Status of Performance Testing of the Mu2e Transport Solenoid Coils

Karie Badgley
Magnet Technology Conference
09/23/2019
Mu2e will search for the neutrino-less conversion of a muon into an electron in the presence of a nucleus, $\mu N \rightarrow eN$

- 10000 improvement over previous experiment
- Could discover the violation of Flavor Symmetry in the charged leptons $\rightarrow$ physics beyond the Standard Model
Mu2e Magnet System

- 66 Solenoids, PS(3), TS(52), DS(11)
- PS and DS fabricated and fully assembled in industry
- Sections of the TS cold mass fabricated in industry, testing and assembly at Fermi
Transport Solenoid

Typically 2 coils per module

1-3 modules per unit

14 units for the TS

5 TSU units delivered

TSU

TSD
Mu2e required efficient muon transmission and no trapped particles

Previous studies helped set the tolerances for fabrication and assembly

$$\Delta V = 10 \text{ mm}$$

$$\Delta P = 5 \text{ mrad}$$
Magnetic Axis

• Vibrating stretched wire measurement made for each coil, with AC current on the magnet to reject earth’s magnetic field and remnant magnetization effects
• Sag correction made ~100 μm
• Position measured with respect to fiducials on the shell and wire system, translated to the Mu2e coordinate system

<table>
<thead>
<tr>
<th>Coils</th>
<th>Requirement (Degree)</th>
<th>Measurement (Degree)</th>
<th>Difference (Degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/2</td>
<td>0 ±0.2</td>
<td>0.174</td>
<td>0.174</td>
</tr>
<tr>
<td>2/3</td>
<td>0 ±0.2</td>
<td>0.067</td>
<td>0.067</td>
</tr>
<tr>
<td>3/4*</td>
<td>0 ±0.2</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>4/5</td>
<td>5.7 ±0.2</td>
<td>5.538</td>
<td>-0.162</td>
</tr>
<tr>
<td>5/6</td>
<td>4.8 ±0.2</td>
<td>4.790</td>
<td>-0.01</td>
</tr>
<tr>
<td>6/7</td>
<td>5.3 ±0.2</td>
<td>5.280</td>
<td>-0.02</td>
</tr>
<tr>
<td>7/8*</td>
<td>5.5 ±0.2</td>
<td>5.624</td>
<td>0.124</td>
</tr>
<tr>
<td>8/9</td>
<td>5.5 ±0.2</td>
<td>5.352</td>
<td>-0.148</td>
</tr>
<tr>
<td>9/10</td>
<td>5.5 ±0.2</td>
<td>5.582</td>
<td>0.082</td>
</tr>
<tr>
<td>10/11</td>
<td>5.5 ±0.2</td>
<td>5.558</td>
<td>0.058</td>
</tr>
<tr>
<td>11/12*</td>
<td>5.5 ±0.2</td>
<td>5.365</td>
<td>-0.135</td>
</tr>
<tr>
<td>12/13</td>
<td>5.4 ±0.2</td>
<td>5.465</td>
<td>0.065</td>
</tr>
</tbody>
</table>

* Marked coils represent boundaries between units; for these coils the angles assume perfect unit-to-unit assembly.
Max temperature differential between the shell and coil of 23 K to avoid stress on coil from differential thermal contraction

Each unit takes ~ week to cooldown/ warm-up
Cold Acceptance Tests

- Coils must reach 2100 A, 120% of 1730 A operating current
- No more than 5 quenches allowed per coil
- Any quench in the coil requires a thermal cycle

Unit 1

- Quench ~1800 A
- Reached 2100 A during second powering
- Suspect quench in leads between coils
- After thermal cycle, we found a few temporary lead supports had popped off
Cold Test Results

Unit 3

• Quenched at ~1500 A, unable to reach 2100 A during first cooldown
• Quench due to motion in leads connecting to the dished head
• Removed from cryostat and added additional lead support
• Reached 2100 A after second cooldown

Unit 4

• Quench ~1800 A
• Quench origin was either in coil 7 or in the leads between coil 6 and 7
• Reached 2100 A on second ramp
• Currently undergoing thermal cycle
Splice Measurements

- Splice voltage measurements made at several currents
- Requirement on splice to be less than 2 nΩ
- All splices below the requirement

<table>
<thead>
<tr>
<th>Splice Measurement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/5</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>5/6</td>
<td>0.46 ± 0.04</td>
</tr>
<tr>
<td>6/7</td>
<td>0.5 ± 0.1</td>
</tr>
<tr>
<td>7/8*</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>8/9</td>
<td>0.38 ± 0.03</td>
</tr>
<tr>
<td>9/10</td>
<td>0.7 ± 0.2</td>
</tr>
<tr>
<td>10/11</td>
<td>0.82 ± 0.06</td>
</tr>
<tr>
<td>11/12*</td>
<td></td>
</tr>
</tbody>
</table>

*Boundary between units. Splices will be made during assembly.
## Transport Solenoid Magnetic Requirements

<table>
<thead>
<tr>
<th>Region</th>
<th>B Initial/Final</th>
<th>dBs/ds (T/m)</th>
<th>dBs/dr (T/m)</th>
<th>Ripple (T)</th>
<th>Location* (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TS1</td>
<td>2.50/2.40</td>
<td>&lt; -0.02</td>
<td>NA</td>
<td>NA</td>
<td>r=0, r=0.15</td>
</tr>
<tr>
<td>TS2</td>
<td>NA</td>
<td>NA</td>
<td>&gt; 0.275</td>
<td>±0.02</td>
<td>r &lt; 0.15</td>
</tr>
<tr>
<td>TS3</td>
<td>2.40/2.10</td>
<td>&lt; -0.02</td>
<td>NA</td>
<td>NA</td>
<td>r=0, r=0.15</td>
</tr>
<tr>
<td>TS4</td>
<td>NA</td>
<td>NA</td>
<td>&gt; 0.275</td>
<td>±0.02</td>
<td>r &lt; 0.15</td>
</tr>
<tr>
<td>TS5</td>
<td>2.10/2.0</td>
<td>&lt; -0.02</td>
<td>NA</td>
<td>NA</td>
<td>r=0, r=0.15</td>
</tr>
</tbody>
</table>

Stretched wire measurements have been completed on coils 1-13.
As-built TS1

- Stretched wire results used to update magnetic model and ensure magnetic requirements are met
- Nominal model with as-built values for coils 1-13

Axial Gradient \( \text{dBs/ds} < -0.02 \text{ T/m} \)
As-built TS2

As-built values for coils 1-13

Radial Gradient dBs/dr > 0.275 T/m

Ripple ± 0.02 T out to 0.15 m
As-Built Axial Field

Nominal-As-built Axial Field

Final as-built field will be determined after cold mass assembly
Swapped Coils 14 & 15

- Due to a fabrication error, we are looking into the feasibility of swapping coils 14 and 15.
- The coil lengths and inner diameter are the same, so the coil center position and angles remain at nominal.
- Coil 15 has one additional layer of conductor, this increases the axial field at 14 and decreases at 15.
• In addition to checking the magnetic requirements, the field map was given to the collaboration for particle tracking studies
• In the process of checking other mechanical and electrical implications
Cold Mass Assembly
Summary

- Transport Solenoid in production
  - Unit on the stretched wire stand, one in cold test preparation, one cold and ready for second powering
- 5 of 14 units delivered, 3 cold tested, 2 in final assembly
- All cold tested units reached 2100 A
- All as-built values for the first 13 coils meet the magnetic requirements
- All splice measurements below the required 2 nΩ
- Swapping coils 14 and 15 looks feasible from a magnetic and particle tracking standpoint