Physics optimization for a new UW-Madison midscale quasi-helically symmetric stellarator

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Physics & Engineering Goals

- Develop a mid-scale quasi-symmetric configuration that can:
  - Improve turbulent transport via configuration modification
  - Show adequate confinement of energetic particles
  - Use new coil design tools to maximize coil-plasma distance
  - Validate divertor concepts for quasisymmetric machines
  - Explore thermal ion confinement in low collisionality regime
  - Use advanced manufacturing techniques to demonstrate that stellarators can be produced cheaply and reliably

Optimization

- Stellarator equilibria are defined by boundaries

$$R(\theta,\zeta) = \sum_{m,n} R_{mn}\cos(m\theta - n\zeta)$$

$$Z(\theta,\zeta) = \sum_{m,n} Z_{mn}\sin(m\theta - n\zeta)$$

- VMEC solves for plasma geometry given boundary shape, current profile, density profile [1]
- Optimizer tools vary R_{mn} and Z_{mn} on boundary

Optimizer Codes

- **STELLOPT** [2]
  - **VMEC** for equilibrium, Levenberg-Marquardt for optimization; Quasi-Newton in development
  - Global optimizer parallelized, subfunctions parallelizable
- **ROSE** [3]
  - **VMEC** for equilibrium, Brents algorithm for optimization
  - Global optimizer not parallelized, subfunctions parallelizable

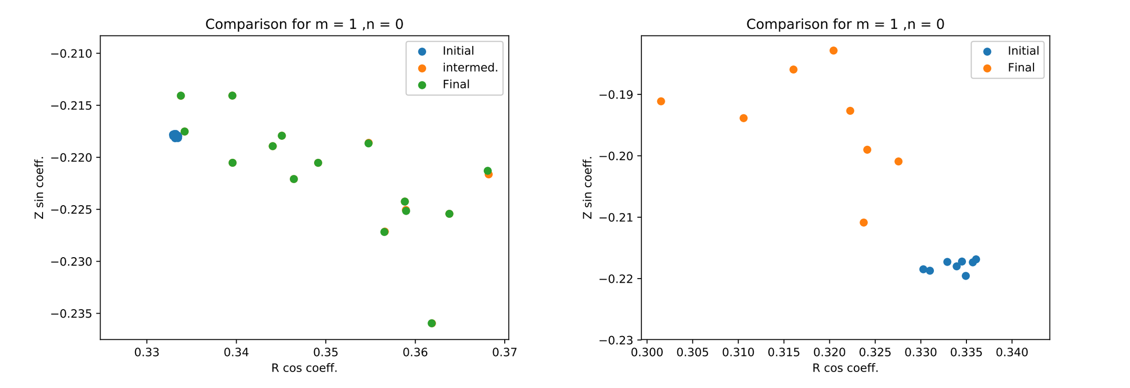
Target functions - optimizer tests

$$P = \sum \left(\frac{Q_i(R_{mn}, Z_{mn}) - T_i}{\sigma_i}\right)^2$$

P is total penalty, T_i is target value for ith constraint, σ_i is weight, Q_i is target function, for example:

$$Q_{qa} = \sum_{n\neq 0} B_{mn}^2/B_{00}^2;\ B(\psi,\theta,\zeta) = \sum_{m,n} B_{\psi,m,n}\cos(m\theta - n\zeta)$$

is the target for quasi-axisymmetry



When targeting quasi-helical symmetry, both **STELLOPT** and **ROSE** display non-convex behavior

