Electron Lens

Main Solenoid and Corrector

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Requirements

1. Maximum design field : 6 T
   - Specified operating field range 1 T to 6 T
2. Field errors, -1050 <z <1050 mm, 1-6 T : <6 x 10^{-3}
3. Fringe field : field along the beam path till RT solenoid > 0.3T
   - Unique situation, unique solution
4. Field straightness: ±50 micron in -1050 <z <1050 mm

Field straightness is the most critical and demanding requirement
   - guides and determines the overall design
     too risky for industry to take this job
   - well beyond the normal construction errors
     corrector magnets become integral part of the overall design
   - must have enough magnetic shielding to limit the influence of surrounding
Superconducting Solenoid with Superconducting Correctors

- Axial field straightness is achieved by compensating transverse field errors (from normal construction) with horizontal and vertical dipole correctors.
- In earlier designs, corrector dipoles were “inside” the solenoid and were made of high current density copper. Now they are moved “outside” and are made with superconducting wire. Benefits:

  ➢ allows stronger correctors (earlier current density in copper was too demanding).
  ➢ significantly reduces the solenoid coil i.d. 292 mm to 200 mm. This in turn reduces the stored energy and Lorentz forces, thus making it a bit less demanding.
Overall magnetic system consists of:

- **Main solenoid**
  - including trim sections

- **Correction coils**
  - long and short
  - horizontal and vertical

- **Fringe field coils**

- **Anti-fringe field coils**

- **Room temperature magnets in beamline**
E-lens Solenoid Wire and Magnet Performance

Max. Design Field: 6 Tesla

Computed Magnet Performance:

<table>
<thead>
<tr>
<th>Temp</th>
<th>Bss</th>
<th>Bpk</th>
<th>I(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2 K</td>
<td>7.1 T</td>
<td>7.65 T</td>
<td>545 A</td>
</tr>
<tr>
<td>4.5 K</td>
<td>6.8 T</td>
<td>7.35 T</td>
<td>523 A</td>
</tr>
</tbody>
</table>

Field margin@4.5 K: ~13%

Stored Energy: ~1.4 MJ, Inductance: ~14 Henry

Main Solenoid and Corrector

Ramesh Gupta, SMD
Relative Field Errors on the Axis

Relative field errors (computed) to 1075 mm < 6 x 10^{-3}

Specifications to 1050 mm < 6 x 10^{-3}

However, the primary goal is to keep field straight rather than uniform.
Corrector Design
Design Considerations for correctors

- For e-lens to work, proton and electron beams must be aligned within ±50 micron.
- Proton beam is aligned to the solenoid axis with long (full length) horizontal and vertical correctors. The maximum strength 0.006 T (more possible).
- Electron field follows the solenoid magnetic axis. However, the tube on which the solenoid is wound can’t be perfect, and the coil winding can’t be perfect either. Moreover, the weight of the coil will also cause some sag.
- Therefore, many short correctors are needed to achieve the desired straightness magnetically.
- The strength (0.02 T, more possible) and number of short correctors (five horizontal and five vertical) is chosen based on estimated errors.
- One must also deal with the field from the components in the surrounding area with sufficient thickness of iron shield over the solenoid coil.
Estimation and correction of axis offset with 0.02 T correctors

Hypothetical Vertical Offset Profile (before correction)

- 4 axial harmonics
- $\lambda = 0.5, 1, 2, 4 m$
- 0.1 mm amplitudes
- All in phase

Comparable to what may be expected for an as-built solenoid.

After correction

It is estimated that a system of 5-6 correctors should be able to reduce axis offsets to $< \pm 50 \mu m$, starting with offsets $\sim \pm 0.2 \text{ mm}$. 

Computed Profile of Vertical Field, $B_y$

Computed Axis Offset Profile

Courtesy: Animesh Jain
Field on the Corrector

- Correctors will be placed outside the solenoid
- They reside in a low field region (<1% of 6T)
- This helps significantly:
  - Large margin in the superconductor
  - Lower Lorentz forces
Combined Corrector Design

Both horizontal and vertical dipole correctors are accommodated in a single layer

- Top & Bottom Windings for Vertical
- Left & Right Windings for Horizontal

Less efficient in terms of conductor use, but that is not a consideration here

- Significantly cuts down on the construction time and cost
- More optimization in geometry and construction (next slides)
Slotted Corrector Design

- Slots are machined in an aluminum tube and superconducting wires are placed in the slots.
- Horizontal and vertical correctors are placed in the same radial location.
- Slotted design removes significant conflict with other projects in the use of certain machine.
Superimposition of Fields of Long and Many Short Correctors (Horizontal & Vertical)

Maximum ~10% drop between two corrector from a flat (peak) field

Field of long corrector

Superimposition of fields of long and short correctors

-0.025
Exterior Field Requirements
Field between superconducting and copper solenoid with superconducting solenoid at 6 T

