BROOKHAVEN NATIONAL LABORATORY
Superconducting Magnet Division www.bnl.gov/magnets

Modular Design and Modular Program for High Gradient Quadrupoles*

Ramesh Gupta

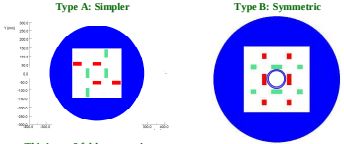
Introduction

- A magnet design with simple flat racetrack coils with large bend radius
- Achieves similarly high gradients as those achieved in cosine theta designs
- Modular design uses coil modules (cassettes) that allows rapid turn around cost effective magnet R&D.
- One can vary the quadrupole aperture and even the magnet type (quadrupole, common coil, open midplane dipole, etc) using the same cassettes (modules)
- Allows both "Wind & React" & "React & Wind"

Modular Quadrupole Design Concepts

Type A: Simpler

Type B: Symmetric



This is not 8 fold symmetric.

In addition to b_{10}, b_{18}, b_{14}, ..., one also gets a_6, a_{10}, a_{14},.... These harmonics need to be minimized.

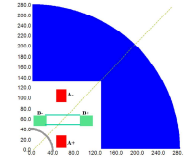
No skew harmonics due to symmetry. Relatively more complex structure. May have lower peak field. Note peak field is not a major concern for HTS.

NOTE: The design needs about twice the conductor. But for a few high performance magnets, conductor cost is only a fraction of overall magnet development cost.

Design Concept : Type B (symmetric)

Cross-section of a Quadrant - made of 2 coils

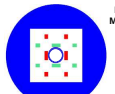
(ideal eight fold quad symmetry - mirror symmetry at 45º)



Most field comes from A+ (return A-) and B-(return B+). B+ and A- make positive but only a small contribution.

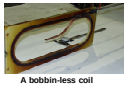
NOTE: The design needs about twice the conductor!

Full Model



Quadrupole with all 8 coils

In this design, horizontal (or vertical) coils must interleave in to other.

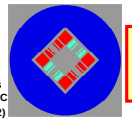


A bobbin-less coil

*Work supported by the U.S. Department of Energy.

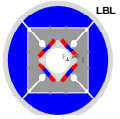
Previous Racetrack Designs (Considered for LHC upgrade or VLHC)

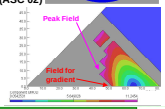
BNL designs for VLHC (ASC'02)



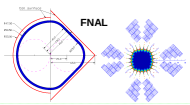
None of these designs were efficient in generating high gradient

LBL



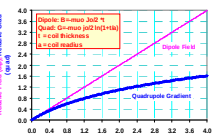


FNAL



High gradient quadrupole design differ significantly from those for high field dipoles.

In dipole field B ∝ "t" (coil thickness), irrespective of the coil radius ("a"); in quadrupole field gradient G ∝ "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.



Basic Considerations

Primary goal:

Develop a racetrack quadrupole design that can generate a field gradient comparable to that created by cosine theta designs

Constraints:

For a few key IR magnets, the design should be efficient in creating field gradient; it need not be efficient in minimizing the conductor usages.

Advantages:

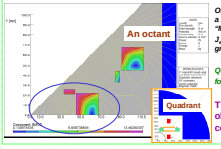
During the reaction process in long magnets, simple flat racetrack coils are less prone to damage or degradation in critical ends and transition regions.

Racetrack coils (and associated tooling) are faster and more economical to build. It allows a modular design and modular R&D program.

Can make program flexible and versatile. One can use the same coils for varying quad aperture or even magnet type (quad or dipole) during the R&D phase.

Efficient Design to Create Gradient (not necessarily to minimize conductor usage)

• The key is to have conductor at or near the midplane (@ quad radius). Quadrupole is different from dipole. Gradient implies increasing field on coil as one moves outward within the aperture. We loose substantially if conductor at midplane does not determine the field gradient.



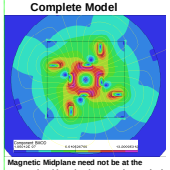
OPERA2d model of the octant of a 2 layer, 90 mm aperture LARP "Modular Quadrupole Design". J_o = 1000 A/mm² generates a gradient of ~284 T/m.

Quench gradient ~258 T/m for J_o = 3000 A/mm² (4.2K, 12T).

This is similar to what is obtained in competing cosine theta designs.