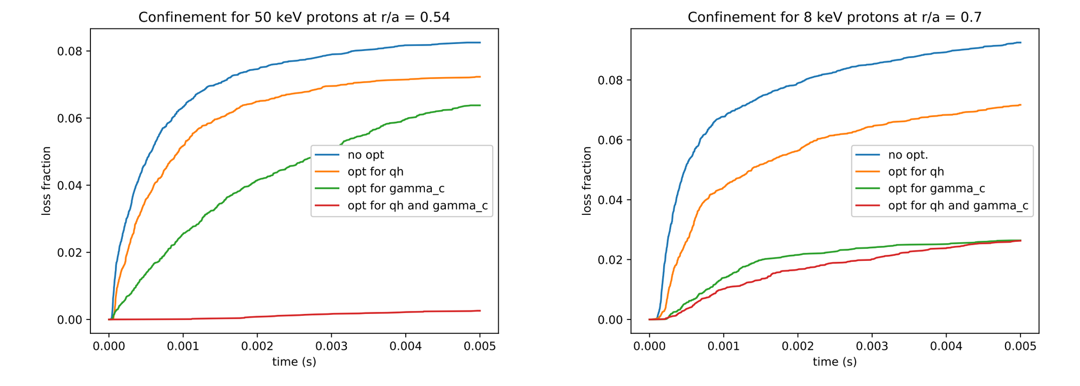
Energetic Particles

- Major issue for stellarator reactors
- Scaled NCSX: ~27% alpha losses, ARIES-CS: ~5% alpha losses (not including coil ripple) [4]
- New metric for optimization Γ_c [5]

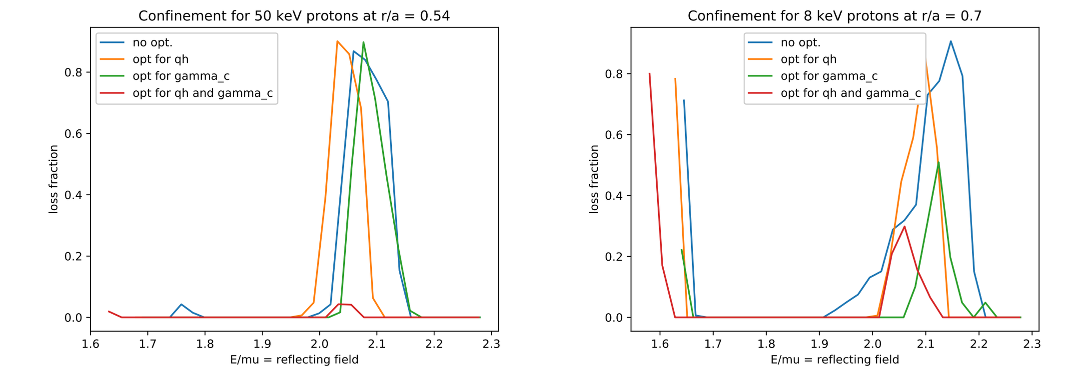
$$\Gamma_c \propto \sum_{\mu} \int_b \arctan(v_r/v_\theta)$$

Sum is over pitch angles, integral is between bounce points. v_r is radial drift, v_θ is poloidal drift

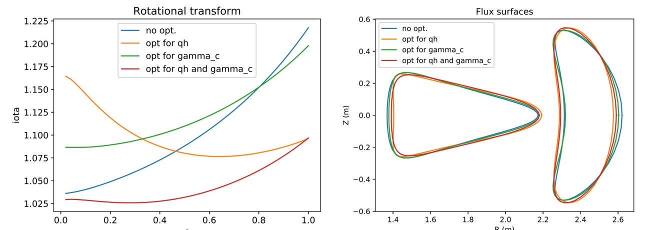
Calculations for R_0 = 2 m, B_0 = 2 T, Aspect Ratio 6.7 Stellarator



