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Stellarator Optimization with Poloidal Field Coils

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Abstract

Stellarators are devices that use magnetic fields to optimize the conditions needed for plasmas to undergo fusion. Unlike tokamaks, stellarators do not rely on a plasma current but can produce a helical magnetic field using only external coils. In a stellarator, the coils surrounding the plasma are called modular coils and those that follow the plasma are called poloidal field coils. Modular coils can be difficult to build if they are too complex. An effort is underway to develop coil conditions that meet both physics and engineering constraints. The FOCUS code was developed to flexibly optimize stellarator coil configurations [C. Zhu, et al., Plasma Phys. Contr. Fusion 60, 065008 (2018)]. In this work, we will use the FOCUS code to develop and analyze coil configurations for a plasma boundary that is optimized for particle confinement. We will examine modular coil configurations with and without a set of poloidal field coils.

1 Introduction & Theory

A stellarator is a type of nuclear fusion reactor. Nuclear fusion is a reaction in which two nuclei combine into one or more different nuclei and subatomic particles. In the process, energy is released. The aim of a fusion reactor is to create as much energy as possible from fusion reactions so that it may eventually be turned into electricity.

Fusion can only occur between very high energy particles. Hydrogen gas must be heated up to temperatures around 100 million Kelvin to overcome the repulsive force between particles. At these extreme temperatures, the atoms in a gas break into ions and electrons, and the gas becomes what we call a plasma. Plasmas are essentially very hot, energetic, and charged gases. The issue, then, is how to force particles collide in a plasma, because their charge and energy makes them want to be as far away from each other as possible. One way we can achieve relatively high densities while maintaining high energies is using magnetic confinement.

Since plasmas are charged, we try to confine them using magnetic fields. The magnetic fields are created by running current through coils that surround the plasma. The two most common magnetic confinement devices are tokamaks and stellarators. Both are generally shaped like a torus. The boundaries of both are shown in Figure 1, with the direction of the magnetic fields shown by the black arrows. The magnetic field for both boundaries is composed of toroidal and poloidal magnetic fields. These directions are shown in Figure 2 by ϕ and θ, respectively. The toroidal direction follows the plasma around the loop and the poloidal direction circles the plasma. The twisting magnetic fields of Figure 1 are due to the superposition of toroidal and poloidal magnetic fields.

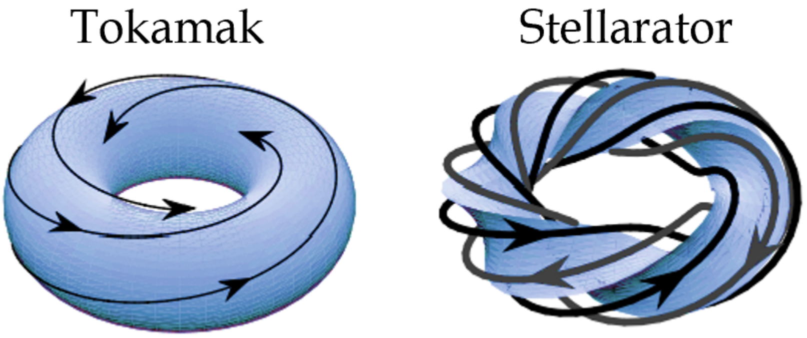


Figure 1: The plasma boundaries (blue) and magnetic field lines (black) typical of a tokamak and stellarator.[2]

The key difference between tokamaks and stellarators is that a tokamak depends upon plasma current to create a toroidal magnetic field. That is, the magnetic field must not only come from coils wrapping the plasma, but from within the plasma itself. Stellarators create their helical magnetic field completely using external coils surrounding the plasma. This results in stellarator coils being

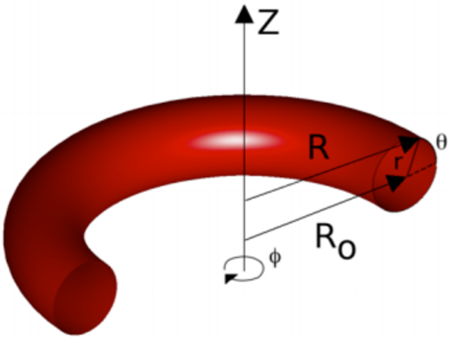


Figure 2: Coordinates to describe a toroidal fusion reactor.

considerably more complex. In a tokamak, each coil wrapping the plasma is identical to the others and arranged axisymmetrically around what would be the z-axis as shown in Figure 2. In stellarators, the coils wrapping the plasma, called modular coils, bend and twist like shown in Figure 3. In

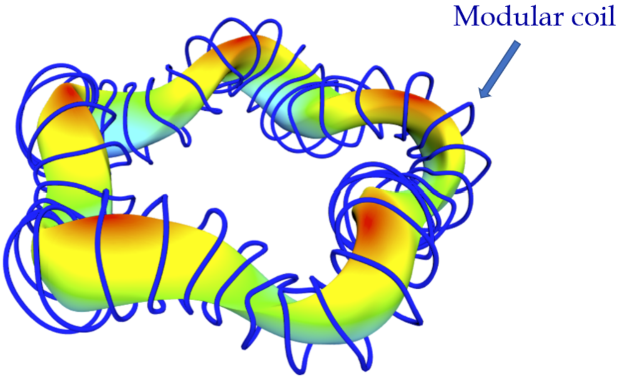


Figure 3: An example of a plasma boundary and the coils that produce a magnetic field surrounding it.

this paper, we use a novel code called FOCUS to optimize the shape and placement of modular coils on two stellarator configurations. We focused primarily on optimizing two parameters: coil length and the magnetic field normal to the plasma surface B_n. By controlling coil length, we minimize the amount of twists and turns the modular coils can make and therefore reduce their complexity. This is considered an engineering constraint. By minimizing B_n, we better match a target plasma boundary. The target plasma boundaries were developed by the WISTELL collaboration at University of Wisconsin and are optimized for particle confinement. Matching the optimized plasma boundary is considered a physics constraint.

2 Methods

All coil optimizations were done using FOCUS, a novel coil optimization code developed at Princeton by C. Zhu.[1] Previous coil optimization codes relied on what is called a winding surface. This surface had to be chosen at an arbitrary distance from the plasma surface and then coils had to be built upon it. FOCUS treats coils as space curves, so their placement is much less restricted. FOCUS has various cost functions that represent distinct optimization parameters. Cost functions map events onto a number that represents the "cost" of that event. The user has the ability to weight cost functions of various optimization parameters depending on what parameters they want to prioritize.

We started with a plasma boundary from the University of Wisconsin called Bila. Bila is the 5-field period boundary case shown in Figure 3. Our main goal was to see the effect on B_n of adding poloidal field coils. Polodial field (PF) coils are coils separate from the modular coils that only influence the poloidal magnetic field. We used two graphs made in Python using data from the FOCUS code to analyze our data. One is of the change in cost functions over all iterations in the optimization code. The user specifies the number of iterations the code will go through before it stops. The second graph is a contour plot of the surface B_n. An example of both of these plots is shown in Figure 4.

