# DESIGN STUDIES OF A DIPOLE WITH ELLIPTICAL APERTURE FOR THE MUON COLLIDER STORAGE RING*

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## *Abstract*

The requirements and operating conditions for superconducting magnets used in a Muon Collider Storage Ring are challenging. About one third of the beam energy is deposited along the magnets by the decay electrons. As a possible solution an elliptical tungsten absorber could intercept the decay electrons and absorb the heat limiting the heat load on superconducting coils to the acceptable level. In this paper we describe the main design issues of dipoles with an elliptical aperture taking into consideration the field and field quality. The discussion is extended presenting a combined function magnet design. The temperature margin and the forces in the coils are presented as well.

## INTRODUCTION

A Muon Collider is seen as a promising machine for the future of high energy physics [1]. Particle collisions in the Muon Collider will occur through the intersection of two circulating beams inside a storage ring. Requirements and operating conditions for a Muon Collider pose significant challenges to superconducting magnet designs and technologies [2]. About one third of the beam energy is deposited along the magnets by the decay electrons. As a possible solution, an elliptical tungsten absorber could intercept the decay electrons limiting the heat load on superconducting coils to a acceptable level. Figure 1 shows the dimensions of the elliptical aperture Muon Collider Storage Ring (MCSR) magnet and the elliptical absorber with shifted beam channel. The absorber dimensions were defined based on azimuthal distribution of heat deposition presented in [2]. Coil aperture was increased by 20 mm to accommodate the cold bore and helium channel.

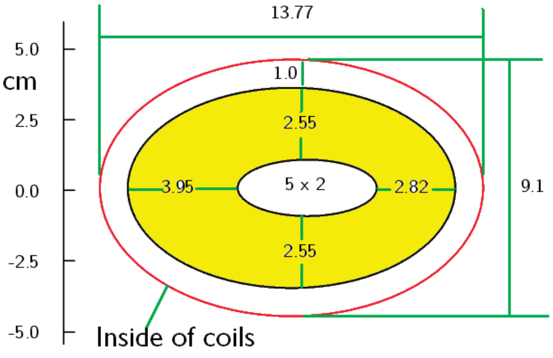

Figure 1: The elliptical aperture with an elliptical absorber. All dimensions are in cm.

Table 1: Specifications

| Parameter | Value |
|---|---|
| Nominal dipole field (T) | 8 |
| Nominal gradient (T/m) | 80 |
| Operation Temperature (K) | 4.5 |
| Coil Major Aperture (mm) | 138 |
| Apertures ratio – (elliptical case only) | 0.66 |

Table 1 summarizes the requirements and operating conditions for this magnet. As shown in [3, 4], it is desirable to combine dipole and gradient fields into a single magnet. This paper will show the practical limits of combining these two functions into a single magnet in terms of maximum gradient and operational margin. A comparison between the elliptical shape and a circular shape will also be presented.

Analysis was performed using ROXIE code [5]. The level of magnetic field in MCSR magnets requires using $Nb_3Sn$ superconductor. The $Nb_3Sn$ strand and cable parameters are summarized in Table 2. The dependence of critical current density of $Nb_3Sn$ superconductor on the magnetic field and temperature was parameterized according to [6].

Table 2: Strand and Cable Parameters

| **Parameter** | **Value** |
|---|---|
| Number of strands | 20 |
| Strand diameter (mm) | 1.0 |
| Cu/non-Cu ratio | 1.3 |
| Jc(12T, 4.2K) (A/mm$^2$) | 2500 |
| Cable mid-thickness (mm) | 1.915 |
| Cable keystone angle (deg) | 0.97 |
| Cable width (mm) | 10.0 |
| Cable insulation thickness (mm) | 0.25 |

## BENDING DIPOLE

Figure 2 shows the comparison between a circular and an elliptical aperture dipole. In the same picture one can see the good field zone of 30 mm radius. The blocks of the coils were designed in such a way to minimize the allowed low order harmonics (for a dipole magnet $b_3$, $b_5$, etc.). The natural asymmetry of the elliptical aperture magnet introduces a slightly higher level of allowed

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harmonics, which is very difficult to minimize to the same levels of the circular.

Magnet parameters are compared in Table 3.

