Simpler Stellarators

M.C. Zarnstorff, L. Bromberg[1], T. Brown, L.P. Ku, A. Boozer[2],
and the PPPL stellarator group.
Princeton Plasma Physics Laboratory, Princeton NJ, USA
[1]*MIT, Cambridge MA, USA*
[2]*Columbia Univ., New York NY, USA*

Stellarators offer solutions to many of the physics challenges of magnetic fusion, in particular operation at high pressure without disruptions, sustainment of the magnetic equilibrium without current drive, simplified plasma control, and operation at high density. However, the strong 3D shaping required for these attractive properties increases the complexity of the magnetic field coils, and the construction and maintenance of the overall device. Simplifying stellarator coils was identified as the highest priority issue for stellarator research by recent US advisory panels [1,2].

Earlier studies [3] showed that increasing the aspect ratio or reducing the rotational transform generated by the coils resulted in smoother, less distorted modular coils, for quasi-axisymmetric configurations optimized for low transport and good MHD stability. However, reducing the rotational transform reduces the equilibrium pressure limit and stability, and increases the non-linear response of the equilibrium to pressure via the bootstrap current. Increased aspect ratio increases costs for a given level of plasma performance. Recent studies have developed methods to produce smoother coils with approximately fixed plasma characteristics [4], however the resulting coils are still strongly three-dimensional in order to produce the helical fields.

In a fusion energy system, it is critical to simplify the design and maintenance of the heat and neutron absorbing blanket that surrounds the plasma. Since the blanket partially shields the coils, this requires large regular-shaped apertures between coils to access and work on the blanket assemblies. This is challenging with either helical or non-planar modular coils. The strategy investigated here is to use simple coils to generate the toroidal magnetic flux. The coils are designed to have planar, parallel outer legs, as in a toroidal solenoid, in order to regularize and simplify access. Toroidal segments of the blanket and shield are accessed between the coils, either horizontally or vertically, as on many tokamak designs. The 3D shape of the magnetic flux surfaces is controlled by separate elements, mounted on the outside of the blanket and shield segments, see Fig. 1. Such magnetic shaping could be provided by saddle coils, providing the difference flux between the simple planar coils and a typical modular coil design. However, the saddle coil currents would be very large, similar to the currents in the modular coils, making the saddle coils challenging to design and fabricate.

A more attractive strategy uses an array of diamagnets to provide the 3D field shaping, reacting to the field produced by the simple coils. The diamagnets can be made of high temperature superconducting (HTS) monoliths, such as YBCO. HTS materials offer stable operation at very high fields and elevated cryogenic temperatures, and are diamagnetic due to the Meisner effect. HTS monoliths are commercially available and used for magnetic bearings and levitation. HTS monoliths have been used to trap magnetic fields up to 17 T, for use as 'permanent' magnetic dipoles. The diamagnets are mounted on a support structure that can be inserted between the coil legs, either surrounding the blanket or as part of the blanket/shield assembly. The support structure must provide cooling and mechanically react the magnetic forces on the diamagnets, but no electrical connections or windings are needed. The modularity of the diamagnets enables the support structure to also be modular. The diamagnets are positioned and oriented to appropriately react to the field generated by the array of simple coils and each other, producing the 3D magnetic field shape desired for plasma physics properties. Since the diamagnets are reshaping the distribution of the magnetic field, they can be used to control ripple, allowing a substantial reduction in the number of coils, if desired.

Two numerical calculations have been done to test this technique. In the first, an array of diamagnets is used to eliminate the toroidal field ripple in a tokamak-like configuration, allowing a substantial reduction in the number of toroidal field coils. An array of 8 planar toroidal field coils is used with the outer leg at R=6 m. At R=4 m, the peak-to-peak ripple in the toroidal field magnitude is ~7.5%. A layer of thin diamagnetic tiles is introduced at R=4.8 m. Each tile is ~35 cm wide, and slightly overlaps its neighbors in the toroidal direction. In addition, the tiles are tilted relative to the R=4.8 surface by an additional angle $\theta = A\sin(N\varphi)$, where A is the tilt amplitude, N is the number of coils, and φ is the toroidal angle. As shown in Fig. 2, by adjusting the tilt amplitude A, the ripple can be reduced, eliminated, or reversed. The optimum tilt amplitude to eliminate the magnetic ripple at R=4 m is ~11 degrees.

