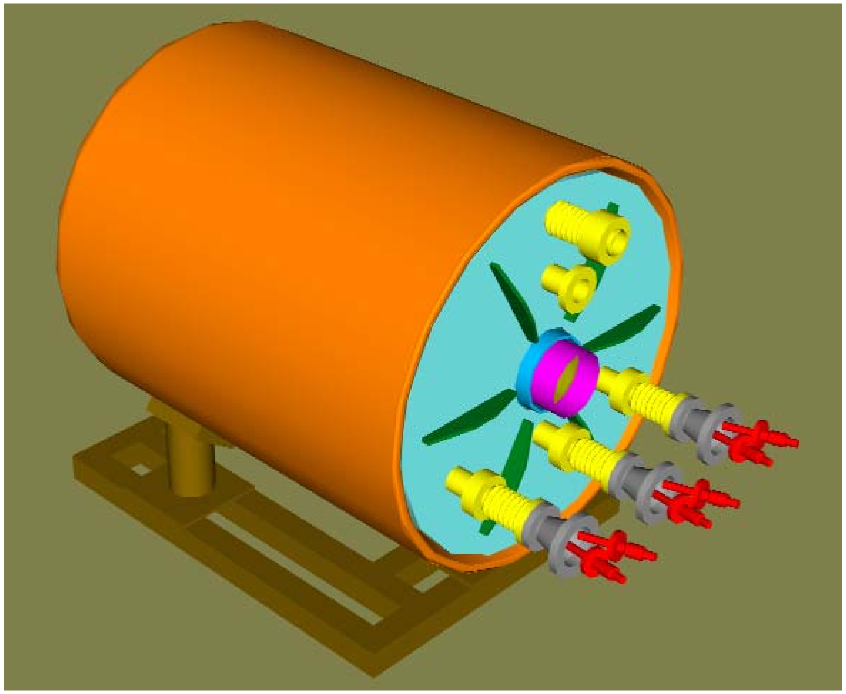
High Power Hg Target Design Meeting
August 31 – September 1, 2004
Oak Ridge Laboratory

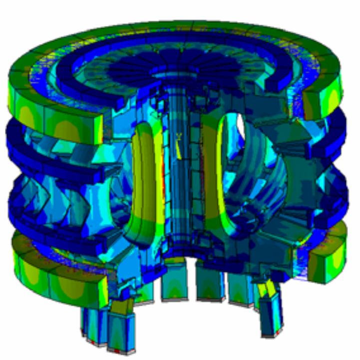
E951 15T Pulsed Magnet for Mercury Target Development Neutrino Factory and Muon Collider Collaboration

Peter H. Titus
MIT Plasma Science and Fusion Center
(617) 253 1344, titus@psfc.mit.edu,
http://www.psfc.mit.edu/people/titus

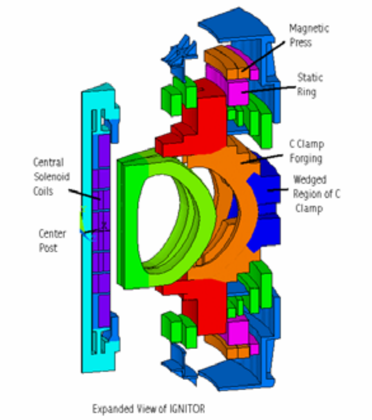
BNL pulsed magnet design builds off of copper magnet experience in fusion research:



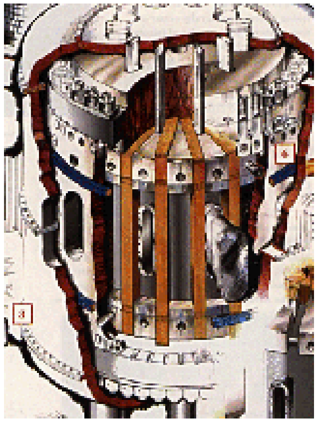
BNL Pulsed Magnet –Inertially Cooled , LN2 or 30K He Gas Cooled Between Shots



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



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



Alcator C-Mod. MIT-PSFC operating Tokamak –Inertially Cooled, LN2 cooled between shots.

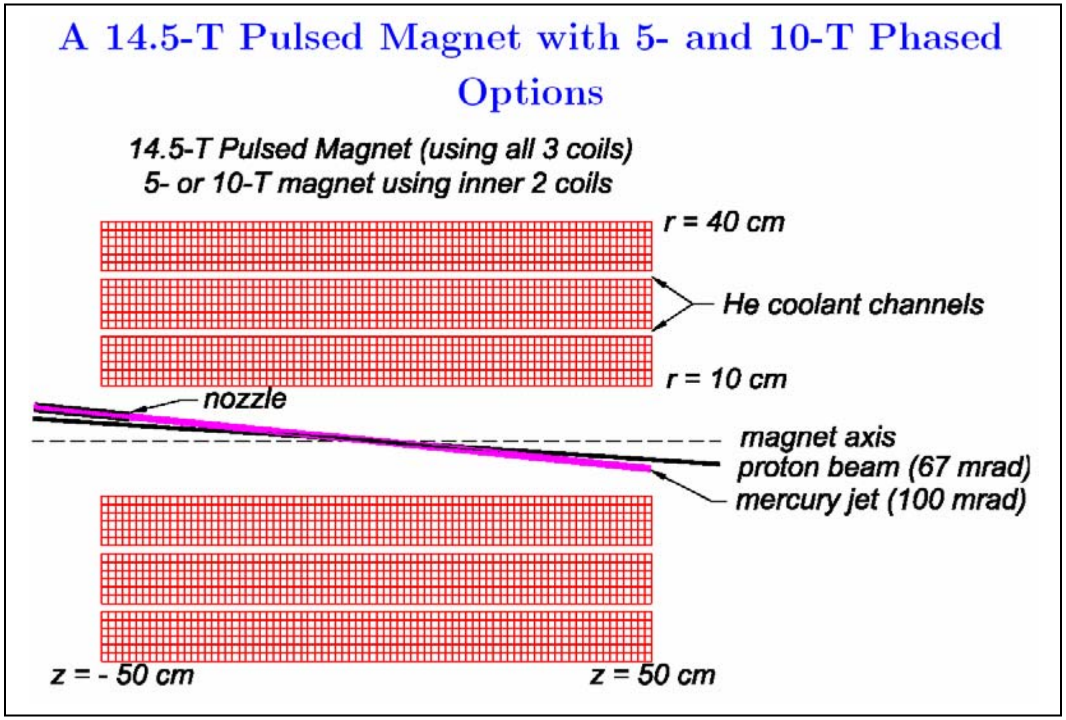
Cost issues dictate a modest coil design.

Power supply limitations dictate a compact, low inductance, high packing fraction design.

A three segment, layer wound solenoid is used for the pulsed magnet. External segment leads allow series and parallel connections.

The conductor is half inch square, cold worked OFHC copper.

The coil is inertially cooled with options for liquid nitrogen or gaseous Helium cooling between shots. Coolant flows through axial channels in the coil.

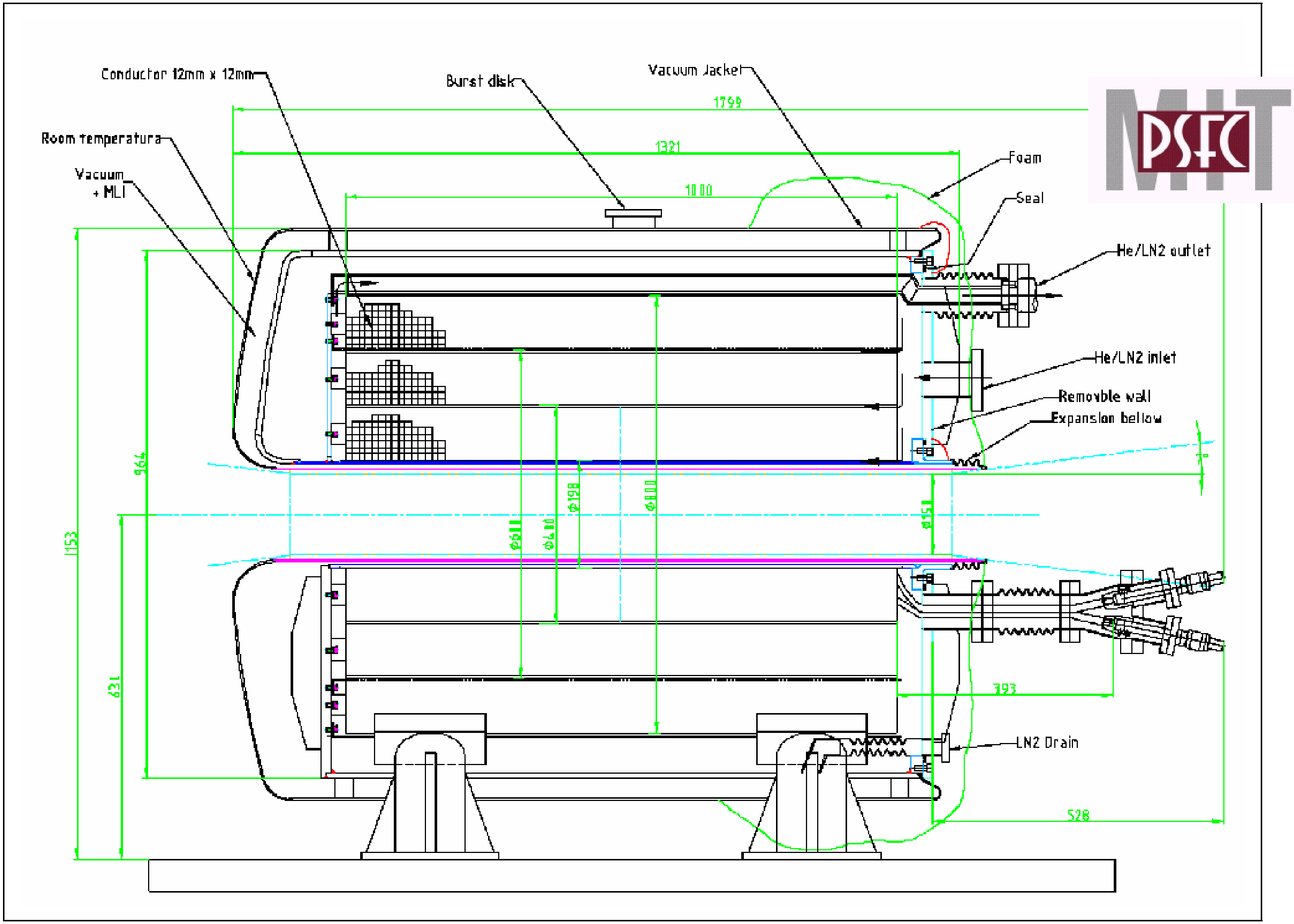

A 14.5-T Pulsed Magnet with 5- and 10-T Phased Options

For the same packing fraction, a hollow conductor would have a 1.4mm diameter hole

The coil will be epoxy impregnated.

Lots of Pictures, Drawings and Calculations at:
http://www.psfc.mit.edu/people/titus/#BNL%20Memos

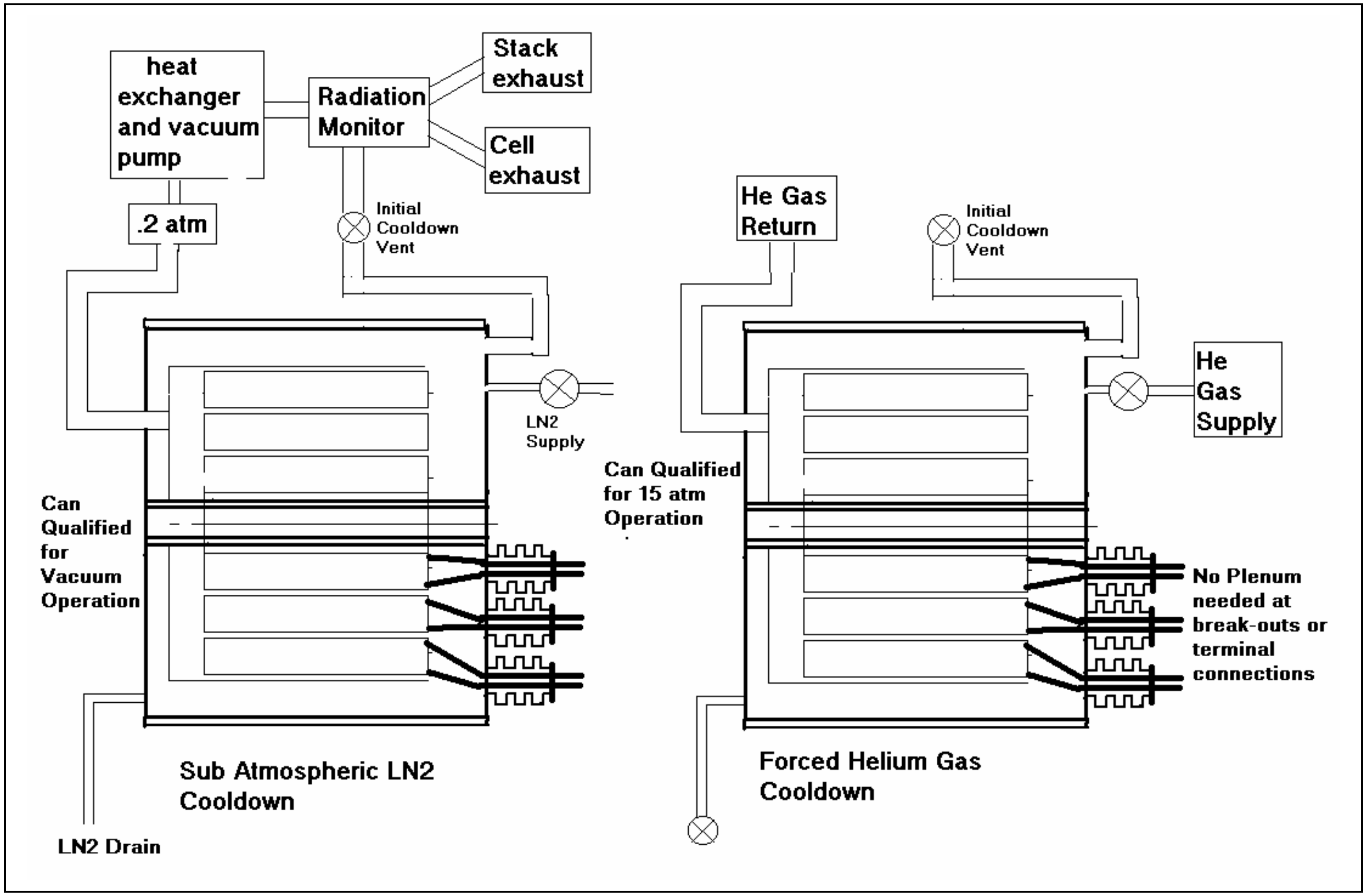
Tip of the Hat to: Bob Weggel who has performed the coil/power supply simulations. He has picked operating temperatures, and basic coil build.



Conductor 12mm x 12mm
Burst disk
Vacuum Jacket
Room temperatura
Vacuum
+ MLI
Foam
Seal
He/LN2 outlet
He/LN2 inlet
Removble wall
Expansion bellow
LN2 Drain
1799
1321
1000
964
1153
431
φ611
φ400
φ198
φ800
φ151
393
528

Early Proposed Operational Scenarios

The coil and cryostat are designed for two cooling modes and three fields



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

Coil Builds used in the finite Element Models:

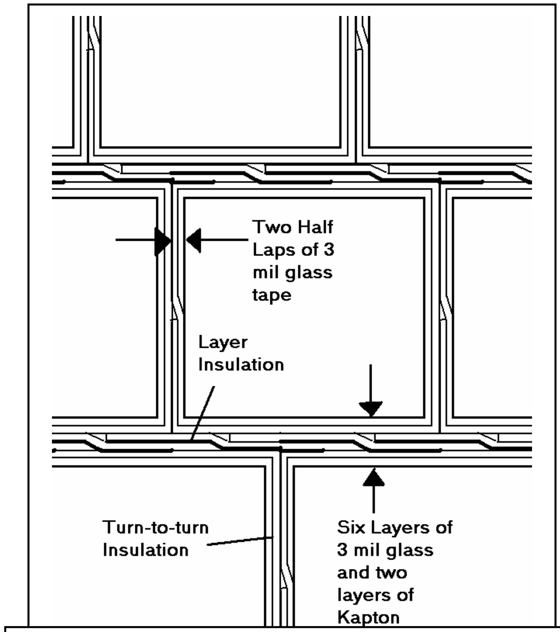
#	r	z	dr	dz	nx	ny
1	.15	0	.098	1.0	16	16
3	.25	0	.098	1.0	16	16
5	.35	0	.098	1.0	16	16

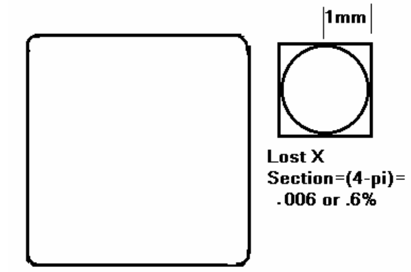
Coil Description:	Mode 1	Mode 2	Mode3
Number of Segments operating:	**2**	**2**	**3**
Number of turns per segment	**624**	**624**	**624**
Total number of turns active	**1248**	**1248**	**1872**
Layers in each coil segment	**8**	**8**	**8**
Turns per layer	**78**	**78**	**78**
Conductor radial thickness	**.0116698 m .45944 in**	**.0116698 m .45944 in**	**.0116698 m .45944 in**
Conductor Axial thickness	**.012516m .49274359 in**	**.012516m .49274359 in**	**.012516m .49274359 in**
Max Operating Field Bore CL	**5T**	**10T**	**15.0T**
Max Terminal Current	**3600A**	**7200A**	**7200A**
Coolant Working Fluid	**77K LN2**	**65K LN2**	**30 K Helium Gas**
Terminal Voltage	**150V**	**300V**	**300V**
Layer to Layer Volts	**18**	**36**	**24**
Turn-to-Turn Volts	**0.12**	**0.24**	**.16**
Design Life			**1000 full power pulses**
Cryostat Pressure - Operating	**12 atm (He) 1atm LN2**	**12 atm (He) 1atm LN2**	**12 atm (He) 1atm LN2**
Number of .54 MVA power supplies	**1**	**4**	**4**
Mode of Ganging Supplies	**None**	**2 X 2**	**2 X 2**
Charge Time	**7.2 sec**	**6.3 sec**	**15.3 sec**
Initial Temperature	**84K**	**74K**	**30K**
Temp Rise	**5.8K**	**21.7K**	**48.3K**
Final temperature	**89.8**	**95.7**	**78.3**
Cumulative heating at end of pulse	**2.7MJ**	**9.1MJ**	**15.2MJ**

Conductor Dimensions

conductor dimensions with 2 millimeter channel tolerance
radial dim 1.1669799e-2 m .45944 in
Axial dim 1.2515712e-2 m .49274359 in
packing fraction= .92998827

These packing fractions are based on the coil winding pack and exclude the channel. If the 2 mm channel is included, the packing fraction drops to .911.





Corner Radius

Keystoning:

H/(2*r)= .012/.1/2=6% (elastic strain) For Plastic bending, (poisson=.5) the Keystoning contraction is 3% at the smallest radius (Same as Everson test bend).

Three Keystone specs are suggested. The keystone geometry for the first segment should be .012/.15/2*.5=2%

The worst case loss in packing fraction is 1%, Average loss is .5%

Keystone allowances in outer two segments are 1.2%, and .86%. Packing fraction losses in outer two segments are .15%, and .007%

Whole Magnet loss of .2%+Corner Loss of .6%=.8%

- 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.

Voltage Capability

	Mode 1	Mode 2	Mode3
Number of Segments operating:	2	2	3
Number of turns per segment	624	624	624
Original Terminal Voltage Spec	150V	300V	300V
Layer to Layer Volts	18	36	24
Turn-to-Turn Volts	0.12	0.24	.16

The turn to turn insulation has 4 layers of 3 mil fiberglass tape, for a total of 12 mils of insulation thickness. This is postulated to crack, and He gas to have penetrated. The standoff possible with such a crack is 1 volt per mil, based on the rule of thumb for He breakdown voltage at 1 atm. - or 12 volts.

The layer to layer insulation is 6 layers of 3 mil fiberglass and 2 layers of 1 mil Kapton. This is ~20 mil or .508 mm thick insulation. The ITER design limit for an insulation system which includes both barrier(Kapton film) and fiberglass-epoxy is 3kV/mm (with a safety factor of 10). Based on this, the layer to layer voltage that our system could withstand is 3000*.508 or 1524 volts. This same insulation is used for voltage to ground, so this sets the voltage limit for the magnet.

Most of the insulation that has been specified for the BNL magnet is either a practical minimum - the half lap of fiberglass on the conductor, or to cover "manhandling" of the winding process. The layer to layer insulation system with 20 mils total thickness could only handle 20V if it cracked and filled with He.

The Kapton, which is quite ductile at room temp is supposed to maintain a film barrier after being crushed during winding. – It survived well in Everson test bend.

Structural and Geometric Design Criteria

Fusion project criteria are used for guidance in coil design

Experimental Volume Spec:

150 mm bore , 1200mm long centered on the magnetic center of the solenoid, with 7 degree

FIRE design document allows the primary membrane stress to be based on the lesser of 2/3 of the Yield Strength (Sy) or ½ of the Ultimate Strength (Su). The ASME Code bases the primary stress on 1/3 ultimate. The fusion project based criteria is based on a distinction between coils that are supported by cases and those that are not.

For structural elements ASME -like criteria are adopted with membrane stresses remaining below the maximum allowable stress, Sm, where Sm is the lesser of 2/3*yield or 1/3 ultimate.

Bending discontinuity, and secondary stresses are treated in a manner similar to the ASME Code.

Guidance for bolting and column buckling is taken from AISC, with average net section bolt stresses kept below 0.6*yield. Yield Strength and Tensile Strength properties are taken at the loaded temperature.

The cryostat and vacuum jackets are to be qualified and manufactured in accordance with ASMEVIII. However the vessels do not need to be stamped.

The magnet is to be seismically qualified in accordance with the (Uniform Building Code? - .1g horizontal).

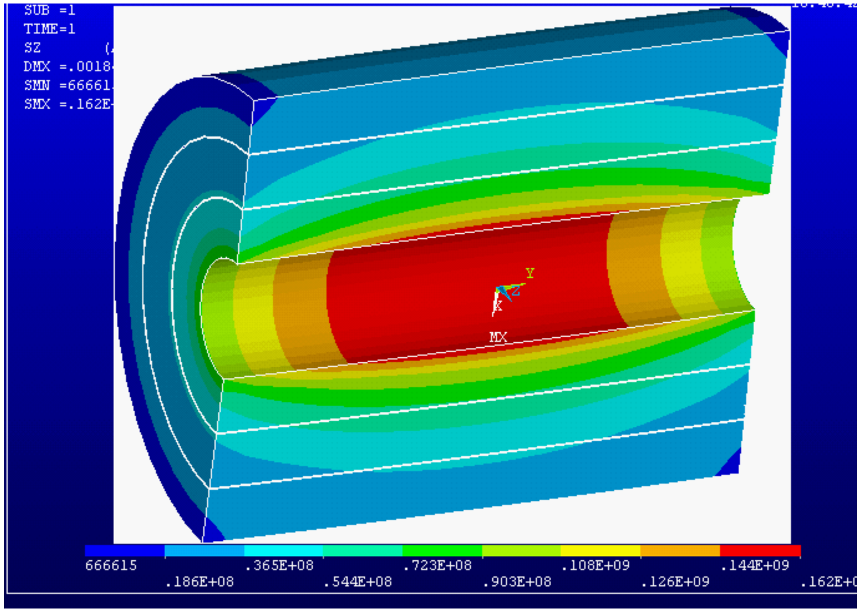
Cryostat Bore Tube Geometry

Building from the Magnet ID and working towards the centerline:

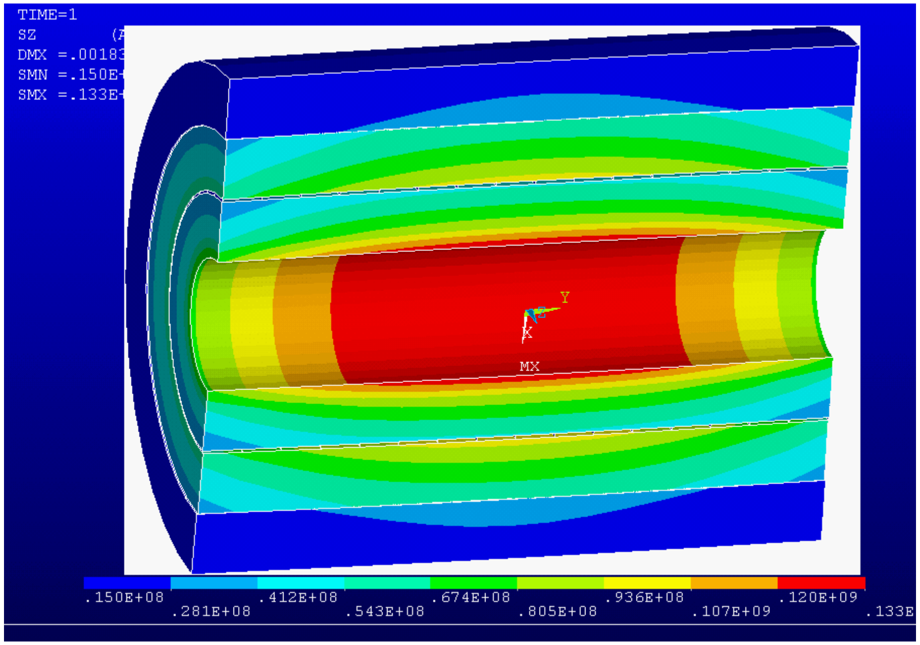
Component	**Thickness (m)**	**Radius (m)**
The ID of the magnet winding		**.15-.98/2= .101**
Coolant Channel	**.002**	**.099**
Cold Cryostat Shell	**.004762(3/16in.)**	**.094237**
Vacuum Space	**.008**	**.086237**
Vacuum shell	**.0005**	**.085737**
Strip heater	**.001**	**.084737**

This leaves a clear bore diameter of .16947m, .15m required

Coil Stress Analysis



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



Re-run with gap elements the hoop stress went down to 133 MPa

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.

Conductor Allowable and Cold Work Spec

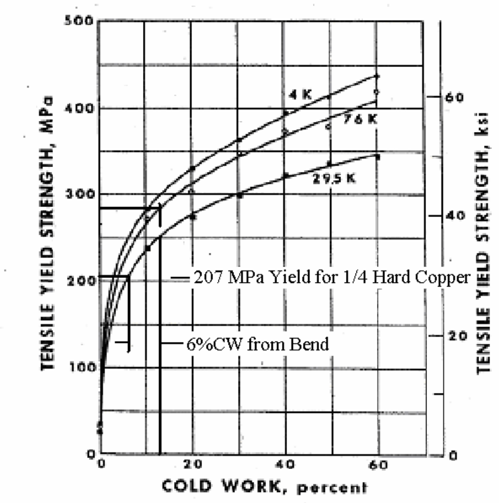
For Fusion magnets the inner skin of the solenoid is allowed to reach the yield - Treating this stress as a bending stress with a 1.5*Sm allowable with Sm based on 2/3 Yield.

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

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.

The conductor is specified as half hard in the spec. Everson has purchased ¼ hard conductor to ease the bending operation, with the expectation that the cold work associated with the forming process will produce an adequate yield. ¼ hard copper would have a yield of 30 ksi or 207 MPa. 160MPa is needed.

From the Figure this would correspond to cold work of about 15%. The bending operation would introduce an additional 6% (see section 4.4) Hardness is assumed to correlate with %cold work.

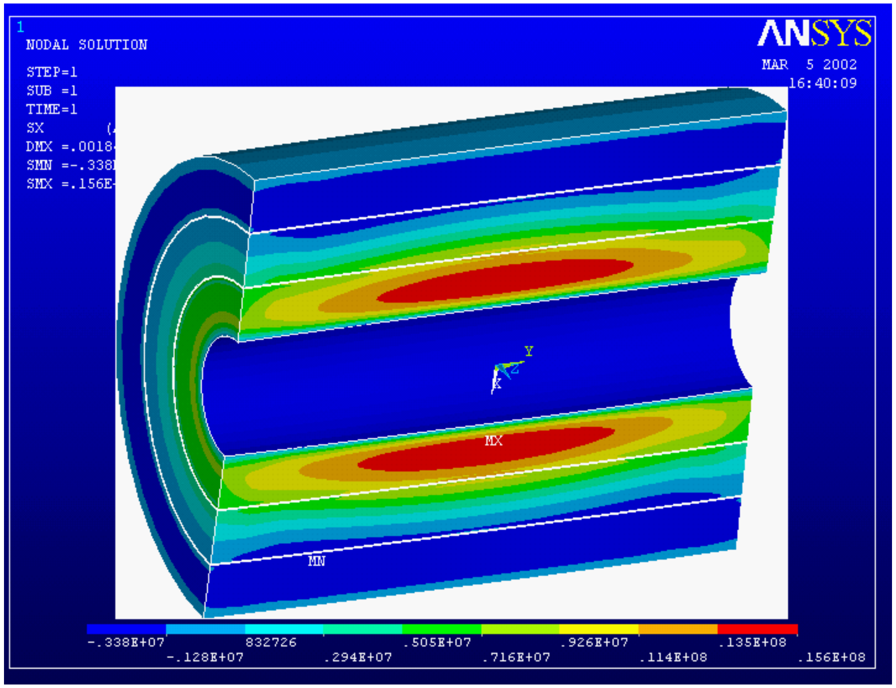


Copper Properties Marked-up with Expected Yields. For Segment 1 ID with CW at 100 K, about 270 MPa would be expected

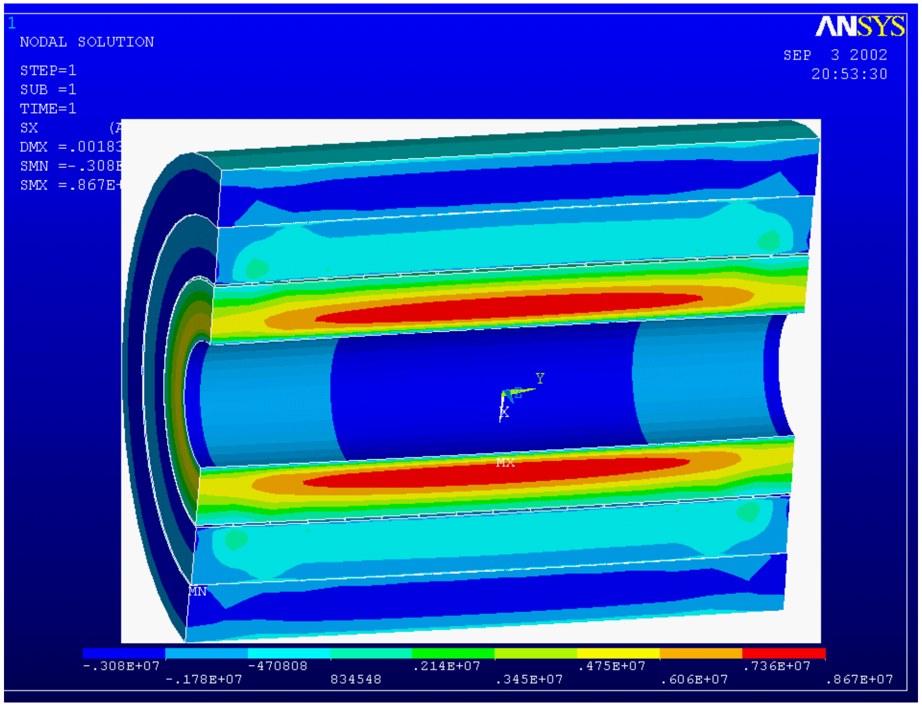
High Strength Bolts Specs (Needed Especially for Inner Closure Head Bolt Circle):

ASTM A193 Grade B8M - Class 2 - Type 316
for 3/4" diameter and under: Su = 110,000 psi , Sy = 95,000 psi

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.

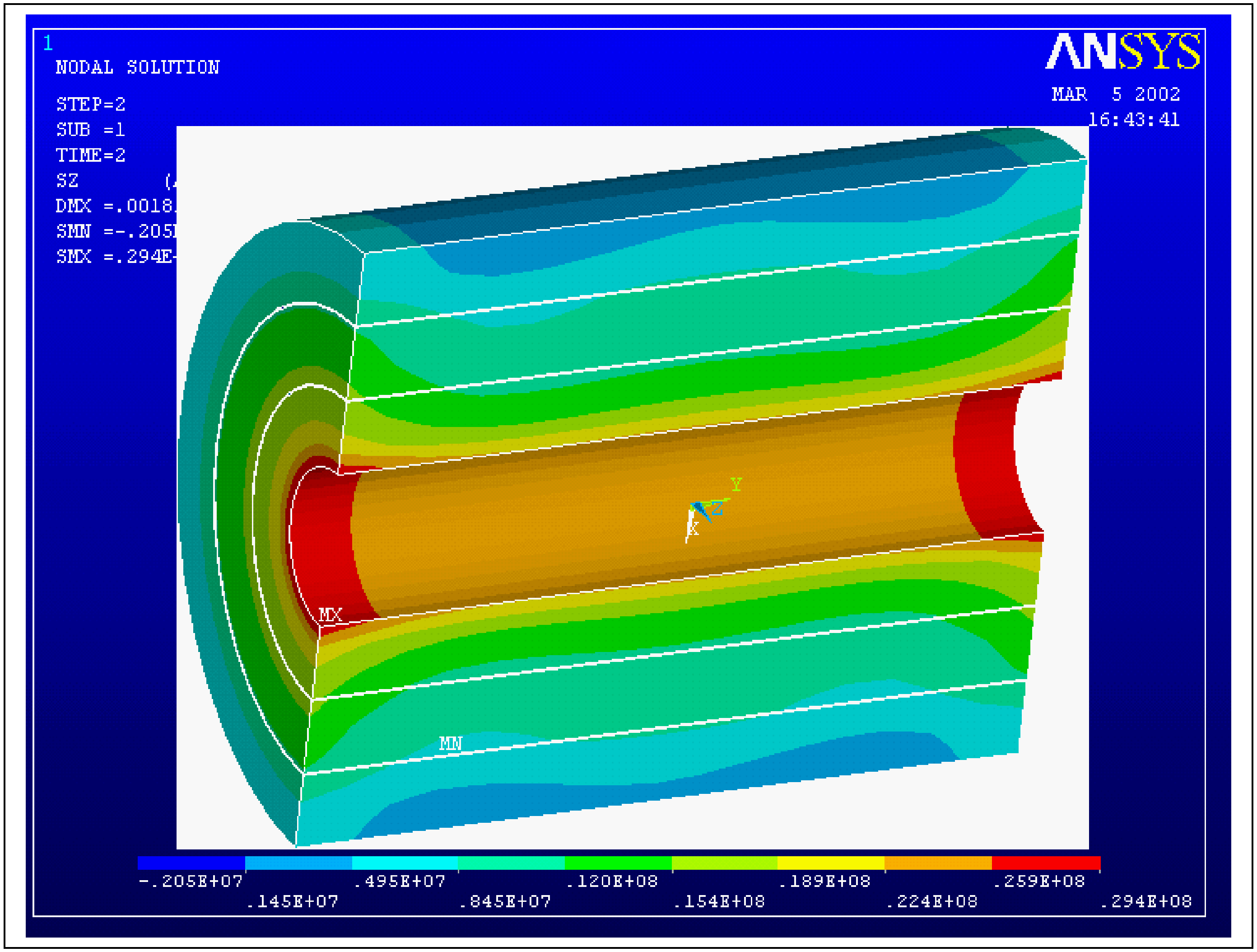


Radial Tension in the winding of the first segment is reduced by about A half with gap elements modeling the interactions of the three coil Segments.

Operating Mode 2, 10T

Hoop Stress
With only the Inner Two Segments Energized.

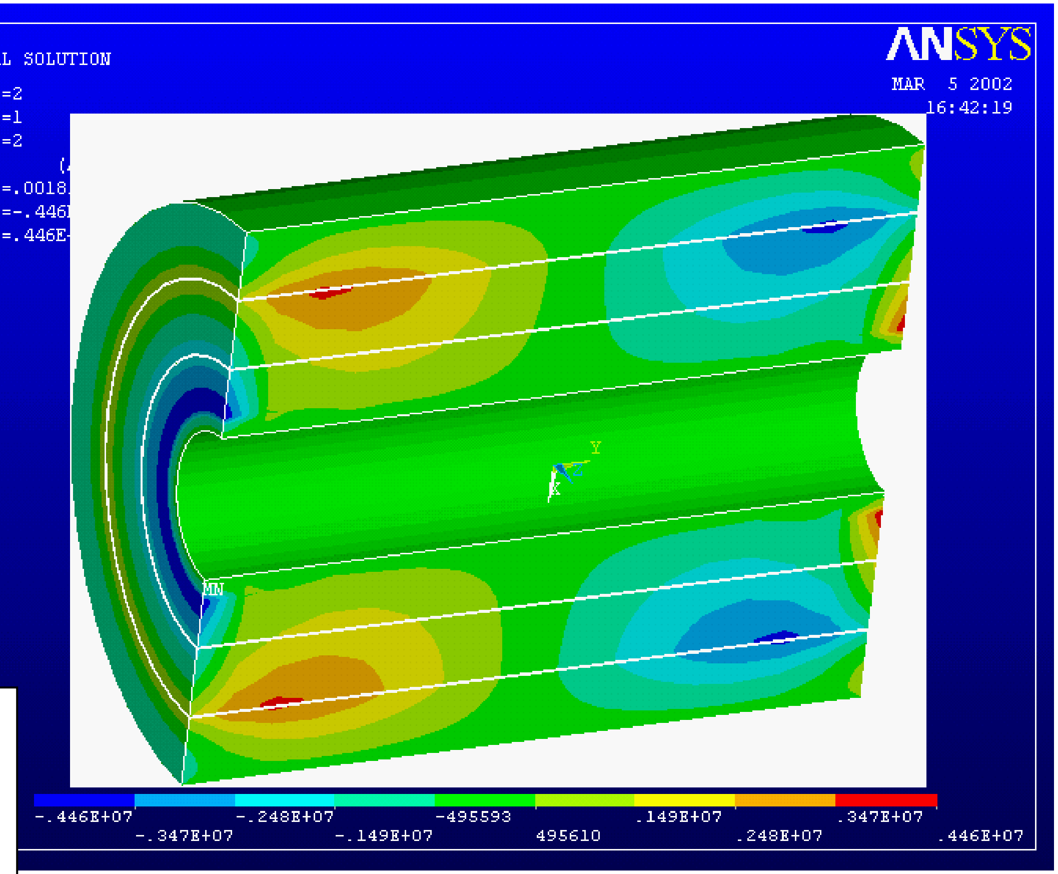
Peak Hoop Stress is Only 29.4 MPa



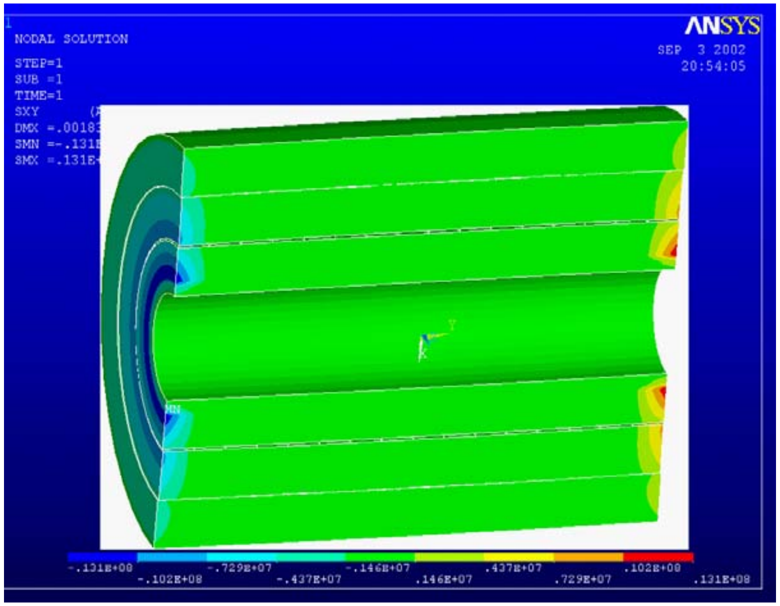
Operating Mode 2, 10T

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

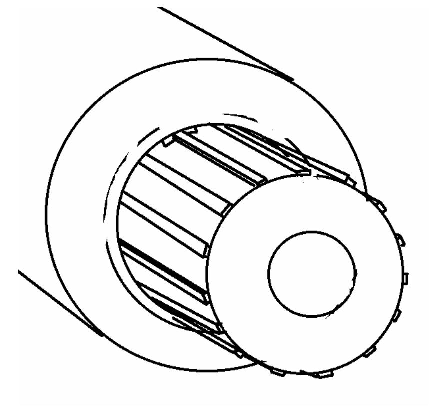
Channel Ligaments would be too weak to support this – Slip Planes are Used.



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.



With gaps modeling the interfaces between segments, only Inner segment shears remain.



Operational Thermal Stresses.

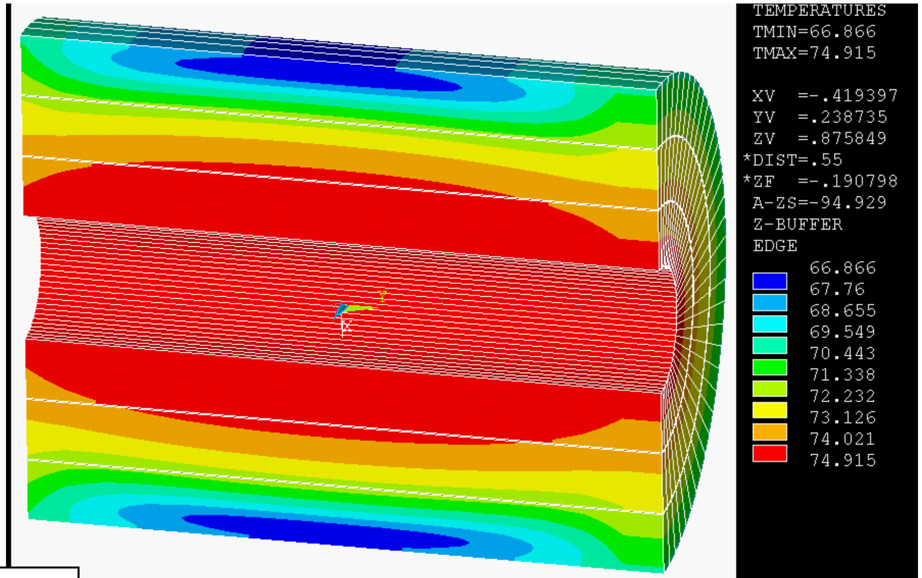
Although a constant current density coil, heat-up during a pulse is not uniform due to the magneto-resistive effects.

Temperatures were calculated for the 15 sec ramp-up, and 2 sec flat top and a 7 sec ramp down. The NIST Kohler plot and fitted equation was used for the magneto-resistance.

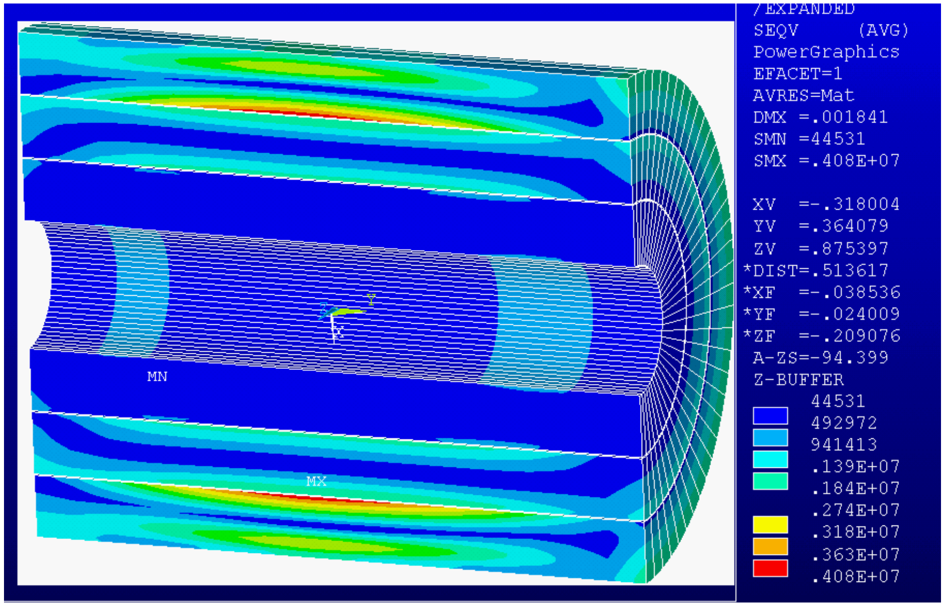
In my calculations, the temperatures were low compared with Bob Weggel's. The difference was the conservatism the Bob applied to his analysis from the scatter of the Kohler plot.

To make some progress on the stress calculations I stretched the time scale to come closer to Bob's temperature distribution.

The stresses from this analysis are small, less than 5 MPa.



Temperatures with magneto-resistive effects, 15.0T

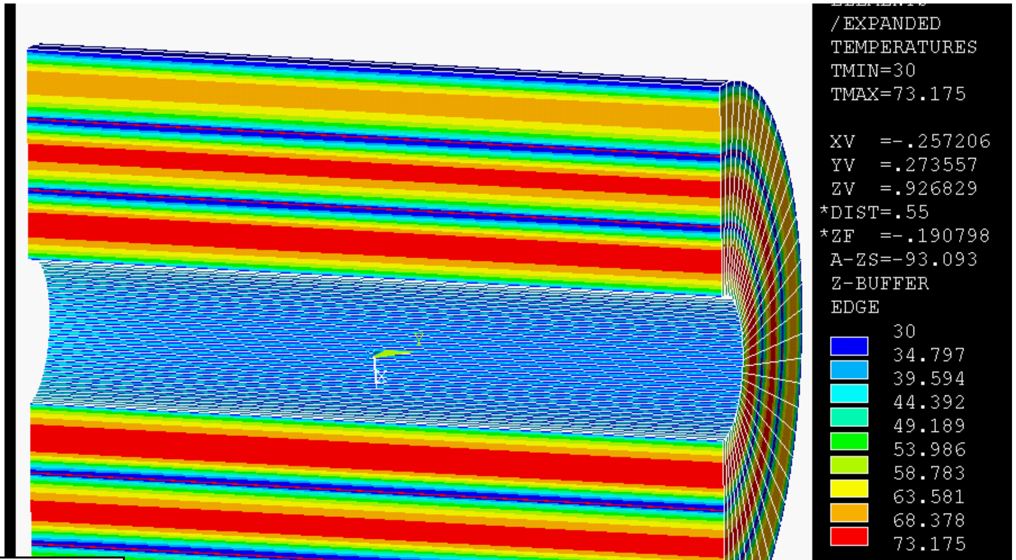


Resulting VonMises Stresses due to Temperature including the magneto-resistive effects, 15.0T.

