PSFC/JA-10-44

Stellarator Configuration Improvement Using High Temperature Superconducting Monoliths

L. Bromberg[a], O. Meneghini[a], J.V. Minervini[a]
T. Brown[b], P. Heitzenroeder[b], G.H. Neilson[b],
M. Zarnstorff[b] and A. Boozer[c]

[a]*MIT Plasma Science and Fusion Center*
[b]*Princeton Plasma Physics Laboratory*
[c] *Columbia University, New York NY*

December 2010

ABSTRACT

Substantial advances have been made in the design of stellarator configurations to satisfy physics properties and fabrication feasibility requirements for experimental devices. However, reactors will require further advances in configuration design, in particular with regard to maintenance and operational characteristics, in order to have high availability. The diamagnetic properties of bulk high temperature superconductor (HTS) material can be used to provide simple mechanisms for magnetic field-shaping by arranging them appropriately in an ambient field produced by relatively simple coils.

A stellarator configuration has been developed based on this concept. A small number of toroidal field coils is sufficient to create a background toroidal field. Discrete HTS monoliths ("pucks" or "tiles") are placed on a shaped structure that can be split in the poloidal direction at arbitrary locations. This allows the stellarator to be designed with large openings that provide access to remove interior plasma facing components, no longer restricted by highly shaped back legs of the modular coil winding. Unlike a coil, the structure can be assembled and disassembled in pieces of convenient size, facilitating maintenance.

Calculations of the effect of the use of monoliths for field modification in stellarators and tokamaks will be described.

I. INTRODUCTION

High temperature superconductors (HTS) were discovered in bulk form, with monoliths of the materials relatively easy to make using conventional crystal growing methods. Since their discovery, the bulk materials have improved, even though HTS research is mainly focused to make wires/tapes.

Because of their high critical temperatures, and consequently, high energy margins, HTS materials are not as prone to flux jumping as low temperature superconductors. Thus, they can be used to replicate fields or to exclude (shield) magnetic fields. There have been discussions of their use of bulk materials in fusion applications, including stabilizing "perfectly" conducting walls in tokamak. More recently, one of the authors (Zarnstorff) suggested their use to provide complex field shaping required for stellarators.

A stellarator configuration has been developed based on this concept, using the ARIES-CS design point [1] and component features as a point of departure. [2] A small number of toroidal field coils may be sufficient to create the background toroidal field. Discrete HTS monoliths ("pucks" or "tiles") are placed on a shaped structure that can be split in the poloidal direction at arbitrary locations. This allows the stellarator to be designed with large openings that provide access to remove interior plasma facing components, no longer restricted by highly shaped back legs of the modular coil winding. Unlike a coil, the structure can be assembled and disassembled in pieces of convenient size, facilitating maintenance.

The excellent properties of HTS materials, *e.g.,* YBCO operating at elevated temperatures (> 30 K), offer additional operational advantages. Since the HTS monoliths require no insulation or copper for stability/quench protection, some of the typical irradiation limits on these materials are eliminated. Nuclear heating, due to the high temperature of operation of the HTS compounds, is also very much relaxed, since at 50 K it is possible to remove more than one order of magnitude higher cryogenic loads than at 4 K, for the same refrigerator power. At the same time, there are challenging issues, such as mechanical support and cooling of the monoliths, performance and lifetime limitations in the fusion environment, field creep, superconducting stability of the monoliths, and cryostat design.

As the 3-D geometry of the stellarators is complex, we have investigated simpler geometries to understand the behavior of arrays of monoliths. Two such geometries are described in this paper. The first one uses a simple geometry, to understand the use of HTS tiles for ripple cancellation in tokamaks. The geometry can be investigated using a 2-D approach, and the results are provided in section II. The

second geometry is that of a linear stellarator (a helical configuration). This case is discussed in section III.

