Elimination of Alpha Particle Losses in Quasi-Helically Symmetric Equilibria

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1. Stellarators and energetic particle confinement in 3D fields
2. How to optimize stellarators for energetic particle confinement
3. Towards eliminating alpha particle losses in stellarator equilibria

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Stellarators offer a reliable reactor concept with low recirculating power

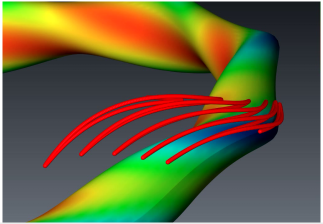
- Advantages of the stellarator concept
  - Do not rely on current: No current driven disruptions
  - Do not require current drive: Low recirculating power
  - Not subject to Greenwald density limits: High density operation possible
- Difficulties of the stellarator concept
  - Particle losses due to 3D configurations. This talk will show how to eliminate them!
  - 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

Stellarators offer the opportunity to design a magnetic confinement device to meet the specifications you choose

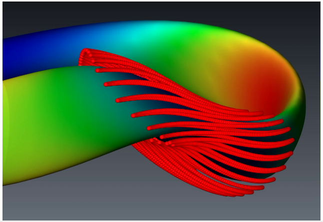
Confining trapped particles by eliminating bounce averaged radial drifts

- Departures from axisymmetry can produce trapped particles with a radial component to the drift
- $J = \oint v_{\|} ds$; $\left\langle \frac{d\psi}{dt} \right\rangle = \frac{1}{Ze\tau_b} \frac{\partial J}{\partial \theta}$; $\left\langle \frac{d\theta}{dt} \right\rangle = -\frac{1}{Ze\tau_b} \frac{\partial J}{\partial \psi}$
- If $J = J(\psi)$ then $\dot{\psi} = 0$ and the particle does not drift off a flux surface

Classical Stellarator



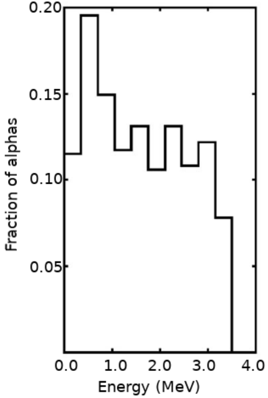
Optimized Stellarator



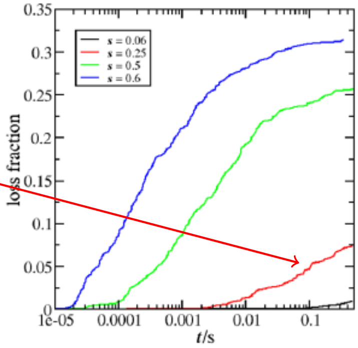
- With optimization, trapped particles can be confined
- Demonstrated in practice by W7-X, HSX

Pictures courtesy of IPP-Greifswald, Germany

Alpha particles are a driving factor for stellarator reactor design



- ARIES-CS predicts 5% Alpha Energy loss (Vol. = 450 m^3, B_0 = 5.6 T)
- Henneberg shows new QA with particle loss ≈ 6% loss at mid-radius (Vol. = 1900 m^3 at B_0 = 5 T)
- Lotz (1992) 3% loss for QH (at AR 20)
- ITER 6.8% loss without ferritics



These loss values are too high or machine size/aspect ratio are too large

We need to do better!

Mau FST 2008, Henneberg NF 2019, Lotz PPCF 1992

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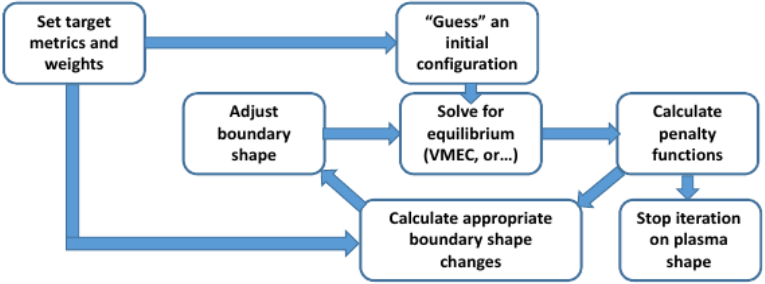
Optimization procedures can find improved stellarator configs

