EIC IR Magnet Design Summary (FY20)

Ramesh Gupta
Superconducting Magnet Division

November 2020
Cables

• Magnet designs based on the cables that can be easily procured

• Two types of 36-strand cables
  – Same width and mid-thickness for both
  – Keystone #1 for B1apF and B1pF
  – Keystone #2 for quadrupoles
These slides summarize the magnetic design work performed in FY20 on EIC IR cable magnets.

The main goal of this exercise was to develop magnetic designs such that all EIC IR magnets can operate at 4.2 K rather than 1.8 K.

Since the electron beam is very close to the proton beam, leakage field from the proton IR magnets must be low in the path traverse by the e-beam.

Another goal was to develop designs based on the cables that can be easily procured (36-strand).
Q2pF
Design studies completed for now for Q2pF. Several cases examined but only the chosen one will be presented.

Operation at 4.2K/4.6K. Peak field (margin), field quality and field in the electron beam region optimized.

Strand/wire used: dia =1.065 mm, Cu/Sc =1.6.

Cable: 19.4 mm wide (19.7 with insulation) with 36 strands, min thickness: 1.788 mm, max thickness: 2.012 mm.
Chosen Cable Design (ROXIE)

Strand dia = 1.065 mm; 36 strands in cable
Cu/Sc = 1.6, width 19.4 mm (bare)

Operating Temperature: 4.2 K / 4.6 K
A good field quality can be obtained with the restriction of designing the cross-section for a good mechanical design (all harmonics <1 unit)

REFERENCE RADIUS (mm) ............................................. 83.4
MAGNET STRENGTH (T/(m^(n-1))) .......................... 36.0373

NORMAL RELATIVE MULTipoles (1.D-4):
b 1:  -0.00000  b 2:  10000.00000  b 3:  -0.00000
b 4:  -0.04348  b 5:  0.00000  b 6:  -0.36357
b 7:  0.00000  b 8:  -0.00184  b 9:  -0.00000
b10:  0.62176  b11:  -0.00000  b12:  -0.00007
b13:  0.00000  b14:  -0.22463  b15:  -0.00000
b16:  -0.00000  b17:  0.00000  b18:  0.01234
Peak Fields in Q2pF

EIC 36 strand cable 4.6 K Q2pF Half Iron

|B| (T)

5.846
5.540
5.233
4.927
4.621
4.314
4.008
3.701
3.395
3.088
2.782
2.475
2.169
1.862
1.556
1.250
0.943
0.637
0.330
0.024

ROXIE 10.2
Field Margin at 4.2 K

Healthy Margin: ~47% over 36 T/m at 4.2K (68% on loadline)
Field Margin at 4.6 K

Healthy Margin: ~38% over 36 T/m at 4.6K (72% on loadline)
Temperature Margin at 4.2 K Over Different Blocks
Field Margin at 4.6 K

Healthy Margin: ~38% over 36 T/m at 4.6K (72% on loadline)
Field Margin at 4.6 K

Margin across the coil: Minimum 28% on the loadline at 36 T/m @4.6 K
Temperature Margin at 4.6 K Over Different Blocks
Field Margin at 4.2 K over 41 T/m

Significant Margin: ~25% over 41 T/m at 4.2K (9 kA) (80% on loadline)
Field Margin over 41 T/m @4.2 K

Margin across the coil: Minimum 20% on the loadline at 41 T/m at 4.2K

A Reasonable Margin: ~25% over 41 T/m at 4.2K (80% on loadline)
Temperature Margin over 41 T/m at 4.2 K Over Different Blocks
Extra layer reduced the space for the flux return and increased the field in the electron beam region.

Field in the electron beam region can be reduced by increasing the yoke size.
A total of five sets of files. 4.2 K and 4.6 K for two hole positions. Also one case at 41 T/m for completeness.
Q1BpF
Overview

➢ Initial design studies of Q1BpF for a possible 4.2 K operation. Several cases examined but only one will be presented.

➢ Peak field (margin), field quality and field in the electron beam region are being optimized.

➢ The design consider several fronts - geometric, mechanical, magnetic design. Anis will continue on further optimization.

➢ Strand/wire used: dia =1.065 mm, Cu/Sc =1.3 (new) and 1.6.

➢ Cable: 19.4 mm wide (19.7 with insulation) with 36 strands, min thickness: 1.788 mm, max thickness: 2.012 mm (same as before).

