THEA ENERGY

Optimization of the Planar Coil Stellarator

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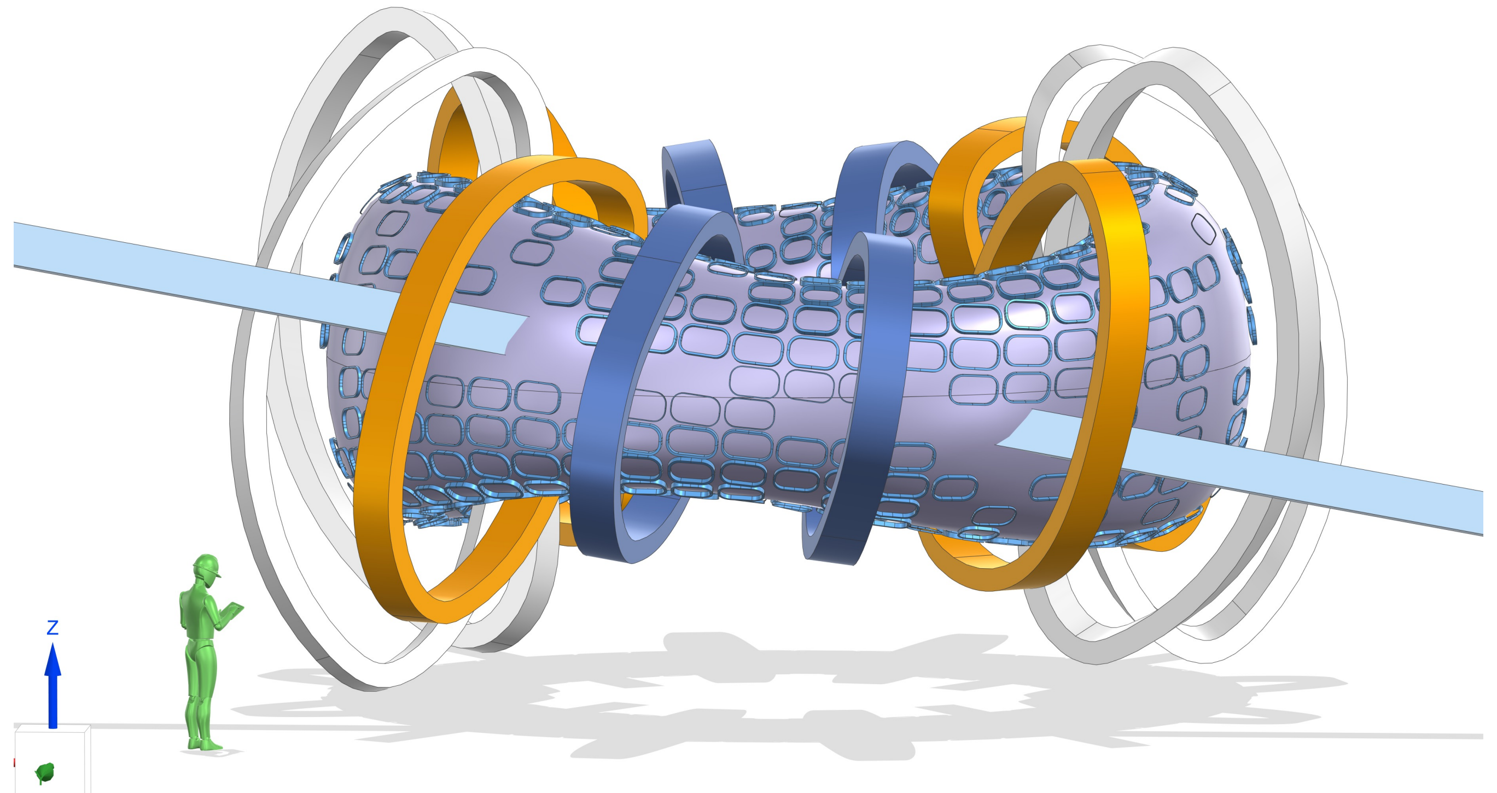
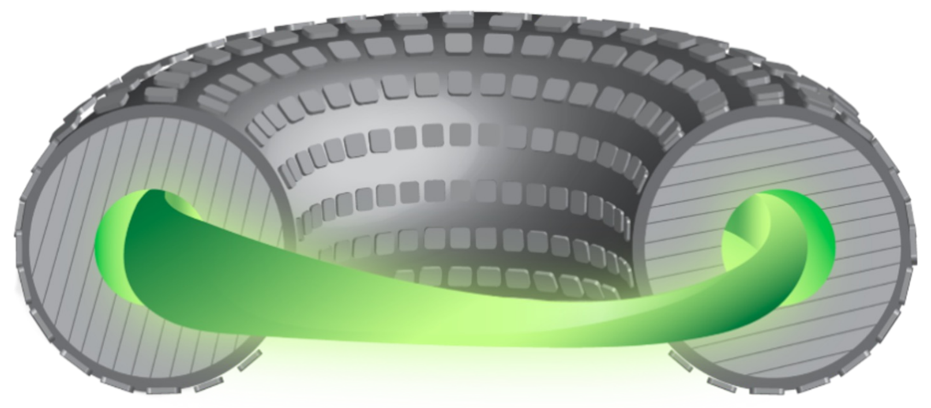
Introduction

