Investigation of High-Recycling Regime in Quasi-Helically Symmetric Geometries

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EMC3-EIRENE adapted for prediction of HSX-like Stellarator edge behavior

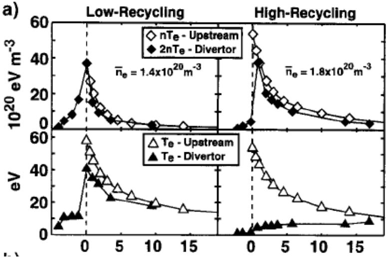
- Examine the roles of remnant island structures in the edge.
  - Islands give rise to counter-streaming ion flows in the edge.
  - These flows are thought to degrade edge performance in stellarators such as W7-AS.
- Two configurations examined, one with large islands, one without.
  - Density scans at constant temperature can mark transitions to high-recycling regimes.
  - Small island configuration *does not* outperform the standard QHS configuration.

Divertors are a key area of research for future Stellarator reactors

- Stellarator edges are complicated
  - Adjacent open field lines can have very different connection lengths.
  - Stellarator edges often have islands or remnant island structures.
  - 3D geometry makes divertor target-plate design difficult.
- Simulations can help inform and distinguish between canonical divertor designs.
  - Island divertor (W7-AS, W7X), Local Island Divertors (LHD), Helical divertors (LHD), bundle and snowflake divertors.
  - Explore numerous design options without the large investment needed to build a new device.
  - Eliminate design options with poor simulated performance.
- Examine role of island structures in the Scrape-off Layer.

High-recycling is desirable for reactor operation.[1]

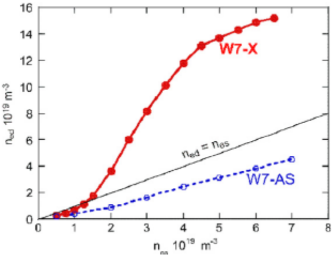
- 2-point model defines different divertor operating regimes for tokamaks.
  - $2p_{ds} = p_{us}$
  - $T_{us}^{7/2} = T_{ds}^{7/2} + \frac{7}{2}\frac{q_{\parallel} L}{\kappa_e}$
  - Parallel temperature gradients supported by limited heat conduction in SoL
- High-recycling regimes are readily accessible in tokamaks



- High-recycling regime characterized by:
  - Density increase at wall.
  - Reduced temperature at wall.
  - Parallel T_e gradients supported by finite parallel heat conduction.

[1] LaBombard J. Nuc. Mat. 241-243 (1997) 149-166

HR regime yet to be demonstrated on Stellarators.[2]



- W7-AS: EMC3 predictions and experimental results show lack of HR regime.
- EMC3 predicts HR regime will be accessible on W7X.

- High-recycling regimes have not been obtained on W7-AS or LHD.
  - Friction from counter-streaming flows in the island divertor of W7-AS is thought to be responsible for lack of HR regime.
  - W7X prediction partly due to increased island size leading to larger perpendicular scale lengths.

[2] Feng Nuc. Fus. **49** (2009) 095002

EMC3 solves fluid equations in arbitrary geometries on a field-aligned coordinate system[3]

Conservation of mass

$$\nabla \cdot \left(n_i V_{i\parallel} \vec{b} - D_i \vec{b_\perp} \vec{b_\perp} \cdot \nabla n_i \right) = S_p$$

Conservation of momentum

$$\nabla \cdot \left(m_i n_i V_{i\parallel} V_{i\parallel} \vec{b} - \eta_\parallel \vec{b}\vec{b} \cdot \nabla V_{i\parallel} - D_i \vec{b}_\perp \vec{b}_\perp \cdot \nabla m_i n_i V_{i\parallel} \right)$$

$$= -\vec{b} \cdot \nabla p + S_m$$

Conservation of energy for electrons

$$\nabla \cdot \left(\frac{5}{2} n_e T_e V_{i\parallel} \vec{b} - \kappa_e \vec{b}\vec{b} \cdot \nabla T_e - \frac{5}{2} T_e D_i \vec{b_\perp} \vec{b_\perp} \cdot \nabla n_e \right) -$$

$$-\nabla \cdot \left(\chi_e n_e \vec{b_\perp} \vec{b_\perp} \cdot \nabla T_e \right) = -k \left(T_e - T_i \right) + S_{ee}$$

Conservation of energy for ions

$$\nabla \cdot \left(\frac{5}{2} n_i T_i V_{i\parallel} \vec{b} - \kappa_i \vec{b}\vec{b} \cdot \nabla T_i - \frac{5}{2} T_i D_i \vec{b_\perp} \vec{b_\perp} \cdot \nabla n_i \right) -$$

$$-\nabla \cdot \left(\chi_i n_e \vec{b_\perp} \vec{b_\perp} \cdot \nabla T_i \right) = +k \left(T_e - T_i \right) + S_{ei}$$

