Measurement and Modeling of an Electron ITB in HSX

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Special thanks to: Walter Guttenfelder (PPPL), Don Spong (ORNL), HSX Team
Overview

• Motivation: Quasisymmetric (QS) stellarators have transport properties which lie between 2D and 3D limits
  – Small radial neoclassical transport (similar to a tokamak)
  – Reduced flow damping in the symmetry direction
  – Need models that capture these physics
  – What is the impact on the fluxes, flows, currents, and $E_r$ in HSX?

• Neoclassical transport calculations for HSX
  – Including momentum conservation (MC) modifies parallel transport
  – Better agreement with measured flows, currents when MC included
  – Ambipolar $E_r$ calculations result in very large fields and strong radial shear

• Experimental electron thermal transport
  – $T_e$ profiles strongly centrally peaked in QHS
  – Peaking is caused by turbulence quenching via $E_r$ shear
HSX is Quasi-Helically Symmetric

- QHS: helical direction of symmetry in \(|B|\)
- Effective transform is larger than physical transform
  - Algebraically modifies transport and equilibrium quantities relative to a tokamak

**Tokamak:** \( \frac{B}{B_0} \approx 1 - \epsilon_t \cos t\phi \)

**QHS:** \( \frac{B}{B_0} \approx 1 - \epsilon_h \cos (n - mt)\phi \)

\( v_{\text{eff}} \sim 3 \)

**HSX Parameters**

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<table>
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<tbody>
<tr>
<td>(&lt;R&gt;)</td>
<td>1.2 m</td>
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<tr>
<td>(&lt;a&gt;)</td>
<td>0.12 m</td>
</tr>
<tr>
<td>(t)</td>
<td>1.05 → 1.12</td>
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<tr>
<td>(B_0)</td>
<td>0.5 - 1.0 T</td>
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<tr>
<td>ECRH 28 GHz</td>
<td>&lt;100 kW</td>
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Motivation for Neoclassical Transport Calculations

- The neoclassical transport coefficients relate the fluxes, flows, and currents to the gradients ($\nabla T$, $\nabla n$, $\nabla \Phi$)
  - From ambipolarity the particle fluxes give $E_r$

- Why should we care about neoclassical transport?
  - Gives irreducible minimum level of radial transport
  - Bootstrap current typically shows good agreement in tokamaks and stellarators
  - $E_r$ agrees well with NC predictions in stellarators
  - $E_r$ can reduce transport, drive transport barriers
    - Sheared flow can suppress turbulent transport
  - LHD results suggest that anomalous transport is lowered when NC lowered (possibly due to decreased zonal flow damping)
Kinetic Neoclassical Calculations

- The NC transport coefficients are calculated by the DKES\textsuperscript{1} code.
- DKES solves the linearized drift kinetic equation (DKE) via a variational method using a pitch angle scattering (PAS) collision operator
  - Kinetic view: Lose interspecies collisions, collisional momentum conservation
  - Fluid view: Lose frictional coupling, implies parallel flows are small or momentum balance violated
- Advantages
  - Allows DKE of each species to be decoupled
  - Conserves speed $v$, reducing dimensionality of problem
  - Leads to fast computation for arbitrary $B$, collisionality, $E_r$
- Disadvantages
  - Parallel flows assumed small, momentum not conserved
  - Intrinsic ambipolarity in (quasi)symmetric limit not recovered
  - Justified in conventional stellarator with strong flow damping

Kinetic + Fluid Approach: Use Fluid Moments to “Correct” Kinetic Coefficients

• The NC transport coefficients can also be calculated using a fluid moment approach\textsuperscript{1}
  – Analytic expressions exist for tokamaks, simplified stellarator fields
• Methods have been developed for general stellarator fields\textsuperscript{2}
  – Momentum conservation is enforced through parallel momentum balance
  – Use coefficients calculated from kinetic methods to define viscosities
• Act as “correction” to kinetic approach (DKES)
  – Calculate parallel flow from parallel momentum balance
  – Add flux driven by parallel flow to radial transport expressions
• These methods have been implemented in the PENTA code
• Want to understand how important this correction is in HSX

2) Taguchi (1992), Sugama and Nishimura (2003, 2008), Maalberg, Beidler, Turkin (2009)
Development of the PENTA Code

• Originally developed by Don Spong (ORNL)
  – Electron-ion only, two terms retained in expansions

• Has been extended to include
  – Multiple ion species of arbitrary mass, charge, temperature (impurity transport)
  – Arbitrary expansion order (improves accuracy, allows for convergence checks)
  – All three existing moment-method momentum correction techniques

• Intrinsic ambipolarity reproduced analytically and numerically in symmetric limit

