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. 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.

The idea and approach used

Resistive Bitter magnets consume a lot of energy, despite a real progress in their optimization [1]. We 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 here. Some experiments can be so "flatly" designed that the 2nd dimension is not utilized or is utilized very little. The idea lies in significant reduction of the 2nd dimension to save on power and/or material.

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], Fig. 1; there also exists an analytical solution for a Bitter disk with confocal elliptical outer and inner boundaries as well [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 appropriate angle to the coil axis to form the circular bore . FEA solutions are used for other shapes.

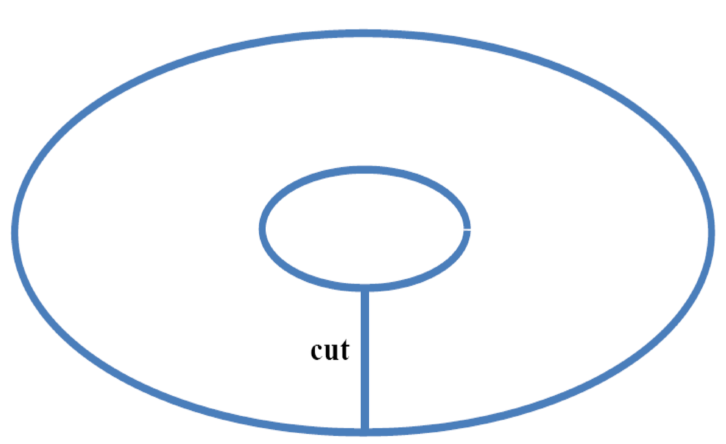

Fig. 1. Schematic of an elliptical Bitter disk of an elliptical bore Bitter coil. The inner and outer ellipses are homothetic, with the short semi-axes significantly smaller than the long semi-axes. The cooling holes are not shown.

[1] J. Toth, and S.T. Bole, "Design for an update of the NHMFL 32-mm bore resistive magnet," this conference, Wed-Af-Or27.

[2] A. M. Akhmeteli, and A. V. Gavrilin, "Superconducting and resistive tilted coil magnets," arXiv:physics/0410002, 2004.

[3] A. M. Akhmeteli, A. V. Gavrilin, and W. S. Marshall, "Superconducting and resistive tilted coil magnets for generation of high and uniform transverse magnetic field," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 1439-1443, 2005.

[4] .A M. Akhmeteli, A. V. Gavrilin, and W. S. Marshall, "Superconducting and resistive tilted coil magnets. Magnetic and mechanical aspects," *chapter 5 in book "Superconductivity, Magnetism and Magnets"*, ed. L.K. Tran, Nova Publishers, ISBN: 1-59454-845-5, pp. 139-172, 2006.

Scale of the effect and gain , demonstrated with examples

Example 1

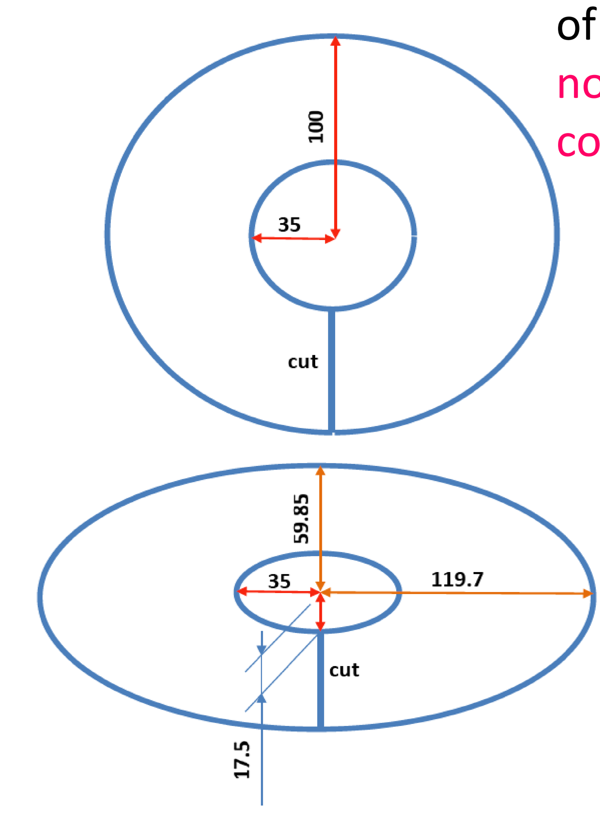

Fig. 2. Schematic and dimensions of Bitter disks of circular bore and elliptical bore Bitter coils . All non-circular bore coils in all 4 Examples are compared with this round coil.

