

Strategies and progress on fast ion confinement optimization in quasisymmetric configurations

A. Bader

Fast Ion Workshop
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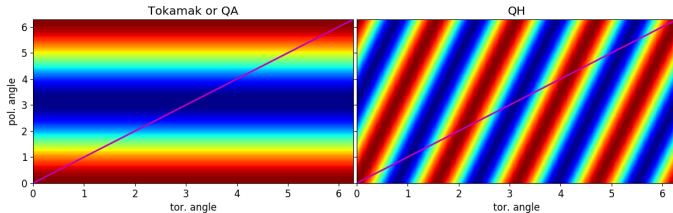
Main conclusions from EP optimization so far

- It is possible to optimize QH configurations for very good energetic particle confinement
 - Optimization metrics appear reasonably robust (the algorithms are not)
 - Integration with other desirable properties can be difficult (especially coils)
- QA configurations appear to perform poorer than QH
 - May require different optimization recipes
 - Will they improve at higher aspect ratios?
 - Collisional calculations appear to close the gap somewhat between QH and QA

- 1 Optimization metrics and application to QH
- 2 Optimization metrics and application to QA
- 3 Adding collisions to the simulations

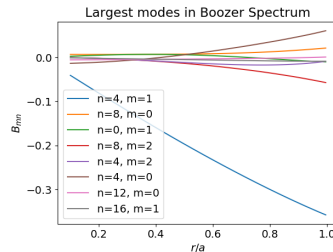
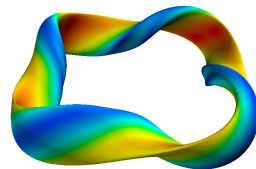
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Quasisymmetry improves confinement of all particles



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

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

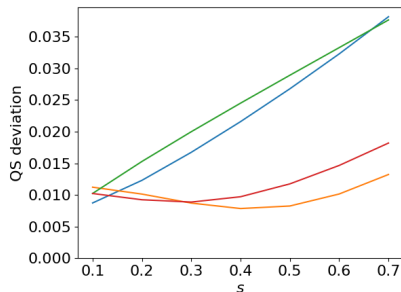


Γ_c attempts to align J contours with flux surfaces

- Proxy developed, which like ϵ_{eff} depends only on geometry
- $\Gamma_c = \frac{\pi}{\sqrt{8}} \lim_{L_s \rightarrow \infty} \left(\int_0^{L_s} \frac{ds}{B} \right)^{-1} \left[\int_1^{B_{\text{max}}/B_{\text{min}}} db' \sum_{\text{well}_j} \gamma_{cj}^2 \frac{v_{Tb,j}}{4B_{\text{min}}b'^2} \right]; \gamma_c = \frac{2}{\pi} \arctan \left(\frac{v_r}{v_\theta} \right)$
- 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
- Nemov provides algorithms for calculating $\langle \dot{\psi} \rangle$ and $\langle \dot{\theta} \rangle$
- **Use Γ_c and QH deviation as optimization parameters**

