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Modular Design and Modular Program for High Gradient Quadrupoles

Ramesh Gupta

Abstract— **A *Modular Design and Modular Program* is introduced here for high gradient quadrupoles. The proposed quadrupole design is based on simple flat racetrack coil modules. Even though many high gradient quadrupole designs using flat racetrack coils have been considered earlier, they have not been able to generate the same maximum quench gradient as produced in conventional *cosine (two) theta* designs. The proposed *Modular Design* is able to overcome those limitations. In addition, a systematic, flexible and cost-effective *Modular R&D Program* is also proposed that can be used in developing both high gradient quadrupoles and a variety of high field dipoles. A rapid turn around magnet R&D program based on flat racetrack coils has been found very useful and efficient in the past. Since the proposed *Modular Design* is based on simple flat racetrack coils with large bend radii, it offers good likelihood of success in both *React & Wind* and *Wind & React* technology for building magnets with brittle superconductors.**

Index Terms— **Accelerator magnets, Quadrupoles, React & wind technology, Racetrack coil magnets, Superconducting magnets.**

I. Introduction

THE design guidelines for high gradient quadrupoles differ significantly from those for high field dipoles. Whereas in an ideal dipole (for example in *cosine (two) theta*), the bore field increases linearly with the coil width (t) irrespective of the coil radius (a), in an ideal quadrupole the increase in field gradient with t saturates as it increases as $log(1+t/a)$. Furthermore, to achieve high gradients in quadrupoles, it is much more important that the conductor is placed close to the coil radius at the midplane. In *cosine (two) theta shell geometry*, all conductor blocks are primarily at the same radius whether they are at midplane or at pole. However, in most quadrupole designs with *flat racetrack coils* [1]-[3], the conductor is closer to the pole and from the midplane (see Fig. 1). Therefore, those types of quadrupole designs with *flat racetrack coils* produce a significantly lower maximum field gradient irrespective of the amount of conductor used.

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The proposed modular quadrupole design [4] overcomes that disadvantage. The design creates a gradient in flat racetrack coils quadrupoles that is close to the gradient that is achieved in *cosine (two) theta* quadrupoles by allowing conductors to be placed at a radius similar to the midplane radius of *cosine (two) theta* quadrupoles. The design, however, uses twice as much conductor as in a conventional design. Therefore, such a design is attractive where only a few magnets are needed and where a higher conductor cost can be tolerated in favor of high performance, or where the use of flat racetrack coils with large bend radii is critical.

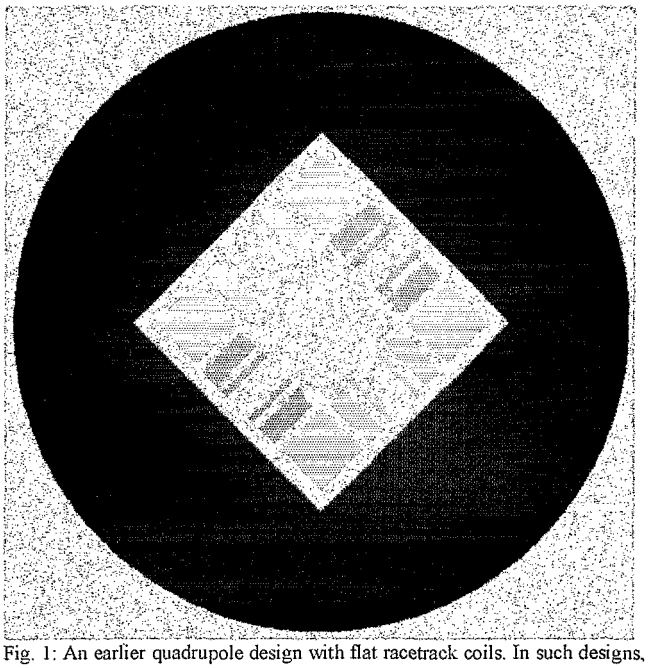

Fig. 1: An earlier quadrupole design with flat racetrack coils. In such designs, turns at midplane are away from the coil radius.

