Superconducting Magnet Division

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Author: R. Gupta

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Title: Modular Program and Modular Design for LARP Quadrupoles

M. Anerella	S. Ozaki
J. Cozzolino	B. Parker
J. Escallier	S. Peggs
G. Ganetis	F. Pilat
M. Garber	S. Plate
A. Ghosh	C. Porretto
R. Gupta	W. Sampson
H. Hahn	J. Schmalzle
M. Harrison	J. Sondericker
J. Herrera	S. Tepikian
A. Jain	R. Thomas
P. Joshi	D. Trbojevic
S. Kahn	P. Wanderer
W. Louie	J. Wei
J. Muratore	E. Willen

Modular Program and Modular Design for LARP Quadrupoles

Ramesh Gupta
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Abstract

A "Modular Program and Modular Design" is introduced here for LARP (LHC Accelerator Research Program) quadrupoles. It is based on simple flat racetrack coil modules. In this note a systematic, flexible and cost-effective "Modular R&D Program" that is built upon these modules is outlined. "Modular Design" allows a relatively simple and inexpensive mechanism for changing magnet aperture and field gradient in the initial R&D using the *same* coil modules. This is particularly relevant as the magnet parameters are not fixed at this stage and a later change in them would require new model magnet programs that invariably result in significant delay and developmental cost. A similar modular design and flat racetrack coil experience has been very positive in various R&D magnet programs based on the common coil dipole design.

Quadrupoles that are being developed under US LARP program use brittle Nb_3Sn coil technology. This requires dealing with differential thermal expansion, the influence of which becomes crucial and more complicated to foresee as coils, particularly those with complex end geometry, become significantly longer. Due to the fact that the proposed design is based on simple flat racetrack coils, it is also expected to have a higher likelihood of success.

Conceptual Design

The basic *Modular Design* concept is shown in Fig. 1. Please note that the Fig. 1 shows the cross-section of one quadrant (two symmetric octants). 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 quadrupole is generated by blocks *"A+"* of module *"A"* and *"B-"* of module *"B"*, with return blocks *"A-"* and *"B+"* adding only a little. Each octant of the quadrupole has quadrupole symmetry in the cross-section with first octant consisting of blocks *"A+"* and *"B+"*. Interleaving of the coil modules and optimization of field quality in the ends will be discussed later. The coils need to have at least part of their center island free of support structure. A photo of such an impregnated coil is shown in Fig. 2.

The design is modular and flexible because it is composed of simple flat racetrack coils. To change the magnet aperture, one would move modules in or out; to increase the gradient within the same aperture one would add more racetrack coils. The support structure for the initial R&D magnets must be designed from the beginning in such a way that these variation/studies can be accommodated.

The design uses about a factor of two more conductor compared to that in the "cosine theta" design since the return blocks contribute little to the gradient. However, the main blocks *"A"* and *"B"* are about as efficient in generating field as the blocks in cosine theta magnets. The Lorentz force considerations may be more favorable in this design.

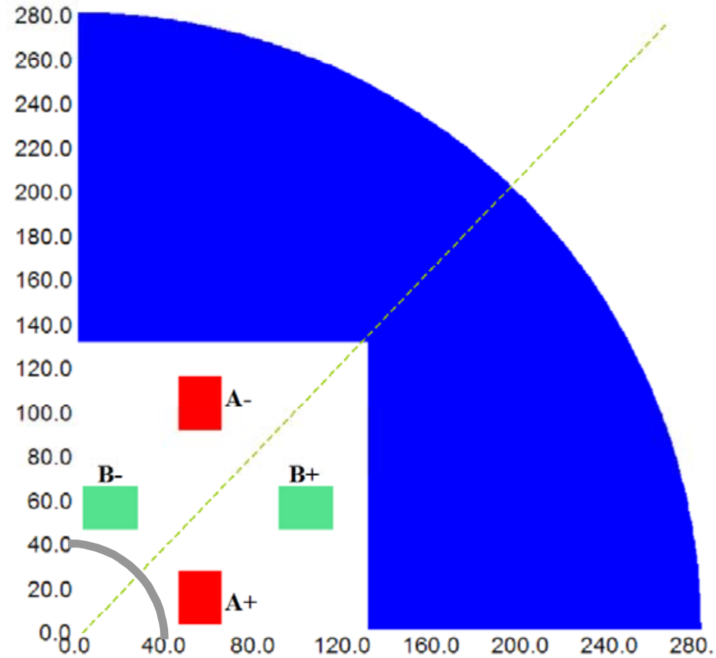

Fig. 1. A quadrant of the modular quadrupole design concept that also facilitates a modular R&D program. The design consists of two flat racetrack coil modules "A" and "B" that provide quadrupole symmetry in the cross-section (i.e. the two octants have mirror symmetry across the 45 degree line). The beam tube is shown in gray. The coils are interleaved in such a way that the integral harmonics in the ends will be small. All dimensions are given in mm.

