Cold Testing Results of the Superconducting Solenoids with Dipole Steering Coils

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Introduction

- SC solenoid with steering coils
  - Main solenoid coil in series with reverse-polarity bucking coils
  - Two pairs of dipole steering coils
  - Solenoid: 6 T, Steering coil: 30 T∙mm
Summary of Electrical Performance Tests

- Measured field strength
  - Solenoid: 6 T at 82.3 A
  - X-dipole: 30 T·mm at 47.3 A
  - Y-dipole: 30 T·mm at 48.2 A
- No quenching/heating on running at those currents.

<table>
<thead>
<tr>
<th>Test at the vendor site</th>
<th>X Coil Current (A)</th>
<th>Y Coil Current (A)</th>
<th>Main Coil Current (A)</th>
<th>Quench Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>49.00</td>
<td>0.00</td>
<td>0.00</td>
<td>No quench</td>
</tr>
<tr>
<td>49.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>No quench</td>
</tr>
<tr>
<td>49.00</td>
<td>49.00</td>
<td>82.36</td>
<td></td>
<td>No quench</td>
</tr>
</tbody>
</table>

Review of the Status and Production Readiness of the 162.5 MHz HWR cryomodule for Project X
Solenoid Field

Stray Field (Simulation)

On-axis Axial Field (Simulation and Measurement)

Review of the Status and Production Readiness of the 162.5 MHz HWR cryomodule for Project X
• Screening effect by the solenoid coil is supposed to be negligible around 6 T solenoidal field. (cf. Lower critical field of this solenoid coil ~ 1500 G)
• In measurement at a certain $z$, solenoid is turned on and off. Measured fields are very symmetric with respect to the middle of the dipole coil. -> The dipole coil is mechanically stable against Lorentz force induced by the solenoidal field.
Test Setup with SRF Cavity

This setup simulates a similar geometrical relationship between a cavity and a solenoid in the PXIE HWR Cryomodule.

- **Low field probe** (Fluxgate Magnetometer)
- **High field probe** (Hall probe)
- **Magnetic field probes**
- **72 MHz QWR**
- **Solenoid**

Review of the Status and Production Readiness of the 162.5 MHz HWR cryomodule for Project X
Magnetic Field on the Cavity Wall

<table>
<thead>
<tr>
<th>Measured</th>
<th>Residual Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before cooldown</td>
<td>45 mG</td>
</tr>
<tr>
<td>After cooldown</td>
<td>45 mG</td>
</tr>
<tr>
<td>During degaussing</td>
<td></td>
</tr>
<tr>
<td>After degaussing</td>
<td>44 mG</td>
</tr>
<tr>
<td>After warm-up</td>
<td>45 mG</td>
</tr>
</tbody>
</table>

The probe is normal to the cavity wall and placed 24 mm distant from the cavity outer surface.

- No significant magnetic material other than NbTi.
- At the end of degaussing, magnetic field goes to the center of the hysteresis curve.
Residual Magnetic Fields on the Axis

- ~100 mG residual magnetic fields were found on the solenoid flange inside of the cryostat after warm-up.
- The source of that residual fields is inside of the solenoid but it is reduced to 2~3 mG at the cavity surface (cf. $R_H = 1 \text{nOhm} @ 9 \text{ mG}, 162.5\text{MHz}$).
**Magnetic Axis Measurement**

Rotating rod: Bakelite (Hall sensor attached)  
Rotation guide: Aluminum  
Solenoid housing: Stainless steel 304

\[
B_r(r) = kr \approx kR \left(1 - \frac{d}{R} \cos \theta \right), \text{if } d \ll R
\]

**Magnetic centers at flanges (unit: mm)**

<table>
<thead>
<tr>
<th>Flange</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.30 ± 0.07</td>
<td>0.17 ± 0.04</td>
</tr>
<tr>
<td>2</td>
<td>-0.08 ± 0.02</td>
<td>0.26 ± 0.07</td>
</tr>
</tbody>
</table>

![Graph showing radial magnetic field vs. probe angle]

Review of the Status and Production Readiness of the 162.5 MHz HWR cryomodule for Project X
Fiducials on the Solenoid Housing