Very high gradient quadrupoles, such as those being developed [5] for Large Hadron Collider (LHC) luminosity upgrade under LHC Accelerator Research Program (LARP), must use brittle conductors like Nb_3Sn. This requires dealing with differential thermal expansion of various components, the influence of which becomes crucial and more complicated to foresee as coils, particularly those with complex end geometry, become significantly longer. A variety of modular designs are presented here that produce field quality as good as in *cosine (two) theta* designs.

II. Magnet Design

A. Conceptual Design

Two styles of *Modular Designs*' are presented here: *Symmetric* and *Simpler*.

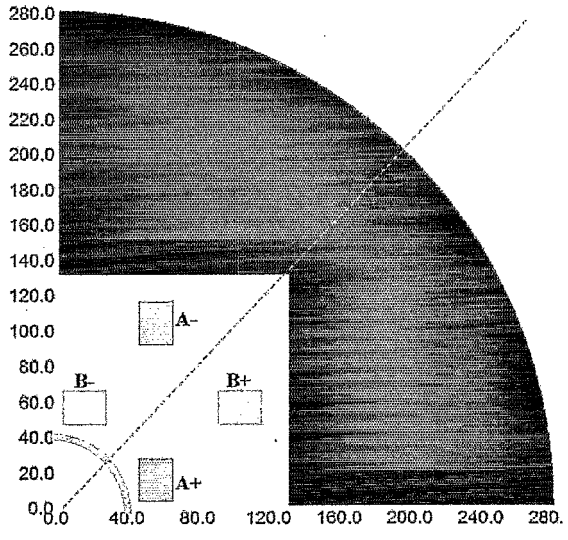

Fig. 2. A quadrant of the *Symmetric Style* of the *Modular Design* concept. The design consists of two flat racetrack coil modules *A* and *B* with a typical eight-fold quadrupole symmetry in the cross-section (i.e. the two octants have mirror symmetry about the 45 degree line). The beam tube is shown by a circular arc. All dimensions are given in mm.

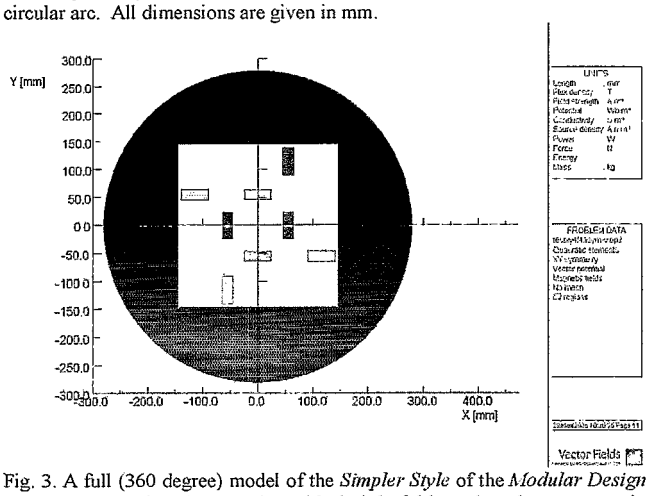

Fig. 3. A full (360 degree) model of the *Simpler Style* of the *Modular Design* concept. The design does not have ideal eight-fold quadrupole symmetry in the cross-section (i.e. the two octants do not have mirror symmetry about the 45 degree line). However, in addition to four-fold symmetry, design has a periodic four-fold rotational symmetry which limits the number of non-allowed skew harmonics.

The *Symmetric Style* of *Modular Design* concept is shown in Fig. 2. Fig. 2 shows a cross-section of one quadrant of quadrupole that contains two octants that have reflection symmetry about 45°. The center of the beam will be at the origin. The design is based on two flat racetrack coil modules *A* and *B*. The relative direction of the current in the coils is indicated in the figure.

Most of the gradient in the *modular quadrupole* design is generated by blocks *A*+ and *B*-, with return blocks *A*- and *B*+ adding relatively small amount (~5% in quench performance). Each octant of the quadrupole has the typical quadrupole symmetry in the cross-section with first octant consisting of blocks *A*+ and *B*+. To accommodate this topology, coils *A* and *B* need to have different length and one needs to go inside (interleave) another. In order to allow the interleaving, the coils need to have at least part of their center island free of support structure. The *Simpler Style* of the *Modular Design* is shown in Fig. 3. It does not require any interleaving of the coils. Moreover, all coils can have the same length and the support structure should be relatively simpler. However, because of the lack of eight-fold symmetry, the magnetic design becomes more involved. In addition to minimizing field harmonics b_6, b_{10}, b_{14}, etc., one would also need to minimize a_6, a_{10}, a_{14}, etc., as they are not zero by symmetry. However, rest of the skew and normal harmonics are zero in this quadrupole geometry because of the four-fold rotational symmetry.