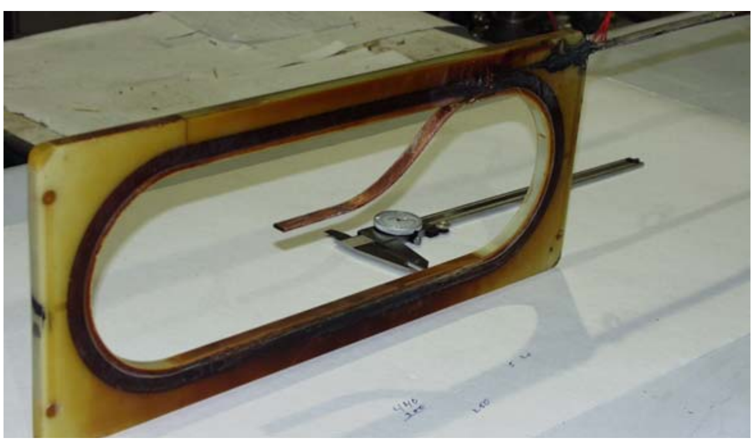

Fig. 2. An impregnated Nb3Sn coil with center space (island) free of any structure except for the splice. One would need similar coils for the modular design (the center space needs to be free of everything.

In a program that relies on the success of a few magnets based on "unproven and state of the art technology", the strength of the overall R&D program and the options retained in the initial stages are more crucial than developing a design that minimizes the volume of conductor. (The situation will be opposite for developing main accelerator magnets that are required in large quantities). In fact the conductor cost is only a fraction of the overall magnet development cost when all R&D costs (tooling, labor design) are included. The "Modular Program" and "Modular Design" are expected to bring a significant overall saving in the "LARP magnet R&D program" and reduce the time needed to make the first long demonstration quadrupole. Moreover, simpler flat racetrack coils not only save time and money, they are also more likely to have better chances of success when conductor used in the coil is brittle. The simple flat ends are less prone to damage due to "strain" caused by the differential thermal expansion in the long coils when cumulated conductor mass in the body of the magnet works against the ends and vice-versa. Moreover, the cable is also less prone to degradation, as it does not require any "keystoning". It is also possible to use this design in both "React & Wind" and "Wind & React" technologies (i.e. it is a technology independent design). This option offers an extra level of insurance in case unknown issues arise when the "Wind & React" technology, which has been successful in producing short magnets, is applied to long magnets. Many length dependent issues are bypassed when magnets are built with "React & Wind" technology.

2-d Magnetic Design

The cross-section of a 2-layer, 90 mm aperture LARP quadrupole based on the modular design is shown in Fig 3. For the purpose of this study, the wire and cable parameters (see Table 1) are those same that used in the racetrack coil designs by Ferracin. The simple design (as shown in Fig. 3) is first optimized by hand using OPERA2d for $\sim 10^{-3}$ field quality. It has 33 turns (3+15+15) per octant for the main coil (the 2-layer cosine theta design by Kashikhin has 34 turns). 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).

Table 1. Cable parameters.

Parameter	Unit	Value
N of strands	-	27
Strand diameter	mm	0.700
Bare width	mm	10.050
Bare inner edge thickness	mm	1.260
Bare outer edge thickness	mm	1.260
Cabling angle	deg.	15.5
Keystone angle	deg.	0
Radial insulation thickness	mm	0.125
Azimuthal insulation thickness	mm	0.125
Copper to non-copper ratio	-	0.97

