Modular High Field Quadrupole Design for Electron-Ion Collider

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Superconducting Magnet Division

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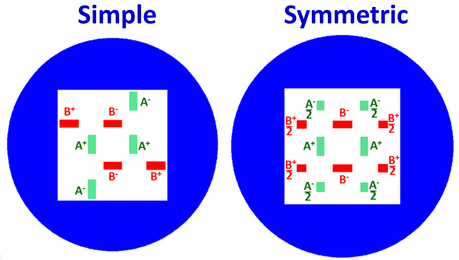
A Modular Quadrupole Design

- A magnet design with simple flat racetrack coils
- Achieves similarly high gradients as those achieved in cosine theta quadrupole designs
- Modular design uses coil modules (cassettes) which allows rapid turn around and low cost R&D

Two Styles of Modular Design

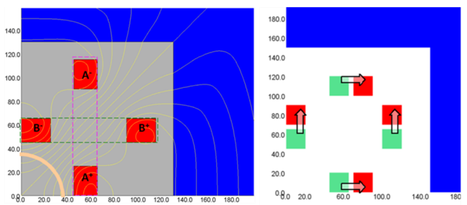


Most field comes from A^+ (return A^-) and B^-(return B^+).
B^+ and A^- make positive but only a small contribution.

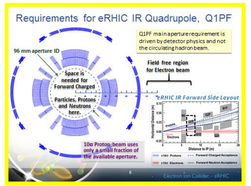
NOTE: The design needs about twice the conductor!

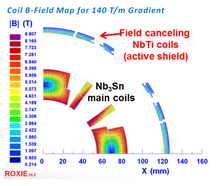
A Unique Feature of the Modular Design
Different Apertures with the Same Coils

In a modular quadrupole design, R&D models of several high gradient EIC quadrupoles having different apertures can be demonstrated with the same racetrack coils by re-assembling them with different spacing providing a significant cost and schedule savings. This is not possible with the cos θ designs.



EIC High Gradient Quad Designs

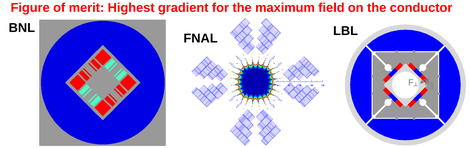


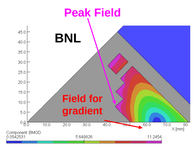


Magnet Location	Magnet Type	JLAB Requirements: Magnet Strength	Magnetic length	Distance from the	Good field	New Inner Radius	Outer radius (cm)
Interaction Region Ion (IR)	Quadrupole QFFB3_US	-116	1	-7.70	3 cm	4	12
	Quadrupole QFFB2_US	149	1.5	-6.00	3 cm	4	12
	Quadrupole QFFB1_US	-141	1.2	-4.20	2 cm	3	10
	Quadrupole QFFB1	-88	1.2	7.60	4 cm	8.5	17.1
	Quadrupole QFFB2	51	2.4	10.40	4 cm	12.6	24.7
	Quadrupole QFFB3	-35	1.2	13.20	4 cm	14.8	26.7

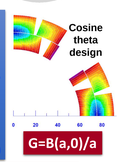
Previous Racetrack Coil Quad Designs

Figure of merit: Highest gradient for the maximum field on the conductor



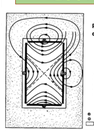


None of these racetrack coil quadrupole designs were as good in generating high gradient for the same cable as a typical cosine theta design is. That was primarily because of the unfavorable conductor configuration at the midplane. (missing conductor or lower field on coil radius at midplane)

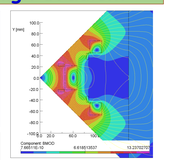


G=B(a,0)/a

Panofsky Quadrupole
Efficient for Generating High Gradient



Rectangular Aperture Panofsky Quadrupole (field at midplane determines the gradient)



Superconducting quadrupole built with Nb_3Sn tapes (Sampson, 1967)

Project Considerations for the Cost of Magnet Development

- Two major project costs for high field magnets:
  - Cost of material, plus cost of labor per magnet
  - Cost of tooling, cost of engineering, and cost of R&D
- If the project needs only one or a few high performance magnets then (a) the cost of material is less important and (b) the cost of design, R&D and cost of tooling, etc. is more
- If there are a number of "*one of a type*" magnets, then a common tooling and a common R&D would reduce cost

Approach for Developing High Gradient Modular Quad for EIC

Primary goal:

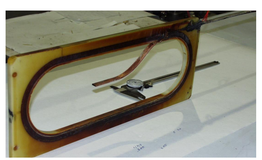
Develop a modular quadrupole design for all high gradient Nb_3Sn quadrupoles in EIC that is simpler and flexible but as good as a typical cos θ design is

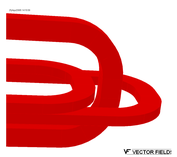
Key design considerations:

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

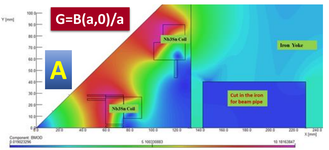
Racetrack coil magnets:

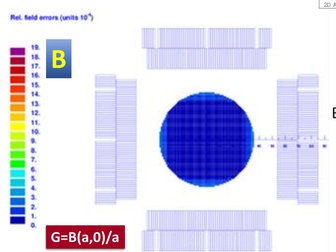
It has been generally observed that the high field Nb_3Sn magnets made with the simple racetrack coils tend to perform better in the first model itself

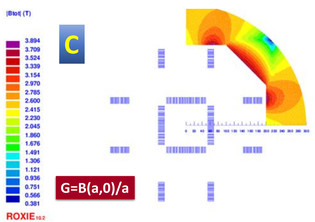


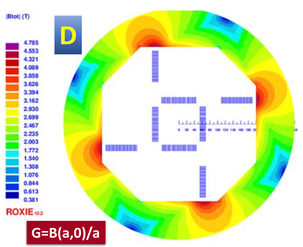


Magnetic Designs

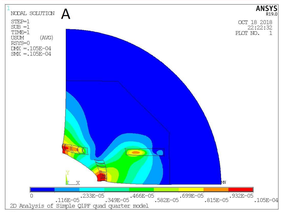




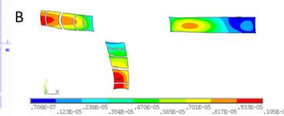




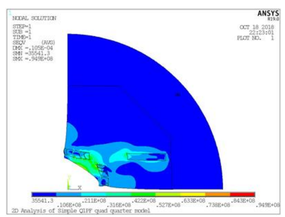
Mechanical Analysis



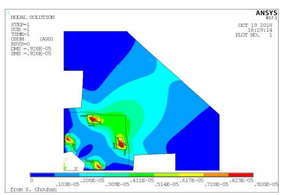
Contour plot of displacements from the Lorentz forces in the modular design D (simple style)



Blow up of the displacements (~10 μm) in the Nb_3Sn coils



Von Mises stress in the design D



Contour plot of displacements (~10 μm) in the symmetric design A

TABLE I
KEY DESIGN PARAMETERS OF Nb_3Sn QUADRUPOLES FOR THE EIC IR

	Q1PF	QFFB1_US	QFFB2_US	QFFB3_US
EIC Design	BNL	JLab	JLab	JLab
Aperture (mm)	96	60	80	80
Field Gradient (T/m)	140	141	149	116
Magnetic Length (m)	1.5	1.2	1.5	1.0

TABLE III
MODULAR DESIGNS OF 96 MM BORE Q1PF WITH A GRADIENT OF 140 T/M

	Design A	Design B	Design C	Design D*
Symmetric or Simpler	Symm	Symm	Symm	Simp
Number of Layers	2	2	1	1
Additional Pole block	Yes	No	No	No
Number of turns	68	56	27	25
Operating Current, A	12880	9,008	17,000	17,073
% on the Loadline	60	62.7	88.2	87.1
b_6 @36 mm	-0.22	-1.15	0.02	-0.03
b_{10} @36 mm	-0.95	-1.60	0.00	0.28
b_{14} @36 mm	0.13	0.43	-0.36	-0.02

*Design D only (a_6 = -0.86, a_{10} = -0.15 and a_{14} = 0.03).

SUMMARY

- Demonstrated a good field quality in both "*symmetric*" and "*simpler*" modular quadrupole designs.
- Demonstrated that the same racetrack coils can be used in the R&D models of Q1PF of eRHIC at BNL, and as well as several JLEIC quadrupoles (QFFB1_US, QFFB2_US and QFFB3_US) of JLab.
- Mechanical design and assembly work still to be performed during the Phase I SBIR.
- Proof-of-principle quadrupole for EIC based on the modular design will be built and tested during the Phase II SBIR, if funded.