CERN
SAFETY REVIEW
MERIT (n-ToF-11) 15T Pulsed Magnet for Mercury Target Development
Neutrino Factory and Muon Collider Collaboration

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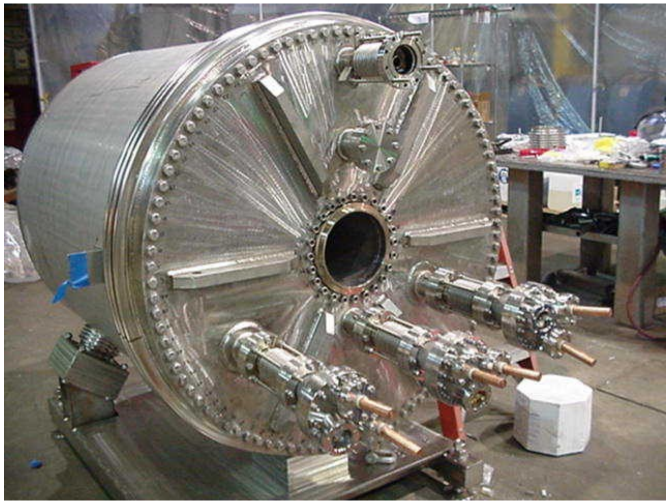

MERIT Pulsed Magnet –Inertially Cooled , 80K LN2 Cooled Between Shots


Assembled Magnet Entering The Test Cell at MIT, Tuesday Jan 10 2006

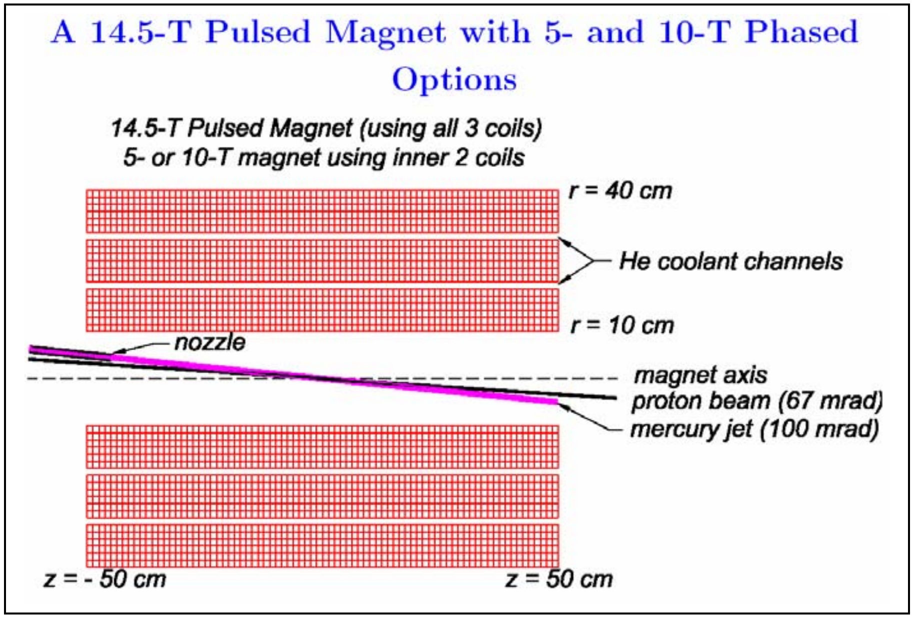
Cost issues dictated a modest coil design.

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

A three segment, layer wound solenoid is used. 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. Originally coolant flowed only through axial channels in the coil.



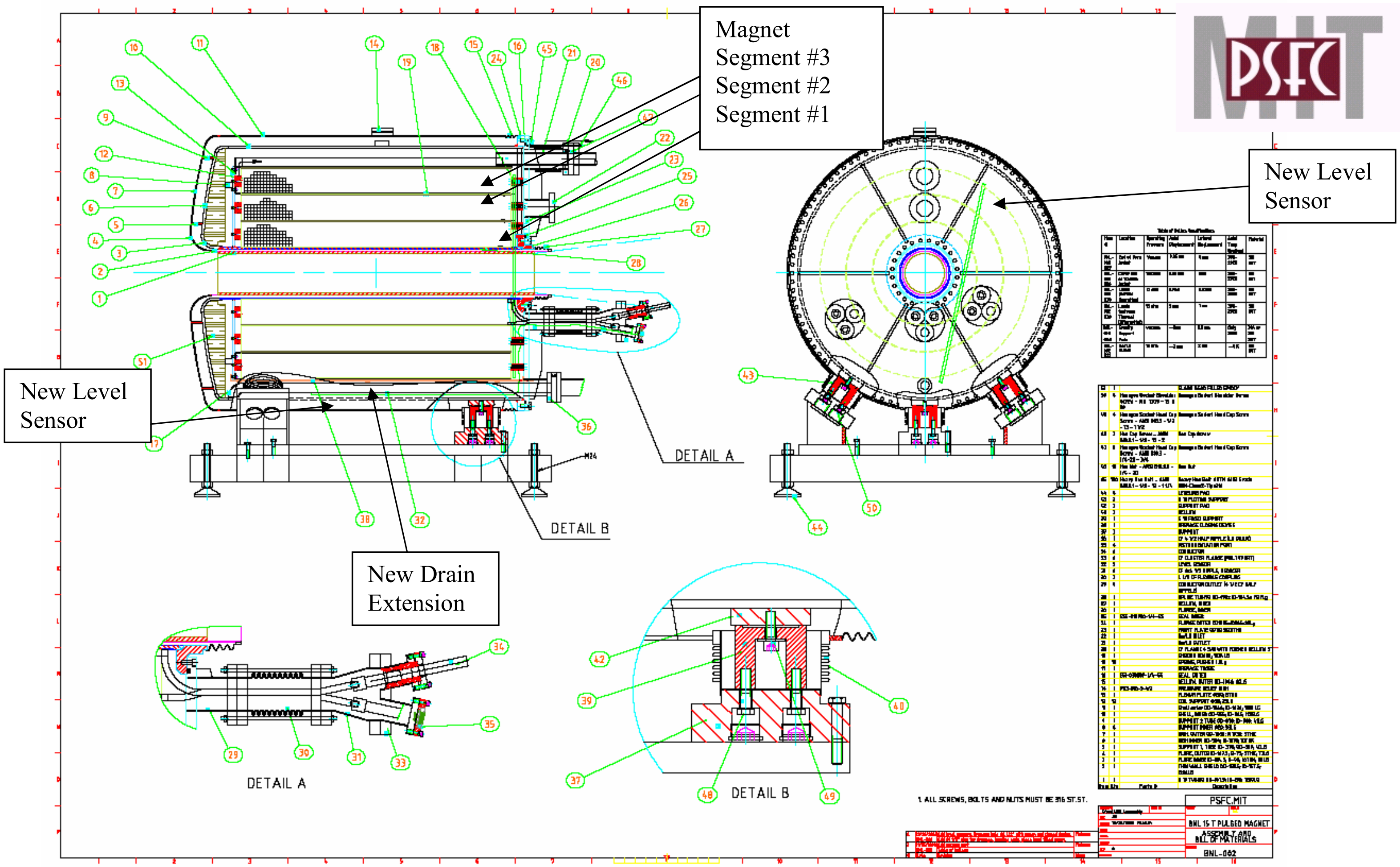
For the same packing fraction, a hollow conductor would have a 1.4mm diameter hole

The coil is 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.

15 atm (design) Cold Vessel



MERIT Magnet Parameters

Experimental Volume Spec:

150 mm bore , 1200mm long centered on the magnetic center of the solenoid, with 7 degree conical exclusion zones at either end

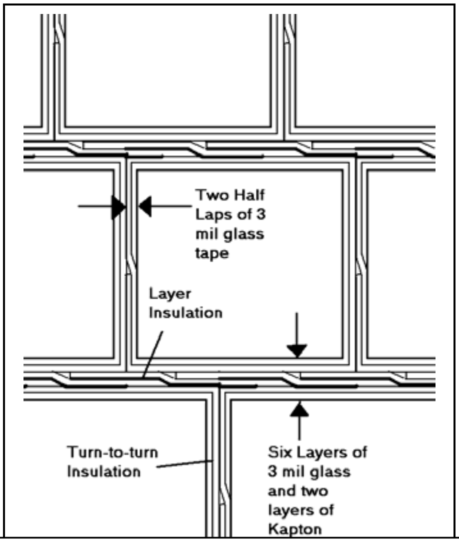
Coil Builds

#	r	z	dr	dz
1	.15	0	.098	1.0
2	.2	0	.002	1.0
3	.25	0	.098	1.0
4	.3	0	.002	1.0
5	.35	0	.098	1.0

Magnet Quantities

	Segment 1	Segment 2	Segment 3
Volume (m^3) 9.2362824e-2	.15393804	.21551326	
numturn	624	624	624
weight (kg)	748.04651	1246.7442	1745.4419
conlen (M)	641.4085	1069.0142	1496.6198
tapelen (M)	5131.268	8552.1133	11972.959
epoxyvol (M^3)	8.3126542e-3	1.3854424e-2	1.9396193e-2
Num Ramp/Trans	32	32	32

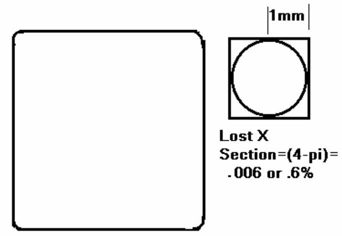
Coil Description:	Current Design Basis
OD	**.8m**
ID	**.2m**
Length	**1.0m**
Number of Segments operating:	**3**
Number of turns per segment	**624**
Total number of turns active	**1872**
Layers in each coil segment	**8**
Turns per layer	**78**
Conductor radial thickness	**.0116698 m .45944 in**
Conductor Axial thickness	**.012516m .49274359 in**
Max Operating Field Bore CL	**15.0T**
Max Terminal Current	**7200A**
Coolant Working Fluid	**80K LN2**
Terminal Voltage	**700V**
Layer to Layer Volts	**80**
Turn-to-Turn Volts	**.4**
Design Life	**1000 full power pulses**
Cryostat Pressure - Operating	**15 atm LN2**
Charge Time	**15.3 sec**
Initial Temperature	**80K**
Temp Rise	**30K**
Final temperature	**110K**
Cumulative heating at end of pulse	**24MJ (?)**



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

- 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.

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%

Safety Review Status:

- **The Magnet and Vessel Design have had Peer Engineering Review by BNL, MIT(P.Stahl) and by George Mulhulland.**
- **The Magnet System has been reviewed by BNL(Peter Wanderer' Group) and MIT-PSFC Safety Review Committees.**
- **The MERIT pulsed magnet design builds off of copper magnet experience in fusion research at MIT (Alcator C-Mod).**
- **The Magnet has been electrically tested by Everson-Tesla and the Vessels have been pressure tested by CVIP and the system will go through Pre-operational tests at MIT-PSFC**

Plasma Science and Fusion Center

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617-253-8440 (Catherine Fiore, head) 617-253-8917 (Matt Fulton, Facilities Manager)
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Some of the Postulated of Safety Issues:

Magnetic Field Hazard 6m to the 5 gauss line
Feromagnetic Material Projectiles
Joint Failure
- Excessive motion
- Omission of a Force Component

Insulation Failure, Arcing
Leaks Oxygen Deficiency Hazards
- He/LN2 Cryostat Leak
  - Mechanical Seal Failure
  - Bellows Crack
  - Ceramaseal Break
  - Lead Gland Nut Leak

Over Pressure
- Hotter than expected Magnet
- Loss of Vacuum in Jacket
- Vacuum Jacket Volume Pressurization
- Quick charge of LN2 with warm cryostat

Failure of Bore Heater
Thermal Shock
- Quick charge of LN2 with warm cryostat – The inner magnet segments were thermally shocked at Everson-Tesla

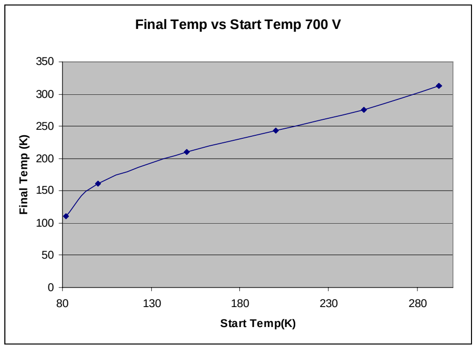
Accident
- Fire - Avoid Flammable Materials
- Seismic

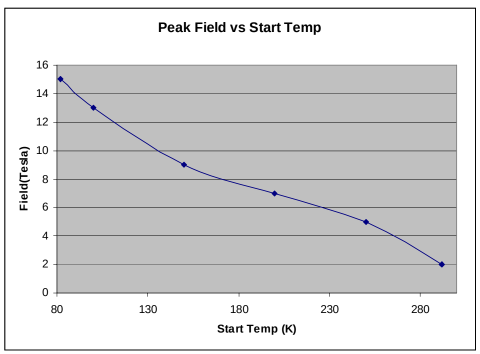
Electrical Simulations

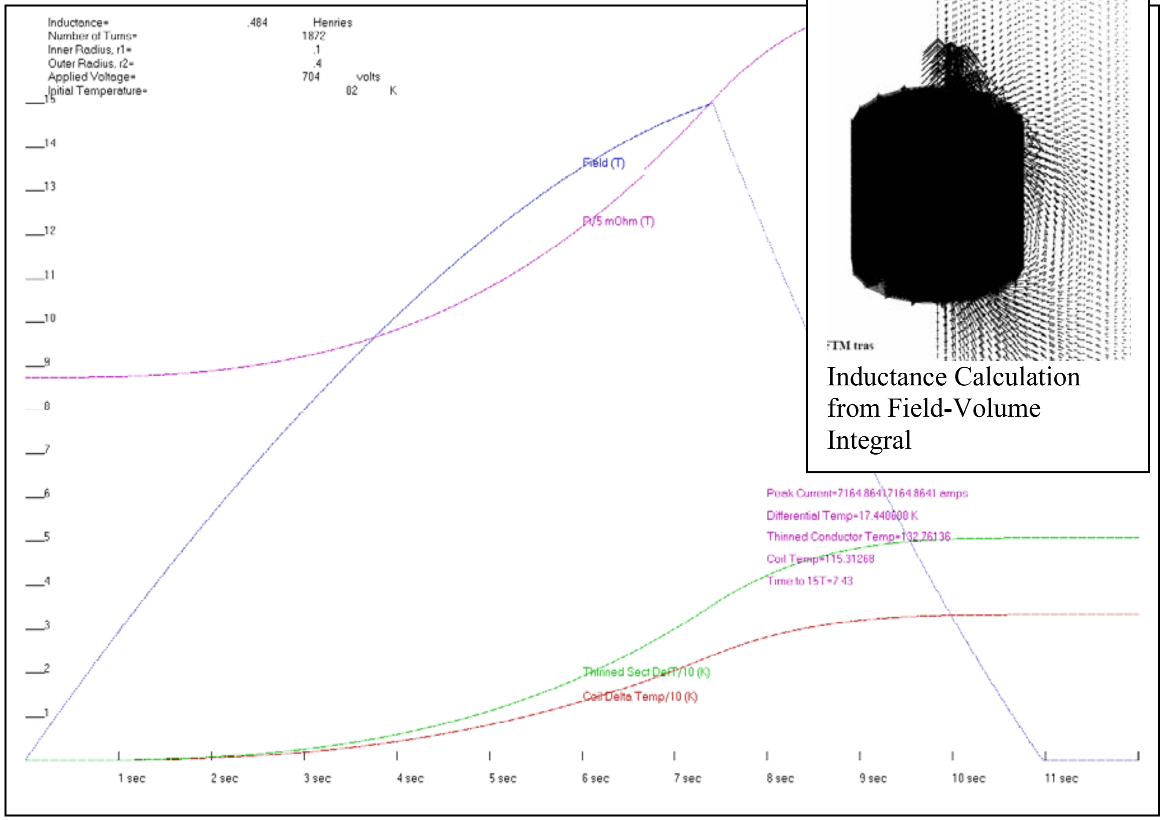
Bob Weggels electrical simulations are the simulations of record. However a coil simulation was run with a local conductor cross section reduced by 25%.

The local temperature went 17.4K higher than the rest of the coil.

Accidental Pulse at Higher Temperatures







Inductance Calculation from Field-Volume Integral

If the Power Supplies are Voltage Limited to 700 V, the response of the magnet is simply to reach lower fields and modest delta T's

If the power supplies try to follow the current profile, and starts at RT it will overheat the magnet (550K) and the voltage will be too high.

Voltage Capability

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.

	Early Design Basis	MIT Tests and CERN Experiment	Capability
Number of Segments operating:	3 in Series	3	
Number of turns per segment	624	624	
Original Terminal Voltage Spec, and Voltage to Ground	300V	700V	1524V
Layer to Layer Volts	24V	80V	1524V
Turn-to-Turn Volts	.16	.373	12V

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.

Specification Content relating to Insulation integrity:

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.

Structural and Geometric Design Criteria

Magnet:

Fusion project criteria are used for guidance in coil design

ITER and FIRE design documents allow 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.

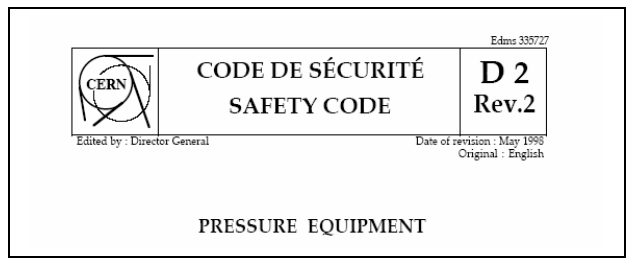
Bending discontinuity, and secondary stresses are treated in a manner similar to the ASME Code.

Bolting, Support Structures:

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.

Vessels:

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


Edms 335727

CERN	CODE DE SÉCURITÉ SAFETY CODE	D 2 Rev.2

Edited by : Director General

Date of revision : May 1998
Original : English

PRESSURE EQUIPMENT

Seismic

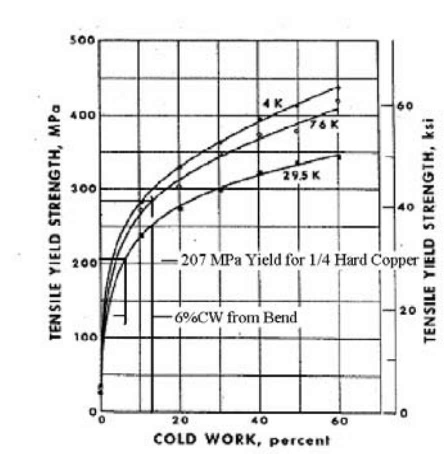
The magnet is to be seismically qualified in accordance with the (Uniform Building Code? - .1g horizontal).

Conductor Allowable and Cold Work Specification

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.



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

Everson has purchased ¼ hard conductor to ease bending, 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. 166 MPa is needed.

From the Figure this would correspond to cold work of about 15%. The bending operation would introduce an additional 6% Hardness is assumed to correlate with %cold work. From CDA data even better performance is expected.

Room Temperature Properties of Copper, C10100 (OFHC) (Identical to C10200)

Standard	Former	Yield Min	Yield Max	Tensile Min	Tensile Max	Elong %	Rockwell F
H01	**Quarter Hard**	**30 ksi (2) 207**		**38 (2) 262 MPa (2)**	**25**	**25 to 35**	**60-84 (1)**

(1) ASTM B152
(2) Copper Development Association Web Page www.copper.org flat form

	100K Yield	***100K Primary Membrane Allowable***	***(100K Bending Allowable ID Stress in a Solenoid)***
Expected Conductor Property	***>207MPa***	***138 MPa***	***207MPa***

Insulation Through Thickness Tensile Allowable

Copper Readily De-bonds from Insulation

The Tensile Bond Strength at best is ~8 MPa. The Insulation Design Must Accommodate D-Bonding Behavior
(Atlas and CMS achieve high bonds to Aluminum and through use of pre-bonded glass-Kapton tapes.)

Tension Test Results-7090 Copper Adhesion
Set #4: Grit Blast + Microclean + Chembond

TEST CONDITIONS

Matrix System:	CTD-101K	*Load Range Card:*	±1 Kip
Reinforcement:	S2-Glass (6781)	*Stroke Range Card:*	±0.5 in.
		Temperature Controller:	Lakeshore 330
Specimen Type:	Tension	*Temperature Sensor:*	Si Diode #D47355
Specimen Reference:	Set #4		
Speciment Prep:	Grit Blast + Microclean + Chembond		
CTD Program #:	7090		
Load Rate:	0.00033 in/s		
Test Fixture:	Tension fixture	*Test Temperature:*	76 K
Test Date:	11/16/2004	*Temperature Hold Time:*	5 minutes

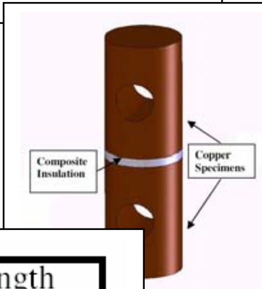
TEST RESULTS

Specimen #	Height (in)	Diameter (in)	Area (in^2)	Ultimate Load (lbs)	Tensile Strength (ksi)	Modulus (ksi)	Failure Mode
4a	0.055	0.498	0.195	262.5	1.3	21.4	A
4b	0.054	0.498	0.195	200.4	1.0	17.9	A
4c	0.055	0.498	0.195	188.0	1.0	17.5	A
4d	0.053	0.498	0.195	340.7	1.7	21.7	A

COMPOSITE TECHNOLOGY DEVELOPMENT, INC.
ENGINEERED MATERIAL SOLUTIONS

Final Test Report
for
Purchase Order PE005392-W

Through-Thickness Insulation and Copper Tensile/Adhesion Tests

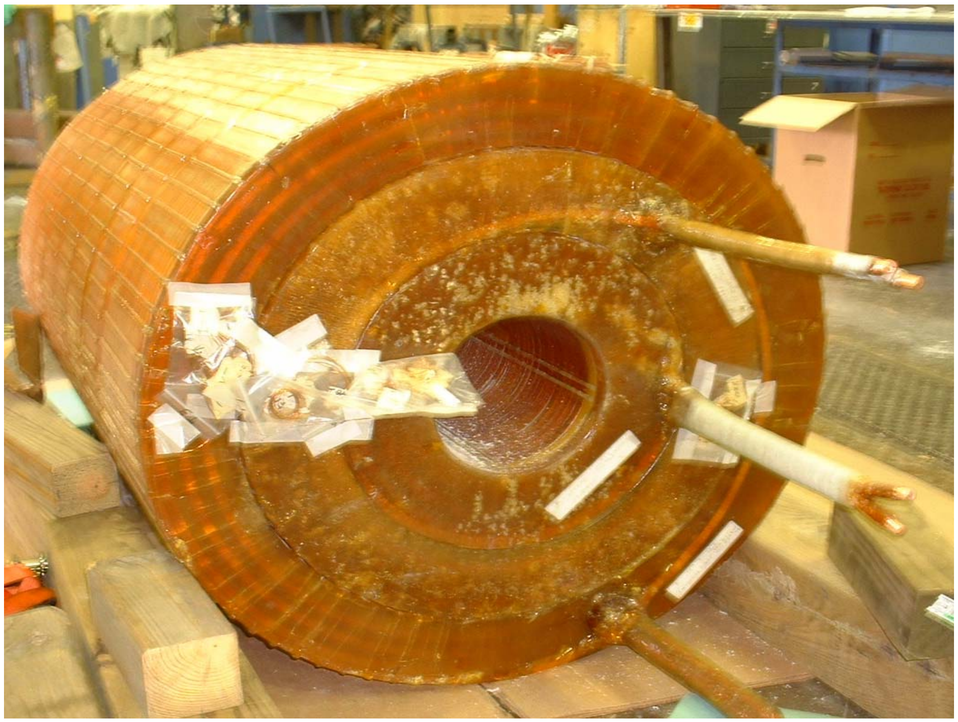


	Tensile Strength ksi	MPa
Average	1.3	8.8
Std. Dev.	0.4	2.5

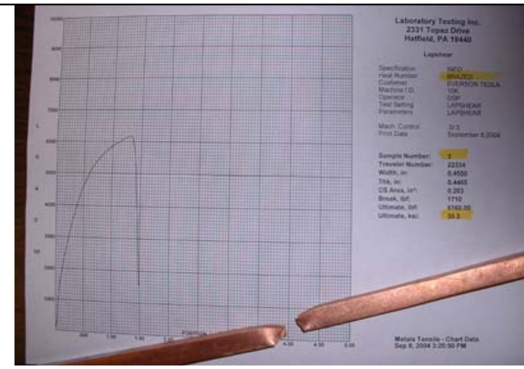
Coil Qualification:

Coils have been Built, Electrically Tested (and even Thermally Shocked)
Subject to a Number of Process Controls Including Test Windings, Joint Pull Tests and Periodic Meggar Electrical Tests

Nested Coils as They Appeared at Everson Prior to Shipping to CVIP

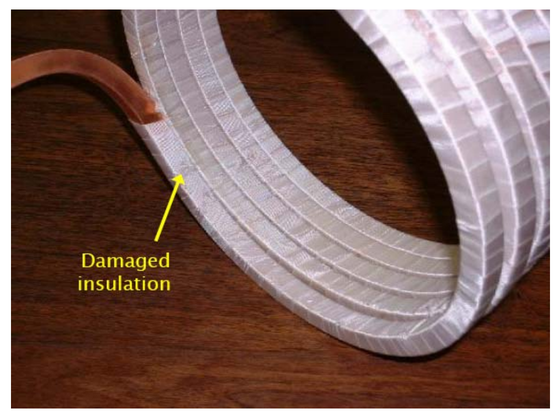


CERNOX Temperature Sensor Leads shown Taped to the Face of the Assembled Magnet



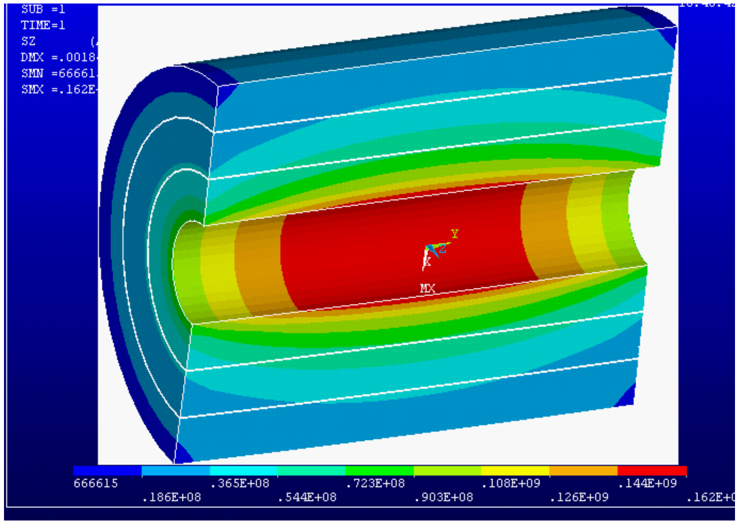
Load Displacement plot of Silver Solder Joint. No Conductor Splice Joints are used in the inner segment

Coil Stress Analysis of Fully

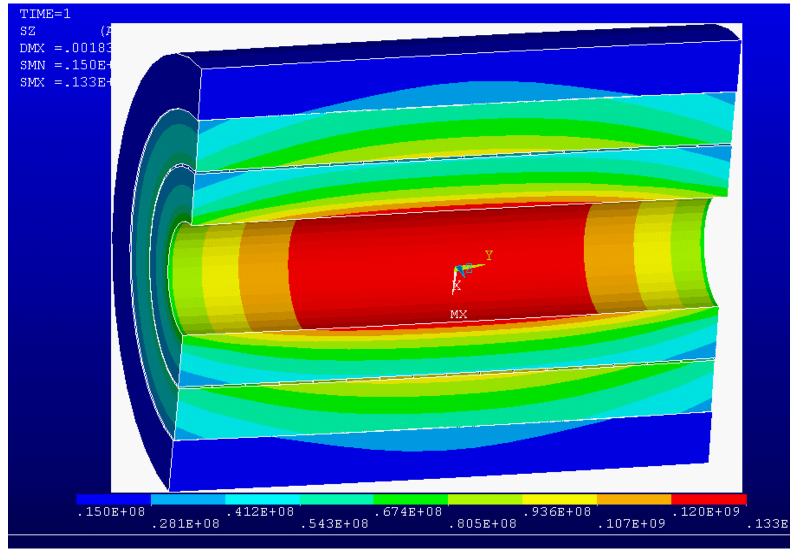


Results of the test bend. Roller geometry was improved to avoid fiberglass tape cuts.

Powered Coil



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



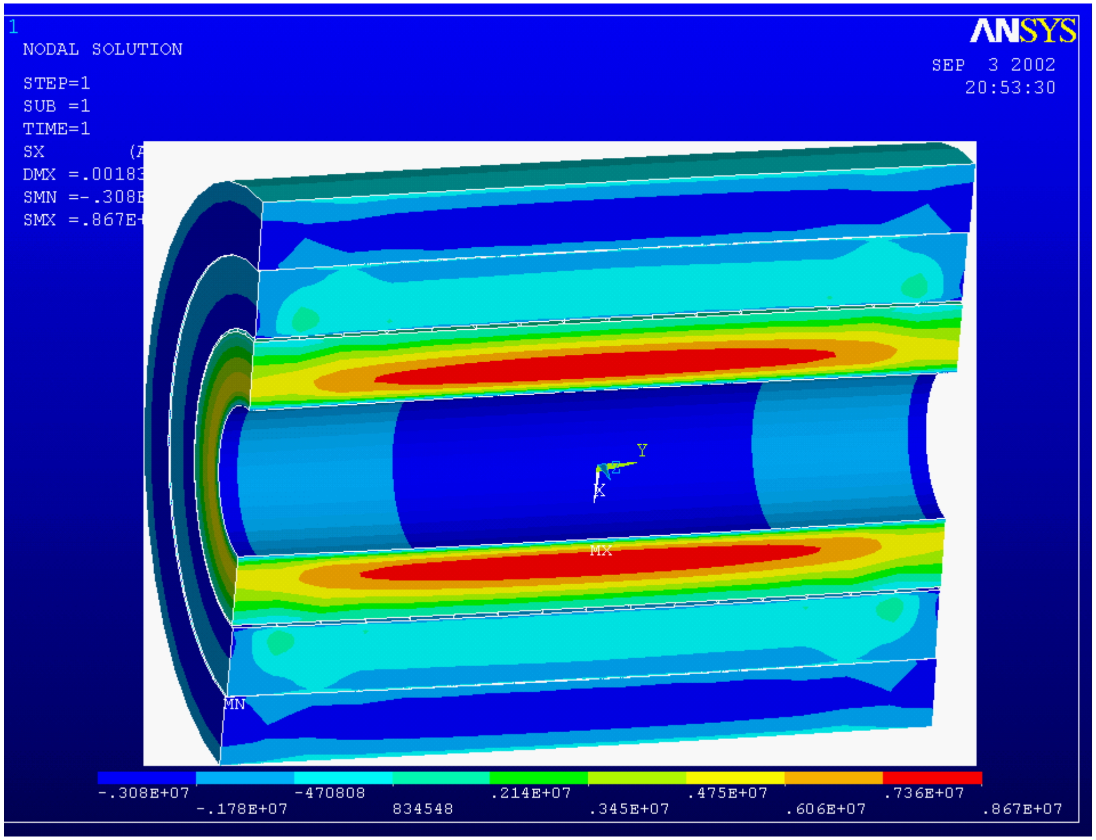
Re-run with gap elements the hoop stress went down to 133 MPa
There is Inner Segment Separation.