B. 2-d Magnetic Design

The cross-section of a 2-layer, 90 mm aperture quadrupole based on the *Symmetric Style* of *Modular Design* for possible use in a LARP R&D program is shown in Fig 4. It is based on the same cable that was used in other LARP quadrupole designs [6] (27 strands of 0.7 mm diameter wire with a cable thickness of 1.26 mm and width of 10.05 mm). The design is first optimized for high gradient using OPERA2d (see Fig. 4) for ~10^{-3} field quality. It has 33 turns (3+15+15) per octant for the main coil. The computed gradient at quench is ~235 T/m for a critical current density of 2000 A/mm^2 (4.2K, 12T) and ~258 T/m for a critical current density of 3000 A/mm^2 (4.2K, 12T). This is similar to what was obtained in 90 mm aperture, 2-layer *cosine (two) theta* designs with the same cable thickness [2,3]. This proves that the *Modular Design* can produce quadrupole magnet designs that are capable of generating high gradients that are similar to those obtained in conventional *cosine (two) theta* designs.

The above design is further optimized for field quality with the computer code RACE2dOPT [7]. The optimized design (see Fig. 5) has 32 turns. These 32 turns are distributed as follows: 17 in the inner layer, 14 in the outer and 1 (single) in the field shaping pole block. The single turn may be left out from initial R&D models. In addition to these 32 turns (Block *A*+ in Fig. 2) in first octant, there are also equal number of turns (*B*+ in Fig. 2) coming from the return side of the second octant. Relative field errors at 2/3 of the coil radius are computed to be of the order of 10^{-7}. The computed field harmonics, shown in Table I, are of the order of 10^{-3} at 30 mm reference radius (2/3 of coil radius). These are well below typical construction errors and well below the typical field errors set by beam physics requirements.

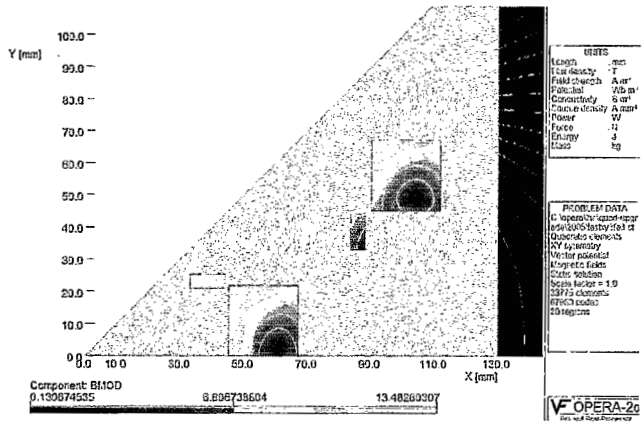

Fig. 4. An OPERA2d model of the octant of a 2 layer, 90 mm aperture LARP quadrupole design. The field lines are shown at the overall current density of 1000 A/mm^2, which generates a gradient of ~284 T/m. This gives a computed quench gradient of ~258 T/m for a critical current density of 3000 A/mm^2 (4.2K, 12T) in superconductor.

TABLE I. FIELD HARMONICS OPTIMIZED FOR *SYMMETRIC STYLE* OF MODULAR DESIGN WITH RACE2DOPT AT 30 MM RADIUS (2/3 OF COIL RADIUS), IN 10^{-4} UNITS.

HARMONIC	VALUE
b_6	0.005
b_{10}	-0.004
b_{14}	0.003
b_{18}	0.000

The cross-section of a 90 mm aperture LARP quadrupole based on the *Simpler Style* of *Modular Design* is shown in Fig 6. The computed field harmonics in this *Simpler Style* design are also well below typical construction errors and are well below the typical field errors set by beam physics requirements. As shown in Table II, this is true for both normal and skew harmonics (those that are allowed by this particular symmetry), as they are all of the order of 10^{-3} at 30 mm reference radius (2/3 of coil radius).

