Measurements and Modeling of Plasma Flow Damping in the HSX Stellarator

Outline

- 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

$B = 0.5T$
$P_{ECH} < 200 \text{ kW} @ 28 \text{ GHz}$
$R \approx 1.3 \text{ m}$

HSX is located at the University of Wisconsin-Madison
HSX Provides Access to Configurations With and Without Symmetry

QHS Configuration

Mirror Configuration

QHS: Helical Bands of Constant $|B|$

Mirror: Helical Bands are Broken

Red $\rightarrow |B| > 0.5$ T

Blue $\rightarrow |B| < 0.5$ T
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$_{\alpha}$ 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

All other parameters ($n_e=1\times10^{12}\text{ cm}^{-3}$, $n_n \approx 1\times10^{10}\text{ cm}^{-3}$, $T_i \approx 25\text{ eV}$, $B=0.5\text{ T}$, $P_{ECH}=50\text{ kW}$) 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

\[
\frac{m_i N_i}{\partial t} \langle B_p \cdot U \rangle = -\frac{\sqrt{gB^z B^a}}{c} \langle J_{\text{plasma}} \cdot \nabla \psi \rangle - \langle B_p \cdot \nabla \cdot \Pi \rangle - m_i N_i \langle \nu_{in} B_p \cdot U \rangle
\]

\[
\frac{m_i N_i}{\partial t} \langle B \cdot U \rangle = -\langle B \cdot \nabla \cdot \Pi \rangle - m_i N_i \langle \nu_{in} B \cdot U \rangle
\]

- Use Hamada coordinates, linear neoclassical viscosities, neglect heat fluxes

- Steady state solution yields radial conductivity

\[
\langle J_{\text{plasma}} \cdot \nabla \psi \rangle = \sigma_\perp \left( \langle E_r \cdot \nabla \psi \rangle - \frac{\langle \nabla p_i \cdot \nabla \psi \rangle}{eN_i} \right)
\]
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

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

- $\textbf{E} \times \textbf{B}$ flows and compensating Pfirsch-Schlueter flow grow on the electric field time-scale

- Parallel flow grows at a “Hybrid rate” $\nu_F$ determined by viscosity and ion-neutral friction

- Two time-scales/two direction flow evolution

\[
U(t) \approx U_E^\alpha \left(1 - e^{-t/\tau}\right) \textbf{e}_\alpha + U_\parallel \left(1 - e^{-\nu_F t}\right)
\]
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:

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

- Large neutral density \( (n_n=1\times10^{12} \text{ cm}^{-3}) \) 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, $\nu_F$

is faster than Slow Rate

![Graph showing damping rates for QHS, Fast Rate, QHS, $\nu_F$, and QHS, Slow Rate as functions of $r_{\text{eff}}$ (cm).]
Mirror Shows Increased Neoclassical Damping Compared to QHS

QHS/Mirror Comparison

Fast rates are comparable

Mirror $\nu_F$ is larger by a factor of 2-3

Mirror slow rate is larger by 1-2 orders of magnitude

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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

\[
\langle \vec{J}_{\text{plasma}} \cdot \vec{\nabla} \psi \rangle = \sigma_\perp \left( \langle \vec{E}_r \cdot \vec{\nabla} \psi \rangle - \frac{\langle \vec{\nabla} p_i \cdot \vec{\nabla} \psi \rangle}{eN_i} \right)
\]
Modeling Predicts the Difference in the QHS and Mirror Slow Rise Rates

- Mirror flows rise more quickly than QHS.

- Neoclassical hybrid time $\nu_F$ shows good agreement with the measurements.
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.

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

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$_\alpha$ 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 ~10-20\( \mu \)s

\[
I_{\text{sat}}(\theta) = A \exp\left(\frac{M}{2}\right) [0.64(1 - \cos(\theta - \theta_F)) + 0.7(1 + \cos(\theta - \theta_F))]
\]

- Probe measures \( V_f \) with a proud pin.

Looking \( \perp \) To The Magnetic Surface
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.
  
  \[ B^\psi = \vec{B} \cdot \vec{\nabla} \psi = 0 \quad \text{Radial Basis Vector} \]

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

  \[ B^\alpha = \vec{B} \cdot \vec{\nabla} \alpha = \frac{t}{2\pi \sqrt{g}} \quad \text{Poloidal Basis Vector} \]

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

\[ J_\parallel = h \frac{\partial p}{\partial \psi} B \quad \text{Method by Nemov}^1, \; h \text{ is numerically calculated} \]

\[ J_\parallel = -\frac{B_\alpha}{B^2 B^\zeta \sqrt{g}} \frac{\partial p}{\partial \psi} B \quad \text{Method by Coronado and Wobig}^2, \; B_\alpha \text{ is the desired quantity} \]

1) V.V. Nemov, Nuclear Fusion 30, 927 (1990), 2) M. Coronado and H. Wobig Phys Fluids B 4, 1294 (1992)

FEC 2004
Floating Potential is a Flux Surface Quantity

Toward Magnetic Axis

Low Field Side

High Field Side

Before Bias

During Bias

LCFS

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Electrode Characteristics at Turn Off
Fit the Decay Model

Electrode Current
Turns off in ~1 µs

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.

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.

\[
\nu_{in} \rightarrow \nu_{eff} \approx 3.6 \text{kHz}
\]

\[
\frac{a^2}{4\tau} \approx \frac{3600(0.11^2)}{4} \approx 10 \text{ m}^2/\text{s}
\]
Steady State Flow Direction Differs Somewhat from Neoclassical Prediction

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

This sort of comparison is only possible if the basis vectors are known:

\[ U = U^\alpha e_\alpha + U^\zeta e_\zeta \]
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.

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