DISCRETE STELLARATOR COIL OPTIMIZATION

[1]K. C. HAMMOND

[1]Princeton Plasma Physics Laboratory, Princeton, NJ, United States of America

Email: khammond@pppl.gov

Design and optimization of magnets that produce precise three-dimensional fields is a challenging but necessary part of stellarator design. In this contribution, a new technique is introduced for coil design that uses fully discrete optimization techniques. The method offers some advantages over previous coil design techniques in its combined abilities to (1) efficiently identify the most important locations for coil placement and/or for shape modifications of existing coils, (2) obey arbitrary spatial constraints on coil location and geometry, (3) exhibit flexibility with the coil topology, with the ability to introduce new coils and remove existing ones, all while (4) producing designs with highly accurate magnetic fields. Such capabilities can be advantageous in designing cost-effective coils for stellarator reactors that are sufficiently simple to construct, assemble, and disassemble for maintenance. Initial solutions generated by this method are presented, including a set of modular coils and a set of saddle coils confined to toroidal sectors. The methods are being implemented in the open-source SIMSOPT codebase.

The design procedure entails the optimization of a current distribution on a "wireframe," a solution space developed specifically for this application. The wireframe essentially consists of a set of interconnected straight segments of filamentary wire that enclose the plasma, an example of which is shown in Fig. 1. The current distribution is then specified by the current flowing in each segment. This simple parametrization of the current distribution makes it easy to impart arbitrary spatial restrictions. For example, if one wishes to avoid having any current in a particular region of space to leave room for a reactor component, one can simply impose constraints for the segments in that region to have zero current. The wireframes explored in this work exhibit toroidal topology. However, in principle, wireframes can be designed with arbitrary topology, e.g. to fill a three-dimensional volume around the plasma.

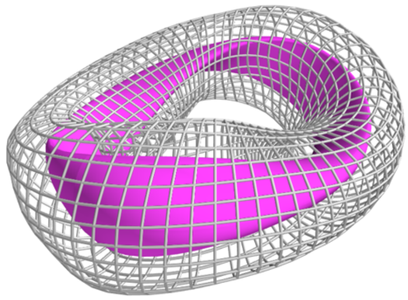

Figure 1: Example of a wireframe (grey) enclosing a plasma (magenta).

The current distribution on the wireframe is optimized by a newly developed optimization method called "Greedy Stellarator Coil Optimization" (GSCO). GSCO works by adding loops of current to the wireframe one by one, each time choosing the location and polarity that brings about the greatest reduction in an objective function. The objective function used in this work targets both field accuracy and sparsity. Targeting field accuracy ensures that the field produced by the current distribution will have the 3D shaping necessary to confine a given plasma equilibrium, while targeting sparsity reduces the complexity and spatial footprint of the current distribution. The GSCO method was inspired by similar procedures that have been developed recently for optimizing arrays of permanent magnets for stellarators [1-3].

Two example current distributions optimized through the GSCO procedure are shown in Figure 2 and described in more detail in Ref. [4]. Both solutions were optimized to generate a magnetic field for the plasma equilibrium with precise quasiaxisymmetry described in Ref. [5]. The equilibrium has zero beta and zero current, a magnetic field on axis of 1 T, a major radius of 1 m, and an average minor radius of about 0.17 m. The first solution (Figure 2a-b) consists essentially of modular coils that link the plasma and produce both the toroidal magnetic field and the three-dimensional field shaping. The second solution (Figure 2c-d) consists of a set of saddle coils that provide field shaping but do not supply a toroidal field (the toroidal field comes from external toroidal field coils). Both solutions produce highly accurate magnetic fields, as indicated by the Poncaré cross-sections computed from the field lines for each solution. While the solutions produce very different coil designs, they were both optimized within the same wireframe solution space. This illustrates the versatility of the GSCO procedure to find very different solutions depending on what constraints are placed on the optimization.