➢ As mentioned during the last meeting, we will “try” to use this cable (and RHIC dipole type cable) for all EIC magnets.
Coil 2 Layers, Three wedges (2+1)  
54 turns/pole (24 inner, 30 outer)

- Poles of inner and outer layers aligned
- Coil poles have proper angles for collaring
- Two wedges in the inner to deal with keystone

Coil radius: 93 mm  (Q2B had 140 mm)
A reasonably good field quality is obtained with a good mechanical design (coil radius 93 mm) (all harmonics <1 unit)

Gradient
66.2 T/m
at ~10 kA
Iron Yoke - Current Design

Yoke: \( ir = \sim 150 \text{ mm}; \) or \( = 550 \text{ mm} \) (or 500 mm)
Hole\( @ x = 288.3 \text{ mm} \) to 312.5 mm
Radius of hole = 83 mm (63 mm for electron beam)
Collar width = \( \sim 20 \text{ mm} \) for 66.2 T/m
Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm
Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm

Initial Design. What is acceptable?
Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm

Tricks to reduce field.
Use holes, special iron?
What is acceptable?
Field Margin at 4.2 K

Healthy Margin: 
~20% over 66.2 T/m at 4.2K 
For Cu/Sc of 1.6 
(83% on loadline)
Field Margin at 4.2 K
Temperature Margin at 4.2 K Over Different Blocks
Field Margin
at 4.6 K, Cu/Sc = 1.3

EIC Quad Q1PF 4.2K, Cu/Sc 1.3, 4.6 K
Field Margin at 4.6 K, Cu/Sc = 1.3

13% Margin on the loadline
15% over the design field
Shielding Solution that Worked in Q1B

Path of flux lines navigated with cutout in yoke and small coils on the two side of yoke over e-beam region added to further navigate flux lines (and reduce saturation) to significantly reduce field in the e-beam region.
Two order of magnitude reduction in field in e-beam region of Q1B

Such fields can be shield with mu-metal, etc.
Quadrupole Symmetric Yoke of Q1B

- It works. Field in the e-beam region $\sim 10^{-4}$
- But it may or may not be the best solution

Note:
Hole covers a larger area than that of e-beam and the field is even lower

Enough space for holes for tie-rods in low field region at pole
Q1BpF with Q1eF (need to remove flat-top)

Flat-top creates non-allowed harmonics and takes away iron from the return yoke. Therefore, it is removed for inserting Q1eF (see below).
Q1BpF (Q1eF in flat-top yoke NOT GOOD)
Q1BpF (Q1eF with one polarity)

Looks good as iron providing the shielding is not saturated

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Looks good as gradient is symmetric around the center of Q1eF (x=288.3)
Q1BpF (Q1eF with opposite polarity)

Does NOT look good as gradient is not symmetric around the center of Q1eF
Q1BpF (Q1eF with opposite polarity)

Does not look good as the iron providing the shielding is highly saturated on one side (>2T)
Solution

Use the technique that we recently invented (strengthen the coils around the iron to reduce saturation)
Q1BpF (Q1eF with opposite polarity AND stronger control coils)

Looks better as the iron providing the shielding is less saturated (1.7 T rather than over 2 T)
Q1BpF (Q1eF with opposite polarity AND stronger control coils)

Still looks good as gradient is symmetric around the center of Q1eF (x=288.3)
Field (gradient) on vertical axis looks good as well around the center of Q1eF (x=288.3)
Q1BpF (Q1eF with good polarity AND stronger control coils)

Looks good as the iron providing the shielding is less saturated (1.3 T)
Q1BpF (Q1eF with good polarity AND stronger control coils)
Field (gradient) on vertical axis looks good as well around the center of Q1eF (x=288.3)
Q1BpF (Q1eF with good polarity AND stronger control coils)

Field (gradient) on vertical axis looks good as well around the center of Q1eF (x=288.3)
Q1ApF
Overview

- Design studies of Q1ApF coil for a possible 4.2 K operation.
- Q1BpF yoke optimization to reduce field in electron beam region.
- Q1BpF coil redesign to increase margin for 4.2 K operation.
- Several cases examined; only one each of above will be presented.
- In all cases, peak field (margin), field quality and field in the electron beam region are being optimized together.
- The design consider several fronts - geometric, mechanical, magnetic design. Anis will continue on further optimization.
- Strand/wire used: dia =1.065 mm, Cu/Sc =1.3 and 1.6.
- Use this cable (and RHIC dipole type cable) for all EIC magnets.
- Some thoughts on system optimization
Q1ApF Coil 2 Layers, Four wedges
41 turns/pole (18 inner, 23 outer)

- Poles of inner and outer layers aligned
- Coil poles have proper angles for collaring
- Two wedges in each layer to deal with keystone

Coil radius: 71 mm (Q1B had 93 and Q2B had 140 mm)
A reasonably good field quality is obtained with a good mechanical design (coil radius 71 mm) (all harmonics <1 unit).

