasing the N4 Mirror Percentage is Efficient at Increasing the Damping



Other Mirror Configurations Result in Less Damping



Deep Hill Mode Leads to a Slight Damping Increase

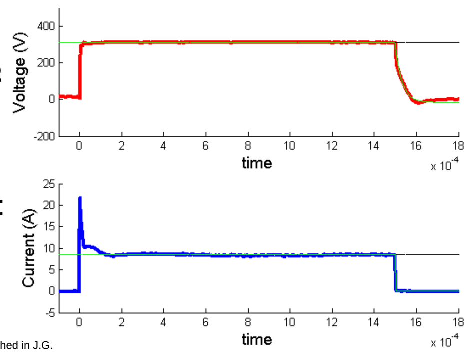


2. I-V Characteristics of Electrode Indicate Transport Limits the Current

Bias Waveforms Indicate a "Capacitance" and an Impedance

Decay Time: τ=33x10^{-6} seconds
Impedance: R=V/I=36 Ω
C= τ /R=8.9x10^{-7}F

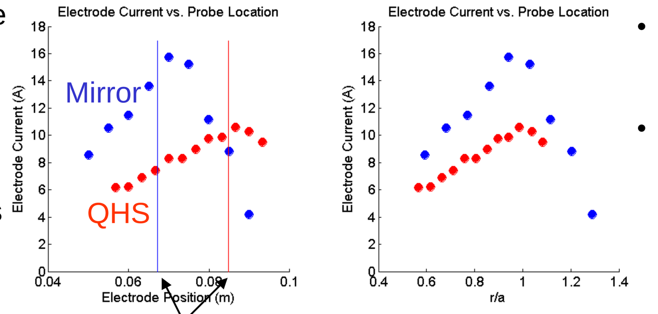
Accumulated Charge from "Charging Current": Q=2.33 Coulombs
Voltage: V=310 Volts
C=Q/V=7.5x10^{-7}F



Original Formulation of Capacitance/Impedance modeling published in J.G. Gorman, L.H. Rietjens, Phys. Fluids 9, 2504 (1966)

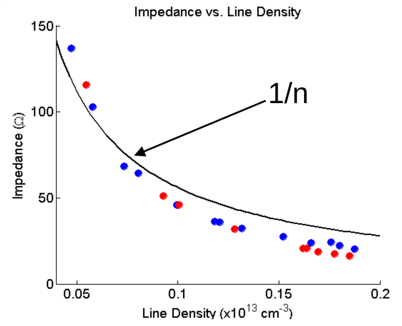
Impedance is Smaller in the Mirror Configuration

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



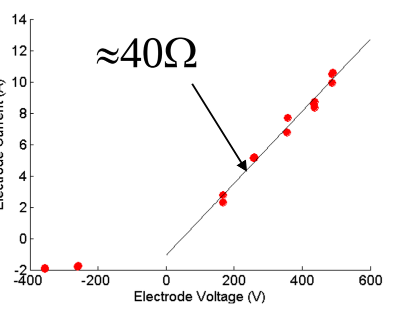
Radial Conductivity Has a 1/n Scaling

- 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.



Positive Part of I-V Curve is Linear

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



Capacitance is Linear in the Density

- •Plasma dielectric constant proportional to density.
- •Low frequency dielectric constant:
- •Expected capacitance: