28th IAEA Fusion Energy Conference (FEC 2020)

Contribution ID: **912** Type: **Regular Poster**

Towards simpler coils for optimized stellarators

Wednesday 12 May 2021 12:10 (20 minutes)

We report recent advances in reducing the coil complexity for optimized stellarators. Three efforts have been dedicated. First, the FOCUS code which uses fully 3-D representations for coils and employs analytically calculated derivatives has been applied in designing coils for new stellarators. FOCUS allows searching for more design space and thus is able to find more possible solutions. Secondly, a Hessian matrix method has been introduced to quickly identify the sensitivity of important error fields to coil deviations. Instead of performing computationally expensive perturbation analysis, the new method can determine the worst scenario by ranking the eigenvalues of the Hessian matrix. Last but not least, the state-of-the-art code, FAMUS, can determine the optimal layout of the magnets in a given design space. By using permanent magnets, a design of half-Tesla NCSX configuration with only planar TF coils is obtained. These tools/methods can help the design of next-generation stellarators in the U.S. and the construction of a new experiment in China.

The stellarator is an attractive approach to fusion energy because it has low recirculating power and is free of disruptions. On the other side, the 3D nature of stellarators generally requires more complicated coils than axisymmetric configurations. This problem remains crucial, as evidenced by the cancellation of NCSX stellarator in the US and the construction delays of the W7-X experiment recently completed in Germany. Stellarator optimization is usually divided into two steps. First of all, a configuration with the desired physics properties is optimized. And then coils are designed to reproduce the target magnetic field.

Conventional coil optimization codes assume that the coils lie on a pre-scribed surface, namely the winding surface. It decreases the degrees of freedom in the geometrical representation of the coils, but a pre-supposed winding surface also provides strong limitations. We have developed the FOCUS code (1) which relaxes the need for the winding surface. By using fully 3-D representations, coils can freely move in the space. Thus, more design space can be explored. FOCUS also employs analytically calculated (first- and second-order) derivatives to apply fast, robust optimization algorithms. Figure 1 shows a candidate coil design for a proposed midscale quasi-helical configuration in Madison, US. The coils can precisely produce the required magnetic field to support the equilibrium and retain the exceptionally good confinement for alpha particles (less than 2% loss on the s=0.3 surface).

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The requirement for high accuracy during coil fabrication and assembly is also challenging, as coil deviation might produce error fields that degrade plasma performance. An error field sensitivity analysis prior to machine construction is necessary to determine acceptable tolerance. Instead of performing computationally expensive perturbation analysis to scan possible deviations, we have introduced a Hessian matrix method (2) that can directly find the worst combination of coil perturbations. The quadratic approximation indicates that the departure in the figure of merit away from the optimum is the eigenvalue-weighted norm in eigenspace. The first principal eigenvector, which is associated with the largest eigenvalue, will have the most significant effect on error fields. The second-order derivatives of normal magnetic field error, resonant magnetic harmonics and quasi-symmetry calculated in FOCUS thus can be used to determine the importance of all possible coil perturbations. As shown in figure 2, the modular coils of CFQS can deviate in a certain direction to enlarge/eliminate the n/m=4/11 islands (3). Important guidance is then provided for the upcoming coil fabrication and assembly.

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The idea of using permanent magnets to provide a secondary magnetic field was proposed recently (4-5). We have developed the FAMUS code (6) to apply the technique of topology optimization determining the optimal layout of permanent magnets. Figure 3 demonstrates the design of half-Tesla NCSX configuration using permanent magnets and only planar TF coils. For engineering simplicity, the magnets are all perpendicular to the supporting surface. The existing ports on the vacuum vessel are explicitly excluded. Minimum magnets are used and remarkably large access on the outboard side is achieved. This calculation is leading to a proposed optimized stellarator at Princeton, US (7).

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The results strongly demonstrate that advances in numerical modeling and optimization can reduce the complexity of stellarator coils and unearth the required coil tolerance. These efforts will help boost the design and construction of next-generation stellarators for pursuing fusion energy.

*This research was supported by the U.S. Department of Energy under Contract No. DE-AC02-09CH11466.

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Session Classification: P3 Posters 3

Track Classification: Fusion Energy Technology