BNL Pulsed Magnet
Magnet System Cooldown and Structural Analyses
2002

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The Collaboration is Useful with Other PSFC Projects:

FIRE – Preconceptual Design and Snowmass Review. Inertially Cooled Be Copper, LN2 Cooling Between Shots, with a Helium Purge to Limit Activation

IGNITOR – Snowmass Review. Inertially Cooled Copper, 30K He Gas Cooled Between Shots

BNL Pulsed Magnet – Inertially Cooled, 30K He Gas Cooled Between Shots
<table>
<thead>
<tr>
<th>Case #</th>
<th>Peak Field</th>
<th>Coolant</th>
<th>T after pulse</th>
<th>T coolant</th>
<th>Start Bulk Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5T</td>
<td>Helium Gas</td>
<td>90K</td>
<td>66K</td>
<td>84K</td>
</tr>
<tr>
<td>1a</td>
<td>5T</td>
<td>LN2</td>
<td>90K</td>
<td>66K</td>
<td>84K</td>
</tr>
<tr>
<td>2</td>
<td>10T</td>
<td>Helium Gas</td>
<td>96K</td>
<td>66K</td>
<td>74K</td>
</tr>
<tr>
<td>2a</td>
<td>10T</td>
<td>LN2</td>
<td>96K</td>
<td>66K</td>
<td>74K</td>
</tr>
<tr>
<td>3</td>
<td>15T</td>
<td>Helium Gas</td>
<td>78K</td>
<td>22K</td>
<td>30K</td>
</tr>
</tbody>
</table>

Proposed Operational Scenarios

The coil and cryostat are designed for two cooling modes


Coil Stress Analysis

The three segment coil has three operational modes, two of which are structurally significant.

The full performance configuration is limiting in terms of hoop stress and equivalent stress. It also has some radial stresses that will have to be mitigated with parting planes at the segment boundaries, or within the winding.

In the initial operating mode the outer coil segment is not energized. This induces some differential Lorentz forces and differential temperatures, that cause shear stresses between segments.

For Fusion magnets the inner skin of the solenoid is allowed to reach the yield - Treating this stress as a bending stress with a 1.5*Sm allowable with Sm based on 2/3 Yield.

Interpolated values:, Work hardened copper-, OFHC c10100 60% red

<table>
<thead>
<tr>
<th>temp deg k</th>
<th>77</th>
<th>90</th>
<th>100</th>
<th>125</th>
<th>150</th>
<th>200</th>
<th>250</th>
<th>275</th>
<th>292</th>
</tr>
</thead>
<tbody>
<tr>
<td>yield</td>
<td>374</td>
<td>369</td>
<td>365</td>
<td>356</td>
<td>347</td>
<td>328</td>
<td>317</td>
<td>312</td>
<td>308</td>
</tr>
<tr>
<td>ultimate</td>
<td>476</td>
<td>466</td>
<td>458</td>
<td>439</td>
<td>420</td>
<td>383</td>
<td>365</td>
<td>356</td>
<td>350</td>
</tr>
</tbody>
</table>

If the highly cold-worked copper is chosen for the winding, the conductor allowable near the inside radius of the coil would be 365MPa. The max stress in the three segment coil is 166 MPa. With this stress level, it is expected that half hard copper could be used, simplifying the winding process.
Radial Tension Stress, All Coils Fully Energized.

There is about an MPa of tension at the boundary between the first and second module. To avoid damage to the channel ligaments, a parting plane will be incorporated in the channel detail. This needs to occur in the ligament to retain thermal connection with the coolant in the channel.
Operating Mode 2, 10T

Hoop Stress With only the Inner Two Segments Energized.

Peak Hoop Stress is Only 29.4 MPa
Operating Mode 2, 10T

Smeared radial-axial shear stress with the inner two segments energized.

*Channel Ligaments would be too weak to support this – Slip Planes are Used.*

This is a peak at the interface between the second and third modules. It must be carried across the thin ligaments between the channels, or relieved via a slip plane.
Von Mises Stress
Operating Mode 2, 10T

Outer Segment Not Yet Installed

The max stress for this case is 85.3 MPa, which is a bit more than with the outer segment in place, but less than for the fully energized three segment coil.
Steady State Heat Gain.

The specification requires that the cryostat heat gain should be <200 W at 22 K Excluding the leads.

A concept which has a 234 watt heat gain has been developed that employs vacuum at the outer and inner shells and foam at the ends around fluid and electrical penetrations.

Piping penetrations are moved to the end plates,

Vacuum shells are used on the ID and OD.

The magnet can be supported off the inner cryostat shell,

The system gravity supports can reach through the foam or vacuum boundary.
<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Thermal conductivity W/m/degK</th>
<th>Area m^2</th>
<th>Length m</th>
<th>delta T</th>
<th>Heat rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner shell vacuum with mli</td>
<td>Vacuum/MLI</td>
<td>*</td>
<td>.75398224</td>
<td>*</td>
<td>292-22</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Inner shell vacuum extensions</td>
<td>.0005m thick sst</td>
<td>16.27</td>
<td>6.283e-4</td>
<td>.2</td>
<td>292-22</td>
<td>13.8</td>
</tr>
<tr>
<td>Outer shell (foam option)</td>
<td>CTD Cryo foam insulation</td>
<td>.03</td>
<td>3.77</td>
<td>.1</td>
<td>292-22</td>
<td>303</td>
</tr>
<tr>
<td>Outer shell foam in series with vacuum+mli</td>
<td>Cryo foam insulation</td>
<td>.03</td>
<td>.1</td>
<td>292-220</td>
<td>49**</td>
<td></td>
</tr>
<tr>
<td>Outer shell Vacuum Extension</td>
<td>sst</td>
<td>16.27</td>
<td>3.14159e-3</td>
<td>.2</td>
<td>292-220</td>
<td>18.4</td>
</tr>
<tr>
<td>End Cover foam (2 ends)</td>
<td>CTD Cryo foam insulation</td>
<td>.03</td>
<td>1.508</td>
<td>.1</td>
<td>292-22</td>
<td>125.7</td>
</tr>
<tr>
<td>Leads</td>
<td>Copper (80 to 292K)</td>
<td>396.5</td>
<td>5.4569e-4</td>
<td>.4</td>
<td>292-22</td>
<td>150.3 (3 pairs)</td>
</tr>
<tr>
<td>Lead bellows</td>
<td>sst</td>
<td>16.27</td>
<td>4.7124e-4</td>
<td>.4</td>
<td>292-22</td>
<td>5.33</td>
</tr>
<tr>
<td>Coil Support pads</td>
<td>g-10</td>
<td>.15</td>
<td>.0016</td>
<td>.4</td>
<td>292-22</td>
<td>1.33</td>
</tr>
<tr>
<td>Total bold red</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>233.6</td>
</tr>
</tbody>
</table>

* Radiation heat gain at bore= 37.281177 watts (no MLI) Stefan Boltzman Constant = 5.668e-8 watts/m^2/degK^4 qrad=area*emis*stefboltz*(trt^4-tcold^4), emis=.12 polished sst From ref [8]: page 152. the heat flux should be divided by the number of MLI layers, conservatively it was divided by 2 – many more layers are practical in this space.

** Radiation and Foam conduction in series. The intermediate temperature (128.5K) of the vacuum shell was found by trial and error assuming a temperature and matching the heat flux for radiation and conduction.
Cryostat/Helium Can Stress

Normal operating Pressure is 15 atm
Flat head thickness is 2 cm.
ID and OD shell thickness is 5mm
Material is 316 or 304 SST

Structure (292 K) Maximum

Allowable Stresses, \( Sm = \) lesser
of 1/3 ultimate or 2/3 yield, and
bending allowable=1.5*\( Sm \)

<table>
<thead>
<tr>
<th>Material</th>
<th>Sm</th>
<th>1.5Sm</th>
</tr>
</thead>
<tbody>
<tr>
<td>316 LN SST</td>
<td>183MPa (26.6 ksi)</td>
<td>275MPa (40 ksi)</td>
</tr>
</tbody>
</table>