The modeling of superconducting tiles is very difficult, with non-linear behavior (current density at the surface is at critical excluding/reducing the external magnetic field, with complex hysteresys behavior when discharged). Although it can be modeled relatively easily for single tiles, the model gets very complicated at when there are multiple adjacent tiles. In this work, two simple models have been used to simply the calculations. The first one assumes that the superconducting material is magnetic material is a relative permeability approaching 0. Low values ($\mu_r = 10^{-3}$) were used. It is necessary to mesh and calculate the fields inside the superconductor. Alternatively, the superconductor can be modeled assuming perfectly diamagnetic materials. In this case, the region inside the superconductor is excluded from the calculation. The first approach was used to calculate the effect of the HTS tiles on magnetic ripple, the second approach has been used for the stellarator calculations.

II. HTS MATERIALS

There is a small program worldwide to develop monoliths of HTS materials. During the initial phases of high temperature superconductivity, the only materials that were available were bulk materials. This was the case for BSCCO 2212 and YBCO. Wires were initially made from 2212, but this effort was dropped because of the relatively poor superconducting properties at 77 K.

Presently, both 2212 and YBCO monoliths are available. 2212 is more developed, because of applications as current leads, and more recently, as components for fault current limiters. 2212 is available from Nexans, either as rods, cylinders or as plates. While its properties are lackluster at 77 K, they are very good at 20-30 K.

YBCO is being developed mainly as materials to be used in bearings, in the US (Boeing), Europe (Nexans) and Japan (ISTEC). The characteristics of this material are nothing less than spectacular, at temperatures up to 60-65 K. YBCO has limited current density capabilities at 77 K, good enough for tapes, but not for high field magnet applications. They need to be subcooled.

The most impressive performance of YBCO pucks has been a 17 T magnet at 29 K without a background field. For 2212, the MIT group has built a 3 T magnet at 4 K, and a 1 T insert in a 19 T background. [3]

These materials are available at costs of 15 €/cm^2 (150 k€/m^2).

II. RIPPLE CANCELLATION IN TOKAMAKS

A preliminary investigation of the use of monoliths for this purpose was recently submitted for publication [3]. It was determined that the presence of gaps between the superconducting monoliths resulted in reduced ripple cancellation. The addition of multiple, staggered layers helped, and resulted in a field ripple cancellation that depended exponentially on the number of layers.
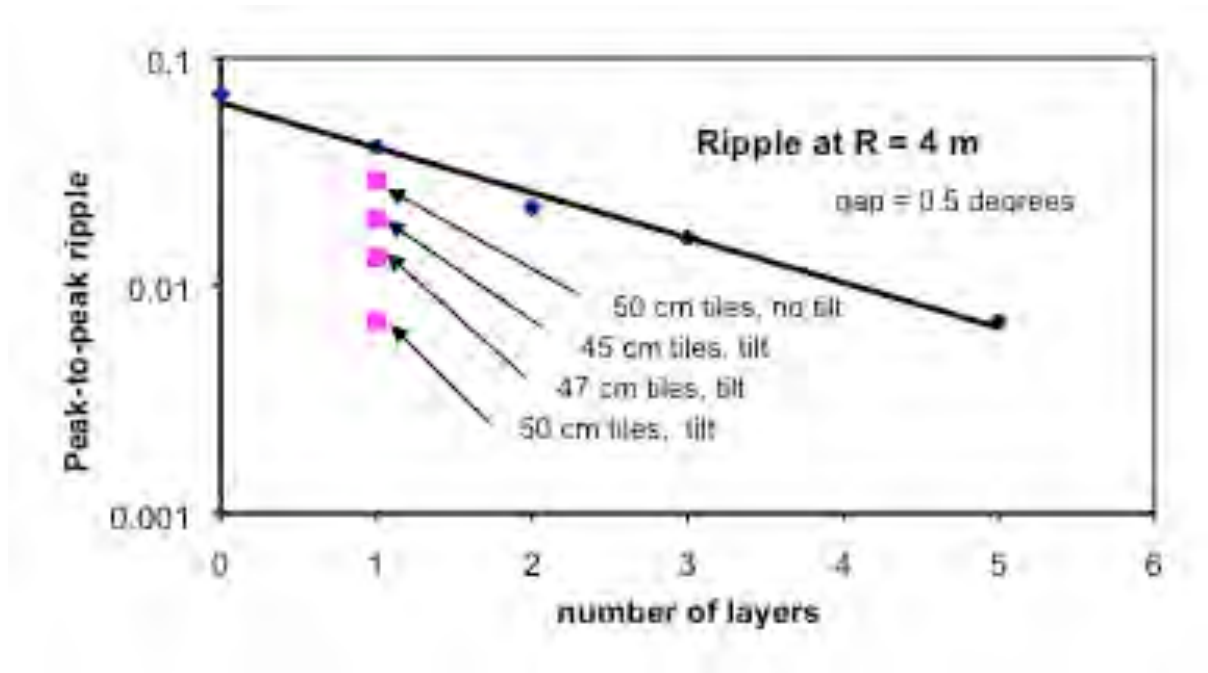

