Optimization of quasi-symmetric equilibria for energetic particle confinement

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1. Methods for optimization of energetic particles

2. Optimization of QHS with Γ_c metric

1. Methods for optimization of energetic particles

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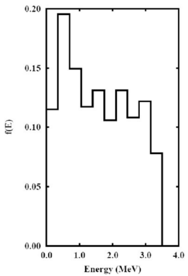
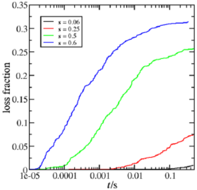
Alpha particle losses may be a driving factor for stellarator reactor design

- 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 under 5% loss at mid-radius
  - Volume of 1900 m^3 at B_0 = 5 T
  - Energy loss at ≈ 6% at mid-radius
- 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





Past optimizations incorporated Monte-Carlo calculations

- Lotz and Henneberg improved confinement mainly by focusing on improving quasi-symmetry
  - Neither directly targeted energetic particles
- Optimization of NCSX to produce ARIES-CS target energetic particles directly
  - Metric used - Monte Carlo simulation of prompt losses
  - Discovered that inclusion of mirror modes improved alpha confinement in axisymmetric configurations

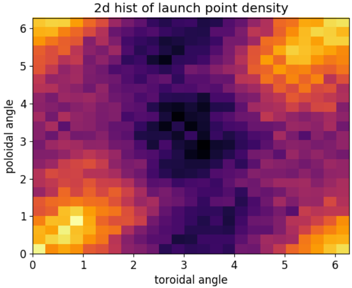
Optimization metrics for energetic particles

- ϵ_{eff}: standard optimization for neo-classical transport
  - Focuses on deeply trapped particles
  - Less effect on particles near trapped-passing boundary
- Quasi-symmmetry
  - Perfect quasi-symmetry has no particle losses
  - Perfect quasi-symmetry is not actually attainable
- Optimize second invariant: $J = \int_b v_{\|} ds = J(\psi)$
  - If $J = J(\psi)$ is a flux function, there should be no losses
  - J^* attempts successful for conventional stellarators
- $\gamma_c = \arctan(v_r / v_\theta)$
  - Seeks to reduce ratio of radial to poloidal drift by aligning J contours
  - Successful at optimizing QH

Nemov PoP 1999, Spong PoP 1998, Nemov PoP 2008

How should we compare configurations?

- Collisionless Monte-Carlo evaluations at various flux surfaces (collisional after)
- Fair comparisons should be at the same volume and field strength
- Velocity distributions should accurately reflect alpha birth profiles
- Launch probability must be consistent to flux surface area rather than uniform in θ, ϕ

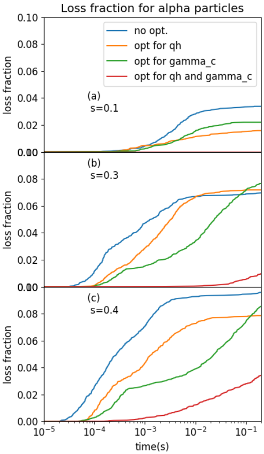


- Outboard side favored over inboard side
- “Triangle” favored over “bean” (an effect of radial axis excursions in QH

1 Methods for optimization of energetic particles

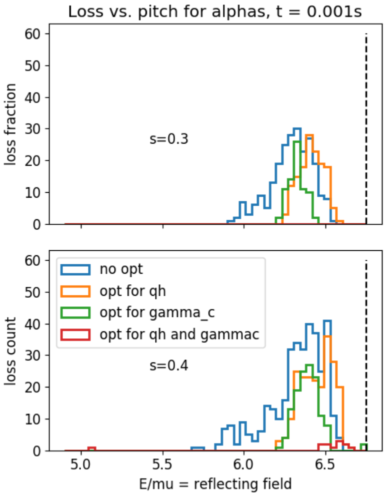
2 Optimization of QHS with Γ_c metric

Best performance when optimization for Γ_c and quasisymmetry



- All configurations scaled to 450 m^3 and B_0 = 5.6 T
- Aspect ratio 6.7
- $\Gamma_c \sim \sum_{E/\mu} \sum_{\mathrm{wells}} \int_b \arctan^2 \left(v_r / v_\theta \right) \tau_b$
- Prompt losses entirely eliminated in best performing case (red)
- All losses eliminated inside s = 0.1 (AR $\approx$ 20)

