Solenoid Magnet System

Outline

• Introduction
• Scope
• Key Design issues
• Conclusions
L2 Solenoid

- Power Supply/Quench Protection
- Cryoplant (actually off project)
- Field Mapping
- Ancillary Equipment
- Insulating vacuum
- Installation and commissioning

• Production Solenoid (PS)
• Transport Solenoid (TS)
• Detector Solenoid (DS)
• Cryogenic Distribution
Design Specifications

• **Field quality**
  – Monotonic axial gradients in transport straight sections
  – Field uniformity in spectrometer

• **Quench margin and stability**
  – 1.5 K in temperature, 30-35% in Jc along load line, stability (TBD)
  – Stabilizer resistivity, conductor heat capacity, thermal conductivity

• **Fits within the cryogenic budget**
  – 1 Satellite refrigerator steady state
  – 1-2 Additional refrigerators for cooldown/quench recovery

• **Limited radiation damage**
  – Superconductor and insulation secondary to stabilizer degradation
  – RRR reductions and annealing compatible with planned thermal cycles
  – Frequency of thermal cycles (for radiation repair) coincides with expected accelerator and/or cryogenic operation cycles
Cost and Time Considerations

• Cost is a major factor
  – Raw materials for both magnet and shields
  – Pool of vendors capable of building large-complex magnets
  – Simplified infrastructure with commonality to rest of muon campus

• Time Constraints
  – Magnets are on the critical path for most of project life.
  – Present Schedule
    • June 2012: Prototype conductor order (1 year lead time)
    • June 2013:
      – Place order for conductor production run
      – Place contract for magnet fabrication

Argues for using proven technologies
PS Baseline Design

4-5T ➞ 2.5 T Axial Gradient

Gradient made by 3 axial coils same turn density but increase # of layers (3,2,2 layers)
- Wound on individual bobbins
- I operation ~9kA
- Trim power supply to adjust matching to TS
- Indirect Cooling (Thermal Siphon)

Aluminum stabilized NbTi
- reduce weight and nuclear heating
- Special high strength/high conductivity aluminum needed (like ATLAS Central Solenoid)

Vadim Kashikhin, task leader
See Next Presentation
3-2-2 magnet design

Gradient Uniformity meets field spec.
PS Quench Studies

Comfortably below 130K quench limits
Quench Stability

• Is magnet stable against quenches caused by expected mechanical motion?
  • Motion of strand within cable
  • Motion of cable within epoxy
  • Epoxy Cracks
• Difficult to predict from first principles
  • Comparison to successful magnet of similar design
  • Scale with properties of material elements
  • Important material attributes:
    • Thermal conductivity
    • Resistivity at operational fields
    • Heat capacity
• This will be covered in the next talk….
New baseline Transport Solenoid

• TS1/TS5: Negative axial gradient and field matching to PS/TG TS1 subject to primary target radiation

• TS2/TS4: Horizontal tilt to compensate for horizontal drift

• TS3: → TS3U, TS3D. Wider coils to compensate for gap

• Two cryostats: TSU, TSD

• New coil fabrication proposed

G. Ambrosio
TS Leader

RESMM'12 Mu2e Soleniods

Feb. 13, 2012
Coil Fabrication

- Fabrication unit consists of two coils with outer support aluminum structure
- Forged aluminum ring, machined to final shape
  - Placement of coil in transport, including bends and tilts are built into outer shell assembly
TS field quality

- Negative Gradient in all straight sections
- Smooth transitions between magnet elements
- Design focus: sensitivity to conductor placement on meeting specs.
**DS Baseline**

- **Gradient section**: 2 layer coils
  - Gradient accomplished by use of spacers
- **Spectrometer**: 3 Single Layer Coils ➔ shorter coils, greatly reduced conductor volume
- Relaxed calorimeter field requirements ➔ shorten spectrometer
- No significant materials issues with respect to radiation damage

