Modeling of HSX Plasmas with EMC3-EIRENE

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Next generation stellarators need to be designed with considerations for the divertor.

- Power handling requirements are a concern on LHD and W7X.
- Stellarator divertors have different physics from tokamaks.
  - Difficulty of achieving high-recycling regime.
  - Possibility of running fully detached.
- 3D nature makes design hard but yields opportunities for innovation.
  - Various different considerations already explored, Island divertor, Helical divertor, Local island divertor.
- Opportunities to contribute to physics understanding.
  - Role of islands in the edge.
  - Perpendicular transport coefficients.
  - Impurity transport.
**Outline**

- EMC3-EIRENE and HSX
- Look at a high-powered device based on HSX geometry capable of accessing relevant divertor regimes.
- Explore the role of edge islands in divertor regime transitions.
- Explore the role of device size in divertor regime transitions.
- Look at the effect of varying transport parameters or including impurities.
EMC3 solves fluid equations in arbitrary geometries on a field-aligned coordinate system.¹

Conservation of mass:
\[ \nabla \cdot \left( n_i V_i \parallel \vec{b} - D_i \vec{b} \perp \cdot \nabla n_i \right) = S_p \]

Conservation of momentum:
\[ \nabla \cdot \left( m_i n_i V_i \parallel \vec{b} - \eta \parallel \vec{b} \cdot \nabla V_i \parallel - D_i \vec{b} \perp \cdot \nabla m_i n_i V_i \parallel \right) = -\vec{b} \cdot \nabla p + S_m \]

Conservation of energy for electrons:
\[ \nabla \cdot \left( \frac{5}{2} n_e T_e V_i \parallel \vec{b} - \kappa_e \vec{b} \cdot \nabla T_e - \frac{5}{2} T_e D_i \vec{b} \perp \cdot \nabla n_e \right) - \nabla \cdot \left( \chi_e n_e \vec{b} \perp \cdot \nabla T_e \right) = -k (T_e - T_i) + S_{ee} \]

Conservation of energy for ions:
\[ \nabla \cdot \left( \frac{5}{2} n_i T_i V_i \parallel \vec{b} - \kappa_i \vec{b} \cdot \nabla T_i - \frac{5}{2} T_i D_i \vec{b} \perp \cdot \nabla n_i \right) - \nabla \cdot \left( \chi_i n_e \vec{b} \perp \cdot \nabla T_i \right) = +k (T_e - T_i) + S_{ei} \]

\[ D_i, \chi_i, \chi_e \] are inputs and constant over domain.
\[ \eta \parallel, \kappa_i, \kappa_e \] are classical (Braginskii).
\[ S_p, S_m, S_{ee}, S_{ei} \] are particle, momentum and energy source terms from neutrals and calculated by EIRENE.

EMC3 predicts lack of HR regime in W7-AS

- EMC3 has been applied to stellarators W7-AS, W7X, LHD and now HSX.
- Also applied to tokamaks with RMPs (AUG, NSTX, DIII-D, Textor).
- Successful prediction of lack of HR in W7-AS. ²

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² Feng Nuc. Fus. 46 (2006) 807
Friction from counter-streaming flows is important in stellarators.

Tokamak regions of counter-streaming flows are well separated.

Stellarators have regions of counter-streaming flows that can interact either between adjacent islands or within the same island.
HSX - a QHS stellarator located right next door.

- HSX is a 4 period stellarator with quasi-helical symmetry.
- Using stellarator symmetry, the device can be divided into 8 equivalent toroidal sections.
- Up-down symmetric planes exist at \( \phi = n\pi/4 \).
HSX geometries offer opportunity for advanced stellarator edge design

• Auxiliary coils in HSX can modify the edge structures.
• Expect large islands to behave similarly to tokamaks and W7X simulations.
• Expect standard islands to behave similarly to W7-AS.
• Expect small islands to behave similarly to LHD.
EMC requires user supplied grids that determine magnetic geometry and resolution.
Use density scans at constant separatrix temperature to explore edge behavior.

- Upstream density is scanned from $1 \times 10^{19}$ to $1.2 \times 10^{20}$ m$^{-3}$.
- Upstream temperature is considered to be an operating point, so input power is adjusted to keep separatrix temperature constant with increasing density.
- $D = 1$ m/s$^2$, $\chi_{e,i} = 3D$.
- No impurities.
Configurations with large $x_\perp$ transition to high-recycling regime.

- Large island case transitions to high-recycling regime at a lower upstream density than the other two cases.
- Double-sized devices transition to high-recycling regimes at lower densities than normal-sized devices.
Small island - low-recycling regime
Medium island - low-recycling regime
Large island - low-recycling regime
Small island - high-recycling regime
Medium island - high-recycling regime
Large island - high-recycling regime
Friction between island chains (small island)

- Small island configuration exhibits friction between 8/7 and 16/15 island chains.
- This is similar to proposed frictional forces exhibited in the stochastic layer of LHD.
\( \mu_\perp \) affects how far flows penetrate into island centers.

\[
D = \mu_\perp = 1 \text{ m}^2/\text{s}
\]

\[
D = \mu_\perp = 0.25 \text{ m}^2/\text{s}
\]

At low values \( \mu_\perp \), flows are confined to the outsides of island structures, suggesting a possible methodology to measure transport parameters in current experiments.
\( \chi \) affects concentration of flux deposition on targets.

\[ \chi_e = \chi_i = 3 \text{ m}^2/\text{s} \]

\[ \chi_e = \chi_i = 0.75 \text{ m}^2/\text{s} \]

Current engineering constraints limit steady-state heat flux to 1000 W/cm\(^2\).
Impurity carbon profiles suggestive of impurity trapping in islands.

- Trapping of impurities inside island chains is thought to allow access to stable detachment. ³
- Large island case has significantly higher radiated fraction compared to the standard island case: 89% to 29%.

³Feng Nuc. Fus. 45 (2005) 89
EMC3 simulations are used to examine advanced QHS stellarators.

- Stellarator edges have complex 3D geometries that prevent simple analysis.
- Simulations can be used to analyze feasibility of future designs.
- Results from EMC3 simulations on HSX like plasmas show that:
  - Larger devices/islands are more likely to reach high recycling.
  - Better estimates of $D$ and $\chi$ are crucial for determining flux limits on targets.
  - Impurity transport studies may yield interesting results (island trapping.)
Looking at challenges of divertor designs.

- Magnetic flux expansion near targets is a bigger payoff than changing impact angles\(^4\).
- Gaining knowledge about perpendicular transport coefficients is crucial to determine feasibility of design.
- Island divertors need to be stable to MHD effects (e.g. plasma healing\(^5\)).
- Must minimize space not occupied by the core plasma.
- Stability of detached plasmas is not yet understood.

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\(^4\) Kotschenreuther Phys. of Plas. 14 (2007) 072502
\(^5\) Hegna Phys. of Plas. 19 (2012) 056101