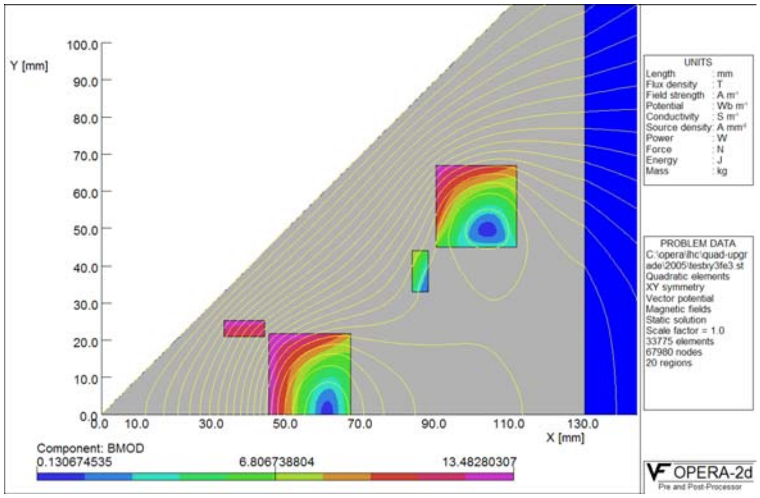

Fig. 3. An OPERA2d model of the octant of a 2 layer, 90 mm aperture LARP quadrupole design. The field lines are shown at the overall current density of 1000 A/mm^2, which generates a gradient of ~284 T/m. The computed quench gradient is ~258 T/m for a critical current density of 3000 A/mm^2 (4.2K, 12T).

A design which is further optimized for field quality (the octant shown in Fig. 4) has 32 turns per octant in the main blocks. These 32 turns are distributed as follows:17 in the inner layer, 14 in the outer and 1 in the field shaping turn. In addition there are equal number of turns coming from the return side of the main block of the second octant. This makes the total number of turns in the magnet about twice as many as in a conventional design. The possibility of returning turns in the same octant and away from the coil was also examined but found much less attractive (see Appendix A for a brief summary).

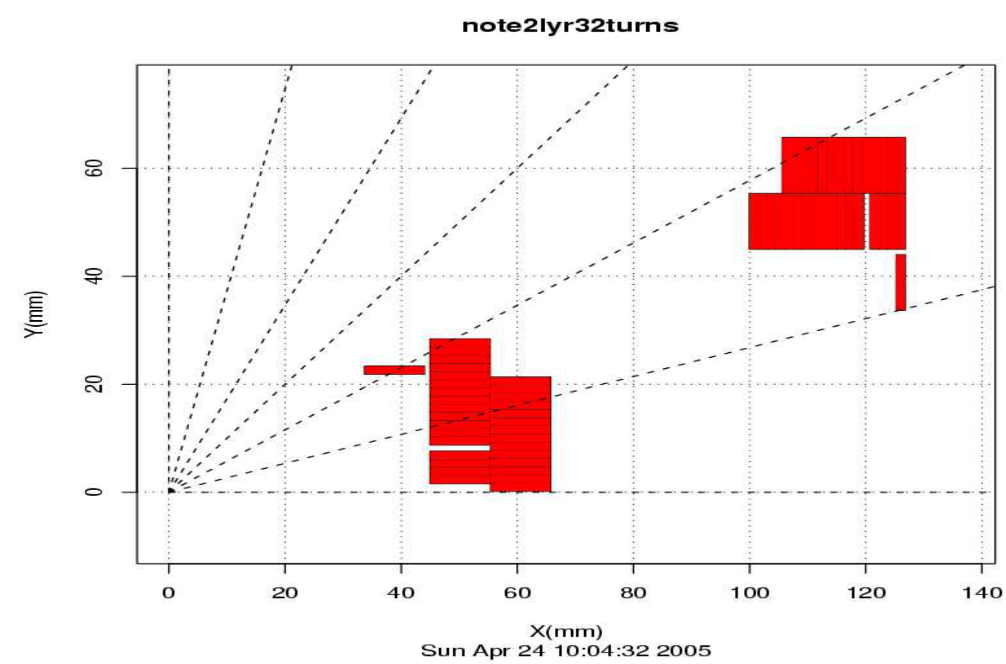

Fig. 4. An octant of 2 layer, 90 mm aperture LARP quadrupole design optimized for field quality using RACE2DOPT. The optimized harmonics are essentially zero.

Two flat racetrack coils make a single double pancake module, which makes it easier to bring the current lead out. In addition there is a single turn coil that poses no problem in bringing a lead out since this itself may be considered as a lead. This single turn is used for minimizing field harmonics and reducing peak field and may perhaps be left out from initial R&D models. 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 2, are of the order of 10^{-3} at 2/3 of coil radius. These are well below typical construction errors or typical field errors set by beam physics requirements.