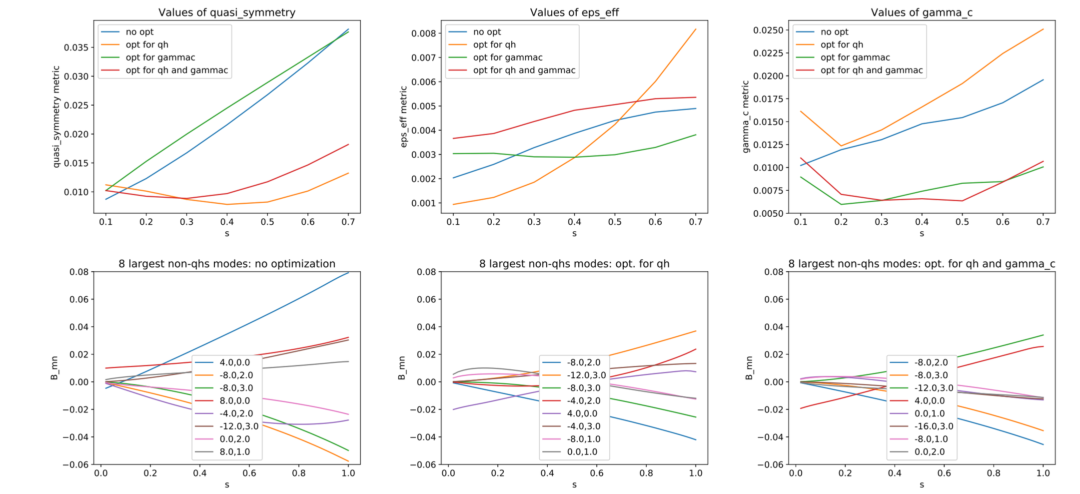
Minimizing Γ_c along with optimizing quasi-helical symmetry can produce configurations with very low EP losses



Losses reduced at trapped passing boundary



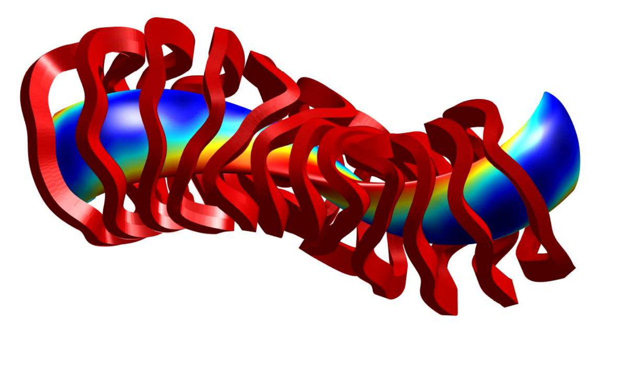
- LCFS shape not significantly modified
- No constraints on rotational transform



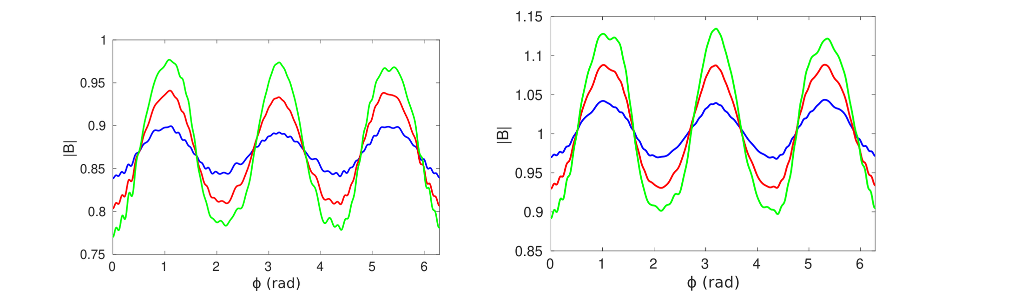
- EP confinement not tied to ϵ_{eff}
- m=0, n=4 mirror term increased in core

