BNL Pulsed Magnet

Magnet System Cooldown and Structural Analyses

2002

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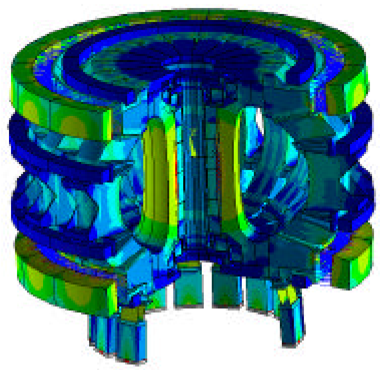
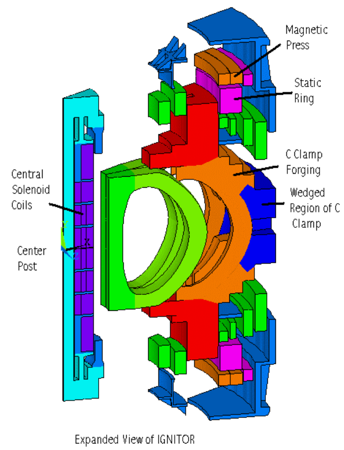
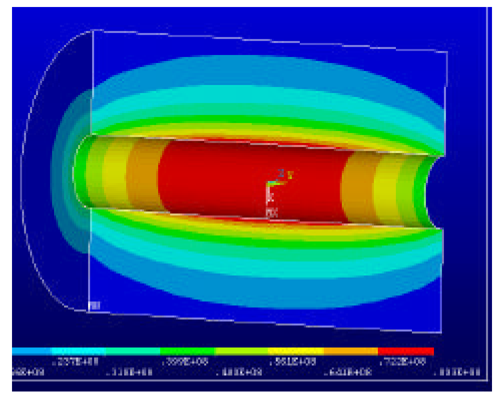
The Collaboration is Useful with Other PSFC Projects:



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

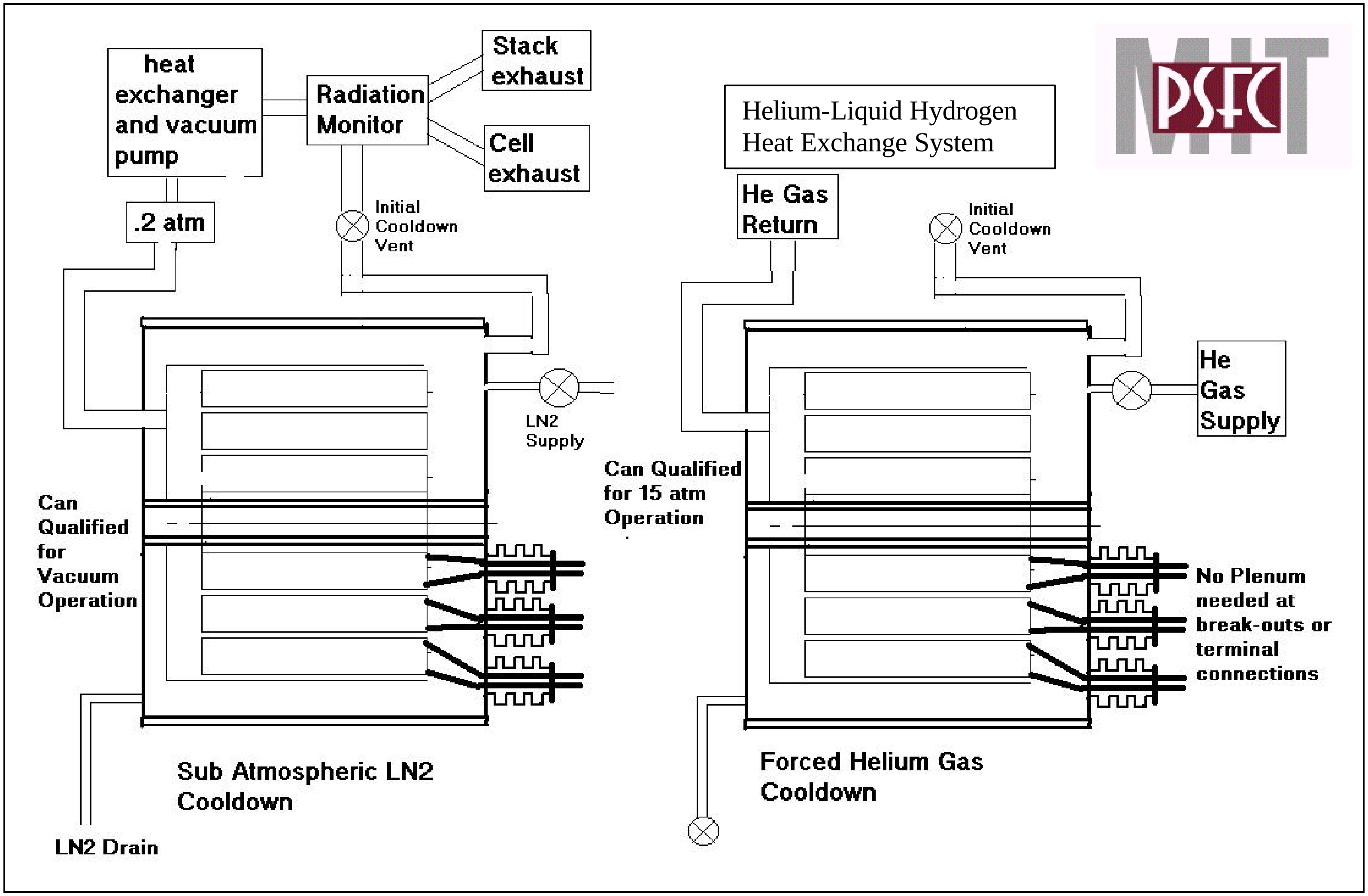


IGNITOR – Snowmass Review. - Inertially Cooled Copper , 30K He Gas Cooled Between Shots



BNL Pulsed Magnet –Inertially Cooled , 30K He Gas Cooled Between Shots

Case #	Peak Field	Coolant	T after pulse	T coolant	Start Bulk Temp
1	5T	Helium Gas	90K	66K	84K
1a	5T	LN2	90K	66K	84K
2	10T	Helium Gas	96K	66K	74K
2a	10T	LN2	96K	66K	74K
3	15T	Helium Gas	78K	22K	30K



Proposed Operational Scenarios

The coil and cryostat are designed for two cooling modes

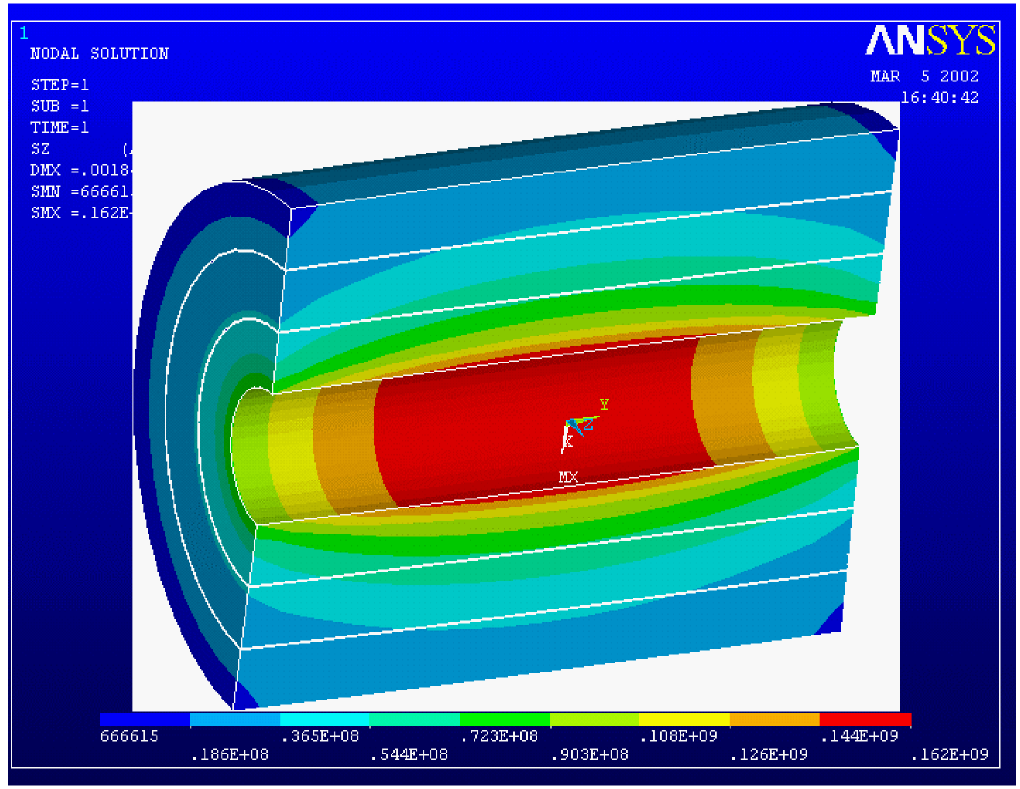
Coil Stress Analysis

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.



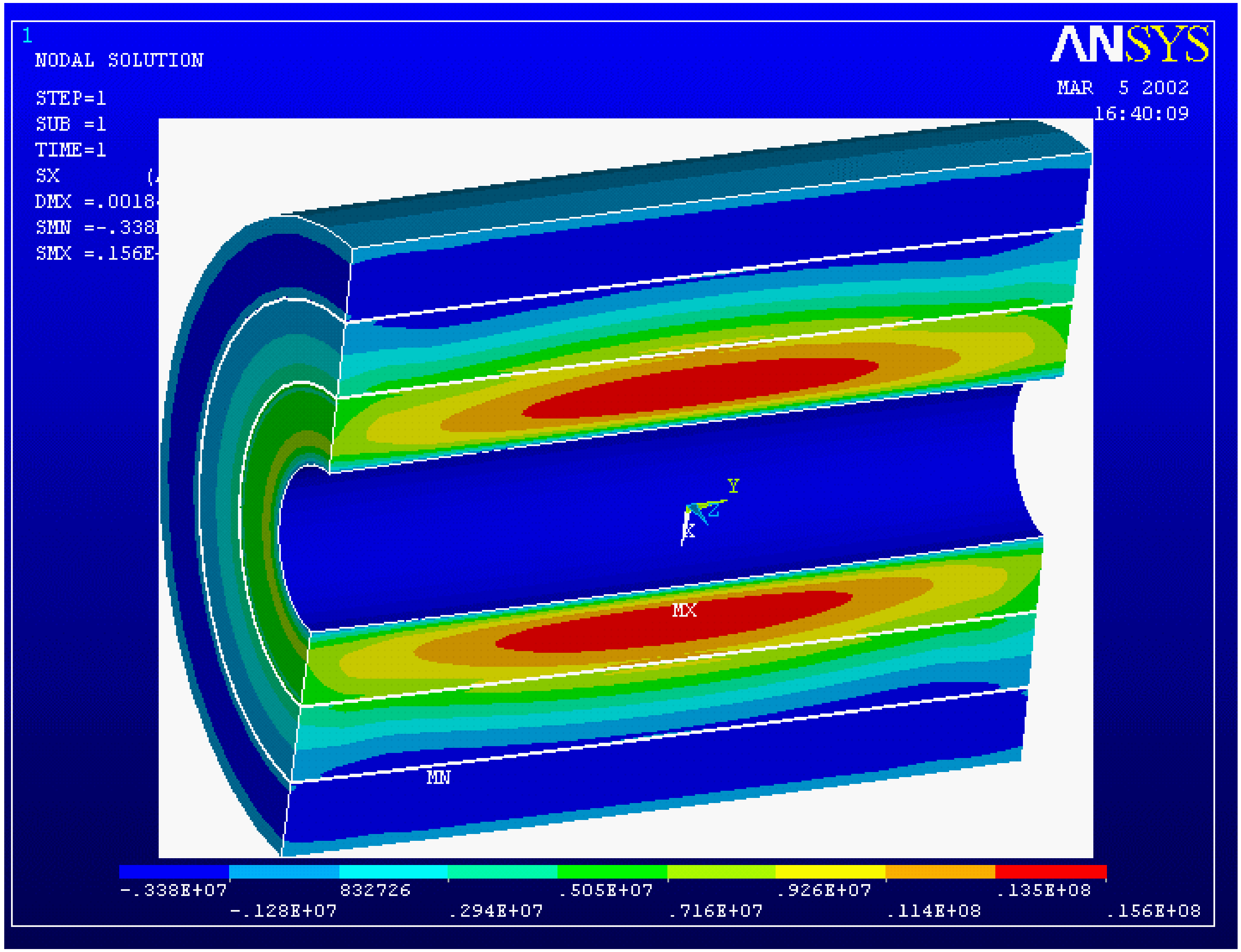
Hoop Stress, all coil segments fully energized. The Von Mises stress plot is similar with a peak of 165 MPa, Tresca is 166 MPa.

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

temp deg k	77	90	100	125	150	200	250	275	292
yield	374	369.	365.	356.	347.	328.	317.	312.	308.
ultimate	476.	466.	458.	439.	420.	383.	365.	356.	350.

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.

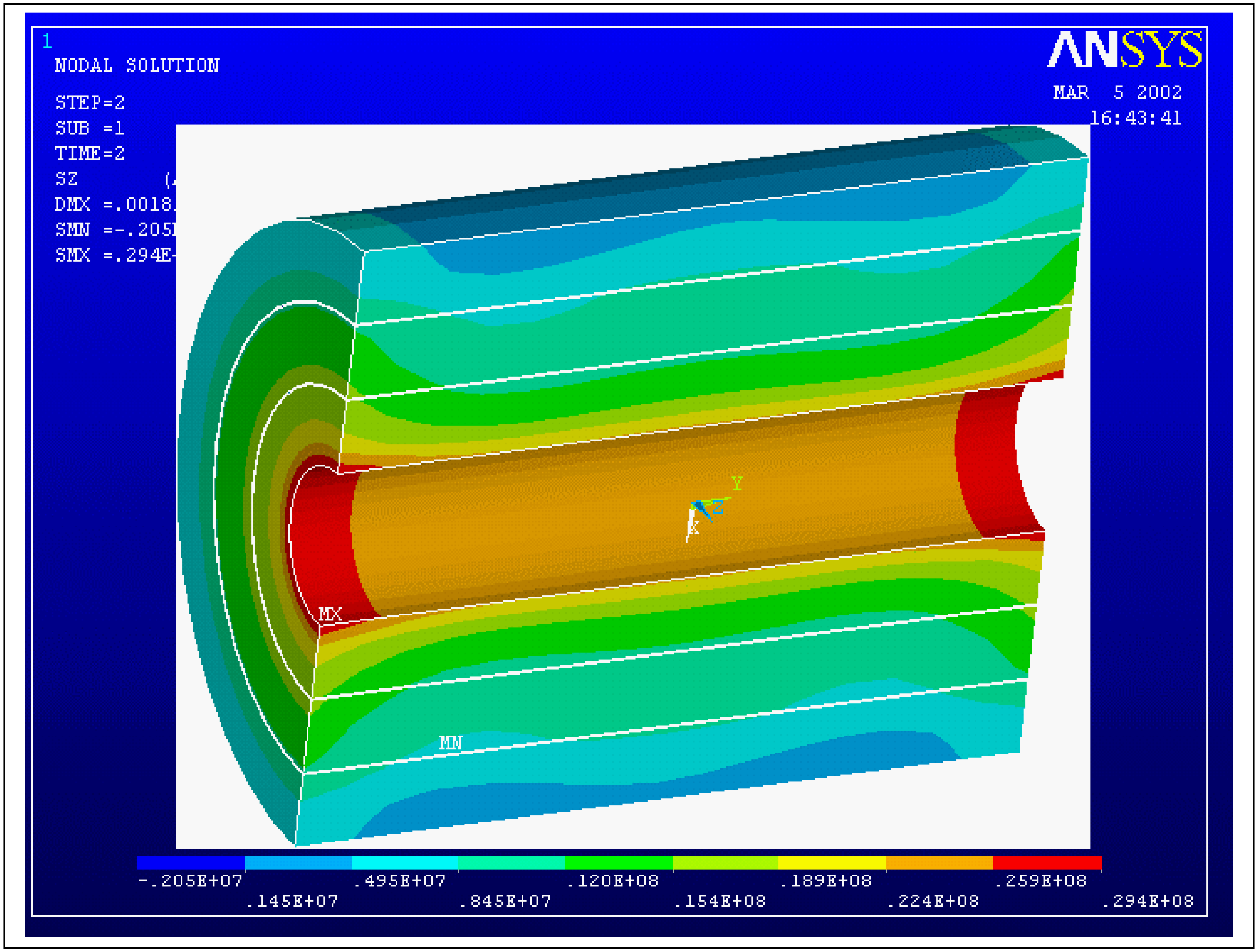


There is about an MPa of tension at the boundary between the first and second module. To avoid damage to the channel ligaments, a parting plane will be incorporated in the channel detail. This needs to occur in the ligament to retain thermal connection with the coolant in the channel.

Operating Mode 2, 10T

Hoop Stress With only the Inner Two Segments Energized.

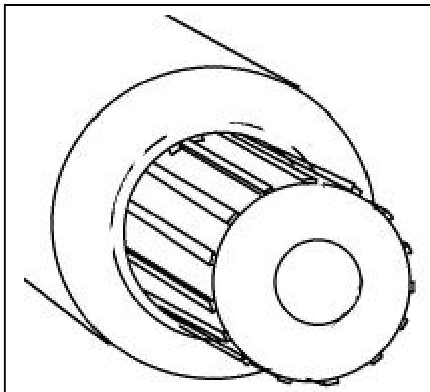
Peak Hoop Stress is Only 29.4 MPa

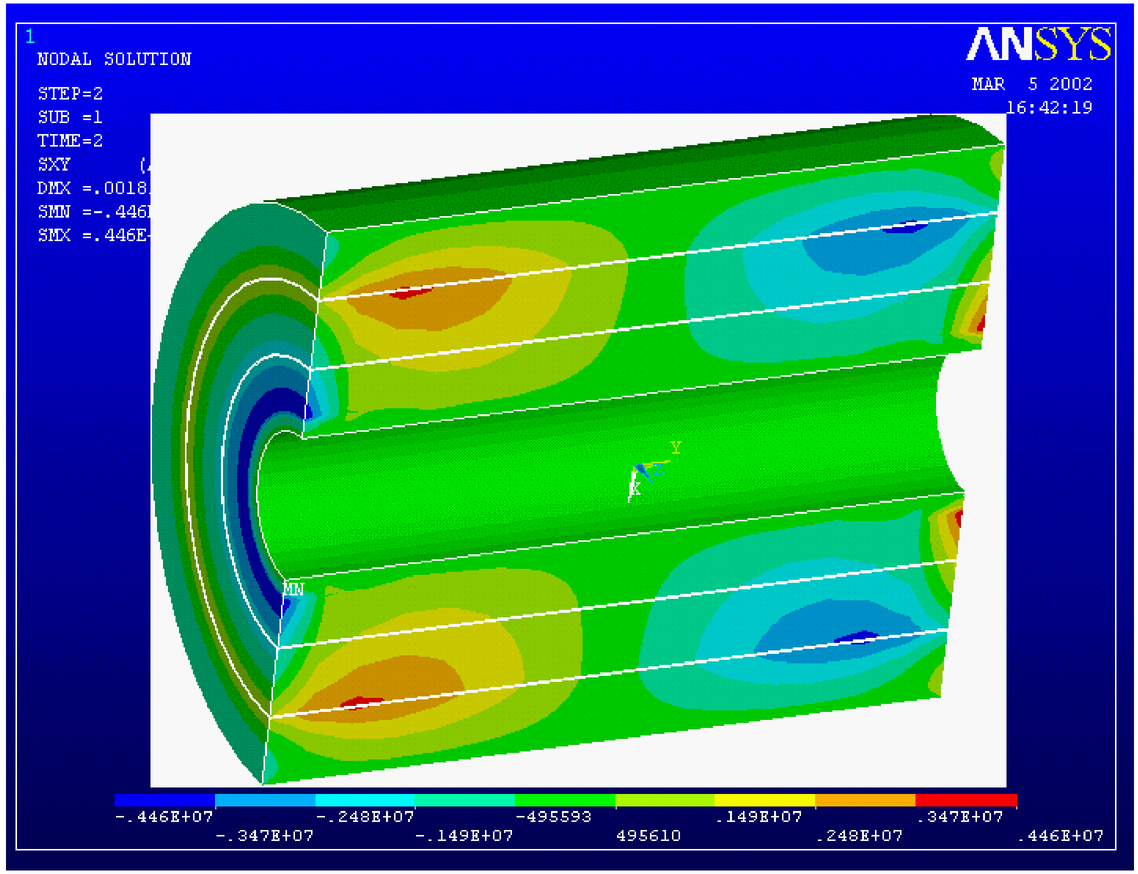


Operating Mode 2, 10T

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

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



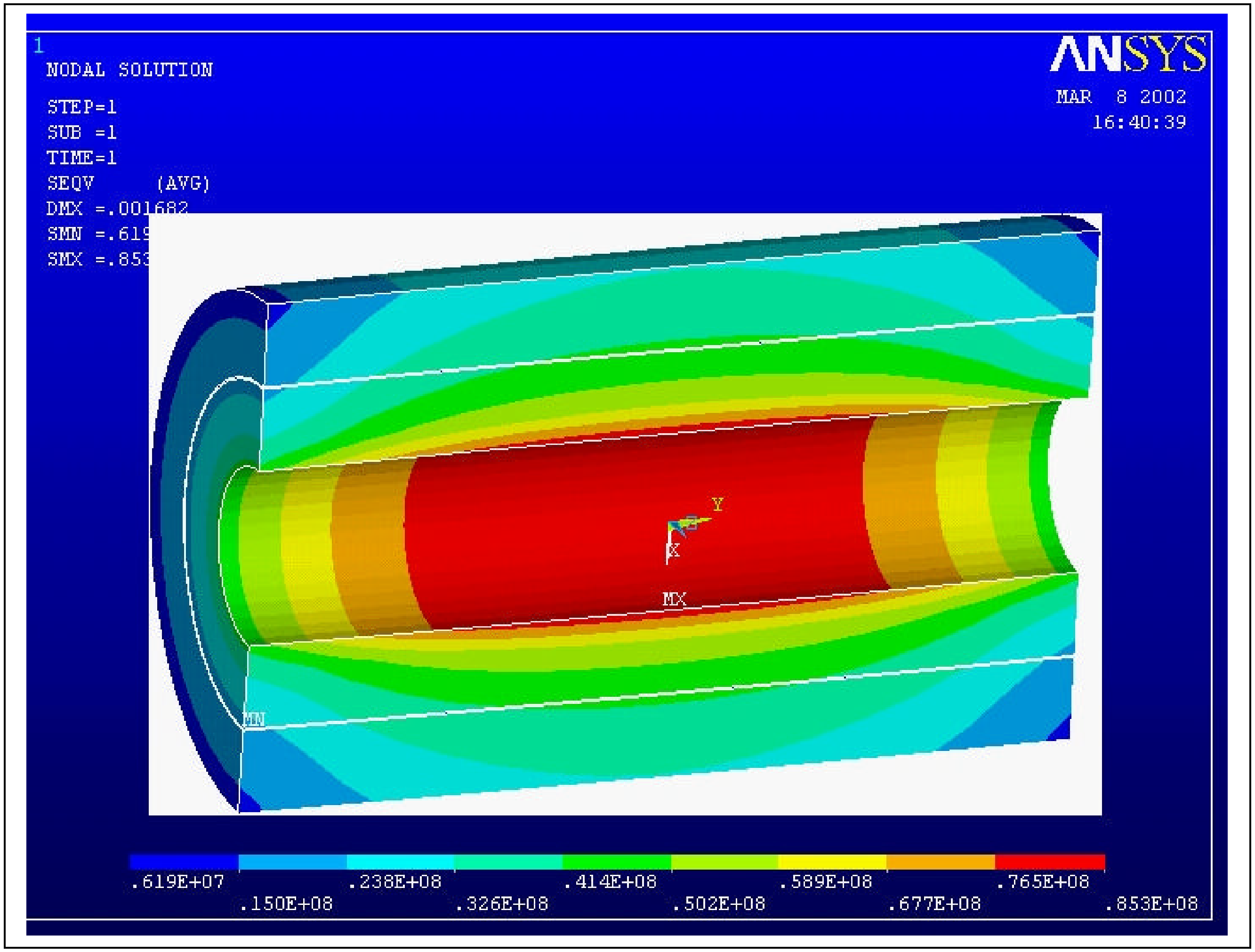


This is a peak at the interface between the second and third modules. It must be carried across the thin ligaments between the channels, or relieved via a slip plane.

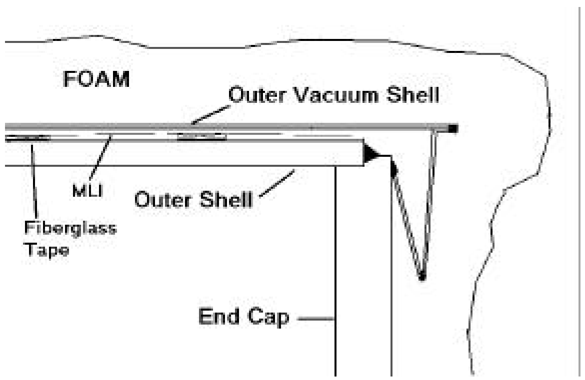
Von Mises Stress
Operating Mode 2, 10T

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.



Outer Vacuum Shell to Cover Connection

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

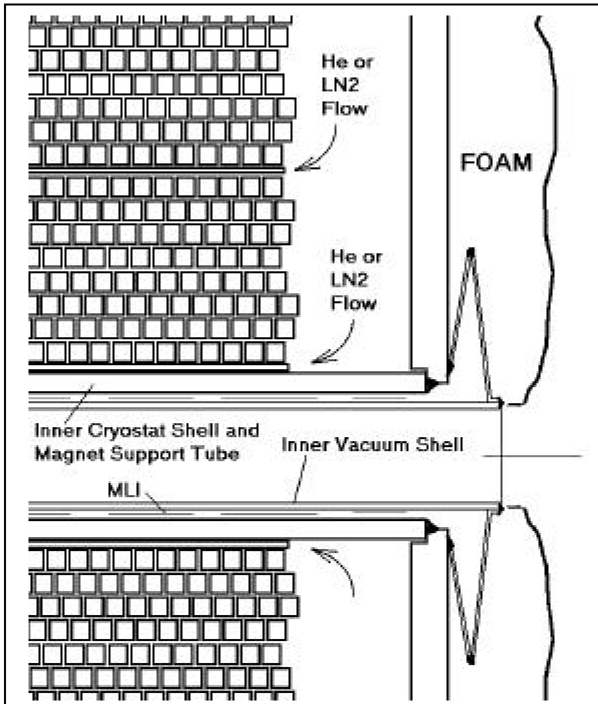
A concept which has a 234 watt heat gain has been developed that employs vacuum at the outer and inner shells and foam at the ends around fluid and electrical penetrations.

Piping penetrations are moved to the end plates,

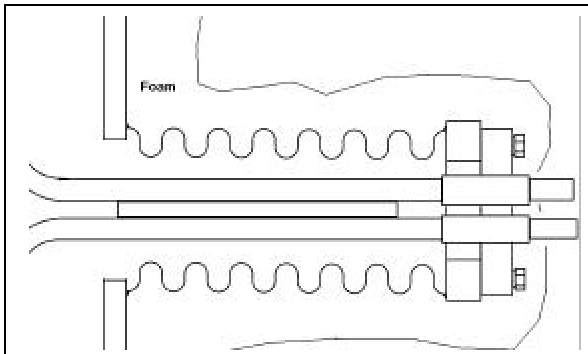
Vacuum shells are used on the ID and OD.