Table 2. Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

Harmonic	Value
b_6	0.005
b_{10}	-0.004
b_{14}	0.003
b_{18}	0.000

3-d Magnetic Design

At this stage the 3-d magnetic design has not been optimized to the same level as the 2-d magnetic design. However a concept presented here shows that it should be possible to minimize non-allowed harmonics despite the inherent asymmetry in the geometry.

The simplest way to interleave the coils is shown in Fig. 5. In this case half of the double pancake coils are shorter than other half. This, however, creates a magnetic asymmetry in the ends between the horizontal and vertical planes and generates a non-zero octupole harmonic.

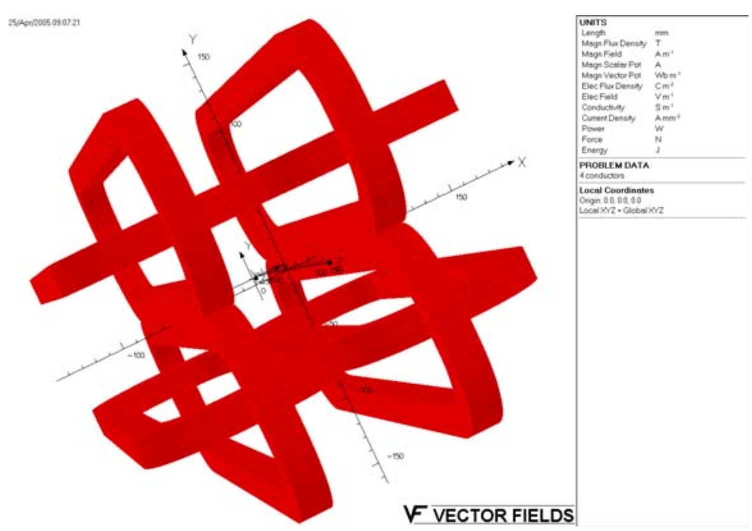

Fig. 5. Coils of modular design in a short magnet. The simplest way of interleaving coils creates a magnetic asymmetry in the ends between the horizontal and vertical planes and generates a non-zero octupole harmonic.

A straight forward 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. In a normal quadrupole the two are identical because of the quadrupole symmetry. However, in the present design this symmetry is broken in the ends and two values are different (see Fig. 6). The magnitude of the field is computed as a function of axial position at a distance of 30 mm (2/3 of the coil radius) from the origin on X-axis and Y-axis. The integral values of field on the two axis is listed at the bottom of the plot. A difference between the two integral reflects that the quadrupole symmetry is broken.

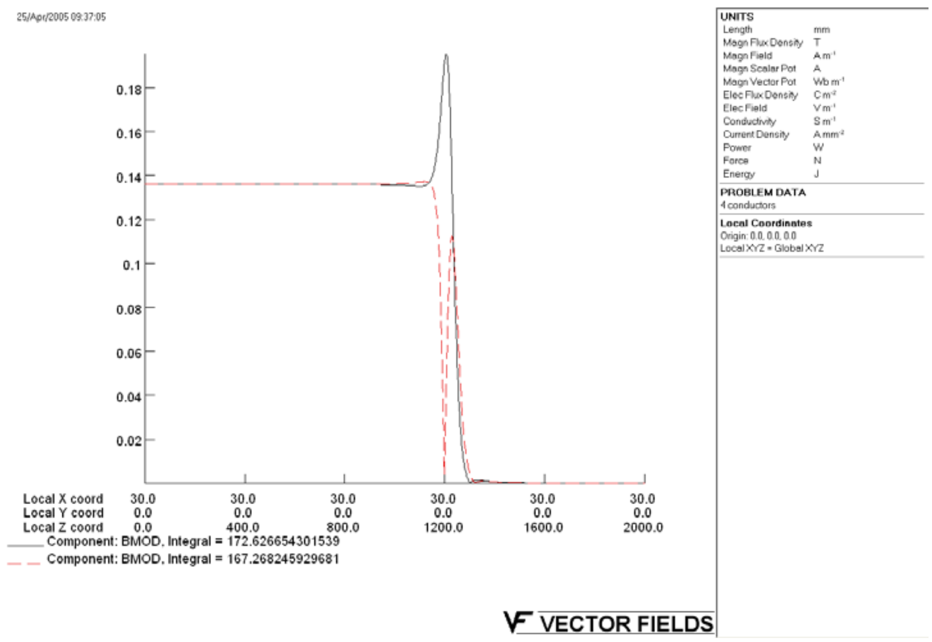

Fig. 6. The magnitude of the field as a function of axial position on the horizontal axis (black full line) and vertical axis mm (dashed red line) at a distance of 30 mm from the origin. The integral value is listed at the bottom of picture. The difference between the two integrals is the measure of integral asymmetry.