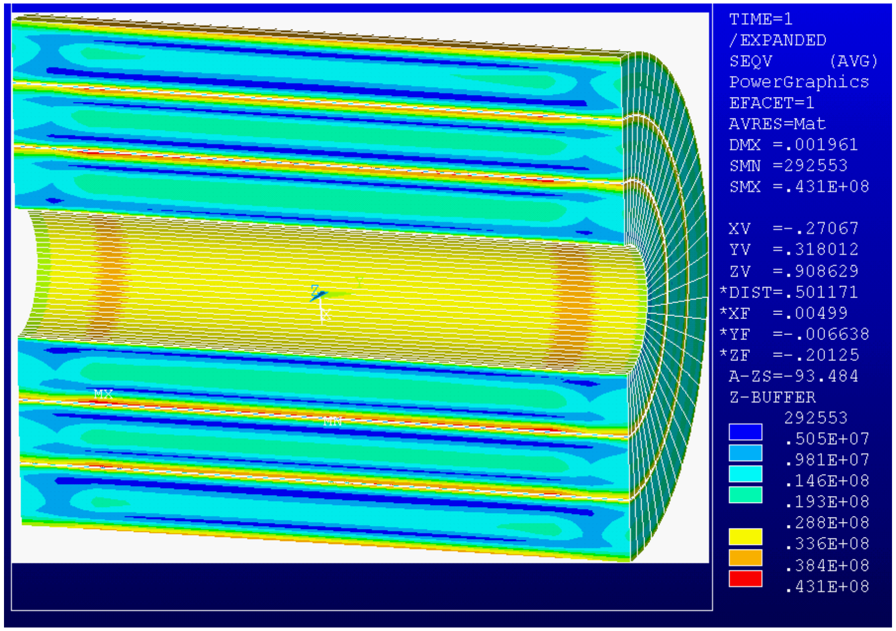
Cooldown Stresses –Von Mises

The channels were held at 30K and the temperature distribution was obtained by averaging nodal temperatures with the final temp distribution from the heat-up calculations. This is not rigorous, and is essentially assumed, but it is representative of temperature distribution, and will serve to provide guidance for further analysis and design.

The VonMises stress is relatively modest, at 43MPa



Cooldown Temperature distribution

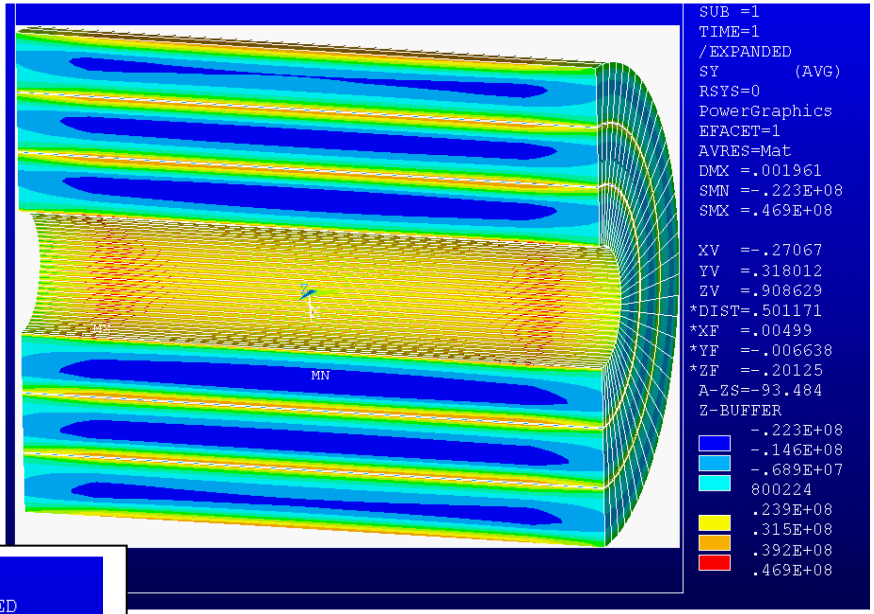


“Smeared” VonMises stress

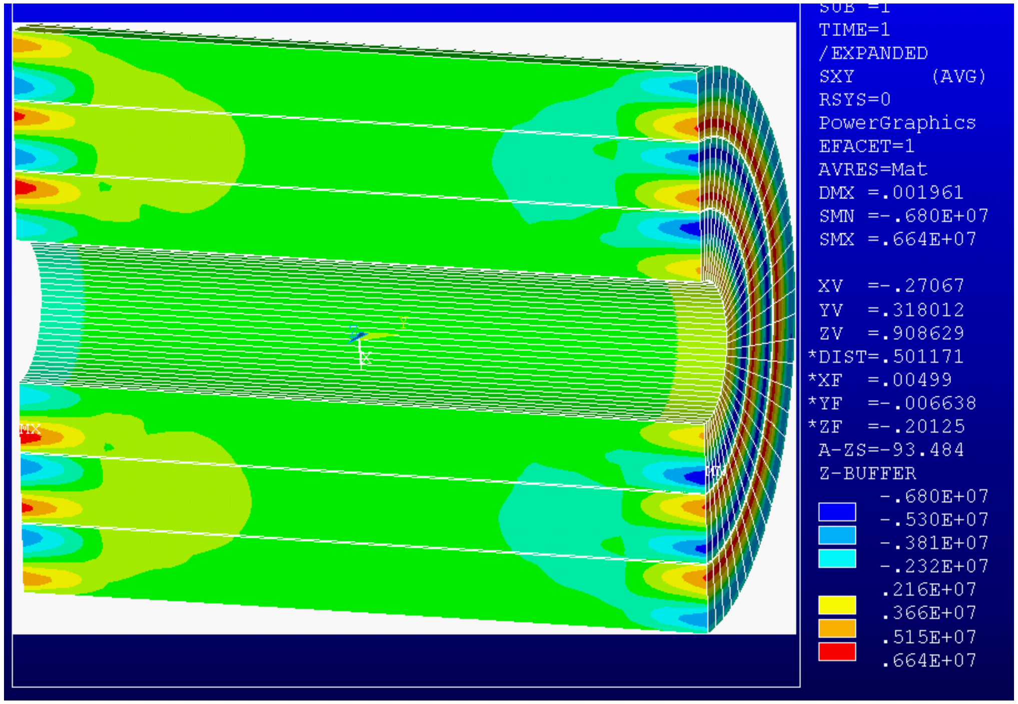
Cooldown Stresses –Shear and Axial Tension

The axial tension near the channels is approaching 50 MPa, beyond the design capacity of epoxy bonded systems. Some provision will have to be made to either throttle the cooling gas to limit the channel temperature or design to allow the bond failure.

The shear stresses that peak at 7MPa are within the usual allowables for insulation systems, for which design allowables are in the range of 15 to 30 MPa (with no aid from compression)

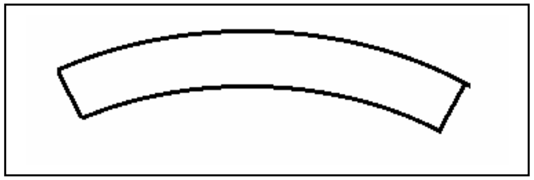


Axial tension



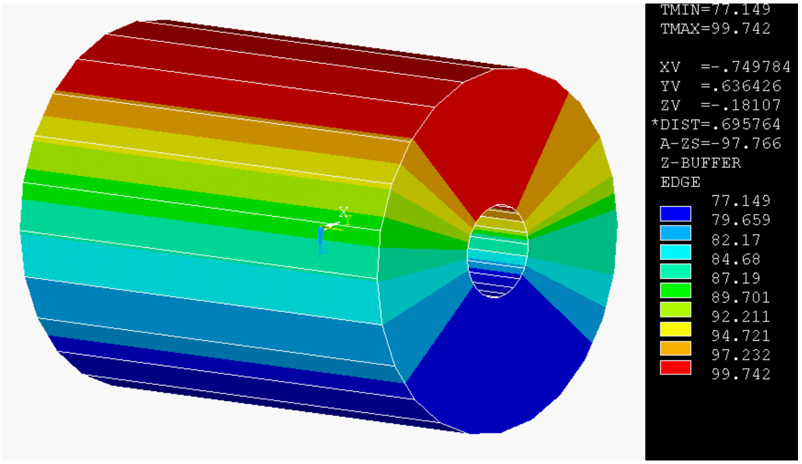
Shear stresses due to the cool down temperature distribution

The Axial Tension will be relieved with Kapton "Arcs" every eighth turn.

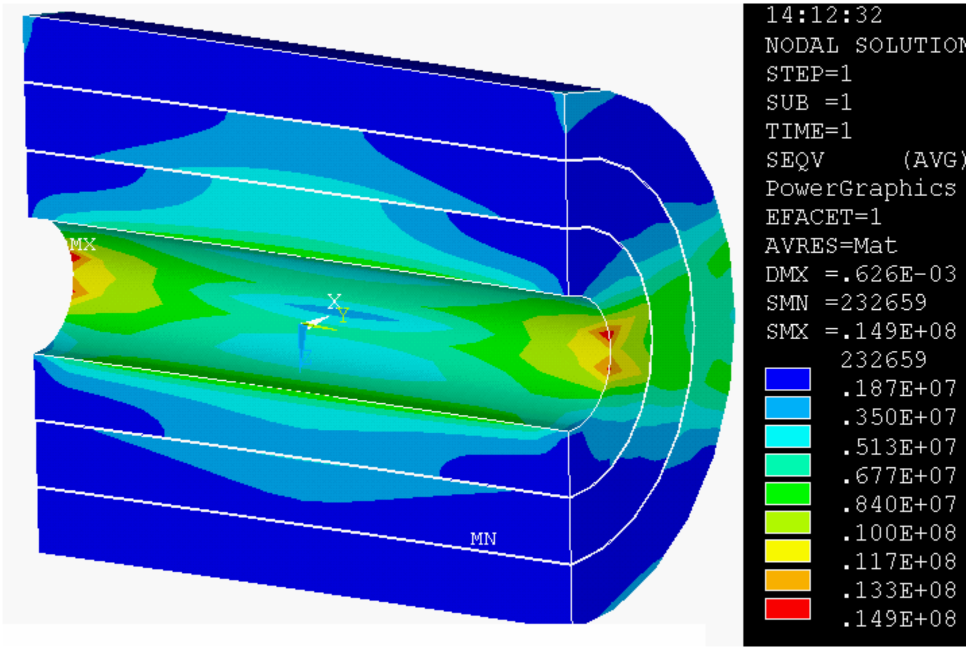


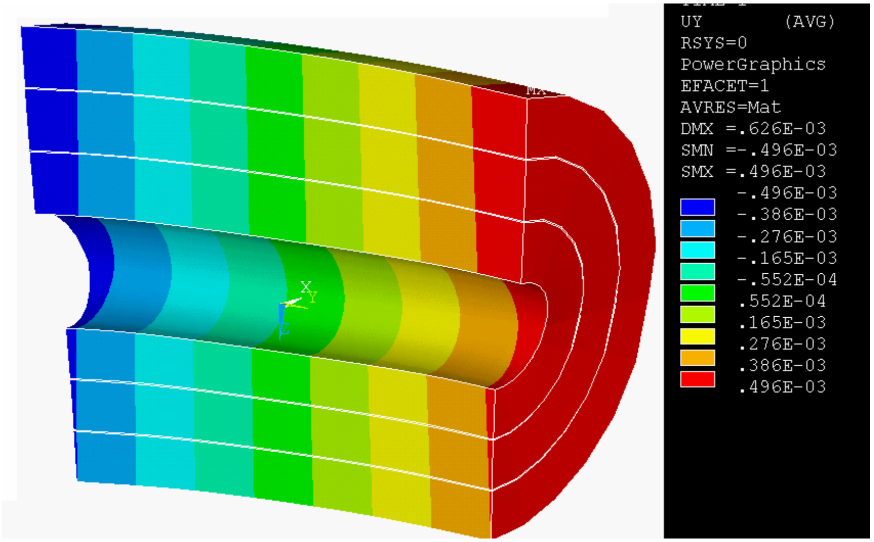
Cooldown Stress, Global Thermal Differential.

If there is stratification of He gas or if LN2 floods the bottom of the cryostat there could be a significant thermal differential between top and bottom of the coil. A 77 to 100 K variation is assumed. The resulting 15 MPa stress is Acceptable



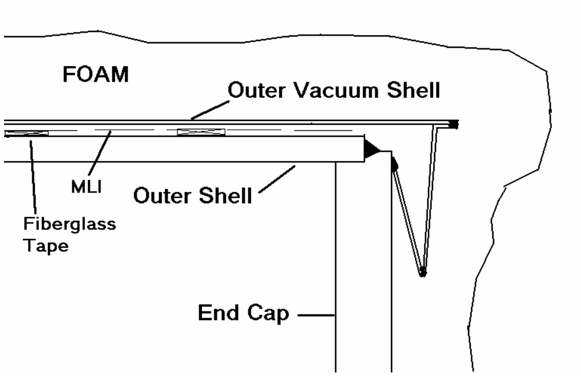
Assumed temperature variation



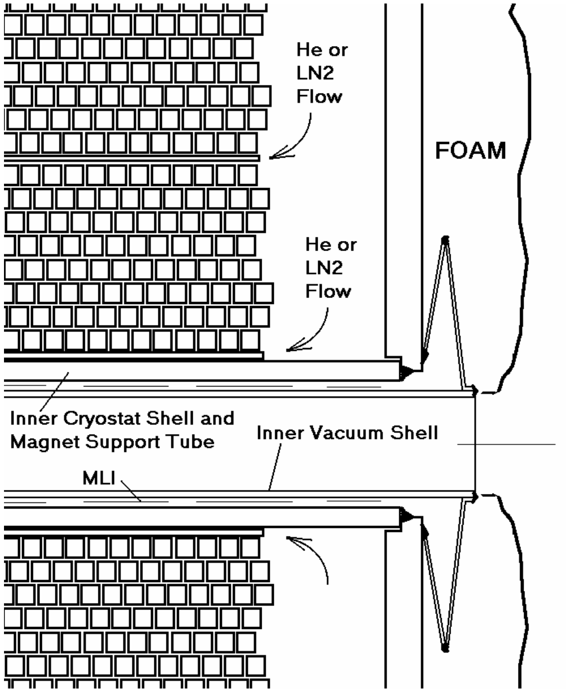


Resulting Displacements

Steady State Heat Gain.



Outer Vacuum Shell to Cover Connection



Inner Vacuum Shell to Cover Connection

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

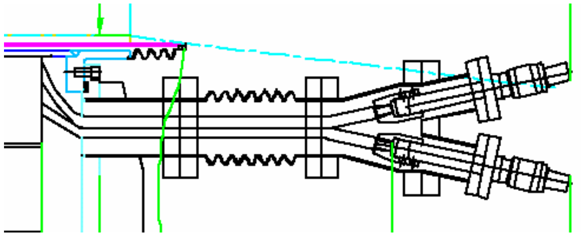
A concept which has a 220 watt heat gain has been developed that employs vacuum at one head, and the outer and inner shells, and foam at the other end around fluid and electrical penetrations.

Piping penetrations are moved to the end plates,

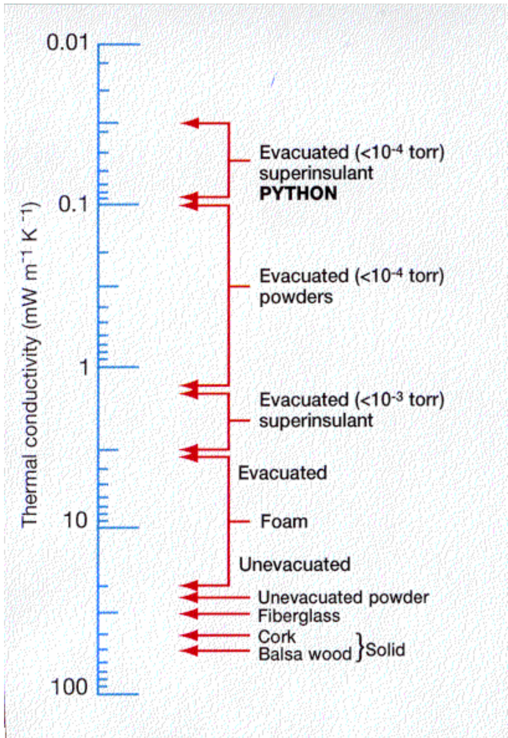
Vacuum shells are used on the ID and OD, and one head.

The magnet can be supported off the inner cryostat shell,

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



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	CTD 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 (1 end)	CTD foam insulation	.03	1.508	.1	292-22	62.85
End Cover	Vacuum +mli					
Leads	Copper (22 to 80K)	396.5	8.64e-4	.4	80-22	49.6 (3 pairs)
Leads	Copper (80 to 292K)	396.5	5.4569e-4	.4	292-80	114.7 (2 pairs)
Lead bellows	sst	16.27	4.7124e-4	.4	292-22	5.33
Coil Support pads	g-10	.15	.0016	.05	292-22	1.296
Total bold red						220.

* 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.

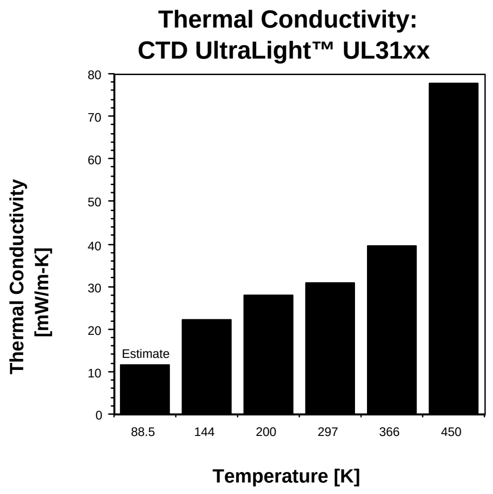
Foam Insulation

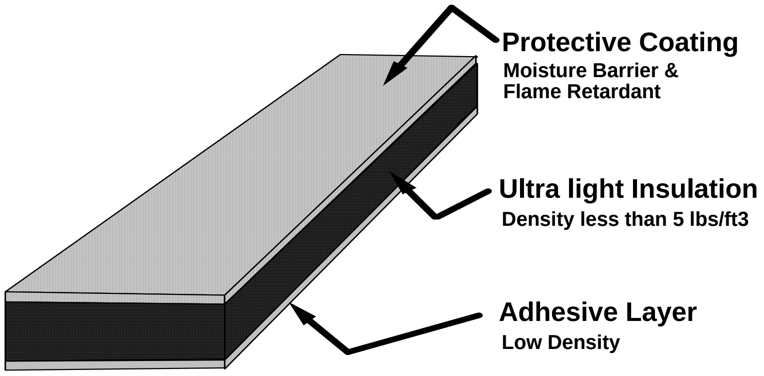
CTD Composite Technology Development Inc.

CryoCoat™ 620T was initially developed to prevent the formation of liquid air on ground-based ***liquid hydrogen vent lines***, and has since found numerous applications as an insulation, adhesive, sealant, protective coating, and grout for ground-based and flight applications. CryoCoat™ 620T offers excellent adhesion to many substrates with minimal surface preparation, and will cure at temperatures as low as 10°C in 8 hours. These characteristics make it especially attractive for retrofit and field installations. Known for its robustness and toughness, this syntactic foam-based insulation is resistant to UV and other environmental factors, and ***does not absorb moisture.*** It can be ***spray applied*** to large surface areas, complex surfaces, and difficult to reach areas.

CryoCoat™ UltraLight™ provides the robust mechanical properties associated with syntactic foam technology in a low-density insulation system (specific gravity from 0.08 to 0.11) with excellent thermal properties. CryoCoat™ UltraLight™ can be used as a mold-in-place insulation system on large, complex and uneven surfaces, or blown into closed molds to form near-net-shape components. CryoCoat™ UltraLight™ UL79 withstands liquid hydrogen temperatures and the elevated temperatures of re-entry from space.

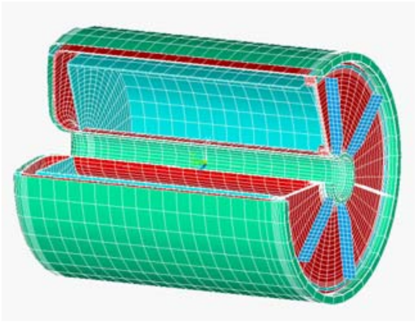
The CryoCoat™ UltraLight™ consists of an adhesive layer, an insulation layer, and an outer moisture barrier/protective coating. Each component can be individually tailored to best meet the requirements of a specific application. For example, for use on a cryogenic fuel tank or rocket engine hydrogen pump, the adhesive layer will use CTD's CryoBond™ 920 adhesive, and the outer coating will be based on CTD's CryoBond™ XVC. The outer coating can be omitted in applications where the insulation will be exposed to a vacuum, improving the overall insulation effectiveness. The outgassing of UL-79 is low enough to maintain a stable vacuum. In applications where the insulation will be formed into a near-net-shaped part, or used on equipment requiring access for maintenance, the adhesive can be eliminated. This will allow easy removal of the insulation. CryoCoat™ UltraLight™ adheres well to itself, enabling easy insulation repair or replacement.





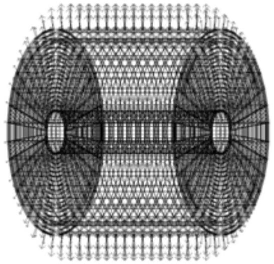
Cryostat/Helium Can/Inner Vessel Stress

Normal operating Pressure is 12 atm
Flat head thickness is 2 cm, Dished head is .5 inch thick, Vacuum Jacket Dished head is .125 in.
Cryostat ID and OD shell thickness is 6.35mm (1/4 inch) (present analysis is based on 5mm)
Material is 316 or 304 SST



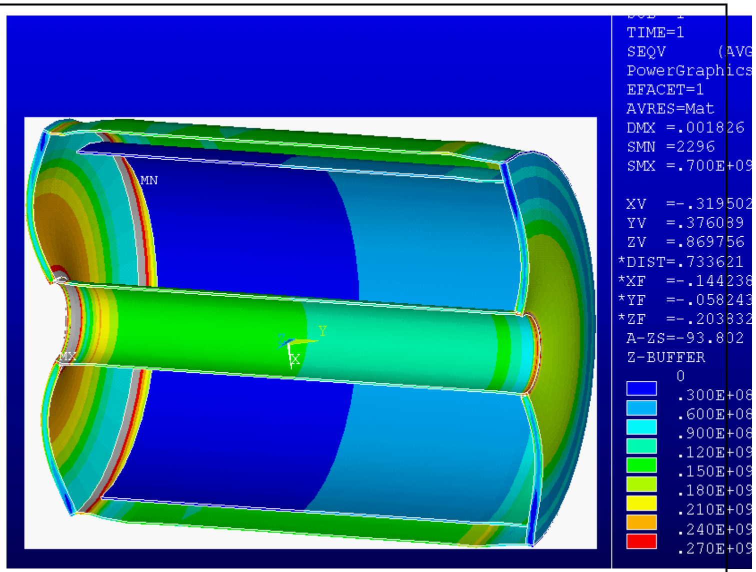
Structure Room Temperature (292 K) Maximum Allowable Stresses,
Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

Material	Sm	1.5Sm – bending
316 LN SST	183Mpa (26.6 ksi)	275Mpa, (40ksi)
316 LN SST weld	160MPa (23.2ksi)	241MPa (35ksi)

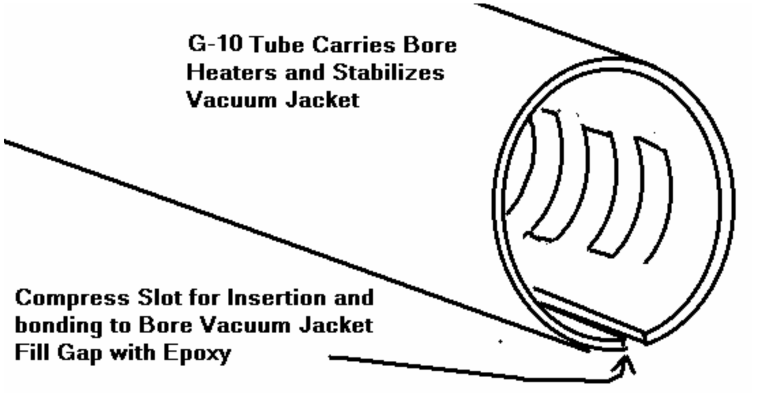


He Can pressure forces.