The second solution (Figure 2c-d) demonstrates some of the key capabilities of the new methodology. First, note that the coils are relatively localized in space. In particular, each saddle coil is confined to lie between two adjacent toroidal field coils, making the coil set relatively easy to assemble and disassemble. This outcome was achieved straightforwardly by applying constraints to wireframe segments underneath each TF coil. In addition, the solution leaves ample open space on the outboard side that can be used for heating systems or other components. This illustrates the ability of the GSCO procedure to find sparse solutions in which coils are placed only in the locations where they are most needed.

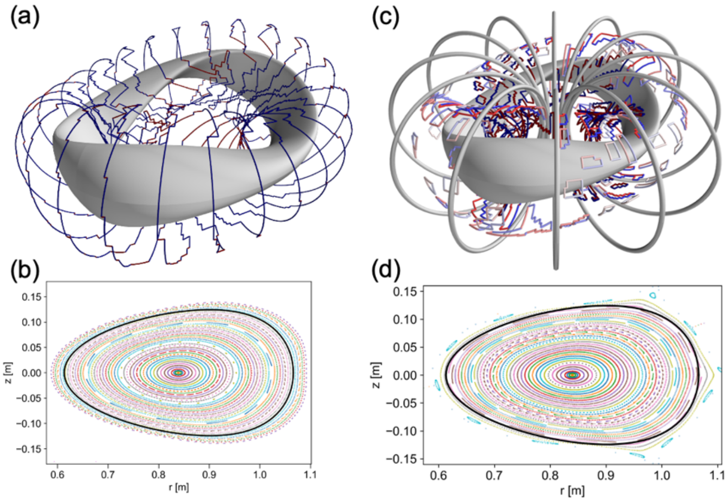

Figure 2: Solutions and corresponding flux surface cross-sections for two GSCO optimizations. (a) Solution for a set of modular coils. (b) Poincaré plot of the flux surfaces produced by the modular solution in (a), alongside the target plasma boundary shown in black. (c) Solution for a set of saddle coils confined to toroidal sectors between adjacent TF coils. (d) like (b), but for the saddle coil solution in (c).

Due to the geometry of the wireframe, the current flows in the solution follow jagged paths with sharp turns at the nodes between connecting segments. Such sharp turns are not realistic features for a real coil, so solutions on the wireframe should not be considered final designs. Rather, the shapes of the current flows in the wireframe can be smoothed out and refined with other optimization tools such as FOCUS to produce a more realistic design.

Next steps will include (1) developing improved “recipes” for finding solutions with multi-step GSCO optimizations and (2) optimizing current distributions on wireframes that fill three-dimensional volumes, which would thereby eliminate the constraint for the solution to lie on a specified toroidal surface. The methods may be applied for many different applications, including designing the main coil set for a stellarator or designing auxiliary coil sets for error field correction on tokamaks or stellarators.

ACKNOWLEDGMENTS

The research described in this submission was conducted under the Laboratory Directed Research and Development (LDRD) Program at the Princeton Plasma Physics Laboratory, a national laboratory operated by Princeton University for the U.S. Department of Energy under Prime Contract No. DE-AC02-09CH11466.

REFERENCES

[1] LU, Z.Y., XU, G.S., CHEN, D.H., ZHANG, X.Y., CHEN, L., YE, M.Y., GUO, H.Y., and WAN, B.N., Development of advanced stellarator with identical permanent magnet blocks, Cell Rep. Phys. Sci. **61** (2022) 100709.

[2] KAPTANOGLU, A.A., CONLIN, R., and LANDREMAN, M., Greedy permanent magnet optimization, Nucl. Fusion **63** (2023) 036016

[3] HAMMOND, K. C., and KAPTANOGLU, A. A., Improved stellarator permanent magnet designs through combined discrete and continuous optimizations, Comp. Phys. Comms. **299** (2024) 109127

[4] HAMMOND, K. C., A framework for discrete optimization of stellarator coils, submitted to Nucl. Fusion, preprint: https://arxiv.org/abs/2412.00267

[5] LANDREMAN, M. and PAUL, E. J., Magnetic fields with precise quasisymmetry for plasma confinement, Phys. Rev. Lett. **128** (2022) 035001