Status of Q2PF Quad EM Design

Ramesh Gupta
Meeting with Fermilab on Options for EIC SC Forward Quadrupoles

April 18, 2024

Electron-Ion Collider
Main Features:

- Two layers, 69 turns
- Only one wedge in each layer
- Poles of Outer and Inner layers aligned
- Symmetric wedges
- Significant midplane gap for tuning allowed harmonics, and possibly some non-allowed also, when used with the pole shims (RHIC and SSC experience)
Coil and Yoke Cross-section

Electron-Ion Collider
Design gradient reached at ~8.5 kA
Peak field Enhancement: 18%
(max field over the midplane field)

Margin on Load-line: 38%
Conventional definition: 56%
(short sample over design)
Field and Temperature Margins
(in individual blocks)

Quench margins in the body of the magnet

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### Field Harmonics at the Design Field

<table>
<thead>
<tr>
<th>Harmonic Analysis Number</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Harmonic</td>
<td>2</td>
</tr>
<tr>
<td>Reference Radius (mm)</td>
<td>83.0000</td>
</tr>
<tr>
<td>X-Position of the Harmonic Coil (mm)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Y-Position of the Harmonic Coil (mm)</td>
<td>0.0000</td>
</tr>
<tr>
<td>Measurement Type</td>
<td>All Field Contributions</td>
</tr>
<tr>
<td>Error of Harmonic Analysis of Br</td>
<td>0.9964E-04</td>
</tr>
<tr>
<td>( \sum (B_r(p) - \sum (A_n \cos(np) + B_n \sin(np)) )</td>
<td>3.176139</td>
</tr>
<tr>
<td>Main Field (T)</td>
<td>3.176139</td>
</tr>
<tr>
<td>Magnet Strength (T/(m^(n-1)))</td>
<td>38.2667</td>
</tr>
</tbody>
</table>

**Normal Relative Multipoles (1.0D-4):**

| \( b_1 \) | -0.30804 | \( b_2 \) | 10000.000000 | \( b_3 \) | 0.06621 |
| \( b_4 \) | -0.02748 | \( b_5 \) | -0.02339 | \( b_6 \) | 0.21543 |
| \( b_7 \) | -0.00139 | \( b_8 \) | -0.00180 | \( b_9 \) | -0.00012 |
| \( b_{10} \) | 0.03688 | \( b_{11} \) | -0.00009 | \( b_{12} \) | -0.00000 |
| \( b_{13} \) | 0.00000 | \( b_{14} \) | -0.29429 | \( b_{15} \) | 0.00000 |
| \( b_{16} \) | 0.00000 | \( b_{17} \) | 0.00000 | \( b_{18} \) | -0.00151 |

**All harmonics < 1 unit**
Yoke Optimization for EIC Magnets

• Yoke must be optimized to make sure that field harmonics due to iron saturation, don’t get out of specifications through-out the range of operation.
• Fringe field in the hole (where electron beam traverses), stays within acceptable limit. This is not common in other colliders, but critical for EIC, and is expected to be worse at high fields.
EM Yoke Optimization (1)

Holes for Tie Rods – Turning them into an opportunity

- Strategy: Large holes for tie rods clearly make a significant impact on iron saturation. Let’s try to make use of those large holes as a tool of opportunity!

Note: \((\mu-1)/(\mu+1)\) in the yoke near i.r. has now become more uniform

Tie rods are strategically placed to control saturation

Electron-Ion Collider
EM Yoke Optimization (2)

Tie Rods to Reduce Saturation-induced Harmonics

Notice a change in scale

Finer optimization not yet performed

Optimized Iron: Major reduction in saturation induced allowed harmonics (order of magnitude)

Field Gradient @7.7 kA goes down from 36.2 T/m to 35.7 T/m for 2X holes (controlled saturation)

Ramesh Gupta

Q2pF Cross-section for 2K Operation

April 5, 2022

A large reduction in saturation induced $b_6$
EM Yoke Optimization (3)

The location and size of holes for tie rods is used to divert field away from the electron beam hole.

Note: Significant reduction in the field inside the hole for e-beam. Also see a change in the shape.

Uniform field brings a much larger reduction in $B_n$’s.