Local (corner) Stresses were high - 700 MPa. Stiffeners or thicker closure heads were specified to protect the seal welds

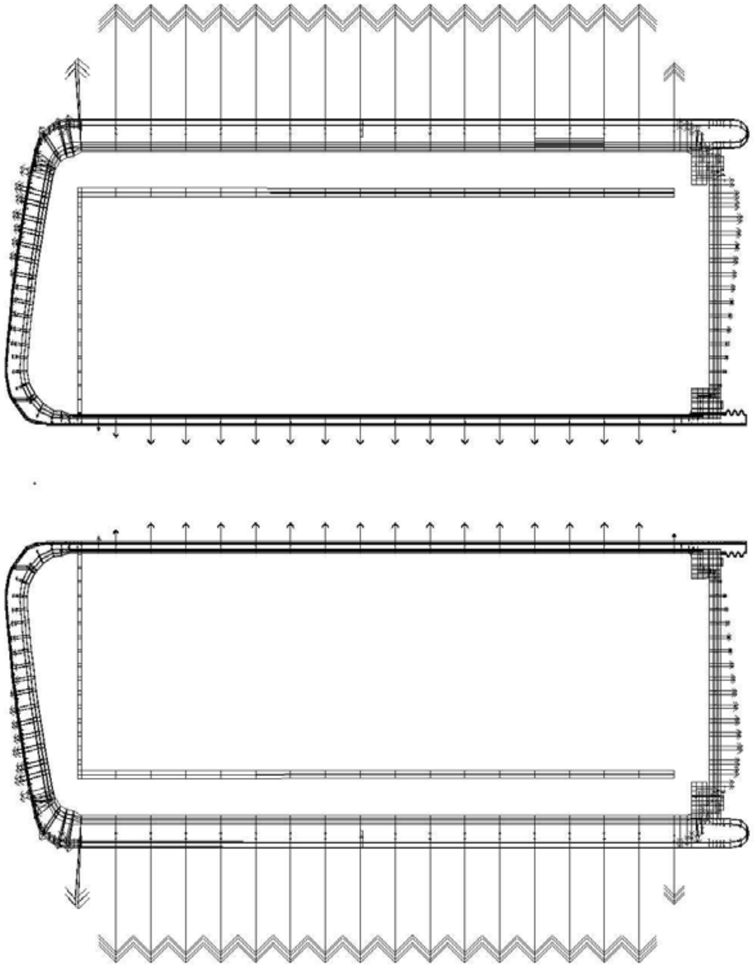


VonMises Stress without ribs.

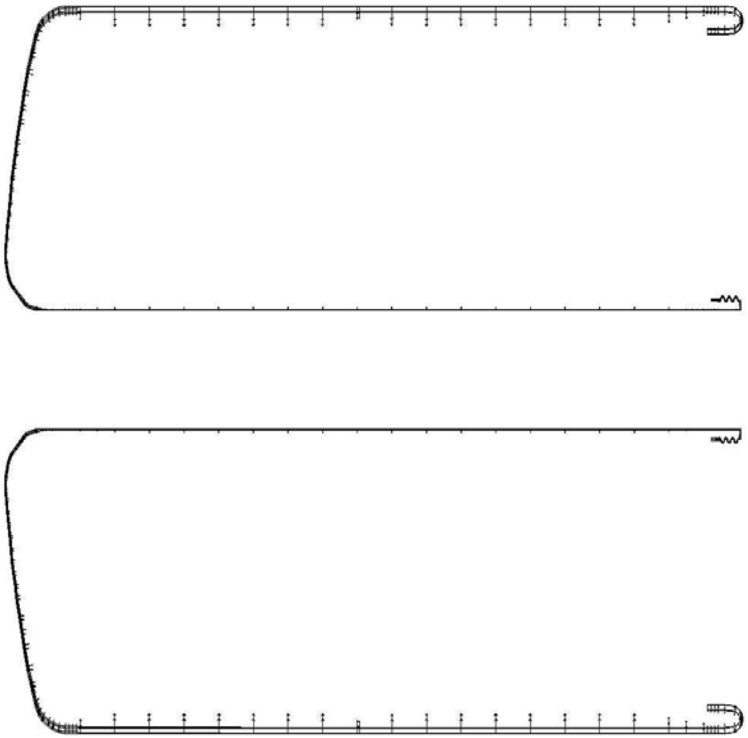


Pressure Load Vectors – Nodal Forces, Pressure times element area

All Cryostat and Vacuum Jacket Stresses (with the exception of the bellows details) satisfy the primary membrane stress of 183 MPa

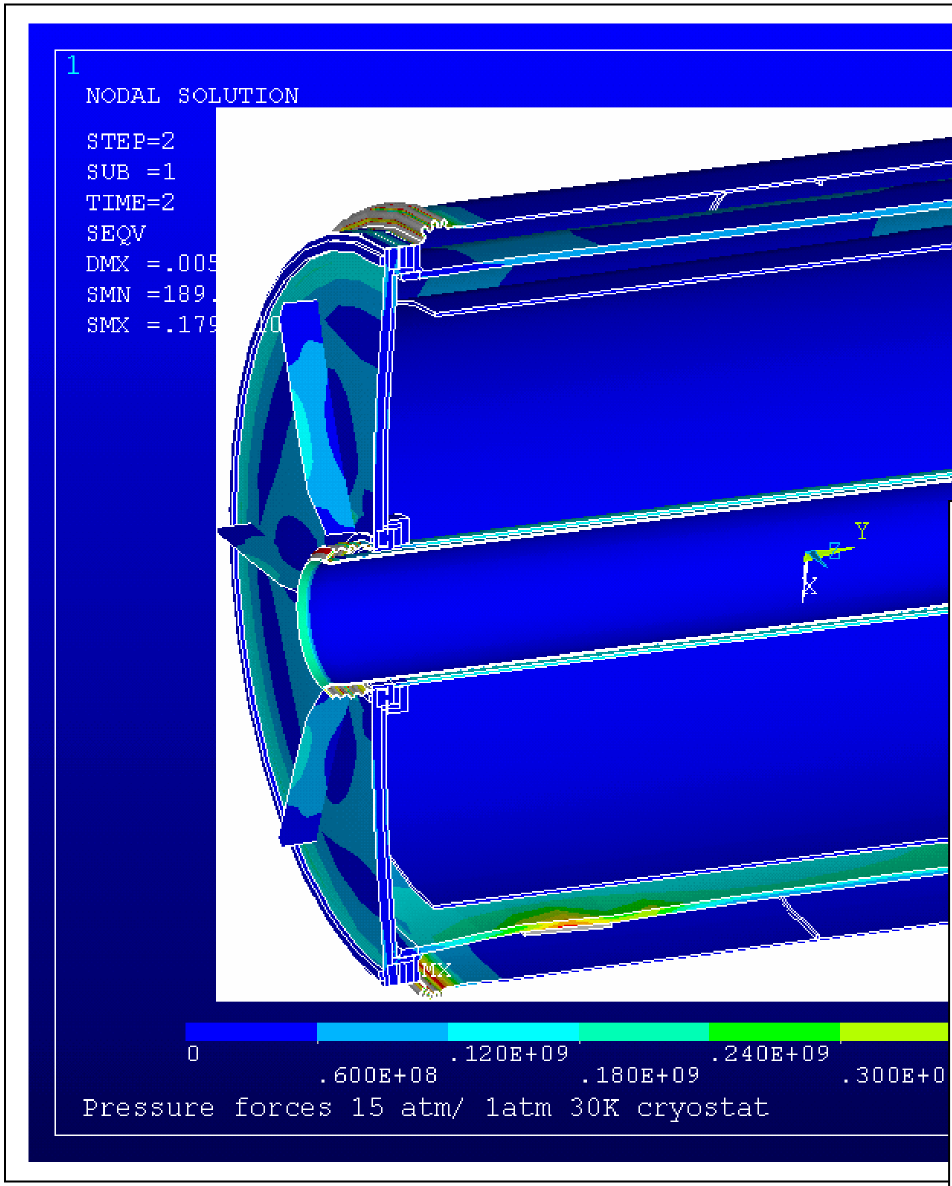


Whole model – Cryostat 15 atm loads dominate



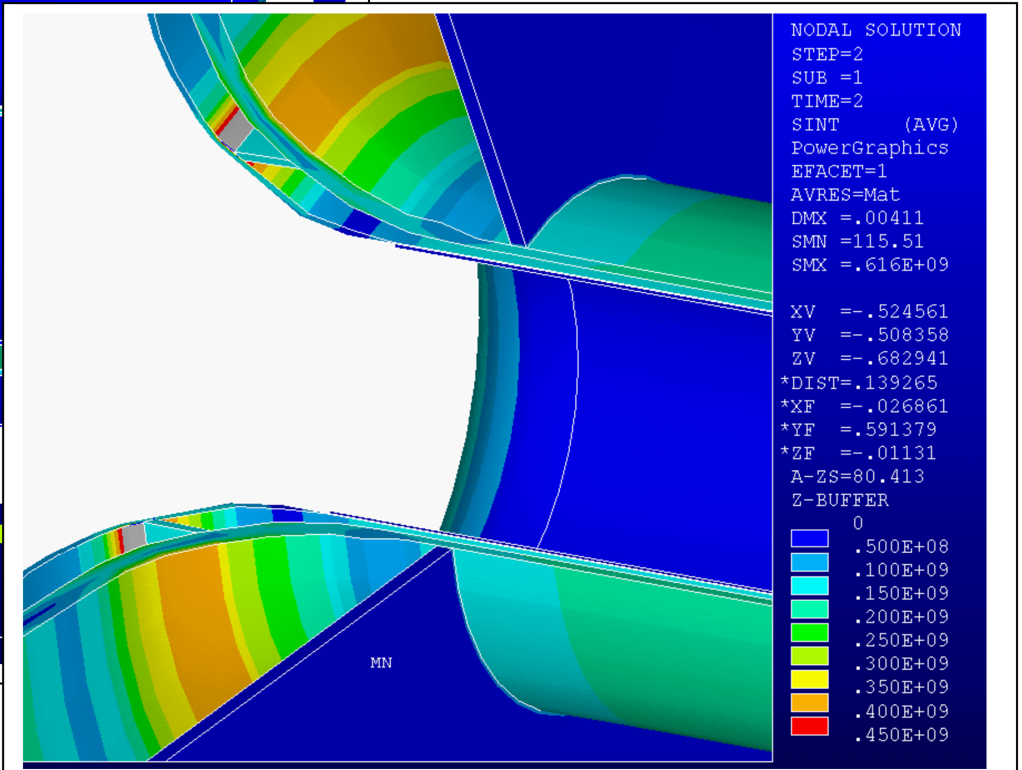
Vacuum loads on vacuum jacket

Cryostat Model



Cover Stiffeners are 1cm thick. (But CVIP has gone back to 2 cm)

Updated bellows models are “representative” They are purchased based on a performance spec.

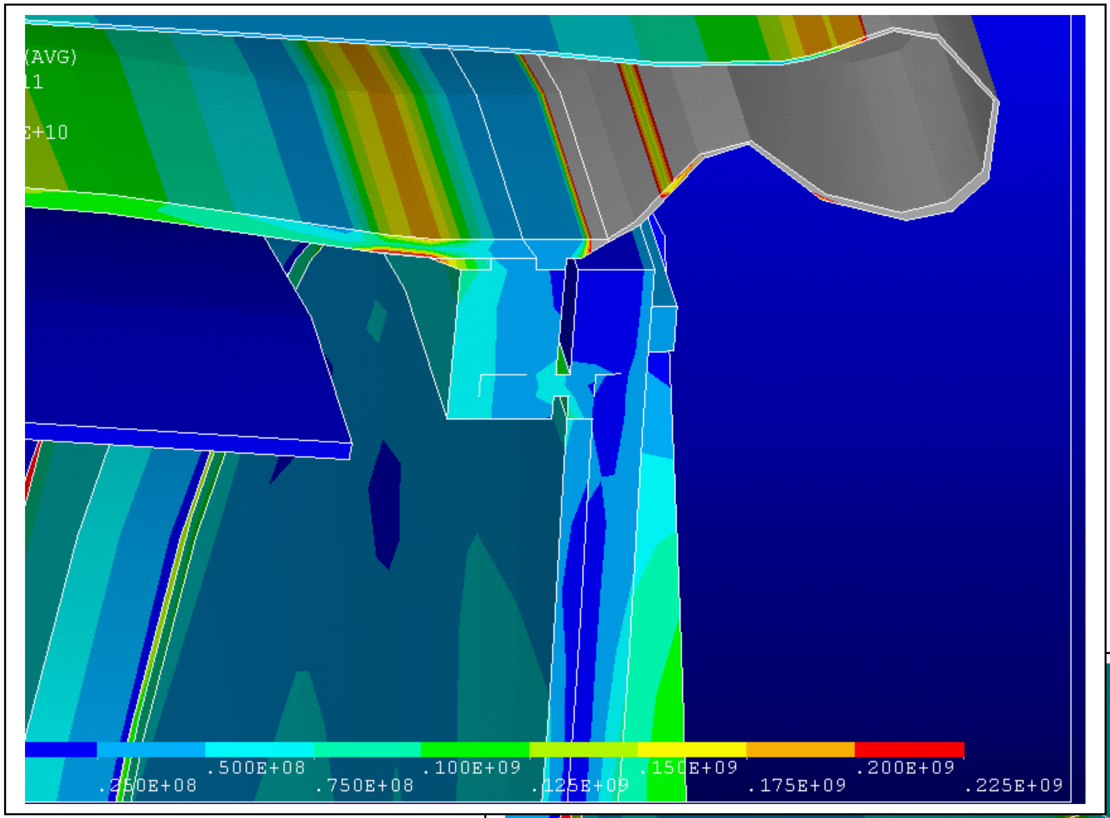


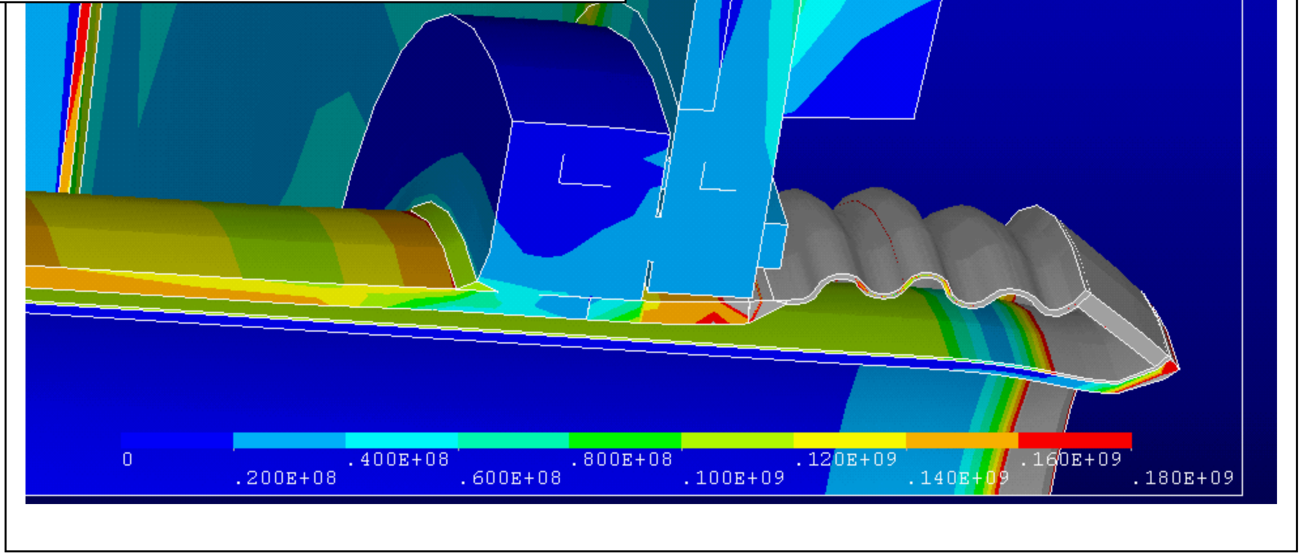
Discontinuity stress(<400 MPa) at Cryostat flare to dished head meets 3Sm allowable at the weld of 480, Membrane stress meets 160 MPa allowable

Local Flange to Shell Connection

Bending stress allowable is 241MPa (room temperature weld allowable in bending)
OD flange stress is at the allowable.
ID flange has a F.S. of 1.5

Bellows details will be specified to sustain the 3 to 4 mm displacement and one atmosphere.

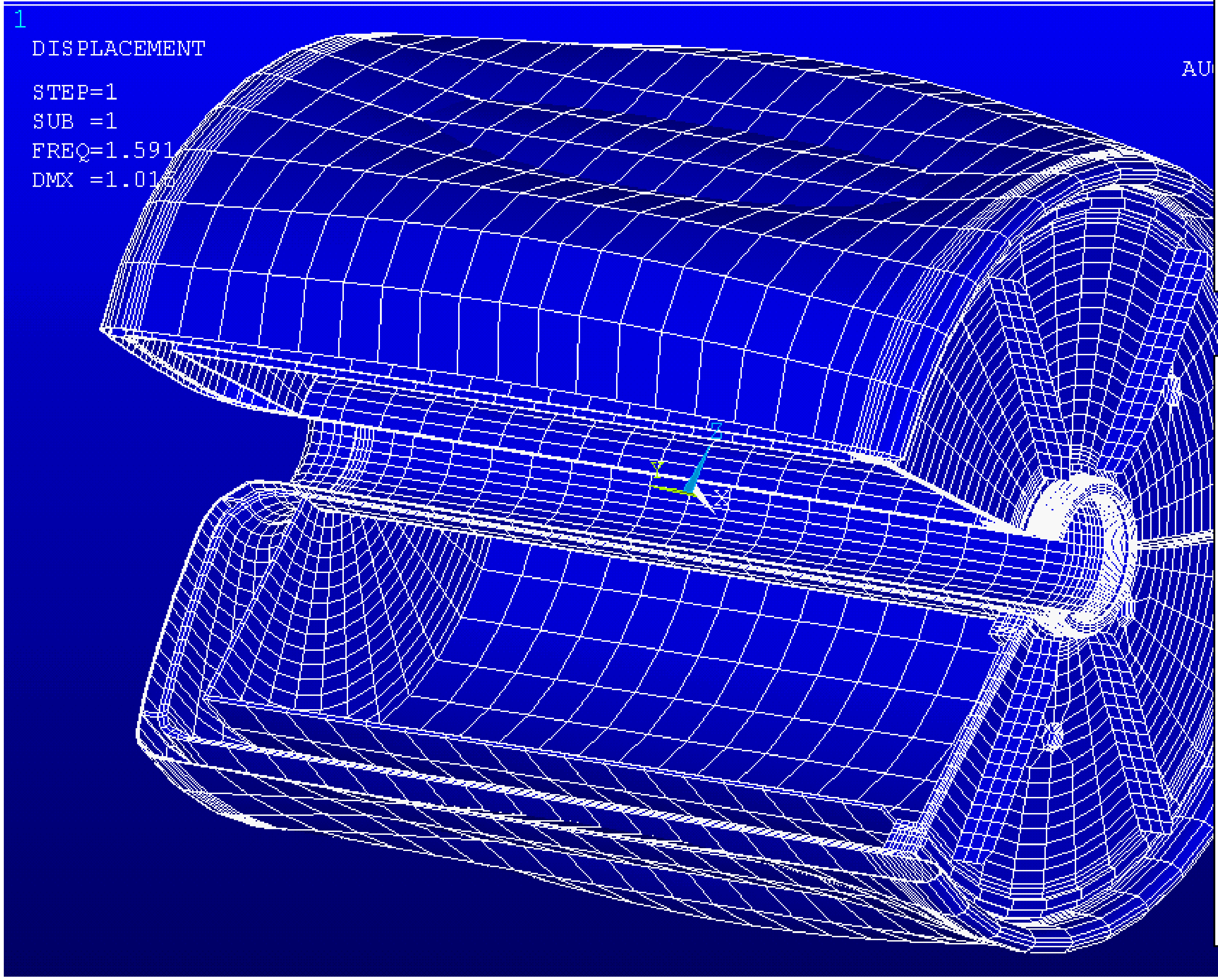




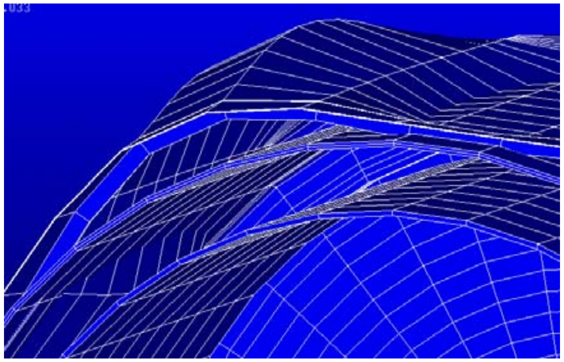
Vacuum Jacket Buckling:

1mm thick vacuum jacket only has a margin of 1.5 against buckling. A factor of 5 is needed.

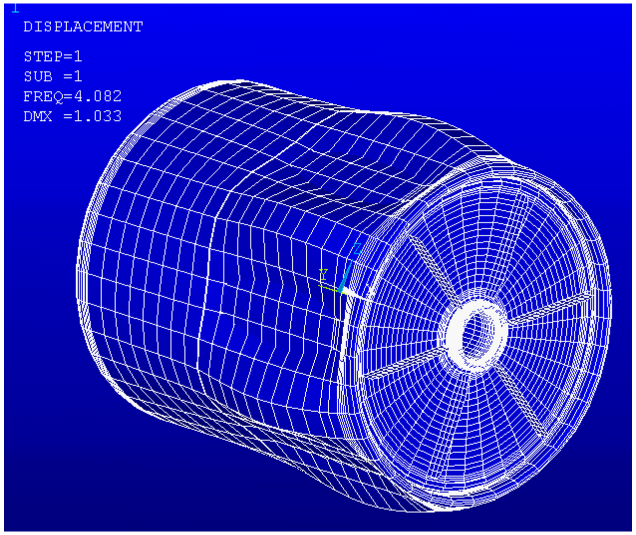
The outer vacuum jacket was thickened to 4.7mm



Eigenvalue Buckling Analysis, Load vector is 15 atm on cryostat and 1 atm on vacuum jacket. Analysis includes Thermal strains and pressure loads.



Stiffener added to inside of cryostat.



Factor against buckling is 4.08 with mid span stiffener.

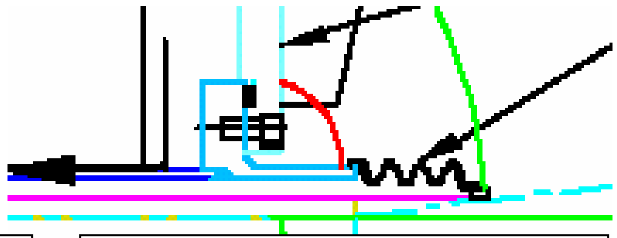
Cryostat/Helium Can Stress – Head Closure Detail

Reviews and small refinements continue

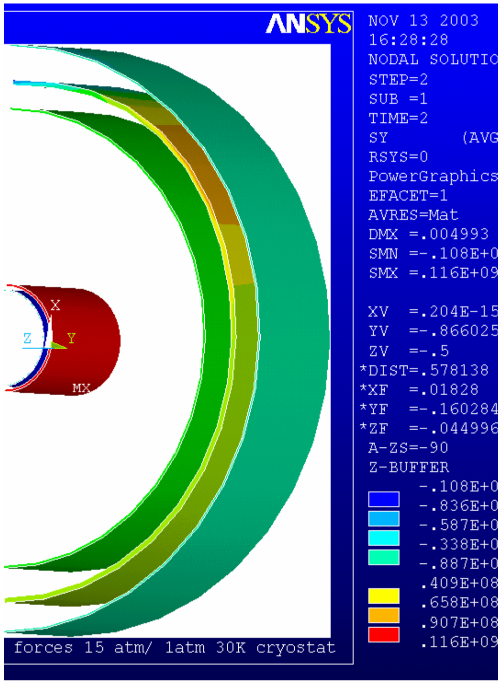
- An example, from a BNL review: - Cryostat bolting thread shear.