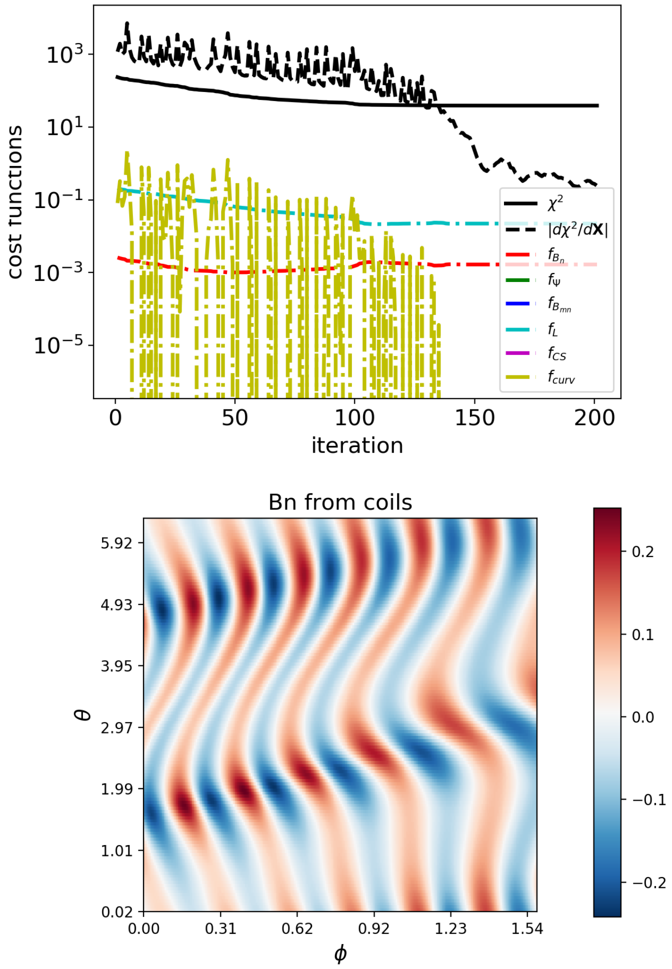


Figure 4: An example of the cost function and B_n graphs we will use in our analysis.

The only lines in the cost function plot that we will be analyzing are that of χ^2, f_{B_n}, and f_L, or the black, red, and blue lines, respectively. The first, χ^2, is an overall measure of optimization for a non-linear least-squares fit, while f_L is the cost function that minimizes coil length and f_{B_n} is the cost function that minimizes B_n. We ideally would like all three to go down. The countour plot shown in Figure 4 is a good example of what we don't want. In Figure 4, we can see distinct coil ripple, but ideally this plot will be much more homogeneous with as low contrast as possible. The closer to zero our B_n is, so the whiter our contour plot, the better we've matched our target.

3 Data

We started with the Bila set of coils and a plasma boundary optimized by the University of Wisconsin. We reduced the number of coils to 40 to allow more coil-to-coil separation, which is an important parameter in engineering stellarators. We optimized the 40 coils in FOCUS with and without a set of PF coils. The coil shapes and target plasma boundary are shown in Figure 5, viewing down the z axis. Two PF coils are placed at $z = 0.6$ and $z = -0.6$ on the inside and outside of the boundary, making a total of 4 PF coils.