On the path to a fusion pilot plant, Thea Energy plans to build Eos, a sub-breakeven, deuterium-deuterium, beam-target fusion, stellarator neutron source facility for producing tritium and other valuable radioisotopes. Thea is pursuing a planar coil stellarator design, without the use of modular coils.



Eos will confine plasma in a quasi-axisymmetric magnetic field produced by a set of planar electromagnetic coils. Planar plasma-encircling coils: White, orange, and blue. Planar shaping coils: Rounded rectangles. NNBI beamline: Light blue rectangular prism.

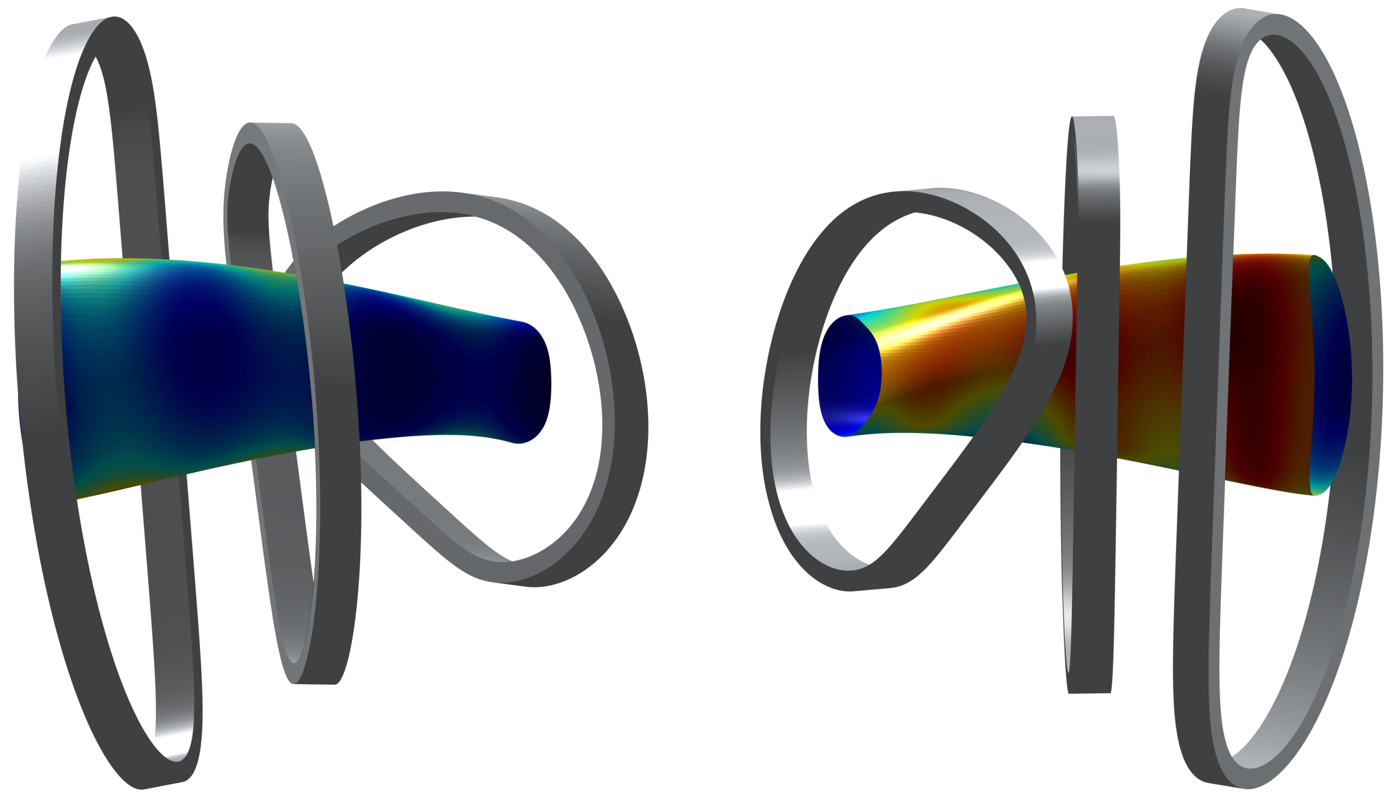
Overview of Eos Coil Design Requirements