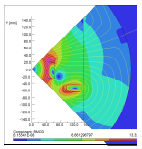
Magnetic Modelling

Complete Model



Magnetic Midplane need not be at the conventional location (may need a rotation)

Need only 1/4 model (with proper boundary conditions)



Question: Is it possible to develop a good magnetic design?

Support Structure

Support structure and assembly

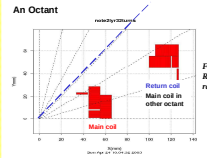
Concepts need to evolve

(start with a few structures before selecting one)

- One can be creative here.
- Think geometry --- it's different!

Field Quality Optimization in Symmetric Modular Design

An Octant



90 mm aperture LARP quadrupole design optimized for field quality with RACE2DOPT (Thank you Pat Thompson for this program).

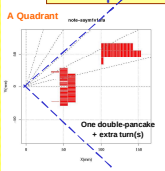
Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

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

NOTE: The 2-d harmonics are essentially zero (within construction errors)

Field Quality Optimization in Simpler Modular Design

A Quadrant



Asymmetric 2-layer design. Number of turns, transfer function, etc. are similar to symmetric design. (Peak field found higher in this particular design)

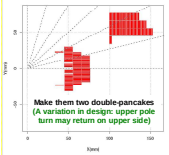
Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

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

NOTE: The 2-d harmonics are essentially zero (within construction errors)

3-Layer Design for Higher Gradient

Relative increase in transfer function (in 3 layer design, as compared to in 2 layer) : ~28%



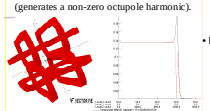
Field harmonics optimized with RACE2DOPT at 30 mm reference radius (2/3 of coil radius).

n	a_n	b_n
6	-0.0049	-0.0015
10	0.0006	0.0075
14	0.0018	0.0231
18	0.0000	0.0000

The 2-d harmonics are small

3-d Magnetic Design (symmetric cross-section)

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 (generates a non-zero octupole harmonic).

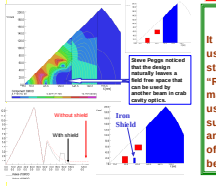


The magnitude of the field as a function of axial position on the horizontal axis (black full line) and vertical axis mm (dashed red line) at a distance of 30 mm from the origin. The integral value is listed at the bottom of the picture.

The difference between the two integrals is the measure of integral asymmetry.

Match average coil lengths for horizontal and vertical coils. (Or use additional small coils in the end).

Possible Use in Crab Cavity Optics



Benefits of Modular Design

Simple, Fast, Flexible & Cost-effective

- Design is consisted of simple, flat, stackable, racetrack coil modules
  - Positive experience with common coil program
  - Fast and cost effective to start and to carry out systematic R&D
  - Large variations in cable, coil and magnet parameters can be accommodated (such deviations are encountered during R&D phase)
- More unique R&D features for "proof-of-principle" magnets
  - To increase field gradient by simply adding more coil modules
  - To increase aperture move coils further out. This should help determine aperture and field gradient combination for beam optics by building and demonstrating a magnet at an early stage.
  - It allows a broad-based magnet R&D program, as high gradient modular quadrupole, common coil dipole, open midplane dipole, etc.- all can be built and tested using the same basic coil modules.

The support structures need to be designed to accommodate such provisions or it may be better to design separate structures for different applications.

More Unique Features

Different Aperture With the Same Coils

One can study different aperture using the same coils in R&D magnets.

Final magnet design will be more optimized for a particular aperture, but this concept offers a cost-effective and fast turn around method to study most technical issues.

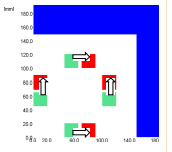
Coils are moved away from the center in going from

green aperture (90 mm)

to red aperture (140 mm).

A flexible and economical design/method to study various aperture and field gradient combinations is useful at this stage, as the magnet parameters can not be fixed yet.

In fact, this feed back should help machine physicist to choose a set of parameters that represents an overall optimum from both magnet and beam optics point of view.



SUMMARY

It is possible to design high gradient quadrupoles with flat racetrack coils using "Modular Design". The design consists of simple coils that can be stacked as cassettes for carrying out a systematic and a variety of magnet "R&D" in a "Modular Program". One can use the same coil modules in making an "Open Midplane Dipole" or a "Common Coil Dipole". One can use this design for both "Wind & React" or "React & Wind" and is also suitable for HTS. Modular program is a cost-effective and 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.