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


Set target metrics and weights

"Guess" an initial configuration

Adjust boundary shape

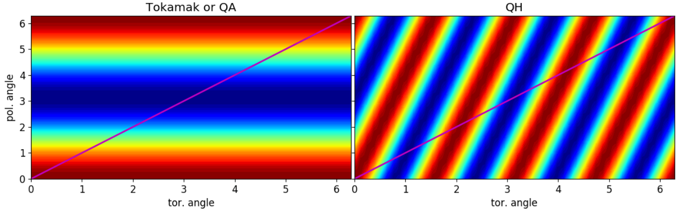
Solve for equilibrium (VMEC, or...)

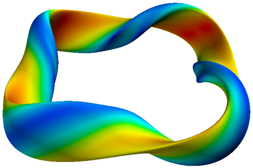
Calculate penalty functions

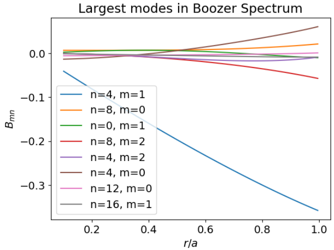
Calculate appropriate boundary shape changes

Stop iteration on plasma shape

Quasisymmetry improves confinement of all particles







- Perfect quasisymmetry will confine all particles
- QS deviation (4 field-period QH):

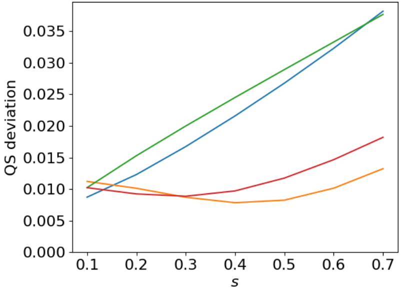
$$\mathrm{QH}_{\mathrm{dev}} = \left(\sqrt{\sum_{|n/m| \neq 4} B_{mn}^2} \right) / B_{00}$$

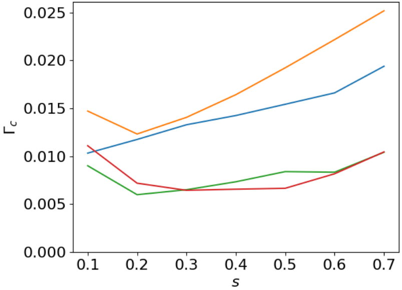
Γ_c attempts to align J contours with flux surfaces

- $\Gamma_c \sim \sum_{E/\mu} \sum_{\text{wells}} \int_b \arctan^2 \left(\langle \dot{\psi} \rangle / \langle \dot{\theta} \rangle \right) \tau_b$
- Γ_c is related to the ratio of the average radial drift, to the average poloidal drift; i.e. if $\Gamma_c = 0$, $J = J\left(\psi\right)$
- Minimizing Γ_c should improve energetic particle confinement
- Nemov provides algorithms for calculating $\langle \dot{\psi} \rangle$ and $\langle \dot{\theta} \rangle$
- **Use Γ_c and QH deviation as optimization parameters**

Nemov PoP 2006, Nemov PoP 2008

Optimization produces different configurations to test EP confinement





Starting equilibrium
Optimize for QHS only

Optimise for Γ_c only
Optimize for QHS and Γ_c

What are the important metrics for alpha particle confinement?

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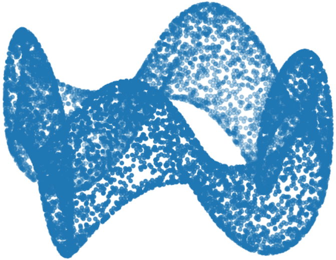
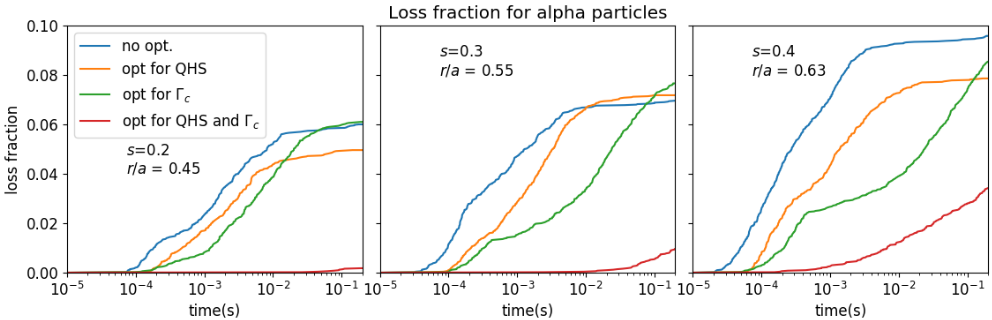
Evaluating configurations for alpha particle confinement