Figure 1. Magnetic field ripple as a function of the number of HTS layers. Cases with overlap and tilt have a single layer of compensating HTS tiles.

In this paper, improvements on the concept are presented that address some of limitations of the concept illustrated in the previous work. Section 2 investigated the use of overlapping tiles. Section 3 uses tilts of tiles. Section 4 summarizes the work and discusses possible analytical models and other applications of the concept.

II.A. Overlapping tiles

The model (with 8 TF coils) has been described previously [4]. We have investigated the case of single layers of overlapping tiles, without tilt. To provide overlap, alternating cylindrical tiles have been displaced radially outward by 5 cm.

Figure 1 shows the magnetic field ripple at a radius of 4 m for several cases. In the case of 50 cm tiles (with about 6 cm overlap), the ripple has been decreased to 2.9% from an uncompensated ripple of 7.5%. Without the overlap, a single layer of monoliths decreased the ripple to about 4.5%. Also shown in Figure 1 are the previous results with multiple, non-overlapping tiles, as a function of the number of layers.

II.B. Tile tilting

In the previous cases studied, the shielding currents that have an impact on the ripple are induced by the radial magnetic field, which is small. By tilting the tiles it is possible to increase the currents flowing in the tiles, as the tiles intersect a larger external field (which in this case has a component from the main toroidal field). In this section, the use of tilting the tiles for control of the ripple is discussed.

The present goal is to understand the tile-tile interaction, rather than optimize the magnetic topology. We have chosen an arbitrary function for the tilting of flat tiles. An arbitrary algorithms has been used: $\varphi \sim A \sin(\alpha N \theta)$ where N is the number of toroidal field coils, θ is the toroidal angle, and φ is the tilt of the tiles (measured between a normal to the tile and a radius). A represents the maximum tile tilt. For $\alpha = 1$ the periodicity is the same as the toroidal field periodicity, while for $\alpha = 2$ is twice as high. In both cases there is no tilt in the region directly under the toroidal field coils ($\theta = 0$), while in-between coils ($\theta = \pi/2$) there is tilt for $\alpha = 1$ and no tilt for $\alpha = 2$. Only a single layer of tiles is used in this case.
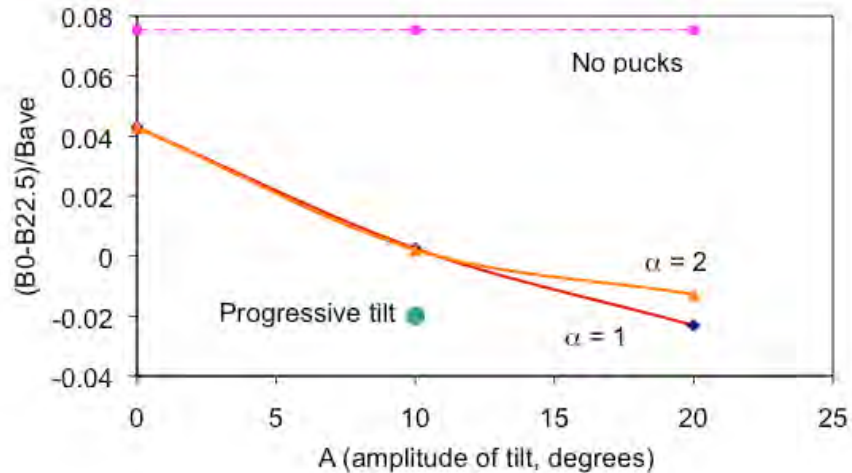

Figure 2. Toroidal field ripple as a function of A, for $\alpha = 1$ and 2.