One way to overcome this asymmetry is to make one coil bigger than other (see Fig. 7) so that the average integrated magnetic length is the same. The computed integral value in the end of a long magnet is shown in Fig. 8. One can see that the integral asymmetry can be practically eliminated. The end harmonics (both allowed and non-allowed) will be minimized with computer codes that optimize the coil ends.

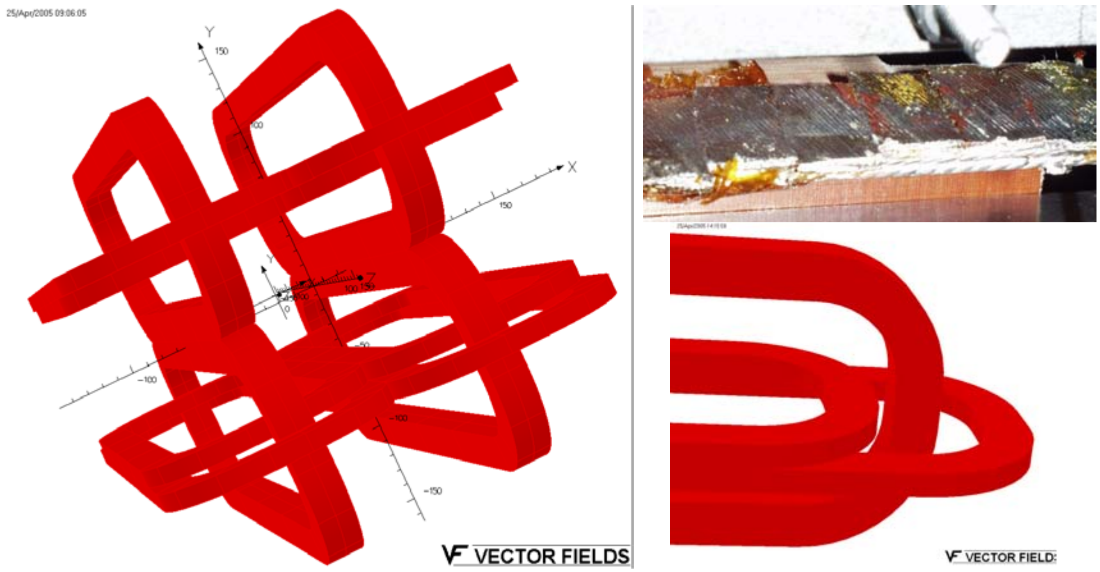

Fig. 7. Some interleaving coils are made smaller and some larger in an attempt to minimize magnetic asymmetry in the ends. Computer model on the left side shows the full magnet and on the lower-right shows the "lower-right" quadrant. The photo on the upper-right shows the type of perpendicular splice that may be used in splicing two single pancake coils of different lengths to a double pancake coil after all coils are put together.