Fiducials were finely machined referenced to the mechanical axis (centers of the solenoid bore at both ends, a scribed mark for the angle reference) used in the magnetic axis measurement.
Experience with Alignment of Cavities and Solenoids in ATLAS Intensity Upgrade Cryomodule

ATLAS Intensity Upgrade Cryomodule

ATLAS Intensity Upgrade Cryomodule

Alignment Tolerances

<table>
<thead>
<tr>
<th>Coordinate</th>
<th>ATLAS Energy Upgrade*</th>
<th>ATLAS Intensity Upgrade**</th>
<th>PXIE HWR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>FRS***</td>
</tr>
<tr>
<td>x (mm)</td>
<td>±0.5</td>
<td>±0.25</td>
<td>±0.5</td>
</tr>
<tr>
<td>y (mm)</td>
<td>±0.5</td>
<td>±0.25</td>
<td>±0.5</td>
</tr>
<tr>
<td>z (mm)</td>
<td>±2</td>
<td>±1</td>
<td>±0.5</td>
</tr>
<tr>
<td>Pitch (degrees)</td>
<td>±0.2</td>
<td>±0.1</td>
<td>±0.06 (S)</td>
</tr>
<tr>
<td>Yaw (degrees)</td>
<td>±0.2</td>
<td>±0.1</td>
<td>±0.06 (S)</td>
</tr>
<tr>
<td>Roll (degrees)</td>
<td>±1</td>
<td>±0.1</td>
<td>±0.06 (S)</td>
</tr>
</tbody>
</table>

*, ** Alignment tolerances for solenoids only

7 QWRs and 4 solenoids operated at 4 K

Review of the Status and Production Readiness of the 162.5 MHz HWR cryomodule for Project X
Kinematic Mounts

Kelvin-type kinematic coupling used in cavity/solenoid mount

Vee block

Flat surface

Vee block with ring

Kelvin type kinematic coupling

L.C. Hale and A.H. Slocum, Precision Engineering (2001)
Room Temperature Alignment

- Fiducials are used as references of the mechanical center of each cavity and solenoid.
- After installing alignment targets, their positions are measured referenced to the beam axis.

<table>
<thead>
<tr>
<th></th>
<th>Solenoids</th>
<th>Cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal offset</strong></td>
<td>0.08 mm</td>
<td>0.36 mm</td>
</tr>
<tr>
<td><strong>Yaw angle</strong></td>
<td>0.03°</td>
<td>0.07°</td>
</tr>
<tr>
<td><strong>Vertical offset</strong></td>
<td>0.17 mm</td>
<td>0.21 mm</td>
</tr>
<tr>
<td><strong>Pitch angle</strong></td>
<td>0.08°</td>
<td>0.15°</td>
</tr>
</tbody>
</table>
Alignment Change on Cooldown

**RMS deviation from the fitted beam axis**

<table>
<thead>
<tr>
<th></th>
<th>Solenoids</th>
<th>Cavities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>0.12 mm</td>
<td>0.50 mm</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.18 mm</td>
<td>0.28 mm</td>
</tr>
</tbody>
</table>

**Target shifts on cooldown and evacuation of insulation vacuum**

- **Left targets**
- **Right targets**
- **Calculation**

**Horizontal shift (mm)** vs **Longitudinal position (cm)**

**Vertical shift (mm)** vs **Longitudinal position (cm)**
Improvements in PXIE HWR Cryomodule

- Machined Stock Ti bars will be used for the strongback. It will need less effort in the room temperature alignment with advanced position adjustment system.
- Maxwell kinematic coupling will be used in the cavity and solenoid mounts. The beam axis will not have thermal motion on the kinematic mount plane.
- 4 targets will be attached per each cavity and solenoid. Changes in pitch and yaw can be monitored on cooldown.
Summary

- Performance of the fabricated solenoid is in good agreement with the designed specifications.
- We experimentally verified this solenoid will work well in the cryomodule.
  - The dipole field is well superposed on the solenoid and the dipole coil is mechanically stable.
  - The residual field generated by the solenoid is successfully reduced to 2~3 mG at the cavity surface after degaussing.
  - The position of the magnetic axis is known referenced to the fiducials. Experience with alignment in the ATLAS Intensity Upgrade cryomodule, in which we achieved 0.25 mm transverse alignment tolerances, is adapted to the PXIE HWR cryomodule with improvements in the support and alignment system.