THEA ENERGY

All Planar Stellarator Coil Optimization

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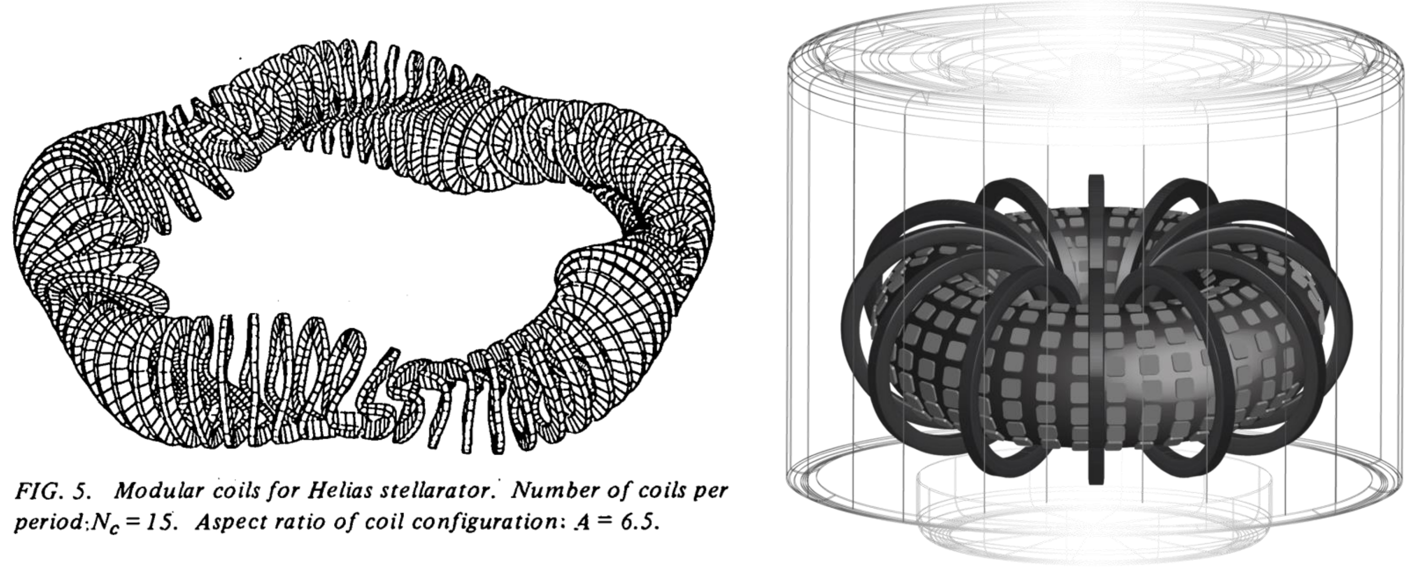
Introduction

Optimized stellarator designs have historically required non-planar, precisely shaped, highly complex coil systems. Recent advances in stellarator theory have enabled the design of much simpler magnet systems. Our stellarator coil sets are entirely composed of planar electromagnetic coils. Planar coils are optimized to reconstruct quasi-symmetric 3D MHD equilibria with an extremely high precision. Planar coil systems greatly reduce the risk of stellarator development.



A preliminary modular coil set design for W7-X is shown on the left (Nucl. Fusion 1987 27 867). A system of planar coils is shown on the right. The planar coil system includes larger linking coils and an array of smaller coils which point normally to the plasma boundary.