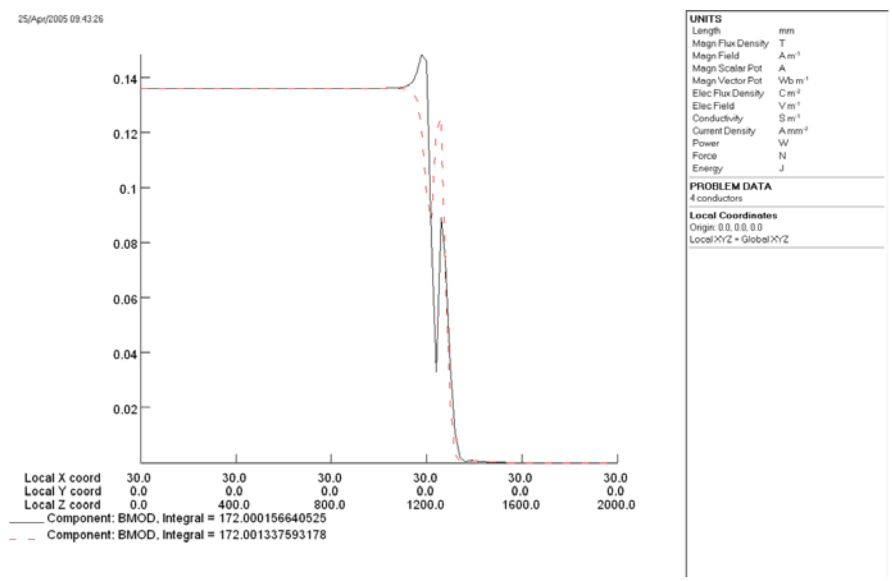

Fig. 8. The magnitude of the field as a function of axial position on the horizontal axis (black full line) and vertical axis mm (dashed red line) at a distance of 30 mm from the origin. The integral value is listed at the bottom of picture. The difference between the two integrals is the measure of integral asymmetry. One can see that the integral asymmetry is practically eliminated by adjusting the length of the coils. Integral harmonics will be optimized by 3-d coil optimization codes.

Other ways to minimize asymmetry were also examined. One interesting possibility is to add small coils in a variety of configurations. They also practically eliminated this asymmetry. The final choice should be determined by magnet assembly considerations.

Lorentz Forces and Support Structure

The direction and magnitude of the Lorentz forces on various blocks in the quadrant of the quadrupole magnet cross section are shown in Fig 9. The forces in the main blocks are somewhat similar to those present in the common coil design. There is no force towards the fictitious center of the four blocks of the quadrant. The fact that the forces are outward should guide the support structure and magnet assembly. Support structure and assembly detailed concepts are yet to be developed.

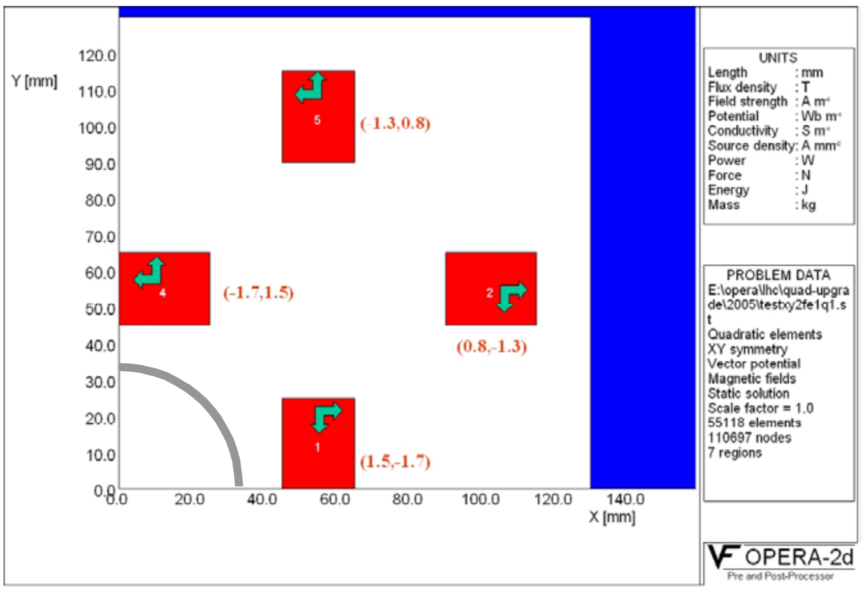

Fig. 9. Magnitude (Mega Newton/meter) and direction of Lorentz forces in blocks at ~235 T/m gradient in the conceptual design of LARP 90 mm quadrupole.

Variations in Magnet Aperture and Field Gradient

To change the magnet aperture in R&D magnets, one just needs to change the spacing between the coils (see Fig. 10). 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. Modular design offers a unique opportunity to examine the viability of different apertures. These options (change in aperture and change in gradient) are particularly interesting for LARP magnets as it may be too early to determine an optimum set of parameters.

The proposed design is modular where the racetrack coils of identical geometry can be stacked. One gets higher gradient when more coils are stacked. However, in quadrupole magnets, the additional fractional increase in field gradient becomes smaller as the number of coils increases. This also means that one can get a significant gradient even with a single layer of coil. The support structure must be designed appropriately to utilize this step-by-step progression in field (and forces).