• In principle, this method can be applied to the full range of configurations:

  tokamaks → rippled tokamaks → quasi-symmetric → conventional stellarators

  Increasing effective ripple

*RFX modeling recently begun.
Determining the Radial Electric Field in a Stellarator

• Fluxes in a stellarator are not intrinsically ambipolar; $E_r$ is determined by enforcing ambipolarity.
  \[ \sum_s e_s \Gamma_s (E_r, D(E_r)) = 0 \]

• LMFP with $T_e \approx T_i$ results in three roots
  – Ion root: ion flux reduced from $E_r=0$ level
  – Electron root: both species flux reduced from $E_r=0$ level

• Electron root can be reached by increasing $\Gamma_e$

• When $T_e \gg T_i$ the ion root solution may not exist near the core
HSX Can Achieve Electron Root Because $T_e >> T_i$

- In HSX $T_e >> T_i$ over most of the plasma radius, with a strongly peaked $T_e$ profile
- For $T_i \approx 100$ eV, ions experience a resonance at modest $E_r$ near plasma core
- The resonance occurs when poloidal velocity is canceled by the poloidal $E\times B$ drift
- Radial transport is increased near the resonance, and is strongly reduced for $E_r > E_r^{\text{res}}$
Radial Electric Field Roots in HSX

\[ P_{\text{inj}} = 100\text{kJ} \]

\[ \rho = 0.1 \]

\[ T_e = 2\text{keV} \]

\[ T_i = 70\text{eV} \]
Radial Electric Field Roots in HSX

\( P_{\text{inj}} = 100kW \)

\( \rho = 0.1 \)

\( T_e = 2keV \)

\( T_i = 70eV \)

\( \rho = 0.3 \)

\( T_e = 750eV \)

\( T_i = 60eV \)
Radial Electric Field Roots in HSX

ρ=0.1
\(T_e=2\text{keV}\)
\(T_i=70\text{eV}\)

ρ=0.3
\(T_e=750\text{eV}\)
\(T_i=60\text{eV}\)

ρ=0.5
\(T_e=300\text{eV}\)
\(T_i=55\text{eV}\)

\(P_{\text{inj}}=100\text{kW}\)
Radial Electric Field Roots in HSX

- Only electron root in core, and only ion root towards edge
  - Somewhere in three root region there is a transition, with strong $E_r$ shear
  - Determining shear layer involves perpendicular viscosity
Kinetic Model Well Describes Radial Transport

- Even in QHS the asymmetric effects are large enough to dominate the radial transport
- Small change to ion root fluxes, $E_r$
- Effect at large $E_r$ masked by resonance
- Larger effect could occur in HSX with large $T_i$ and gradients (large flows) and small $T_e$ (collisional)
Parallel Transport is Strongly Affected by MC

- Both the electron and ion particle flows are affected by MC.
- Ion flows are strongly increased
  - Without MC the ion flows are almost zero
  - Near the core the ion root solutions even exceed the thermal velocity
- Electron flows are decreased in the ion root, and change sign in the electron root
  - Important when calculating parallel current
CXRS Flow Measurements

- CXRS measurements are the focus of work by Alexis Briesemeister
- Parallel flow measurements show good agreement with predictions including MC
- Indicate a transition to electron root occurs
- Without MC ion flows are much smaller than measured
- Comparisons to measurements for several powers, densities, configurations is an important validation of PENTA
Solving the Diffusion Equation for $E_r$

- The radial electric field profile can be determined by solving a diffusion equation\(^1\)
  - $D_E$ (related to perpendicular viscosity) is generally not known\(^2\)
    - Solutions for different $D_E$ show a region of strong $E_r$ shear at $r/a \sim 0.25$

\[
\frac{\partial E_r}{\partial t} - \frac{\partial}{\partial V} \left[ \langle \nabla V \rangle D_E \left( \frac{\partial E_r}{\partial r} - \frac{E_r}{r} \right) \right] = \frac{e}{\varepsilon_\perp} (\Gamma_e - \Gamma_i)
\]

Strong $E_r$ Shear is Predicted in Region of Peaked $T_e$

- The radial electric field profile can be determined by solving a diffusion equation\(^1\)
- $D_E$ (related to perpendicular viscosity) is generally not known\(^2\)
  - Solutions for different $D_E$ show a region of strong $E_r$ shear at $r/a \sim 0.25$
- $T_e$ peaking occurs within the strong $E_r$ shear region
  - $E_r$ shear can suppress turbulent transport
  - Similar values of $D_E$ used for W7-AS

Applying a 2D Turbulent Transport Model to QHS

- The 2D quasi-linear Weiland model has been used to model turbulent transport in QHS\(^1\)
  - Like a tokamak, QHS has a single class of trapped particles.
  - With local geometry considerations, good agreement with 3D gyrokinetic GS2 growth rates.
  - Stored energy and confinement times predicted within 10%.
- Predictive transport (NC + Turb.) simulations underestimate \(T_e\) in core
  - Turbulent diffusivity in this region is 10x experimental
  - Transport can be reduced via ExB shear

