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Energy and Material Efficient Non-circular Bore Bitter Magnets

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***Abstract*— Resistive Bitter magnets are still widely used to produce very high continuous magnetic fields. There exist a number of experiments/applications where the second dimension of the bore of Bitter magnets is not fully utilized and thus can be minimized accordingly. Evidently, a significant reduction of one of the dimensions of the bore should result in significant decrease in consumed power and/or coil material, typically with no reduction in applicable science. However, no efforts were mounted before to quantify the benefits, likely owing to the problem intricacy. Using an analytical solution for magnetic field and current density in homothetic elliptical bore coils and finite element analysis solutions for other shapes as well, we make up for the deficiency to a degree. Relevant structural mechanical aspects are viewed to complete the picture. In closing, possibilities to enhance the cooling efficiency of Bitter magnets are discussed, albeit very briefly.**

***Index Terms*—Bitter magnets, high field, non-circular bore.**

I. Introduction

IT is common knowledge that Bitter magnets, made from copper alloy sheet metal (so-called Bitter disks), produce continuous magnetic fields significantly above 30 T. The up-to-date Florida-Bitter technology developed at the National High Magnetic Field Laboratory (NHMFL), Tallahassee, Florida, enables one to build 40-T class magnets using about 28 MW of power [1], which is a real progress from the standpoint of energy consumption reduction (in terms of MW per Tesla) at the top range of field available for experimentalists/users presently.

At the same time, even 28 MW of power is still a lot, and so an active search for avenues for reduction of power consumed by Bitter magnets continues. In this work, we would like to suggest a different line of attack on the problem of energy bill reduction. Also, a considerable gain in Bitter disk material, which is expensive and expendable, can be obtained by application of an approach discussed below.

Traditionally, a Bitter magnet bore is of perfectly round shape, a circle, i.e., a geometrical figure having 2 dimensions. Do magnet users always utilize both of these dimensions? Do they need badly the entire bore? The answer seems to be the following: most of experiments in Condensed Matter Physics, where Bitter magnets are mainly used, do not need the second dimension, whereas some other experiments/applications in this and other fields can be so "flatly" designed that the second dimension is utilized very little. In other words, the idea that we would like to discuss here lies in significant diminution of the second dimension to save on power and/or material. One of the practical solutions may turn out to be a Bitter magnet with an elliptical bore and correspondingly elliptical outer surface (Fig. 1). An elliptical bore magnet is the first choice to examine, because there is an analytical solution for a Bitter disk whose outer and inner boundaries are homothetic ellipses [2-4]; there also exists an analytical solution for a Bitter disk with confocal elliptical outer and inner boundaries as well (see [4]). In [2-4], these solutions were used to calculate the magnetic field generated by a so-called tilted (canted) coil assembled from elliptical Bitter disks at an acute angle to the coil axis to form the circular bore [5,6]; the very first conceptual design of a Bitter magnet consisted of such coils was suggested by M.D. Bird [6]. However, the same mathematical apparatus can be also employed to calculate the magnetic field of an elliptical bore Bitter coil assembled from elliptical disks at a 90-degree angle with respect to the coil axis. It is almost obvious that the field homogeneity cannot be adversely affected due to the bore change in shape.

We have made some estimates for magnets with more or less typical dimensions. The estimates enable us to see the scale of the effect from one dimension reduction and to reveal and understand new structural mechanical aspects resulted from this. Some features, e.g., cooling holes, are not included, as it is a first level comparative analysis.

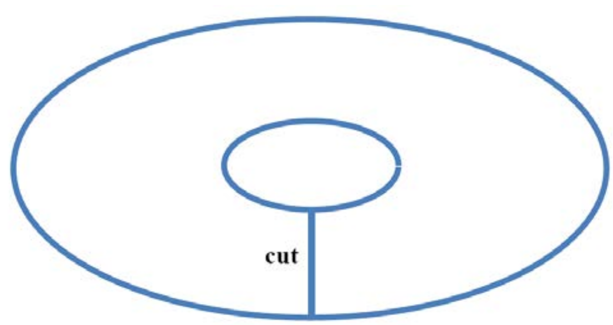

Fig. 1. Schematic of an elliptical Bitter disk / cross-section of an elliptical bore Bitter coil. The inner and outer ellipses are homothetic, with the short semi-axes significantly smaller than the long semi-axes. The cooling holes are not shown and not included in the analysis.

