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# *Magnetic Field Shaping Using High Temperature Superconducting Monoliths*

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**Abstract—** The use of monolithic High Temperature Superconductors (HTS) for field shaping in stellarators and tokamaks is presented. Design issues relevant to stellarator magnets using single crystal or highly textured YBCO monoliths will be discussed. The excellent properties of YBCO operating at elevated temperatures ( $> 10$  K) will be summarized. High field, cryo-stable, highly complex magnet field topologies can be generated using the techniques discussed in this paper. The diamagnetic properties of the bulk HTS material can be used to provide simple mechanisms for providing field-shaping. Engineering constraints, such as stresses in the superconducting monoliths, support, quench protection, superconducting stability of the monoliths and required external support structure will be described. The limitations imposed by different fusion environments on the performance and lifetime of the HTS monoliths will be reviewed, both for near term experiments as well as long term stellarator fusion reactors. Since the HTS monoliths require no insulation or copper for stability/quench protection, the typical irradiation limits on these elements 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. In addition, irradiation damage limits on HTS, and YBCO in particular, are no lower than for Nb<sub>3</sub>Sn.

*Keywords-component; HTS bulk, monoliths, stellarator, magnetic field shaping*

## I. INTRODUCTION

Stellarators offer substantial physics advantages for fusion reactors, both near term as experimental facilities as well as long term as commercial fusion reactors [1,2,3,4]. Stellarators do not have disruptions, they are truly steady state and have high beta limits that make them attractive, among others. On the other hand, engineering of stellarators is challenging, in particular, the design of the magnetic field coils and the diverter [5,6].

In this paper and its accompanying paper [7] a novel method is investigated to simplify the magnetic field coils. The use of monolithic High Temperature Superconductors (HTS) for field shaping in stellarators and tokamaks is presented. The basic concept investigated in this paper is to use a relatively simple coil set that generates a background magnetic field, and

use monoliths of superconductor to shield/shape the magnetic field to the desired configuration.

The properties of presently available monolithic HTS are described in section II, as well as the physical model used to describe the superconducting monoliths. YBCO has excellent properties operating at elevated temperatures ( $> 10$  K). High field, cryo-stable, highly complex magnet field topologies can be generated using this material. The diamagnetic properties of the bulk HTS material can be used to provide simple mechanisms for providing field-shaping.

Section II describes the design issues relevant to stellarator magnets using single crystal or highly textured YBCO monoliths. Engineering constraints, such as stresses in the superconducting monoliths, support, quench protection, superconducting stability of the monoliths and required external support structure are described.

## II. HTS MONOLITHS

### A. *Properties and availability*

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 B-2212, but this effort was dropped because of the relatively poor superconducting properties at 77 K.

Presently, both B-2212 and YBCO are available. B-2212 is more developed, because of applications as current leads, and more recently, as components for fault current limiters. This material 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.

Bulk YBCO is being developed mainly as a material to be used in bearings, in the US (Boeing), Europe (Nexans) and Japan (ISTEC), among others. 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 operated in subcooled liquid nitrogen.

The most impressive performance of YBCO pucks has been a 17 T magnet at 29 K without a background field [8]. For B-2212, the MIT group has built a 3 T magnet at 4 K, and a 1 T insert in a 19 T background [9].

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

### B. Modeling of HTS bulk

The interaction of the superconducting bulk material with magnetic fields is very non-linear and complex. In this section two methods that simplify the complex behavior is described. These methods are used in the remainder of the paper to analyze the interaction between tiles and the magnetic field.

Using the simple Bean model of superconductivity, the superconducting monoliths are assumed to be at critical current density. As the external field is raised, currents are generated on the surface of the monolith to prevent penetration of the field to the bulk. The current density is a function of the temperature of the monolith and the local applied field. The “skin” current thickness increases with increasing magnetic fields. As the field decreases, edge currents flow in the reverse direction on the surface, trapping locally some magnetic field.

If the current density capability of the monoliths is large and the thickness of the skin currents is small compared with the size of the monoliths, the monoliths can be described as “diamagnetic” elements.

Two methods have been used to describe the diamagnetic model of the HTS monoliths. The first one assumes that the magnetic field is parallel to all the surfaces of the monolith. The second one just assumes that magnetic permeability of the HTS monoliths is very small. While either method works, the second one is easier to implement, as applying the boundary conditions to the all the surfaces of the monoliths is time consuming.

We have used  $\mu = 0.001$  in the remainder of this paper to describe the HTS monoliths.