Coils

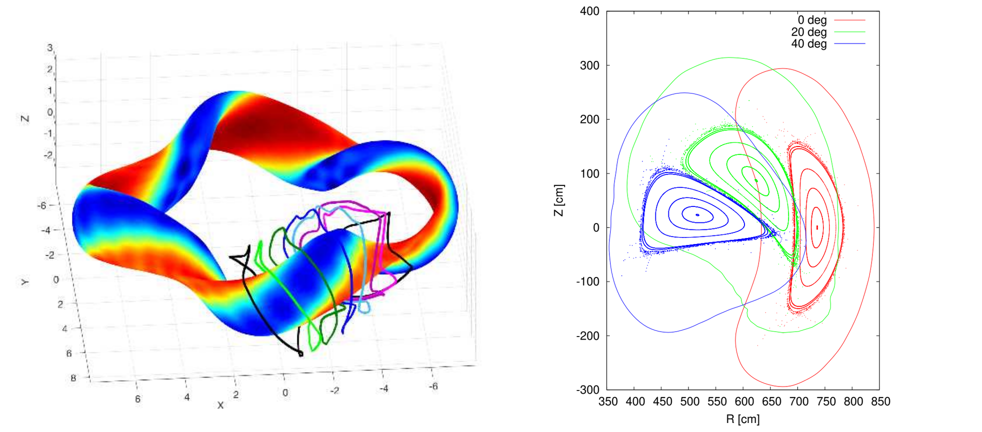
- Coil design tools have greatly improved over last decade
- Challenge: Move coils further from plasma
  - Allows more room for divertor
  - Reduces energetic particle losses from coil ripple



- Coils expanded with **FOCUS** code [6]
- Avg. coil-plasma distance increased by 8%
- Lower coil ripple achieved