- All encircling and shaping coils are planar and convex
- Small number of encircling coils leaving gaps for sector maintenance
- Small number of unique shaping coils
- Sufficient coil offset leaving space for blanket/shield
- Critical current constraint on HTS tapes (future work)
- Sufficient magnetic control in shaping coils for dynamic access to high-pressure equilibrium (future work)

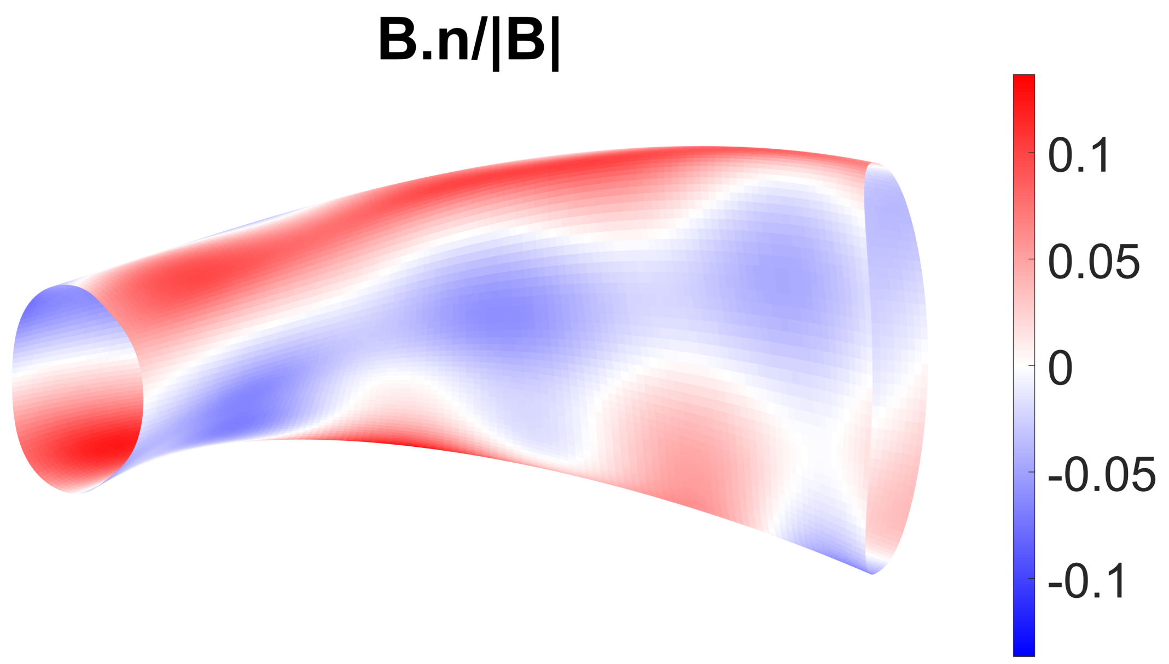
Step 1/3: Preliminary Encircling Coil Optimization