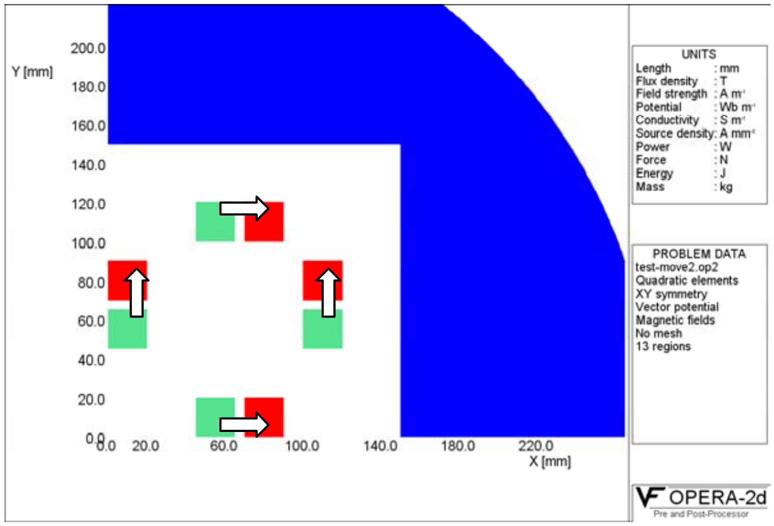

Fig. 10. In modular design the magnet aperture can be changed easily by changing the spacing between the coils. Coils in green location shows the case when the magnet aperture is 90 mm and the same coils in red location shows the case when the magnet aperture is 140 mm. Arrows indicates the direction in which two coils will have to move to increase aperture from 90 mm to 140 mm.

R&D Program

A major attraction of this modular design is the potential for a cost effective, systematic and dynamic R&D program that comes with it. A similar possibility was foreseen when the common coil dipole design was proposed together with a cost effective modular design based on flat racetrack coils. In this regard, the common coil experience has been very successful in bringing out a cost effective rapid turn around R&D at various institutions. A similar modular program that requires minimum tooling to build R&D magnets and examine various technological options, is proposed here.

In last decade major progress has been made in high field Nb_3Sn magnets (particularly at LBL) where several short demonstration models have been built and tested. The primary challenge of LARP (or any Nb_3Sn magnet program) at this stage is the unknown associated in making long Nb_3Sn magnets. No long magnets or coils has ever been made with such brittle and strain sensitive superconductor, especially in light of the fact that different parts of the coils go through different thermal expansion. Many techniques, design features, etc. that are used in making short coils may not be appropriate for long coils. The areas of particular concerns are the transition region where body and end meet and any other region where the change in coil shape is irregular. The concern arises due to possible excessive strain caused by the push and pull when the material goes through large volumetric changes, a change that increases as the length (and hence volume) increases. The complex geometry of cosine theta ends may be more susceptible to such damage/degradation than the geometry of flat racetrack coils.

In addition, one would like to start the long coil program first with racetrack coils because the tooling for winding, reacting and impregnating coil is also simpler, cheaper and therefore faster to design and build.

The coils used in the above design have only small number (~15) of turns in each layer and therefore it requires only a limited amount of conductor to make the actual coils. One would first test two coils in a common coil configuration. (It may be noted that the force configuration in the modular design is similar to the force configuration in the common coil design.) Next these two coils can be tested in a magnetic mirror quadrupole configuration. To visualize this configuration one must look at the field lines in a quadrant of the quadrupole (see Fig. 11). The iron for making this mirror configuration would be placed on the X-axis and the Y-axis where the field lines are perpendicular. For this test, the two coils should have different lengths, as they need to be interleaved. At this stage, we would have also partially tested many assembly and support structure features of the modular design. One would require all coils and support structures for a more complete test. Once these tests are successful in short magnets, one can carry a similar program in long magnets. It is assumed that tooling for winding, reacting and impregnating long coils was proceeding in parallel.

The ability to exercise options to change magnet aperture and increase gradient while using the same coils facilitates a dynamic R&D program. It is assumed that such studies will continue in a systematic manner during the course of this program.

