Simpler Optimized Stellarators Using Permanent Magnets

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Magnetic coil complexity is one of the main challenges for stellarator based plasma confinement. Stellarators optimized for good confinement require complex three-dimensional coils to produce the needed 3D magnetic field structure. These coils are significantly more complicated than for equivalent tokamaks, reducing the apertures for maintenance access to the diverter and internal components, and increasing cost. As a consequence, simplification of coils has long been identified as a high priority gap for the stellarator approach to fusion energy [1].

This paper is about a new approach: simplification of stellarator coils using permanent magnets to generate the 3D magnetic field structure combined with simple planar coils. The planar coils generate the toroidal magnetic flux, and additional simple coils could be used to modify the equilibrium shape (for example, poloidal field coils or trim coils) for flexibility. The permanent magnets are embedded in the magnetic field produced by the coils. The general strategy is to replace complex 3D coils, which often require manual fabrication and many steps, with a mechanical assembly of commercially available permanent magnets. This is made possible by modern rare earth magnets [2], which have both a high remnant magnetization and a very high coercivity. For rare-earth-Fe-B magnets, the remnant magnetization can be as high as 1.4T and coercivity as high as 3T at room temperature. By cooling the magnets to ~100 K, the remnant magnetization can increase to 1.6T and the coercivity increases to > 7T [3]. The relative permeability is very low and highly anisotropic, being as high as 1.05 in the direction of magnetization. High precision magnets are readily available and extensively used commercially. Advanced manufacturing can be used to fabricate precise magnet support structures, simplifying the metrology required for experiment assembly.

Permanent magnet arrays can be designed to generate a target stellarator equilibrium with the magnets oriented either perpendicular to the stellarator boundary flux surface, or as a combination of perpendicular and tangentially oriented magnets [4], similar to a Halbach array. The design of perpendicular magnets is similar to the design of saddle-coils for producing stellarator shaping [5], and makes use of the "current potential" on a surface surrounding the plasma [6], which is usually used for designing coils. For permanent magnets, the current potential gives the jump in the magnetostatic potential Φ_M on the surface, or equivalently the magnetic dipole moment density on the surface [7]. Numerical codes have been developed to calculate and optimize the arrangement of permanent magnets needed to produce a specified stellarator magnetic equilibrium [8,9].

This approach is being used to design and construct two new experiments:

- MUSE, a table-top quasi-axisymmetric (QA) stellarator for basic research, and
- PM4STELL, a 1.4 m major radius QA stellarator engineering design and construction test of permanent magnet shaping.

The goal of the MUSE experiment is to design and construct an inexpensive numerically optimized stellarator for fundamental physics studies and student research using commercially available components where possible. The vacuum vessel is assembled from four 90-degree glass pipe bends, and the overall structure is constructed from G10 sheet-stock, see Fig. 1. Sixteen planar circular coils are re-used from earlier experiments to generate the toroidal magnetic field B_t = 0.15T. The axisymmetric vacuum vessel has a major radius R=30.5 cm and a minor radius of 7.6 cm. The plasma configuration was numerically optimized using STELLOPT with three criteria to:

- have good quasi-axisymmetry (i.e. the magnitude of B is approximately independent of toroidal angle in Boozer coordinates),
- have low effective helical ripple (ε_{eff}) [10], and
- fit inside the vacuum vessel.

Quasi-axisymmetry and low ε_{eff} were targeted at the half-volume surface (normalized minor radius $\rho \sim 0.7$) of the equilibrium. Several configurations were designed with different average shapes and compared for ease of construction and minimal contact with the vacuum vessel. The plasma shape of the selected configuration is shown in Fig. 2, and has two stellarator periods, edge rotational transform of 0.197, and a plasma aspect ratio of 7.2.

The permanent magnets are arranged in a layer between the vacuum vessel and the toroidal field coils, with their magnetization perpendicular to the vacuum vessel. A discrete permanent magnet arrangement was optimized by the FAMUS code [8] to produce the target stellarator equilibrium as accurately as possible, while avoiding having magnets at the location of vacuum vessel diagnostic ports, and minimizing the volume of permanent magnets. The magnet layer thickness was constrained to 2.2 cm by the needed assembly clearance. The arrangement of permanent magnets is not unique, but the optimization is limited by the use of gradient-decent algorithms and trapping in local minima. A final series of hand optimization was used to locally simplify some of the magnet arrangements and to allow the magnet support structure to be fabricated and assembled in sections.