- 2.4% beta equilibrium scaled and reoptimized from a highly symmetric QA [1]
  - Aspect ratio 6
  - Major radius 3.24 m
  - Average field 5 T



Low field side of equilibrium plotted on left and high field on right. QA like magnetic field magnitude on plasma boundary but with large ripple.

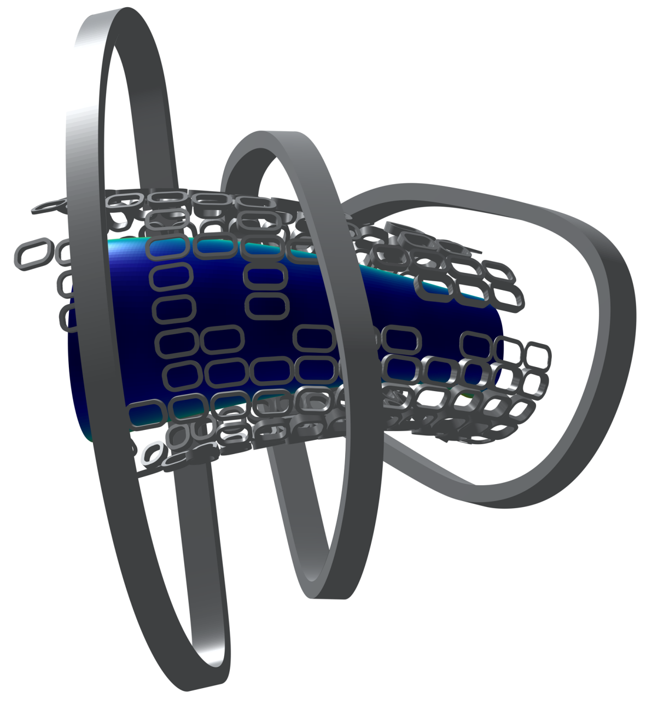
- Optimized encircling coils generate 97% of confining magnetic field [2,3]
  - Eases requirements on shaping coils
- Maximum field error: $\max(|\mathbf{B}\cdot\boldsymbol{n}|) = 0.7\ \mathrm{T}$
- Average field error: $\left\langle\frac{|\mathbf{B}\cdot\boldsymbol{n}|}{|\mathbf{B}|}\right\rangle = 3.1\%$



Normal magnetic field errors on plasma boundary are sufficiently low to begin shaping coil optimization.

Step 2/3: Preliminary Shaping Coil Optimization

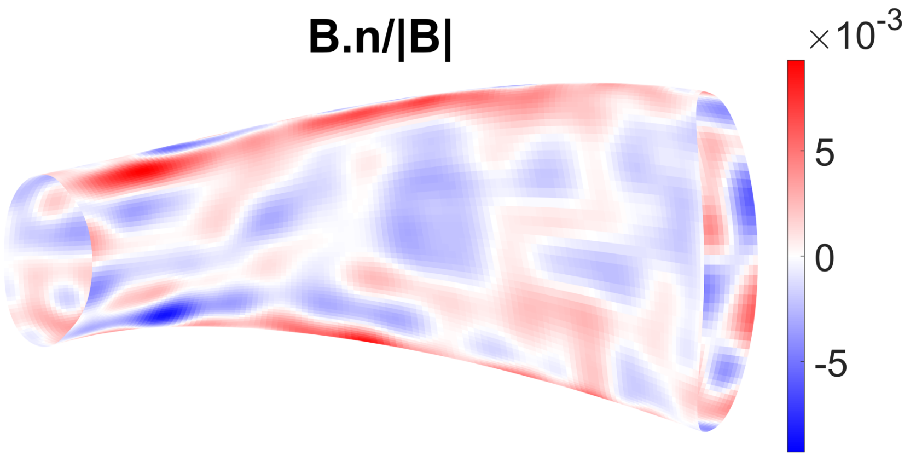
- Shaping coil array is initialized with sector maintenance in mind [4]
  - 5 unique shaping coils
- Encircling coils are held fixed during shaping coils optimization
  - ~30% of shaping coils are not needed [5]
    - Tangential injection of NNBI [6]
  - Optimization is locally convex
  - Maximum current constraint on shaping coils
- Maximum field error: $\max\left(\frac{|\mathbf{B}\cdot\boldsymbol{n}|}{|\mathbf{B}|}\right) = 1.1\%$
- Average field error: $\left\langle\frac{|\mathbf{B}\cdot\boldsymbol{n}|}{|\mathbf{B}|}\right\rangle = 0.18\%$