Design Pressure= 15 atm

```
Allowable Bolt Stress= 57000
Bolt Ultimate Strength= 110000
Bolt Yield Strength= 95000
Number of Inner Bolts: 24
Number of Outer Bolts: 96
Bolt Tensile Area= .1416   Bolt Thread
Shear Area= .53014376
Tensile Load on inner Cyl: 110378.99
lbs
Tensile Load on inner Cyl: 491009.75 N
Inner Bolt Tensile Stress 32479.694
Inner Bolt Pull Out Shear Stress
8675.2406
Inner Bolt Tensile Factor Of Safety
1.1289105
Inner Bolt Shear Factor Of Safety
1.8443293
Inner Cylinder Stress Based on Bolt
Loading 178.33716 MPa
Tensile Load on outer Cyl: 138553.87
lbs
Tensile Load on outer Cyl: 616342.83 N
Outer Bolt Tensile Stress 10192.581
Outer Bolt Pull Out Stress 1837.6278
Outer Bolt Factor Of Safety 3.5973878
Outer Bolt Shear Factor of Safety=
8.7068776
Outer Cylinder Stress Based on Bolt
Loading 20.309319 MPa
```

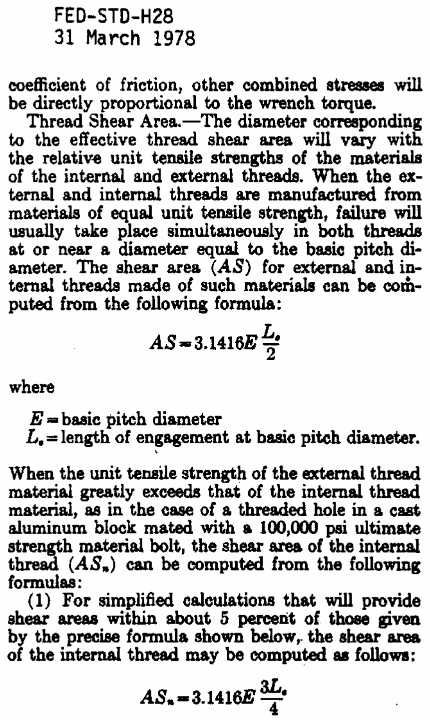


olte



```
NOV 13 2003
16:28:28
NODAL SOLUTIO
STEP=2
SUB =1
TIME=2
SY          (AVG
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.004993
SMN =-.108E+0
SMX =.116E+09

XV   =.204E-15
YV   =-.866025
ZV   =-.5
*DIST=.578138
*XF  =.01828
*YF  =-.160284
*ZF  =-.044996
A-ZS=-90
Z-BUFFER
      -.108E+0
      -.836E+0
      -.587E+0
      -.338E+0
      -.887E+0
      .409E+08
      .658E+08
      .907E+08
      .116E+09
forces 15 atm/ 1atm 30K cryostat
```

The axial tension in the bore tube is 116 MPa, which is lower than the bolt Basic program calculations predict (178 MPa). The reported inner bolt tension



FED-STD-H28
31 March 1978

coefficient of friction, other combined stresses will be directly proportional to the wrench torque.

Thread Shear Area.—The diameter corresponding to the effective thread shear area will vary with the relative unit tensile strengths of the materials of the internal and external threads. When the external and internal threads are manufactured from materials of equal unit tensile strength, failure will usually take place simultaneously in both threads at or near a diameter equal to the basic pitch diameter. The shear area (AS) for external and internal threads made of such materials can be computed from the following formula:

$$AS = 3.1416E\frac{L_e}{2}$$

where

E = basic pitch diameter
L_e = length of engagement at basic pitch diameter.

When the unit tensile strength of the external thread material greatly exceeds that of the internal thread material, as in the case of a threaded hole in a cast aluminum block mated with a 100,000 psi ultimate strength material bolt, the shear area of the internal thread (AS_n) can be computed from the following formulas:

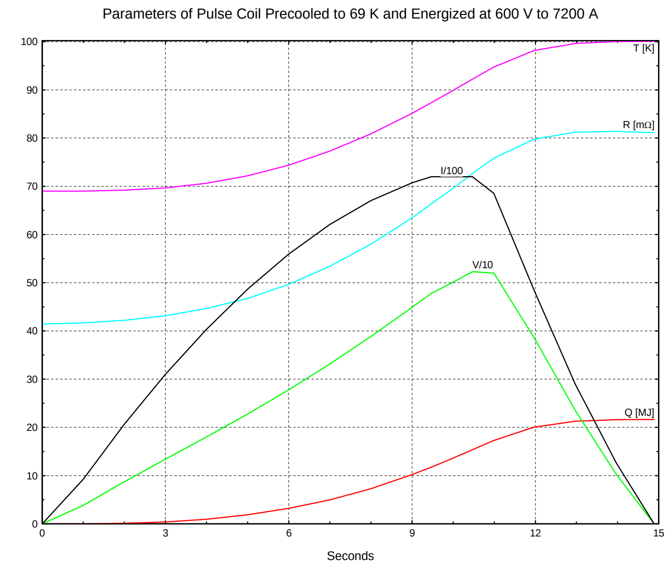
(1) For simplified calculations that will provide shear areas within about 5 percent of those given by the precise formula shown below, the shear area of the internal thread may be computed as follows:

$$AS_n = 3.1416E\frac{3L_e}{4}$$

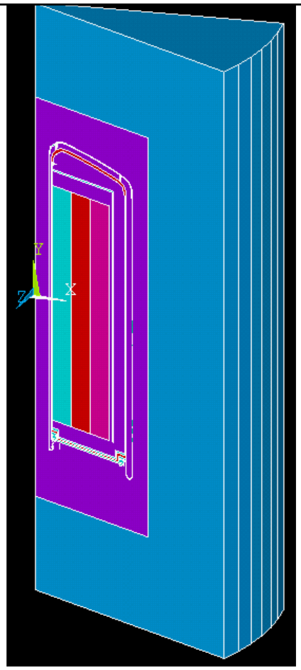
Excerpt from ref 15, the Federal Standards for Screw Threads, showing the recommended thread shear area for strong bolts in a weak threaded hole.

Cryostat Eddy Current Analysis– A Non-Problem for the Magnet and Cryostat – Maybe interesting for the Hg Cassette?

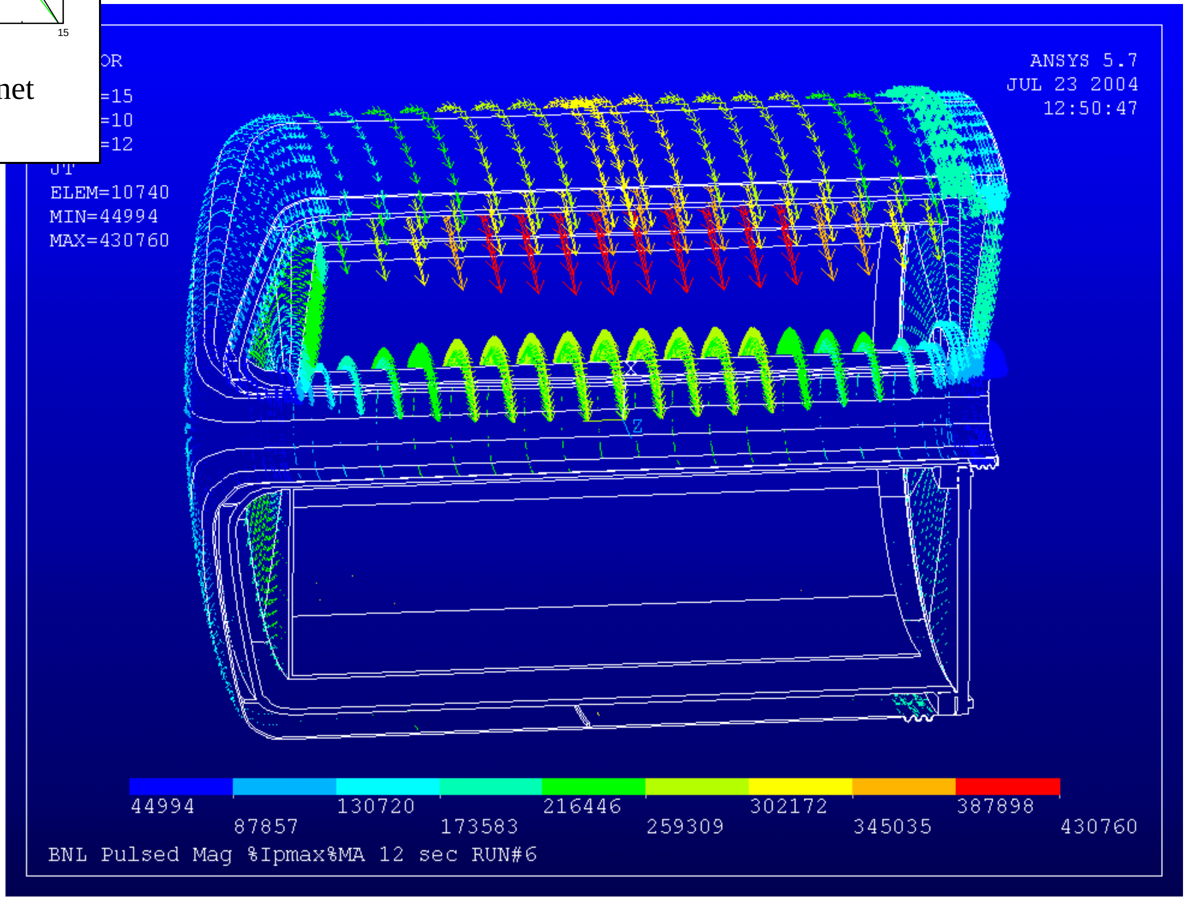
Vector Potential Solution, ~7 sec Ramp-Up , (Weggel 10-14-03 Analysis Used)
Field Loss Due to Eddy's is
of the Order of a few
milliTesla.



Bob Weggel's 10-14 analysis of the LN2 magnet operation

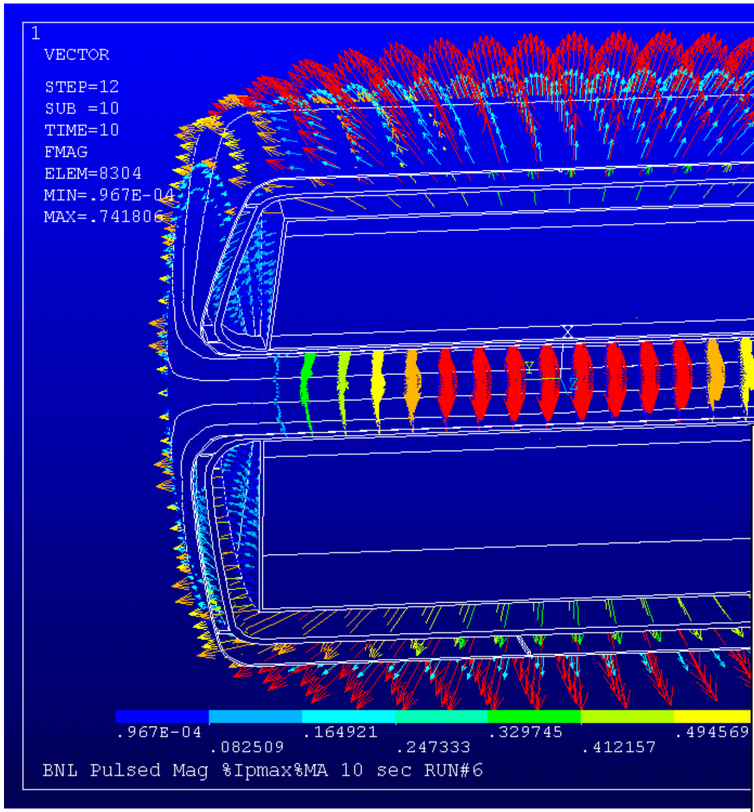


Electromagnetic Model with Air

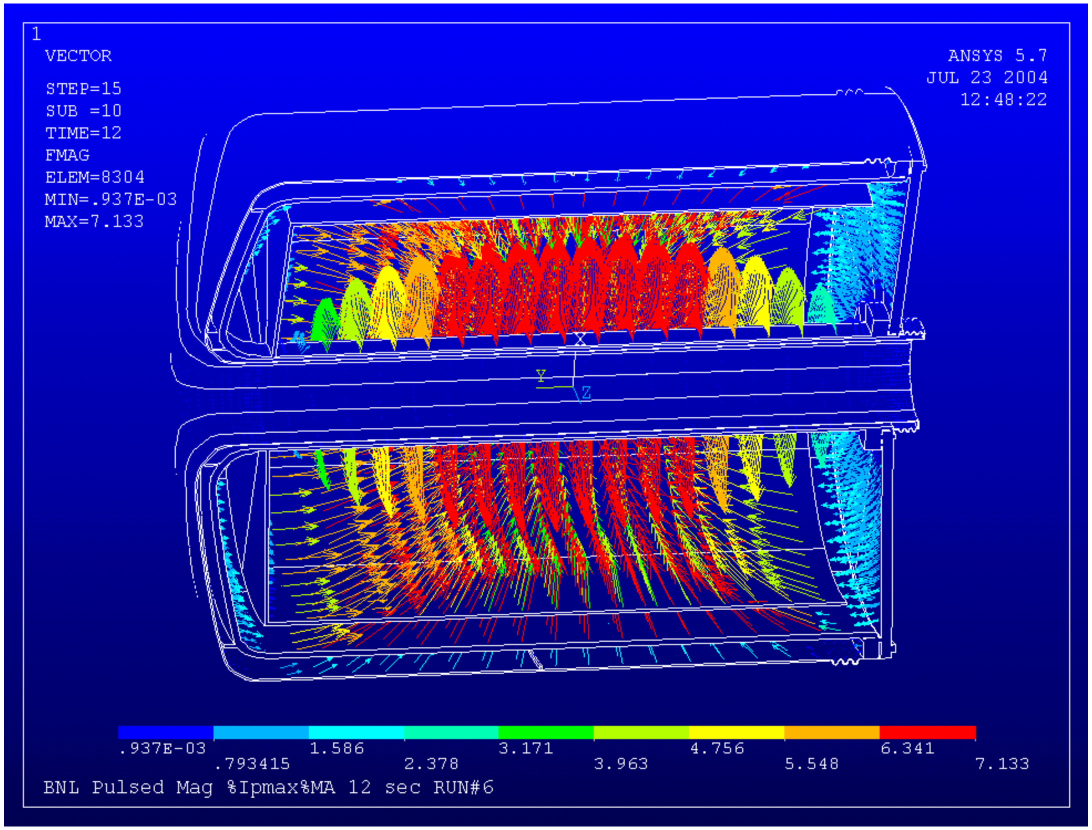


Eddy Currents At Max Stress Point. –Actually During Ramp-Down

Cryostat Eddy Current Analysis



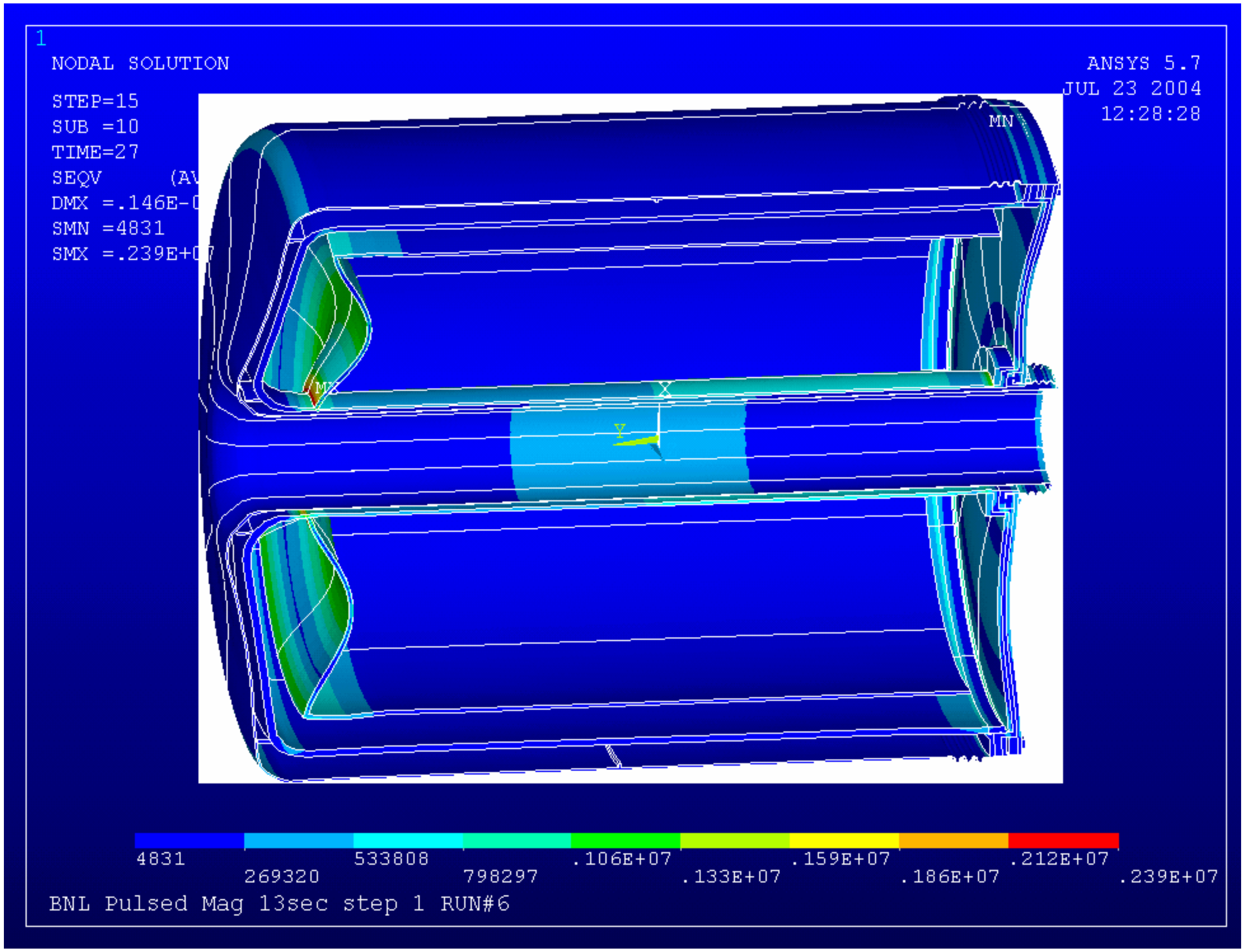
Eddy Current Forces During Ramp-Up

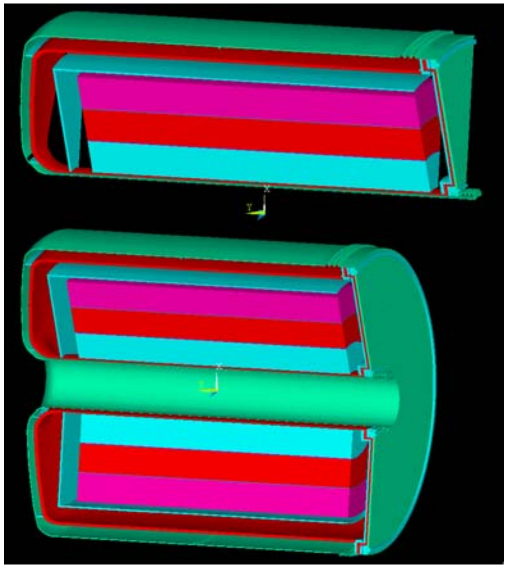


Eddy Current Forces During Ramp-Down

Structural Response to Eddy Currents

Peak Stress is Only 2.4MPa



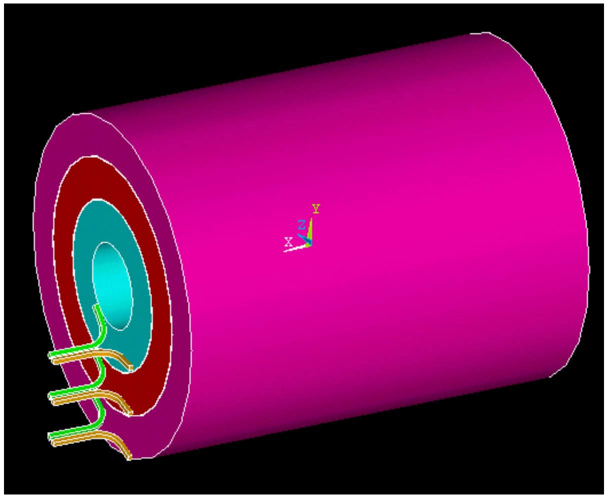


Structural Model (Sub-Set of E-M Model)l Shown with Coils that are removed for structural analysis. The upper plor is the 30 degree cyclic symmetry model, below is a 7 segment symmetry expansion.

Heat-up due to the eddy current loading on the cryostat produces less than 1 degree K

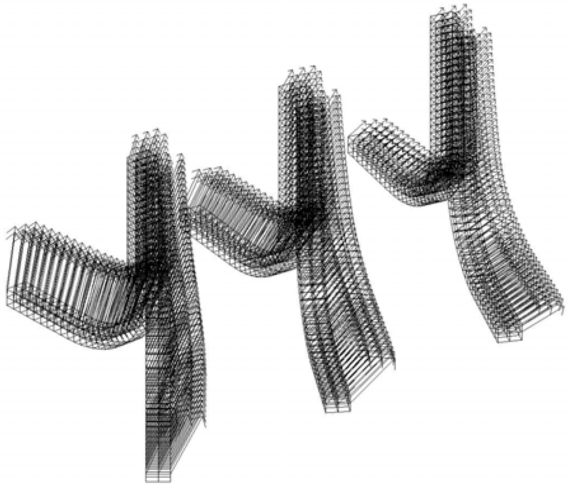
Break-Outs, Leads, and Penetrations

- 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.

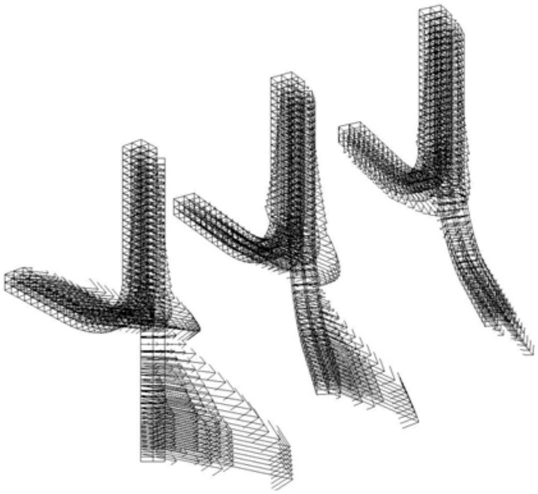


The electromagnetic model.

