PIP-II Solenoid Focusing lens for SSR2 Cryomodule

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• Each cryomodule of the SSR2 section of the PIP-II linac contains five 325 MHz superconducting single spoke cavities and three solenoid-based focusing lenses operating at 2 K. The total number of SSR2 focusing lenses to be built for the PIP-II accelerator is 25 (including four spare devices).

**Magnet Cavity string arrangement for SSR2 cryomodule for PIP-II**
(Figure shown for representation purpose only; not true scale drawing)
## Functional requirement Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specified SSR1</th>
<th>Specified SSR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focusing Strength</td>
<td>4 T²m</td>
<td>5 T²m</td>
</tr>
<tr>
<td>Bending strength of Dipole correctors</td>
<td>2.5 mT-m</td>
<td>5 mT-m</td>
</tr>
<tr>
<td>Beam pipe aperture</td>
<td>30 mm</td>
<td>40 mm</td>
</tr>
<tr>
<td>Uncertainty in the location of magnetic axis w.r.t Reference points (Transverse and angular alignment)</td>
<td>&lt;0.5 mm RMS, &lt;1 mrad RMS</td>
<td>&lt;0.1 mm RMS, &lt;0.5 mrad RMS</td>
</tr>
<tr>
<td>Effective length of solenoid (FWHM)</td>
<td>Not constrained</td>
<td>&lt;15 cm</td>
</tr>
<tr>
<td>Active magnetic shielding requirements</td>
<td>0.5Q₀ criterion</td>
<td>minimal</td>
</tr>
<tr>
<td>Maximum current in the solenoid</td>
<td>100A</td>
<td>100A</td>
</tr>
<tr>
<td>Maximum current in the dipole correctors</td>
<td>50A</td>
<td>50 A</td>
</tr>
</tbody>
</table>

- Main design features of the SSR2 lens are quite similar to SSR1 Focusing lens.
- A new design is suggested and verified to meet the main requirements because of increased beam aperture and focusing strength for SSR2.
- Focusing strength and Fringe field on the SSR2 cavity surface has been optimized for PIP-II.
EM design and parameters

<table>
<thead>
<tr>
<th>Sr. no</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Designed value of focusing strength</td>
<td>5.33</td>
<td>T²m</td>
</tr>
<tr>
<td>2.</td>
<td>Magnetic Field Integral</td>
<td>1.01</td>
<td>T·m</td>
</tr>
<tr>
<td>3.</td>
<td>Peak transverse Magnetic field in the lens aperture</td>
<td>6.22</td>
<td>T</td>
</tr>
<tr>
<td>4.</td>
<td>Peak Magnetic field on the wire strand</td>
<td>6.878</td>
<td>T</td>
</tr>
<tr>
<td>5.</td>
<td>Nominal current</td>
<td>77.4</td>
<td>A</td>
</tr>
<tr>
<td>6.</td>
<td>Nominal Current Density</td>
<td>260</td>
<td>A/mm²</td>
</tr>
<tr>
<td>7.</td>
<td>B max at the cavity Surface</td>
<td>0.179</td>
<td>Gauss</td>
</tr>
<tr>
<td>8.</td>
<td>Field Integral (along the radial line 0 to 0.3m) at axial Distance of 0.5 mm</td>
<td>3.9</td>
<td>G-cm</td>
</tr>
</tbody>
</table>

Objective function:

\[ \int B_z^2 \cdot dz \geq 5 \text{T}^2\text{m} \]

Minimize \( \int_{r=0}^{r=0.3} B \cdot dl \) at \( z = 0.5 \text{m} \)

Constraints:

\[ \frac{\int (B_z \cdot dz)}{B_0} \leq 150 \text{ cm} \]

\( I_{\text{exc}} < 100 \text{A} \)

Optimization Parameters:

\( N_{\text{main}}, L_{\text{main}}, R_{\text{main}} \)
\( N_{BC}, L_{MC}, R_{MC}, Z_{\text{center-BC}} \)
The magnetic field generated by magnetic elements inside cryomodule must be sufficiently small to limit the degradation in $Q$.

$$R_{surf} = R_{BCS} (v,T) + R_{res} + R_{mag} (H_{ext})$$

External DC magnetic field on the cavity surface due to fringing field of the solenoid magnet has been restricted to below 1 mT.
Tolerance studies on Bucking Coil Geometrical parameters

- Tight tolerance is required for the bucking coil winding dimensions and its placement w.r.t main coil.
- The positional inaccuracy of the Bucking coil effects the fringe magnetic field on the cavity surface.
Operating Curve for the SSR2 focusing lens

Predicted performance of main coil for SSR2 Magnets (Curve shown for proposed conductor 0.4mm bare diameter NbTi/Copper monolith SC wire)

Max magnetic Field on Sc strand [T] vs Current [A]
Dipole Corrector Coil

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<tr>
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<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Designed value of Bending strength of corrector coils</td>
<td>5.25</td>
<td>mT-m</td>
</tr>
<tr>
<td>2.</td>
<td>Designed value of integrated Gradient of focusing quadrupole</td>
<td>0.2</td>
<td>T</td>
</tr>
<tr>
<td>3.</td>
<td>Nominal current</td>
<td>~39.2</td>
<td>A</td>
</tr>
</tbody>
</table>
Fringe field on the cavity surface increases slightly when DC coil powered on with MC coil but field values are still within the acceptable limits.
Quench Analysis

- Although the total stored magnet Energy of 14KJ is small, the Quench analysis needs to be carried out to verify the maximum hot spot temperature and the maximum coil to ground voltage are within safe limits.
- A quench circuit is defined to include main coil, bucking coils, dump resistance and coil-diodes. An inductance matrix is needed in the quench circuit for QUENCH analysis.
- Inductance matrix of the sub-coils

\[
I = \begin{bmatrix}
4.82H & -0.59H & -0.59H \\
-0.59H & 0.694H & 0.082H \\
-0.59H & 0.082H & 0.694H \\
\end{bmatrix}
\]

- To compute the maximum temperature after quench, a het flux is introduced at the point of maximum magnetic field to initialize a quench.
Quench Initiated in Main Coil

Quench initiated at $t=0.1\text{s}$

Quench propagation at $t=0.105\text{s}$

Quench propagation at $t=0.175\text{s}$

Quench propagation at $t=0.3\text{s}$

Quench propagation at $t=0.5\text{s}$

Quench propagation at $t=20\text{ s}$
Quench Initiated in Main Coil

Temperature rise in main coil after quench initiation

Energy Dissipation in main coil
Coil resistance growth in main coil after quench initiation

\[ V_{mc} = \frac{Ld}{dt}_{\text{main}} = 744 \text{Volts} \]

\[ V_{bc} = \frac{Ld}{dt}_{\text{BC}} = 79.35 \text{V} \]

di/dt across main coil and bucking coil after quench initiation

Current decay in main coil and bucking coil after quench initiation
Quench Initiated in Bucking Coil

Most severe quenching scenario takes place when the quench is initiated in Bucking coil and a large $\frac{dl}{dT}$ introduces interlayer voltage in the main coil.
Quench Initiated in Bucking Coil

Temperature Rise in Bucking coil after quench initiation

Quench Energy released in form of heat
Quench Initiated in Bucking Coil

\[ V_{mc} = \frac{Ld_i_{\text{main}}}{dt} = 1080 \text{ Volts} \]
\[ V_{bc} = \frac{Ld_i_{\text{BC}}}{dt} = 34.5 \text{V} \]
Scope and Schedule

• Technical Deliverables (as part of PIP-II IIFC collaboration)
  – SSR2 Focusing Solenoids
    • Electromagnetic/Mechanical and quench protection design of solenoid and current leads by BARC.
    • 4 no's of SSR2 solenoids to be delivered in R&D phase.
    • BARC to lead the Development effort. FNAL Test and measurement infrastructure will be used for qualification of prototype and series magnets at 2K.

• Intermediate milestones (R&D Phase)
  – Completion of 1 prototype Solenoid assembly – Q2-CY17
  – Qualification of Prototype Solenoid at 4 K @BARC – Q3-CY17
  – Qualification of Prototype Solenoid at 2 K @FNAL – Q4-CY17
  – Completion of 4 no.s solenoid magnet assemblies – Q1-CY18
  – Qualification of series magnet assemblies – Q2-CY18
Test and measurement Plan

The following measurements shall be made after training the cold mass at 4K:

- Axial magnetic field along the axis of the solenoid at the nominal current;
- Position of the magnetic axis at 4K using Hall probe technique.
- Transverse magnetic field of each steering coil (dipole mode) along the axis at nominal current.

After the cold mass is assembled with LHe vessel, the following measurements shall be made:

- Quench currents at 4 K for the solenoid and steering coils in the dipole mode.
- Position of the magnetic axis at 4K using Hall probe technique.
- Quench current at 2 K (only for the solenoid and only for prototype magnets).
Summary and next steps

- The latest SSR2 focusing lens design satisfies the project needs in term of EM performance and Fringe field requirements.

- Quench Analysis has been completed and maximum temperature and voltage in case of Quench are found to be within specified limits and of same order as in SSR1 which has been successfully tested.

- Bending strength of corrector coils and Quadrupole gradient in case of skew quadrupole arrangement meets the main requirement and the operating point is well within the range of specified current limit.

- Mechanical design of Coil former and He vessel has been initiated.

- Prototype Lens development to be initiated once the mechanical design is complete and approved.
References

- PIP-II Reference Design Report V1.00, June 2015
- FRS for the SSR2 cryomodule, Team Centre Document ED0001829
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