Optimization of Quasihelically Symmetric Equilibria

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1. Stellarator Optimization
2. Optimization for energetic particle transport
3. Improved coil algorithms
4. Non-resonant divertors for QS
5. New QHS configuration for midscale experiments

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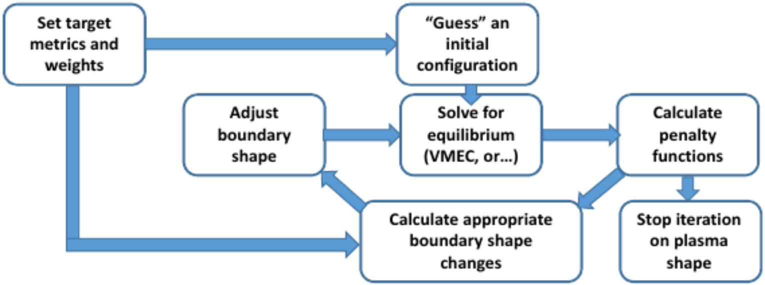
Stellarators offer a reliable reactor concept with low recirculating power

- Advantages of the stellarator concept
  - Do not rely on current: No current driven disruptions
  - Do not require current drive: Low recirculating power
  - Not subject to Greenwald density limits: High density operation possible
- Difficulties of the stellarator concept
  - More complicated design: Increased cost of construction. Opportunity for advanced manufacturing to reduce costs
  - Lack of experimental data. Opportunities for mid-scale devices to significantly advance the concept

Optimization procedures can find improved stellarator configs

Define a boundary: $R = \sum_{m,n} R_{m,n}\cos(m\theta - n\zeta)$, $Z = \sum_{m,n} Z_{m,n}\sin(m\theta - n\zeta)$

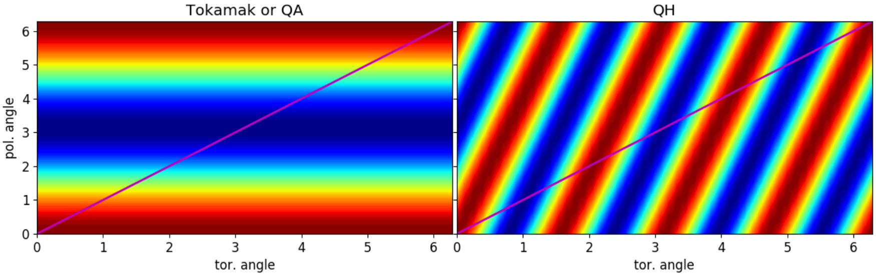
- Define targets to optimize and set weights for targets
- Solve for equilibrium, evaluate target functions
- Perturb $\mathbf{R}, \mathbf{Z}$ in an optimization scheme



New understanding allows optimization beyond HSX, W7-X

- Already demonstrated optimization for neo-classical transport, quasisymmetry, low plasma currents
- Breakthroughs in recent years allow optimization for new phenomena, and new improvements
  - Turbulent transport (B. Faber - next talk)
  - Energetic particle confinement
  - Simplified coils (see posters by L. Singh P73 and T. Kruger P72 Thur.)
  - Non-resonant divertors (see poster by H. Frerichs P80 Thur.)
  - MHD stability (not in this talk, see poster by J. Schmitt P30 Tues.)

Quasisymmetry - Tokamak transport in stellarator configurations



Benifits of QH

- Low flow damping in direction of symmetry (Gerhardt PRL 2005)
- Short connection lengths, lower bootstrap currents, lower Shafranov shift (than QA).

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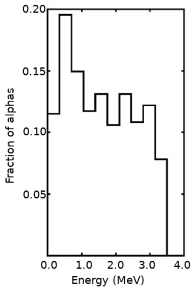
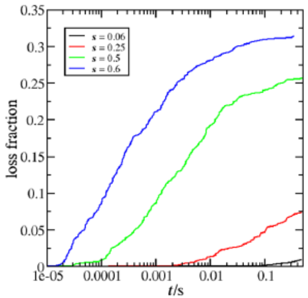
Alpha particle losses may be a driving factor for stellarator reactor design



- ARIES-CS predicts 5% Alpha Energy loss
  - ARIES-CS has volume 450 m^3 and B_0 = 5.6 T
  - Lost particles impact specific areas - above heat flux limits
- Henneberg shows new QA with particle loss $\approx$ 6% loss at mid-radius
  - Volume of 1900 m^3 at B_0 = 5 T
  - Loss suppressed deep in core



- Lotz (1992) predicts that QH and stellarators without bootstrap current should have better confinement
  - QH config. had 3% loss at Aspect Ratio 20