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.

	100K Yield	***100K Primary Membrane Allowable***	***(100K Bending Allowable ID Stress in a Solenoid)***
Expected Conductor Property	***>207MPa***	***138 MPa***	***207MPa***

Improvements in the qualified field look promising, but conductor witness sample testing is recommended.

Radial Tension Stress, All Coils Fully Energized.



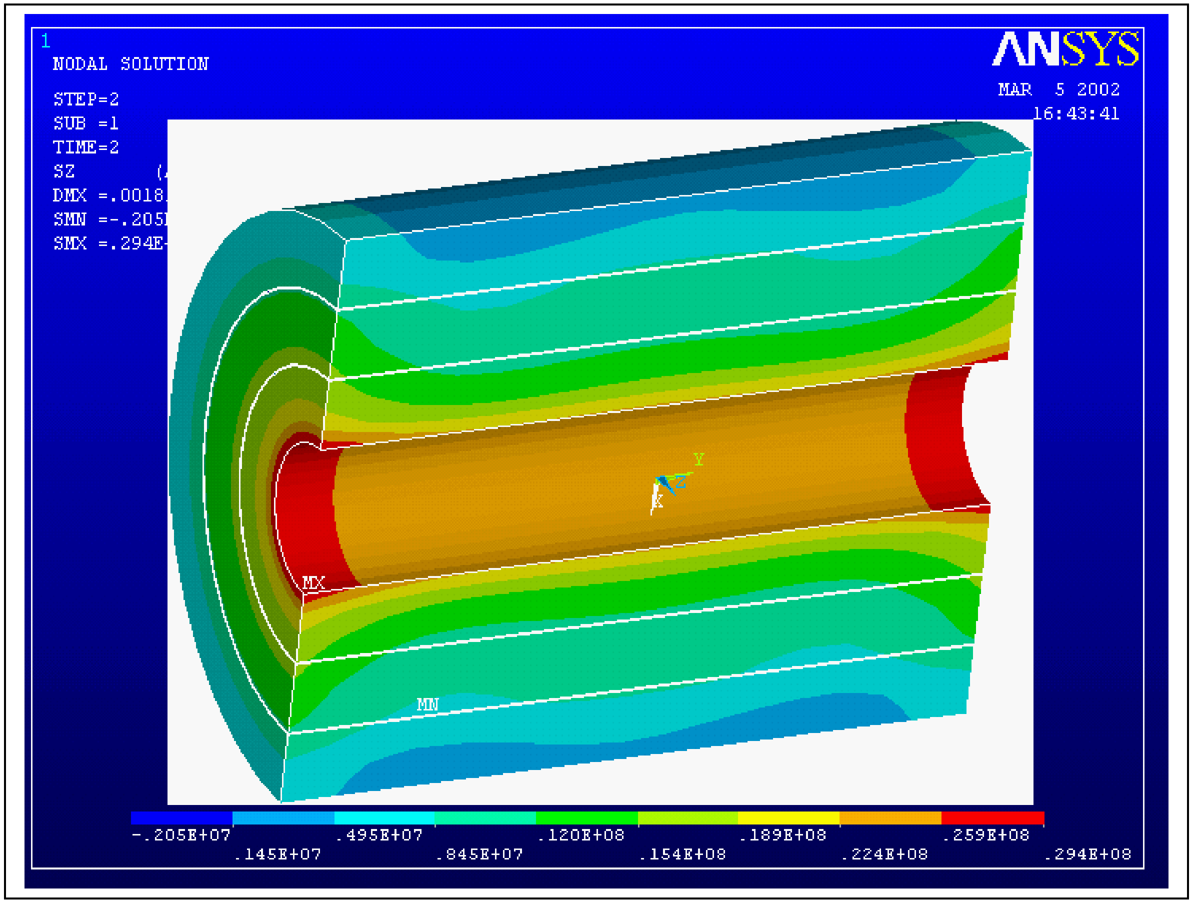
Radial Tension in the winding of the first segment. gap elements model the interactions of the three coil Segments.

This is at the "Optimistic" Tensile strength of the copper to epoxy and epoxy to Kapton Bond. The consequence is the possibility of slight de-lamination. (the strains are tiny) This does not have a safety effect. It could effect thermal conduction – but de-lamination would occur mid-build and conduction is from both sides.

Early Design Condition can be thought of as a possible fault.

Hoop Stress With only the Inner Two Segments Energized. 10T

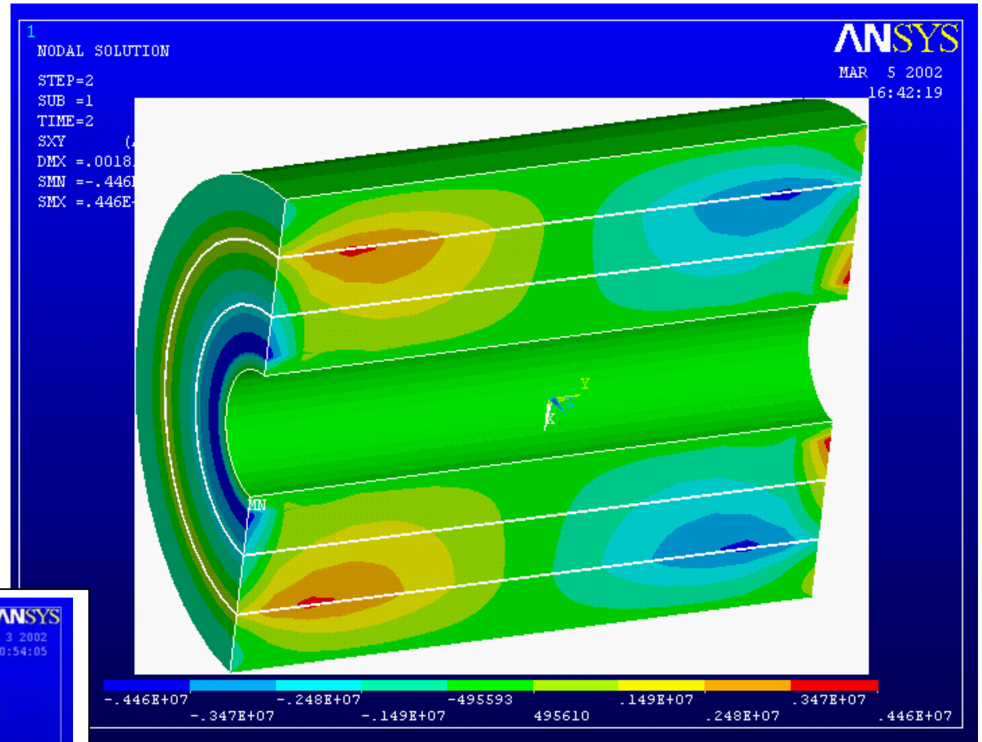
Peak Hoop Stress is Only 29.4 MPa



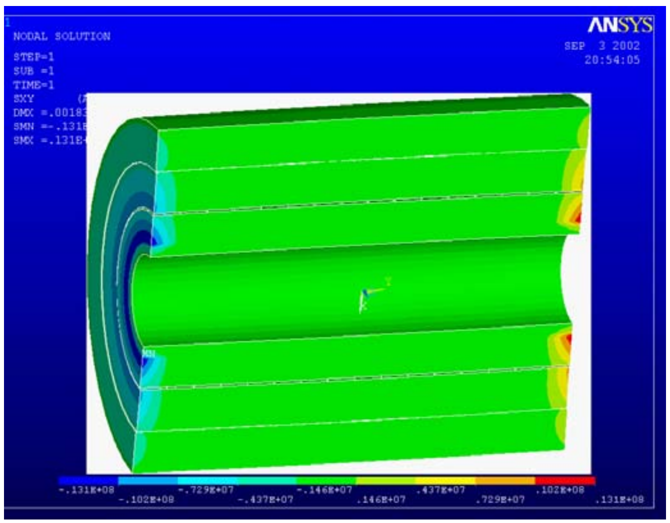
10T Inner Coils Powered Fault

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

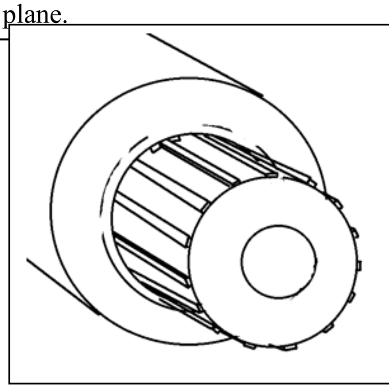
Channel Ligaments would be too weak to support this – Slip Planes are Used.



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.



Coils would survive a non-uniform current distribution

Operational Thermal Stresses.

Coils are fully instrumented to ensure they are not pulsed with an unacceptable initial temperature distribution.

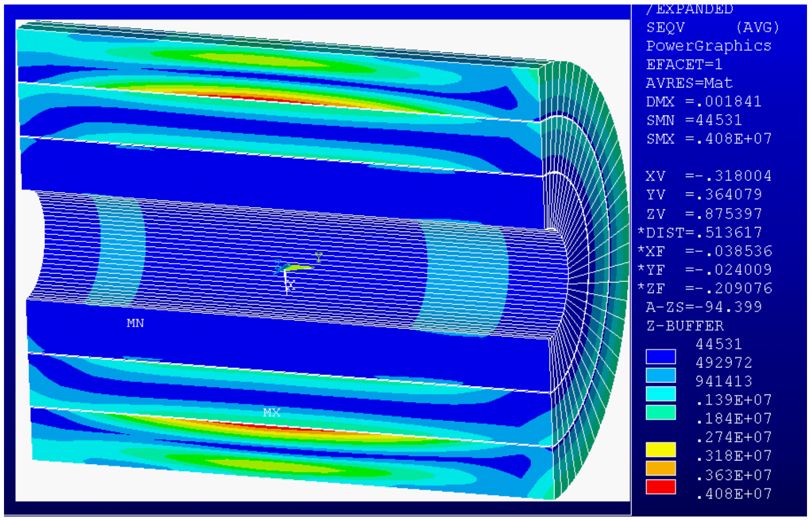
CERNOX Thermal Sensor Leads Pass through an ISI Insulator Seal

Magneto-Resistive Effects.

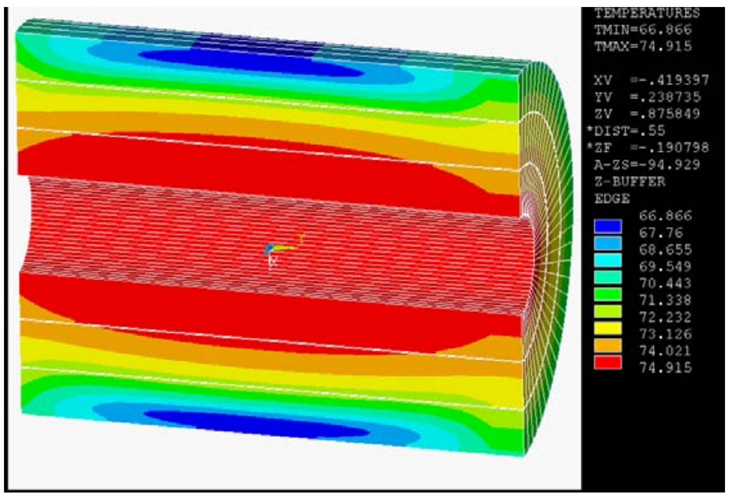
Although a constant current density coil, heat-up during a pulse is not uniform due to the magneto-resistive effects. – This was more of a concern when the design was based on 30K operation. Now it is operated at 80K

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.

The stresses from magneto-resistivev effects are small, less than 5 MPa.



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

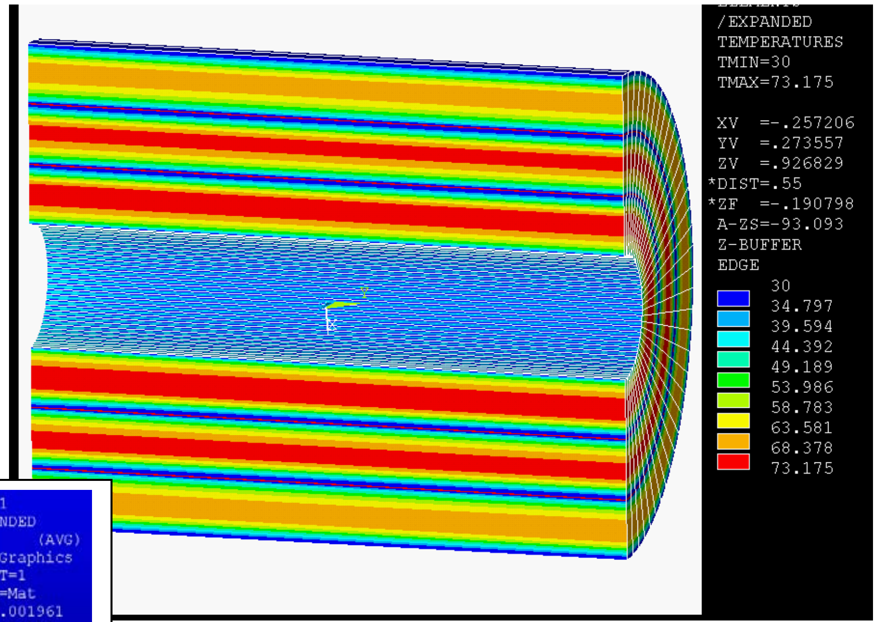


Temperatures with magneto-resistive effects, 15.0T

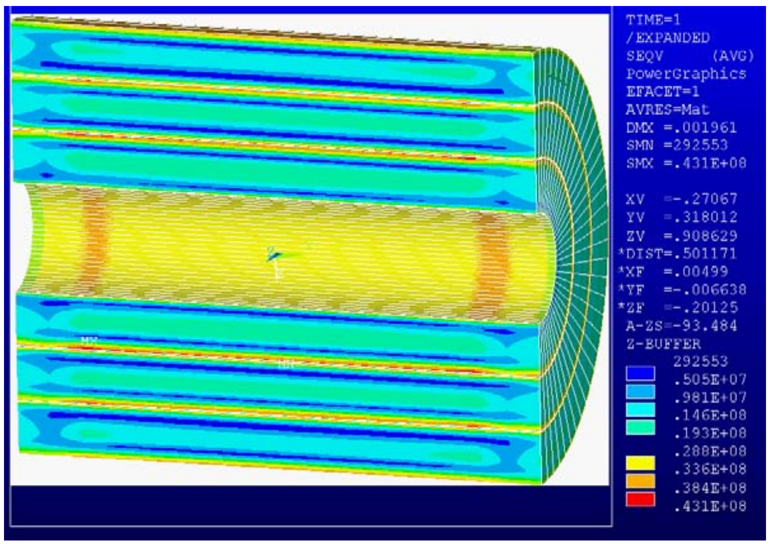
Cooldown Stresses –Von Mises

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 Von Mises stress is relatively modest, at 43MPa