Methodology

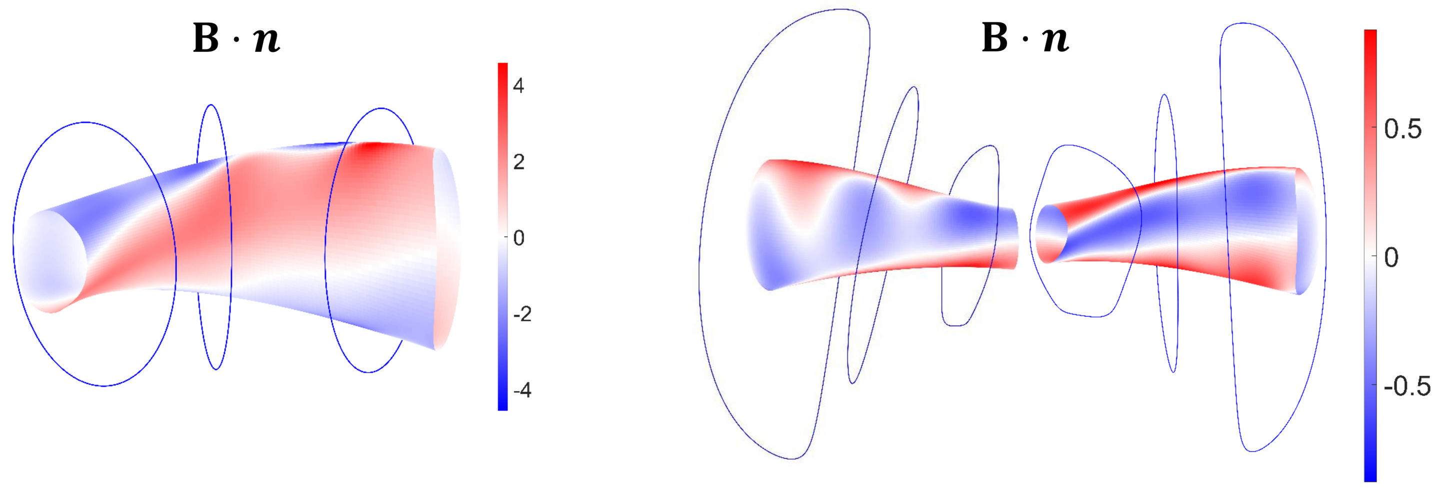
Coils for the all planar stellarator are designed in a multi-step procedure where each step is a constrained non-linear optimization.

1. An initial set of planar encircling coils is optimized to reconstruct the majority of a target magnetic field. A minimum coil to plasma constraint ensures there is sufficient room for a small coil array.
2. An array of smaller shaping coils is constructed between the plasma boundary and the encircling coils. Encircling coil planes are used to define columns of the shaping array.
3. Coil currents are optimized to produce the remainder of the target magnetic field. The shaping array geometry is fixed.
4. The least important coils within an array are removed with a discrete optimization. Gaps in the coil array provide access to the plasma.
5. The encircling coils and the coil array currents are optimized again to reconstruct the target magnetic field with high precision.

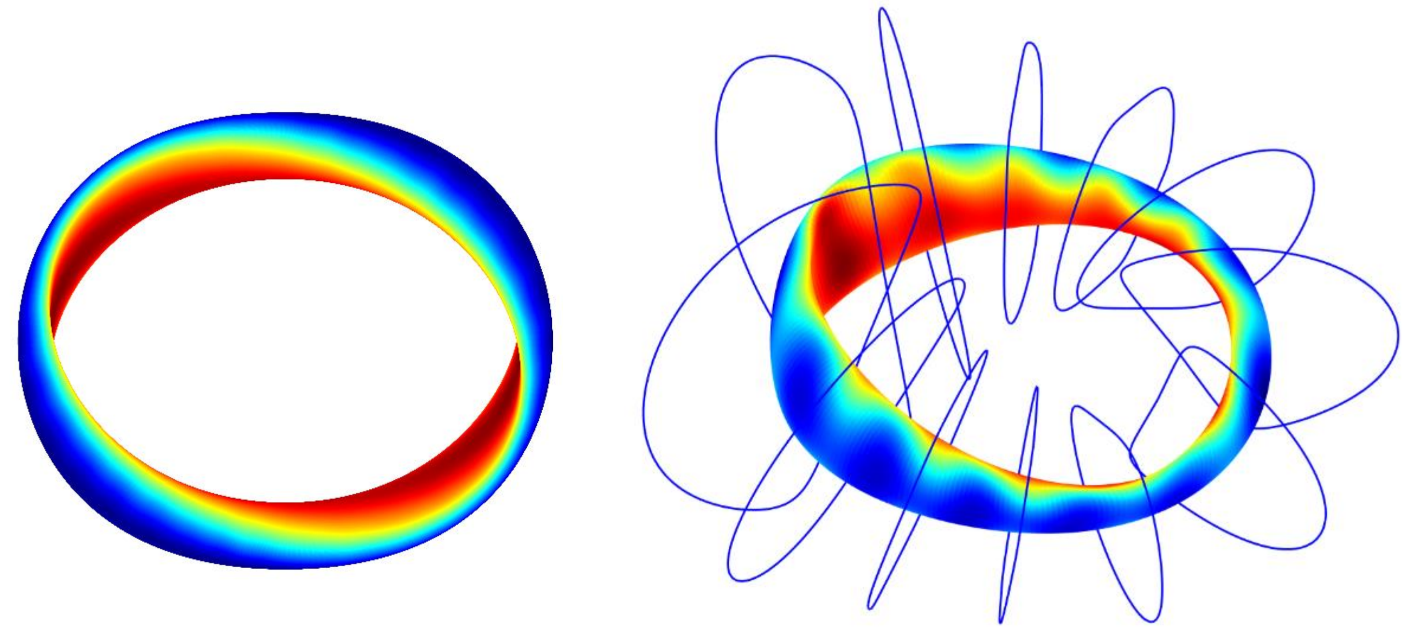
Encircling Coil Optimization

Planar coils are optimized for the β = 2.5% QA from (Phys. Plasmas 2022 29 082501). Encircling coils are enforced to be planar by using a 2D Fourier series parameterization. The normal magnetic field on the plasma boundary is minimized to reconstruct the target equilibrium's magnetic field.