Table 3: Dipole Parameters

| Parameter | Round aperture | Elliptical aperture |
|---|---|---|
| Bmax coil at 4.5K (T) | 10.0 | 10.9 |
| Operational Field (T) | 8.0 | 8.0 |
| Inductance at Bop (mH/m) | 33.7 | 23.5 |
| Stored energy at Bop (kJ/m) | 53.4 | 43.8 |
| Fx at Bop (kN/m) | 7.0 | 8.2 |
| Fy at Bop (kN/m) | 5.4 | 6.4 |

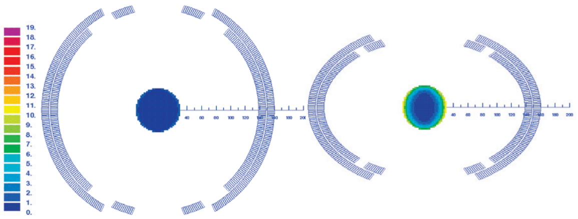

Figure 2: Circular vs. Elliptical aperture dipole. The colour-scale represents the sum of the high-order harmonics in units (1 unit = $10^{-4}$ of the main field).

## COMBINED FUNCTION MAGNET

One can combine the dipole and gradient functions into a single magnet. This can be done by introducing the left-right coil asymmetry for example by opening the coil winding in one of the sides of the magnet (see Figure 3). However, combined function magnets usually have the disadvantages of creating a full spectrum of harmonics. Moreover the level of those harmonics is high and they are very difficult to minimize (see Tables 3 and 4). Therefore the good field region of the combined function magnet is sacrificed.

The other disadvantage of the combined function magnet is that the gradient is fixed by the geometry since the field main dipole field is fixed. Figure 4a shows the gradient as function of coil radial thickness. The field was fixed in 8T and the maximum angle of the split coil is 90°.

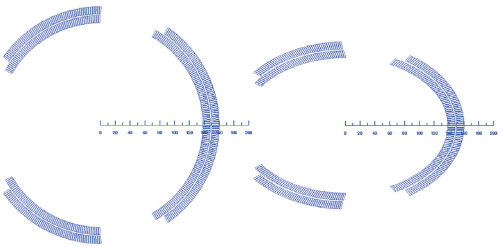

Figure 3: Circular vs. Elliptical aperture combined function magnet.

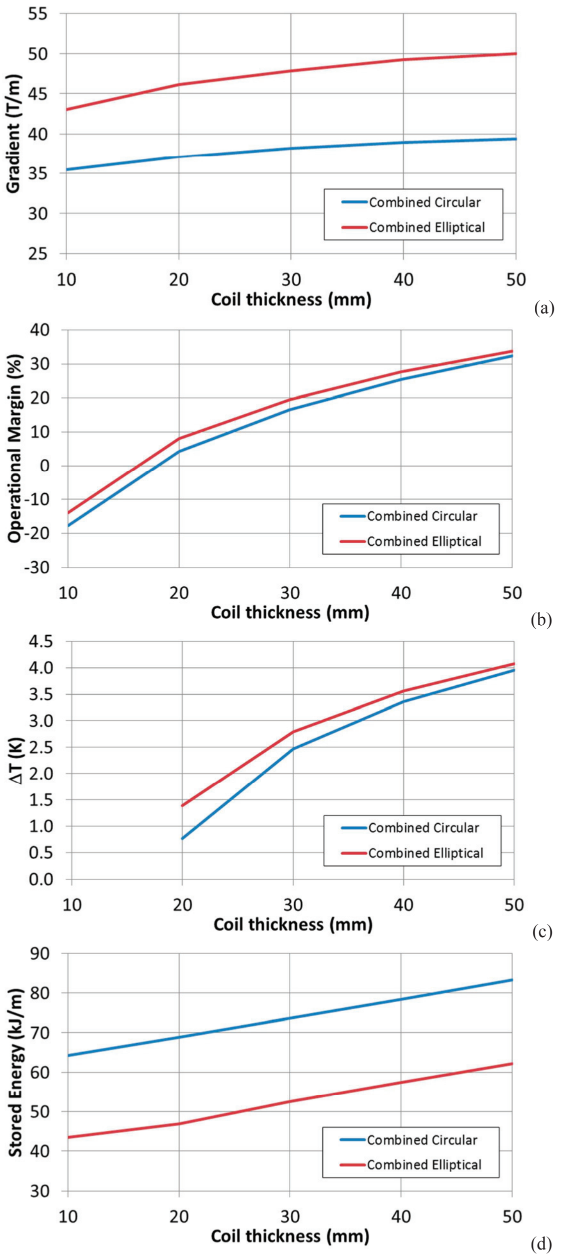

Figure 4: (a) gradient, (b) operation margin, (c) temperature margin and (d) stored energy as function of the coil radial thickness.