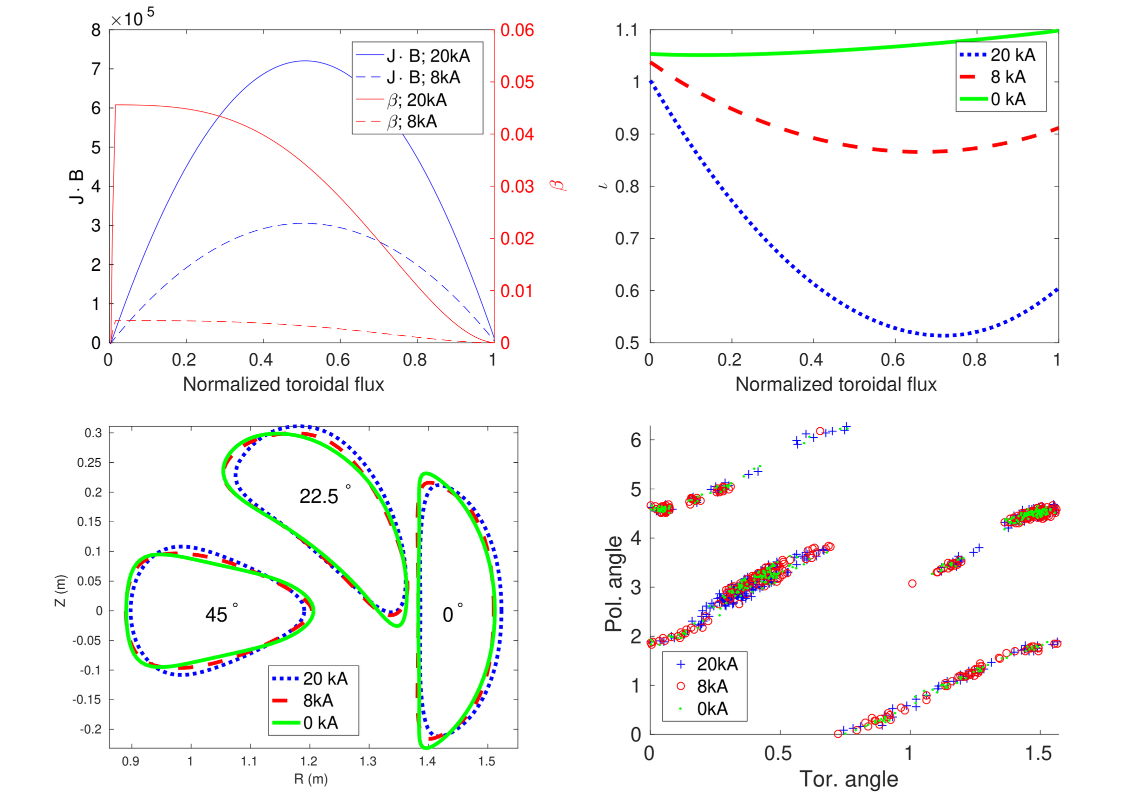


REGCOIL [7] combined with **STELLOPT** optimizes coil winding surface



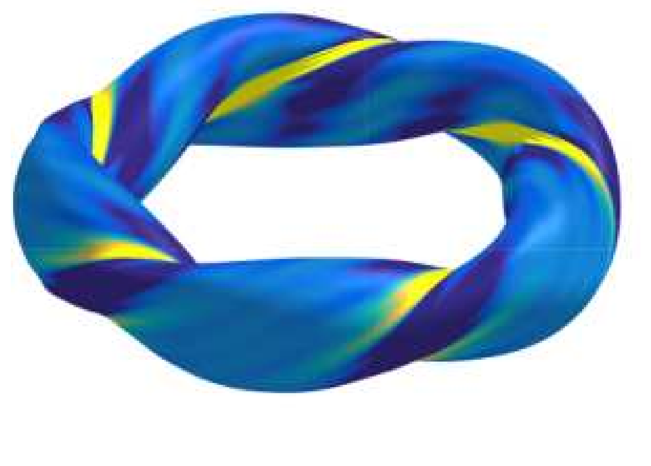
Divertor

- Divertors for quasi-symmetric devices must be resilient to configuration changes due to finite plasma currents
- Island divertors (W7-X) and helical divertors (LHD) may not be feasible in QS systems

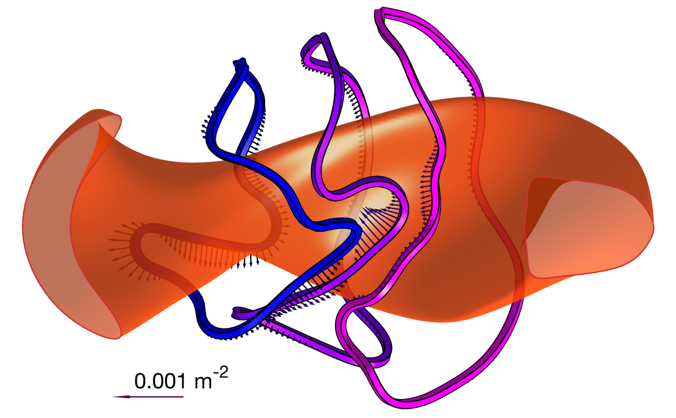


- HSX configuration resilient to boundary changes resulting from finite current [8]
- Feature is generic to equilibria with "ridges" and no large islands
- May require induced stochastization of edge region
- Divertor experiments on mid-scale devices necessary to evaluate non-resonant divertor concepts

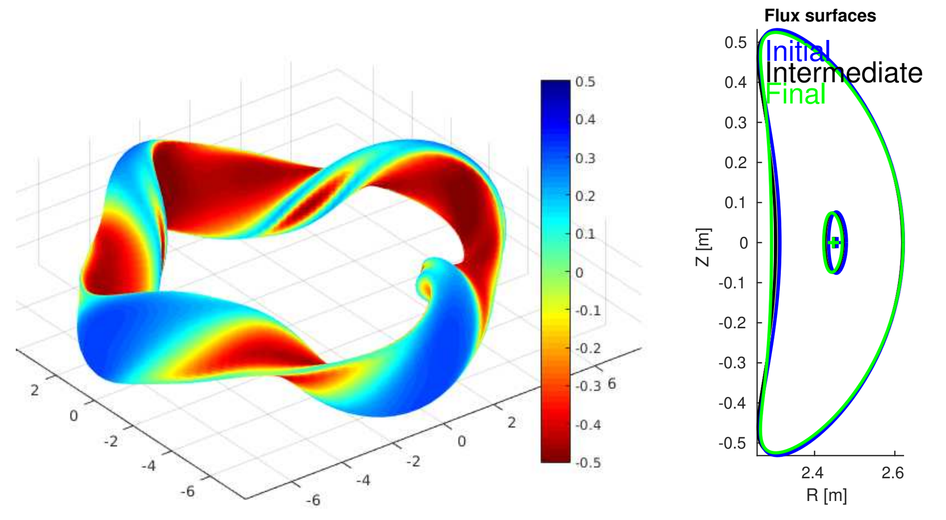
Coil Sensitivity and Divertor Locations



- Sensitivity of winding surface to matching $|B|$ on boundary [9]
- Winding surface for W7-X most sensitive to position at inboard side