$$f_{Bn} = \int_S (\mathbf{B} \cdot \boldsymbol{n})^2 \, dS$$



An initial circular coil set is shown on the left. Two views of the optimized coils are shown on the right with much smaller normal field errors on the plasma boundary. The average magnetic field strength for this equilibrium is 6 T. The average normal field error in the optimized coil set is .2 T.

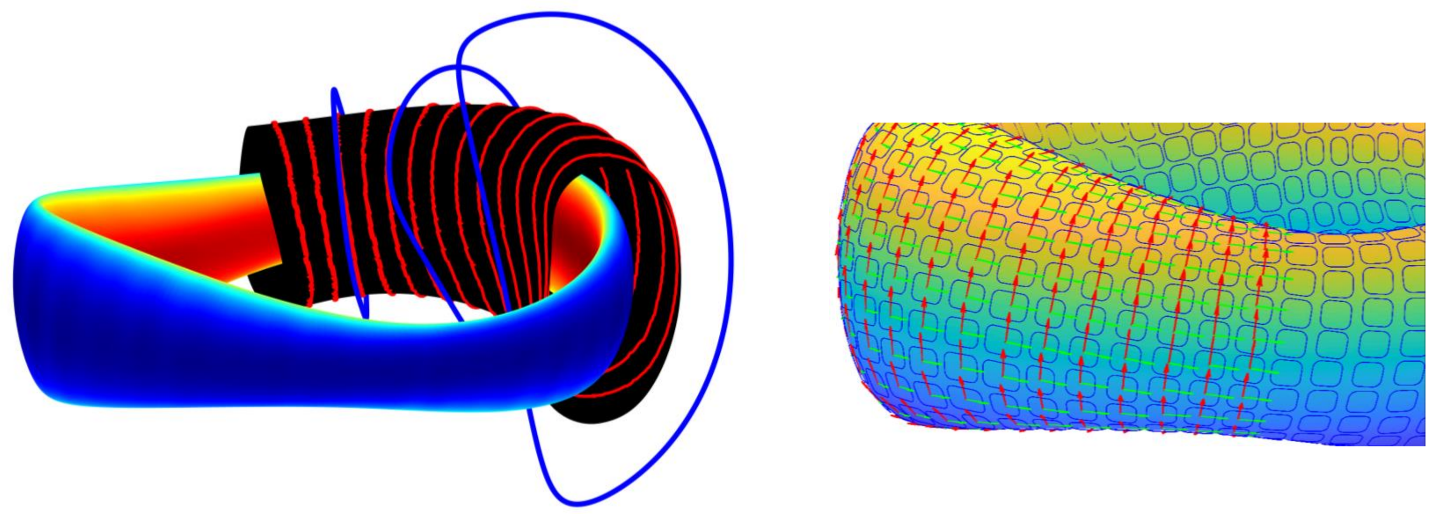


The target (fixed-boundary) magnetic field is plotted on the left. The reconstructed magnetic field from only encircling coils is plotted on the right. The vast majority of the magnetic field is generated by the encircling coils.

Coil currents and geometries are optimized under a set of constraints while minimizing normal magnetic field errors on the plasma boundary

- Minimum coil to plasma separation to leave room for shield/blanket/coil array
- Coil to coil separation
- Maximum coil curvature
- Coil convexity for ease of HTS tape winding
- Total linking current (toroidal flux)
- Coil length (current-length/cost)