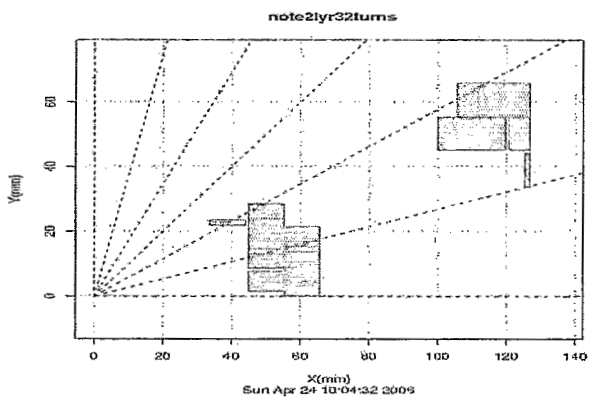

Fig. 5. An octant of 90 mm aperture *Symmetric Style* of *Modular Design* for LARP quadrupole that is optimized for field quality using *RACE2DOPT*. The optimized harmonics are essentially zero.

TABLE II: FIELD HARMONICS OPTIMIZED FOR *SIMPLER STYLE* OF *MODULAR DESIGN* WITH *RACE2DOPT* AT 30 MM RADIUS (2/3 OF COIL RADIUS), IN 10^{-4} UNITS.

n	a_n	b_n
6	-0.0007	0.0000
10	0.0016	-0.0010
14	-0.0020	-0.0006
18	0.0000	0.0000

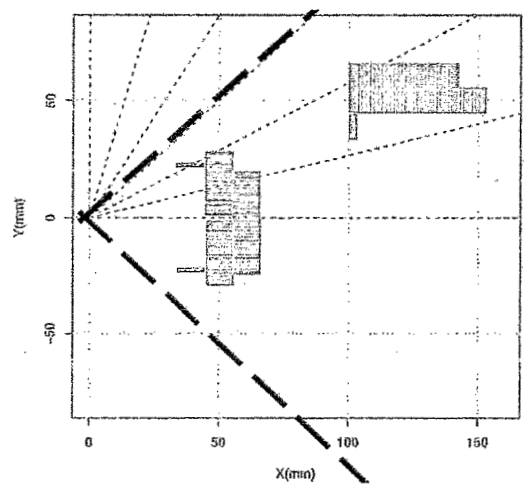

Fig. 6. An quadrant of 90 mm aperture *Simpler Style* of *Modular Design* for LARP quadrupole that is optimized for field quality using RACE2DOPT. The optimized harmonics are essentially zero.

C. 3-d Magnetic Design Concepts

The 8-fold quadrupole symmetry that was retained in 2-d magnetic design in *Symmetric Style* of *Modular Design* cannot be obtained in 3-d since for interleaving purpose some coils have to be longer than others. The 3-d magnetic design has not yet been optimized to the same level as the 2-d magnetic design. However, a strategy is presented here that should make non-allowed harmonics small despite the above inherent asymmetry in the ends. One way to examine this asymmetry is to compare the integral of the magnitude of the field on the x-axis and on the y-axis at a certain distance from origin. In a normal quadrupole the two are identical but not in *Modular Design* for the reasons mentioned above. One way to overcome this asymmetry in an integral sense is to make one coil layer bigger than the other in a 2-layer design to make the average integrated magnetic length the same in two octants. The magnitude of the field as a function of axial position at a distance of 30 mm (2/3 of the coil radius) from the origin on the X-axis and the Y-axis is shown in Fig. 7. The computed integral value in the end of a long magnet is also listed. One can see from the number shown at the bottom of the plot that the integral asymmetry can be practically eliminated.

In a more optimized magnetic design, the end harmonics (both allowed and non-allowed) will have to be minimized with 3-d computer codes. A similar situation was faced in the common coil dipole design [8] where most turns return on one side. It was shown there that by using certain techniques (such as using asymmetric end spacers) one could compensate above asymmetry and obtain low end-harmonics.