The second calculation is an initial attempt to numerically generate a stellarator field using only diamagnetic shaping. VMEC is used to calculate an approximate vacuum flux surface surrounding the three-period ARIES-CS equilibrium. The plasma aspect ratio is 4.5 and the aspect ratio of the surrounding surface is 1.7. The minimum separation between the plasma and surrounding surface is comparable to the plasma minor radius, see Fig. 3. For each period, an 8 by 8 array of thin diamagnetic tiles is positioned on the outer, surrounding surface, with gaps between the tiles of 0.5% of the major radius. Each tile is further divided into and 8 by 8 array of flat sections, with no separating gaps. The flat sections are locally tangential to surface surrounding the plasma, without any additional tilt or overlap between adjacent tiles. The diamagnets are excited by an external 1/R toroidal magnetic field. The total magnetic field distribution, including the coupling between the diamagnets, is calculated by the SPARK code [5]. Field line tracing is used to generate the Poincare sections in Fig. 4 demonstrating closed flux surface and magnetic rotational transform. A similar calculation was performed assuming that the outer surface was a continuous superconducting layer, without gaps. The calculated rotational transform for the calculation with discrete tiles and gaps is lower by a factor of ~3 than for the continuous superconducting surface, so the gaps and tile sizes are significant. Overlapping the tiles and optimizing their tilt and location will clearly be important for producing optimized equilibria, just as in the tokamak ripple test problem.

In summary, new strategies to simplify stellarator coils have been investigated, focused in part on simplifying design and maintenance of blankets and other components inside the coils. High temperature superconducting diamagnetics offer an attractive method to shape the magnetic flux and field by mechanically positioning passive elements. This allows the coils to have simple shapes including a straight outer leg, which enables large aperture access to internal components. To further develop these techniques, stellarator equilibrium and optimization tools must be modified to include the effects of (linear) magnetic materials, such as diamagnets.

References:

[1] "Advancing the Science of Science of Alternate Toroidal Magnetic Fusion Concepts", Nov. 2008, FESAC. http://www.science.doe.gov/ofes/FESAC/Nov-2008/Toroidal%20Alternates%20Panel%20Report.pdf

[2] "Research Needs for Magnetic Fusion Energy Sciences", September 2009, US DOE. http://burningplasma.org/web/ReNeW/ReNeW.report.web2.pdf

[3] L.-P. Ku and A. Boozer, Phys. Plasmas 16, 082506 (2009)

[4] L.-P. Ku and A. Boozer, "Application of a boundary perturbation method to the study of field error effects in quasi-symmetric stellarators", to be submitted.

[5] D.W. Weissenburger, Report PPPL-2494, Jan 1988.

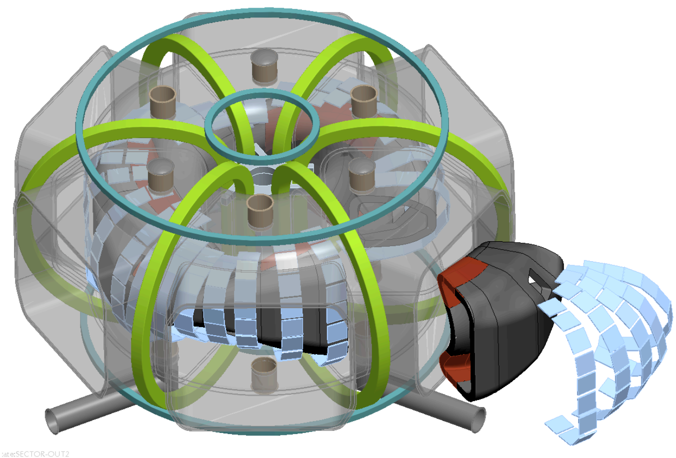

Figure 1. Sketch of 3D shaping elements inserted between coils, surrounding blanket/shield.