- Scale equilibria to ARIES-CS size (450 m^3, 5.6 T)
- Generate randomized spawn points, such that the probability of finding particle in volume element $dV_0 \propto \mathcal{J}(s_0, \theta_0, \zeta_0)$
- For each particle generate a randomized isotropic velocity
- Follow for 200 ms or until particle crosses the LCFS



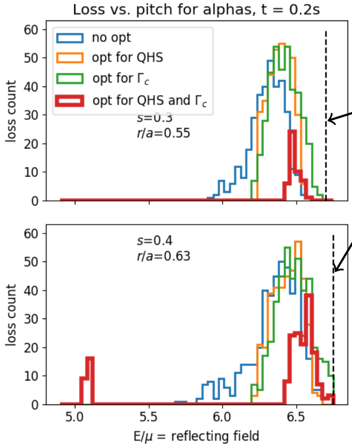
Optimizing for Γ_c and QHS reduces collisionless losses to reactor relevant levels



- Prompt losses entirely eliminated in best performing case
- In best case losses below 1% within s=0.3

Bader JPP 2019

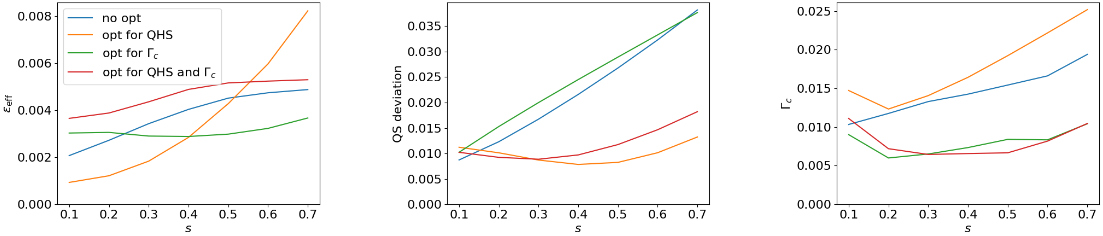
Loss reduction appears mostly at trapped passing boundary



- Most losses occur near the trapped passing boundary (dashed line)
- The best confinement case 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

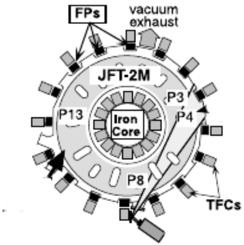
ϵ_{eff} is not correlated to improved EP confinement

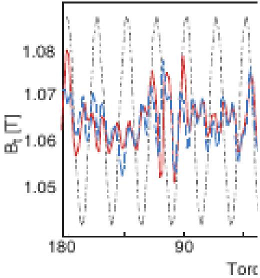
- In $1/\nu$ (low-collisionality) regime $\chi \sim \epsilon_{\text{eff}}^{3/2}$
- Previous configurations (such as NCSX) were optimized to reduce ϵ_{eff}

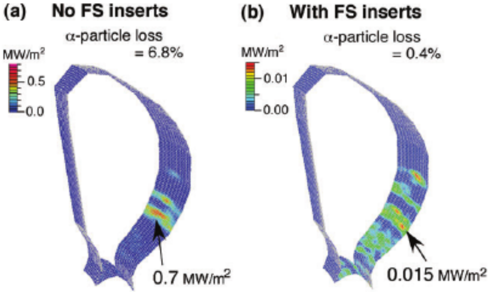


Coil effects compound energetic particle loss issues

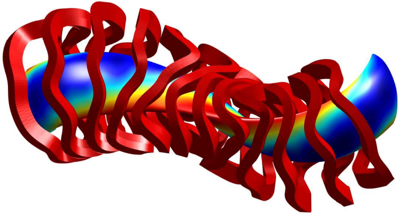
- Some stellarator configurations are difficult to reproduce with coils (Landreman NF 2018, Paul NF 2018)
- Additionally, coils also introduce ripple terms in the harmonic spectra
- Coil-ripple is a non-axisymmetric problem for tokamaks also (Shinohara NF 2003, Shinohara FST 2006, Tobita PPCF 2003)