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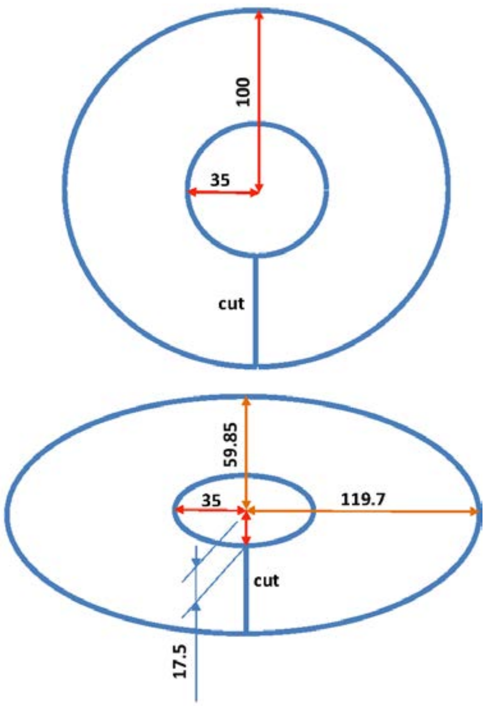

Fig. 2. Schematic and dimensions of Bitter disks of circular (upper) and elliptical bore (lower) Bitter coils of Example 1.

II. Examples of Elliptical Bitter Coils

A. Example 1

Let us consider a single coil Bitter magnet with a circular bore 35 mm in inner radius and 100 mm in outer radius and compare it with an elliptical bore single coil Bitter magnet being equal in power consumed to generate the same on-axis magnetic field, albeit using less material. The inner ellipse (the bore) semi-major and semi-minor axes of the “elliptic” magnet are 35 mm and 17.5 mm, respectively, whereas the outer ellipse semi-major and semi-minor axes were chosen to be equal to 119.7 mm and 59.85 mm, respectively, to obtain the same on-axis field and to make the disk inner and outer ellipses homothetic (Fig. 2). Thus, the second dimension of the bore is reduced by 50% (while the first one is intact). This brings down the amount of material actually used in the coil by 25%, although the coil width along the major axis increases (Fig. 2).

B. Example 2

Let us compare the same (as above) circular bore Bitter coil with an elliptical bore Bitter coil being equal to the former in the amount of material (of Bitter disks) used at the same on-axis field, hoping that such a coil will use less power. The elliptical bore of this coil is the same as the elliptical bore coil has in Example 1 (the bore second dimension is halved), and the outer ellipse was chosen to have the semi-major and semi-minor axes 137.022 mm and 68.61 mm, respectively (so as to keep the material amount constant). Indeed, it turns out that this elliptical bore coil needs 11% less power than the circular bore coil does. The powers in both examples were calculated by integration over the volumes of coils.

C. Example 3

The currently available implementation of the analytical solution has limitations. For example, it needs some modifications for calculation of magnetic field for an elliptical bore with high eccentricity, and such calculation is desirable to get an idea of the potential of the optimization proposed in this work. Furthermore, the analytical solution is not applicable to non-homothetic inner and outer ellipses or other shapes of the disk. Therefore, we used a numerical computation of the magnetic field. The Laplace problem for potential was solved for a quarter disk using the finite element method. Using the symmetry of the problem, the Dirichlet conditions with constant potentials were posed at the straight boundaries of the quarter disk and the Neumann conditions at the curvilinear boundaries. The current density equals the gradient of the potential up to a factor and was computed using numerical differentiation; and the component of the magnetic field along the axis of the (infinite) magnet was computed by integration of the current density using the curl theorem. The accuracy of the numerical computation method was checked by comparison with the results of the analytical solution for Example 2 above. In the following examples (3 and 4), the ratio of the transverse dimensions of the bore is 1:10.

In Example 3, we compared a single coil Bitter magnet with a circular bore 35 mm in inner radius and 100 mm in outer radius with an elliptical bore single coil Bitter magnet with the same larger dimension of the bore, power consumed and disk area. The inner ellipse’s (the bore’s) semi-major and semi-minor axes of the “elliptical” magnet are 35 mm and 3.5 mm, respectively, whereas the outer ellipse’s semi-major and semi-minor axes were chosen to be equal to 100 mm and 89 mm, so the inner and outer ellipses are not homothetic (Fig. 3). As the analysis implies, the magnetic field is 23% higher for the elliptical bore coil magnet. When we tried to change the major and minor semi-axes of the outer ellipse without changing the area of the disk, we did not obtain better results.