The amplitudes of the magnetic field ripple at 4 m for several cases are shown in Figure 2. The ripple is defined between $\theta = 0$ (under the toroidal field coil) and half-way between the coils (at $\theta = 22.5^\circ$). The method is much more effective, and the field ripple actually reverses for $A = 10$. The case without ripple compensation is also shown in Figure 2 (labeled "no pucks).

One additional case is shown in Figure 2, where the tiles, in addition to tilt are displaced inwardly progressively (with tilt and overlap), with no displacement at $\theta = 0$ degrees and maximum inward displacement at $\theta = 22.5^\circ$, with better ripple cancelation.

III. STELLARATOR CASE

Simple stellerators geometries have been considered. The analytical low-beta stellarator case calculated by Freidberg was used. [5] A geometry with l = 2 was chosen (basically, a helical 3-D geometry made from a rotating ellipse). Only a field period of the model was used, with periodic boundary conditions at the ends of the model.

The magnetic field and resulting flux surfaces calculated when a continuous superconducting wall, with an externally applied uniform magnetic field demonstrated that the computational model matched the analytical solution.

Two models were built for the l = 2 geometry, shown in Figure 3(a) and 3(b). Fig. 3(a) has a very tight pitch, and had tiles that were placed to follow the surface of the outermost flux surface (Figure 3a). There are substantial gaps between the tiles, and there is no pitch between the flux surface and the tiles. Calculations in this case showed very poor performance of the tiles, as the tiles only modified the field locally, the field escaping through the gap between tiles. The field away from the tiles was not substantially modified.

The second case has a longer field pitch period and has tiles that are tilted. The tilting of the surfaces was chosen after some thought, trying to tilt the surfaces so that when looked from the end the surface looked solid (no radial gaps) when the tiles are projected axially upon the end of the model. The tilt algorithm is arbitrary, and no attempt was made to optimize the geometry, as at this time the goal was to develop tools and preliminarily asses the concept. In addition, it was difficult to generate meshes when there was overlap between the surfaces. The results here include thus only the tilt, but not the overlap.
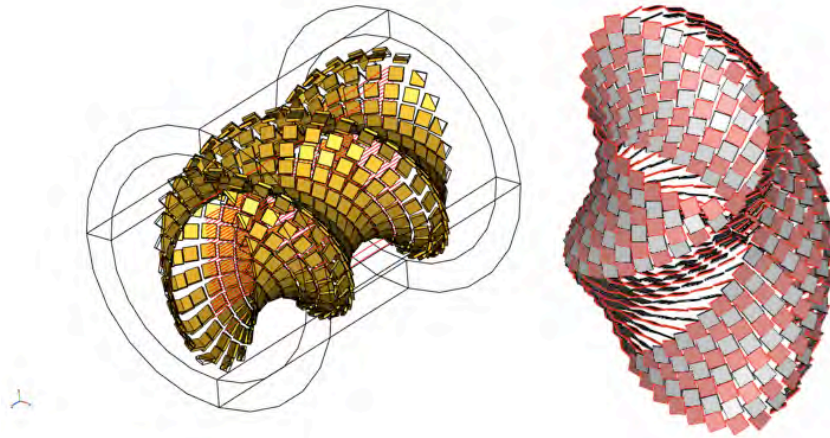
Fig. 3. Models developed for tiled linear stellarator (l = 2). (a) tiles closely matching the last flux surface (b) tiles tilted with respect to the last flux surface.