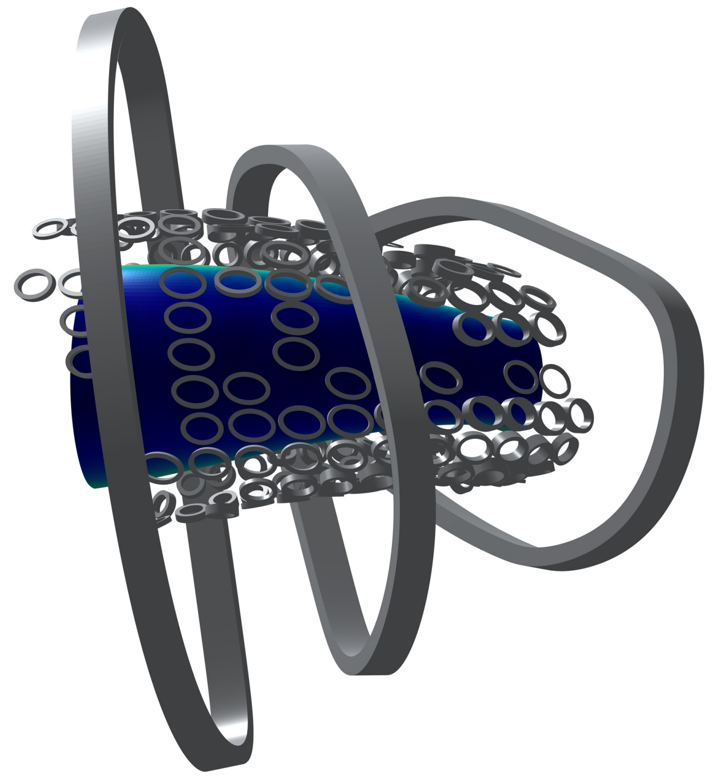
Gaps in the shaping coil array are in regions where encircling coil errors are small

Step 3/3: Encircling and Shaping Coil Optimization

- Combinatorial optimization for shaping coils [7]
- Maximum field error: $\max\left(\frac{|\mathbf{B}\cdot\boldsymbol{n}|}{|\mathbf{B}|}\right) = 0.93\%$
- Average field error: $\left\langle\frac{|\mathbf{B}\cdot\boldsymbol{n}|}{|\mathbf{B}|}\right\rangle = 0.15\%$