It can be seen that the elliptical aperture provides approximately 25% more gradient with respect to the circular aperture magnet. The field gradient reaches its maximum of 50 and 40 T/m for elliptical and circular apertures. The limiting gradient as function of the coil width (for a given aperture) is also observed in pure superconducting quadrupoles and it is described with more details in [7]

The operational margin (defined as the percentage of the operational point with respect to the short sample limit of $Nb_3Sn$ at 4.5 K along the load line) is seen in Figure 4b. The minimum coil thickness for this magnet is at least 20 mm. Figure 4c shows the temperature margin (with respect to operation temperature of 4.5 K). There is essentially no difference between the elliptical and circular apertures in terms of the margins. The stored energy is shown in Figure 4d. The elliptical aperture magnet has around 28% less stored energy (although the differences in the areas of the apertures are around 35%).

The Lorentz forces acting on the coils were calculated for the two geometries and the differences are on the level of 3%.

## NESTED MAGNETS

An attractive option to generate the combined fields is nesting dipole and quadrupole magnets. Most efficiently it can be done with the dipole coil located outside (Fig. 5) [4].

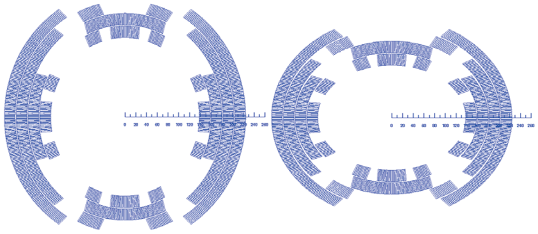

Figure 5: Circular vs. Elliptical aperture of a nested Dipole and Quadrupole magnets.

The nested magnets presents lower higher order harmonics because each magnet can be individually optimized to have its allowed harmonic at acceptable levels. One may have separate power supplies for the dipole and the quadrupole windings; therefore the gradient is not coupled to the dipole (like in the combined function). The limit is given by the superconductor. In order to achieve higher fields, it was assumed for these simulations a wider cable (20 mm width with 40 strands). The maximum gradients of elliptical and circular aperture magnets with the dipole in the outer region without any operation margin (considering 8T for the main dipole field) are 73 and 63 T/m respectively. A more realistic design of nested magnets can be found in [4].

## HARMONICS

The harmonics of the circular and elliptical aperture magnets are summarized in the Tables 4 and 5 respectively. As mentioned before, the combined function magnets generate all the harmonics. Furthermore, the B3 component is high (even higher for the elliptical aperture). An optimization process with blocks of coils is possible to lower these values, but it is unlikely that the B3 will be lowered to acceptable levels. As stated before, the elliptical aperture magnet presents higher harmonics which reduce the good field region.

Table 4: Harmonics for Circular Aperture Magnet

| **Bn=(bn/b1)x$10^4$** | **Dipole** | **Combined function** | **Nested Q+D** |
|---|---|---|---|
| **B2** | 0.0 | 1418.1 | 2343.5 |
| **B3** | -0.1 | -178.2 | 4.0 |
| **B4** | 0.0 | -0.1 | 0.0 |
| **B5** | -1.3 | -0.4 | -0.4 |

Table 5: Harmonics for Elliptical Aperture Magnet

| **Bn=(bn/b1)x$10^4$** | **Dipole** | **Combined function** | **Nested Q+D** |
|---|---|---|---|
| **B2** | 0.0 | 1771.7 | 2746.8 |
| **B3** | -2.4 | -323.1 | -1.0 |
| **B4** | 0.0 | -9.1 | -24.7 |
| **B5** | -9.4 | 5.0 | -1.3 |

## SUMMARY

Elliptical and circular aperture magnets were compared. Initially the dipole only function magnet results show that the elliptical geometry has a natural higher level of harmonics.

The combined function magnets were studied as function of coil thickness when the dipole field is fixed at 8 T. The elliptical aperture provides 25% more gradient than the circular aperture. It also stores around 28% less stored energy. There are essentially no differences between operation margin and temperature margin. The good field region for the combined function magnets is sacrificed mainly because of the high B3 component. The differences in the Lorentz forces acting on the coils are negligible between the two geometries.

The nested magnets could be an attractive option in terms of harmonics and could achieve higher gradients uncoupled from the main dipole field.

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