1) Guttenfelder, (‘07,’ 08), Lore (‘10)
ExB Shearing Rate >> Linear Growth Rate for r/a < 0.3

- ExB shear suppression is modeled using a linear quench rule:\(^1\)
  \[
  D \Rightarrow D \cdot \max\left(1 - \alpha_E \frac{\gamma_E}{\gamma_{\text{max}}}, 0\right)
  \]
  - \(\gamma_E = \) ExB shear rate
  - \(\gamma_{\text{max}} = \) maximum linear growth rate
- Shear suppression expected inside of r/a = 0.3

\[\gamma_E = rt \frac{\partial}{\partial r} \frac{v_{ExB}}{rt}\]

1) Kinsey (2005)
Turbulence Suppression via ExB Shear can Reproduce Experimental Profiles

- ExB shear suppression is modeled using a linear quench rule:\(^1\)
  \[
  D \implies D \cdot \max \left( 1 - \alpha_E \frac{\gamma_E}{\gamma_{\text{max}}} , 0 \right)
  \]
  - \(\gamma_E\) = ExB shear rate
  - \(\gamma_{\text{max}}\) = maximum linear growth rate
- \(E_r\) shear required to reproduce peaking of experimental \(T_e\) profile
- Coupled turbulent and NC transport model can self-consistently explain measured \(T_e\) profiles
CERC Transport Barriers

- Core Electron Root Confinement (CERC) transport barriers have been observed in several other stellarators\(^1\)
  - Characterized by peaked \(T_e\) profiles, neoclassical electron root \(E_r\)

CERC Transport Barriers

• Core Electron Root Confinement (CERC) transport barriers have been observed in several other stellarators\(^1\)
  – Characterized by peaked \(T_e\) profiles, neoclassical electron root \(E_r\)

• One common feature is the existence of thresholds for achieving a CERC in \(P_{\text{inj}}\) and \(n_e\)
  – In other stellarators thresholds are attributed to ECRH effects (convective fluxes)
  – W7-AS showed lower threshold when \(\varepsilon_{\text{eff}}\) increased – thought to be difficult to achieve CERC in QS configurations

• Experiments under carbonization indicate a threshold in QHS plasmas
Recent Experiments Suggest a CERC Density Threshold

- For same input power, small increase in density results in less peaked $T_e$ profile
  - $P_{inj} = 45kW$
- At higher density $a/L_{Te}$ is 2x smaller in core

![Graph showing $T_e$ and $a/L_{Te}$ profiles for different densities.](image)
Ion Root is Predicted Across the Plasma Radius at High Density

- The higher density case results in ion root solutions across the entire plasma radius
  - Core ion root is caused by reduced $T_e$, $\nabla T_e \Rightarrow$ reduced electron flux
  - Without external drive the plasma would remain in the ion root
- Note that this threshold does not appear to require any additional fluxes (e.g. ECRH driven)
- CERC effects in HSX are consistent with NC predictions, unique among stellarators that observe CERCs
Future Directions

• PENTA is a useful tool for future HSX research
  – Predictions of fluxes, $E_r$, currents, flows consistent with QS geometry
  – Comparisons of impurity and bulk flows

• Moving the shear location
  – Off axis heating (2\textsuperscript{nd} gyrotron online soon)
  – Increase electron flux via symmetry breaking

• Characterization of threshold behavior
  – Investigate effect of impurities (threshold higher in “clean” plasma?)
  – Effect of symmetry breaking (threshold lowered with increasing $\varepsilon_{\text{eff}}$ in W7-AS)
  – Look for bifurcations in ECE signals
  – GNET can be used to evaluate impact of ECRH fluxes
Conclusions

• Momentum conservation is important for NC calculations in HSX
  – Parallel flows and currents strongly affected
  – Better agreement with measurements when MC included
  – Kinetic analysis appears sufficient for determining radial transport

• Neoclassically driven transport barrier in QHS
  – Ambipolarity results in large $E_r$ with strong shear in same region of $T_e$ peaking
  – Turbulent + NC transport model used to simulate $T_e$ profiles
  – Core $T_e$ profiles only reproduced when ExB shear included
  – Threshold behavior consistent with NC predictions

• Upgraded PENTA code available for future research
Acknowledgments

• W. Guttenfelder for turbulent analysis and predictive simulations.
• D.A. Spong for the original version of PENTA and help with the development.
• A. Briesemeister for CXRS data.
• HSX team
Effect of wall conditioning on the CERC

• “Cleaner” plasma has reduced temperatures, no peaking