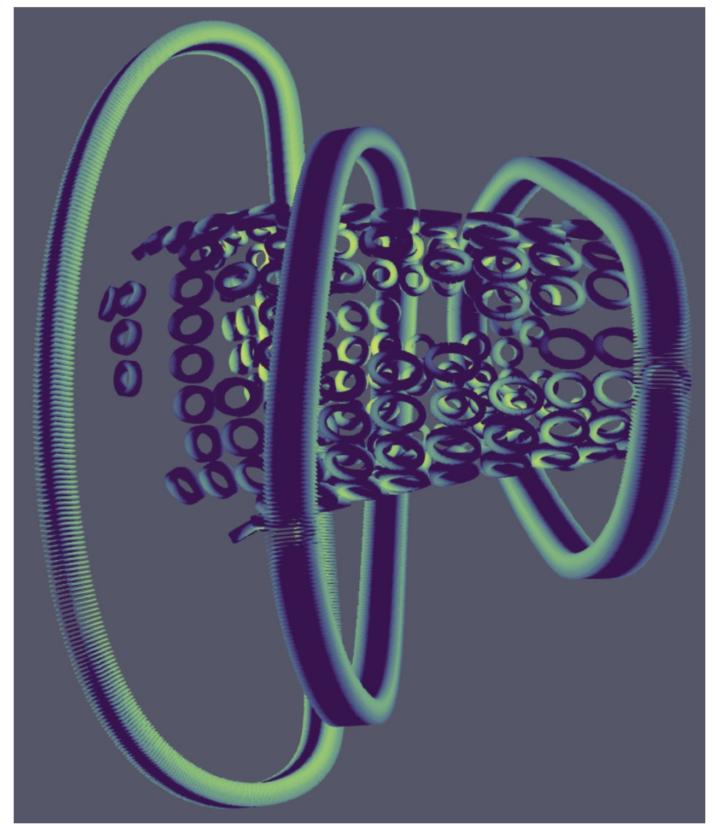
Normal magnetic field error shows acceptably small regions of error close to 1% in higher curvature regions.



Shaping coils shapes are also optimized to significantly reduce curvature, field error, and conductor usage

Finite-build coil optimization

- Matt Landreman's finite-build code calculates magnetic field inside of conductors [8]
  - Modified Biot-Savart (1D integral)
  - Interfacing with DESC for optimization
- Fast calculation/optimization of engineering targets
  - Lorentz loads on conductors
  - Normal magnetic field on HTS tapes
  - Critical current
- Coil architecture design/optimization
  - Conductor usage/cost
  - Space allocation



Critical current map calculated from normal magnetic field on HTS tapes

Conclusion

Thea Energy will design, construct, and operate a large-scale neutron source stellarator, Eos. A set of planar encircling coils is optimized to produce the vast majority (~97%) of a candidate QA equilibrium's magnetic field. An additional set of smaller shaping coils reconstructs the remaining magnetic field with a maximum normal field error of .93% and an average field error of .15%. The coil model used for optimization is updated from a filamentary to a finite build model enabling the calculation of more relevant engineering targets such as HTS critical current. Thea Energy is producing plausible planar coil assembles that will be leveraged in future stellarator designs like Eos and follow-on fusion power plants.

References

1. Landreman, M., Buller, S., & Drevlak, M. (2022). Optimization of quasi-symmetric stellarators with self-consistent bootstrap current and energetic particle confinement. Physics of Plasmas, 29(8).
2. Kruger, T. G., Zhu, C., Bader, A., Anderson, D. T., & Singh, L. (2021). Constrained stellarator coil curvature optimization with FOCUS. Journal of Plasma Physics, 87(2), 175870201.
3. Dudt, D. W., Conlin, R., Panici, D., & Kolemen, E. (2023). The DESC stellarator code suite Part 3: Quasi-symmetry optimization. Journal of Plasma Physics, 89(2), 955890201.
4. Gates, D., et al, (2024). Stellarator fusion systems enabled by arrays of planar coils. Submitted to Nuclear Fusion July 2024.
5. Wu, R., Kruger, T. G. (2024). Sparse regression for planar coil stellarator optimization. In preparation for submission.
6. Swanson, C., et al, (2024). The scoping, design, and plasma physics optimization of the Eos neutron source stellarator. Submitted to Nuclear Fusion July 2024.
7. Kruger, T. G., Martin, M., Gates, D. A., (2024). The planar coil stellarator: coil optimization methods. Submitted to Nuclear Fusion July 2024.
8. Hurwitz, S., Landreman, M., & Antonsen, T. M. (2023). Efficient calculation of the self magnetic field, self-force, and self-inductance for electromagnetic coils. arXiv preprint arXiv:2310.09313.

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