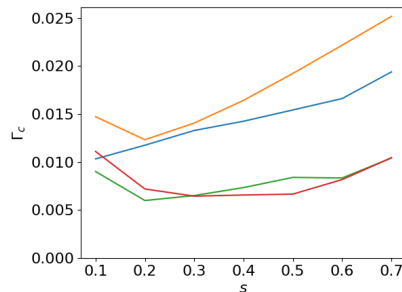
Nemov PoP 2006, Nemov PoP 2008

Optimization produces different configurations to test EP confinement



Starting equilibrium

Optimize for QHS only

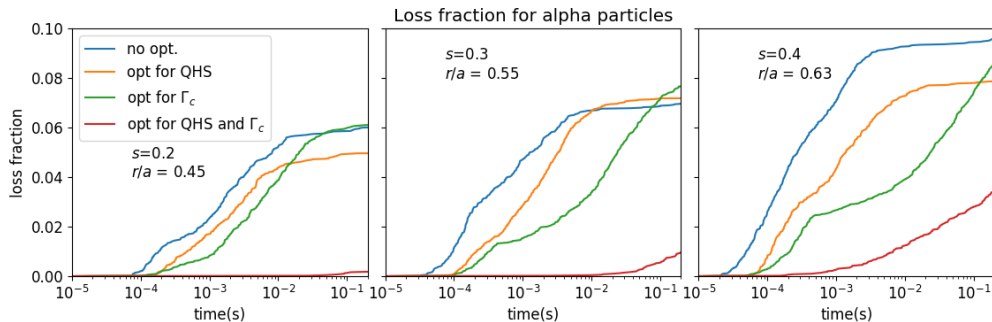


Optimise for Γ_c only

Optimize for QHS and Γ_c

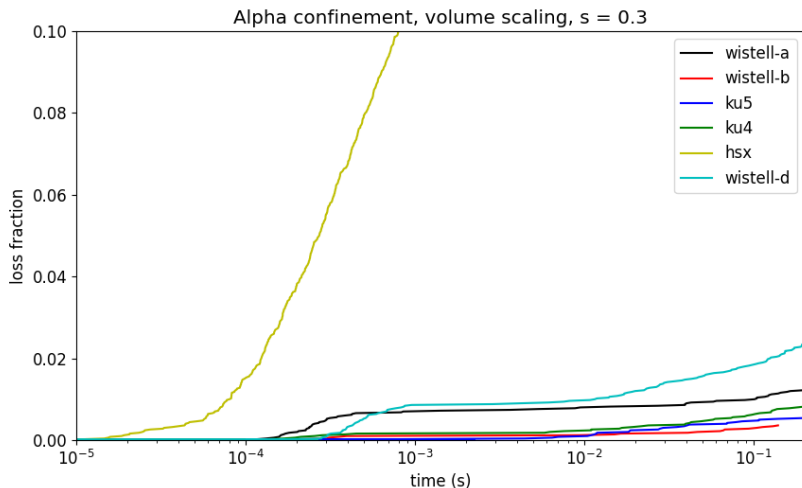
What are the important metrics for alpha particle confinement?

Best performing configurations appear when both QH metric and Γ_c are low

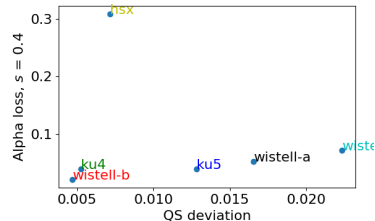
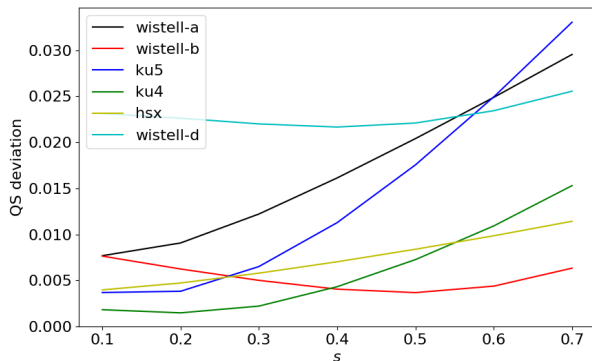


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Alpha particle confinement radius at ARIES-CS volume/field

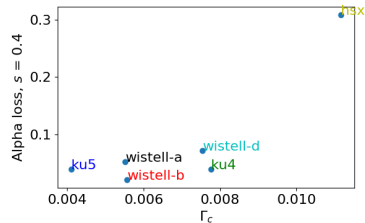
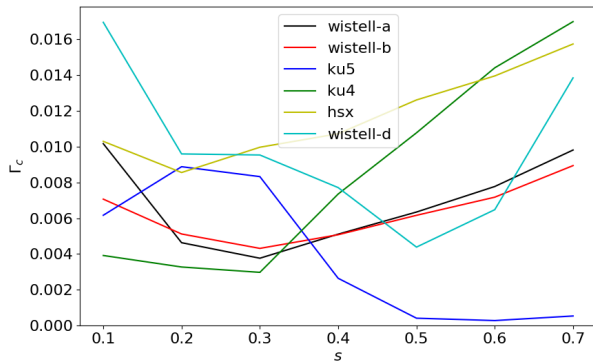