Cooldown Temperature distribution

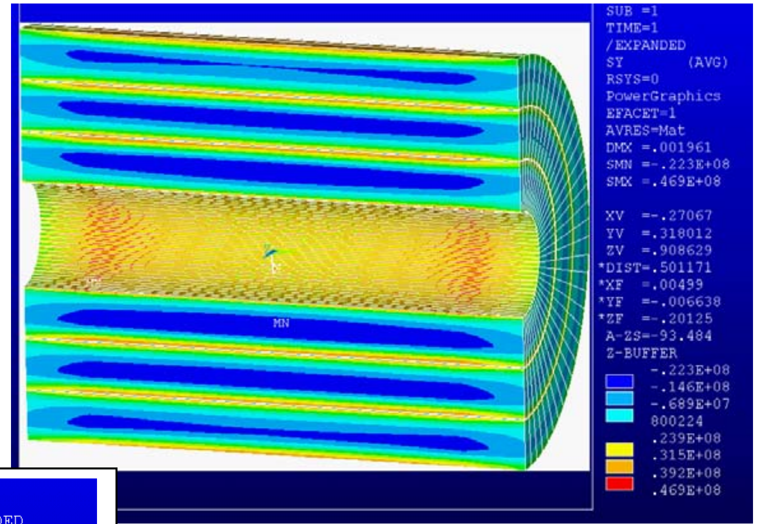


“Smeared” VonMises stress

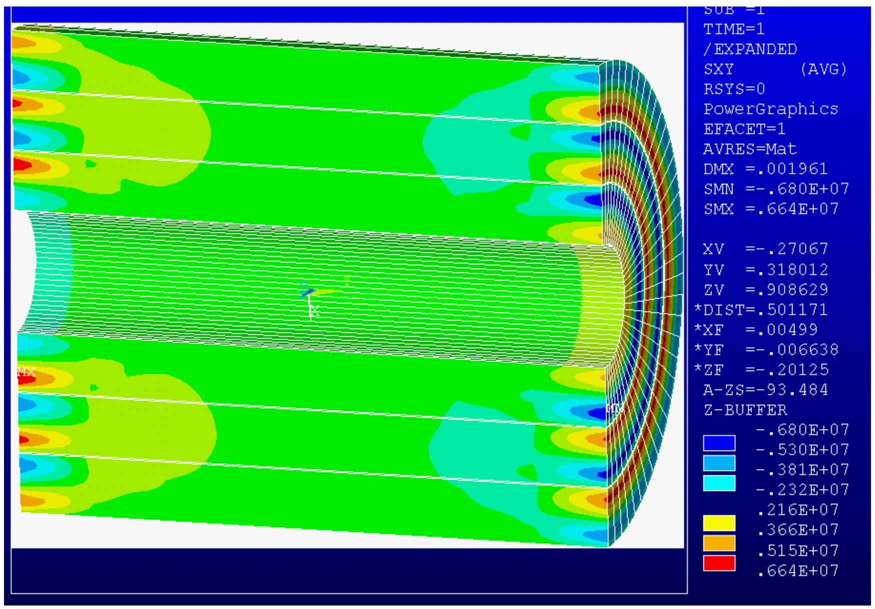
Cooldown Stresses –Shear and Axial Tension

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)



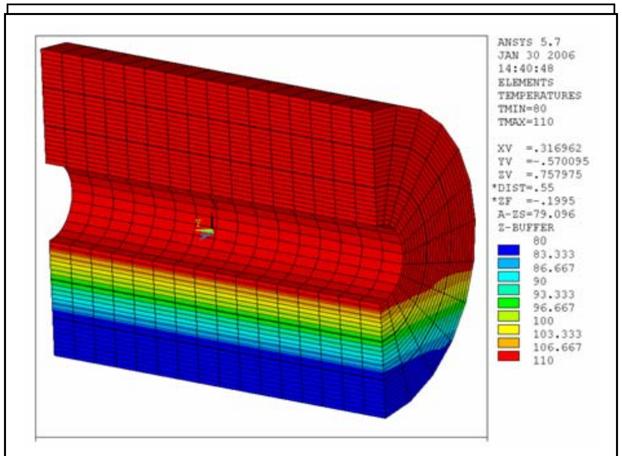
Axial tension

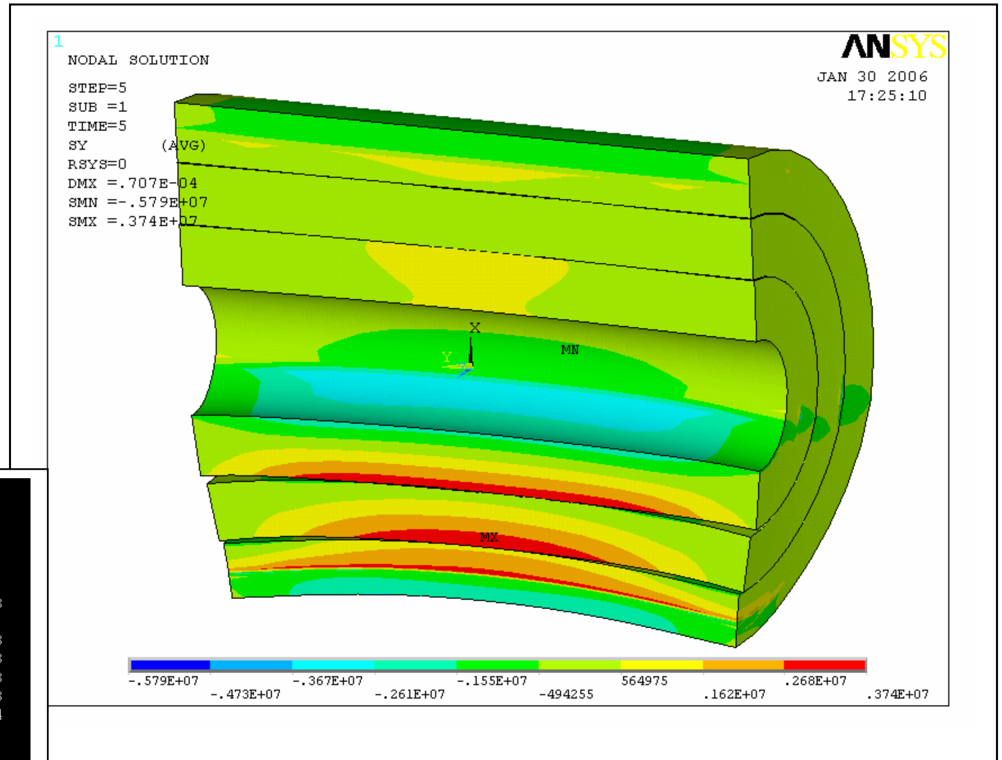


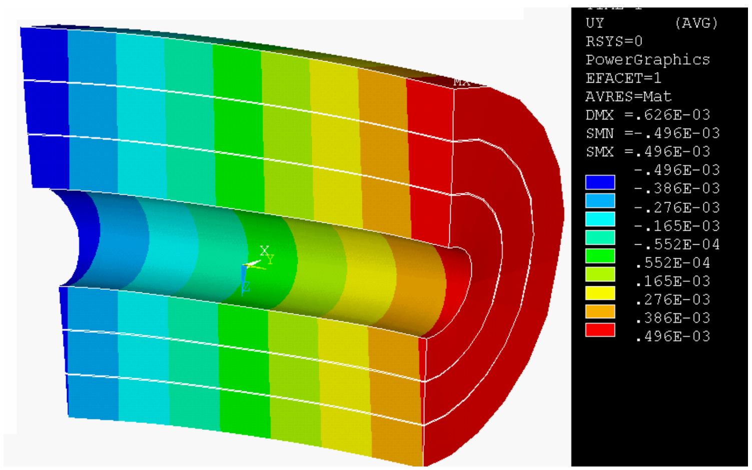
Shear stresses due to the cool down temperature distribution

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 80 to 100 K variation is assumed. The resulting 8 MPa stress is Acceptable

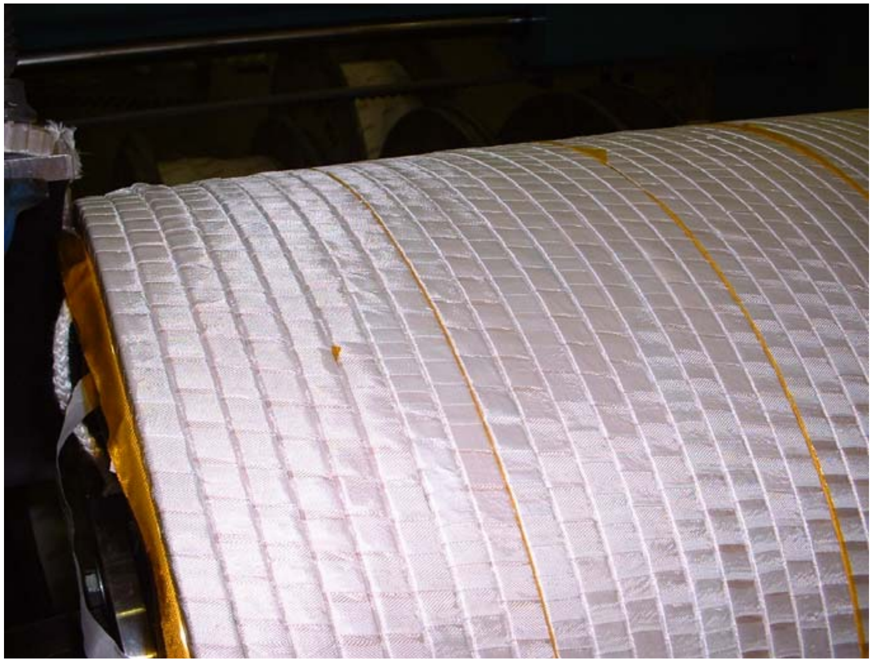






Resulting Displacements

Some De-Lamination is Expected and is Included in the Winding Design



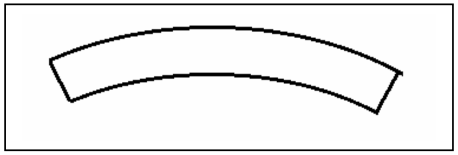
Segment #1 being wound. Photo taken by Dave Rakos at Everson 09-08-04. Kapton layer spaced at every eighth turn relieves axial tension in the layers near the cooling channels. First Layer, Coil Segment#2

Possible De-Lamination:

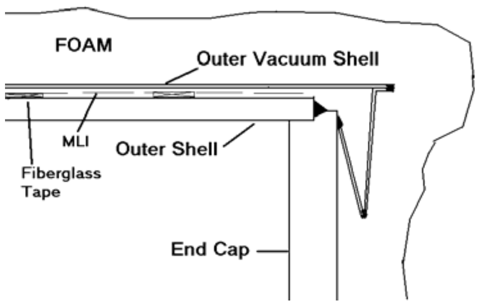
First Segment Radial Stress (Layer to Kayer Kapton Parting Plane)

Cooling Channel Axial Stress (Kapton Arcs Added)

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



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.

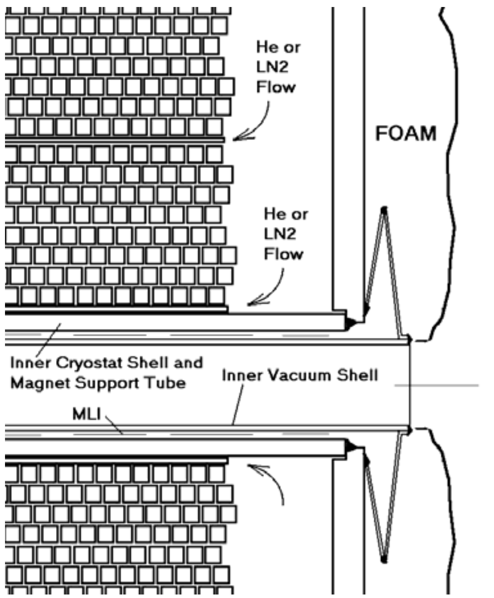
A concept which has a 220 watt heat gain has been developed that employs vacuum at one head, and the outer and inner shells, and foam at the other end around fluid and electrical penetrations.

Piping penetrations are moved to the end plates,

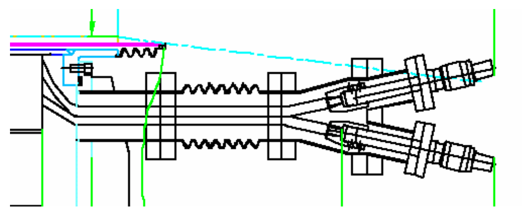
Vacuum shells are used on the ID and OD, and one head.

The magnet can be supported off the inner cryostat shell,

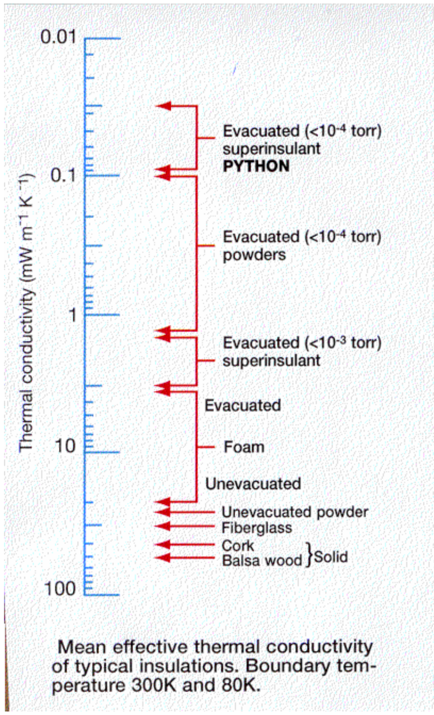
The system gravity supports can reach through the foam or vacuum boundary.



Inner Vacuum Shell to Cover Connection



Lead with bellows



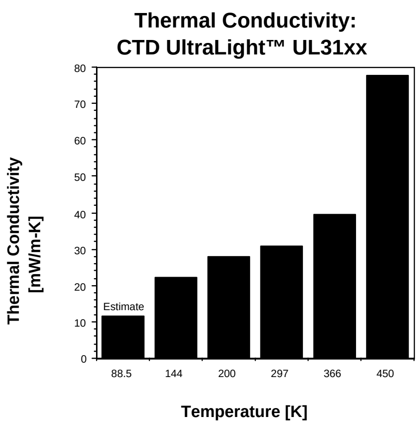
Foam Insulation

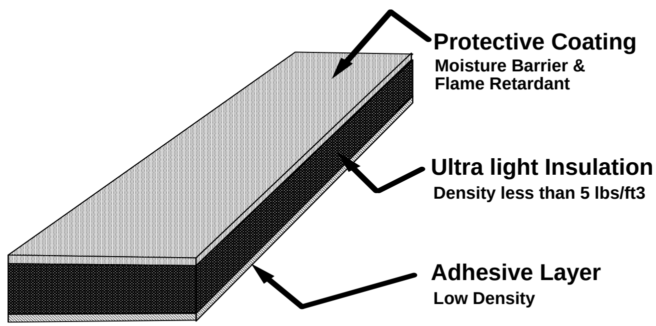
CTD Composite Technology Development Inc.

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. ***It is fire-retardant.***

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.

This Material is hard to remove





At MIT-PSFC we will also use removable foam sheet wraps. We will use spray home insulation on mechanical closures, flanges, bolts, and instrumentation. CERN may want to replace this material.

Qualification of the Vessels

Vessel Fabrication is Complete. The Inner Cold Vessel has been Pressure tested to 245 Psi Qualifying 15atm operation

From a 11-21-05 email from David Nguyen:

"We performed pressure test last Saturday. The actual pressure was 245psi hold for 25 minutes.
The inner flange did not leak at all. We only found a small leak at the top of the outer flange.
We released the pressure, tight four bolts, and brought the pressure back up to 245psi again."