Local (corner) Stresses are high - 700 MPa. Stiffeners or thicker closure heads may be needed to protect the seal welds
Cryostat Eddy Current Analysis

Vector Potential Solution, 7 sec Ramp-Up, (Envelopes ramp-up and ramp down)

Field Loss Due to Eddy’s is of the Order of a few milliTesla

Electromagnetic Model with Air
Cryostat Eddy Current Analysis

Structural Model
(Sub-Set of E-M Model), Centerline Axis is Vertical

Structural Response to Eddy Currents. External Vacuum Jacket is only .5mm thick and Will have to be made thicker. The internal Vacuum Jacket is loaded in hoop and axial Compression, and will have to be checked for buckling.
Break-Outs, Leads, and Penetrations

- The choice of modular design favors duplicating the break-out and lead design for all three segments, even though two of the segments are connected in series.
- The break-out concept structurally connects the inner layer break-out with the outer layer break-out.
- The leads are closely coupled to cancel the net loads on the lead conductors.
- Loads cancel, but there is a small torque.
- To achieve the interconnection of the leads, they cross the face of the winding.
- Bending stresses for combined thermal and Lorentz force loading of 200 MPa can be expected for the cantilevered leads. The analysis model has minimal fiberglass wrap and more extensive interconnection of the leads, and support at the winding pack end will be needed.

The electromagnetic model. The fields and forces in the leads are calculated with 7200 amps in the leads, and the appropriate solenoid end field solution is

Fields at the break-outs, 14.5T Full field operation.

Lorentz Forces at the break-outs. 14.5T Full field operation.
Break-Outs are interconnected to cancel loads, and equilibrate hoop stress.

Winding ends well supported, terminal ends un-supported and not interconnected. Lorentz Forces Only

Winding ends well supported, terminal ends interconnected at the end of the lead pair. Lorentz Forces Only
Lead Thermal Stresses

- A bellows is used because of differential thermal motions, and flexure of the end cap under pressure loading.
- This also has the effect of lengthening the cold length of the lead, reducing the heat gain.
- A conduction solution is used to obtain the temperature gradient for the structural solution.

Thermal+Lorentz stress. Winding ends well supported at extreme of the radius, where the thermal constraint was applied. The peak stress occurs where the relatively short interconnection ends. This will be lengthened, and will reduce the peak stress.

Joint thermal stress. Winding ends well supported at extreme of the radius, where the thermal constraint was applied.
2.1.3 Convective Heat Transfer

It is important to estimate how much heat the superfluid gas (T > 77 K) could absorb before exiting the cooling channel. The convective heat transfer coefficient, \( h \), could be obtained from:

\[
\frac{h}{D_e} = \frac{0.023 \text{Re}^{0.8} \text{Pr}^{0.4} 
}{D_e}.
\]

(14)

This coefficient is about \( 21 \times 10^{-3} \text{ W/cm}^2 \text{ K} \) at a vapor temperature of 200 K, vapor velocity of 40 m/s, and hydraulic diameter of 2 cm. It drops to \( 17 \times 10^{-3} \text{ W/cm}^2 \text{ K} \) at a vapor temperature of 100 K, keeping the mass flow rate constant. It is interesting to note that the heat transfer coefficient for film boiling at 200 K from Fig. 4 is about \( 12 \times 10^{-3} \text{ W/cm}^2 \text{ K} \), which partially justifies the third assumption in Sect. 2.1.

excerpt from: ORNL/FEDC-85-10 Dist Category UC20 c, dated October 1986
66K inlet temperature, Time Step = .0001 sec – 100 K after Pulse Temp. The bulk temp is computed at a mid -axial slice. Time to 85K is about 600 sec or 10 min. Exclusive of time to flatten temp distribution.