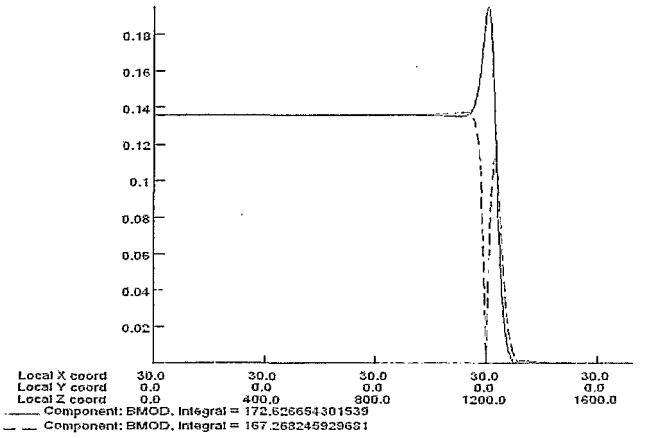

Fig. 7. The magnitude of the field as a function of axial position on the horizontal axis (full line) and vertical axis (dashed line) at a distance of 30 mm from the origin. The integral value is listed at the bottom of picture. The difference between the two integrals is the measure of integral asymmetry.

D. Mechanical Design

A mechanical design for the *Modular Quad* has not yet been developed. A mechanical design must, obviously, be developed before considering this design for a potential accelerator magnet. The purpose of this paper is to introduce an overall concept to possibly design and build *racetrack coil* quadrupoles with gradients as high as those achieved in conventional *cosine (two) theta* quadrupole designs. Lorentz forces, etc. have been presented elsewhere [4].

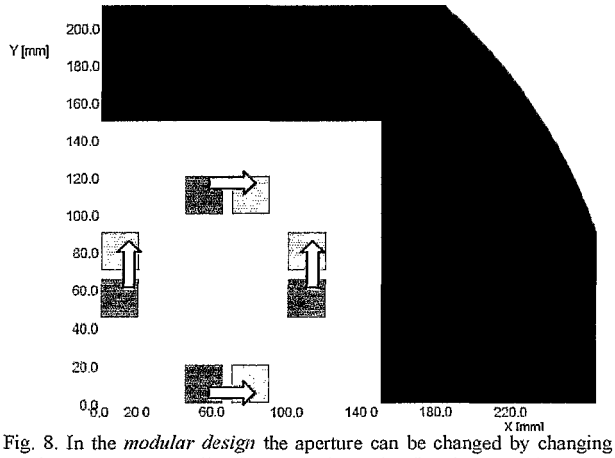

Fig. 8. In the *modular design* the aperture can be changed by changing the spacing between the coils. Arrows indicate the direction in which two coils will have to move to increase the aperture from 90 mm to 140 mm.

III. Modular R&D Program

Modular Design offers a rapid-turn-around and a relatively simple and inexpensive mechanism for carrying out a versatile magnet R&D program. One can, for example, change the apertures and field gradients in the R&D modular quadrupole design while using the same coil modules (see below and in Fig. 8). In addition, the same coil modules can also be used in building 2-in-1 *common coil dipole* [9] and *open midplane dipole* [10] R&D magnets.

In addition, the large bend radii in coil ends allow the use of both *Wind & React* and *React & Wind* technologies [11].

As shown in Fig. 8, the modular design offers an opportunity to vary quadrupole apertures in R&D magnets while using the same coil modules. To change aperture in R&D magnets, one just needs to change the spacing between the coils (Fig. 8). Smaller aperture gives higher gradient for the same pole tip field and vice versa. The Lorentz forces and coil stress also change with a change in aperture. The magnet support structure must be designed appropriately to allow such an R&D program.

The proposed design is inherently modular where the racetrack coils of identical geometry can be stacked or their relative positions changed. These coil modules need not have the same width. One gets higher gradient when more coil modules are stacked. However, in quadrupole magnets, the fractional increase in field gradient becomes smaller as the number of coil increases. This also means that one can get a significant gradient even with a single layer of coil.

IV. Conclusion

It has been shown that is possible to design high gradient quadrupoles with flat racetrack coils using *Modular Design*. The design is consisted of simple flat racetrack coils that can be stacked as cassettes for carrying out a systematic and a variety of magnet *R&D* in a *Modular Program*. This is expected to be similar to the positive experience gained with the common coil magnet design that facilitated a cost-effective rapid-turn-around R&D program. Such R&D is particularly useful in the early stages of an accelerator program where the magnet and lattice parameters cannot be frozen without a feedback from proof-of principal magnets.

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