The elliptical bore single coil Bitter magnet and round single Bitter magnet are equal in power consumed to generate the same on-axis magnetic field, but the elliptical Bitter uses less material. The second dimension of the bore of the elliptical magnet is reduced by 50% (while the first one is intact). This results in the material reduction by 25%, although the elliptical bore coil turns out to be slightly wider along the disk's major axis than the circular bore coil.

Example 2

The elliptical bore is the same as the elliptical bore coil has in Example 1 (the bore second dimension is halved), and the outer ellipse dimensions are changed to keep the material amount constant (the same as in the round coil) @ the same on-axis field. The elliptical bore coil needs 11% less power than the circular bore coil does.

Example 3 (FEA)

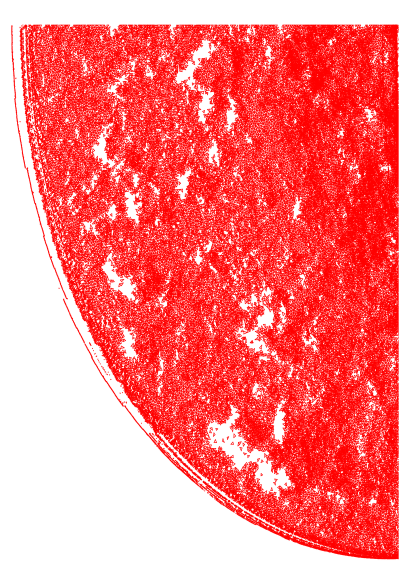

Fig. 3. Shape of elliptical bore coil magnet (non-homothetic ellipses). The ratio of the transverse dimensions of the bore is 1:10.

An elliptical bore single coil Bitter magnet with the same larger dimension of the bore, disk area and power consumed. The magnetic field is 23% higher. Extremely fine FE mesh is used.

Example 4 (FEA)

Fig. 4. Shape of racetrack bore coil magnet. The ratio of the transverse dimensions of the bore is 1:10.

A racetrack bore single coil Bitter magnet with the same larger dimension of the bore, disk area and power consumed. The magnetic field is 20% higher. Extremely fine FE mesh is used.

Structural mechanical aspects (with Example 1)

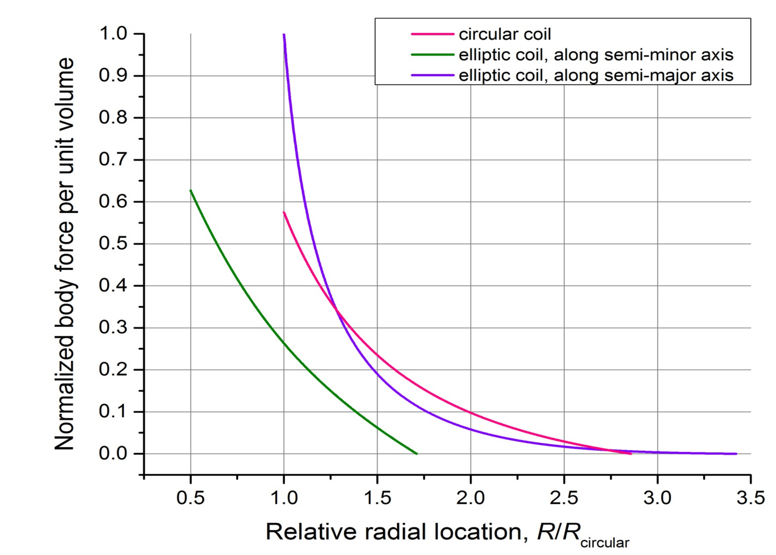

Fig. 5. Comparison of body force per unit volume in the elliptical (Example 1) and round coils. The force is the highest in value in the area where the radius of curvature is the smallest (on the major axis), and this force is noticeably higher than that in the round coil. Bending moments are the issue.