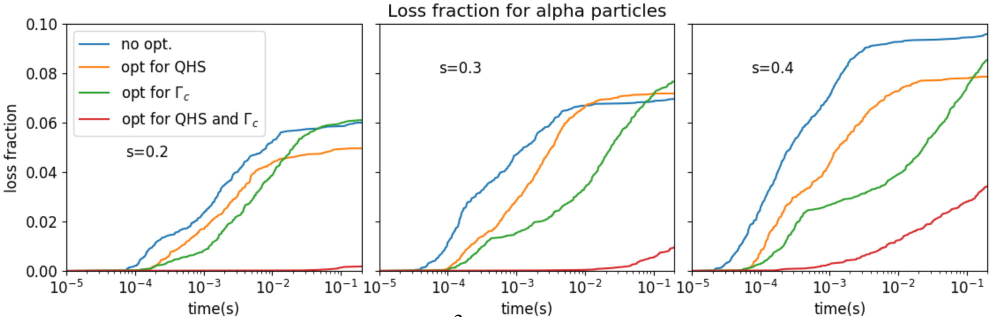
Mau FST 2008, Henneberg NF 2019, Lotz PPCF 1992

Γ_c metric aligns $J_{||}$ contours with flux surfaces

- $J = \oint v_{||} ds$; $\left\langle \frac{d\psi}{dt} \right\rangle = \frac{1}{Ze\tau_b}\frac{\partial J}{\partial \theta}$; $\left\langle \frac{d\theta}{dt} \right\rangle = -\frac{1}{Ze\tau_b}\frac{\partial J}{\partial \psi}$
- If $J = J(\psi)$ then $\dot{\psi} = 0$ and the particle does not drift off a flux surface
- $\Gamma_c \sim \sum_{E/\mu} \sum_{\text{wells}} \int_b \arctan^2 \left(\langle \dot{\psi} \rangle / \langle \dot{\theta} \rangle \right) \tau_b$
- Γ_c is related to the ratio of the average radial drift, to the average poloidal drift; i.e. if $\Gamma_c = 0$, $J = J(\psi)$
- Minimizing Γ_c should improve energetic particle confinement
- Testing effectiveness of Γ_c
  - Start with a QHS configuration and attempt to optimize QHS, and Γ_c, separately and together
  - Evaluate equilibria with collisionless Monte Carlo calculation that mimic alpha particle production

Nemov PoP 2008

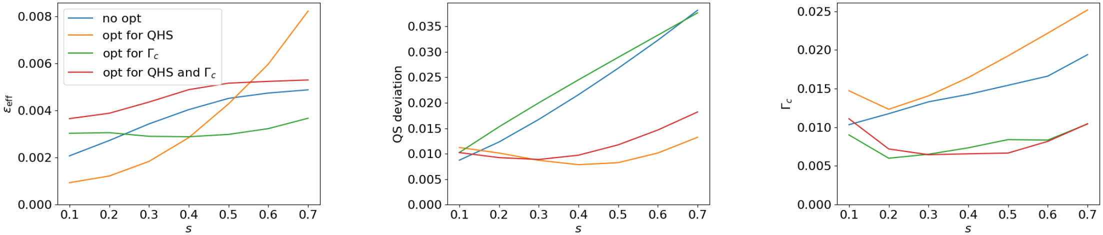
Optimizing for Γ_c and QHS reduces collisionless losses to reactor relevant levels



- All configurations scaled to 450 m^3 and B_0 = 5.6 T at aspect ratio 6.7
- Prompt losses entirely eliminated in best performing case (red), and below 1% within s=0.3

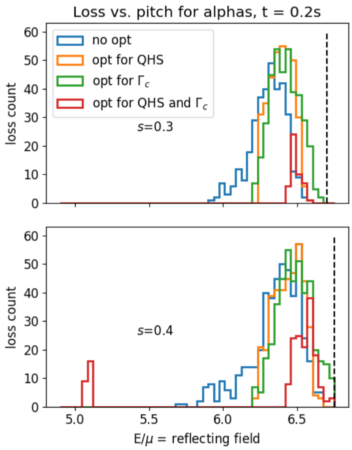
Bader accepted to JPP 2019

Improvements in alpha confinement is not correlated to $\epsilon_{\rm eff}$



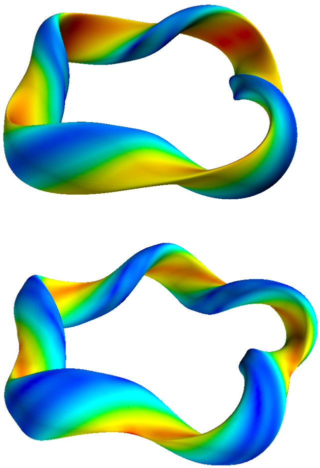
- Optimizer succeds in optimizing QHS and Γ_c
- Improvement of alpha confinement despite worse $\epsilon_{\rm eff}$ across most of the radius