- The desired field (>0.3 T between copper solenoids and superconducting solenoid along the electron beam path) with desired spacing is not possible with copper solenoid alone.
- This requirement is satisfied by inserting superconducting coils inside the cryostat of the main superconducting solenoid.
- The size and location of the fringe field coil is optimized to minimize space usage.
- Strong fringe field coils have a significant impact on the field inside the main solenoid.
Field between superconducting and copper solenoid with superconducting solenoid < 6 T

- However, the situation becomes complicated when the main solenoid is operated at a field lower than 6 T – the desired range is field as low as 1 T.
- In this case the outside field becomes significantly smaller because (a) the leakage field from the main solenoid becomes lower and (b) exterior field from the fringe field coil also becomes lower if it scales with the main solenoid to maintain field quality.
- To obtain desired the desired (>0.3 T) field between copper solenoids and the superconducting solenoid, the fringe field must run at full power.
- To obtain the required field quality, an additional coil (anti-fringe field coil) is added and powered independently to adjusted field quality.
Field Quality in Main Solenoid at 1T & 3T with the desired fringe field (>0.3 T)

- To obtain the desired (>0.3 T) field between copper solenoids and the superconducting solenoid, the fringe field must run at full power.
- To obtain the required field quality, the current in the anti-fringe field coil is adjusted.
- To minimize the amp-turn requirements, anti-fringe field coils have a nominal zero current when the main solenoid is at 6 T.
- The current in anti-fringe coil must be negative at 3T (~-16 A) and even more at 1T (~-33 A). These give the desired field quality (errors < 6 x 10^{-3} from z=-1050 to +1050).
Quench Protection

Total MIITs in the circuit:

\[ \int I^2 \, dt \approx 1.5 \text{ MIITs} \]

(for I=\(\approx\)500 A, L=\(\approx\)14 H, \(R_{\text{dump}}\)=\(\approx\)1.2 \(\Omega\); giving time constant: \(\tau\)= \(\approx\)12 sec)

Diodes are across segments of the coil to limit the energy deposited in the coil segment (\(<\) 0.5 MIITs).

Bus & diodes are designed to handle a much higher MIITs than the coil conductor (> 1.5 MIITs).

Energy extraction is used to limit the maximum MIITs in the bus & diodes

- This is safe as temperature remains well below 350 K

Energy extraction and quench protection diodes are used to control temperature rise in the coil in the event of a quench

\[ y = 675.7x^4 + 363.36x^3 + 351.39x^2 + 291.83x + 25.899 \quad R^2 = 1 \]

Keep temperature < 350 K (0.5 MIITs)

Courtesy Joe Muratore
George Ganetis

E-Lens Main Solenoid Temp vs MIITS

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Main Solenoid and Corrector

Ramesh Gupta, SMD
Mechanical Analysis
Lorentz Forces (Contour Plot of Force Density)

Radial Lorentz force (hoop stress) : ~24 MN
- Large radial force requires significant structure

Axial force: ~35 kN per side
- large axial forces, only in the ends
Radial Force Restraint

- Outward pressure (hoop stress) from 24 MN Lorentz forces.
- Radial forces can be restrained by 6 mm of material stressed (hoop) to 40,500 psi with coil energized.
- Resulting stress in support tube (pressure vessel) is 17,000 psi. Required strain for S.S. tube is 0.014.
- S.S. Tube heated to 80 degree C will give the required interference.
- Tube has 10 mm radial taper.
Axial force containment

- Insert structure towards the end of the coil to contain forces
- Coil is wound continuously through the end structure to keep axial forces contained throughout (during quench).
- The axial forces exerted by the outer solenoid sections are transferred around the center section.
- The keyed support discs transfer the load to the support tube and the compression sleeve.

Courtesy: A. Marone
Summary

This is a demanding magnet system with unique challenges

- Magnet aperture is large with significant stored energy and Lorentz forces
- The field should be very straight inside the magnet and the field magnitude should be large outside the magnet
- In addition, significant effort is made to keep cost low and schedule accelerated

The following major steps have been taken to meet various requirements:

- Novel and robust cryo-mechanical structure is developed (details not discussed)
- Corrector magnets are made superconducting and compact (H&V together) to reduce size, stored energy and Lorentz forces in the superconducting solenoid
- A corrector design is developed that to facilitate the required field straightness
- Significant work is being done in magnetic measurement area (not discussed here) to assure that straightness
- Superconducting fringe field and anti-fringe coils have been added to obtain the large field outside while maintaining good field quality inside for 1 T to 6 T range.
Extra slides
Project Scope

Design, Build and Test 2 eLens Solenoid Magnets:

• Magnetic, mechanical, electrical requirements as specified by C/AD
• Conduct ongoing communications & meetings to significantly clarify scope, improve design and performance
• Maintain cost control
• Deliver by April 2012

Courtesy: M. Anerella
Magnet Mechanical Design Overview

17 separate circuits / max. current:

• 1 main solenoid / 460A
• 2 fringe field solenoids / 47A
• 2 anti-fringe field solenoids / 33A
• 5 0.5m vertical correctors / 26A
• 5 0.5m horizontal correctors / 26A
• 1 2.5m vertical corrector / 34A
• 1 2.5m horizontal corrector / 34A