### C. Estimate of forces/currents in HTS monolith

The interaction between HTS monoliths and magnetic field can be divided into two effects. The first one is the surface currents that exclude the external magnetic field from the superconductor. It is straightforward to estimate the value of these currents. The surface current density excited by the presence of the field is simply

$$K = B/\mu_0$$

where  $B$  is magnetic field external to the surface of the monoliths. The critical current densities of YBCO are on the order of  $10^9$ - $10^{10}$  A/m<sup>2</sup>. Thus, to expel a field of 5 T, the thickness of the current carrying layer is less than 0.01 m (1 cm). It is expected that the value of the field outside of the surface of the monolith is comparable to the applied field,  $B_0$ , (the assumption being that the main effect of the HTS monoliths is to “globally” turn the direction of the magnetic field. These currents exist even if the wide surface of the monolith is aligned with the magnetic field, and thus it is not expected to modify the direction of the field.

The second effect is due to the interception of fields perpendicular to the wide surface of the monolith. Assuming that the tiles have a dimension of a diameter, (or average diameter of the tiles), the magnetic moment generated by the presence of the monolith is

$$m \sim \pi^2/4 B_0 a^3 \cos(\delta) / \mu_0$$

where  $\delta$  the angle between the main normal to the monolith and the applied magnetic field.

The main difficulty with these simple model arises because of the interaction with the adjacent tiles, which generate local magnetic fields. Thus, arises the need to solve the problem using multidimensional models.

The torque that a monolith will experience in the presence of an externally applied magnetic field  $B_0$  is on the order of

$$\tau = m \times B_0 \sim \pi^2/4 B_0^2 a^3 \sin(\delta) \cos(\delta) / \mu_0$$

The forces/torques are very large, and need to be supported. In order to calculate the forces quantitatively, the full multidimensional effects must be calculated.

### D. Effect of gaps between monoliths

The magnetic field does not have to follow the main surface of the superconducting monoliths in the gaps between monoliths; that is, the magnetic field can “escape” through these regions.

One option to avoid the effect of the gaps between monoliths is to stack multiple layers of monoliths, such that they are staggered. Although the field can escape through the gap, it is intercepted by the monolith behind.

The impact of the staggered layer of monoliths also requires numerical calculation. This is done in the next section.

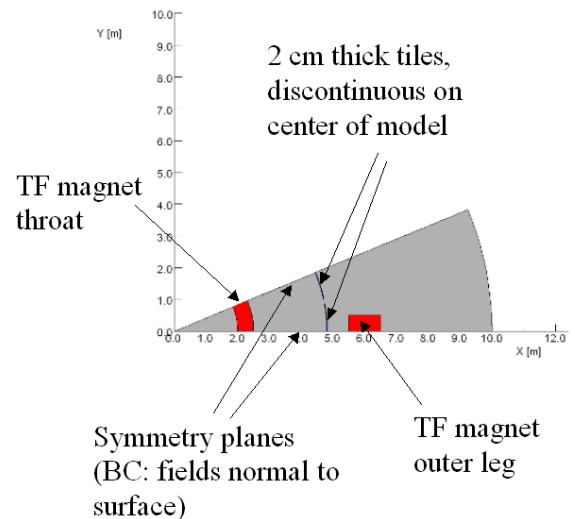


Figure 1. Schematic of geometry used to calculate the effect of multiple HTS monoliths on the toroidal field ripple in tokamaks.

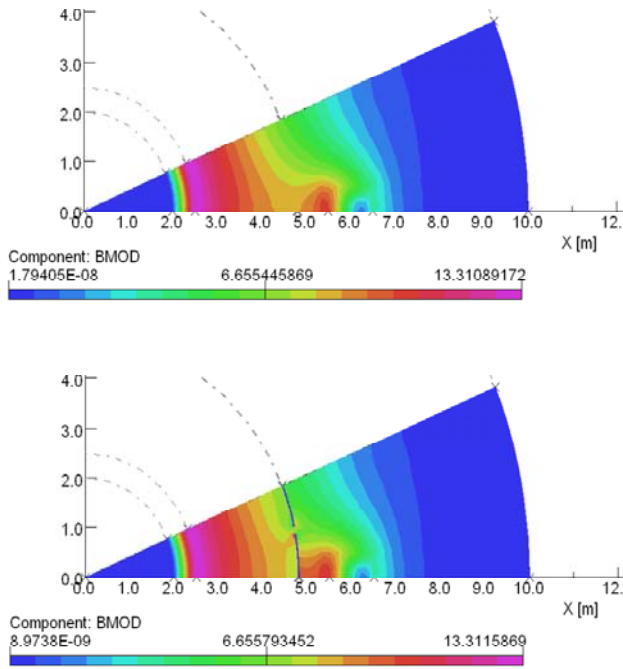


Figure 2. (a) Contours of constant magnetic field for the tokamak case with 8 coils and no HTS monoliths (base case)’ (b) Same as (a) but with the presence of 16 HTS monoliths.