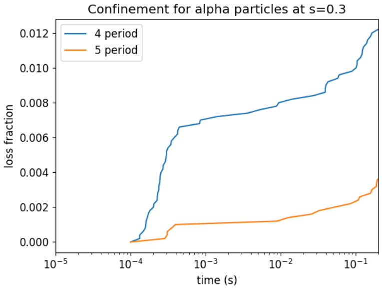
Loss reduction appears mostly at trapped passing boundary



- Most problematic region is near the trapped passing boundary
- The best confinement case (red) sacrifices confinement of deeply trapped particles to better confine particles near the trapped passing boundary
- If $p = p(\psi)$ and alpha velocity is isotropic, then fewer particles will be born deeply trapped than at the trapped passing boundary

Five period configuration: losses below 1% at s=0.3





- Both configurations at aspect ratio 6.7
- Collisionless alpha losses below any published result to date

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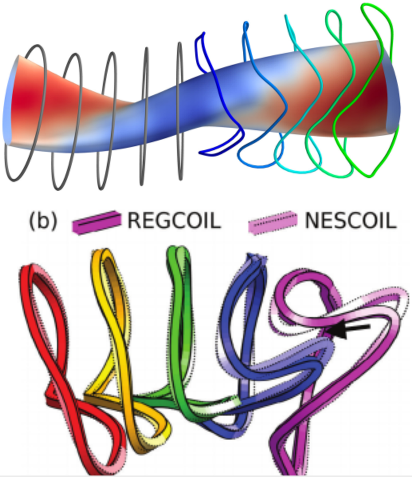
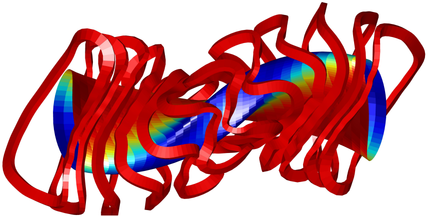
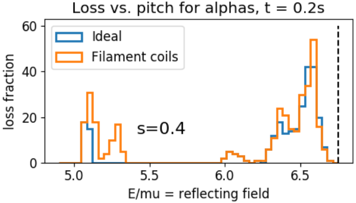
New codes have advanced coil design

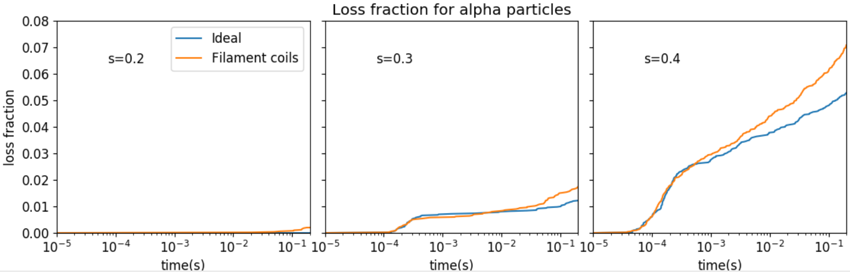


- FOCUS: solve coils in 3D space. (Zhu NF 2017)
- REGCOIL: solve for current potential on boundary surface, coils are contours of current potential. (Landreman NF 2017)
- Additional codes (not shown) ONSET, COILOPT++

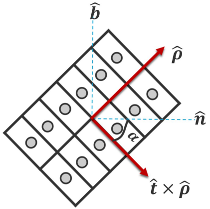
FOCUS + REGCOIL accurately reproduce boundary

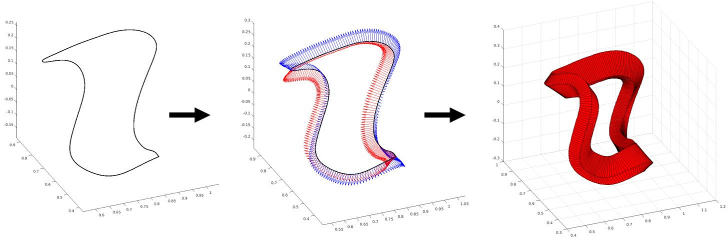


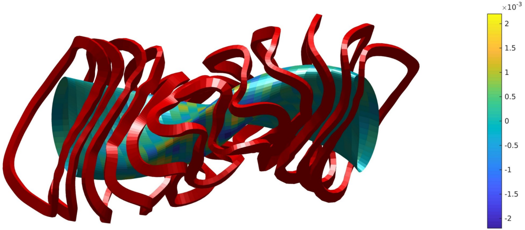




Developed new optimization for finite build coils







- Specify angle α, orientation of coil winding pack
- Optimize over α as additional parameter along with coil position

See L. Singh P73 Thur.