Measure the merit of a solution by $|B|$ or by $B_n$’s?
Evaluation of the impact of the fringe field on the electron beam from the nearby hadron magnets

• Current approach is to make the fringe field below the earth’s magnet field.
• Shouldn’t this be evaluated as the harmonic errors?
• Otherwise, we may be putting unnecessarily stringent requirements on the magnets and infrastructure cost.

➢ Suggestion: Study the beam dynamics impact of the computed error harmonics on the electron beam from the excitation of the nearby hadron magnet.
➢ There are other sources and ways to deal with small field or field gradient
Cross-talk in the current design of Q2pF

Cross-talk for electron beam (harmonics are in Tesla.unit)

- B1 (dipole) and B2 (quad) should be of little concern

Cross-talk for hadron beam (harmonics normalized to quad field)

- Remain very small

Design current: ~8500 A, error harmonics remain small 30% above that
Superconducting Shield for electron Beam (1)

*Work supported by two Phase I SBIR/STTR and one Phase II, specifically for EIC

Demo of SC Shielding in Phase I

Phase II Test

If SC shield works, field in this cutout should become zero!

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If successful, will be used in Phase IIA

Compare the fields in two cutouts: one without SC shield, another with shield
Superconducting Shield for electron Beam (2)

*Work supported by two Phase I SBIR/STTR and one Phase II, specifically for EIC

Demonstration of Superconducting Shielding in a Phase II Magnet

Demonstration of Superconducting Shielding (with Additional A4K)

NbTi tube from Luvata

High permeability
*A4K to shield persistent field

Field at the center of magnet

Field inside the shield

Noise in testing to be removed

Field in cutout without shield

*B4K: High permeability Amumetal 4K (A4K) from Amunecal Manufacturing Corporation

Ramesh Gupta for PBL/BNL Team, A Novel, Medium-field Optimum Integral Dipole, MT-28

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Slides on the End design

(if time permits)
Strategy for Optimizing Layout of Turns in EIC Magnet

• EIC IR cable magnet coils have much larger aperture than that in typical NbTi accelerator magnets.
• Therefore, the criterion or optimization methods used in designing ends of previous cable magnets (as in ROXIE or bend or in earlier BNL design), may not be valid.
• This was realized early in the program, and a single turn winding test with similar cable was planned for an initial check.
• A request was made to CERN for leftover LHC cable (same width but a slightly different keystone). CERN provided. THANKS.
• Single turn winding tests were performed for B1pF. It was found that it is best to use ROXIE for creating layout of turns in the ends, but not for optimizing as they produce excessive tilt.
• A similar strategy is being followed on all EIC cable magnets.
Return End (min tilt angle 70°)

➢ End turns of the outer layer and the inner layers aligned

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Peak Field Enhancement in the Ends

ROXIE calculations

- Peak field in 2-d: 6.89 T
- Peak field in 3-d: 7.09 T

Only about ~2.9% higher peak field than that in the x-section (calculation errors?)

End configuration iterated for smaller peak fields in the ends. Final optimization after the winding trials.

Turn #34 is the pole turn in the outer layer
Integrated harmonics (3-d) in the Return End

A reasonable end design:

• All integrated field harmonics are well within 1.
• Final optimization to be performed after the winding trials and with non-linear iron.
Lead End (min tilt angle 70°)

- End turns of the outer layer and the inner layers aligned

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Renderings of the Outer Layer of Lead End

Looks reasonably ok; to be examined more carefully
Renderings of the Inner Layer of the Lead End

Looks reasonably ok; to be examined more carefully
Renderings of Both Layers of the Lead End

Looks reasonably ok; to be examined more carefully
EM 3-d yoke

(earlier coil ends but for yoke it shouldn’t matter much)
Calculation of Peak Field with OPERA3d (non-linear iron)

Integration method for the coil field to assure a reasonable accuracy

Peak Field: 6.37 T @ 8.5 kA

Gradient @ center: 38.218 T/m

Peak field from ROXIE (mirror iron):
7.03 T @ 8.5 kA
Gradient: 41.8 T/m
Scaled Peak field:
6.42 T for 38.2 T/m

Brookhaven National Laboratory
Magnet Division
Ramesh Gupta
Results from OPERA3d Models of Q2pF
September 20, 2022

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