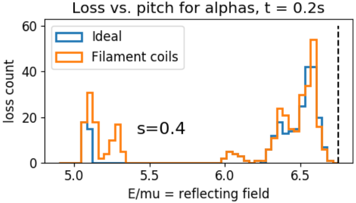




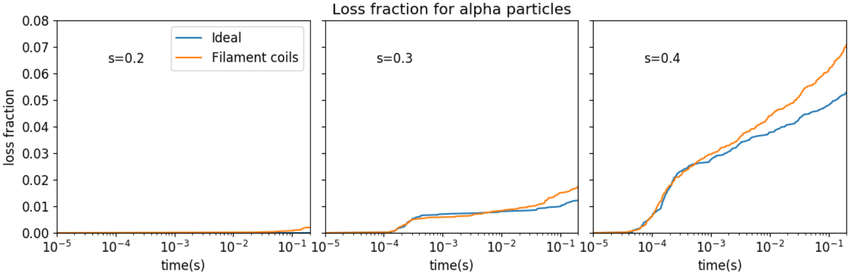


New coil algorithms greatly improve performance

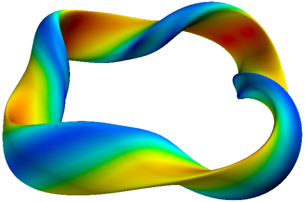




Coils made with REGCOIL (Landreman NF 2017) and FOCUS (Zhu NF 2017)



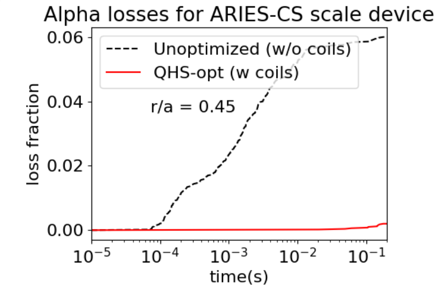
Midscale experiment can advance stellarator knowledge

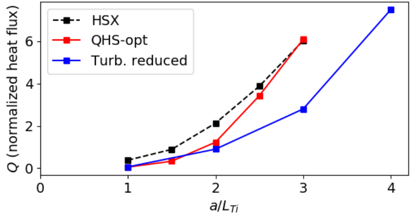


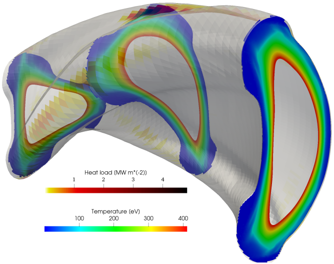
- Phased approach begins at 1.25 T, upgrade to 2.5 T
- Physics goals: Control turbulent transport, demonstrate good EP confinement, validate non-resonant divertor concept

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	0.9
T_e (keV)	3.2	2.5
T_i (keV)	0.3	2.5
β %	0.7	1.5
ν_i^*	0.4	0.04
τ_E (s)	0.06	0.13

A Mid-scale experiment can close gaps in stellarator research







- EP losses almost entirely eliminated at s=0.2
- Turbulent heat flux reduced by factor of $\approx$3
- Non-resonant divertor

See also D.T. Anderson (BP10.00066 Mon.)

New stellarator configurations can solve the alpha particle confinement problem

- Alpha particle confinement is a key gap for stellarator designs to date.
- New optimization with Γ_c and quasihelical symmetry can reduce energetic particle losses to reactor relevant levels.
- Experimental confirmation, at the midscale size, is possible and such a device would help advance the stellarator concept towards a demonstration pilot plant.

See Also

- D.T. Anderson (BP10.00066 - Mon.)
- C.C. Hegna (BP10.00055 - Mon.)
- T. Kruger (BP10.00065 - Mon.)
- L. Singh (JP10.00037 - Wed.)
- I.J. McKinney (UP10.00015 - Thurs.)
- B.J. Faber (UP10.00017 - Thurs.)