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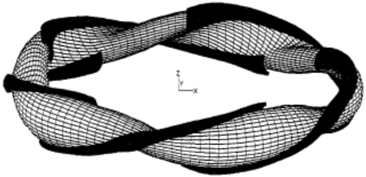
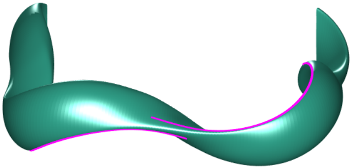
Quasi-symmetric stellarators may not be compatible with helical or island divertors

Early W7-X



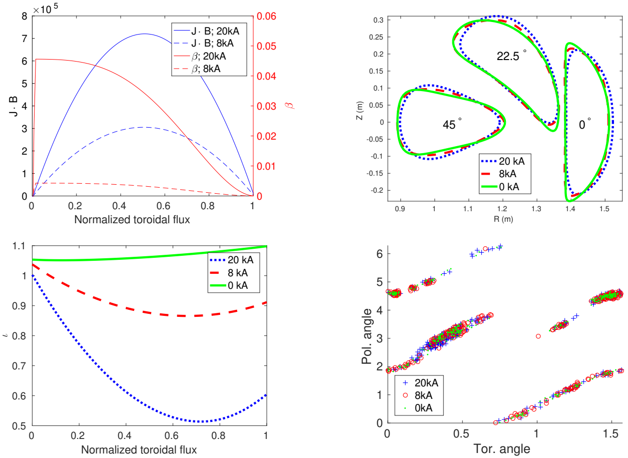
HSX



- Island divertor and helical divertors may not be suitable for other optimizations with finite bootstrap current, such as quasi-symmetric stellarators
- Early designs of W7-X exploited non-resonant divertors
- Stellarator shapes tend to have “ridges” on the surface
- Field lines follow along the ridges, like in a tokamak X-point
- **Difference from tokamaks: finite toroidal extent**

Strumberger NF 1992, Bader PoP 2017

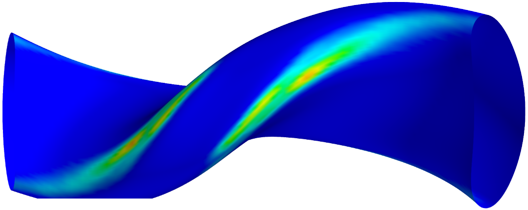
Non-resonant divertors resilient to plasma evolution



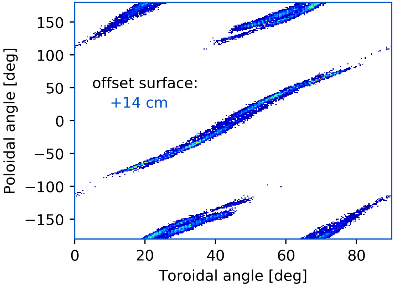
Bader PoP 2017

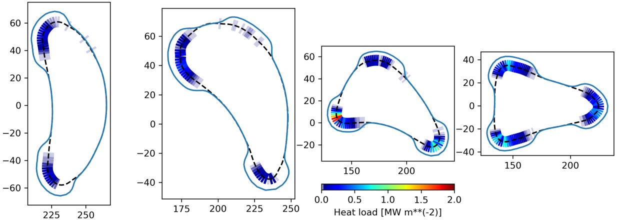
- Quasi-symmetric stellarators will have finite bootstrap currents and Shafranov shifts
- Rotational transform profiles will alter making island divertors difficult
- Non-resonant divertors promise similar performance despite changes in plasma boundary shape

Construction of a non-resonant divertor



- Calculate strike patterns on uniform wall
- Create troughs in strike locations
- Iterate until uniform distribution
- Check resiliency
- See H. Frerichs poster P.80 Thur.