Particles losses at trapped passing boundary are suppressed



- 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

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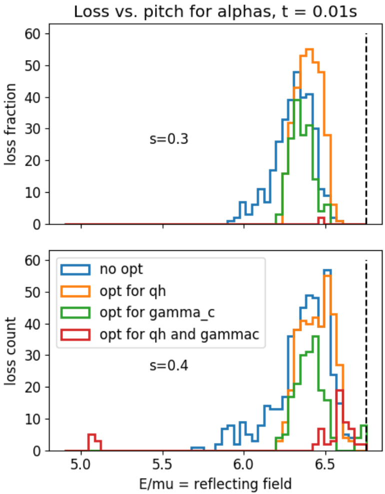

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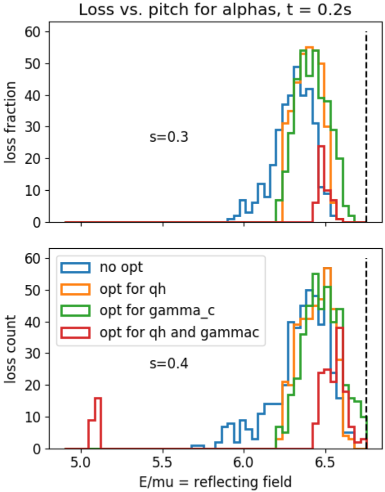

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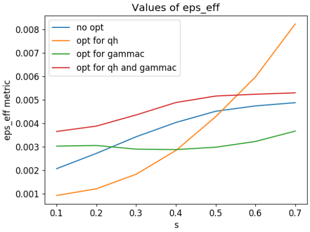
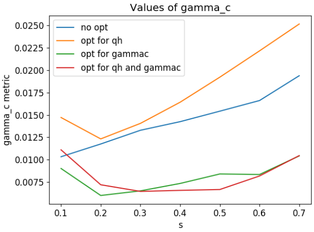
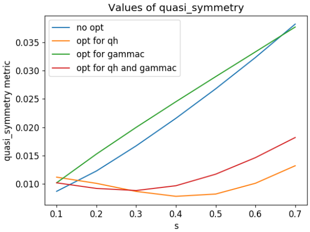
ϵ_{eff} is not the correct metric for energetic particles

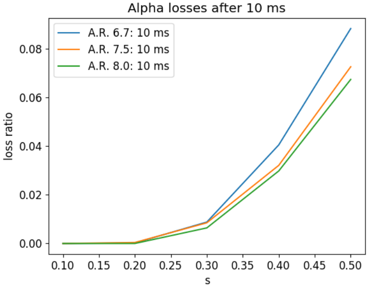


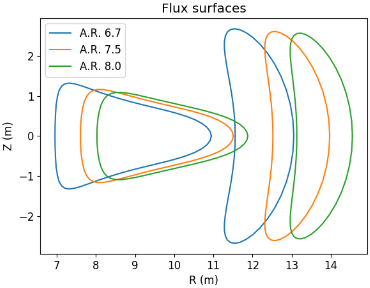




- Improvement of alpha confinement despite worse ϵ_{eff} across most of the radius

Good performance at higher aspect ratio





- Configurations have equivalent volume
- Larger aspect ratio configs have lower minor radius, and larger ρ^*

Optimization of Γ_c and quasihelical symmetry produces configurations with excellent particle confinement

- Work with community to discuss ways to properly compare EP confinement across configurations
  - Make sure we're launching the same distributions
  - Determine appropriate collisional models and “fair” profiles
- Is it possible to optimize J directly?
- Attempt optimizations of QA equilibria
- Examine effects of finite coils
  - Ferritic inserts for stellarators