Gradient
72.6 T/m
at ~9.3 kA
Peak Fields in Q1ApF
Field Margin at 4.2 K

Very Good Margin
Field Margin at 4.2 K

Margin to quench (%)

ROXIE_{10.2}
Temperature Margin at 4.2 K Over Different Blocks
Field Margin at 4.6 K, Cu/Sc = 1.6

Margin to quench (%)
Iron Yoke - Initial Design

Yoke: \( ir = \sim 131 \text{ mm} \); or \( r = 550 \text{ mm} \) (or 500 mm)
Hole@ \( x = 230.5 \text{ mm} \) to 259 mm
Radius of hole = 44.6 & 58.4 mm (+20 mm for electron beam)
Collar width = \( \sim 20 \text{ mm} \)
Iron Optimization to Reduce Field in the electron Beam Region
Field in the electron beam region
Yoke OR = 550 mm, Hole@288.3 mm

Shown a couple week ago (6/30/2020)
Field in electron Beam Region 0.02 T
Several techniques from the first principle examined.

Only a couple of cases shown.
Technique: Guide flux away from electron beam region

Provide circular shielding for electron and ion beam
Over an order of magnitude reduction in field

This field can be shield with mu-metal, etc.
Further Reduction
Tiny current on the two side of circular yoke over e-beam (still shielding for electron and ion beam)
Two order of magnitude reduction

Tiny current on the two side of circular yoke over e-beam gives a solution (still shielding for electron and ion beam)
Yoke Design of Q1A for a low field e-beam region
Optimized Q1A Yoke with Small Coil (same technique that worked in Q1B)

Path of flux lines navigated with cutout in yoke and small coils on the two side of yoke over e-beam region added to further navigate flux lines (and reduce saturation) to significantly reduce field in the e-beam region.

Small coils may be wound on a bobbin.
Original Case (nothing done)
Original Case (nothing done)

Very high field in electron beam region
Very high field in electron beam region
Original Case (nothing done)

Very high field in electron beam region
Yoke around electron beam region highly saturated
Cutout in the Yoke of Q1A
Cutout in the Yoke of Q1A

MODEL DATA
C:\Users\gupta\OneDrive - Brookhaven National Laboratory\yEICQ1APF\operaq1APF\c0.00
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107398 elements
54117 nodes
110 regions

Component: B
8.90890E-05

2.8944368

5.78874674

UNITS
Length: mm
Flux density: T
Field strength: A m⁻¹
Potential: V m⁻¹
Conductivity: S m⁻¹
Source density: A mm⁻²
Power: W
Force: N
Energy: J
Mass: kg

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Cutout in the Yoke of Q1A

![Graph showing values of B vs. X coord and Y coord]
Cutout in the Yoke of Q1A
Cutout in the Yoke of Q1A
Cutout and Small Coil in Q1A
Cutout and Small Coil in Q1A

Component: B
4.1943e-06
7.84786E-05
1.52763E-04

UNITS
- Length: mm
- Flux density: T
- Field strength: A m⁻¹
- Potential: Wb m⁻¹
- Conductivity: S m⁻¹
- Source density: A mm⁻²
- Power: W
- Force: N
- Energy: J
- Mass: kg

MODEL DATA
C:\Users\guptaOneDrive - Brookhaven National Laboratory\yEICQ1APF\Q1p\EICQ1APF\E2.01
Linear elements
XY symmetry
Vector potential
Magnetic fields
Static solution
Case 2 of 2
Scale factor: 2.15
107384 elements
54110 nodes
110 regions

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Cutout and Small Coil in Q1A
Cutout and Small Coil in Q1A
B1pF
Cable for B1pF and B1apF

- Cross-sections of B1pF and B1apF are based on the cables that can be easily procured.
- B1pF and B1apF are designed with 36-strand cable which is a fully keystone cable for B1apF. The same cable is used in B1pF.
- Present designs retain the rectangular yoke as before; however, can be changed to circular.
Good Field Quality
B1pF with Keystoned Cable