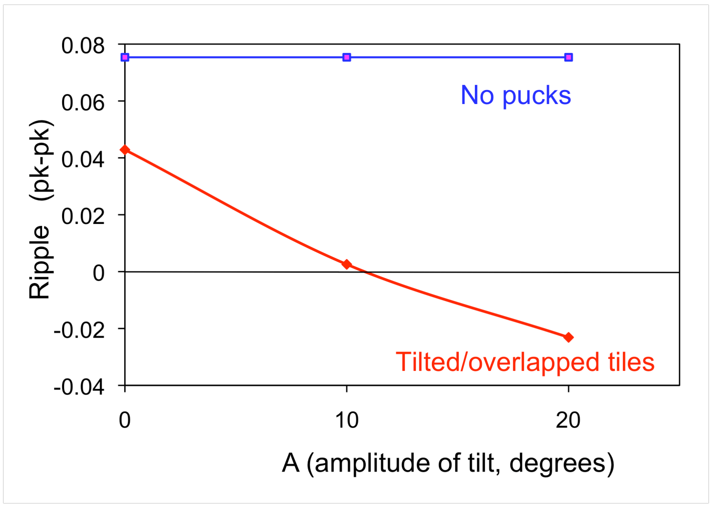

Figure 2. Variation of magnetic ripple with tile tilt amplitude.

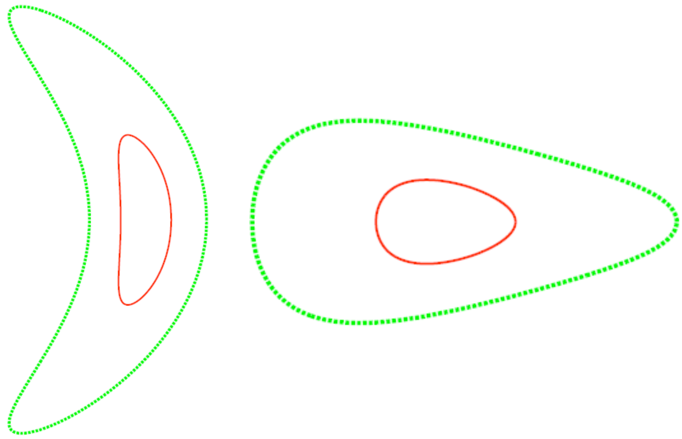

Figure 3. VMEC flux surfaces at two toroidal angle: (red) plasma surface, (green) surrounding vacuum surface for mounting diamagnetic tiles.

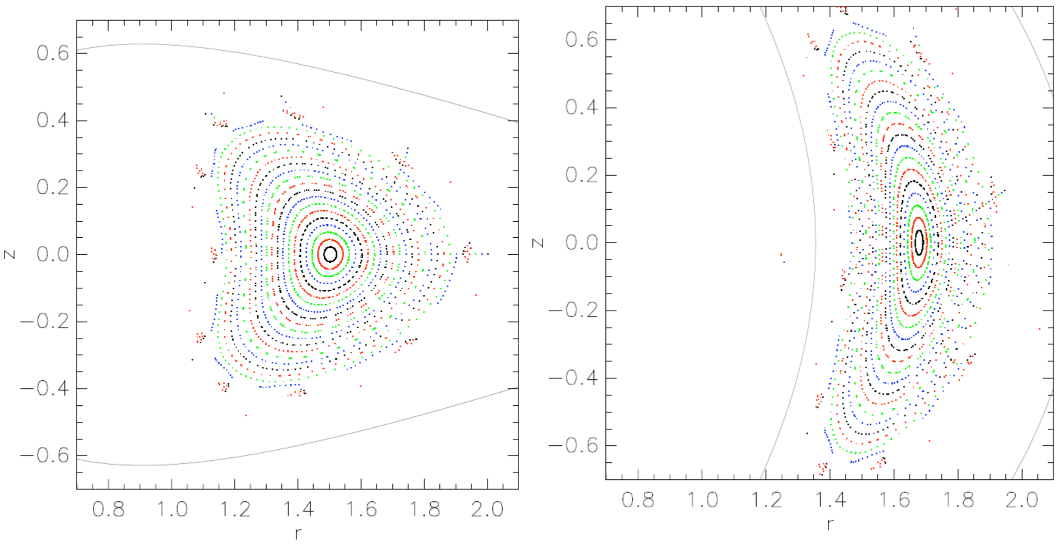

Figure 4. Poincare sections at two toroidal angles of flux surfaces generated by diamagnetic tiles mounted on green surface of Fig. 3.