The magnet can be supported off the inner cryostat shell,

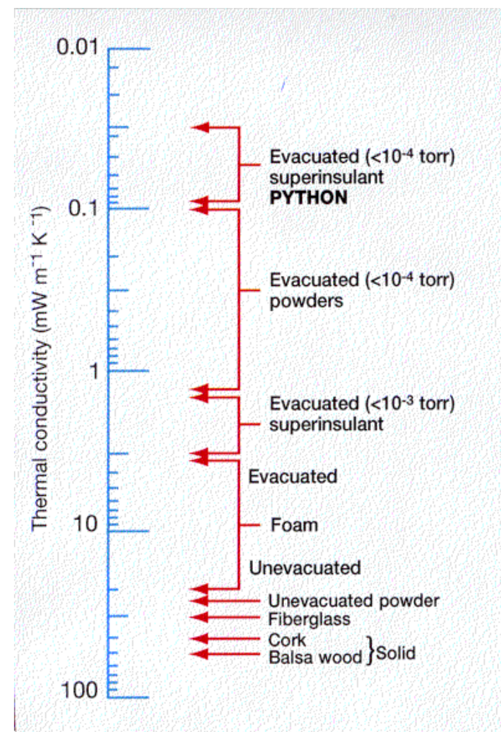
The system gravity supports can reach through the foam or vacuum boundary.



Inner Vacuum Shell to Cover Connection



Lead with bellows



Mean effective thermal conductivity of typical insulations. Boundary temperature 300K and 80K.

Heat Gain Summary

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

*** 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.**

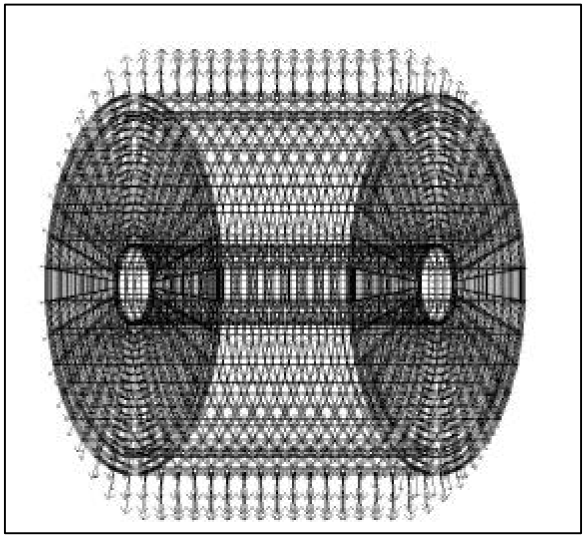
Cryostat/Helium Can Stress

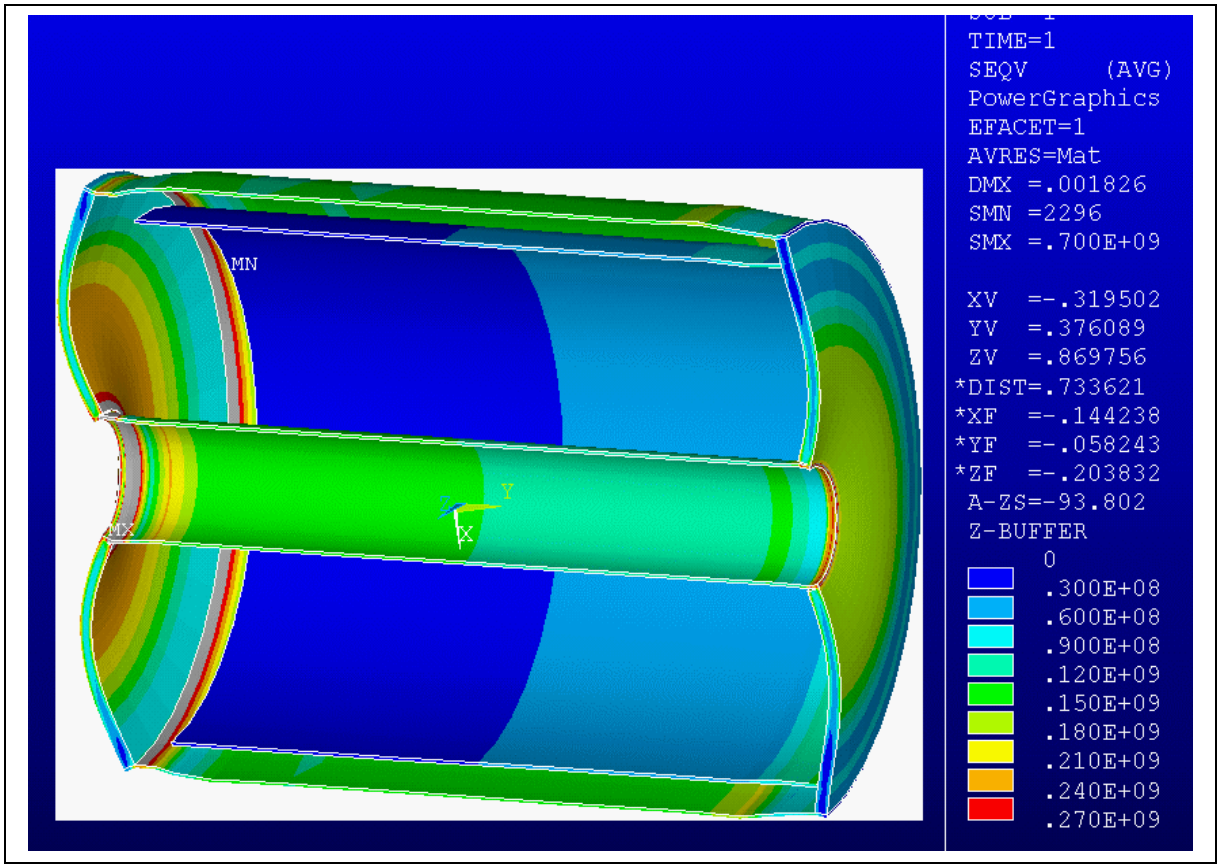
Normal operating Pressure is 15 atm
Flat head thickness is 2 cm.
ID and OD shell thickness is 5mm
Material is 316 or 304 SST

Structure (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

Material	Sm	1.5Sm
316 LN SST	183MPa (26.6 ksi)	275MPa(40 ksi)