"Spline Tube" or Inner Bore Tube
– Main Magnet Support

Cryostat/Helium Can/Inner Vessel/Vacuum Vessel Stress Analysis

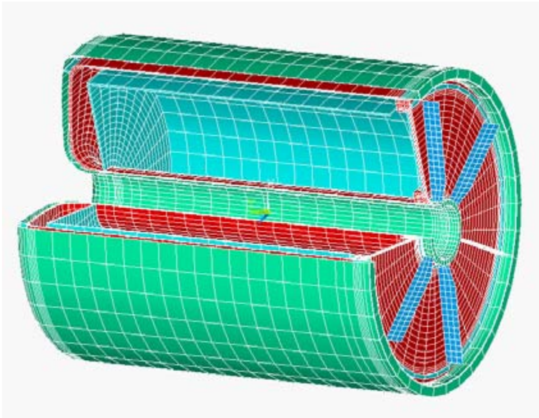
Normal operating Pressure is 15 atm
Flat head thickness is 2 cm, Dished head is .5 inch thick, Vacuum Jacket Dished head is .125 in.
Cryostat ID is 6.35mm (1/4 inch) and OD shell thickness is .5 Inches Thick
Material is 316 for the cold components and 304 SST for warm Components

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

Cold Vessel RT Allowables

Material	Sm	1.5 Sm bending	3 Sm Primary+ Bending +Discontinuity
316 LN SST	183Mpa (26.6 ksi)	275Mpa, (40ksi)	549 MPa
316 LN SST weld	160MPa (23.2ksi)	241MPa (35ksi)	480 MPa

Better Properties are expected for the inner vessel at operating temperatures, but the vessels are qualified for RT testing and off-normal operation.



Early Version of the Simulation model

Shell Stresses – Simplified Analysis

Note that the ASME VIII sizing equations (UG27 and UG28) don't apply to the annular geometry. The inner bore tube of the cryostat is loaded in hoop compression and axial tension. It also supports the weight of the magnet. The axial stress contribution to the stress intensity is different than a normal vessel. In the outer shell the axial stress is reduced from a usual vessel stress. The inner shell is loaded in compression and the axial tension adds significantly to the stress intensity.

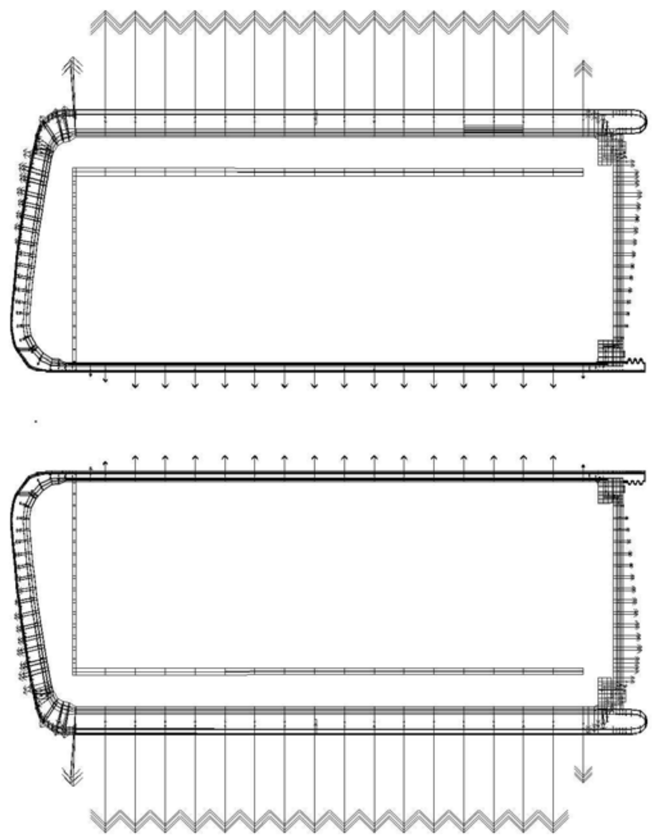
.Cold Vessel Shell Stresses

IR	OR	t	Pressure atm	pressure MPa	P*r/t Stress	E*	Hoop σ/E	Axial σ	Tresca	Sm	F.S. against allowable
.09424	.1	.00476	-15	-1.5203	-20.7	.7	-29.63	78.2	107	160MPa	**1.48**
.4693	.482	.0127	15	1.5203	56.94	.7	59.96	30	81.34	160MPa	**1.99**

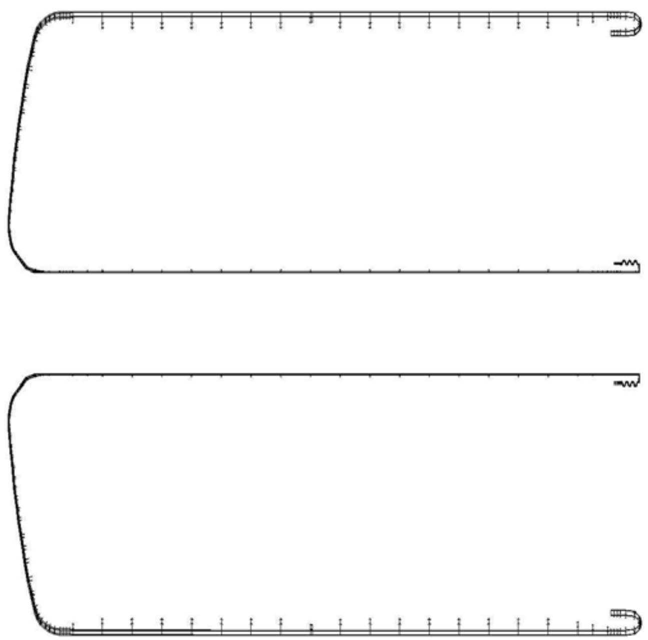
*Weld efficiency, from Table UW-12, For Longitudinal butt welds, welded from both sides, and ground smooth, with no radiographic examination, the weld efficiency is 70% .

Simulation Model 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

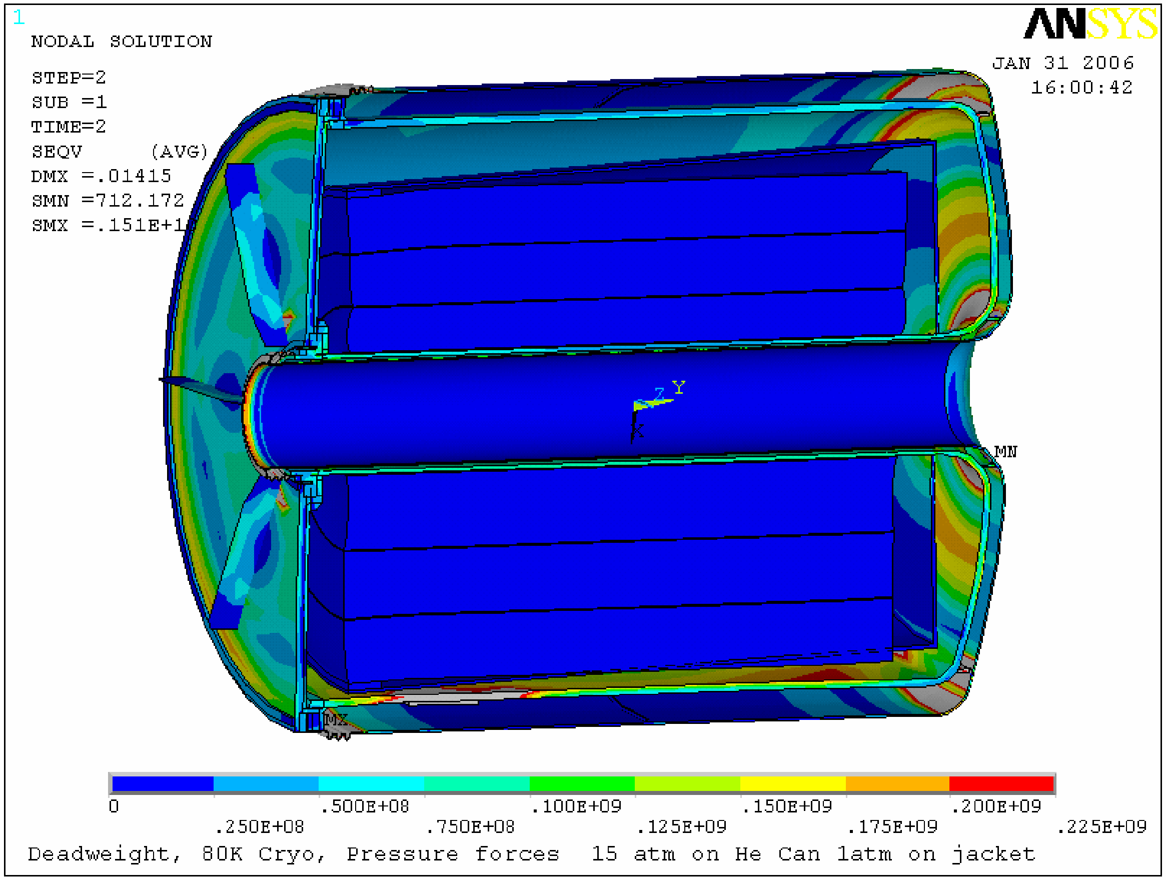


Whole model – Cryostat 15 atm loads dominate



Vacuum loads on vacuum jacket

Vessel Simulation Model - Updated in Jan 2006 with As-Built Dimensions
Cover Stiffeners are 1inch thick.

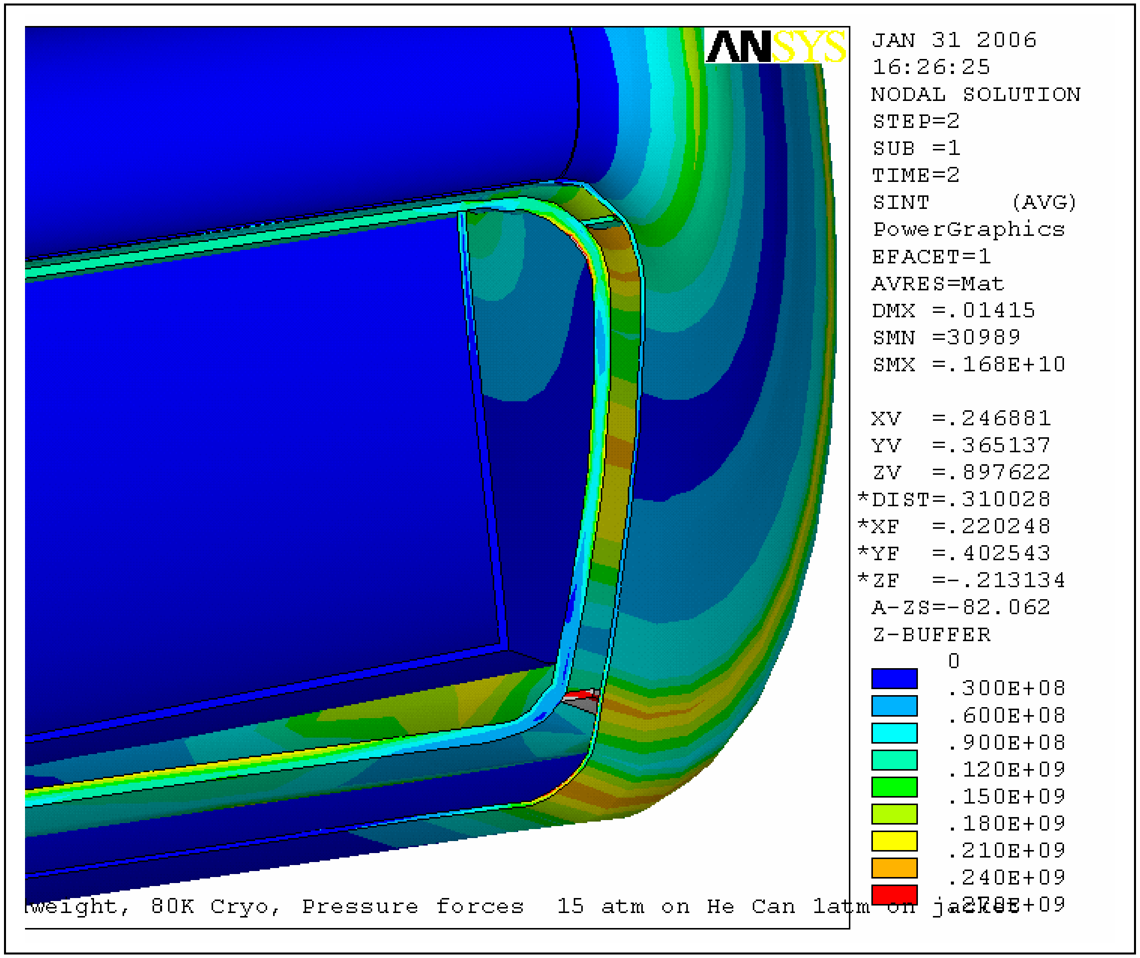


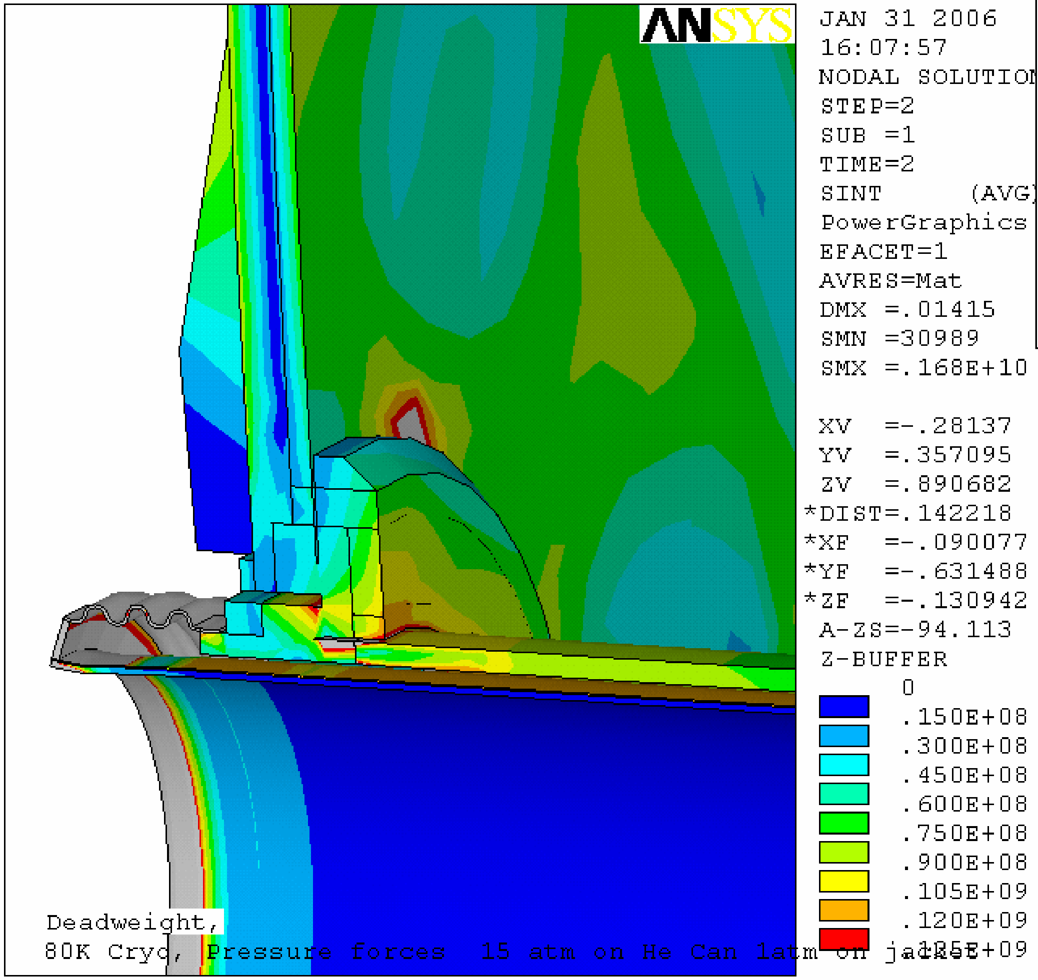
In this plot, the primary membrane stress allowable183Mpa (26.6 ksi) is at the boundary between yellow and brown