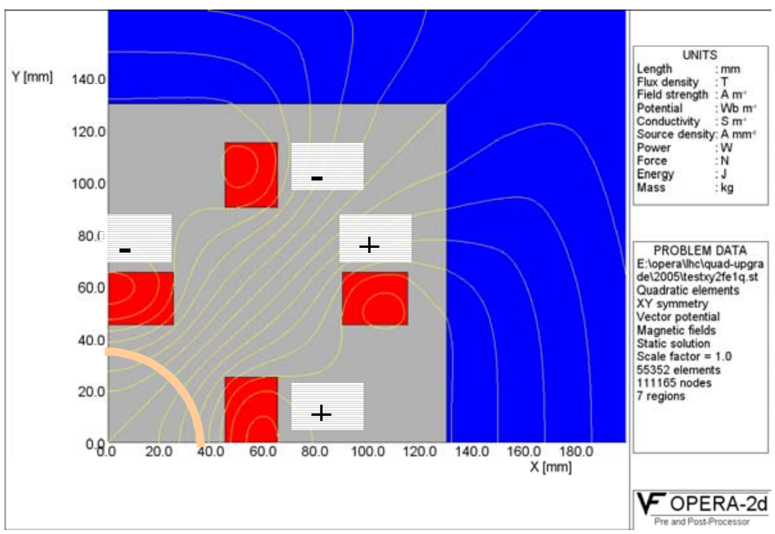

Fig. 11. Field lines in the first quadrant of modular design. Mirror iron can be placed on the X-axis and the Y-axis as the field lines are perpendicular there and an octant contains the complete coils.

Appendix A

Fig. 12 shows an alternate design with flat racetrack coils utilizes many features and benefits of the modular design. In this case turns return in the same octant. In the modular design discussed in the main section, the turns return on the other octant (as shown in Fig. 1). However, it is much less attractive for LARP quadrupoles since it reduces the gradient and increases the peak field on the conductor at places that are not critical for generating high gradient. Putting iron between the main blocks and return blocks helps only a limited way in such high field magnets. Another variation of this approach is shown in Fig 13, where blocks are segmented. However, once again similar conclusions are drawn.

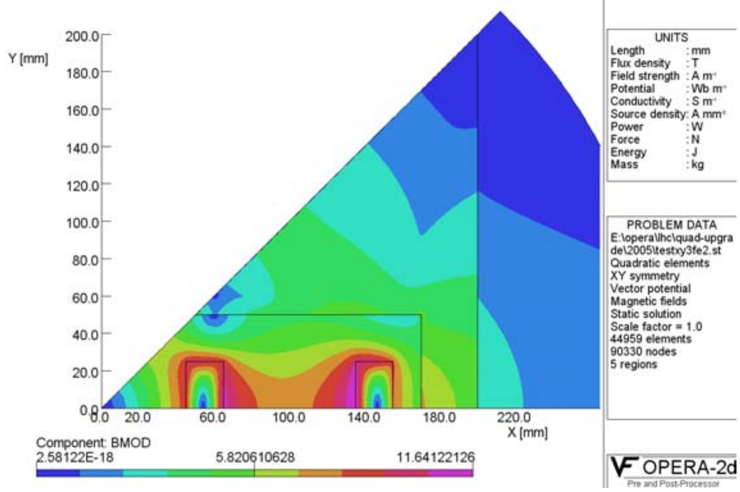

Fig. 12. An alternate design with flat racetrack coils that utilizes many features and benefit of the modular design. However, the design is not efficient for high field magnets since it reduces the gradient and increases the peak field.

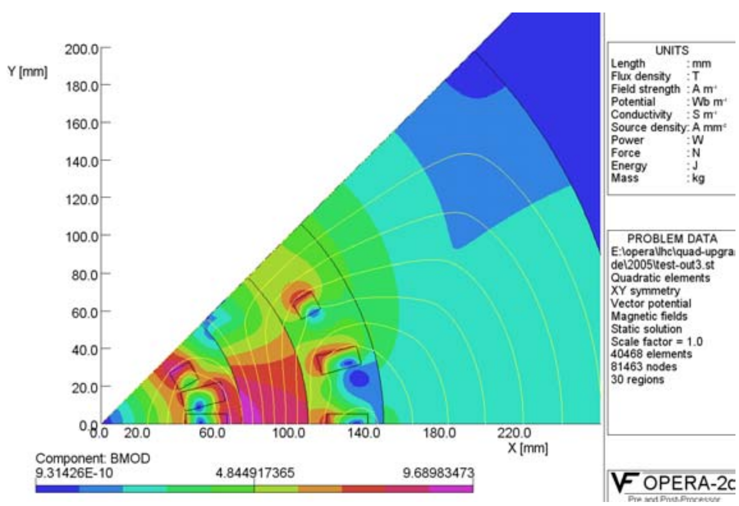

Fig. 13. Another alternate design with flat racetrack coils that utilizes many features and benefit of the modular design. This design is also not efficient for high field magnets since this too reduces the gradient and increases the peak field.