Configuration comparison: quasi-symmetry



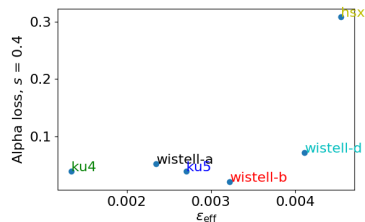
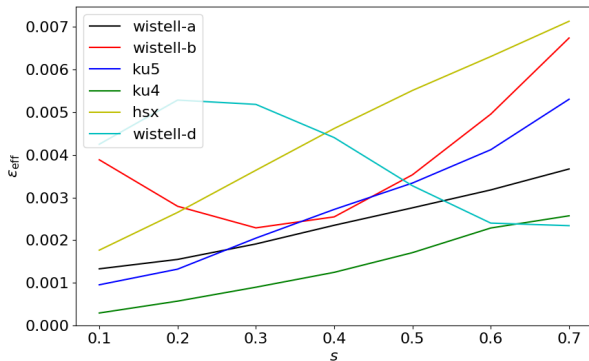
- Correlation exists between QS and alpha losses for QH and QA separately

Configuration comparison: Γ_c



- Correlation less strong for Γ_c
- Neither metric properly captures coil ripple effects (HSX outlier)

Configuration comparison: ϵ_{eff}

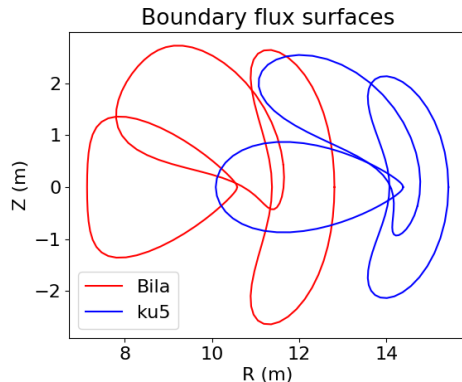
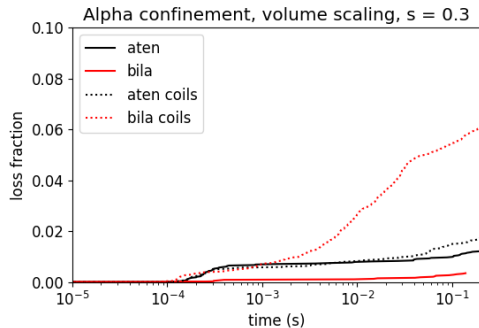


- Almost no correlation for ϵ_{eff}

Notes on Optimization

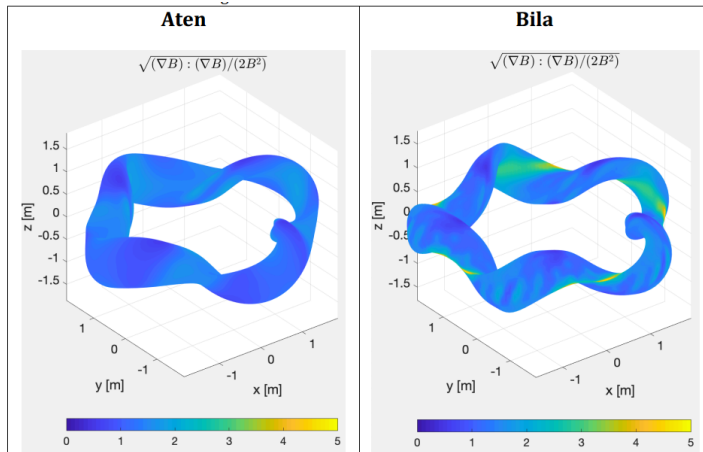
- In general there is good correlation between the QH and Γ_c metrics and energetic particle performance, but it is not exact!
- Sometimes best performing configurations in *both* metrics is obtained with only QH active in optimization
- Better overall QS metric is obtainable when optimizing on an outer surface, $s > 0.5$ (see also Henneberg PPCF 2020)
- There appears to be some difference in good QH vs good Γ_c when dealing with prompt losses, but this needs some dedicated study

Best QH configs appear difficult to produce with coils



- Indentation in teardrop shape is a major problem area for coil generation codes

