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Stellarator Simplification with Permanent Magnets

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Perhaps the most attractive fusion reactor concept is the stellarator since it has minimal recycling power, minimal auxiliary systems and no time dependent electro-magnet systems. However, progress has been delayed by two formidable challenges: obtaining sufficient

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confinement in three dimensional fields and engineering the magnetic configuration with sufficient precision at low cost. Stellarators have experienced a rebirth in recent years due to fundamental breakthroughs in the calculation and optimization of the confinement properties of three-dimensional magnetic systems. Optimized stellarator experiments have shown conclusively that the neoclassical ion-confinement has been raised to values similar to tokamaks (1) - thus the first challenge is beginning to be met and further optimization is in development (2). However along with these improved physics-driven design criteria came substantial magnet complexity and precision requirements that are extremely demanding ($\sim 10^{-3}$) (3). Thus, the second challenge, magnet simplification has been identified as a critical research need for stellarators in a recent report (4).
Recently, a new concept using permanent magnets and simple planar coils for making the complex fields required by stellarators was proposed [5,6]. Calculations show that permanent magnets can broaden the space of achievable stellarator configurations, reduce construction costs and increase availability. Thus ultimately, they can reduce the cost of fusion electricity.
The technical goal of the current activity is to develop the technology required to achieve stellarator fields using permanent magnets and to verify that the fields meet accuracy requirements. The assembled magnetic field structures will be verified with measurements made using Hall probes. An important feature of the design will be a system of adjustments that enable tuning of the magnet positions to minimize error fields within tolerance. The permanent magnet assembly will be designed so that it can be a part of a planned but as yet unfunded future stellarator that will re-use some components of the NCSX device.

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In addition to the reduced assembly cost, the use of demountable permanent magnets will also provide a viable sector maintenance scheme that will increase the availability of the reactor. This reduces the cost of electricity by reducing down time. Additionally, one of the barriers to stellarator innovation and research is the cost of high complexity which has been prohibitive for smaller research programs. Reduction in complexity will lower the cost barrier enabling the pursuit of novel physics optimization strategies. Furthermore, we have already shown that designs that were unattainable with coils can be easily achieved with permanent magnets.
A method of designing practical magnets that can be mounted to a relatively simple cylindrical mount with radial ribs was devised for the preconceptual design. The computational methods described above are then used to design an array of trapezoidal pyramid shaped magnets. It is envisioned that these magnets will be contained within stainless steel boxes the back face of which will be the interface to a radial rib that acts as the mounting point for the magnet. The magnets will be held to the rib with screws. The radial ribs will in turn be mounted to a central support cylinder.
The design activities on this concept have just begun and we will continue to investigate addition mounting concepts and magnet distributions. The details of this design effort as well as the additional design options under consideration will be presented.

(1) "Overview of first Wendelstein 7-X high-performance operation"T. Klinger, et al., Nucl. Fusion 59 (2019) 112004

(2) See the Hidden Symmetries activity website at: https://hiddensymmetries.princeton.edu

(3) "Engineering cost & schedule lessons learned on NCSX"R. Strykowsky, et al., 2009 IEEE/NPSS Symposium

on Fusion Engineering, DOI: 10.1109/FUSION.2009.5226449
(4) "Stellarator Research Opportunities: A Report of the National Stellarator Coordinating Committee", D. A. Gates, et al., Journal of Fusion Energy 37 (2018) 51 https://www.osti.gov/biblio/1414416-stellarator-research-opportunities-report-national-stellarator-coordinating-committee
(5) M. Zarnstorff, S. Cowley, and C. Forest, "Simple method to create 3D and poloidal magnetic fields by permanent magnets for efficient steady-state plasma confinement", Provisional Patent, 2019.
(6) "Stellarators with permanent magnets"P. Helander, et al., Accepted for publication in Physical Review Letters January 2020, https://arxiv.org/abs/1907.01363 , https://journals.aps.org/prl/accepted/4d070YdbT431f67083cc6383685fd810890bedb52

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