### III. TOROIDAL FIELD RIPPLE CANCELLATION

The quantitative work was complex. Simpler geometries were investigated and reported here. A simple geometry using helical coils for a cylindrical configuration proved to provide none of the simplifications that a 2D model would have. That is, the helical geometry still needs a 3D model for analysis.

The rest of the paper describes these calculations that are directly relevant to tokamaks. It is possible to build a simple 2D model where the monoliths are used for ripple control.

The simple model is shown in Fig. 1. The model uses a TF system with only 8 coils, with relatively large ripple. The coils outer leg are at 6 m. The ripple calculations in the following material are estimated at a radius of 4 m.

The throat of the magnet is assumed to be continuous, with discrete legs in the outboard side. The symmetry of the problem was used to decrease the size of the required mesh. The planes with boundary conditions of normal magnetic fields are shown. It is assumed that the model is 2D, with coils extending in the direction out of the plane. Thus, the model is applicable to the midplane region of tokamaks.

#### A. Single layer of monoliths with 16 azimuthal monoliths

The commercial code VectorFields Opera-2D software is used to model this system. The problem is solved with multiple adaptations of the grid until 0.1% accuracy of the solution is achieved.

Contours of constant magnetic field are shown in Fig. 2. Fig. 2(a) shows the results for no monoliths, while Fig. 2(b) shows the results for one layer with large tiles. Fig. 2(b) has 16 monoliths, with the centerline of one of the monoliths

corresponding to the shadow of the TF coils. There is a substantial perturbation of the field around the region of the tiles, and also shown is the effect of the gap. As described above, the field tends to “squeeze out” between the monoliths.

The effect of smaller tiles, and multiple layers, is described in the next section.

#### B. Multiple layers

Multiple layers of smaller monoliths is discussed in this section. There are 8 tiles in-between TF coils, or 64 tiles around the device. For the geometry chosen for the example, the monoliths are about 30 cm in width. In call cases, the thickness of the monoliths is assumed to be 0.02 m (2 cm).

The first layer of monoliths occurs at 4.8 m, and each subsequent layer is placed at 5 cm intervals, that is, the separation between layers is 0.03 m (3 cm). The gap between the tiles has been varied from about 0.01 m (1 cm) to about 0.04 m (4 cm).

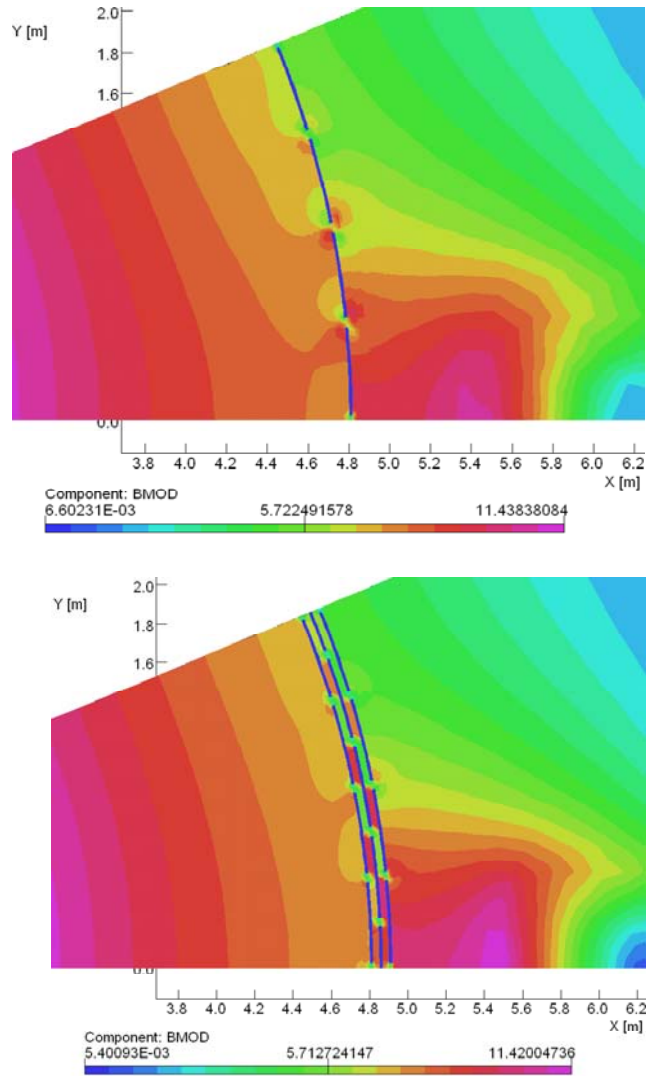


Figure 3. Contours of constant magnetic field. (a) for the case of a single layer of 0.3 m monoliths (b) for the case of 3 layers of monoliths with 3 cm between layers.