The resulting flux surfaces for the case of Fig. 3(b) are shown in Figure 4. Fig. 4 (a) shows the result for a continuous superconducting surface. Figure 4(b) shows the flux surfaces when discrete tiles were used, for the case shown in Fig. 3(b).
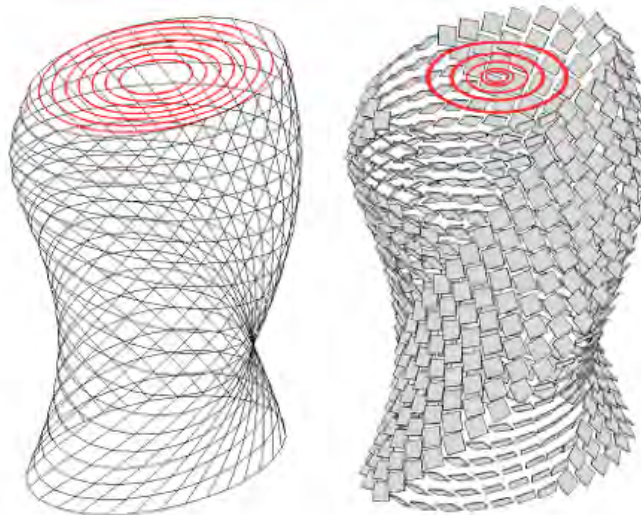

Fig. 4 Flux surfaces for the continuous (a) and discrete SC coverage.

The resulting poloidal field $(B_x^2 + B_y^2)^{1/2}$ at the mid-height of the model is shown in Figure 5. The field is a monotonic function of the radius, as expected. The poloidal field is about 0.025 at the half-way radius, with a background axial field of 1 T. The value of the rotation transform is 0.33 per pitch length, or a factor of 5 lower than for the ideal case. Some of the field is escaping through the tiles, and as was

found for the case of toroidal field ripple, it may be possible to substantially decrease this leakage (and thus increase the rotational transform per pitch length) by appropriately arranging the tiles (overlap, pitch and yew of the tiles.

The surface currents on the tiles are shown in Fig. 6. The peak surface current density for this case is around 3×10^6 A/m. Assuming the current density in the monolith is 10^9 A/m^2, the thickness of the surface current is around 3 mm. Since the tiles are 1 cm thick, the assumption of magnetic insulating boundary condition is justified. The force on the tiles is about 20 N and the torques, assuming 4.5 cm squares, are about 1 N-m. The forces and torques will scale as B^2L^2, and B^2L^3, respectively, where L is the side of the square and B is the background magnetic field. With a tile length of about 0.4 m and $B \sim$ 5 T (_i.e._, ARIES-CS scale), the force is relatively small (resulting in pressures around 10 MPa). The torques would be in the range of 10,000 N-m (about 10 k lb-ft), also relatively small because adjacent tiles balance the edge forces.

Table 1. Forces and torques for tiled case

		2706	3944
Normal force	(N)	16.51	29.55
Tx	(Nm)	-0.07	-0.15
Ty	(Nm)	0.04	0.65
Tz	(Nm)	-0.04	-0.08

I. DISCUSSION AND SUMMARY

The potential for the use of superconducting tiles for modification of field has been demonstrated. It has been shown that it is capable of producing closed magnetic surfaces.

Tile currents for the case calculated are well within present HTS capabilities. However for higher fields, it will be necessary to provide either thicker tiles, multiple tile layers, or lower temperature operation.

Future work includes optimizing the arrangement to achieve desired plasma properties, optimizing tile orientation (pitch, yaw) and tile overlap. Toroidal geometry needs to be investigated, modeling of an entire sector (or at least, half a sector).