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

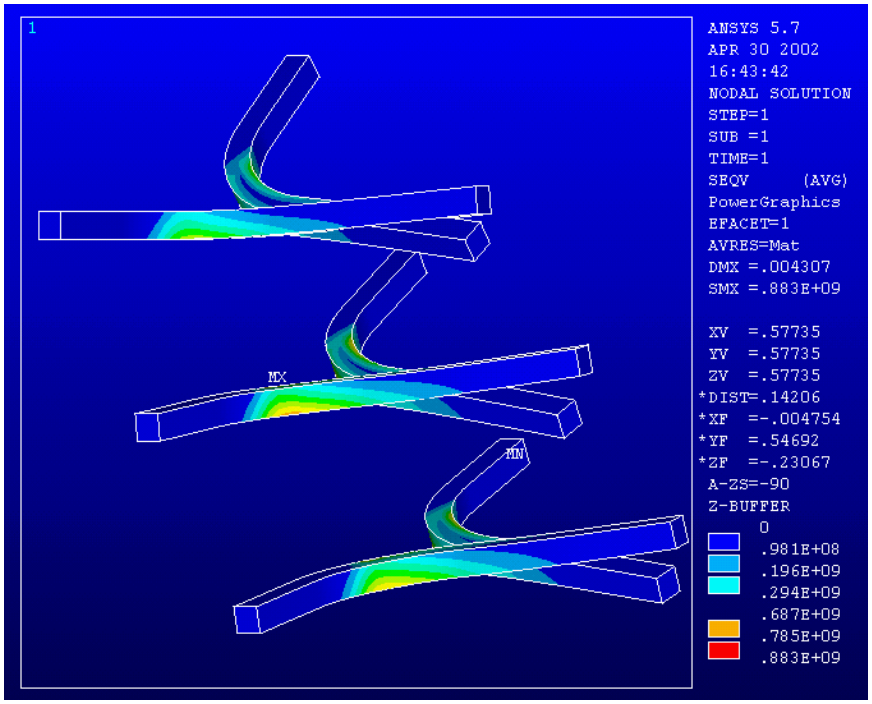


Fields at the break-outs, 15.0T Full field operation.

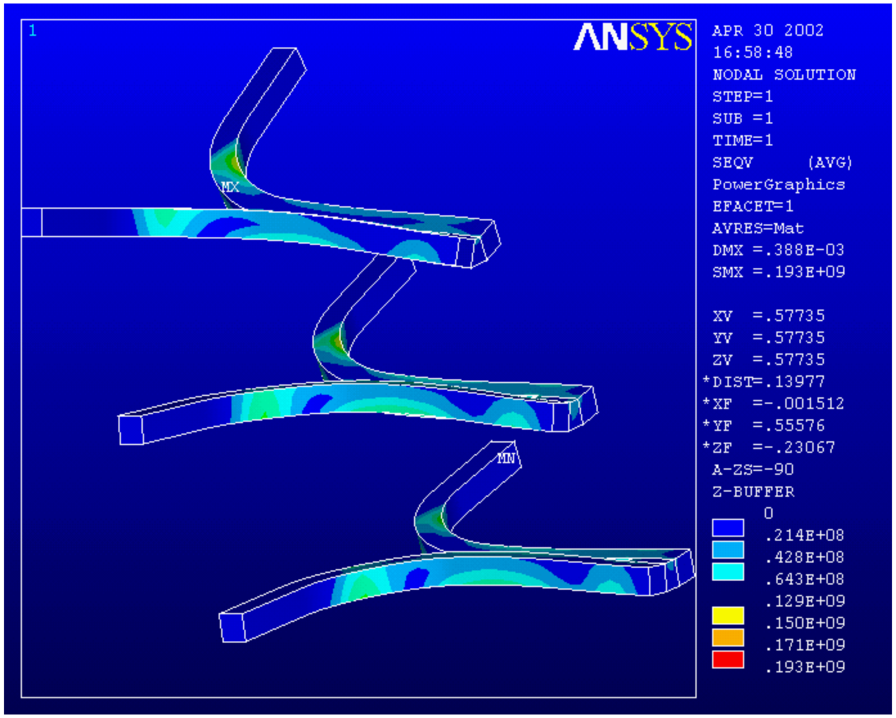


Lorentz Forces at the break-outs. 15.0T Full field operation.

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



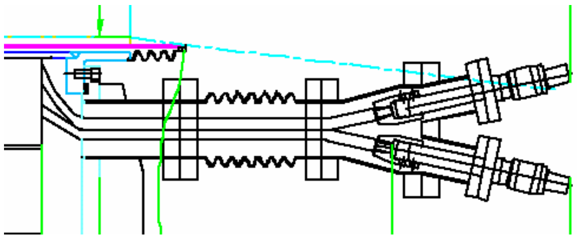
Winding ends well supported, Terminal ends Un-supported and not interconnected. Lorentz Forces Only



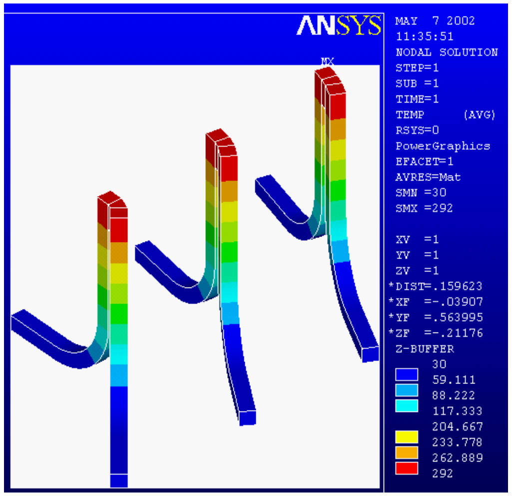
Winding ends well supported, Terminal ends interconnected at the end of the lead pair. Lorentz Forces Only

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.**



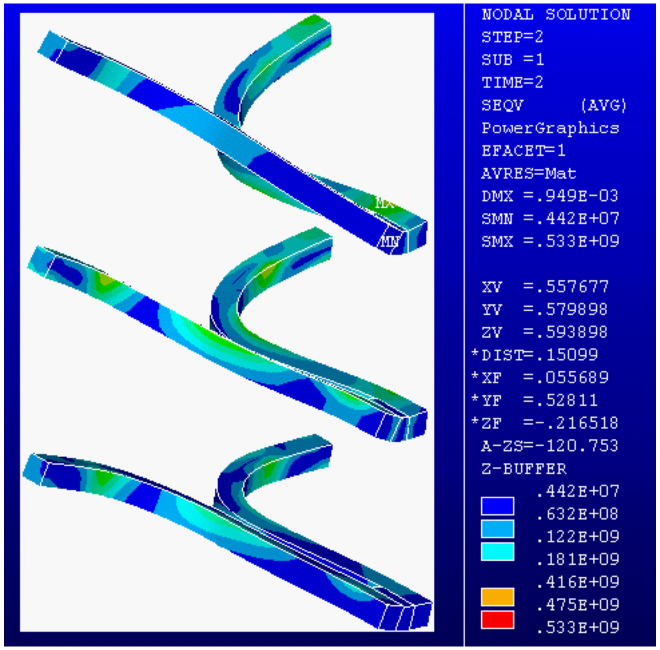
Lead with bellows



```
MAY  7 2002
11:35:51
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
TEMP       (AVG)
RSYS=0
PowerGraphics
EFACET=1
AVRES=Mat
SMN =30
SMX =292

 XV  =1
 YV  =1
 ZV  =1
*DIST=.159623
*XF  =-.03907
*YF  =.563995
*ZF  =-.21176
 Z-BUFFER
       30
       59.111
       88.222
       117.333
       204.667
       233.778
       262.889
       292
```

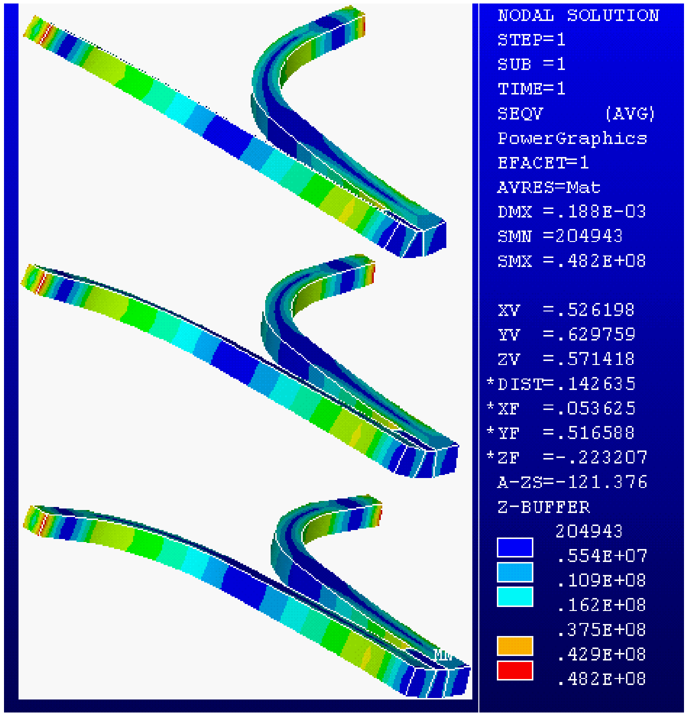
Joint Temperature

- **A conduction solution is used to obtain the temperature gradient for the structural solution**



```
 NODAL SOLUTION
 STEP=2
 SUB =1
 TIME=2
 SEQV      (AVG)
 PowerGraphics
 EFACET=1
 AVRES=Mat
 DMX =.949E-03
 SMN =.442E+07
 SMX =.533E+09

 XV  =.557677
 YV  =.579898
 ZV  =.593898
*DIST=.15099
*XF  =.055689
*YF  =.52811
*ZF  =-.216518
 A-ZS=-120.753
 Z-BUFFER
       .442E+07
       .632E+08
       .122E+09
       .181E+09
       .416E+09
       .475E+09
       .533E+09
```

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.

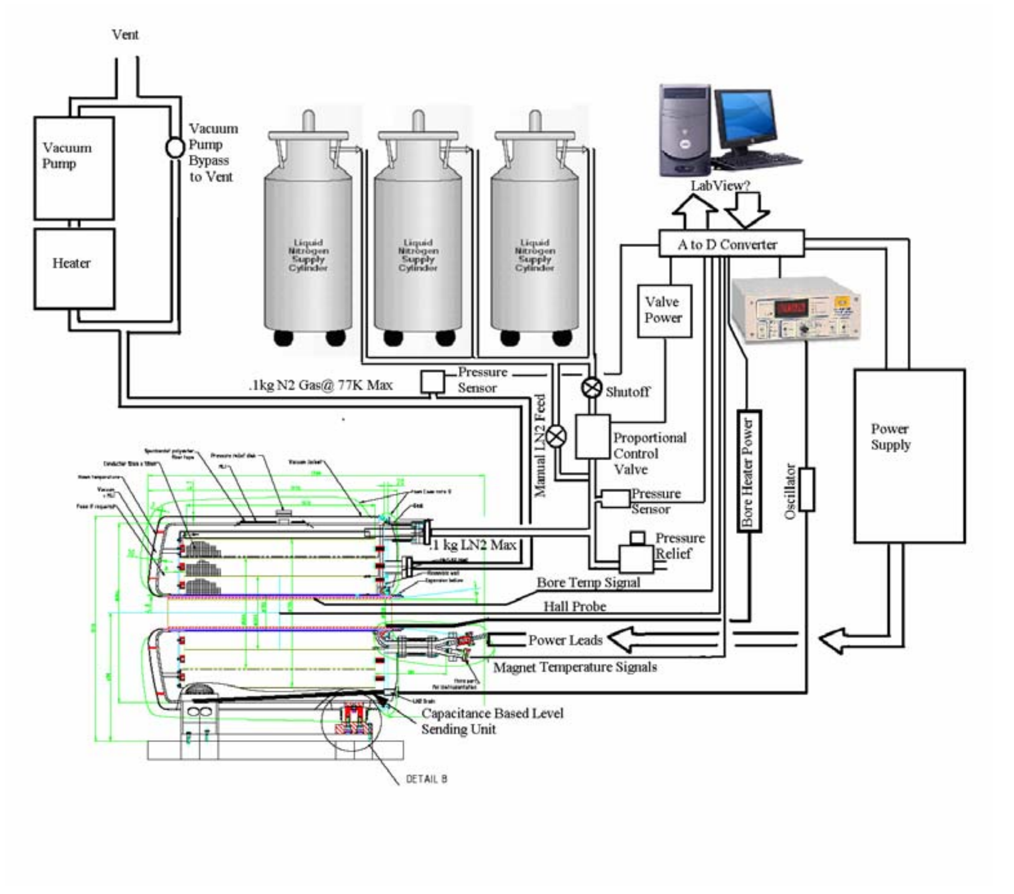


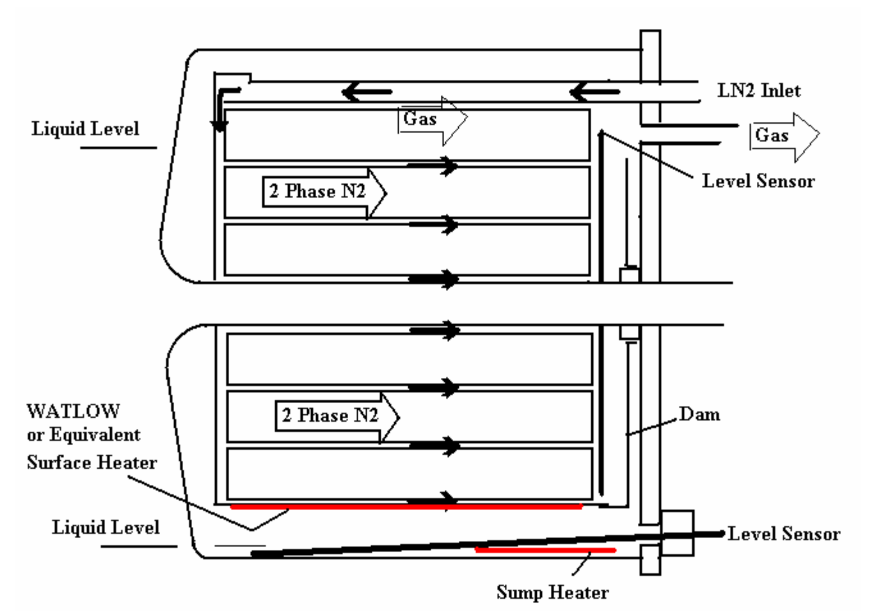
```
 NODAL SOLUTION
 STEP=1
 SUB =1
 TIME=1
 SEQV      (AVG)
 PowerGraphics
 EFACET=1
 AVRES=Mat
 DMX =.188E-03
 SMN =204943
 SMX =.482E+08

 XV  =.526198
 YV  =.629759
 ZV  =.571418
*DIST=.142635
*XF  =.053625
*YF  =.516588
*ZF  =-.223207
 A-ZS=-121.376
 Z-BUFFER
       204943
       .554E+07
       .109E+08
       .162E+08
       .375E+08
       .429E+08
       .482E+08
```

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

Cooldown

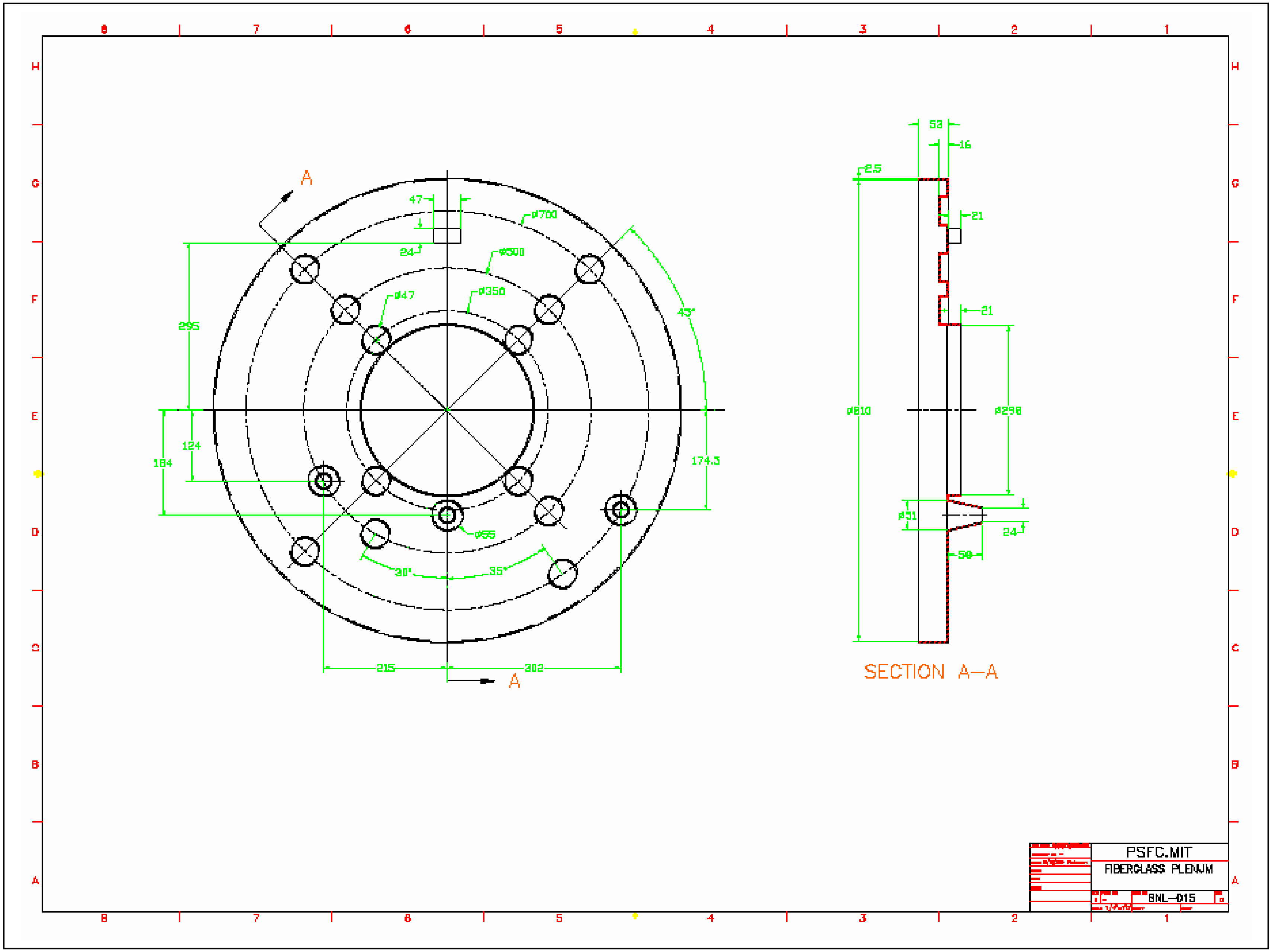
- **Subcooled LN2 Cooling is now the Baseline. Helium Gas Cooling is retained as a Possible Upgrade**
- **Two LN2 Modes are Being Considered:**
    - **Fill – Drain – Then Pulse**
    - **A "Drainless" "Elaborate" LN2 System with flow metering capability.**



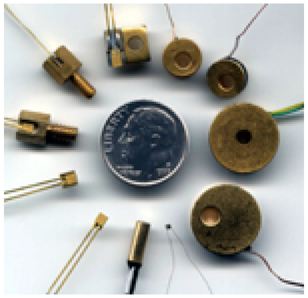


The 10kW Watlow Heater is used To Vaporize the Trapped volume of LN2. The Heater would be turned on at around 300 sec and the 2 phase flow provides Vertical Natural Circulation, and better cover of the magnet.

Dam or Plenum Needed to Restrict LN2 Inventory. Sealing the Break-outs Will be Difficult



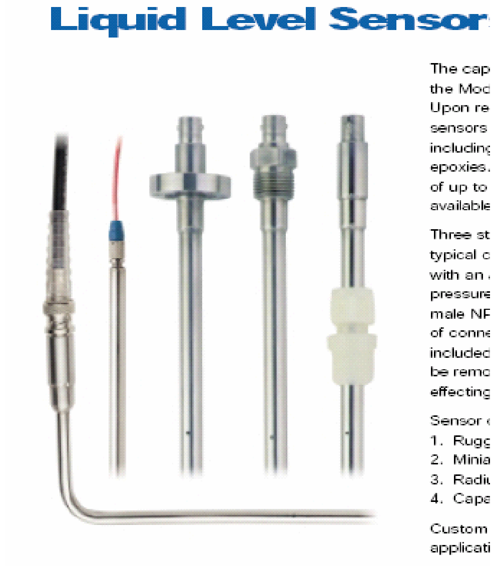
Instrumentation



Cernox™ thin film resistance temperature sensors offer a negative temperature coefficient, monotonic response over a wide temperature range, low magnetic field induced errors and high resistance to ionizing radiation.

- Low magnetic field-induced errors
- High sensitivity at low temperatures and good sensitivity over a broad range
- Excellent resistance to ionizing radiation
- Fast characteristic thermal response times: 1.5 ms at 4.2 K; 50 ms at 77K (in bare chip form in liquid)
- High Temperature Cernox offers a wide temperature range from 0.3 K to 420 K
- Broad selection of models to meet your thermometry needs
- Manufactured by Lake Shore, insuring control over wafer level quality and yield for the future
- Excellent stability
- Variety of packaging options

ISI Insulator Seal



Liquid Level Sensor

The cap
the Moc
Upon re
sensors
including
epoxies.
of up to
available

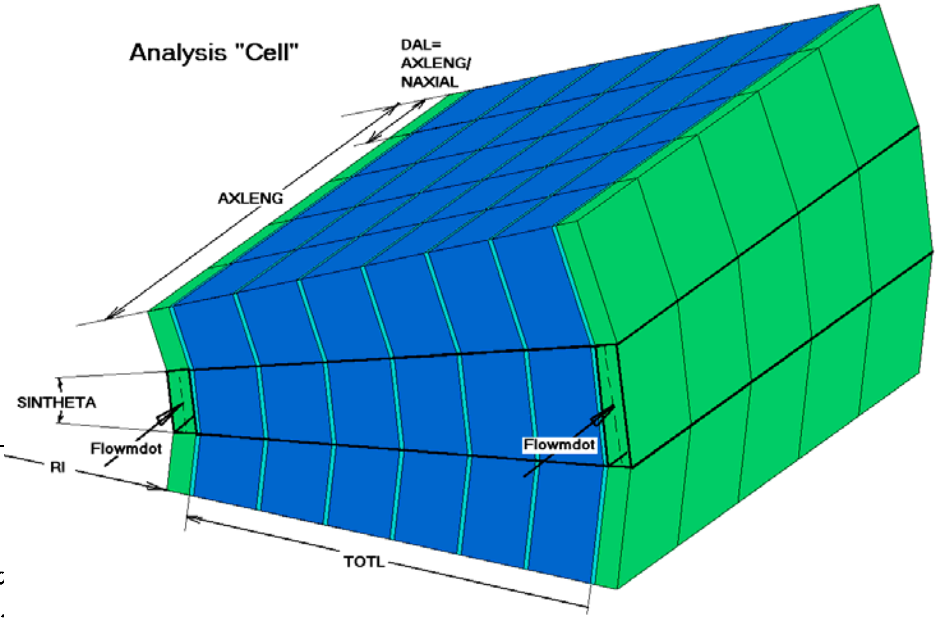
Three st
typical c
with an
pressure
male NF
of conne
included
be remo
effecting

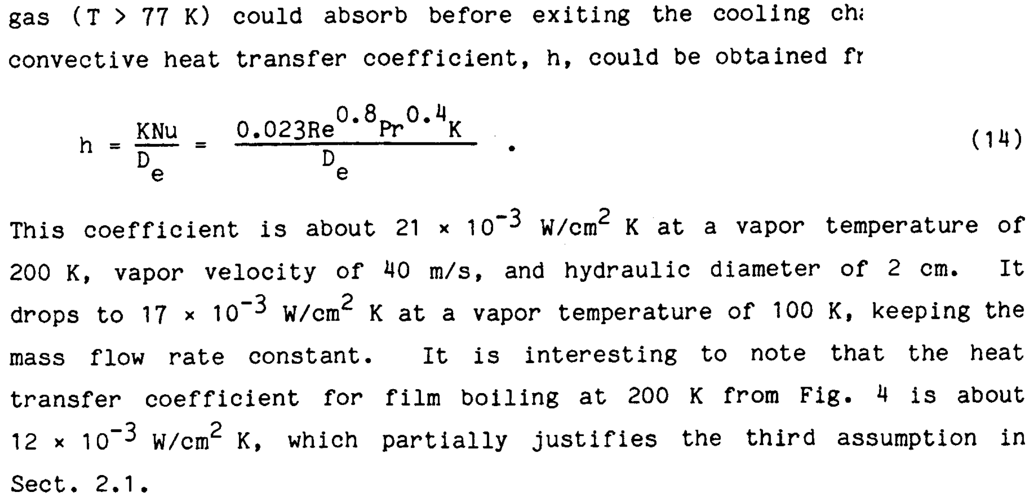
Sensor
1. Rugg
2. Minia
3. Radi
4. Capa

Custom
applicati

Capacitance based level sensor

Cooldown Calculations:
Finite Difference Model is Used.
Axial Channel Flow and
Transient Heat Conduction
Reducing the Kapton between Layers Allows
8 layers to be cooled from axial channels.