Fig. 3 shows the resulting field profiles for the cases of 1 and 3 layers of 0.3 m monoliths. It is interesting to note the dark regions of high intensity magnetic field in between some of the tiles. The field is not prevented from penetrating between tiles by the presence of monoliths downstream, but instead the field “squeezes-out” in-between the tiles in a staircase-like pattern. However, it is clear that the magnetic field ripple has been decreased, as the contours of constant magnetic field look more axisymmetric.

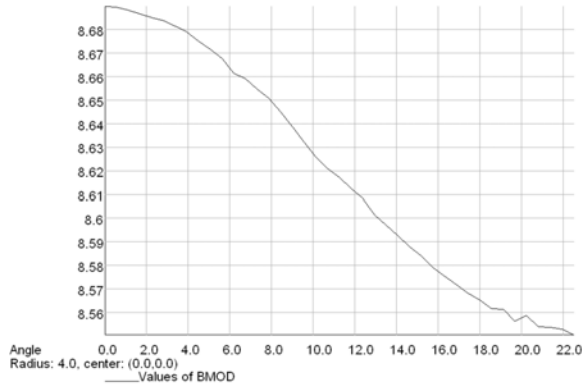


Figure 4. Magnetic field magnitude as a function of the toroidal angle for the case of 3 layers of 0.3 m monoliths, corresponding to the case shown in Figure 3b.

Fig. 4 shows the magnetic field along an arc at 4 m, along the toroidal direction. Shown in Fig. 4 is half-distance between coils, using the symmetry properties of the model. The field is sinusoidal. There are no higher harmonics visible in the field, showing that the local field from the individual monoliths has been “washed” out.

The corresponding values of peak-to-peak ripples is shown in Fig. 5, as a function of the number of layers. The field ripple is about 7% in the absence of correction by the monoliths, and decreases exponentially with increasing number of layers. The exponent is about 0.5. Between 4 and 5 layers are required in order to bring the ripple down to below 1%.

Ripple at R = 4 m

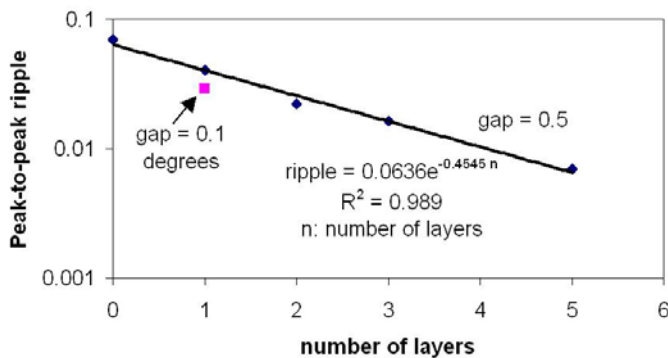


Figure 5. Peak-to-peak ripple at 4 m as a function of the number of layers, for two cases of gaps between monoliths.

Also shown in Fig. 5 is the ripple for the case with decreased gap between monoliths. In the results up to now the

toroidal gap between monoliths is  $0.5^\circ$ , corresponding to about 0.04 m between tiles. The point indicated with  $0.1^\circ$  between monoliths in Fig. 5 corresponds to about 0.008 m between tiles.

Although the results are for infinitely long monoliths, the results are expected to be relevant even in the case of limited extent of the tiles in the poloidal direction.

The thickness of the current carrying layer can be determined from these results. It is on the order of 1 cm, so the assumption of perfectly diamagnetic monoliths, although not exact, does provide a good insight into the performance of the monoliths for shaping fields in toroidal geometries.

#### IV. STELLARATOR GEOMETRY

The complex geometry of the stellarator is presently being investigated using the same model. Figure 6 shows the model that is presently being implemented in VectorFields.

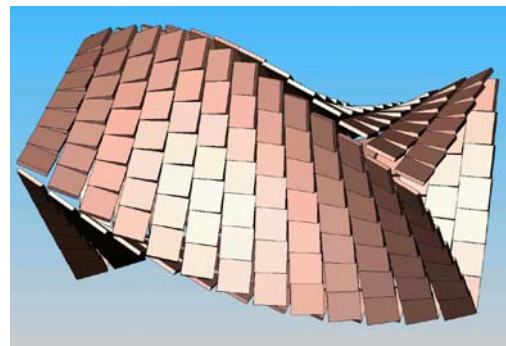


Figure 6. Helical geometry with tiles along three surfaces, for future investigation of the field shaping.

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