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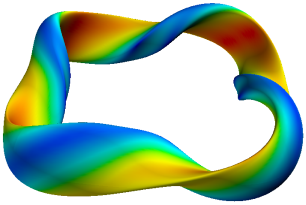
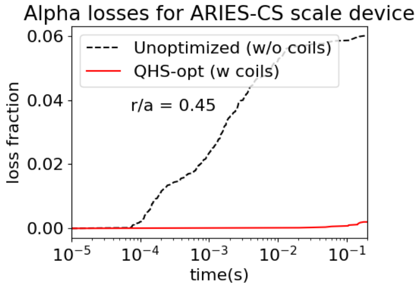
Midscale experiment can advance QS knowledge

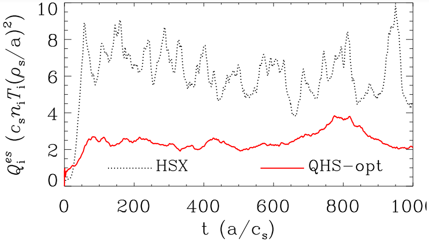


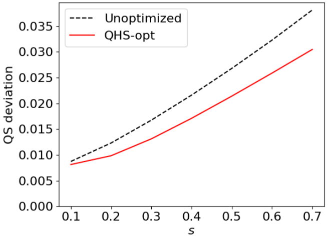
- Phased approach begins at 1.25 T, upgrade to 2.5 T
- Physics goals: Control turbulent transport, demonstrate good EP confinement, validate non-resonant divertor concept

Param.	Initial	Upgrade
R(m)	2.0	2.0
a(m)	0.3	0.3
B(T)	1.25	2.5
ECH (MW)	0.5	1.0
NBI (MW)	0.0	1.0
n (10^{20} m^{-3})	0.15	0.3
T_e (keV)	3.2	4.0
T_i (keV)	0.3	4.0
ν_i^*	0.4	0.005
τ_{ei} (s)	0.5	0.9
τ_E (s)	0.06	0.07

Excellent EP confinement with reduced turbulent transport

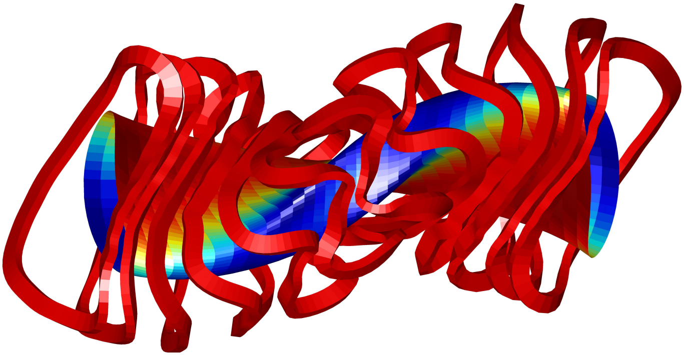






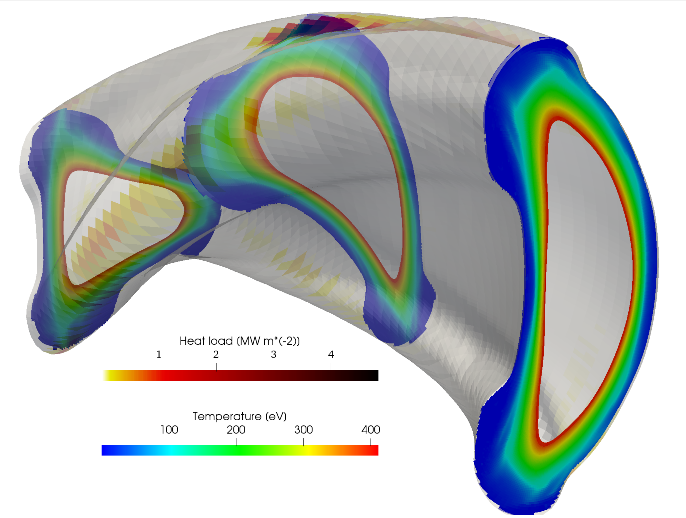
- EP losses almost entirely eliminated at s=0.2
- Turbulent heat flux reduced by factor of $\approx$3
- Slightly improved QHS metric

New coil design capabilities improve fidelity of magnetic structure



Min. Coil-plas. dist. (Single filament)	19.5 cm
Ave. Coil-plas. dist. (Single filament)	22.5 cm
RMS error (Single filament)	0.53%
Min. Coil-plas. dist. (Multi-filament)	14.6 cm
Ave. Coil-plas. dist. (Multi-filament)	17.7 cm
RMS error (Multi-filament)	0.60%

Expanded wall to test resonant divertor



- First attempt at generating walls for non-resonant divertors
- Localized toroidal hotspots indicate some finessing is necessary
- Iteration to improve divertor has begun
- See H. Frerichs poster P.80 Thur for more details

New metrics, tools, and optimizers improve design for next generation of optimized equilibria

- Energetic particle confinement at Tokamak levels within the mid-radius
- New coil algorithms can produce high fidelity, realistic coils
- First explorations of non-resonant divertor design has begun
- Stay tuned for next talk by Benjamin Faber on turbulent transport optimization