- All field harmonics small (3.4 T @ 8.1 kA)

<table>
<thead>
<tr>
<th>MAIN HARMONIC</th>
<th>REFERENCE RADIUS (mm)</th>
<th>X-POSITION OF THE HARMONIC COIL (mm)</th>
<th>Y-POSITION OF THE HARMONIC COIL (mm)</th>
<th>MEASUREMENT TYPE</th>
<th>ERROR OF HARMONIC ANALYSIS OF Br</th>
<th>SUM (Br(p) - SUM (An cos(np) + Bn sin(np)))</th>
<th>MAIN FIELD (T)</th>
<th>MAGNET STRENGTH (T/(m^(n-1)))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ALL FIELD CONTRIBUTIONS</td>
<td>0.1501E-04</td>
<td></td>
<td>3.390620</td>
<td>3.39061</td>
</tr>
</tbody>
</table>

NORMAL RELATIVE MULTipoles (1.D-4):

| b1  | b2 | b3 | b4  | b5  | b6 | b7  | b8  | b9  | b10 | b11 | b12 | b13 | b14 | b15 | b16 | b17 | b18 | b19 | b20 |
|-----|----|----|-----|-----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 10000.0000 | -0.00000 | 0.00574 | 0.00000 | -0.00729 | 0.00000 | -0.01287 | -0.00000 | -0.12301 | 0.00000 | -0.11449 | 0.00000 | 0.02768 | 0.00000 | 0.00316 | 0.00000 | 0.00076 | 0.00000 |
**Good Margin (B=3.4T, T=4.6K)**  
B1pF with Keystoned Cable

- **Very healthy margin in cross-section @4.6 K**
  - >78% field margin, >2.2 K temperature margin

<table>
<thead>
<tr>
<th>BLOCK NUMBER</th>
<th>20</th>
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<tbody>
<tr>
<td>PEAK FIELD IN CONDUCTOR 280 (T)</td>
<td>4.0120</td>
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<tr>
<td>CURRENT IN CONDUCTOR 280 (A)</td>
<td>-8050.0000</td>
</tr>
<tr>
<td>LOWEST FIELD IN CONDUCTOR 276 (T)</td>
<td>2.3731</td>
</tr>
<tr>
<td>SUPERCONDUCTOR CURRENT DENSITY (A/MM2)</td>
<td>-652.6459</td>
</tr>
<tr>
<td>COPPER CURRENT DENSITY (A/MM2)</td>
<td>-407.9037</td>
</tr>
<tr>
<td>PERCENTAGE ON THE LOAD LINE</td>
<td>54.9393</td>
</tr>
<tr>
<td>QUENCHFIELD (T)</td>
<td>7.3026</td>
</tr>
<tr>
<td>TEMPERATURE MARGIN TO QUENCH (K)</td>
<td>2.2178</td>
</tr>
<tr>
<td>PERCENTAGE OF SHORT SAMPLE CURRENT</td>
<td>20.8573</td>
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<tr>
<td>MAXIMUM LOADLINE IN BLOCK 15 (%)</td>
<td>56.3052</td>
</tr>
<tr>
<td>MINIMUM TEMPERATURE MARGIN IN BLOCK 4 (T)</td>
<td>2.1593</td>
</tr>
</tbody>
</table>
Peak Field Enhancement

~18%
B1apF
B1apF with Keystone Cable
(keystone chosen for B1apF)

EIC Dipole B1APF fully keystone cable 4.6K

|B| (T) values:

- 3.447
- 3.269
- 3.091
- 2.914
- 2.736
- 2.558
- 2.381
- 2.203
- 2.026
- 1.848
- 1.670
- 1.493
- 1.315
- 1.137
- 0.960
- 0.782
- 0.605
- 0.427
- 0.249
- 0.072

ROXIE 10.2
**Superconducting Magnet Division**

### EIC IR Magnet Design Summary (FY20)

**-Ramesh Gupta**

### Good Field Quality

**B1pF with Keystoned Cable**

- All field harmonics small (2.7 T @ 7.3 kA)