R. Ostojic  
DS Leader
Cryogenic Distribution Scope

T. Peterson
Production solenoid thermal siphon cooling scheme

- Bottom fill line for cool-down, filling, and warm-up
- Liquid supply valves shielded from ionizing radiation
- Liquid level sensor (LL)
- Liquid supply column (not thermally anchored to magnet)
- Liquid helium
- Heater in liquid space
- Helium vapor
- Heat transfer tube around magnet
- Helium return (4.4 K vapor, not thermally anchored to transmission line)
- Thermal shield return (90K helium)
- Helium trace cooling for transmission line and supply to magnet

RESMM'12 Mu2e Soleniods
Thermal Siphon vs. Forced Flow

- Present baseline
  - Thermal Siphon for PS
  - Forced flow for TS and DS
- Advantages to Thermal Siphon
  - Maintain lowest temperature at magnet
  - Simple, passive ➔ cost effective for both design, fabrication and operation
- Advantage to Forced Flow
  - Can tie together circuits that are not well thermally coupled; less sensitive to geometric constraints (might be better for TS)
  - Less passive ➔ more control
Refrigeration loads at 4.5 K

- For cooling entirely with thermal siphons
  - Total heat load at 4.5 K (which equals the refrigeration load) is 230 W
  - Total 4.5 K helium flow rate is 12 grams/sec

- For cooling PS with thermal siphon and others with forced flow
  - Total refrigeration load (which is circulating pump heat plus the transfer and magnet heat loads) = 350 W
  - Peak helium temperature (assuming 50 grams/sec circulating flow and a 4.50 K inlet temperature) = 4.68 K.
Cool-down and Warm-up

- **First look – Production Solenoid.** Treat as simply 11.8 metric tons of aluminum for thermal energy estimate
  - Start at 300 K and cool to 80 K by means of the same heat exchanger system used for thermal shield cooling
  - Then cool to 5 K by means of one satellite refrigerator running in liquefier mode (getting warm gas back)

- **Result**
  - Time from 300 K to 80 K is about 18 hours
  - Time from 80 K to 5 K is about 26 hours

- **Conclusion**
  - Assuming no constraints due to thermal stresses (no delta-T constraints) for the 80 K portion of the cool-down, one could cool the 11.8 ton PS solenoid in about 2 days.
  - This is just a rough estimate, but it seems reasonable considering that we cooled multi-ton SSC and LHC cold iron magnets at MTF in a day.

- **In reality, we may have some constraints so as not to thermally stress the magnet, resulting in a time of more like 4 – 7 days.**

- **Warm up time back to ~273K is comparable**
Conclusion

- Present design meets mu2e experiment requirements
- Radiation studies (presented in related talks) show that magnet temperature will not exceed 5K.
- Warm up to repair radiation damage: >1 between thermal cycles
  - Time for warm up/cool down 1-2 weeks
  - Consistent with reasonable expectations for accelerator operations
- At 300 kGy/year,
  - Damage to epoxy and superconductor ➔ > 20 year lifetime
Heat and flow estimates