Quench protection via cold diodes
Helium vessel cooled by liquid bath from RHIC supply
Outer heat shield actively cooled from 4K boil-off, inner shield conductively cooled
RHIC support posts / cryostat

Courtesy: M. Anerella
# Main Parameter List

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil i.d.</td>
<td>200 mm</td>
</tr>
<tr>
<td>Coil length (main)</td>
<td>2360 mm</td>
</tr>
<tr>
<td>Yoke length</td>
<td>2450 mm</td>
</tr>
<tr>
<td>Wire, bare</td>
<td>1.78 mm X 1.14 mm (70 mil X 45 mil)</td>
</tr>
<tr>
<td>Wire, insulated</td>
<td>1.91 mm X 1.27 mm (75 mil X 50 mil)</td>
</tr>
<tr>
<td>Wire Ic specification (4.2 K, 7 T)</td>
<td>&gt;700 A</td>
</tr>
<tr>
<td>Turn-to-turn spacing (axial, radial)</td>
<td>2.03 mm X 1.42 mm (80 mil X 56 mil)</td>
</tr>
<tr>
<td>Number of layers (main, full length)</td>
<td>22 (11 double layers)</td>
</tr>
<tr>
<td>Additional layers for trimming end fields (in series)</td>
<td>4 (2 double layer)</td>
</tr>
<tr>
<td>Length of layers for trimming end fields</td>
<td>173 mm on each end</td>
</tr>
<tr>
<td>Coil o.d. (without trim)</td>
<td>262.6 mm</td>
</tr>
<tr>
<td>Coil o.d. (with trim)</td>
<td>274 mm</td>
</tr>
<tr>
<td>Coil o.d. with trim coil and over-wrap</td>
<td>277 mm</td>
</tr>
<tr>
<td><strong>Maximum design field</strong></td>
<td><strong>6 T</strong></td>
</tr>
<tr>
<td>Current for 6 T</td>
<td>~460 A</td>
</tr>
<tr>
<td><strong>Peak Field on the conductor @ 6T</strong></td>
<td>~6.5 T (~8% peak field enhancement)</td>
</tr>
<tr>
<td><strong>Computed Short Sample @4.2 K</strong></td>
<td>~7.0 T (6.6 T, specified)</td>
</tr>
<tr>
<td>Stored energy @ 6 T</td>
<td>~1.4 MJ</td>
</tr>
<tr>
<td>Inductance</td>
<td>~14 Henry</td>
</tr>
<tr>
<td>Yoke i.d.</td>
<td>330 mm</td>
</tr>
<tr>
<td>Yoke o.d.</td>
<td>454 mm</td>
</tr>
<tr>
<td>Yoke width (radial)</td>
<td>62 mm</td>
</tr>
<tr>
<td><strong>Field on the axis</strong></td>
<td><strong>1 to 6 T</strong></td>
</tr>
<tr>
<td>Maximum computed error on axis</td>
<td>~6 X 10^{-3} (~1050 to 1050 mm and within 20 mm)</td>
</tr>
</tbody>
</table>
Dimensions

• Yoke length 96.5 inches (~2.5 m)
• Yoke OD 17.9 inches

• Cold mass length 104.7 inches
• Cold mass OD 19.5 inches

• Magnet OD 24.0 inches
• Magnet length 110.6 inches

• Magnet weight ~7000 lbs.

Courtesy: S. Plate
Value Engineering

- Use existing designs, materials, etc. wherever possible
  - Existing spare RHIC CQS cryostat
  - Surplus IsaBelle stainless steel helium vessels
  - Stock RHIC corrector superconducting wire
  - Stock RHIC Ultem support posts
- Use existing equipment, e.g.:
  - SMD direct wind machine, BEPC-II precision solenoid gantry
  - SMD automated take-up spools
  - C-AD curing oven
- Incorporation of Corrector Coils into superconducting magnet system:
  - Increased Solenoid costs, but reduced other eLens program costs (i.e. change is cost neutral) and improved eLens performance
- Development of fringe field solenoid coils:
  - Resolved previously unaddressed operational eLens issue

Courtesy: M. Anerella
Fringe & Anti Fringe Coils

- **Fringe**
  - 40,000 lbs. axially inward (toward main Solenoid).
  - 2000 psi radially outward (@ O.D. of coil)

- **Anti Fringe**
  - 15,000 lbs. axially outward (toward fringe coil).
  - 225 psi radially inward

Courtesy: A. Marone
Project Team

- Project / Engineering Supervision – Mike Anerella
- Scientist, Magnetic Design – Ramesh Gupta
- Mechanical Engineer, Magnet – Steve Plate
- Mechanical Engineer, Coils – Andy Marone
- Mechanical Engineer, Design – Paul Kovach
- Electrical Engineer, Coils – John Escallier
- Electrical Engineer, Tooling – Piyush Joshi
- Scientist, Magnetic Measurements – Animesh Jain
- Scientist, Cold Test – Joe Muratore

Many other experienced SMD personnel involved at some level

Courtesy: M. Anerella