The optimized discrete magnet array is depicted in Fig. 3. Most of the magnetic material is on the inside of the torus. On the outside of the torus, the magnets are generally thin, and in many areas they are spatially sparse. There are conspicuous rings of magnets around the vertical ports at the vertically elongated symmetry planes of the stellarator periods.

The magnet support structure will be 3D printed using high strength nylon by commercial printers. The support structure consists of four quadrants of two different designs, depicted in Fig. 4, surrounding the four vacuum vessel quadrants. Each magnet support quadrant is centered on a symmetry plane of the two-period stellarator to minimize the required support force, and is assembled around the vessel from three poloidal segments. The support quadrants are connected to the support structure by adjustable mounting stages to allow accurate alignment. The support quadrants have holes where there are no magnets to permit viewing of the plasma. Test 3D prints of sections of the magnet holders show high accuracy and high strength glue-bonds to the permanent magnets. The available 3D printing processes appear to be easily precise enough to accurately locate the magnets and produce the desired magnetic equilibrium, in part due to the averaging of uncorrelated deviations in the location and orientation of individual magnets.

The stellarator equilibrium produced by the optimized discrete magnets is calculated to have exceptionally good quasi-axisymmetry and low neoclassical transport. See Figure 5. The contours of |B| are very close to straight and toroidally aligned in Boozer coordinates. The calculated profile of $\varepsilon_{eff}^{3/2}$, which characterizes the strength of the 3D neoclassical transport, is a factor of ~200 lower than NCSX, and a factor of ~1000 lower than W7-X or LHD at ρ~0.5 [11]. This level of $\varepsilon_{eff}^{3/2}$ optimization has not been achieved using 3D coils in any constructed stellarator, so far, due to coil-ripple. This illustrates the capability permanent magnets to produce highly optimized physics configurations with simple coils.

The MUSE experiment is preparing for its Final Design Review. Construction is expected to be complete by the end of 2021. Operation will start with electron beam mapping of the experimental configuration, and adjustment of the magnet support stages as needed.

The goal of the PM4STELL project is to develop and test engineering approaches for permanent magnet stellarators at the R=1.4 m scale. It will construct a 1/2-period section of a 3-period QA-optimized configuration at B_t=0.5T, reusing the NCSX vacuum vessel and planar TF coils (but not the NCSX modular coils). The plasma configuration is being optimized to include improved fast ion confinement. Construction will start in 2022.

Future fusion reactors will require large aperture maintenance access and optimized magnetic configurations. This can be satisfied by coils with approximately straight outer legs, in combination with permanent magnets on the low field side of the torus. This is the region that appears to require the least amount of magnetic material in our designs. The magnets would be designed to be demountable. For higher magnetic field, permanent magnets could be combined with related approaches, including diamagnets [11] or saddle coils.

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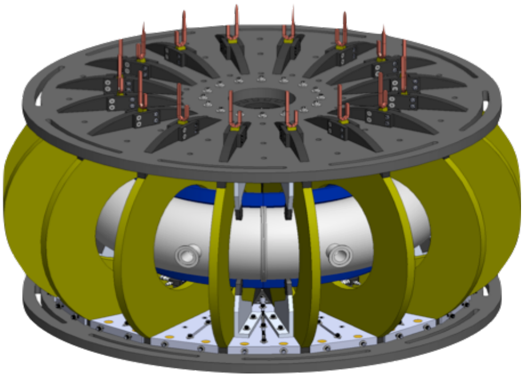


Fig. 1. MUSE design approach: planar TF coils around permanent magnet holder (blue) and a symmetric glass vacuum vessel.

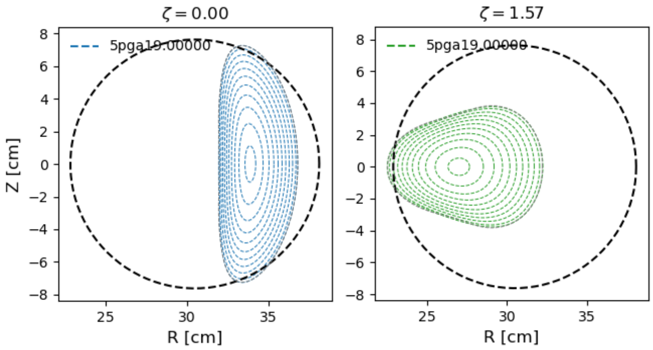


Fig. 2. Plasma cross-sections at ϕ=0° and 90° inside the circular cross section vacuum vessel.