### Table: Main Field and Magnet Strength

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN HARMONIC</td>
<td>1</td>
</tr>
<tr>
<td>REFERENCE RADIUS (mm)</td>
<td>80.0000</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>0.9843E-06</td>
</tr>
<tr>
<td>SUM (Br(p) - SUM (An cos(np) + Bn sin(np)))</td>
<td></td>
</tr>
<tr>
<td>MAIN FIELD (T)</td>
<td>2.712609</td>
</tr>
<tr>
<td>MAGNET STRENGTH (T/(m^(n-1)))</td>
<td>2.7126</td>
</tr>
</tbody>
</table>

### Table: Normal Relative Multipoles (1.D-4):

<table>
<thead>
<tr>
<th>b1</th>
<th>10000.00000</th>
<th>b2</th>
<th>0.00000</th>
<th>b3</th>
<th>0.00437</th>
</tr>
</thead>
<tbody>
<tr>
<td>b4</td>
<td>0.00000</td>
<td>b5</td>
<td>0.00488</td>
<td>b6</td>
<td>-0.00000</td>
</tr>
<tr>
<td>b7</td>
<td>0.02281</td>
<td>b8</td>
<td>-0.00000</td>
<td>b9</td>
<td>0.07717</td>
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<tr>
<td>b10</td>
<td>-0.00000</td>
<td>b11</td>
<td>0.15408</td>
<td>b12</td>
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<td>b13</td>
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<td>b14</td>
<td>0.00000</td>
<td>b15</td>
<td>0.00157</td>
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<tr>
<td>b16</td>
<td>-0.00000</td>
<td>b17</td>
<td>0.00016</td>
<td>b18</td>
<td>-0.00000</td>
</tr>
<tr>
<td>b19</td>
<td>-0.00021</td>
<td>b20</td>
<td>-0.00000</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Good Margin (B=2.7T, T=4.6K)
B1pF with Keystoned Cable

• Very healthy margin in cross-section @4.6 K
✓ ~110% field margin, >2.5 K temperature margin

<table>
<thead>
<tr>
<th>Block Number</th>
<th>Block Number in Conductor</th>
<th>Block Number in Conductor</th>
<th>Block Number in Conductor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>320 (T)</td>
<td>3.4471</td>
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<td>47.8841</td>
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<td></td>
<td>2.5238</td>
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<td></td>
<td>47.8841</td>
<td>2.5238</td>
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</table>
B1pF
Table 6.8: Parameters of the B1PF magnet.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Magnetic length [m]</td>
<td>3</td>
</tr>
<tr>
<td>Maximum dipole field [T]</td>
<td>3.4</td>
</tr>
<tr>
<td>Aperture [m]</td>
<td>0.262</td>
</tr>
<tr>
<td>Required field quality [%]</td>
<td>0.01</td>
</tr>
<tr>
<td>Coil width [m]</td>
<td>0.34</td>
</tr>
<tr>
<td>Coil height [m]</td>
<td>0.34</td>
</tr>
<tr>
<td>Superconductor Type</td>
<td>NbTi</td>
</tr>
<tr>
<td>Current density [A/mm²]</td>
<td>241</td>
</tr>
<tr>
<td>Cu:Sc ratio</td>
<td>1.3</td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>4.2</td>
</tr>
<tr>
<td>Peak field wire [T]</td>
<td>4.37</td>
</tr>
<tr>
<td>Magnetic energy [MJ]</td>
<td>1.36</td>
</tr>
<tr>
<td>Ampere turns [MA·t]</td>
<td>1.16</td>
</tr>
<tr>
<td>Margin loadline [%]</td>
<td>58</td>
</tr>
</tbody>
</table>

Figure 6.34: Vertical magnetic field on the center plane for the hadron beam (a). Figure (b) shows the good field region.
Good Field Quality
B1pF with Keystoned Cable