- Shape gradient of coils for NCSX for ϵ_{eff} [10]
- Gradient is largest in inboard section
- Low sensitivity in divertor region
- See M. Landreman GI3.00005

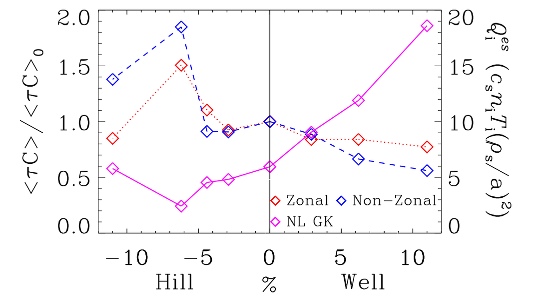


- Sensitivity corresponds with second principle curvature evaluated on plasma boundary (left for HSX)
- Curvature can be targeted in **STELLOPT** to reduce concavity of boundary (right)

Turbulence

- Proxy model for ITG turbulence obtained from 3-wave mode coupling [11]

$$Q \sim \frac{1}{c\tau};\ \tau = \frac{1}{i\,[\omega_i^* - \omega_j - \omega_k]}$$

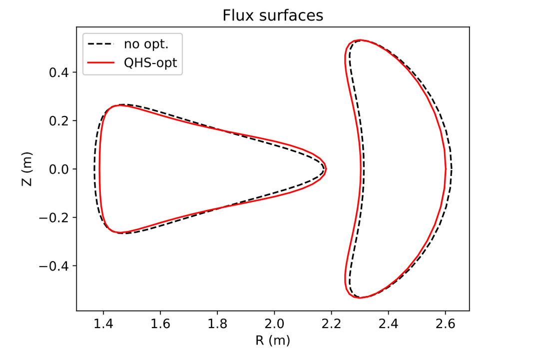


- Calculation shows peak coupling at 6% hill, low coupling in well
- Non-linear gyrokinetics shows transport inversely related to coupling
- Maximizing coupling is an optimization metric for ITG
- For more information, see B. Faber BP11-00034 and C.C. Hegna GI3-00006

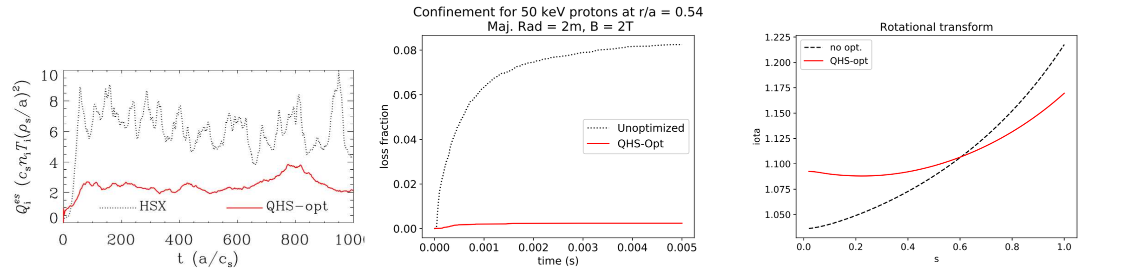
Opportunities for New QS Stellarator in US

- A mid-scale machine will significantly advance the physics basis of the Quasi-symmetric stellarator concept
- Staged approach is possible
- Initial stage: $\langle a\rangle \sim 0.25$ m with $n_e \sim 3\times10^{19}$ m^{-3}, 1.25 T with 70 GHz ECRH
- Upgradable to 2.5 T with 140 GHz ECRH

Present Configuration Under Study



- Improved turbulent transport over HSX
- Good energetic particle confinement
- Low magnetic shear with a magnetic well



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Acknowledgments

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