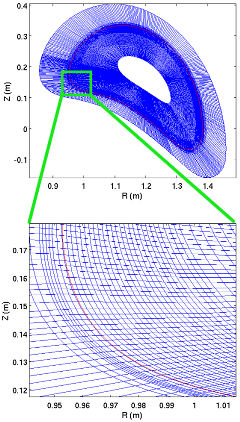
D_i, χ_i, χ_e are inputs and constant over domain

$\eta_\parallel, \kappa_i, \kappa_e$ are classical (Braginskii)

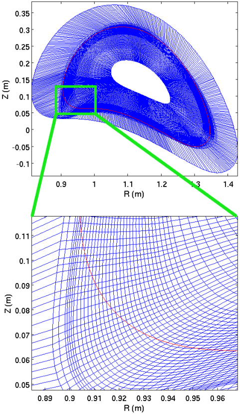
S_p, S_m, S_{ee}, S_{ei} are particle, momentum and energy source terms from neutrals

[3] Feng Contrib. Plas. Phys. **44** No. 1-3 57-69 (2004)

Full grid of domain is found by following vacuum field lines



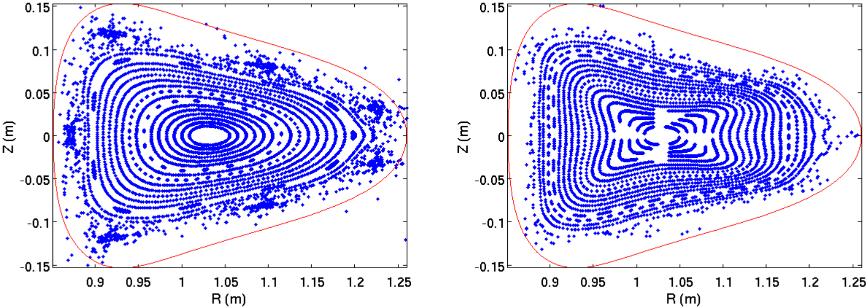
Grid at 22.5° with even flux surfaces extending beyond the wall (red).



Grid at 27° showing deformation of flux surface after moving 4.5°.

- Toroidal extent of domains is limited by cell deformation.
- Innermost cells form good flux surfaces.
- Cells beyond the wall (red) are marked as wall cells and do not have plasma.
- The outermost cells are not generated by field-line following.

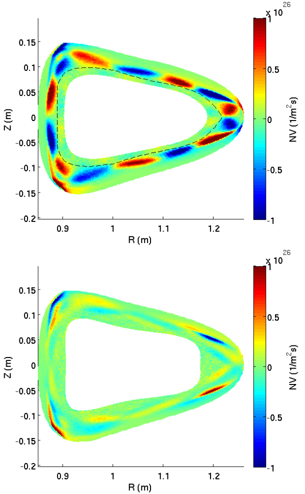
8/7 island structure dominates edge in QHS geometry



Poincare plots for QHS (left) and 5% hill (right). The LCFS of QHS is bounded by an 8/7 island chain that intersects the walls in various places. The LCFS of the 5% hill is bounded by a much thinner 16/15 island chain that does not intersect the wall.

Friction from counter-streaming flows can cause momentum loss along field line

- Stellarators have connection lengths much longer than tokamaks
  - Cross-field effects can be important and even dominate the momentum balance
  - $D_i \cdot \left(\vec{b}_\perp \vec{b}_\perp \cdot \nabla m_i n_i V_{i\|}\right) \approx -\vec{b} \cdot \nabla p$
- In QHS (top plot), the 8/7 island structure right outside the LCFS (black dashed line)
- 5% Hill configuration has smaller islands and less flows and is thus expected to have less friction from counter-streaming flows.

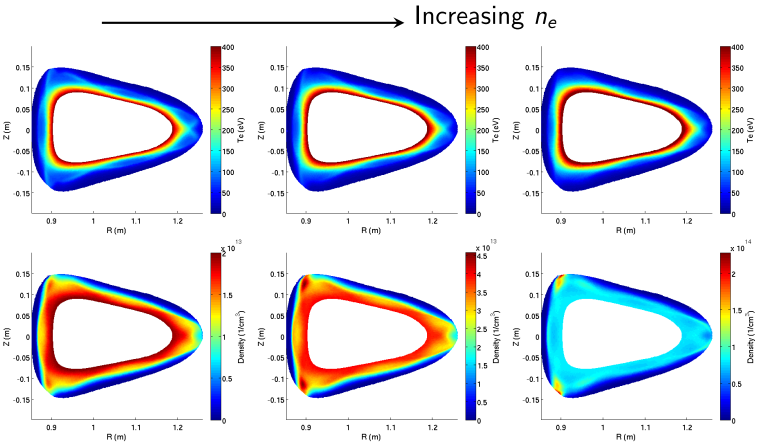


EMC3 calculation of $n_e V_{\|}$ at phi $= 45^\circ$ for QHS (top) and 5% hill (bottom).