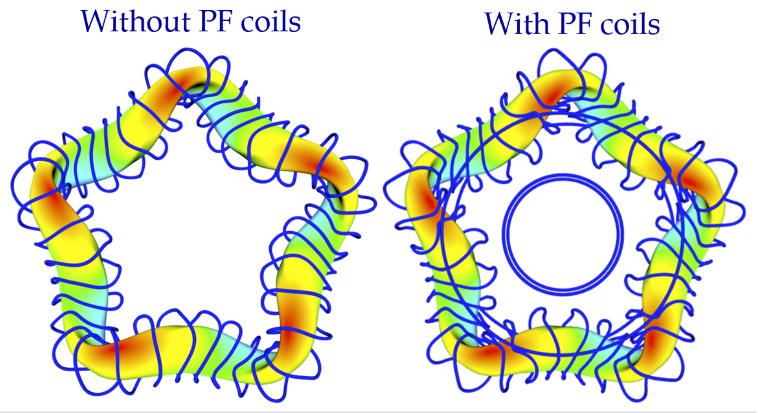
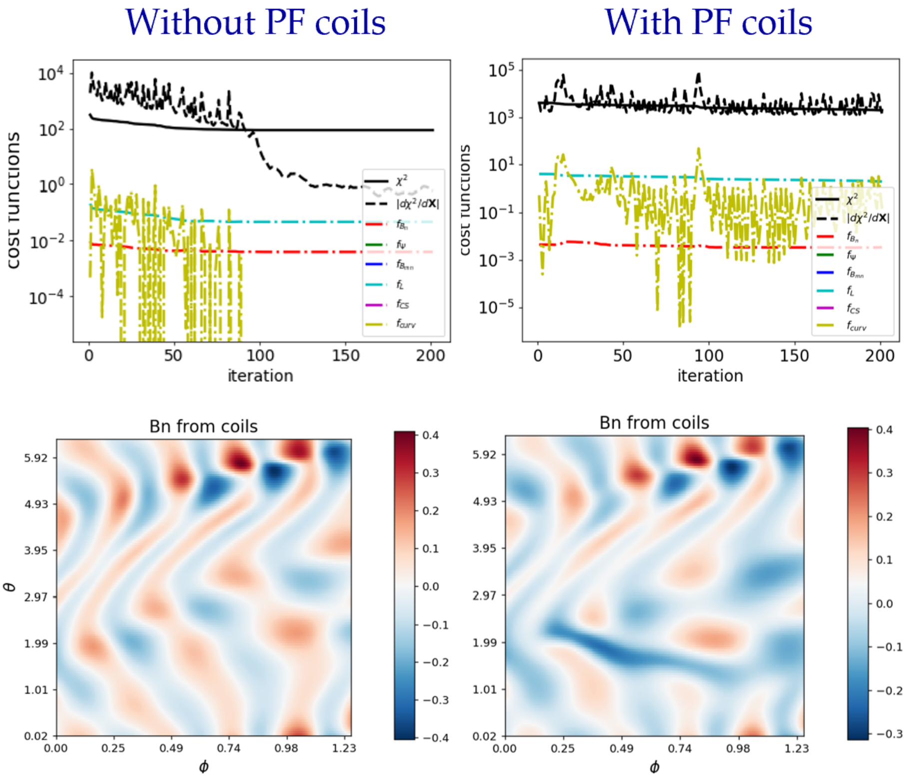


Figure 5: A view down the z-axis of the Bila boundary with modular coils, both with and without PF coils as well.

The cost function and B_n analysis graphs are given in Figure 6 for both cases. Note that χ^2 decreases more in the non-PF case, but that f_{B_n} and f_L do not decrease much in either case. We also notice that f_L is relatively higher for the PF case, which we assume is on account of the PF coils being of a greater length than the modular coils, so our length function has reflected the "cost" of that. The Bn contour plot has changed considerably. Note that the scale on the PF coil case goes down to only -0.3 as opposed to -0.4 in the first case, so the blue "valleys" in the plot are not as deep. This is a slight improvement in the B_n as it has homogenized slightly more with the PF coils and does not stray as far from 0, so we have matched our target plasma boundary better.

We would prefer our B_n to be at least a tenth smaller than seen in the last case, so we decided to lessen the length constraint by lowering the weight of f_L in FOCUS by a factor of 10. That resulted in the coils and boundaries shown in Figure 7. The modular coils have become considerably more

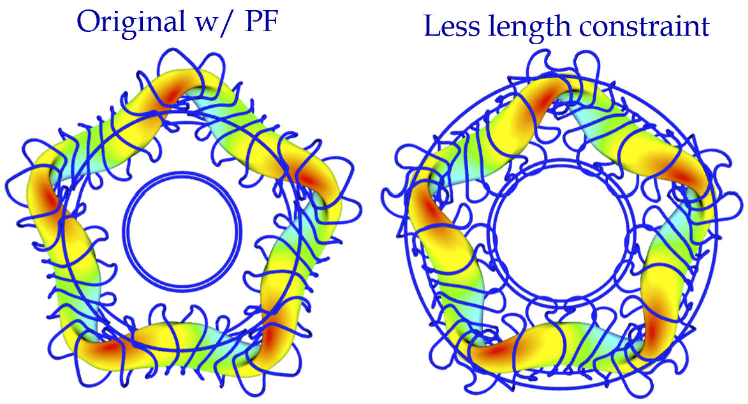

Without PF coils

With PF coils

Figure 6: The cost function and B_n analysis graphs for the optimization of Bila with and without PF coils.