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

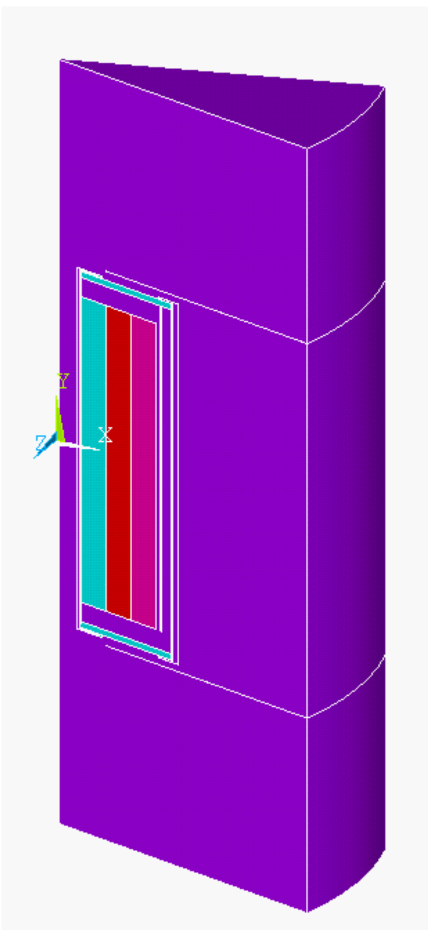




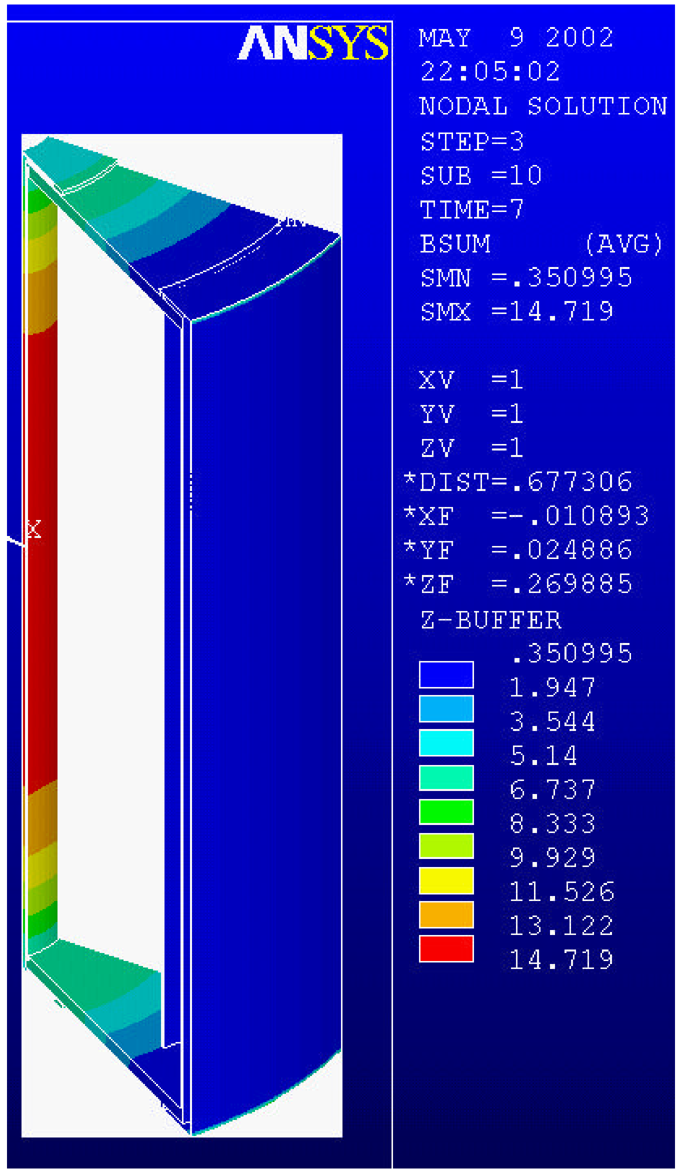
Cryostat Eddy Current Analysis

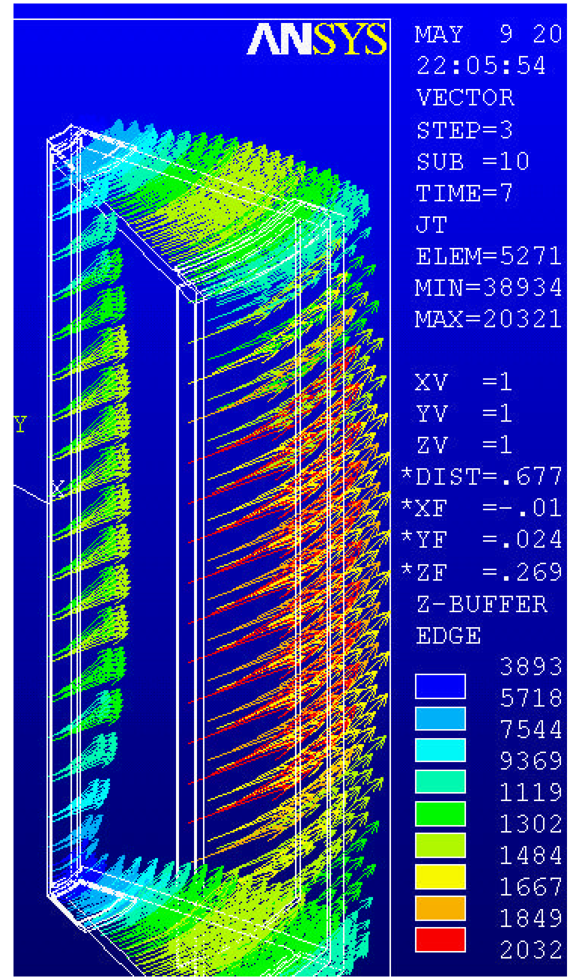
Vector Potential Solution, 7 sec Ramp-Up , (Envelopes ramp-up and ramp down)

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

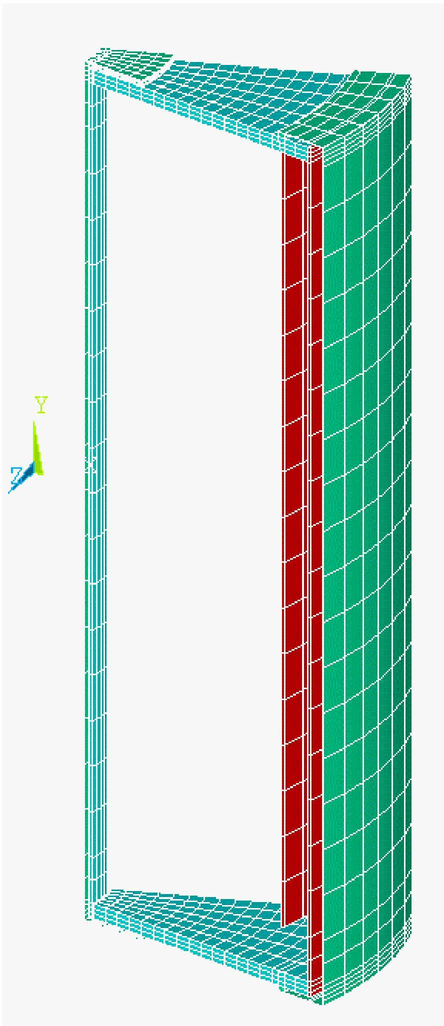


Electromagnetic Model with Air

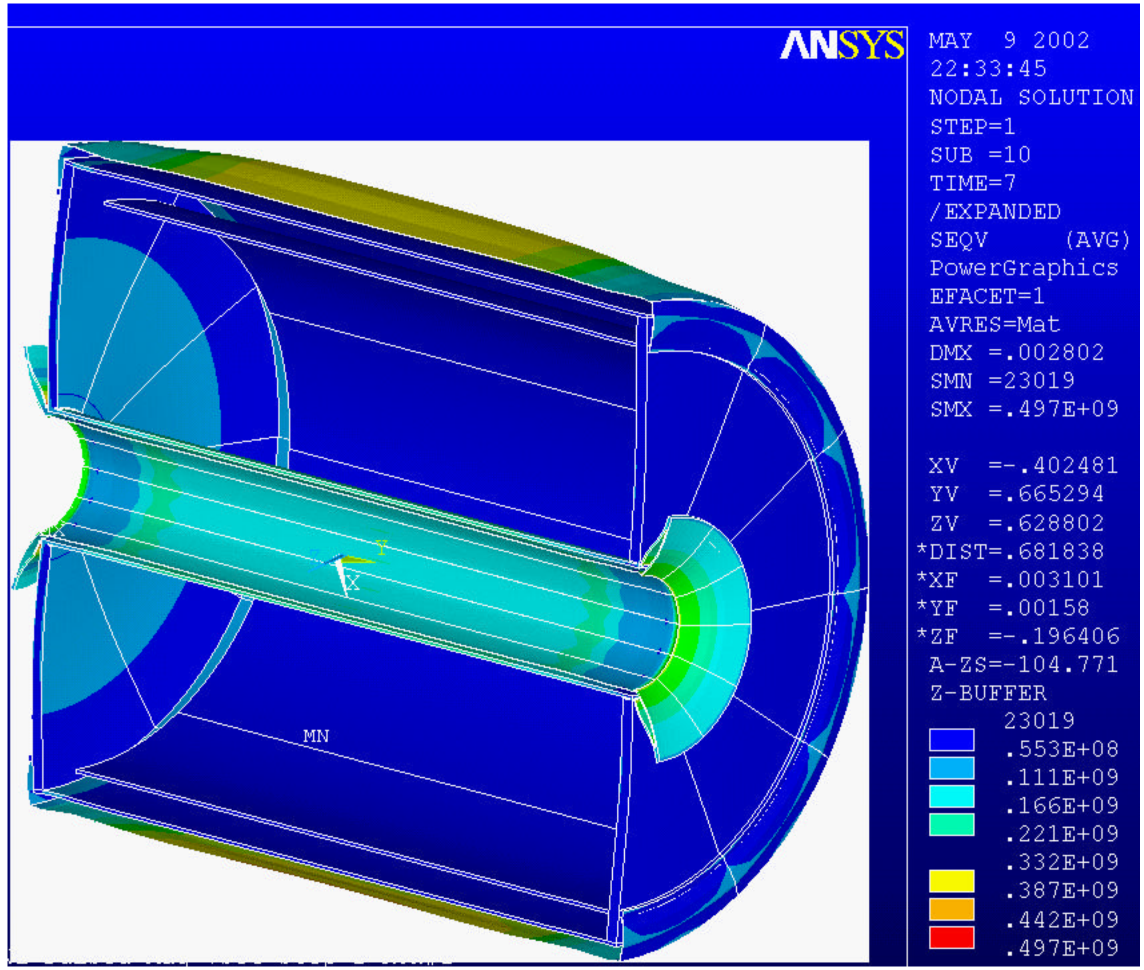




Cryostat Eddy Current Analysis



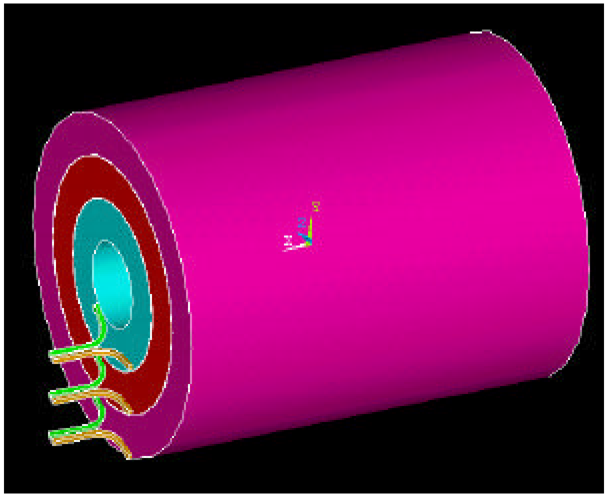
Structural Model
(Sub-Set of E-M Model), Centerline
Axis is Vertical



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

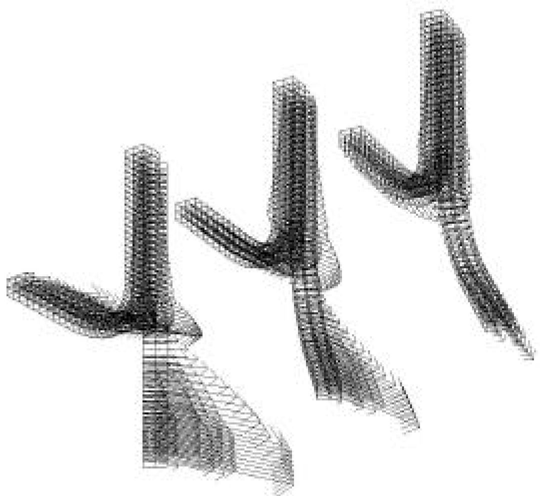
Break-Outs, Leads, and Penetrations

- 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.