Small Coil Array Design

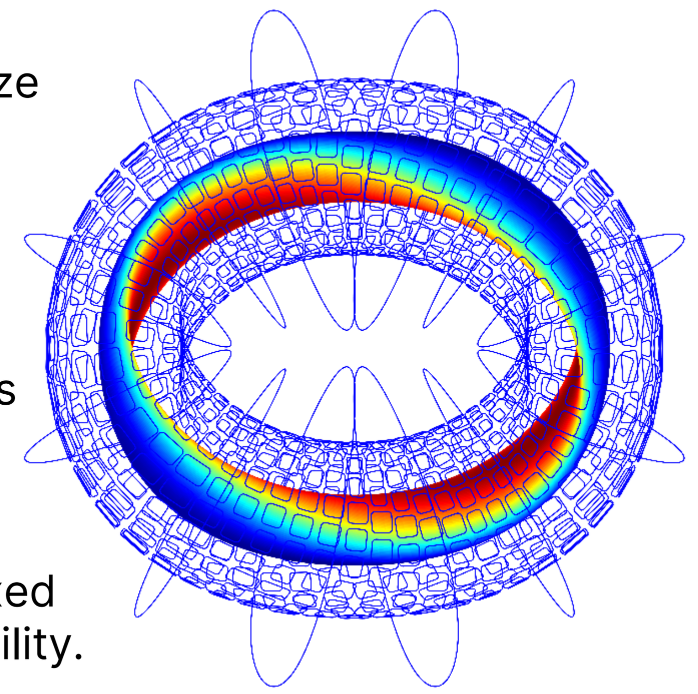


- A "winding-surface" (plotted in black) locates the small coils within an array
- Cut planes on the winding surface are defined by the encircling coils (left in red)
- Coil centroids are initialized by taking equal arclength steps along the red cut planes
- Small coil shapes are chosen from a short list of options to reduce the number of unique coils in the design (5 in this case)

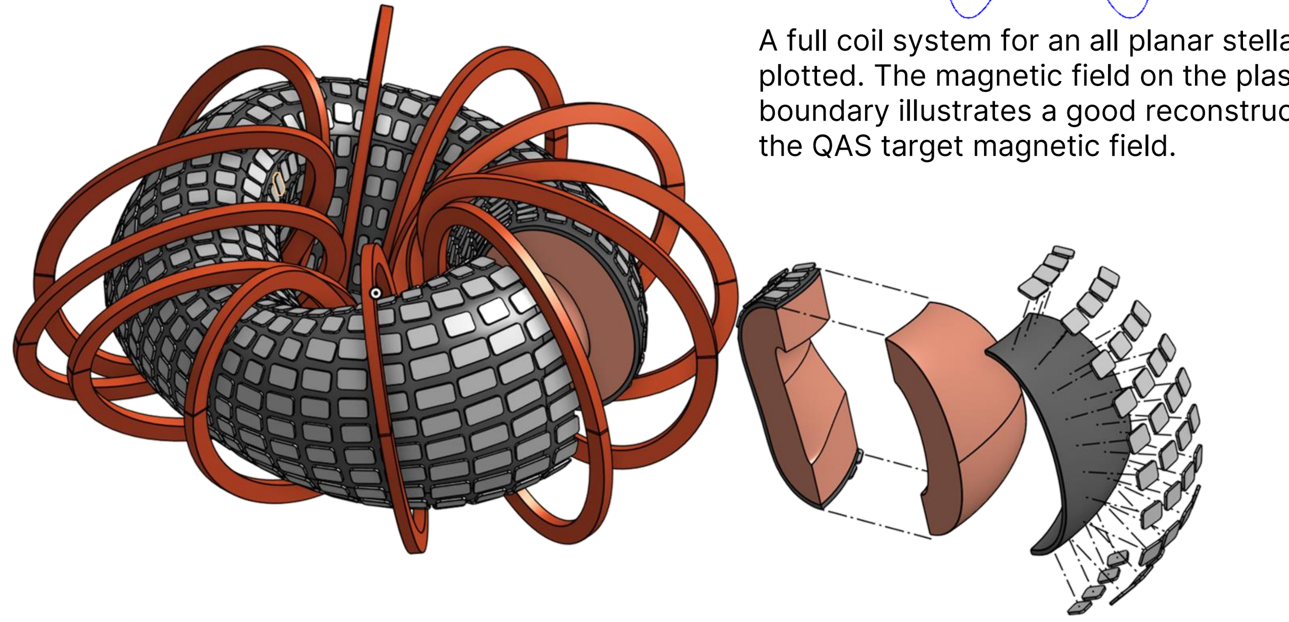
Coil currents are perturbed to minimize normal field errors on the plasma boundary.

Currents in the small coils are constrained by engineering limitations e.g. HTS critical current.