Present Operational Scenarios:

<table>
<thead>
<tr>
<th>Case #</th>
<th>Peak Field</th>
<th>T after pulse</th>
<th>T coolant</th>
<th>Start Bulk Temp</th>
<th>Guestimated Time</th>
<th>Guestimated Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5T</td>
<td>90K</td>
<td>66K</td>
<td>84K</td>
<td>~200 sec</td>
<td>3.3 min</td>
</tr>
<tr>
<td>2</td>
<td>10T</td>
<td>96K</td>
<td>66K</td>
<td>74K</td>
<td>~800 sec</td>
<td>13.3 min</td>
</tr>
<tr>
<td>3</td>
<td>14.5T</td>
<td>78K</td>
<td>22K</td>
<td>30K</td>
<td>~1500 sec</td>
<td>25.0 min</td>
</tr>
</tbody>
</table>
Analyses to date: Time to target bulk temp. ½ inch Copper Conductor, 100K.

<table>
<thead>
<tr>
<th>Description</th>
<th>T after pulse</th>
<th>T coolant</th>
<th>Cond Layers</th>
<th>Time to 85K sec</th>
<th>Time to 30K sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent 5 Kapton .001in wrap</td>
<td>100K</td>
<td>66K</td>
<td>6 layers</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>Equivalent 5 Kapton .001in wrap</td>
<td>100K</td>
<td>66K</td>
<td>8 layers</td>
<td>&gt;850</td>
<td></td>
</tr>
<tr>
<td>Equivalent 3 Kapton .001in wrap</td>
<td>100K</td>
<td>66K</td>
<td>8 layers</td>
<td>450</td>
<td></td>
</tr>
<tr>
<td>Equivalent 5 Kapton .0001in wrap</td>
<td>100K</td>
<td>30K</td>
<td>6 Layers</td>
<td>2000</td>
<td></td>
</tr>
</tbody>
</table>

Bulk Temp Is Computed Mid Axial Build - It Bottoms out before the down stream end.

tout 1 and tout2 are Outlet Temperatures
Assembly and Manufacture

The Coil is layer wound
The Coil is made in three segments. Phased manufacture is allowed
Three separate mandrels are planned.
Mandrels maintain a precise bore geometry
Ribs are applied to outer surface of the wound and impregnated coil
Ribs are machined to match the ID of the next coil segment
Coils are slipped on to one another. – with a temperature difference if needed
Conductor Dimensions
with 2 millimeter channel tolerance
radial dim 1.1669799e-2 m .45944 in
Axial dim 1.3028533e-2 m .5129333 in
packing fraction= .95025227

Kapton is the limiting element in the thermal conduction through the coil.
Kapton was expected to be wound around the conductor. This produced the equivalent of 5 mils of Kapton between layers.
To improve conduction, Kapton is used only between the layers. Turn to turn voltage is lower than layer to layer. The turn to turn voltage is less than the rule of thumb for He breakdown voltage (1 volt/mil at 1 atmosphere) for the insulation thickness proposed.
The layer to layer voltage exceeds this however, and would need the Kapton if there was an imperfection in the epoxy/glass insulation. Half laps of kapton and fiberglass, similar to the CS model coil will retain some structural integrity.
Once a layer of conductor is wound, a layer of Kapton/glass would be wound on the completed layer of conductor. This produces the thermal conduction equivalent of 3 mils of Kapton rather than 5 if the conductor is wrapped individually. Every 8th layer channel strips are layed on.

Layer Insulation

Cryostat Bore Tube Geometry
Building from the Magnet ID and working towards the centerline:

<table>
<thead>
<tr>
<th>Component</th>
<th>Thickness (m)</th>
<th>Radius (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The ID of the magnet winding</td>
<td>.15-.98/2= .101</td>
<td></td>
</tr>
<tr>
<td>Coolant Channel</td>
<td>.002</td>
<td>.099</td>
</tr>
<tr>
<td>Cold Cryostat Shell</td>
<td>.004762(3/16in.)</td>
<td>.094237</td>
</tr>
<tr>
<td>Vacuum Space</td>
<td>.008</td>
<td>.086237</td>
</tr>
<tr>
<td>Vacuum shell</td>
<td>.0005</td>
<td>.085737</td>
</tr>
<tr>
<td>Strip heater</td>
<td>.001</td>
<td>.084737</td>
</tr>
</tbody>
</table>

This leaves a clear bore diameter of .16947m