<table>
<thead>
<tr>
<th>Nominal temperature Level</th>
<th>4.5K</th>
<th>80K</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5 K full power magnet heat (W)</td>
<td>64.9</td>
<td>130.7</td>
</tr>
<tr>
<td>4.5 K feedbox and link heat (W)</td>
<td>14.0</td>
<td>140.0</td>
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<tr>
<td>Thermal siphon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total heat load (W)</td>
<td>78.90</td>
<td>270.7</td>
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<tr>
<td>Total helium flow (g/sec)</td>
<td>4.20</td>
<td></td>
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<tr>
<td>2.3 bar to 2.0 bar forced flow</td>
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<tr>
<td>Helium inlet temperature (K)</td>
<td>4.50</td>
<td>4.50</td>
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<tr>
<td>Total heat added (W)</td>
<td>58.00</td>
<td>50.00</td>
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<tr>
<td>Selected flow rate (g/s)</td>
<td>56.00</td>
<td>50.00</td>
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<tr>
<td>Exit temperature</td>
<td>4.68</td>
<td>50.00</td>
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<tr>
<td>Circulating pump real work (W)</td>
<td>25.00</td>
<td>25.00</td>
</tr>
<tr>
<td>Circ pump system static heat (W)</td>
<td>15.00</td>
<td>25.00</td>
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<tr>
<td>Total refrigerator cooling load (W)</td>
<td>98.00</td>
<td>96.00</td>
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<tr>
<th>Nominal temperature Level</th>
<th>4.5K</th>
<th>80K</th>
</tr>
</thead>
<tbody>
<tr>
<td>80 K magnet heat (W)</td>
<td>130.7</td>
<td>252.0</td>
</tr>
<tr>
<td>80 K feedbox and link heat (W)</td>
<td>140.0</td>
<td>140.0</td>
</tr>
<tr>
<td>Total 80 K heat (W)</td>
<td>270.7</td>
<td>392.0</td>
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<tr>
<td>N2 usage for shield (liquid liters per day)</td>
<td>149.93</td>
<td>217.11</td>
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<tr>
<td>Number of 10000 Amp HTS leads</td>
<td>2</td>
<td>0</td>
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<tr>
<td>Number of 2000 Amp vapor cooled leads</td>
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<td>0</td>
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<tr>
<td>Nitrogen lead flow per magnet (g/s)</td>
<td>2.20</td>
<td>2.20</td>
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<tr>
<td>N2 usage for leads (liquid liters per day)</td>
<td>237.60</td>
<td>237.60</td>
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<tr>
<td>Liquid helium lead flow per magnet (g/s)</td>
<td>0.16</td>
<td>0.16</td>
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</tbody>
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Heat budget is < 420.0 W
Total 4.5 K heat = 349.4 W
Total heat / budget = 0.83
## Properties of Al and Cu

### Compare Aluminum and Copper properties at 5K

<table>
<thead>
<tr>
<th>Aluminum</th>
<th>Thermal conductivity</th>
<th>W/(m*K)</th>
<th>Electrical resistivity</th>
<th>nOhm*m</th>
</tr>
</thead>
<tbody>
<tr>
<td>T = 5 K</td>
<td>B = 0 T</td>
<td>1 T</td>
<td>2 T</td>
<td>3 T</td>
</tr>
<tr>
<td>RRR = 100</td>
<td>487</td>
<td>419</td>
<td>415</td>
<td>412</td>
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<tr>
<td>RRR = 200</td>
<td>959</td>
<td>727</td>
<td>713</td>
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<td>RRR = 400</td>
<td>1907</td>
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<td>1132</td>
<td>1117</td>
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<td>RRR = 600</td>
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<td>1468</td>
<td>1412</td>
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<table>
<thead>
<tr>
<th>Copper</th>
<th>Thermal conductivity</th>
<th>W/(m*K)</th>
<th>Electrical resistivity</th>
<th>nOhm*m</th>
</tr>
</thead>
<tbody>
<tr>
<td>T = 5 K</td>
<td>B = 0 T</td>
<td>1 T</td>
<td>2 T</td>
<td>3 T</td>
</tr>
<tr>
<td>RRR = 50</td>
<td>375</td>
<td>326</td>
<td>293</td>
<td>267</td>
</tr>
<tr>
<td>RRR = 100</td>
<td>749</td>
<td>576</td>
<td>481</td>
<td>415</td>
</tr>
<tr>
<td>RRR = 150</td>
<td>1122</td>
<td>775</td>
<td>611</td>
<td>509</td>
</tr>
<tr>
<td>RRR = 200</td>
<td>1494</td>
<td>936</td>
<td>707</td>
<td>574</td>
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Data from MATPRO:

L. Rossi, M. Sorbi, "MATPRO: a Computer Library of Material Property at Cryogenic Temperature"

INFN/TC-02/02 and CARE-Note-2005-018-HHH