Head to Shell Discontinuity Stresses

Primary membrane + bending + discontinuity stresses are less than 240 MPa , less than the weld 3*Sm allowable of 480 MPa

Primary Membrane Stresses are below the Sm allowable of 160 MPa



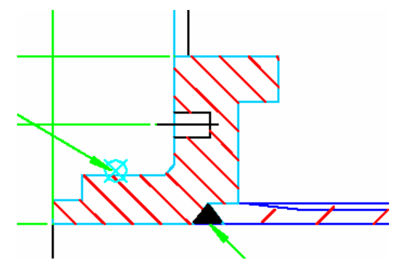


Local stress in the shell to head weld. 6cm high, by 1 inch thick ribs are modeled. The contours for this plot were picked to eliminate the high stresses in the bellows and rib stiffener end, and show the stresses in the support tube where the flange end rotation will induce bending. Here the membrane stress is well below the weld membrane limit of 160 MPa. And bending allowable of 240 MPa

Local Inner Flange to Shell Connection

Bending stress allowable is 241MPa (room temperature weld allowable in bending) . The ID flange flange to shell area has a bending stress of about 125 MPa

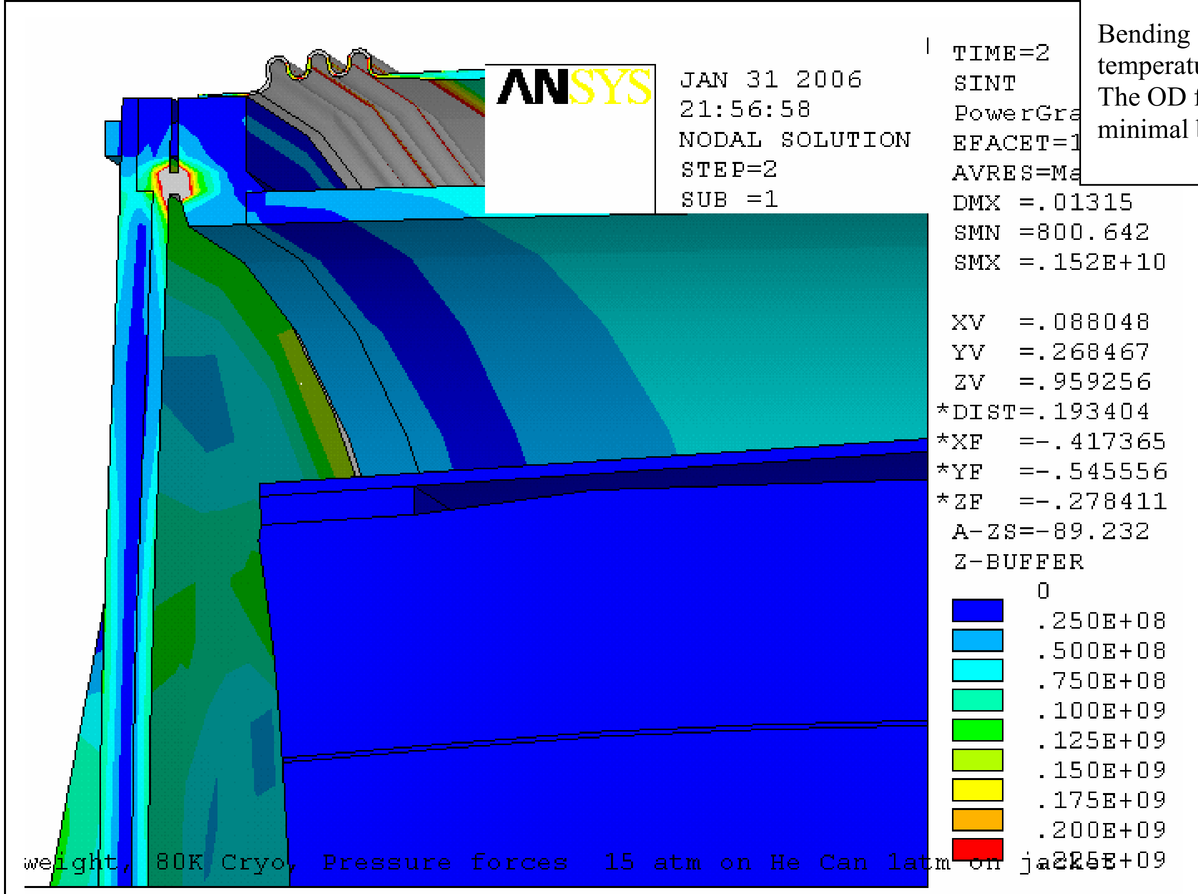
Bellows details will be specified to sustain the 3 to 4 mm displacement and one atmosphere.



The weld between the bore support tube and flange is a full penetration weld backed by the flange step. The weld is made from the bore side after the magnet is assembled on the bore support tube.

Local Outer Flange to Shell Connection

Bending stress allowable is 241MPa (room temperature weld allowable in bending) . The OD flange flange to shell area has a minimal bending.



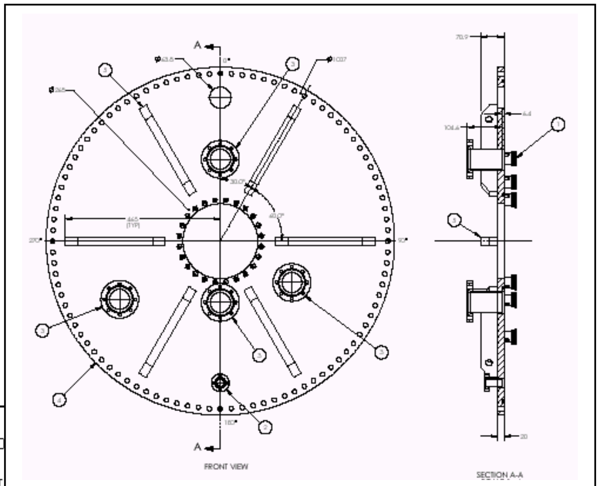
Local Tresca stress in the shell to head weld. 6cm high, by 1inch thick ribs are modeled. The local stress at the flange to shell weld is actually reduced by the flange stiffness.

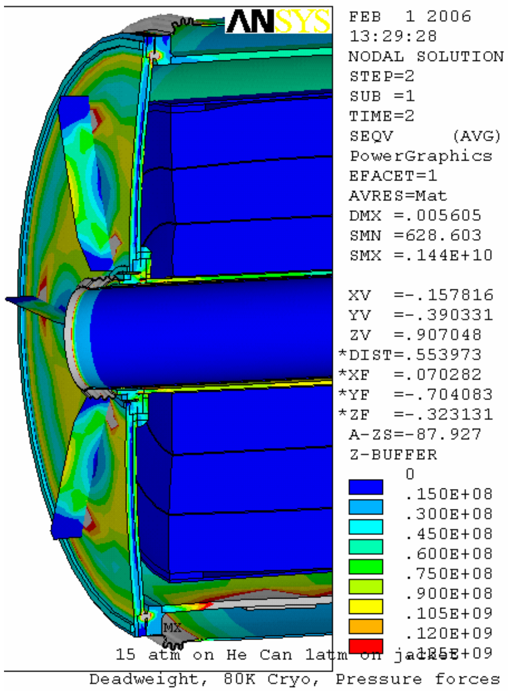
Cover Functions:

Instrumentation – Level Indicators, and Temperature Sensors are supported on the Covers.

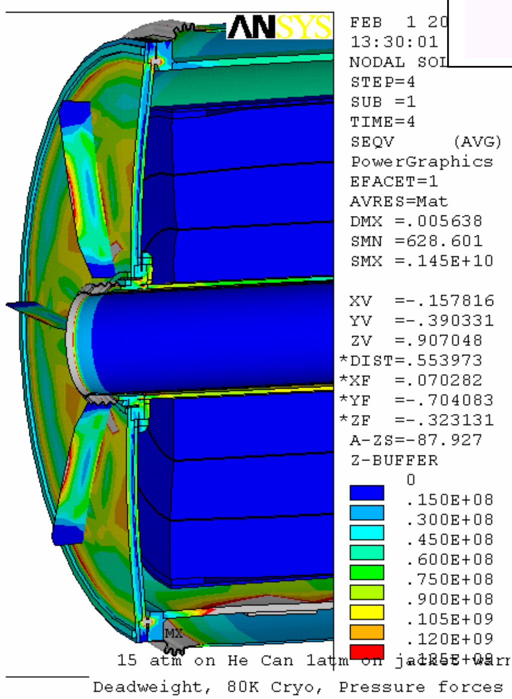
Terminals and Cryogen Connections Pass Through the Covers

Mechanical closure seals are used. 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.





Ribs at 80K



Ribs at 150K

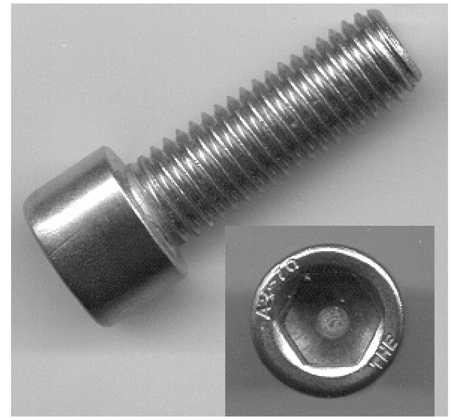
The ribs may protrude beyond insulation applied to the cover. If they are at a different temperature, this could impose some stresses on the ribs and closure details. This effect does not appear to be of concern.

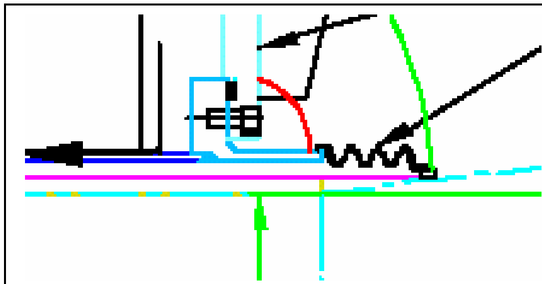
Cryostat/Helium Can Stress – Head Closure Detail

(Thread Shear Consideration Resulted from a BNL Safety Review)

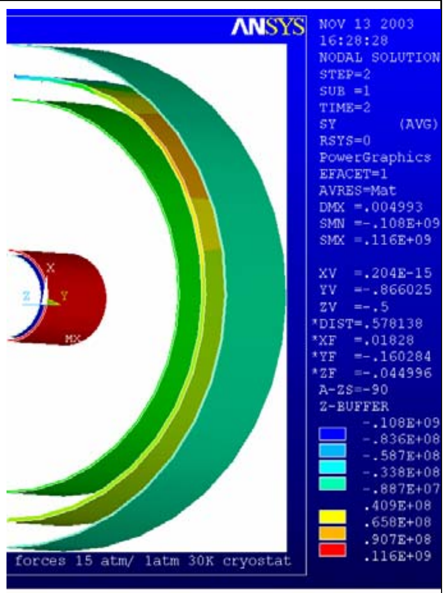
Design Pressure= 15 atm with M12 Bolts, with 8mm Thread Engagement

```
Allowable Stress= 57000
Bolt Ultimate Strength= 110000
Bolt Yield Strength= 95000
Number of Inner Bolts: 24
Number of Outer Bolts: 96
Bolt Tensile Area= .13033826   Bolt Thread Shear Area= .50092224
Tensile Load on inner Cyl: 110378.99 lbs
Tensile Load on inner Cyl: 491009.75 N
Inner Bolt Tensile Stress 35286.067
Inner Bolt Pull Out Shear Stress 9181.3146
Inner Bolt Tensile Factor Of Safety 1.0391259
Inner Bolt Shear Factor Of Safety 1.1617
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 2881.2246
Outer Bolt Factor Of Safety 3.5973878
Outer Bolt Shear Factor of Safety= 5.5531
Outer Cylinder Stress Based on Bolt Loadi
```





Bolted Head Closure detail



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.

Cold Vessel and Cover Component Leaks

Oxygen Deficiency Hazard, and Frostbite are the most significant dangers.

We use hand held ODH sensor for our test at MIT

LN2 Cryostat Leak

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

Major leaks are not anticipated from the vessels.

Mechanical Seal Failure

CVIP Pressure tests confirm room temperature seal integrity

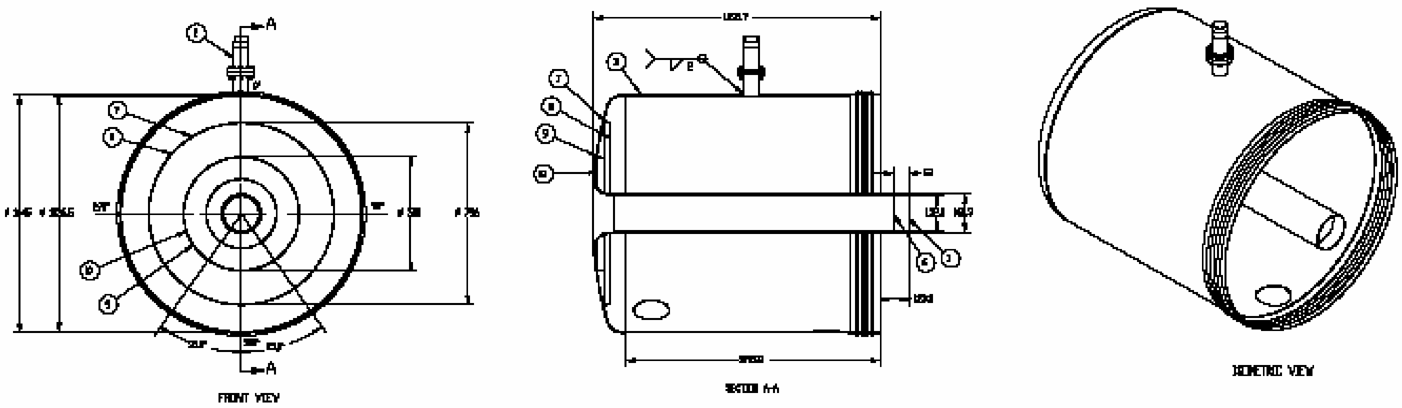
MIT-PSFC Pre-Operational Tests will confirm seal integrity at temperatures cycled between LN2 and Room Temperatures

A redundant welded seal is possible as a back-up. Spare mechanical seals are provided

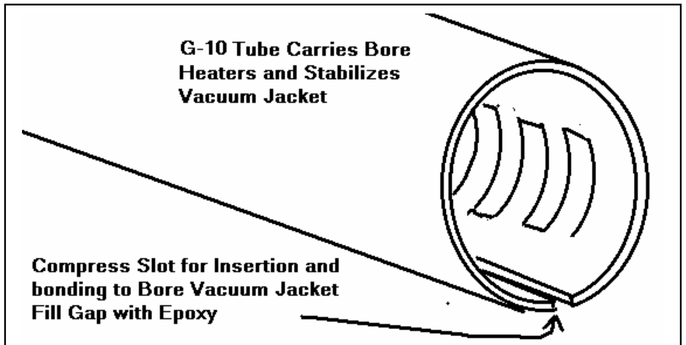
Spare metallic seals for the cover flange