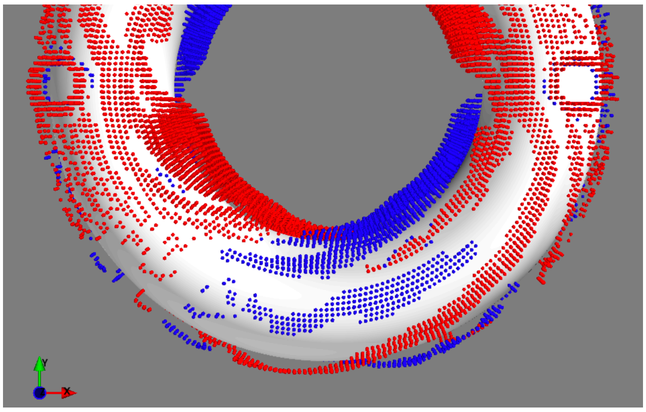


Fig. 3. Distribution of permanent magnets around vessel. Red and blue indicate the magnet polarity.

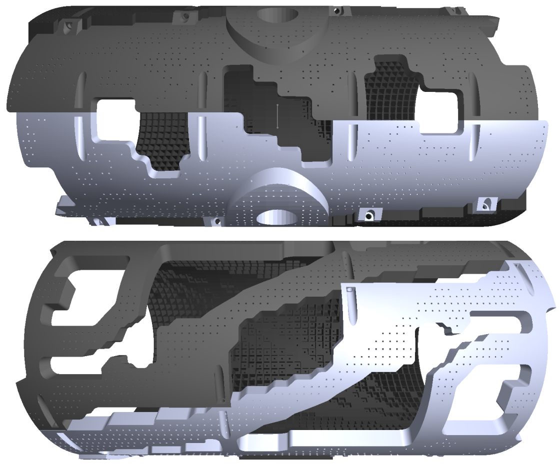
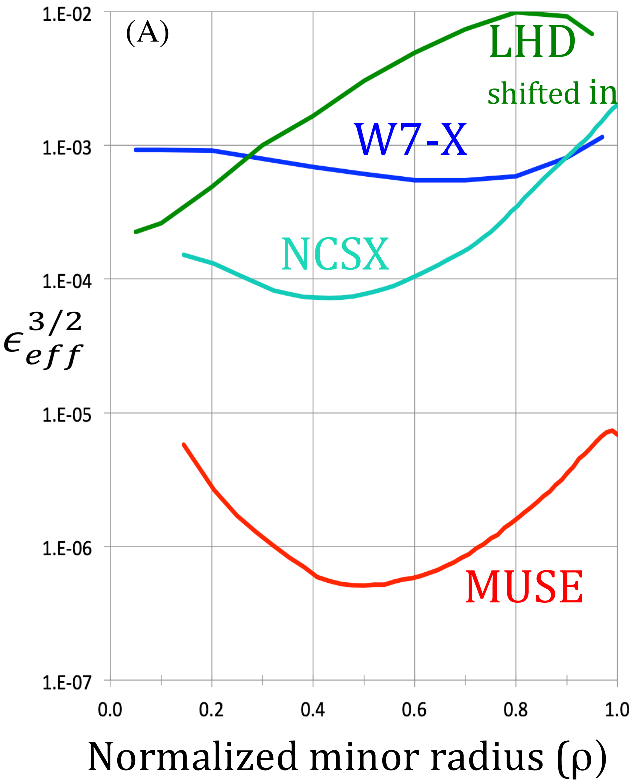


Fig. 4. Magnet holder toroidal quadrants. viewed from the large major radius mid-plane. Cut-outs are for ports and to directly view the plasma.



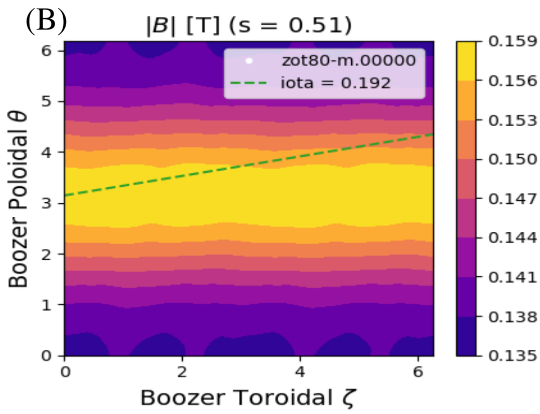


Fig. 5. (A) Profile of $\varepsilon_{eff}^{3/2}$ vs. normalized minor radius ρ, comparing MUSE and other stellarator experiments. (B) Contours of |B| for MUSE at the half volume surface (approximately ρ =0.7)