Construction of grids for HSX geometries.

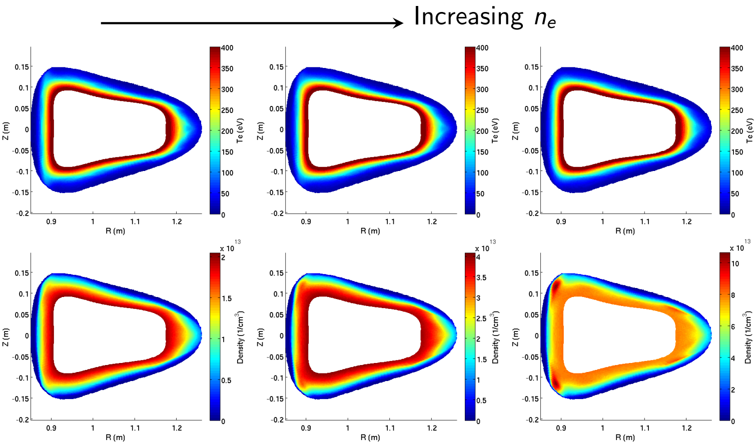
- 5 toroidal section, each spanning 9°.
  - New toroidal grid every 0.5°
  - EMC3 maps grids at boundaries.
  - Boundary locations at 0°, 9°, 18°, 27°, 36° and 45°
  - Stellarator symmetry invoked at 0° and 45°.
- Good flux surfaces until LCFS, and then uniform extension past wall in toroidal section centers.
- Increased resolution near wall and near LCFS.
  - QHS: 60 radial, 400 poloidal points in 95 toroidal grids
  - 5% Hill: 47 radial, 394 toroidal points in 95 toroidal grids
- $D_i = 1\ \mathrm{m}^2/\mathrm{s}$, $\chi_i = \chi_e = 3D_i$.

Transition to High-recycling regime at higher densities in QHS



QHS configuration T_e and n_e plots for inner flux surface densities of 2×10^{13} cm^{-3} (left), 4×10^{13} cm^{-3} (middle), and 8×10^{13} cm^{-3} (right). A transition to an HR-like regime can be seen by noting the large density increases near the strike points.

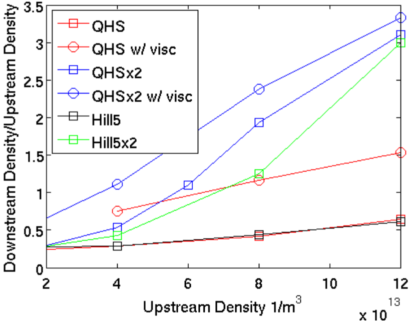
Transition to High-recycling regime at higher densities in 5% Hill



5% Hill configuration T_e and n_e plots for inner flux surface densities of 2×10^{13} cm^{-3} (left), 4×10^{13} cm^{-3} (middle), and 8×10^{13} cm^{-3} (right). A transition to an HR-like regime can be seen by noting the large density increases near the strike points.

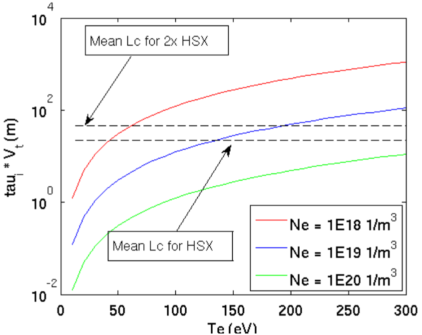
Ability to enter high-recycling regime is dependent on machine size.

- In high recycling regimes, $n_d \propto n_u^3$.
  - n_d = density at target (downstream).
  - n_u = separatrix density, (upstream).
- Comparisons are made for current HSX parameters and double-sized machines.
- Easier to enter high-recycling regime for larger machines.
  - Larger machines = larger perpendicular scale lengths = less friction from counter-streaming flows.
  - No improvement in performance in 5% hill configuration.



n_u/n_d for various configurations and upstream densities. Temperatures are held constant.

Collisional treatment for parallel viscosity only justified for low T, high n_e SoLs



Calculation of $\lambda_c \approx \tau_i V_{i,t}$ for various SoL conditions. Also included are the typical parallel scale lengths for both HSX and double sized HSX calculated as half of the mean connection length L_c.

- Turning on parallel viscosity yields unphysical downstream behavior with low collisionality SoLs (high temperature, low density)
- Collisional treatment for viscosity only valid when $\lambda_c \gg x_{\|}$, the collisional length is much larger than the parallel scale length.
  - The inequality is satisfied below the dashed lines on the plot to the right.
- Kinetic viscosity treatments are not yet included in EMC3.