- All field harmonics small (3.4 T @ 8.1 kA)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN HARMONIC</td>
<td>1</td>
</tr>
<tr>
<td>REFERENCE RADIUS (mm)</td>
<td>73.0000</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>0.1501E-04</td>
</tr>
<tr>
<td>SUM (Br(p) - SUM (An cos(np) + Bn sin(np)))</td>
<td></td>
</tr>
<tr>
<td>MAIN FIELD (T)</td>
<td>3.390620</td>
</tr>
<tr>
<td>MAGNET STRENGTH (T/(m^(n-1)))</td>
<td>3.3906</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Multipoles</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>b 1:</td>
<td>10000.0000</td>
</tr>
<tr>
<td>b 2:</td>
<td>-0.00000</td>
</tr>
<tr>
<td>b 3:</td>
<td>0.00574</td>
</tr>
<tr>
<td>b 4:</td>
<td>0.00000</td>
</tr>
<tr>
<td>b 5:</td>
<td>-0.00729</td>
</tr>
<tr>
<td>b 6:</td>
<td>0.00000</td>
</tr>
<tr>
<td>b 7:</td>
<td>-0.01287</td>
</tr>
<tr>
<td>b 8:</td>
<td>-0.00000</td>
</tr>
<tr>
<td>b 9:</td>
<td>-0.12301</td>
</tr>
<tr>
<td>b10:</td>
<td>0.00000</td>
</tr>
<tr>
<td>b11:</td>
<td>-0.11449</td>
</tr>
<tr>
<td>b12:</td>
<td>0.00000</td>
</tr>
<tr>
<td>b13:</td>
<td>0.02768</td>
</tr>
<tr>
<td>b14:</td>
<td>0.00000</td>
</tr>
<tr>
<td>b15:</td>
<td>0.00780</td>
</tr>
<tr>
<td>b16:</td>
<td>-0.00000</td>
</tr>
<tr>
<td>b17:</td>
<td>0.00316</td>
</tr>
<tr>
<td>b18:</td>
<td>0.00000</td>
</tr>
<tr>
<td>b19:</td>
<td>0.00076</td>
</tr>
<tr>
<td>b20:</td>
<td>0.00000</td>
</tr>
</tbody>
</table>
Good Margin (B=3.4T, T=4.6K) B1pF with Keystoned Cable

• Very healthy margin in cross-section @4.6 K
  ✓ >78% field margin, >2.2 K temperature margin

<table>
<thead>
<tr>
<th>BLOCK NUMBER</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEAK FIELD IN CONDUCTOR</td>
<td>280 (T)</td>
</tr>
<tr>
<td>CURRENT IN CONDUCTOR</td>
<td>280 (A)</td>
</tr>
<tr>
<td>LOWEST FIELD IN CONDUCTOR</td>
<td>276 (T)</td>
</tr>
<tr>
<td>SUPERCONDUCTOR CURRENT DENSITY (A/MM2)</td>
<td>-652.6459</td>
</tr>
<tr>
<td>COPPER CURRENT DENSITY (A/MM2)</td>
<td>-407.9037</td>
</tr>
<tr>
<td>PERCENTAGE ON THE LOAD LINE</td>
<td>54.9393</td>
</tr>
<tr>
<td>QUENCHFIELD (T)</td>
<td>7.3026</td>
</tr>
<tr>
<td>TEMPERATURE MARGIN TO QUENCH (K)</td>
<td>2.2178</td>
</tr>
<tr>
<td>PERCENTAGE OF SHORT SAMPLE CURRENT</td>
<td>20.8573</td>
</tr>
<tr>
<td>MAXIMUM LOADLINE IN BLOCK</td>
<td>15 (%)</td>
</tr>
<tr>
<td>MINIMUM TEMPERATURE MARGIN IN BLOCK</td>
<td>4 (T)</td>
</tr>
</tbody>
</table>
Peak field over 3.5 T

Peak field enhancement

~18%
Very Good Overall Margin

Over 70% field margin
Temperature Margin over 4.6 K

Over 2.1 K Temperature Margin
B1apF
### Parameters of the B1APF Dipole Magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic length [m]</td>
<td>1.5</td>
</tr>
<tr>
<td>Maximum dipole field [T]</td>
<td>2.7</td>
</tr>
<tr>
<td>Aperture front [m]</td>
<td>0.3360</td>
</tr>
<tr>
<td>Aperture rear [m]</td>
<td>0.3360</td>
</tr>
<tr>
<td>Design field quality</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Physical length [m]</td>
<td>1.6</td>
</tr>
<tr>
<td>Physical width [m]</td>
<td>0.41</td>
</tr>
<tr>
<td>Physical height [m]</td>
<td>0.41</td>
</tr>
<tr>
<td>Superconductor type</td>
<td>NbTi</td>
</tr>
<tr>
<td>Conductor</td>
<td>Cable 20x2mm$^2$</td>
</tr>
<tr>
<td>Current density [A/mm$^2$]</td>
<td>148</td>
</tr>
<tr>
<td>Cu:Sc ratio</td>
<td>1.3</td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>4.2</td>
</tr>
<tr>
<td>Peak field wire [T]</td>
<td>3.5</td>
</tr>
<tr>
<td>Magnetic energy [MJ]</td>
<td>0.717</td>
</tr>
<tr>
<td>Ampere turns [MA-t]</td>
<td>1.16</td>
</tr>
<tr>
<td>Number of turns</td>
<td>154</td>
</tr>
<tr>
<td>Current [A]</td>
<td>7670</td>
</tr>
<tr>
<td>Inductance [H]</td>
<td>0.024376</td>
</tr>
<tr>
<td>Margin loadline [%]</td>
<td>60</td>
</tr>
</tbody>
</table>