There are issues that need to be concerned about the superconducting properties of the monoliths. Field creep, which allows current to penetrate partially into the superconductor even at conditions away

from critical, need to be modeled. The required tolerance for the positioning of the tiles also has to be determined.
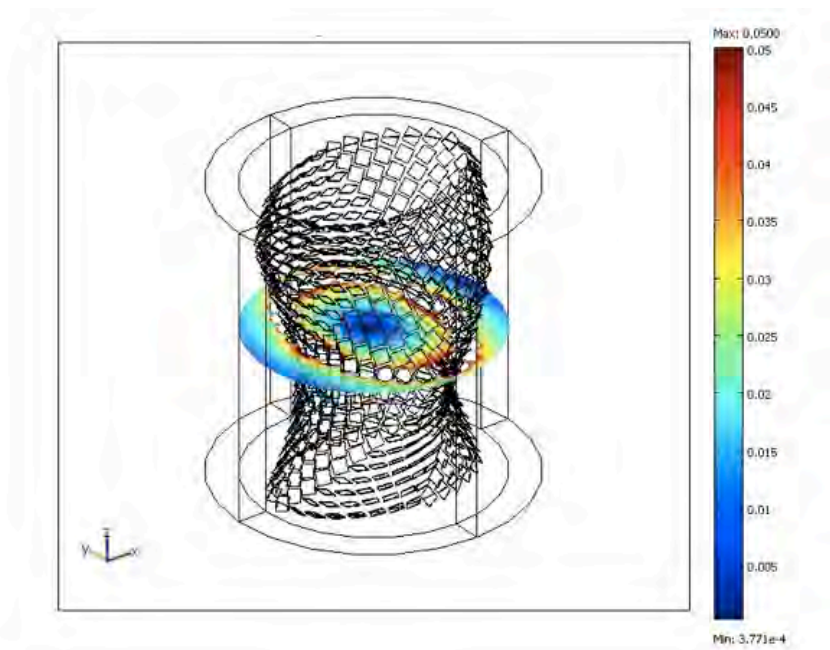
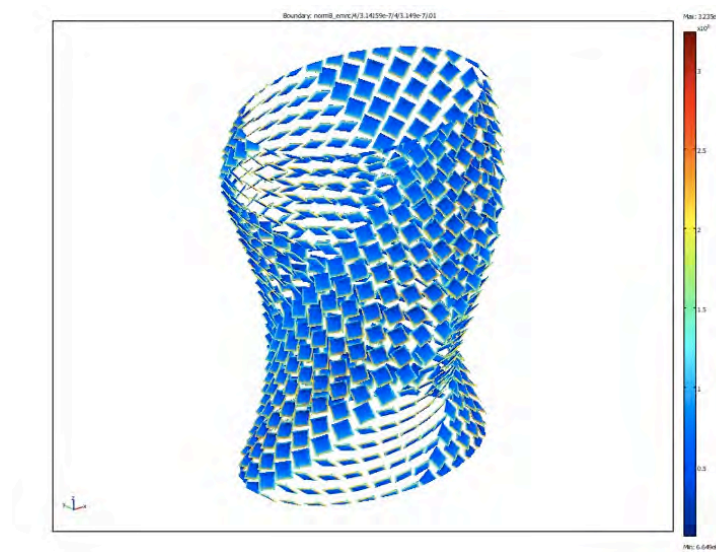## ACKNOWLEDGMENTS

Fig. 5 Contours of constant poloidal field.

Fig. 6 Contours of constant surface current density

REFERENCES

[1] F. NAJMABADI and the ARIES-CS TEAM, "The ARIES-CS Compact Stellarator Fusion Power Plant," *Fusion Science and Technology* **54** (2008)

[2] T. BROWN, L-P. KU, N. POMPHREY, *et al., Development of a Simpler Stellarator Power Plant Design*, submitted to publication

[3] M. TOMITA and M. MURAKAMI, *High-temperature superconductor bulk magnets that can trap magnetic fields of over 17 T at 29 K, Nature* **421** 517 (2003)

[4] BROMBERG, L., J.V. MINERVINI, J.H. SCHULTZ, *et al., Shaping in Stellarators Using High Temperature Superconducting Monoliths*, in *Proceedings of the Symposium of Fusion Energy (SOFE)*, San Diego 2009

[5] J.P. FREIDBERG *et al, Stability of a High-β, l-3 Stellarator, Phys Fluids* **19** 1599 (1976).