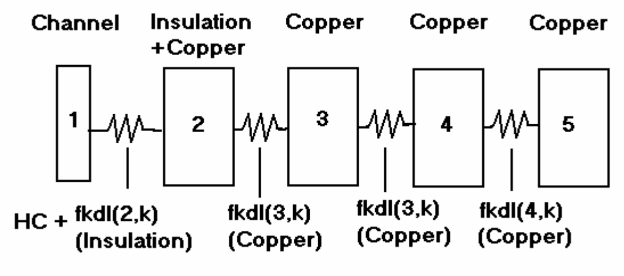
2.1.3 Convective Heat Transfer

It is important to estimate how much heat the superheat
gas (T > 77 K) could absorb before exiting the cooling cha
convective heat transfer coefficient, h, could be obtained fr

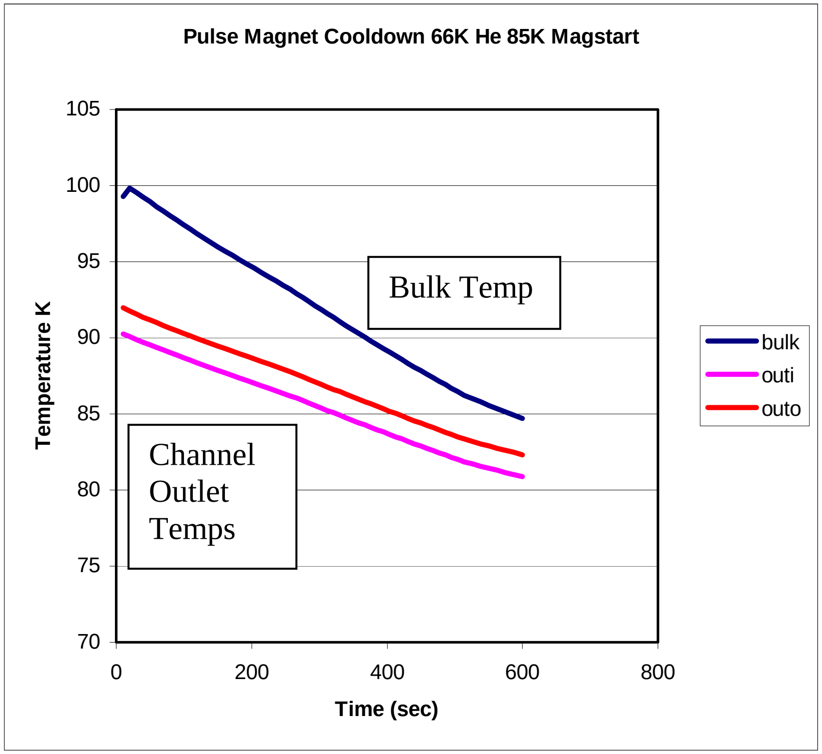
$$h = \frac{KNu}{D_e} = \frac{0.023Re^{0.8}Pr^{0.4}K}{D_e} . \qquad (14)$$

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.

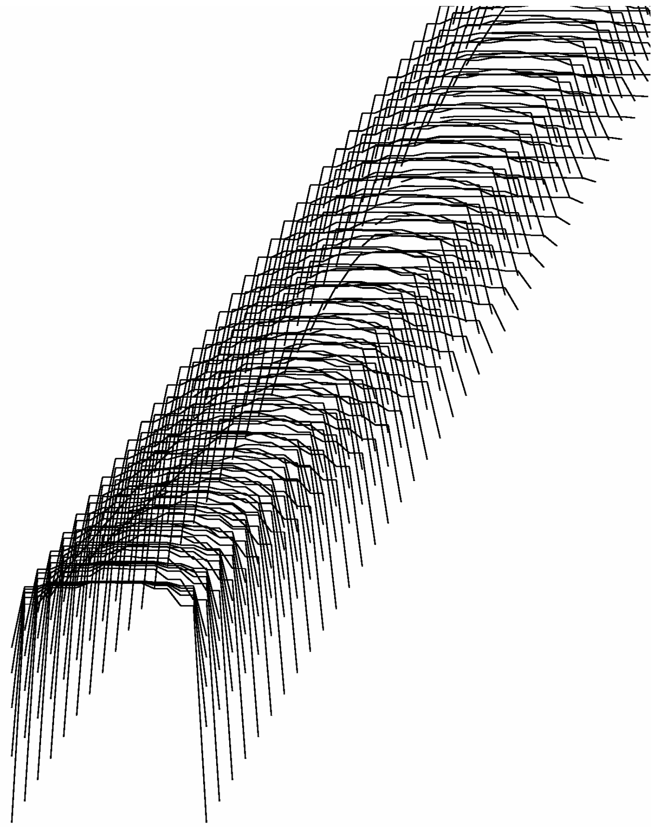
excerpt from: ORNL/FEDC-85-10 Dist Category UC20 c,dated October 1986



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	15.0T	78K	22K	30K	~1500 sec	25.0 min

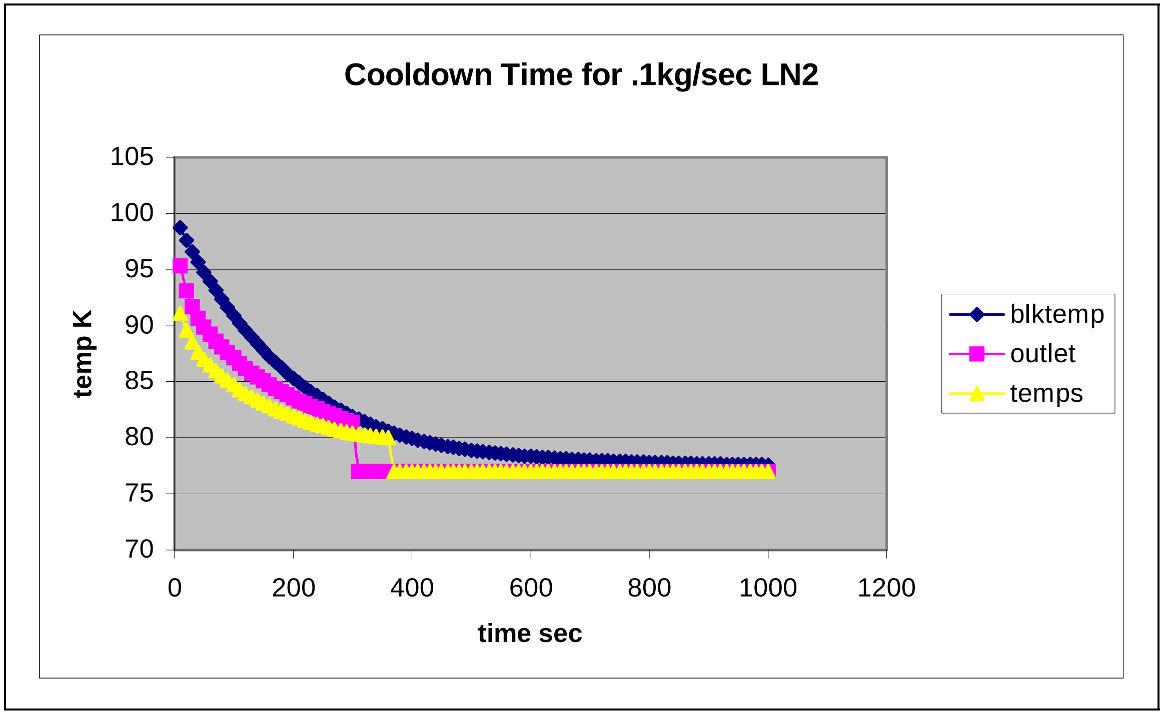
Two Phase N2 Cooling

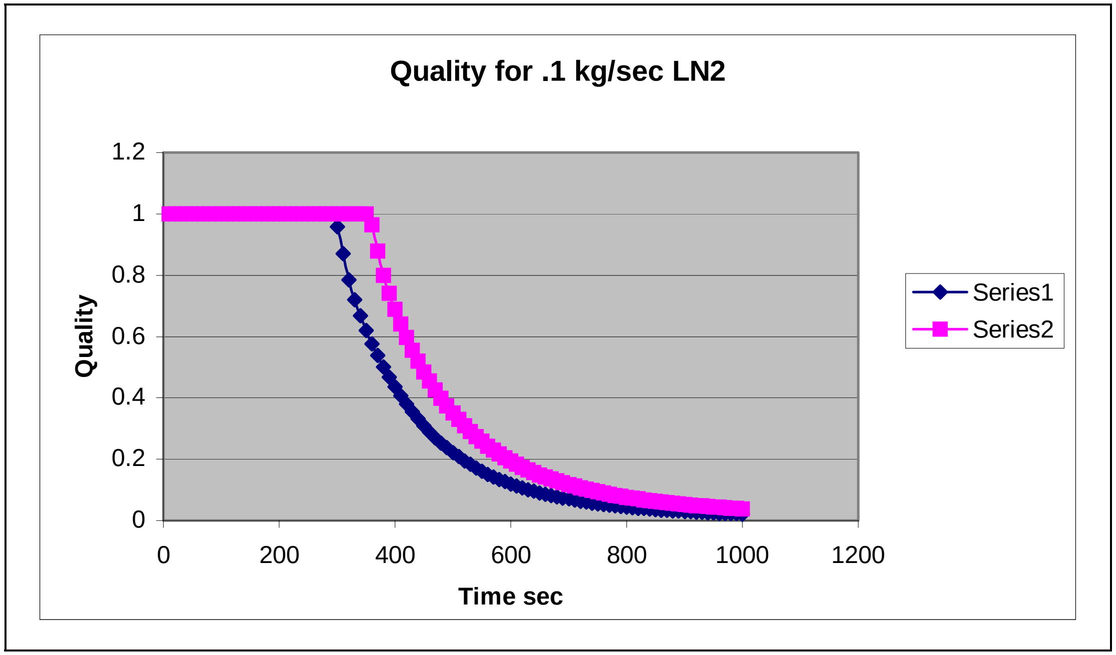
Axial Flow Is Still Assumed in the Analysis.

Design Features are Being Added to Encourage Vertical Natural Convection.

The intention is to control the LN2 flow with a proportional valve to provide only as much LN2 as is fully vaporized by the surface heat flux. After 700 sec, this would be only .1 * .1 = .01 kg/s

For the sub-cooled option requiring the use of a vacuum pump. Directly vent the cold gas until .05kg/sec LN2 is reached.





Vacuum Pump and N2 Gas (and Residual LN2) Heater:

.05 kg/sec of LN2 is 144 cu-m/hr gas flow at RT and 1 atm

```
Exhaust Pipe Flow Velocity, 4in pipe= 16.515614 feet/sec
Exhaust Pipe Flow Velocity, 6in pipe= 7.1942017 feet/sec
Heater Power= 10.608 kW
```

MIT and CERN have Roots Blowers. Two Toyota Vacuum pumps could be purchased, each with 100 cu-m/hr. Vacuum Pump: TBD

```
  !   **  Calculations   ****
clear
let mflow=.05   !kg/sec   Vacuum Pump Flow
let N2gasden=1/.7996   !kg/m^3 STP ref air liquide web site
let N2gasspht=1.04   !kJ/kg/degc   ref air liquide web site
print "Gaseous Nitrogen Density=";N2gasden;"kg/m^3"
print "Gaseous Nitrogen Specific Heat=";N2gasspht;"kJ/kg/degC"
let N2gasden=1.25   !kg/m^3 STP ref air liquide web site
let vflow=mflow/N2gasden*60*60    ! cu meter/hr
print "mass flow=";mflow;"kg/sec"
print "volume flow=";vflow;"cu-m/hr"
let vflow= vflow*(39.37^3/12^3)/60/60      !cu ft/sec
print "volume flow = " ;vflow; "cu ft/sec"
let area6=.5^2*pi/4
let area4=.33^2*pi/4
print "Exhaust Pipe Flow Velocity, 4in pipe=";vflow/area4;"feet/sec"
print "Exhaust Pipe Flow Velocity, 6in pipe=";vflow/area6;"feet/sec"
let heatpower=mflow*N2gasspht*(292-88)      !kJ/sec or KW
print"Heater Power=";heatpower;"kW"
end
```

Thermacast Heater

Vacuum Pump Inlet Heater

For a standard 12KW he provided a budgetary price of $4600. Because of the low pressure we might need a larger heat transfer area. This was estimated at $8500. It looks like this would have to be engineered a bit. The unit size is 2’ by 1’ by 4’ tall. So we can get it into our lab. Their web page is at:

http://www.thermaxinc.com/indirect.htm

Thermacast™ Electric Vaporizers and Trim Heaters

Cover Functions:

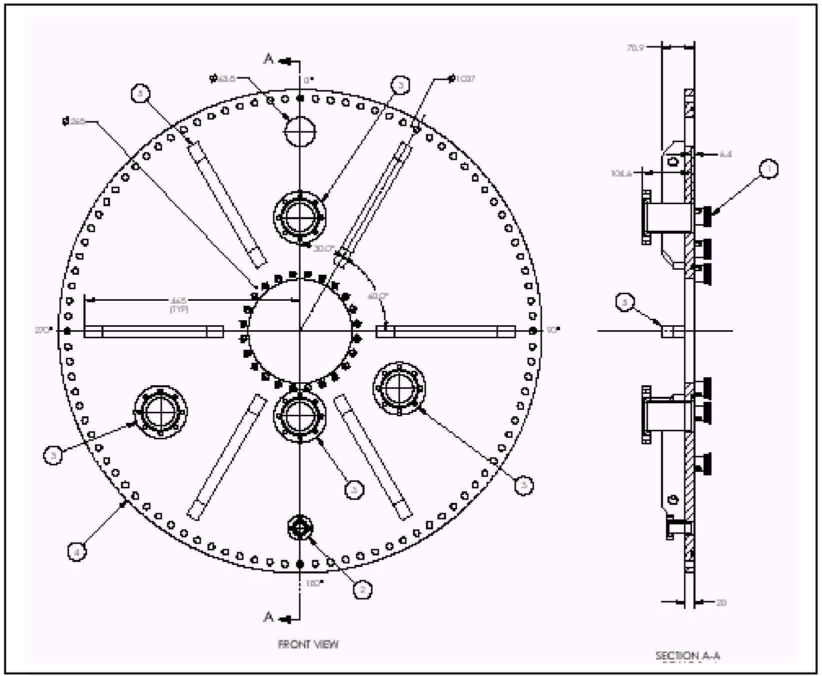
Instrumentation Adjustments – Level Indicators, and Temperature Sensors

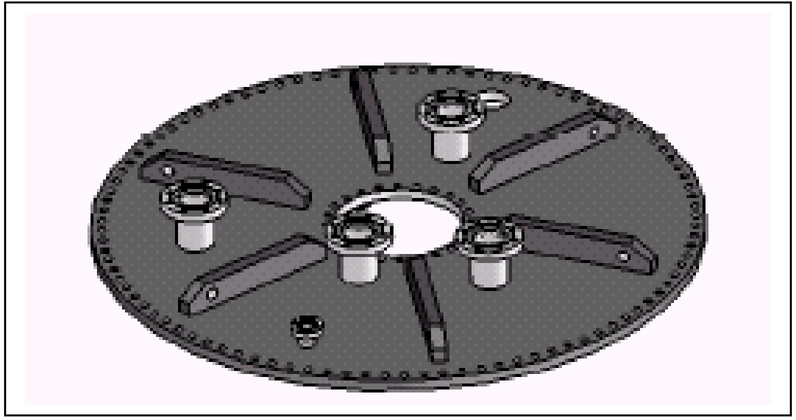
Spring activated metal “C” seals are specified. These are nominally single use, but can be re-used if high vacuum or high pressures are not required, and small leak rates (cc’s per hr) can be tolerated.

Flow Equalization

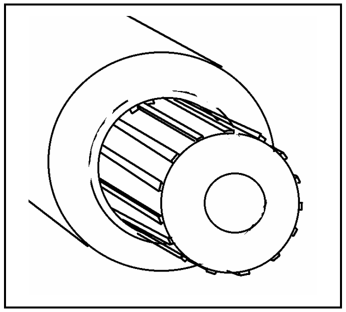
Specification Content:
The Seller shall perform a flow test of the assembled magnet by blowing air in the Helium outlet connection, and with the flat cover of the cryostat removed, flow velocity of each channel shall be measured with a Pitot tube. Restrictions on the channels will be applied until uniform flow is achieved. Restrictions can be in the form of g-10 strips bonded into portions of the channel opening.

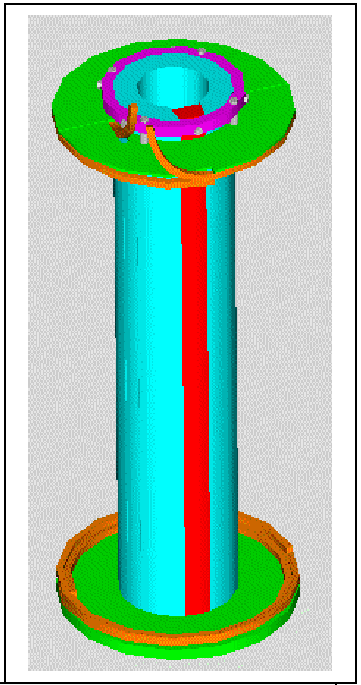
(This will have to be replaced with something more appropriate to LN2 cooling





Assembly and Manufacture





The Coil is layer wound

The Coil is made in three segments. Phased manufacture is allowed

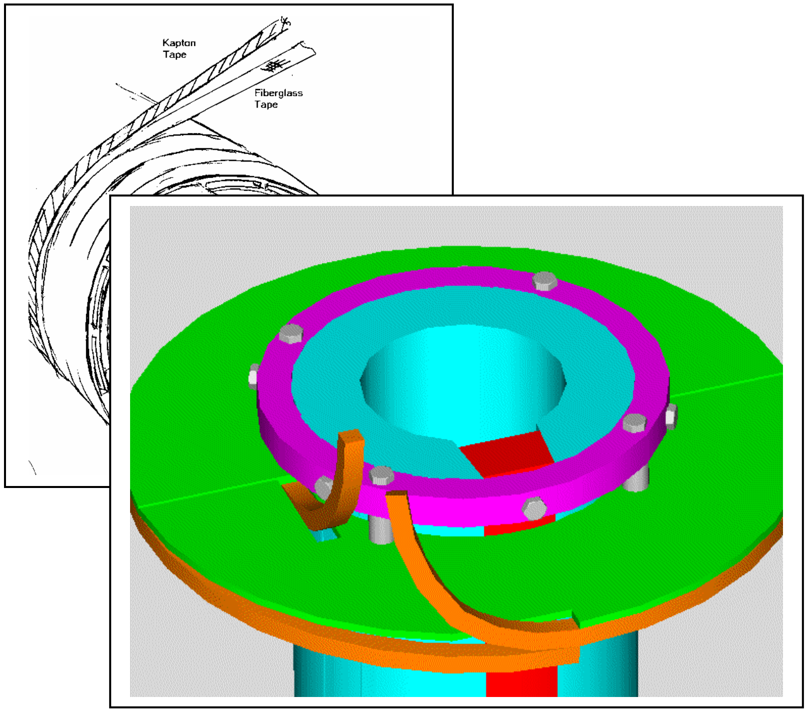
Three separate mandrels are planned.

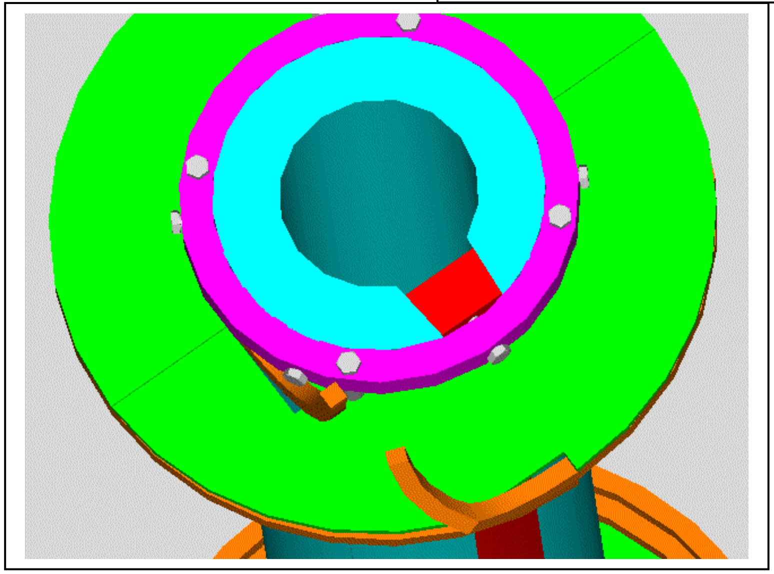
Mandrels maintain a precise bore geometry

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





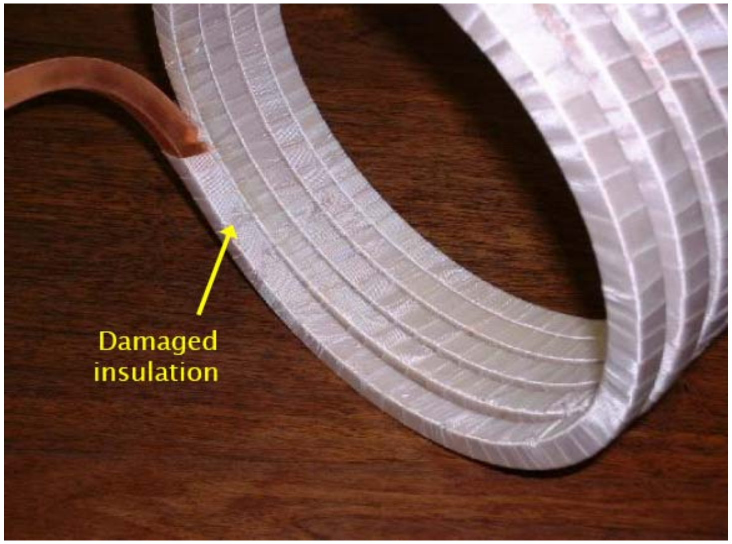
Assembly and Manufacture

Winding Procedure Specification Content:

The bidder shall describe his proposed winding procedure, and any change to the purchaser's suggested procedure as a part of bid proposal. Prior to purchase of the conductor, the Seller shall perform a test bend of a sample length of conductor, over a mandrel or bend fixture which has minimum radius required for winding the coil segment. The conductor sample shall have the same physical properties, - yield strength ultimate and % elongation, as the specified conductor. The test sample of the conductor shall be wrapped with glass tape, and the mandrel surface shall have a Kapton sheet applied. Cuts in the Kapton, or tears in the fiberglass tape shall be reported to Purchaser for resolution.