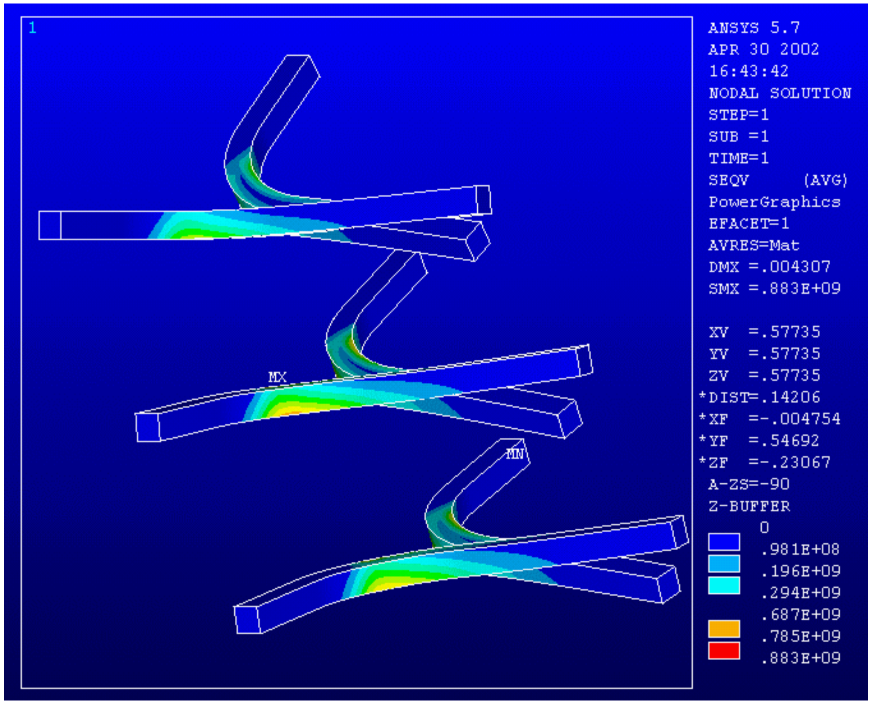
The electromagnetic model.
The fields and forces in the leads are calculated with 7200 amps in the leads, and the appropriate solenoid end field solution is

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

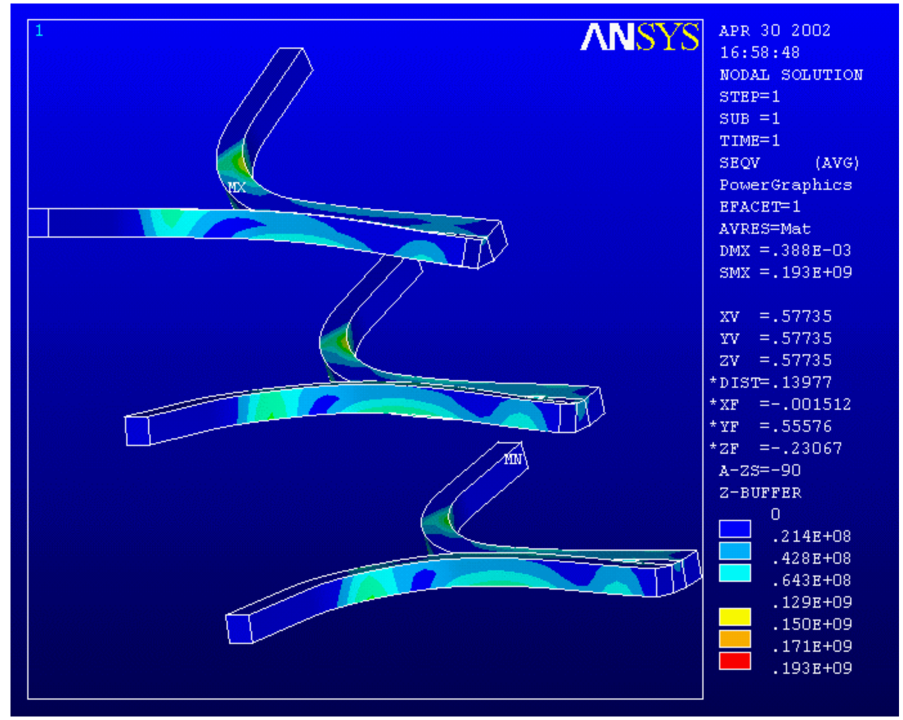


Lorentz Forces at the break-outs. 14.5T Full field operation.

Break-Outs are Interconnected to Cancel Loads, and Equilibrate Hoop Stress.



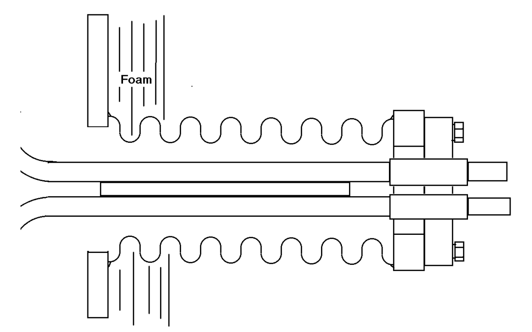
Winding ends well supported, Terminal ends Un-supported and not interconnected. Lorentz Forces Only



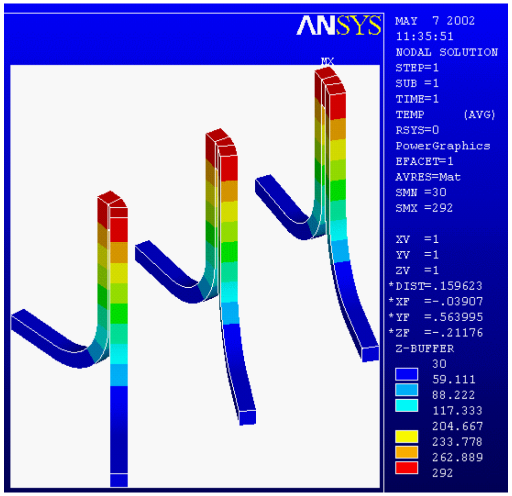
Winding ends well supported, Terminal ends interconnected at the end of the lead pair. Lorentz Forces Only

Lead Thermal Stresses

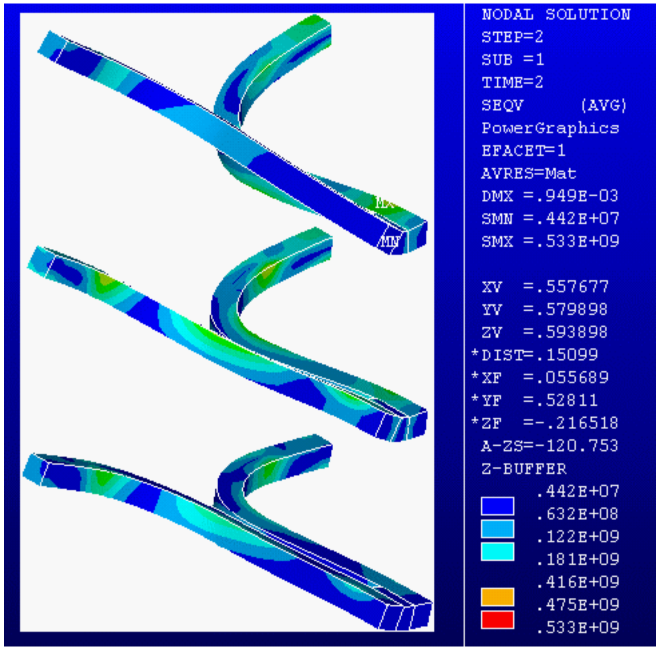
- **A bellows is used because of differential thermal motions, and flexure of the end cap under pressure loading**
- **This also has the effect of lengthening the cold length of the lead, reducing the heat gain.**
- **A conduction solution is used to obtain the temperature gradient for the structural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