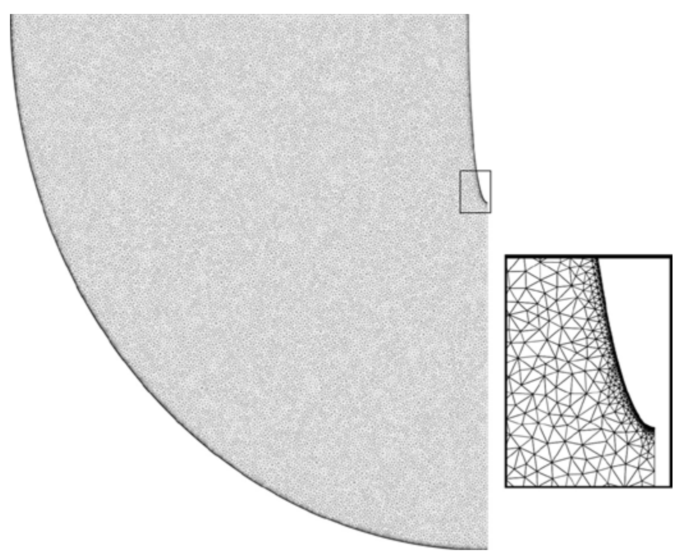

Fig. 3. Shape and fine FE mesh of elliptical bore coil of Example 3 (non-homothetic ellipses). A quarter of the coil cross-section (on the left) and the bore fragment (at the bottom right) are shown. The mesh is excessively refined to maximize the computation accuracy.

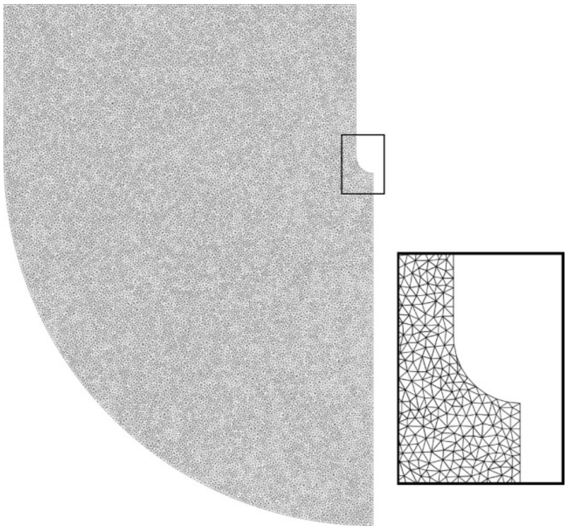

Fig. 4. Shape and fine FE mesh of the racetrack bore coil of Example 4 A quarter of the coil cross-section (on the left) and the bore fragment (at the bottom right) are shown. The mesh is excessively refined to maximize the computation accuracy.

D. Example 4

We compared a single coil Bitter magnet with a circular bore 35 mm in inner radius and 100 mm in outer radius with a racetrack bore single coil Bitter magnet with the same larger dimension of the bore, power consumed and disk area. The radii of the turns of the outer and inner curves of the racetrack are 76.5 mm and 3.5 mm, respectively, whereas the length of the straight segments of the racetrack is 63 mm (Fig. 4). As calculated, the magnetic field is 20% higher for the racetrack bore coil magnet. This is slightly less than for the elliptical bore coil magnet of Example 3, simply because the racetrack bore cross-section area is somewhat larger than the elliptical bore one. In other words, the difference obtained does not necessarily mean that the elliptical bore coil is slightly more efficient. Also, the shape of the racetrack bore may be preferable for some applications, and the racetrack-shaped disks may turn out to be easier to produce and stack.

E. Discussion

As can be inferred from the examples, even a rather moderate reduction in the bore's second dimension can result in noticeable gain in either power or material used, or both. This gain may turn out to be more impressive if one further reduces the second dimension. Presumably, the saving on power may exceed 25% at greater than 2, albeit still technologically and practically reasonable, ratios between the semi-major and semi-minor axes. Obtainment of more precise values invites a comprehensive analysis that can be done later.