EMC3 impurity model (improve title)

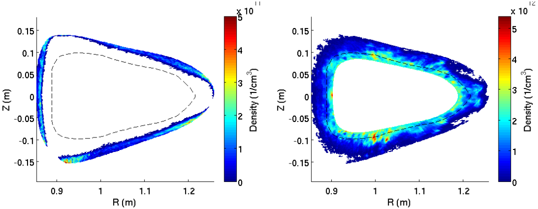
- EMC3 impurity model solves for all charge states of a given species.
- Impurities couple into the electron energy equation.

Continuity of mass:

$$\nabla \cdot \left(n_I^z V_{I,\parallel}^z \vec{b} - D_I^z \vec{b}_\perp \vec{b}_\perp \cdot \nabla n_I^z \right) = S_{z-1\to z} - S_{z\to z+1} + R_{z+1\to z} - R_{z\to z-1}$$

Continuity of momentum:

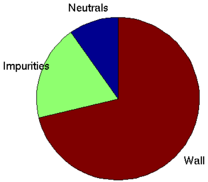
$$U_{I,i}^z \left(V_{I,\parallel}^z - V_{i,\parallel} \right) = -\vec{b} \cdot \nabla n_I^z T_i + n_I^z ZeE_\parallel + n_I^z Z^2 C_e \vec{b} \cdot \nabla T_e + n_I^z C_i \vec{b} \cdot \nabla T_i$$

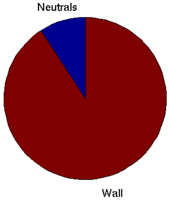


Plots of C^{+} (left) and C^{6+}(right) impurities for $n_e = 8 \times 10^{13}$ cm^{-3} plasma.

EMC3 impurity model (improve title)

- Full impurity sputtering model not yet implemented.
- Instead impurity generation is tied to recycling flux.
  - Here $\Gamma_{\mathrm{imp}} = 0.03 * \Gamma_{\mathrm{recyc.}}$.
- Detached plasmas - power radiatively exhausted through impurities and neutrals.
  - Detached condition not reached in HSX simulations.
  - Possibly due to unoptimized divertor.
  - Conditions for stable detached regimes not yet known.





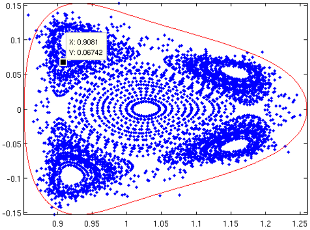
Portions of power exhausted through wall, impurities and neutrals for $\Gamma_{\mathrm{imp}} = 0.03 * \Gamma_{\mathrm{recyc.}}$ (top) and $\Gamma_{\mathrm{imp}} = 0$ (bottom).

Stable detached regimes may be a possible operation regime for Stellarators

- Detachment - ion heat flux does not reach target, stopped by dense gas region in front of target.
- In tokamaks, impurity and neutral penetration into the pedestal leads to a collapse of H-mode confinement.
  - Tokamaks have not been able to maintain a steady H-mode in detached regimes
- Stable detached regimes have been seen in W7-AS[4] but not in LHD[5]

[4] Feng Nuc. Fus. **45** (2005) 89-95
[5] Feng Nuc. Fus. **48** (2008) 024012

Future work - 9% Hill case with large islands.



Poincare plot for 9% Hill.

- 9% Hill has large 4/4 islands that dominate an enlarged SoL.
- Preliminary results expect these islands to possess large flows.
  - Ideal case for investigation of island size on HR attainment.
- Grid construction for 9% hill is more difficult.
  - Needs fine resolution over larger region.
  - Coarsely resolved grids do not converge.

Future work - Refine future Stellarator design.

- QHS possesses good core plasma confinement properties, but exploration of divertor properties is only beginning.
  - Divertor design must be robust to plasma generated currents (cannot trust vacuum island structure).
  - Divertor must obtain either a high-recycling regime or a stable detached regime.
  - Model testing - refined wall design, additional external coils.
  - Can a bundle divertor work in a reactor?
- Validate EMC3 code on current HSX device.
  - Attempts to measure flow structures in edge are underway.
  - Comparisons with neutral and impurity radiation measurements are also possible.

EMC3-EIRENE adapted for prediction of HSX-like Stellarator edge behavior

- Examine the roles of remnant island structures in the edge.
  - Islands give rise to counter-streaming ion flows in the edge.
  - These flows are thought to degrade edge performance in stellarators such as W7-AS.
- Two configurations examined, one with large islands, one without.
  - Density scans at constant temperature can mark transitions to high-recycling regimes.
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