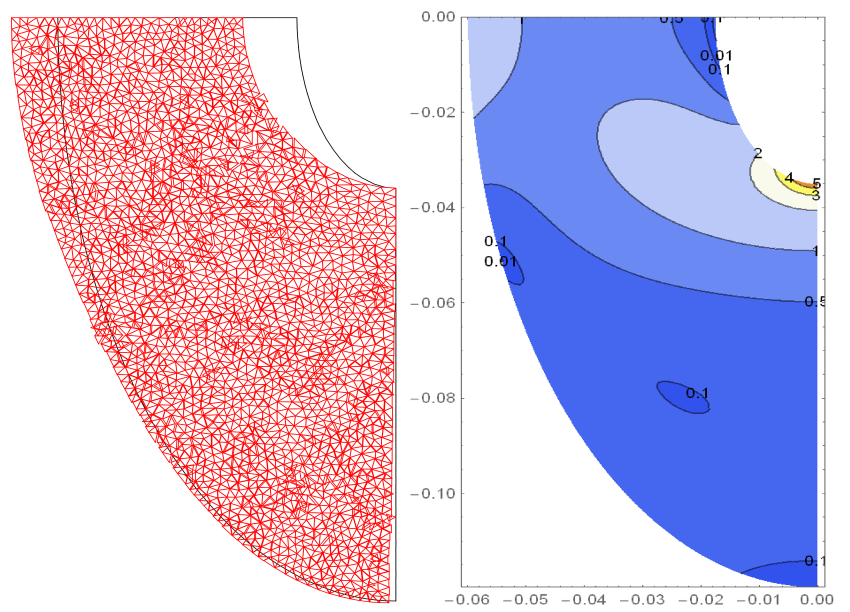

Fig. 6. The boundary of one fourth of an elliptic bore coil with no current versus the deformed mesh under current, with no support (left), and contour plot of von Mises stress (right). Rotated.

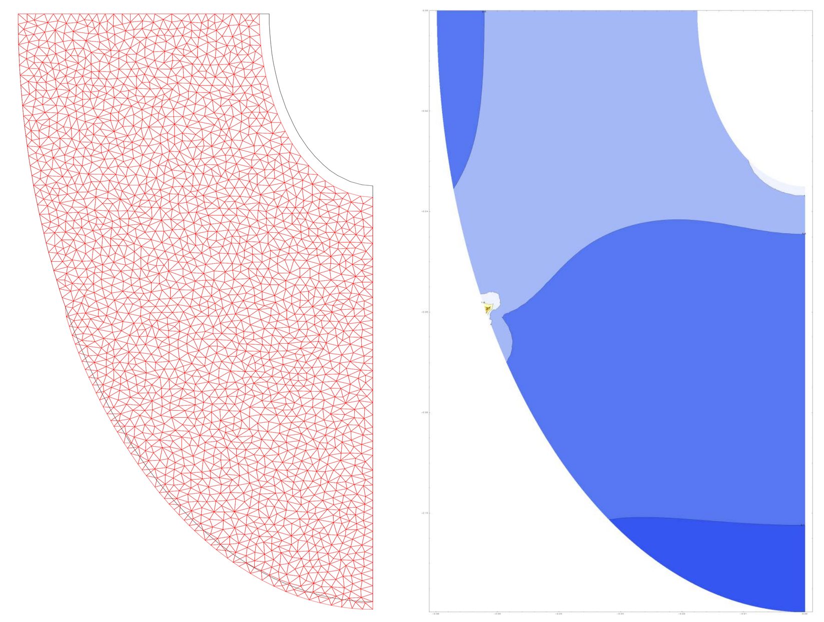

Fig. 7. The boundary of one fourth of an elliptic bore coil with no current versus the deformed mesh under current, with support (left), and the contour plot of von Mises stress (right). Rotated. The stress is lower than in the round coil.

Cooling Efficiency Enhancement

Cooling of high-power resistive magnets is a challenging problem [7]. 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 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.

[7] M. D. Bird, "Resistive magnet technology for hybrid inserts," *Supercond. Sci. Technol.*, vol. 17, pp. R19-R33, 2004.

[8] EuroMagNET II, 2nd Periodic Report, 2012.

[9] ITER Newsline 264, 15 Apr., 2013, http://www.iter.org/newsline/264/1556 .