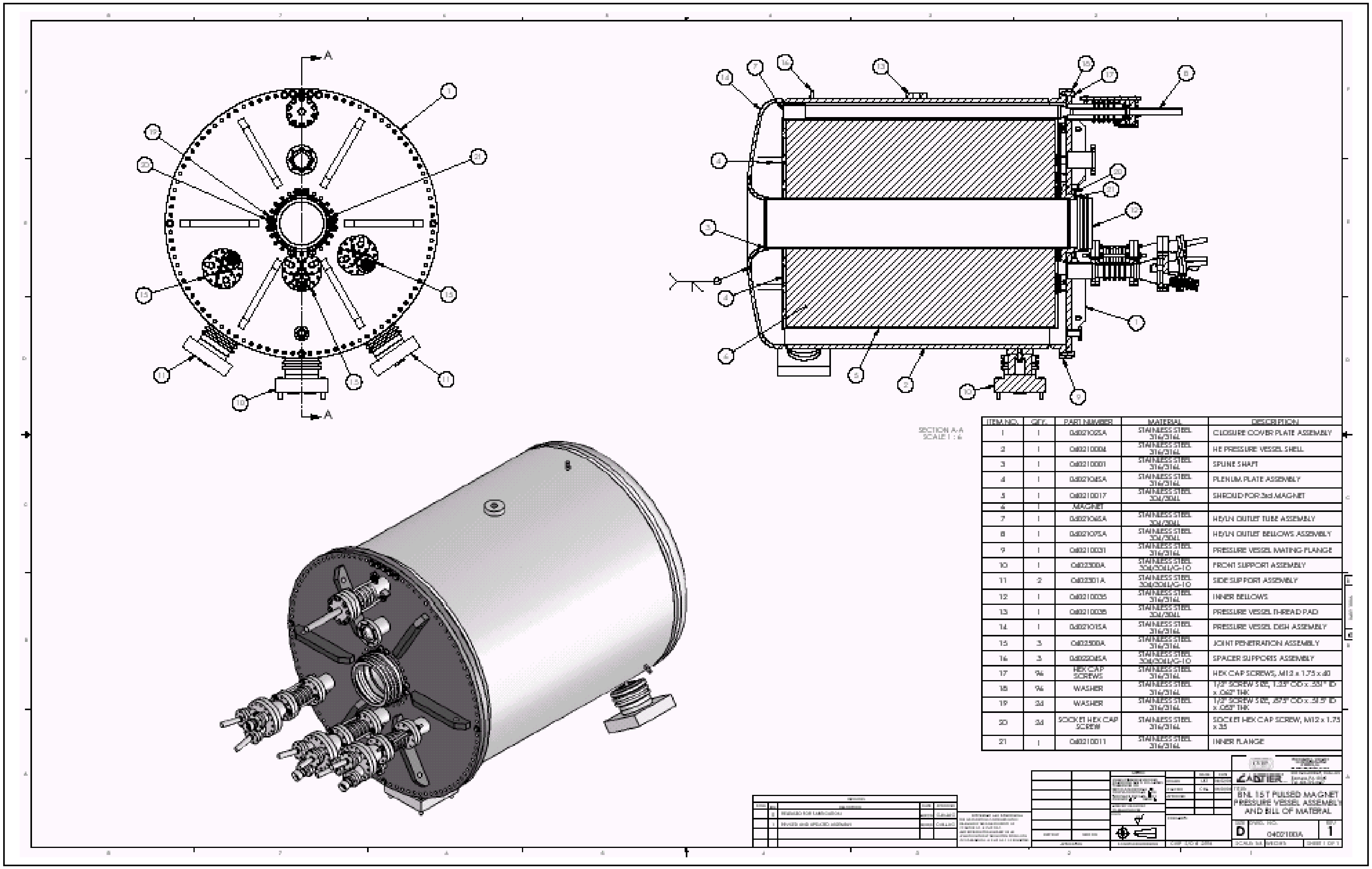
Results :

- Feed rollers needed to be modified to avoid cuts in the fiberglass tape
- Keystoning was a bit more severe than anticipated. Provision has been made for longer magnet.



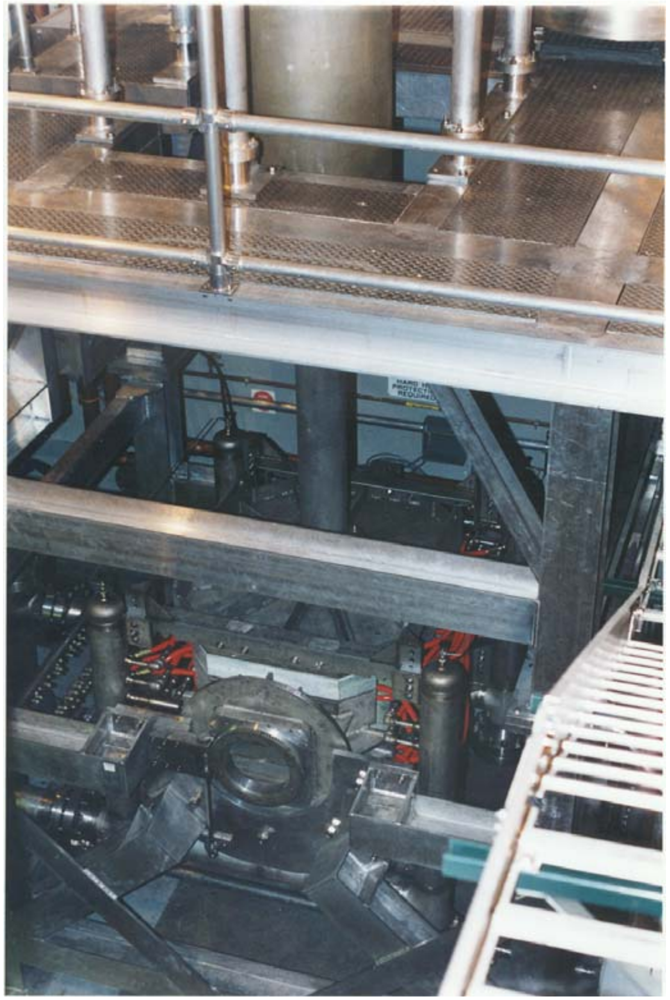
Results of the test bend. Roller geometry was improved to avoid fiberglass tape cuts.

CVIP Manufacturing Drawings are Nearly Complete.



ITEM NO.	QTY.	PART NUMBER	MATERIAL	DESCRIPTION
1	1	04021025A	STAINLESS STEEL 316/316L	CLOSURE COVER PLATE ASSEMBLY
2	1	040210004	STAINLESS STEEL 316/316L	HE PRESSURE VESSEL SHELL
3	1	040210001	STAINLESS STEEL 316/316L	SPLINE SHAFT
4	1	04021045A	STAINLESS STEEL 316/316L	PLENUM PLATE ASSEMBLY
5	1	040210017	STAINLESS STEEL 304/304L	SHROUD FOR 3rd MAGNET
6	1	MAGNET		
7	1	04021065A	STAINLESS STEEL 304/304L	HE/LN OUTLET TUBE ASSEMBLY
8	1	04021075A	STAINLESS STEEL 304/304L	HE/LN OUTLET BELLOWS ASSEMBLY
9	1	040210031	STAINLESS STEEL 316/316L	PRESSURE VESSEL MATING FLANGE
10	1	0402300A	STAINLESS STEEL 304/304L/G-10	FRONT SUPPORT ASSEMBLY
11	2	0402301A	STAINLESS STEEL 304/304L/G-10	SIDE SUPPORT ASSEMBLY
12	1	040210035	STAINLESS STEEL 316/316L	INNER BELLOWS
13	1	040210038	STAINLESS STEEL 304/304L	PRESSURE VESSEL THREAD PAD
14	1	04021015A	STAINLESS STEEL 316/316L	PRESSURE VESSEL DISH ASSEMBLY
15	3	0402500A	STAINLESS STEEL 316/316L	JOINT PENETRATION ASSEMBLY
16	3	04022045A	STAINLESS STEEL 304/304L/G-10	SPACER SUPPORTS ASSEMBLY
17	96	HEX CAP SCREWS	STAINLESS STEEL 316/316L	HEX CAP SCREWS, M12 x 1.75 x 40
18	96	WASHER	STAINLESS STEEL 316/316L	1/2" SCREW SIZE, 1.25" OD x .531" ID x .063" THK
19	24	WASHER	STAINLESS STEEL 316/316L	1/2" SCREW SIZE, .875" OD x .515" ID x .063" THK
20	24	SOCKET HEX CAP SCREW	STAINLESS STEEL 316/316L	SOCKET HEX CAP SCREW, M12 x 1.75 x 35
21	1	040210011	STAINLESS STEEL 316/316L	INNER FLANGE

Pre-Operational Testing – Proposed to be Performed at MIT-PSFC Pulsed Test Facility

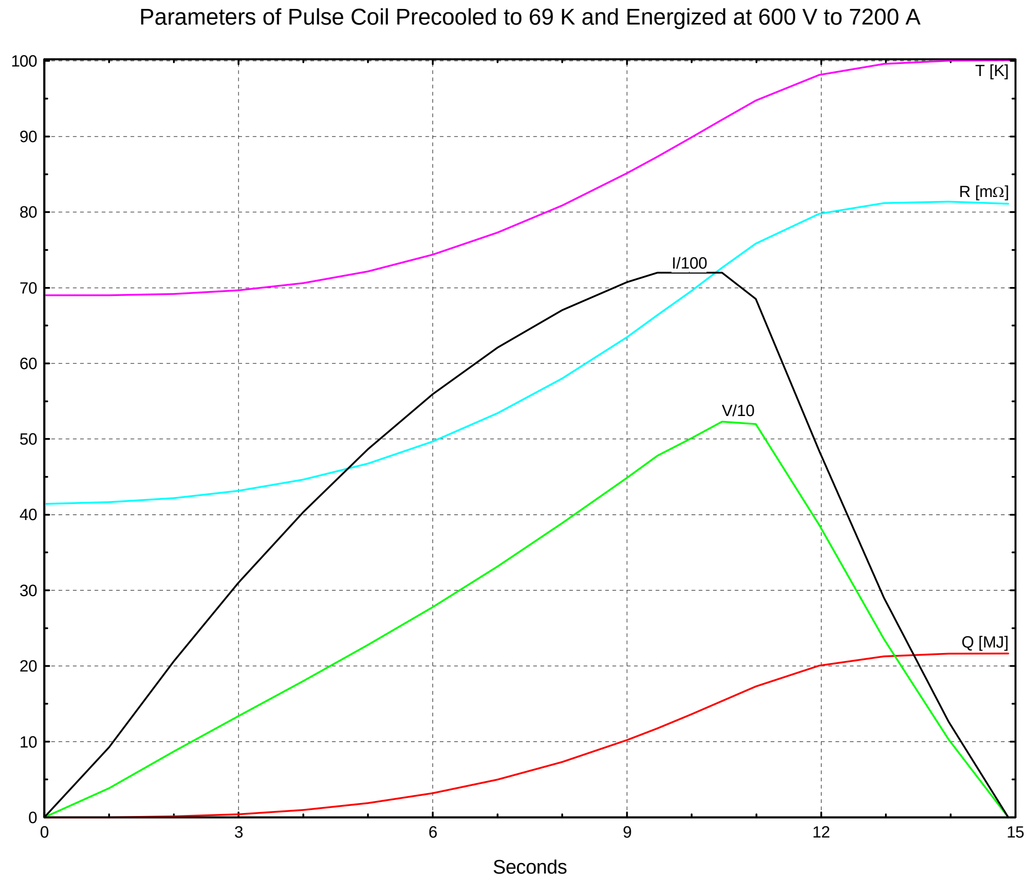


Lower Water Cooled Split Pair Copper Magnet - The BNL Pulsed Magnet would be in front of this Where the HXC Prototype cryostat is now positioned

PTF Upper Cryostat

Preliminary Review of the current /voltage profiles indicates that the PTF power supplies will meet the test requirements.

PTF Power Supplies



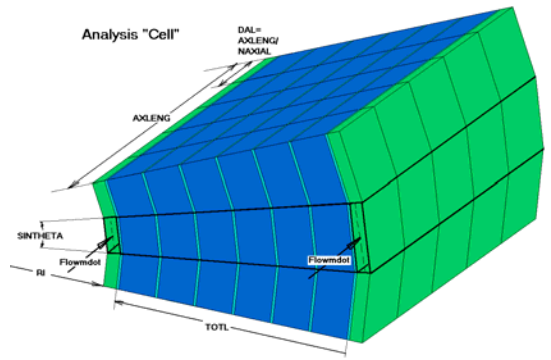
Bob Weggel's 10-14 analysis of the LN2 magnet operation

Only Liquid Nitrogen Cooling Will Be Employed During Pre-Operational Testing

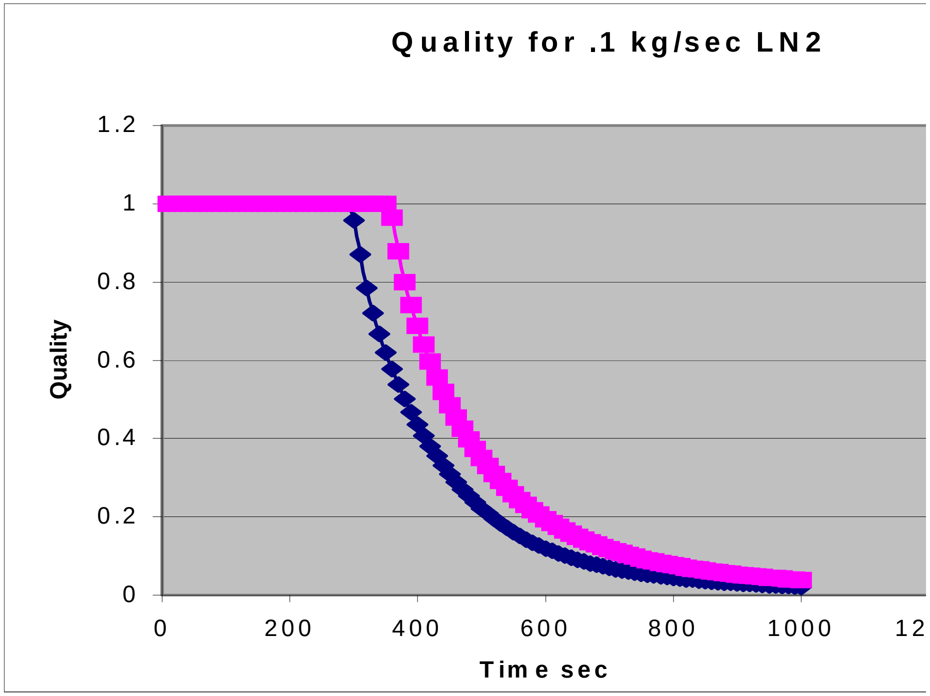
C-Mod Main LN2 Supply Tank will be used with the LDX VTF supply line

Two Approaches are possible:

- **Flood and Wait - Then Drain and Pulse.**
- **Develop and implement a “skid mounted” , deliverable Controlled LN2 Cooling System**



Finite Difference Cooling Model.



The intention is to control the LN2 flow with a proportional valve to provide only as much LN2 as is fully vaporized by the surface heat flux. After 700 sec, this would be only .1 * .1 = .01 kg/sec

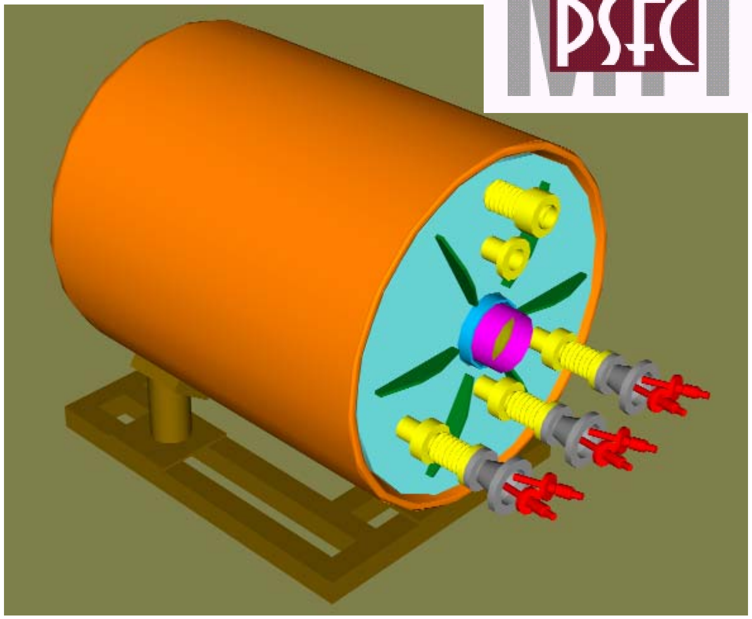
C-Mod’s LN2 Supply Tank

Postulation of Safety Issues:

- Failure of Bore Heater

- Joint Failure
  - Excessive motion
  - Omission of a Force Component
- Insulation Failure
- Leaks
  - He/LN2 Cryostat Leak
    - Mechanical Seal Failure
    - Bellows Crack
    - Ceramaseal Break
- Over Pressure
  - Hotter than expected Magnet
  - Loss of Vacuum in Jacket
  - Vacuum Jacket Volume Pressurization
  - Quick charge of LN2 with warm cryostat
- Thermal Shock
  - Quick charge of LN2 with warm cryostat

- Accident
  - Fire
  - Seismic



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

Failure of Bore Heater

There is no safety consequence – Only frosting of the experimental boundary

Joint Failure - The most common kind of magnet failure

Excessive Motion

Joints are cantilevered, but hoop tension and Lorentz force compensated as in a coax. Bellows allow motion. The Joints will be insulated and wrapped with epoxy Glass

= Omission of a Force Component

George Mulhulland helped with a reminder of the pressure force. This is about 1400 lbs, and is taken by tension in the joint. G-10 guides have been added to reduce the moment on the ceramaseal connections.

Insulation Failure

Conservative insulation design is employed. All insulation planes above one volt are insulated with Kapton. Regions where thermal contraction cracks are possible are insulated with Kapton to produce a reliable parting plane, and provide insulation against tracking behavior.

Specification Content:

Electrical Testing

The Seller shall assign a trained personnel and provide all necessary test equipment including digital multimeters for resistance measurement and DC hipot testers for ground insulation testing, during assembly process and at the completion of the prototype cryostat. Electrical testing of the electrical connection and component, including pulsed coil and bus connection, sensors, and diagnostic wiring, shall be performed after a component becomes inaccessible for service unless the enclosure is disassembled. The checkpoints and the type of electrical testing during assembly stage shall be defined by Seller in the fabrication plan and approved by the Purchaser's Representative.

Insulation test

No measurable electrical connection at mega-Ohm range shall be allowed between the ground and any diagnostic component / connection, between different sensors, and between sensor and the coil circuit.

DC Hipot Testing

The initial DC hipot testing shall be performed on the pulsed magnet coils and lead connections before they are installed. All subsequently measured leakage currents shall be compared with the initial value for verification.

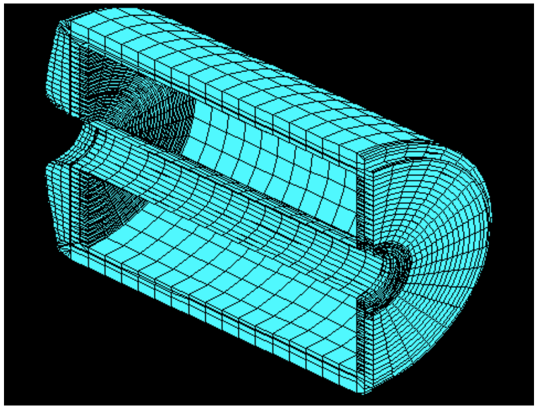
The coils and lead connections shall be tested at 1 kV for 1 minute with the limiting current of a DC hipot tester set to 10 micro Amp. The allowable leakage current shall be no more than 5 micro Amp.

Caution:

- *Do not perform hipot testing with the coil / lead in evacuated enclosure.*
- *Isolate the voltage tap wires when the coil / lead is tested with hipot tester.*
- *Do not use hipot tester on any sensor.*

Leaks

Probably Frostbite is the most significant danger. Even a small leak would fill the test cell with cold He.



Elements modeling Helium total 2*.167 m^3 Or .335 m^3. This is 5 m^3 at 30 K and 49 m^3 of Helium at RT and 1 atm. The dished head and annulus can be filled to reduce the He inventory. The dished head volume is .044

He/LN2 Cryostat Leak

The Cryostat and vacuum jacket are designed in accordance with ASMEVIII, including proof tests, (but not stamped?)

Mechanical Seal Failure

A redundant welded seal is available as a back-up. It can be applied if there are problems in-service? Or in the shop?

Bellows Crack

These need to be specified conservatively with respect to displacement, and pressure rating. Axial displacement of the bore bellows, and lateral and radial displacements of the bellows support feet are both around 3mm.

Ceramaseal Break

The ceramaseal joint penetration is loaded in compression and restrained by it’s connection with the conductor break-out. It is intended to be either immersed in LN2 or traced with LN2 cooling tubes – This is probably an argument for tracing . Mechanical qualification is in Process (We have one and dunk tests, and load tests are needed)

Leak Related Specification Content:

Sniffing Tests During Manufacture

The following shall be performed in the prescribed order:

1) *Confirm the sensitivity of sniffer is better than 5 x* 10^{-5} *std atm-cc/second helium with a calibrated helium source.*
2) *Use an appropriate temporary cover to close the vessel / volume, and introduce helium gas into the test volume without cracking the temporary seal.*
3) *Confirm the background helium reading is below the sensitivity of the sniffer.*
4) *Spot leak checking shall be performed by inserting the sniffer in the envelop, which covers the outer surface of the joint area.*
5) *At high background helium count, consider isolating the first envelop from the background with a second envelope, which is flushed with nitrogen gas.*
6) *Remove leak checking attachments and clean up the surface. Flush out helium gas if necessary.*

Over Pressure

Hotter than expected Magnet

Magnet insulation damage occurs above 100C. Our operating range is 30 to 100K

Loss of Vacuum in Jacket

Cryogenic Foam limits heat gain to less than 1000 watts. The magnet stored energy is of order 1e7 Joules

The Cryogenic Foam planned for use on the cryostat is fire retardant, and will limit heat gain and resulting pressurization during an external fire.

For Liquid N2 operation, we can vent liquid to the "shuttle tank" via pressure relief? The pressure relief valve be positioned at the bottom so we vent liquid and reduce the probability of overpressure due to relief valve pressure drop? . For He operation, since there is only a small volume of He gas - not liquid, loss of vacuum accident cannot be of much consequence in terms of relief valve performance. This is an issue with the LHe superconducting magnets not in resistive magnets. In our magnet, the loss of vacuum would produce a small heat gain with respect to the mass inventory of He. Much less time rate of expansion than pulsing the magnet.

Vacuum Jacket Volume Pressurization

A relief disk is provided. Pressure beyond one atmosphere loads the bellows and can damage them. The "Bumpers" that take the net lateral vacuum load do not work in tension if the vacuum jacket is pressurized.

PR3 SERIES
2 - 15 PSIG RELIEF

CPC-Cryolab™

VACUUM TIGHT
PRESSURE RELIEF DISCS

Quick charge of LN2 with warm cryostat

Thermal stress in the magnet?

Bore Heater Strip Vendor and Specifications (Willie Burke?)

Accident

Fire

Foam has good fire retardant properties

CryoCoat™ UltraLight™ provides the robust mechanical properties associated with syntactic foam technology in a low-density insulation system (specific gravity from 0.08 to 0.11) with excellent thermal properties. CryoCoat™ UltraLight™ can be used as a mold-in-place insulation system on large, complex and uneven surfaces, or blown into closed molds to form near-net-shape components. CryoCoat™ UltraLight™ UL79 withstands liquid hydrogen temperatures and the elevated temperatures of re-entry from space.

Application of the foam is intended to occur at BNL. Application procedures and use of solvents etc. will have to meet BNL safety procedures.

Seismic

The magnet is supported on three legs. One is fixed and two are sliding. The sliding block feet will have to have some tensile capacity to ensure magnet stability against side loads.
Supports are robust otherwise – not as delicate as superconducting magnets supports.