III. Structural Mechanical Aspects

There exist very important structural mechanical aspects that should be studied to generalize and complete the picture. Let us start with the following. As can be inferred from Fig. 5, the body forces in the elliptical bore coil (from Example 1) are distributed in a different and more complicated way compared to that in the circular bore coil. The force is the largest in the area where the radius of curvature is the smallest (on the major axis), and this force is larger than that in the circular bore coil.

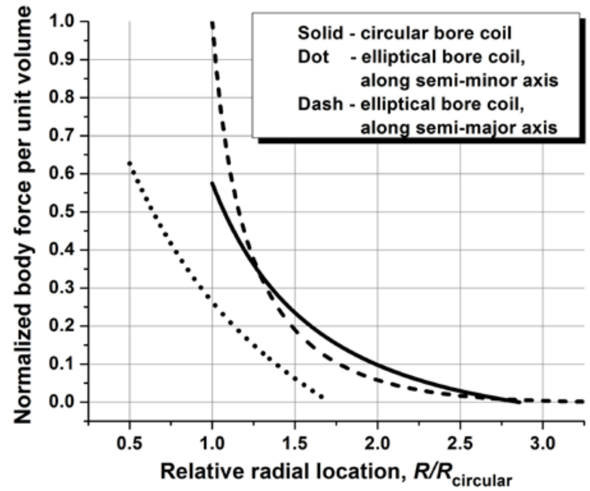

Fig. 5. Comparison of body force per unit volume in the elliptical bore and circular bore coils of Example 1.

We performed computations of stress in the elliptical bore coil and circular bore coil of Example 1 using plane stress finite element analysis. The boundary of the elliptical bore coil without current (no magnetic field) versus the deformed mesh of the same coil with a current is shown in Fig. 6 (left). The displacement is in arbitrary units, the Poisson ratio is 0.33.

The maximum von Mises stress was 3.18 times higher for the elliptical bore coil than that for the circular bore coil, evidently because of the presence of bending moments. In order to address the issue, we mimicked a support (overlapping) counteracting the moments (in the elliptical bore coil) as follows: the displacements were assumed to vanish on the part of the external elliptical boundary that is symmetric with respect to the minor axis of the ellipse and has a length of projection on the major axis equal to the semi-major axis (of the external ellipse). The boundary of the elliptical bore coil without current (no magnetic field) versus the deformed mesh of the same coil with a current is shown in Fig. 7.

The maximum von Mises stress turned out to be only 1.67 times higher than that in the circular coil (without a support) and was concentrated at the ends of the support. Elsewhere the von Mises stress was smaller than the maximum von Mises stress in the circular coil (the maximum factor was 0.85), and this may turn out to be the result, a quite encouraging one, that we need. The high stress at the ends of the support is largely an artifact of the crude model of the support on the one hand, the support was assumed to be completely "glued" to the coil; on the other hand, the ends of the support were not rounded. The stress would be noticeably lower if contact elements were used and the support size and shape were optimized, as that would lead to better stress distribution and thus to reduction of the maximum stress.

We have not performed stress computations for the coils of Examples 3 and 4, but we expect the results to be similar qualitatively to those for Examples 1 and 2.

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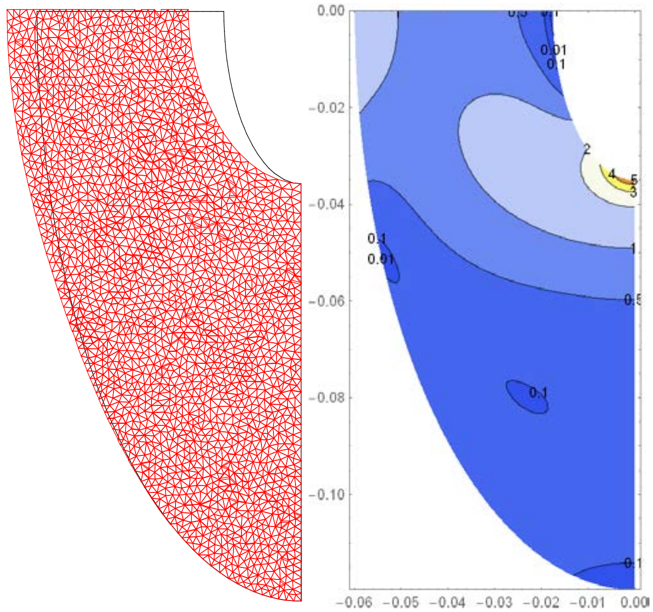

Fig. 6. The boundary of one fourth of an elliptical bore coil with no current versus the deformed mesh under current, with no support (left), and contour plot of von Mises stress (right). Rotated.