Vacuum Jacket Qualification

Design Pressure is 0 atm Absolute. Pressure relief is set at 0 atm Gauge – Vacuum Jacket over pressure is not credible. Vacuum was tested at CVIP and is being tested at MIT-PSFC



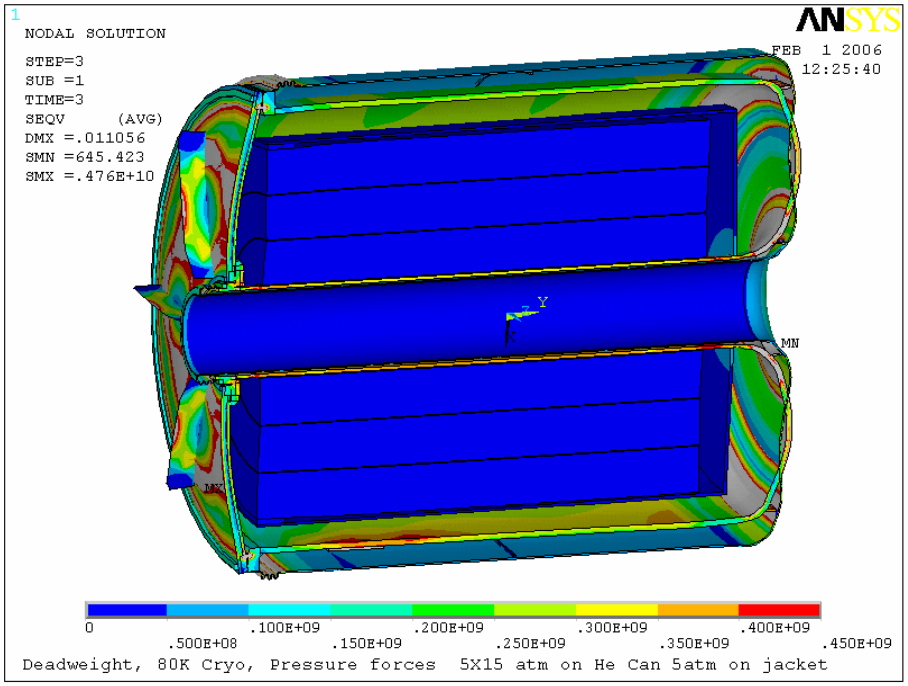
Segment of Vacuum Jacket Drawing



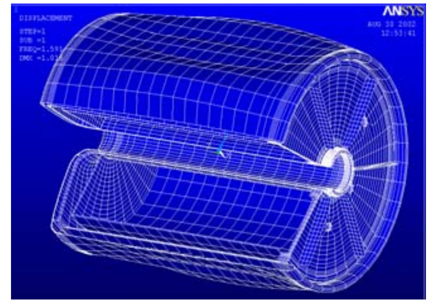
Vacuum Jacket Buckling:

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

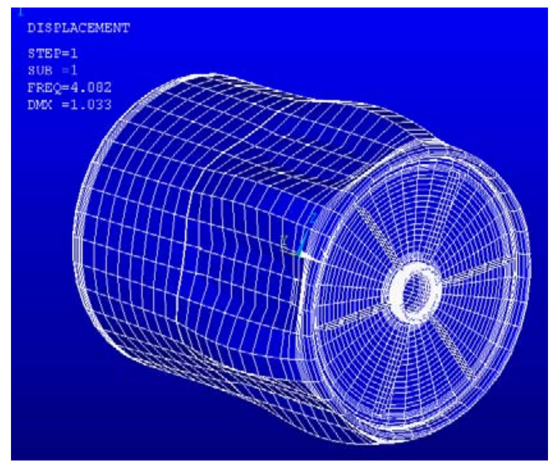
The outer vacuum jacket was thickened to 4.7mm



Large Displacement Analysis with 5 time the Design Pressures was Bounded.
- With As-Build Thicknesses, No Elastic Collapse Mode was Found.



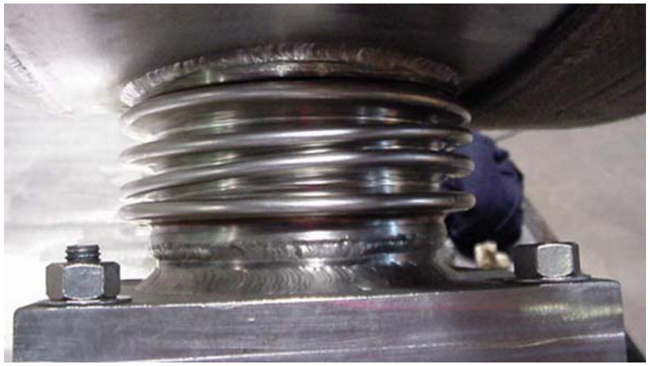
Eigenvalue Buckling Analysis, Load vector is 15 atm on cryostat and 1 atm on vacuum jacket. Analysis includes Thermal strains and pressure loads.



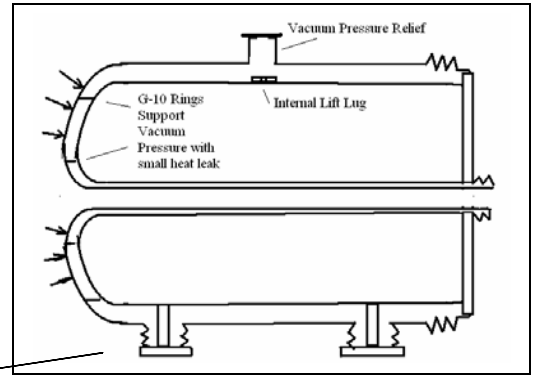
Factor against buckling is 4.08 with mid span stiffener. – The Shell was Thickened Instead

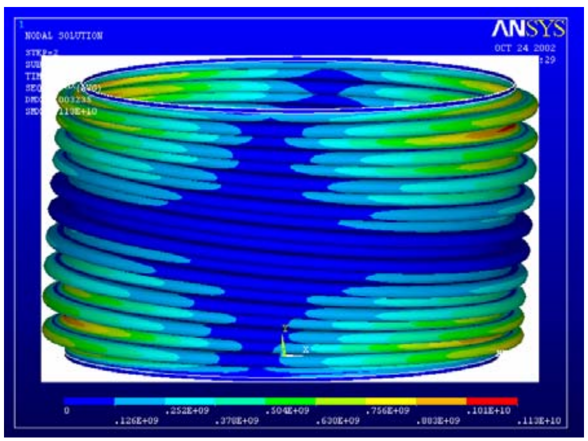
Vacuum Leaks Slowed Delivery in December

Bellows Weld flaws and G-10 Ring Fit-up were Problems. Acceptable Vacuum Load Support has been Demonstrated.



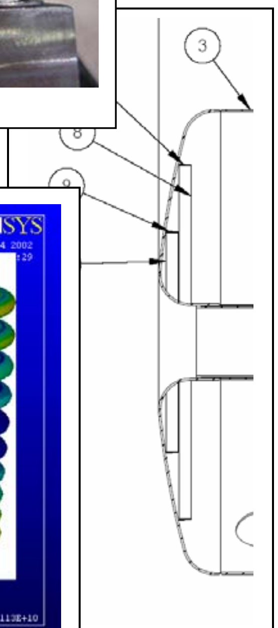
Bellows Displacement during Vacuum Test.

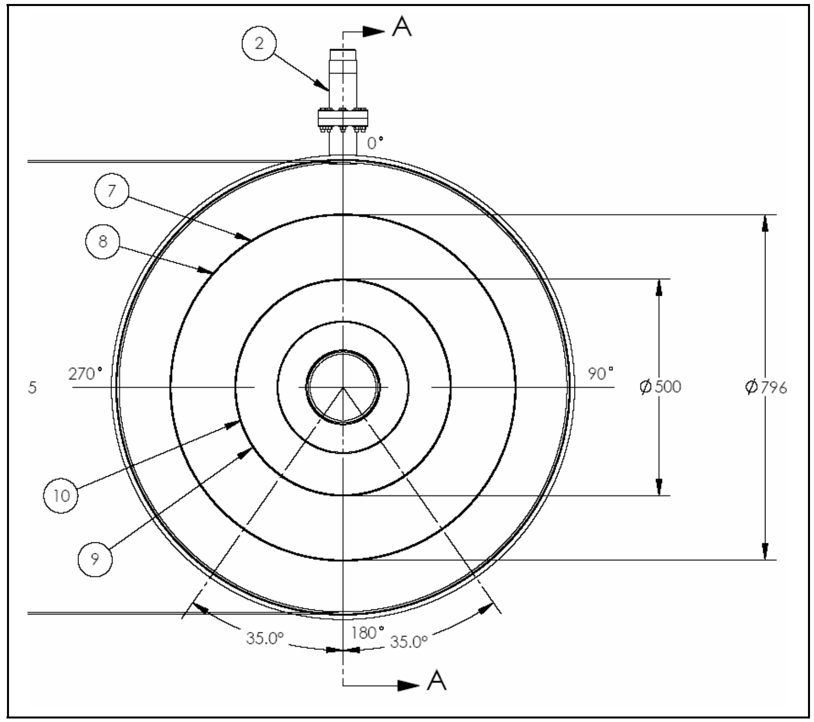


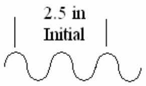


Vendor EJMA calculations were used to qualify actual bellows. Analyses of "Postulated" Bellows designs served as an existence proof.

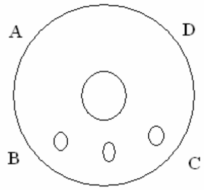
"Squirm" was expected.





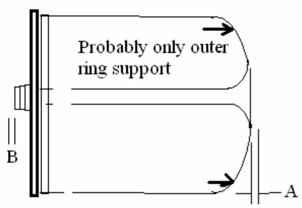


Large Bellows Axial Contraction Starting at a marked 2.5 inches



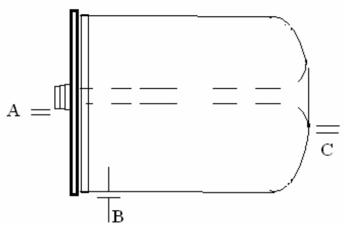
Pressure in Hg	A	B	C	D
0	0	0	0	0
-6	0	0	0	0
-15	1/32	0	0	1/32
-22	1/16	0	0	1/16
-30	3/32	0	0	3/32

The Inner Bore moves Towards the Terminal End, Bottoms out to the G-10 Ring, and then Flexes the Inner Part of the Dished Head



Pressure in Hg	A	B
0	0	0
-6	0	0
-15	1/32	1/32
-22	1/16	1/16
-30	3/32	3/32

The Vacuum Jacket Moves Downward at B (But not A) as the outer G-10 Ring Seats

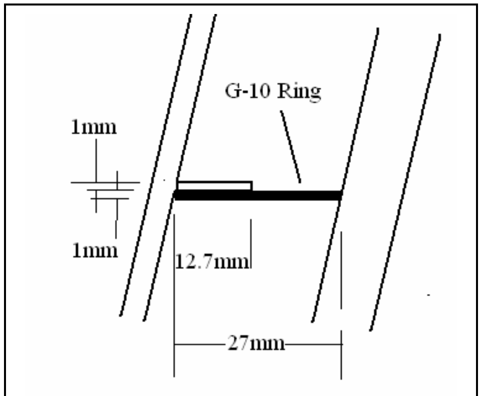


Pressure in Hg	B	A	C
0	0	0	0
-6	0	0	0
-15	1/32	0	0
-22	1/16	0	0
-30	3/32	0	0

Displacements under Vacuum Pressure, Taken at CVIP December 29th 2005

Measurements indicate that the inner ring is not in contact. This allows the 3/32 displacement of the bore under vacuum. The shell "tips" slightly (but the bore tube doesn't) under vacuum.

Only 7% of the ring needs to be in contact to support the vacuum load.



From CVIP Drawings #04022007,8,9,10

Vacuum Space Leaks

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. Unfortunately there were some problems with leaks in the bellows. Bellows leaks introduce air into the vacuum jacket space and degrade insulating properties. More LN2 will boil off, and Liquid may accumulate on the cold vessel and in the MLI that might pressurize the vacuum space – pressure relief is provided.

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.*

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.

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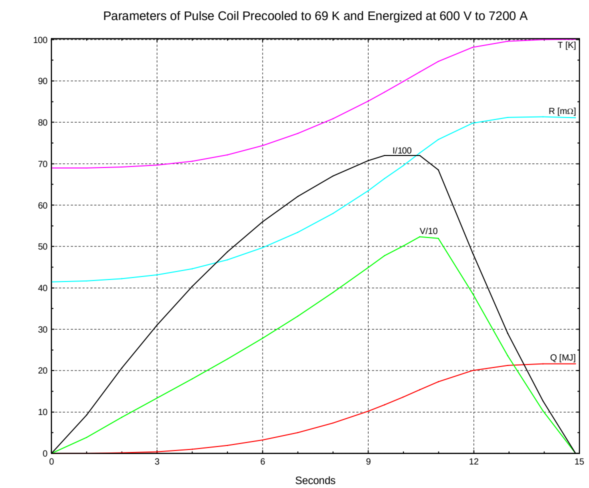
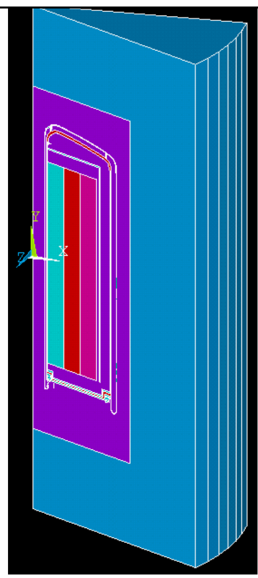
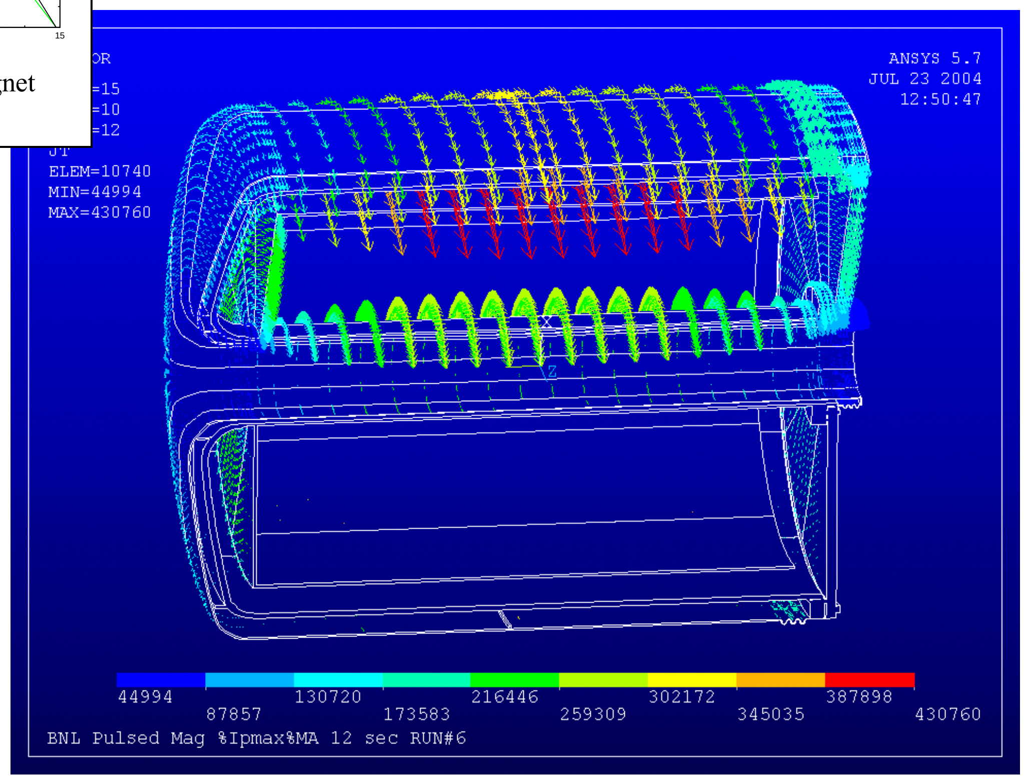