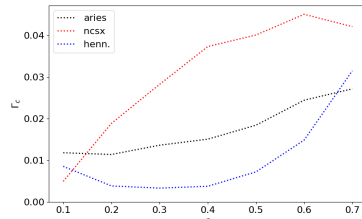
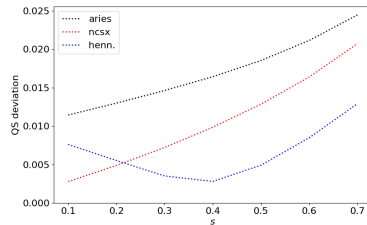
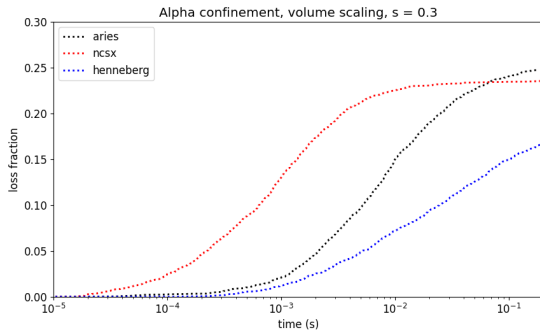
New metric may help indicate problem configs



Metric and picture courtesy of Matt Landreman

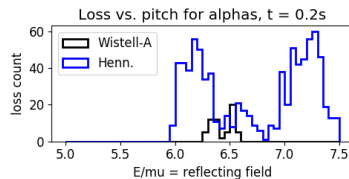
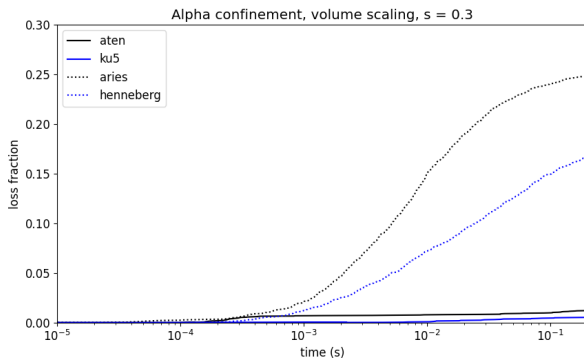
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Metrics appear to correlate well also for QA



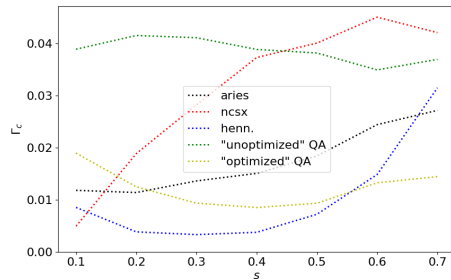
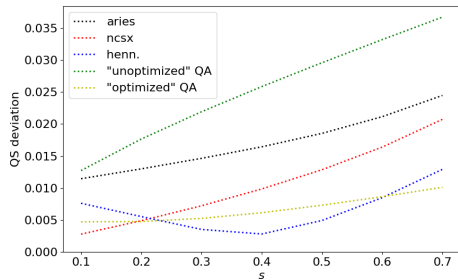
- As with QH, Γ_c improvements correlate to a reduction of prompt losses

Collisionless losses: Optimized QH's outperform best QAs

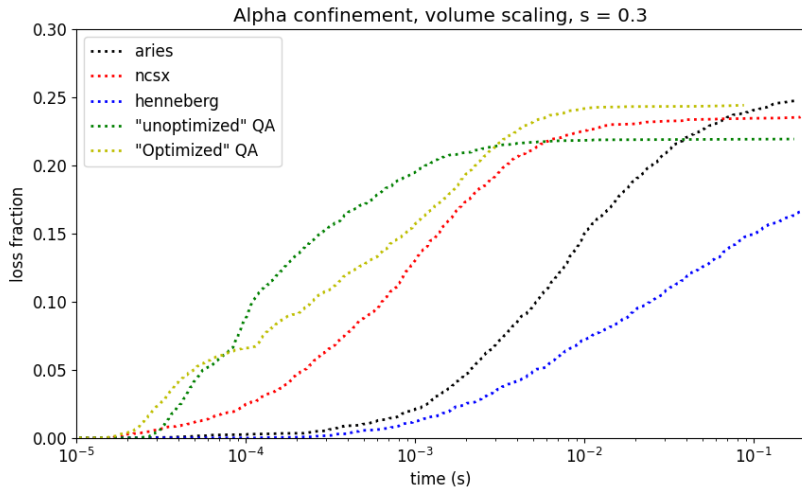


- Note: discovered that at low aspect ratios scaling with "b0" in VMEC is problematic. Will need to rescale with volavgB as the target