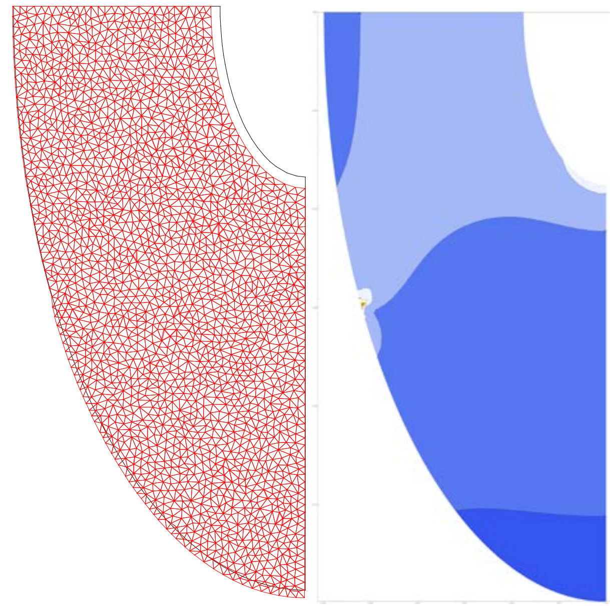

Fig. 7. The boundary of one fourth of an elliptical bore coil with no current versus the deformed mesh under current, with support (left), and the contour plot of von Mises stress (right). Rotated.

In addition, we are cognizant of the fact that a real high field Bitter magnet consists of multiple nested coils with rather limited gaps between them that complicates placement of an external support structure on each coil. Perhaps, the forces can be translated to the housing which is supposed to be properly reinforced. Anyway, there is an intricate problem to be addressed.

It is also worthy of notice that comprehensive optimization of cooling holes in the elliptical bore coils may turn out to be somewhat more complicated and require a larger number of iterations compared to the circular coils. Also, in an elliptical bore coil, each disk cut location is supposed to be calculated carefully, since the disks are not round.

Certainly, the results obtained raise more questions than give answers and thus invite further analysis, clarification, and refinement.

IV. Cooling Efficiency Enhancement Opportunities

Cooling of high-power Bitter magnets is an increasingly challenging problem [7], and it may turn out to be even more challenging for non-circular bore Bitter coils, where the current density non-uniformity is larger and more complicated. As two-phase flow cooling has some obvious advantages and is widely used for various demanding applications, its feasibility for resistive magnets was discussed earlier. Work [8] emphasizes that it is difficult to control instabilities of two-phase flow and concludes: "For good reasons, the nuclear power industry has made the step from boiling water to pressurized water reactors to avoid two-phase flow heat exchange. It does not seem reasonable to go the opposite way in magnets." However, presently, the heat flux in advanced high-power resistive magnets [1] is typically significantly higher than in nuclear power reactors [8] and quite comparable to the heat flux in the most critical components of the future ITER nuclear fusion reactor, whose design includes two-phase flow cooling, e. g., for the first wall and the divertor dome [9]. Therefore, the tremendous potential of two-phase flow cooling for resistive magnets may deserve closer attention. This issue will be discussed in more detail elsewhere.

V. Concluding Remarks

We do not claim that the elliptical bore is the best choice, because a somewhat different shape may turn out to be more optimal and thus beneficial or preferable in terms of mechanical strength of the magnet (there may be some trade-offs). Particularly, we are planning to check up if the stress can be managed better in the case of racetrack bore coil. Indeed, in the racetrack curves, the curvature is uniform (where it does not vanish), which may bring about lower stress. Nonetheless, the concept workability depends evidently on a number of factors.

In closing, another part of the future work could be to test the concept validity and practicability with respect to wire-wound superconducting magnets with a view to saving on the conductor and/or reducing the stress due to Lorentz forces. We are aware of the fact that wire-wound non-round coils were considered and built, however, to our knowledge, nobody did it yet in an effort to save on the materials or to increase magnetic field at the same stored energy: the shape choice was dictated by the applications mostly, if not only.

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