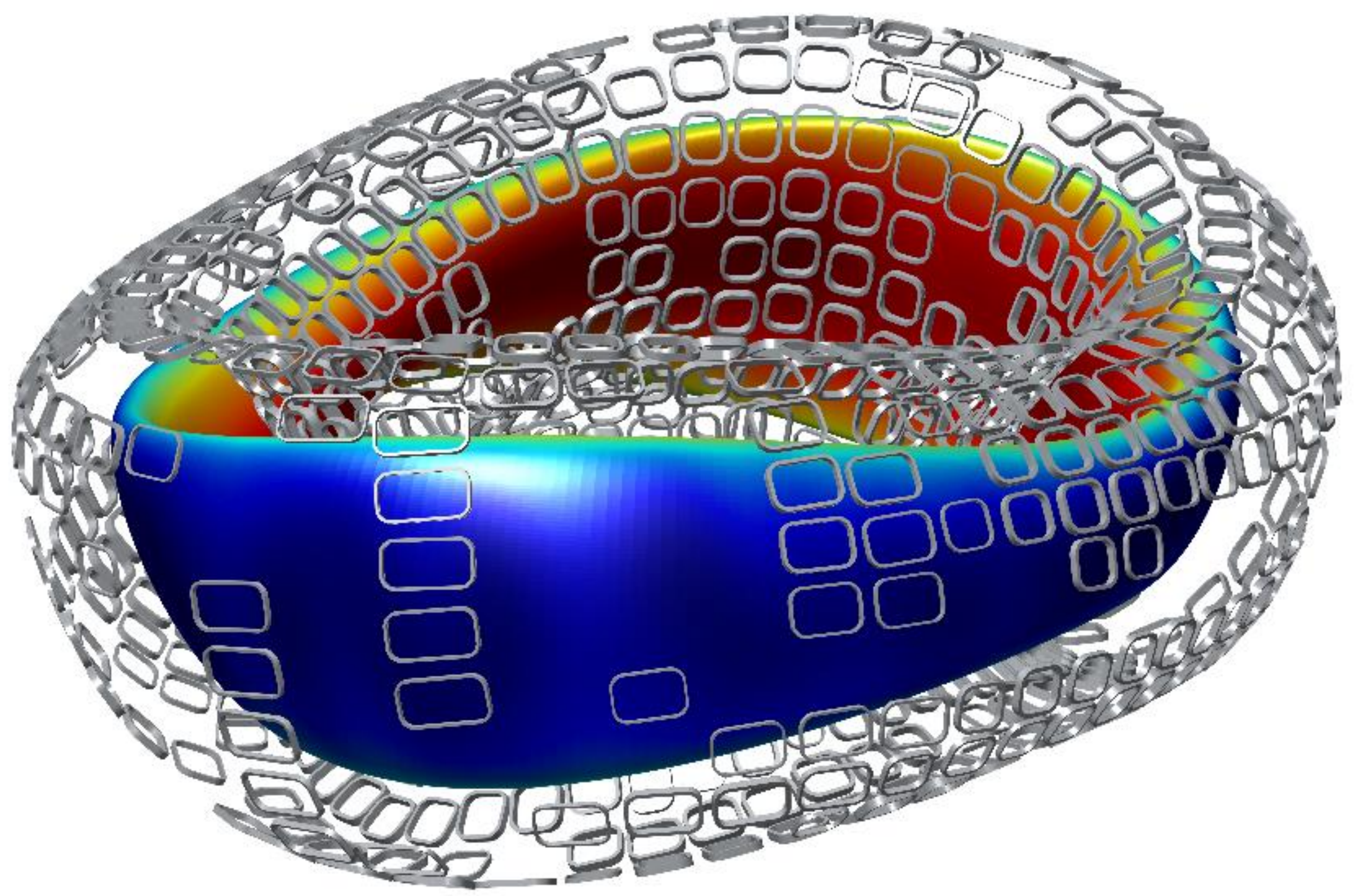
Encircling coil geometries are kept fixed to retain a sector maintenance capability.



A full coil system for an all planar stellarator is plotted. The magnetic field on the plasma boundary illustrates a good reconstruction of the QAS target magnetic field.



A sector of the small coil array and blanket can be extracted radially between the encircling coils



A quarter of the coil array can be deleted without significantly affecting the magnetic field. Gaps within the coil array are conveniently located on the outside of the plasma allowing for tangential beam access, diagnostics, plumbing, etc.

Conclusions

Quasi-axisymmetric magnetic fields are fully generated by a series of planar encircling coils and an array of shaping coils

- No more reliance on precisely shaped modular/helical coils
- Reduces engineering design complexity/project risk

High-fidelity reconstruction of the target magnetic field is achieved with only planar coils

Plasma control is enabled by modulating currents in the coil array

- Operational startup from vacuum
- Runtime scenario development
- Island elimination

Arrays of shaping coils are offset from the plasma boundary to leave adequate room for a shielding/breeding blanket

Sectors of the shaping array are extracted radially between linking coils, providing a sector maintenance capability

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