Attempts at optimizing QA equilibria

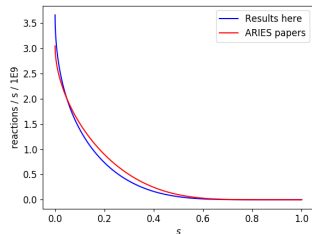
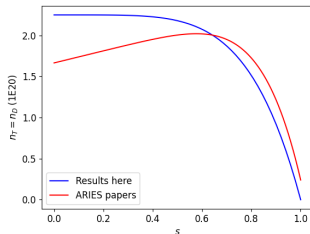
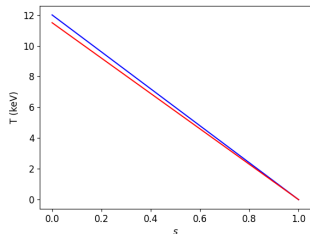


Failure of optimization metrics - more to learn for QA



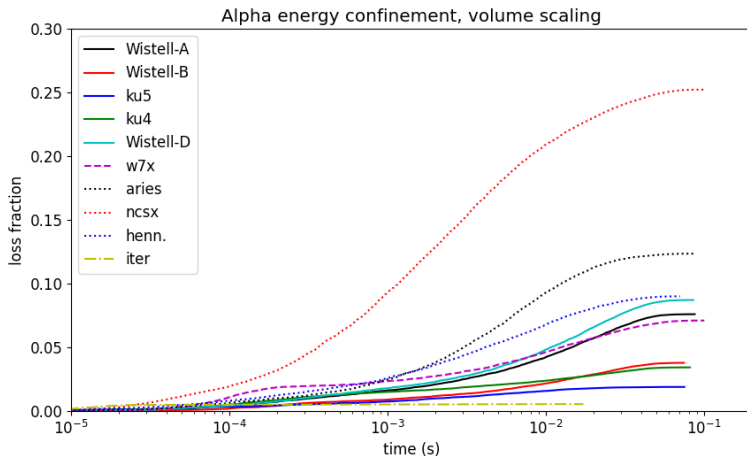
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Setting up collisional profiles for ANTS

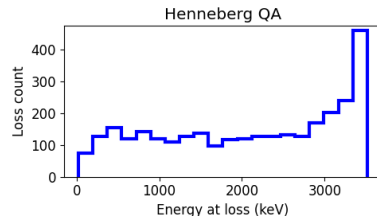
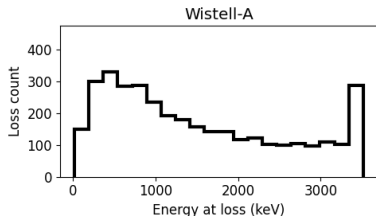
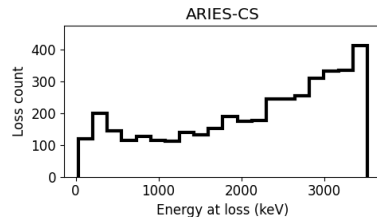
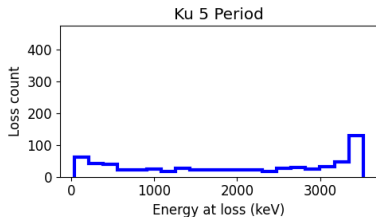


- Density profile $n = n_0(1 - s^5)$; Temperature $T = T_0(1 - s)$
- Density profile is flat, but monotonically decreasing, in contrast to the hollow ARIES profile. Reactivity is thus slightly more peaked
- Reactivity profile prescribes ANTS particle sourcing in the radial direction

Collisional Energy Loss: smaller gap b/w QA, QI and QH



Energy loss spectrum more favorable for QH



Conclusions

- Recipe for optimizing QH for EP confinement appears to work well and is repeatable
 - QH optimizing improves overall losses, Γ_c appears to reduce prompt losses
 - Best QH configurations are probably impossible to produce with coils
- Optimizing QA appears trickier, requires some dedicated effort
- Collisional calculations reduces the performance gap between QA and QH somewhat (although i need to recalc. henneberg QA)