**Figure 6.39: Magnetic field equivalent to the magnetization in the B1APF magnet.**

**Figure 6.40: Cross-section of B1APF.**
• Mechanically good cross-section

➢ Collar angle
➢ Wedge angles

Part of the coil missing because of the choice of scale
**Superconducting Magnet Division**

**EIC IR Magnet Design Summary (FY20)**

**- Ramesh Gupta**

**November 2020**

---

- **Good Field Quality B1pF with Keystoned Cable**

- **All field harmonics small (2.7 T @ 7.3 kA)**

---

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAIN HARMONIC</td>
<td>1</td>
</tr>
<tr>
<td>REFERENCE RADIUS (mm)</td>
<td>80.0000</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>0.9843E-06</td>
</tr>
<tr>
<td>SUM (Br(p) - SUM (An cos(np) + Bn sin(np)))</td>
<td></td>
</tr>
<tr>
<td>MAIN FIELD (T)</td>
<td>2.712609</td>
</tr>
<tr>
<td>MAGNET STRENGTH (T/(m^(n-1)))</td>
<td>2.7126</td>
</tr>
</tbody>
</table>

**NORMAL RELATIVE MULTIPOLES (1.D-4):**

- b 1: 10000.00000
- b 2: 0.000000
- b 3: 0.00437
- b 4: 0.000000
- b 5: 0.00488
- b 6: -0.000000
- b 7: 0.02281
- b 8: -0.000000
- b 9: 0.07717
- b10: -0.000000
- b11: 0.15408
- b12: 0.000000
- b13: -0.00641
- b14: 0.000000
- b15: 0.00157
- b16: -0.000000
- b17: 0.00016
- b18: -0.000000
- b19: -0.00021
- b20: -0.000000
Good Margin (B=2.7T, T=4.6K) B1pF with Keystoned Cable

- Very healthy margin in cross-section @4.6 K
  - ~110% field margin, >2.5 K temperature margin

<table>
<thead>
<tr>
<th>BLOCK NUMBER</th>
<th>PEAK FIELD IN CONDUCTOR (T)</th>
<th>CURRENT IN CONDUCTOR (A)</th>
<th>LOWEST FIELD IN CONDUCTOR (T)</th>
<th>SUPERCONDUCTOR CURRENT DENSITY (A/MM2)</th>
<th>COPPER CURRENT DENSITY (A/MM2)</th>
<th>PERCENTAGE ON THE LOAD LINE</th>
<th>QUENCHFIELD (T)</th>
<th>TEMPERATURE MARGIN TO QUENCH (K)</th>
<th>PERCENTAGE OF SHORT SAMPLE CURRENT</th>
<th>MAXIMUM LOADLINE IN BLOCK (%)</th>
<th>MINIMUM TEMPERATURE MARGIN IN BLOCK (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>320</td>
<td>320</td>
<td>316</td>
<td>-369.9003</td>
<td>-591.8404</td>
<td>47.8841</td>
<td>7.1989</td>
<td>2.5238</td>
<td>16.3463</td>
<td>47.8841</td>
<td>2.5238</td>
</tr>
</tbody>
</table>
Peak Fields at 2.7 T

Peak field enhancement ~25%

(peak field can be reduced in design iteration but already a very high margin)

Peak field over 2.7 T
Very Good Overall Margin

About 110% field margin
Over 2.5 K Temperature Margin
Some thoughts on the non-circular iron yoke

Coldmass can be circular even if yoke really has to be rectangular.

Put extra warm iron outside the coldmass
Summary

➢ Initial cross-section of cable all magnets developed for 4 K operation

➢ All cross-sections are based on the superconducting wire and cable designs that can be easily procured

➢ Two types of 36-strand cable used (a) Quad cable that is fully keystone for Q2BpF and (b) dipole cable which is fully keystone for B1apF

➢ Techniques developed to minimize fringe field from the proton/ion quad on the path of the electron beam, including cases when the quadrupole for electron beam were also present