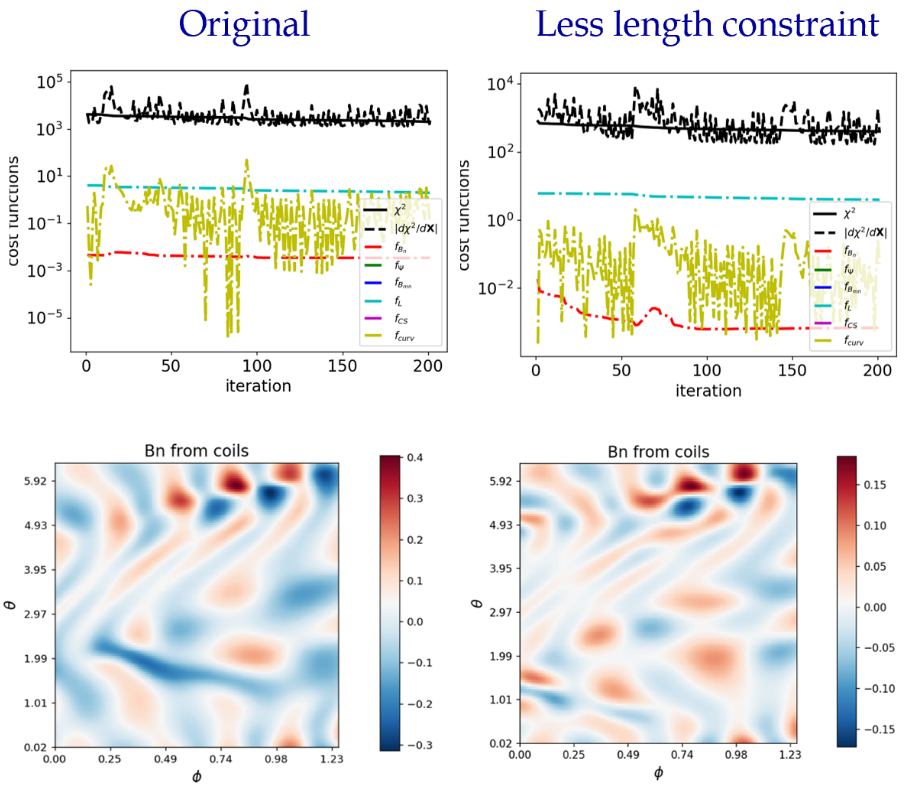
complex and the PF coils have expanded away from the z-axis.

The cost function and B_n analysis graphs are shown in Figure 8. The most notable change in cost functions is that f_{B_n} has decreased significantly more than in any previous run. This is in no doubt due to the more complex coil shape, and analysis of the B_n contours tell the same story. First, the scale is about a fifth smaller, and the coil ripple is not so pronounced. There are less extreme peaks and valleys as well.


Original w/ PF

Less length constraint

Figure 7: A comparison of the coil shape of the previous optimization with PF coils and a new optimization with a decreased weight on f_L.


Original

Less length constraint

Figure 8: Cost function and B_n analysis associated with the cases in Figure 7.

4 Conclusion

Optimizing modular coils in tandem with PF coils changed modular coil shape and led to improved surface B_n. The coil optimization code FOCUS allowed flexibility to put priority on minimizing B_n instead of coil length, which led to even further improvements in B_n. While the increased coil length led to the coils being more complex to potentially build, the overall decrease in B_n is a worthwhile trade-off that we'd like to explore further. There are many more cost functions in FOCUS that we'd like to familiarize ourselves with. Future work will be to test equilibria in the boundaries produced by our optimized coil configurations and to experiment with new PF coil shapes and amounts.

References

[1] C. Zhu, et al., Plasma Phys. Contr. Fusion 60, 065008 (2018)

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