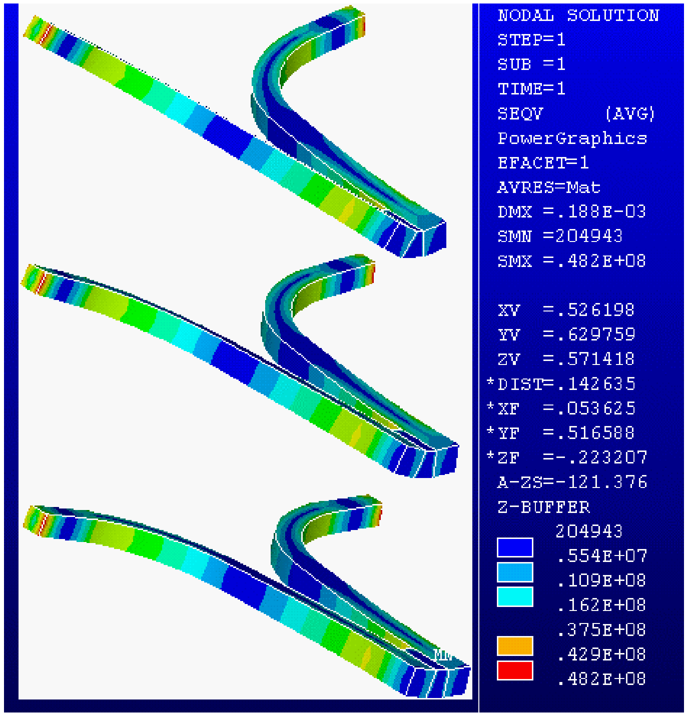
Lead penetration



Joint Temperature

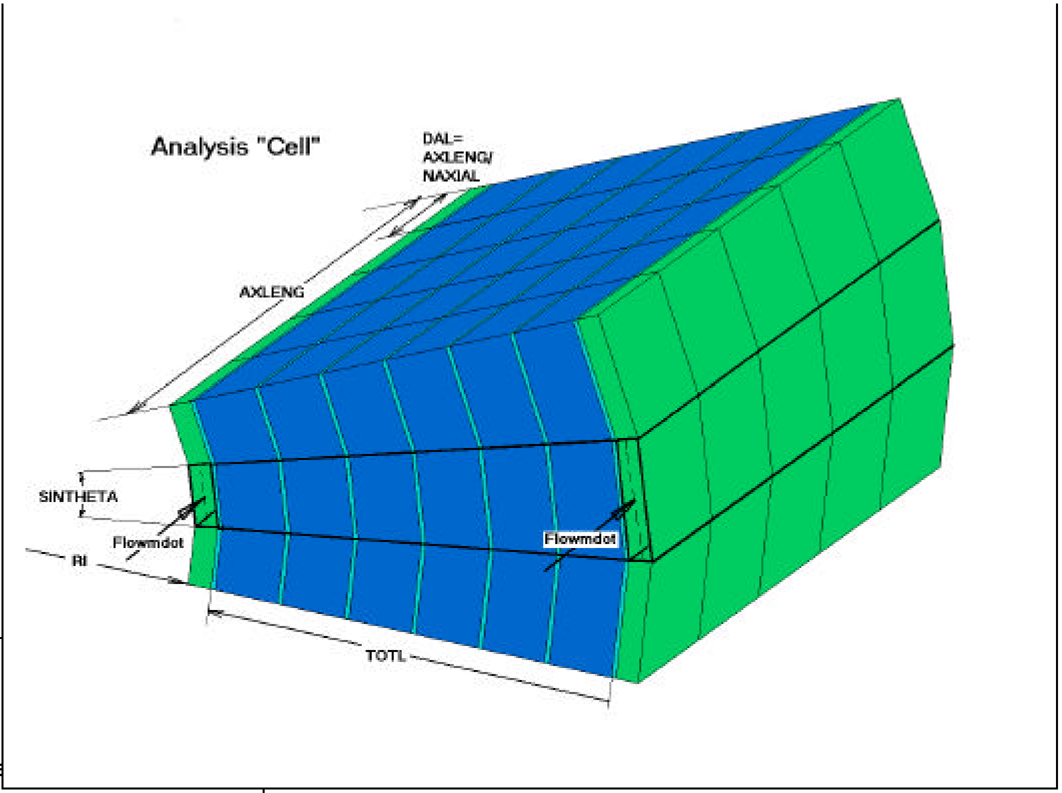


Thermal+Lorentz stress. Winding ends well supported at extreme of the radius, where the thermal constraint was applied. The peak stress occurs where the relatively short interconnection ends. This will be lengthened, and will reduce the peak stress.



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

Cooldown Calculations:
Finite Difference Model is Used.
Channel Flow and
Transient Heat Conduction
Reducing the Kapton between Layers Allows



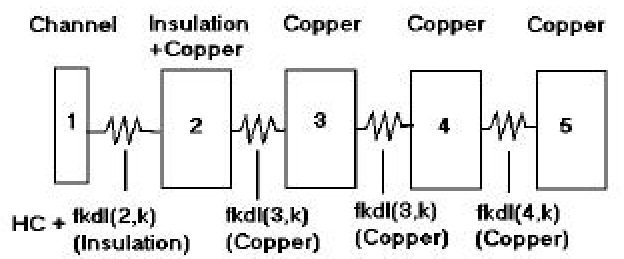
2.1.3 Convective Heat Transfer

It is important to estimate how much heat the supe gas (T > 77 K) could absorb before exiting the cooling channel. The convective heat transfer coefficient, h, could be obtained from[9]

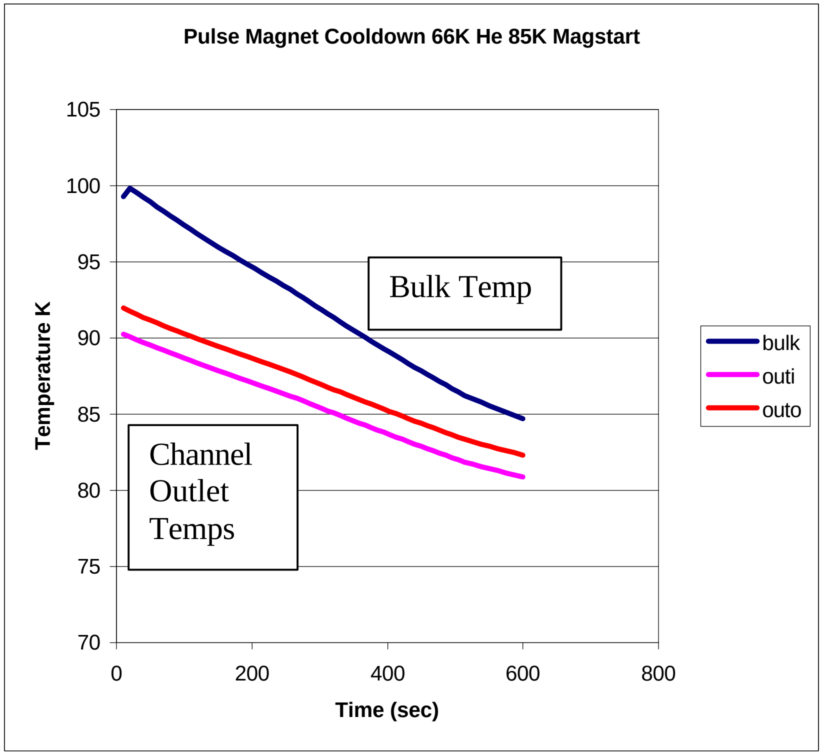
$$h = \frac{KNu}{D_e} = \frac{0.023Re^{0.8}Pr^{0.4}K}{D_e} \quad . \qquad (14)$$

This coefficient is about 21×10^{-3} W/cm^2 K at a vapor temperature of 200 K, vapor velocity of 40 m/s, and hydraulic diameter of 2 cm. It drops to 17×10^{-3} W/cm^2 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 12×10^{-3} W/cm^2 K, which partially justifies the third assumption in Sect. 2.1.

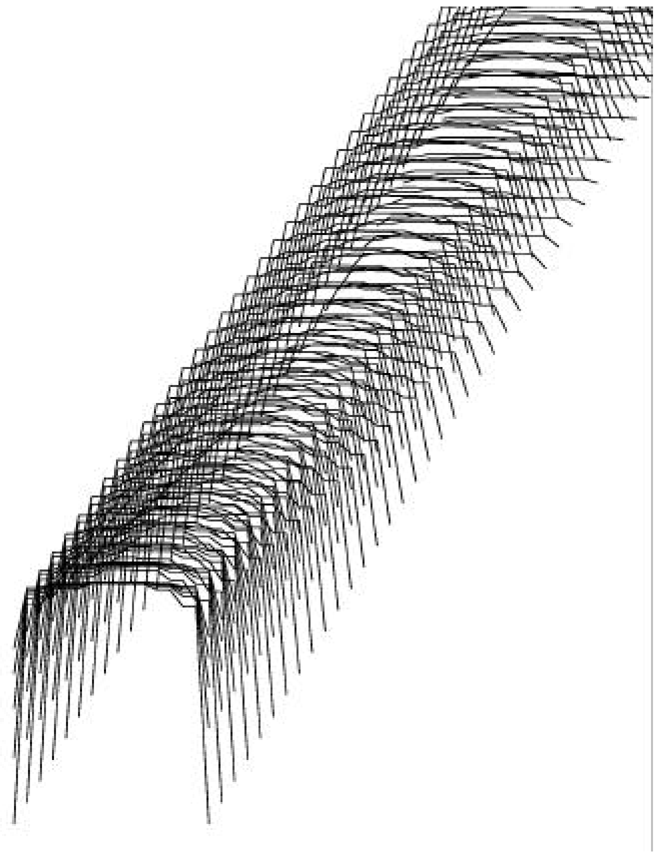
excerpt from: ORNL/FEDC-85-10 Dist Category UC20 c,dated October 1986



Channel Edge Thermal Model



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.

