An Analysis of Coil Optimization Parameters for a Stellarator Nuclear Fusion Device

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Overview

- Stellarator fusion reactor designs can have difficulties confining particles, but recently, quasi-symmetric geometries have been found with excellent calculated confinement
- To prove the feasibility of these geometries, coils must be found which both produce the target magnetic field and can be easily manufactured
- This project looks at the process of optimizing coils for a specific quasi-helical symmetric surface.

Optimization Function

To find reasonable coils that reproduce the target geometry, a Least-Squares optimization is performed, using simsopt.

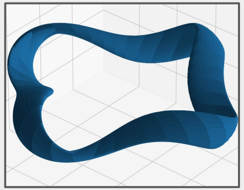
$$\sum_i w_i f_i^2$$

The coil fourier modes and currents are the variables changed in optimization.

The following objectives f_i were included:

- Integral of squared magnetic field normal to target surface
- Coil Length
- Coil to Coil Distance
- Coil to Surface Distance
- Maximum Curvature of the Coil
- Mean Squared Curvature of the Coil
- Linking Number between coils (returning an integer if the coils are linked, and 0 if they are not

The target surface is a Quasi-helical stellarator configuration from (Landreman & Paul, Phys. Rev. Lett. 128 (2022) 035001) was used for the target surface. No previous coil optimizations had been performed for this surface.



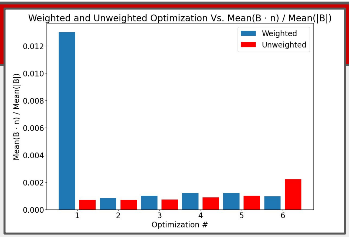
Surface-varying weight to accuracy of reproduction

To test the importance of uniform accuracy to the target surface, a weight function was added to the integral of the magnetic field normal to the surface. This factor increases when radial drift is large

- A weight function is applied to each point on the surface during optimization
- The weight applied is proportional to the drift of particles away from the surface at that point
- This weight is compared to the unweighted function
- Results varied significantly depending on initial parameters. More research must be done to determine cause

$$\int w(\theta,\zeta)(\mathbf{B}\cdot\mathbf{n})^2 \mathrm{d}S$$

$$w(\theta,\zeta) = (\nabla B \times \mathbf{B}\cdot\mathbf{n})^2$$

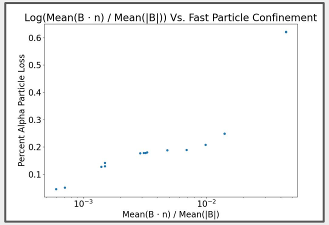


Comparison of B · n / |B| for unweighted and weighted optimizations

Each optimization changes weights of the function

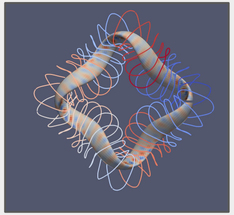
Field Accuracy Metric

- To reproduce the target surface, coils are varied to minimize B · n / |B|.
- n: unit normal of target surface
- B: Magnetic field created by coils
- To gauge importance of accuracy to the field, B · n / |B| was compared to fast alpha particle confinement.
- Simsopt was used to trace simulated 5KeV alpha particles, beginning on the magnetic axis. Particles were traced for 0.01 seconds.
- There is a strong correlation between B · n / |B| and fast particle confinement.



$$\mathrm{link}(\gamma_1,\gamma_2) = \frac{1}{4\pi}\oint_{\gamma_1}\oint_{\gamma_2}\frac{\mathbf{r}_1-\mathbf{r}_2}{|\mathbf{r}_1-\mathbf{r}_2|^3}\cdot(d\mathbf{r}_1\times d\mathbf{r}_2)$$

Linking Number Equation (Wikipedia)

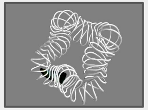


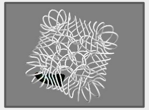
Best set of coils produced
5 coils per half period
B · n / |B| of 0.0006
Particle Loss of 0.046

Coil Complexity Metrics

Curvature and Mean Squared Curvature

- Variables affecting distance between components of a reactor should stay fixed
- Changing curvature maintains the necessary parameters for a reactor while still affecting confinement
- At certain lengths, coils become messy





Conclusions

- B · n / |B| is a useful metric to estimate particle confinement in an optimization for this quasi-helical target surface
- Curvature and MSC are the best metrics to vary when coil to plasma and coil to surface distances must be maintained
- Adding weights to individual points on the surface where particle drift is especially bad can cause significantly worse or better results. More testing should be done to determine when this occurs.