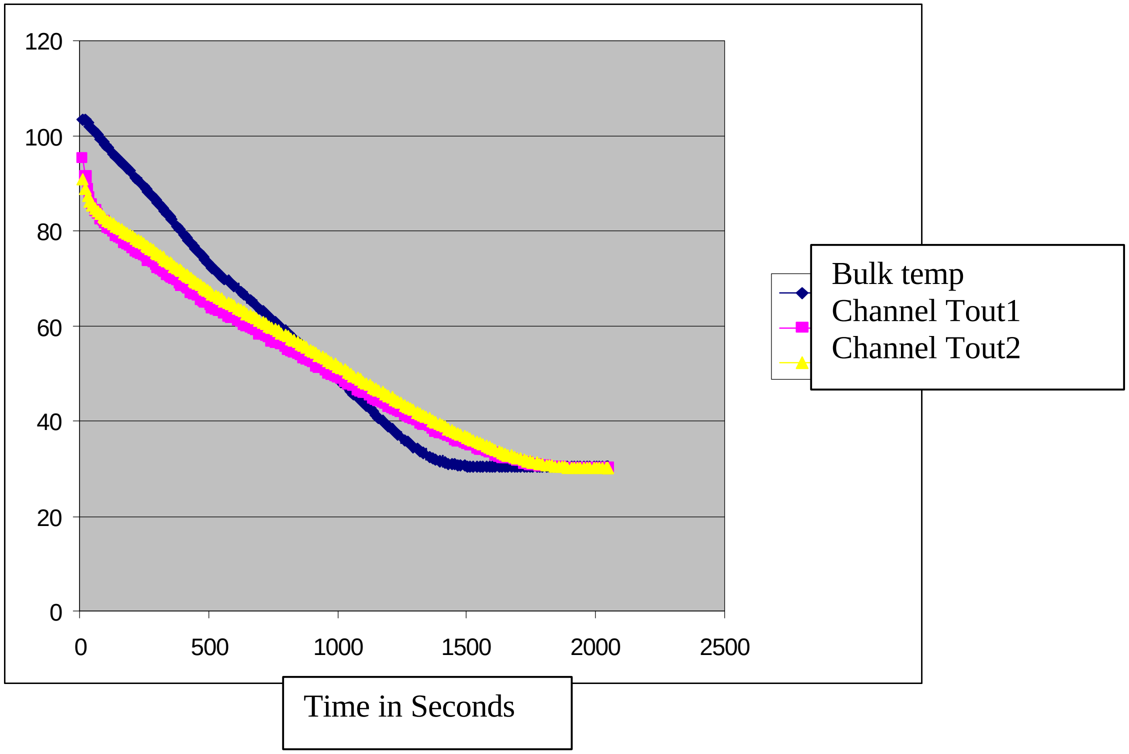


"Cell " Temperature profiles. Time is diagonally to the right. “Bunched” lines represent the axial temperature distribution.

Present Operational Scenarios:

Case #	Peak Field	T after pulse	T coolant	Start Bulk Temp	Guestimated Time	Guestimated Time
1	5T	90K	66K	84K	~200 sec	3.3 min
2	10T	96K	66K	74K	~800 sec	13.3 min
3	14.5T	78K	22K	30K	~1500 sec	25.0 min

30K Coolant, Cooldown from 100K



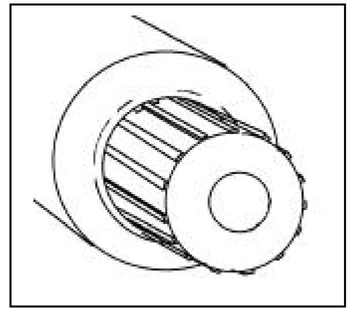
Bulk Temp Is Computed Mid Axial Build - It Bottoms out before the down stream end.

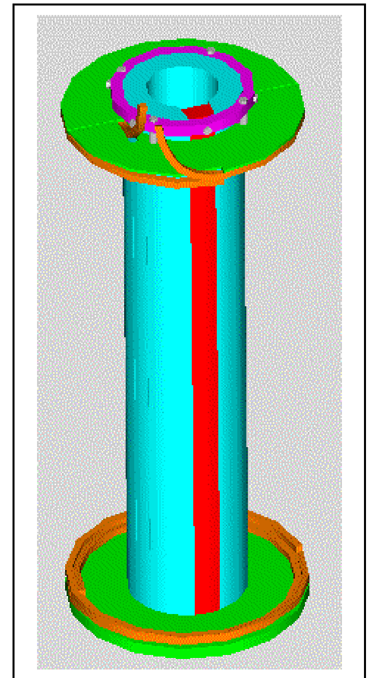
tout 1 and tout2 are Outlet Temperatures

Analyses to date: Time to target bulk temp. ½inch Copper Conductor, 100K ,

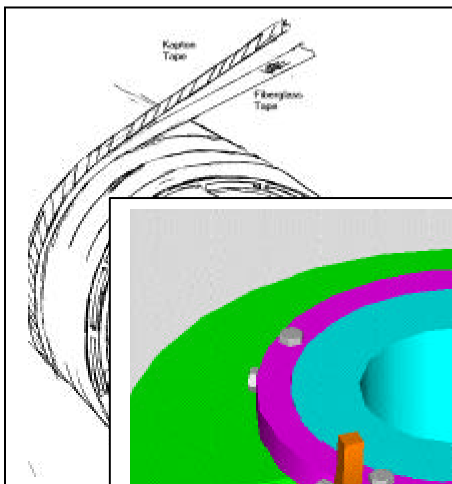
	T after pulse	T coolant	Cond Layers	Time to 85K sec	Time to 30K sec
Equiv 5 Kapton .001in wrap	100K	66K	6 layers	600	
Equiv 5 Kapton .001in wrap	100K	66K	8 layers	>850	
Equiv 3 Kapton .001in wrap	100K	66K	8 layers	450	
Equiv 5 kapton .0001in wrap	100K	30K	6 Layers		2000

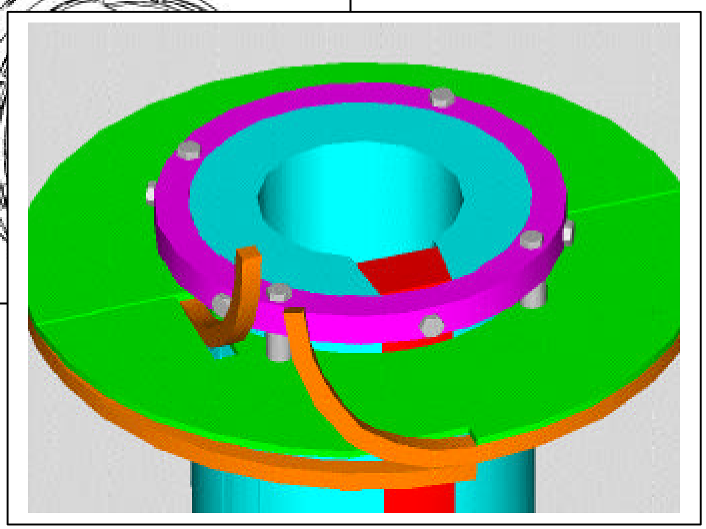
Assembly and Manufacture

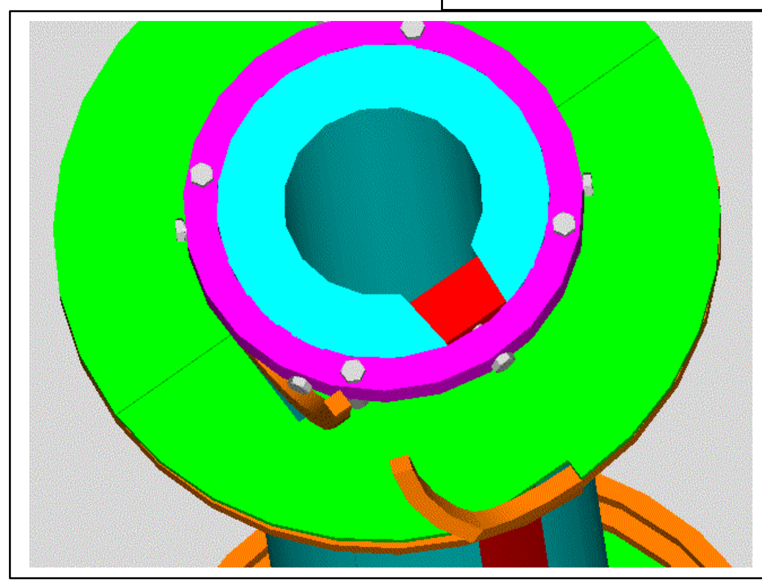


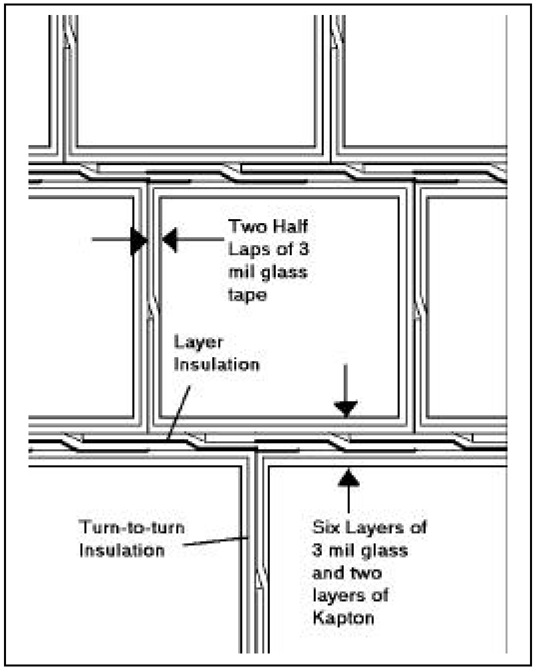


The Coil is layer wound
The Coil is made in three segments. Phased manufacture is allowed
Three separate mandrels are planned.
Mandrels maintain a precise bore geometry
Ribs are applied to outer surface of the wound and impregnated coil
Ribs are machined to match the ID of the next coil segment
Coils 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 .51293333 in
packing fraction= .95025227

Layer Insulation

- 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 lapps 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.

Cryostat Bore Tube Geometry

Building from the Magnet ID and working towards the centerline:

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

This leaves a clear bore diameter of .16947m