Bob Weggel's 10-14 analysis of the LN2 magnet operation



Electromagnetic Model with Air



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

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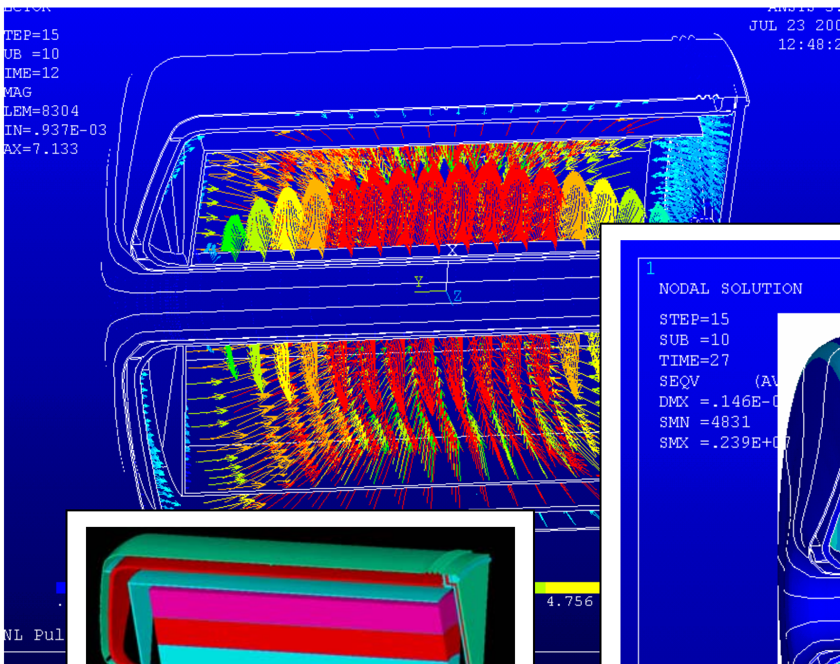
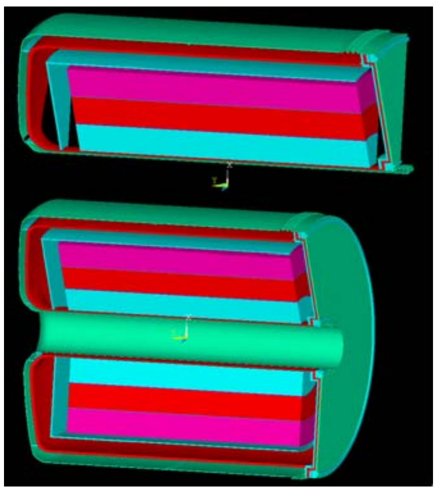
Cryostat Eddy Current Analysis



Eddy

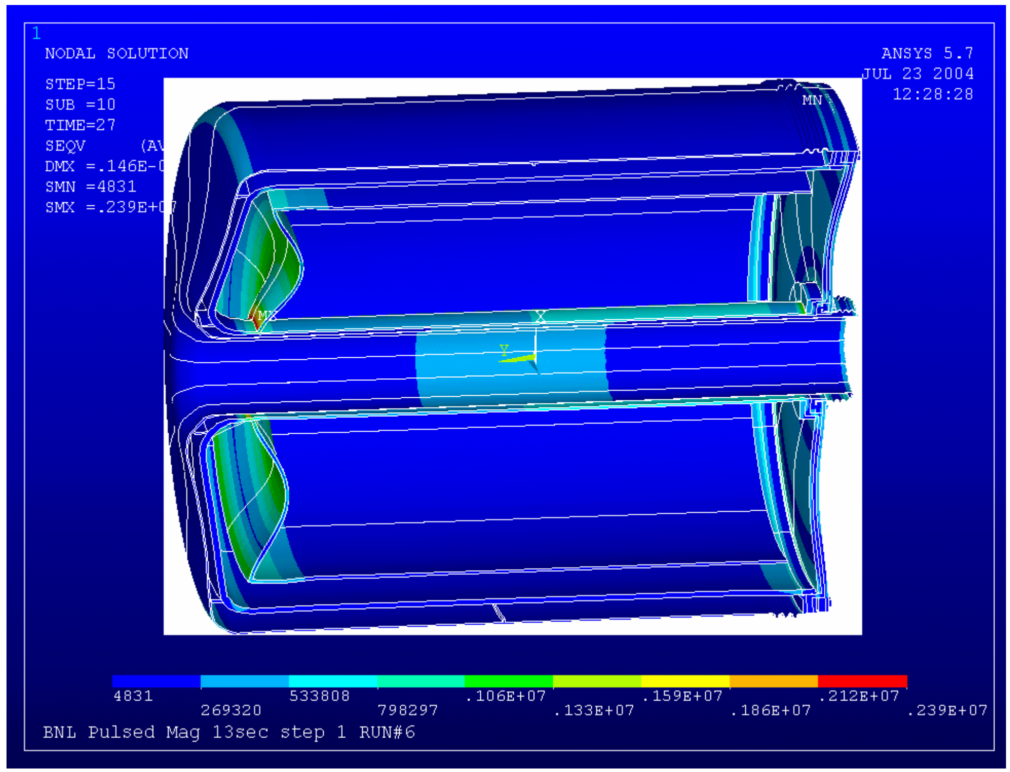


Structural Model.

Structural Response to Eddy Currents

Peak Stress is Only 2.4MPa

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



Qualification of Joints and Leads

Leads threaded, prepared for shipping

Joint Failure - The most common kind of magnet failure

Excessive Motion

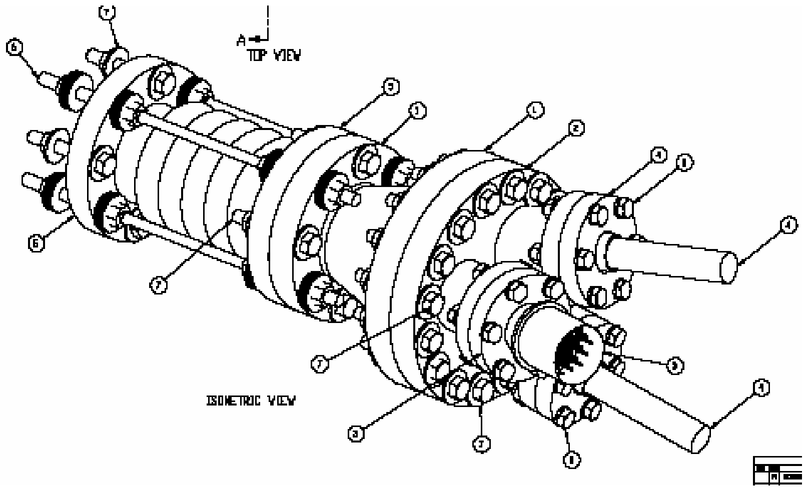
Joints are cantilevered, but hoop tension and Lorentz force compensated as in a coax.

Bellows allow motion, Tie rods support internal pressure. The joints are insulated and wrapped with glass-epoxy

Omission of a Force Component

George Mulhulland helped with a reminder of the pressure force. This is about 1400 lbs, and is taken taken by tierods.

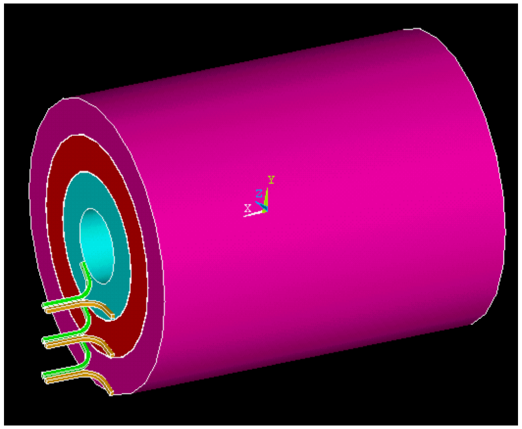
Lorentz loads have been analyzed



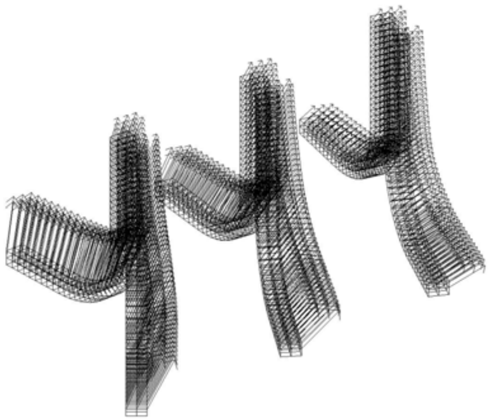
Tie Rods Take Pressure load

Break-Outs, Leads, and Penetrations

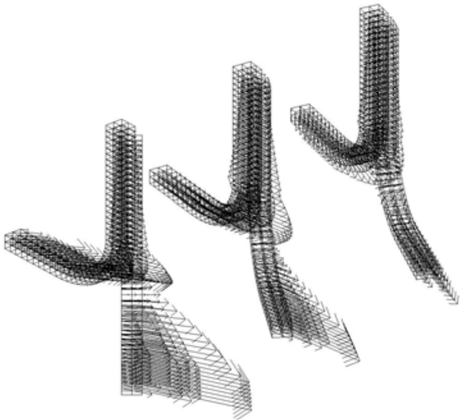
- The break-out concept structurally connects the inner layer break-out with the outer layer break-out.
- The leads are closely coupled to cancel the net loads on the lead conductors.
- Loads cancel, but there is a small torque.
- To achieve the interconnection of the leads, they cross the face of the 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
th 7200 amps in the leads, and the appropriate
enoid end field solution is results.

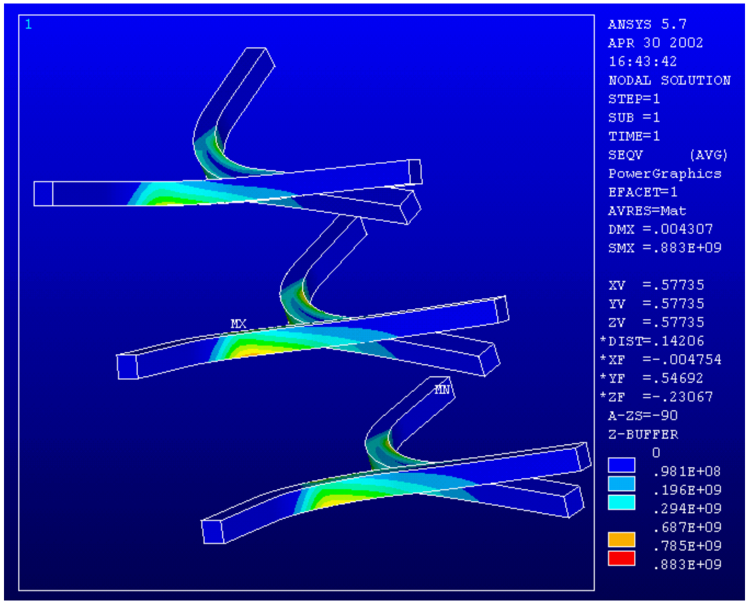


Fields at the break-outs, 15.0T Full field operation.

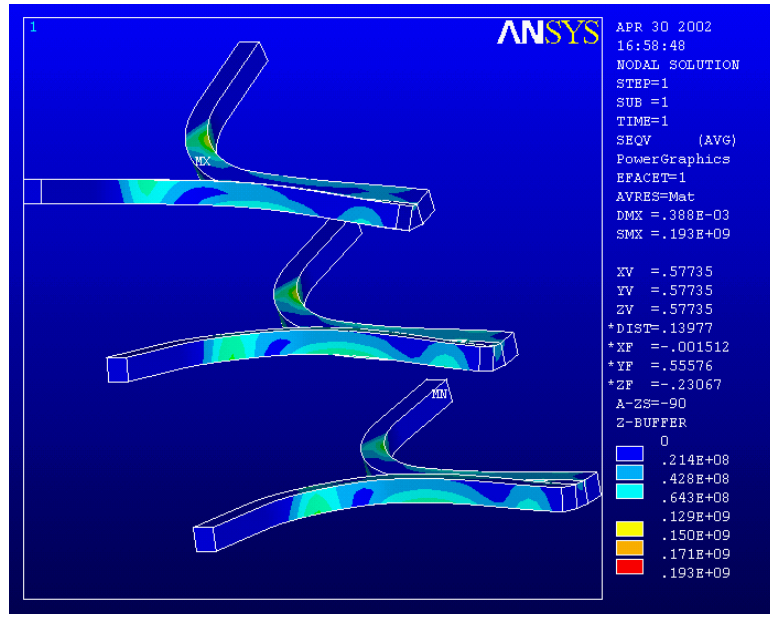


Lorentz Forces at the break-outs. 15.0T Full field operation.

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



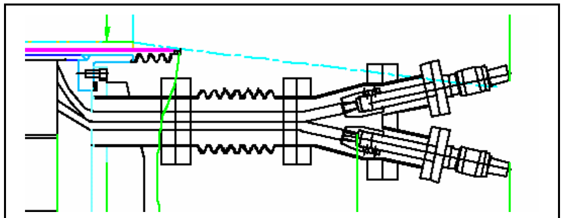
Winding ends well supported, Terminal ends Un-supported and not interconnected. Lorentz Forces Only



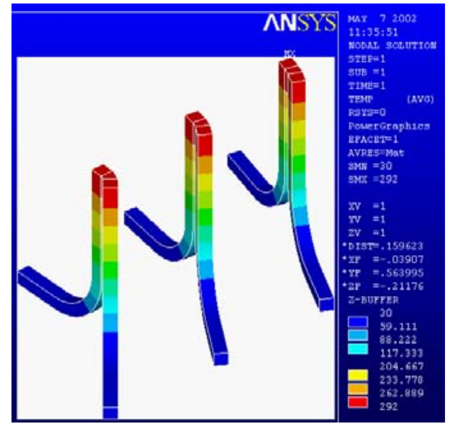
Winding ends well supported, Terminal ends interconnected at the end of the lead pair. Lorentz Forces Only

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.**

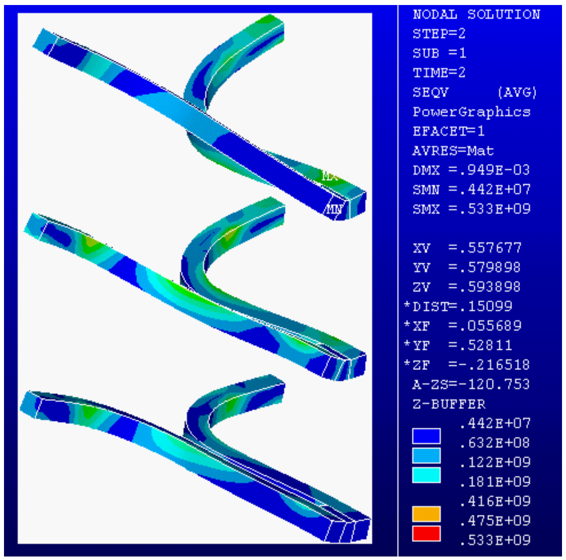


Lead with bellows

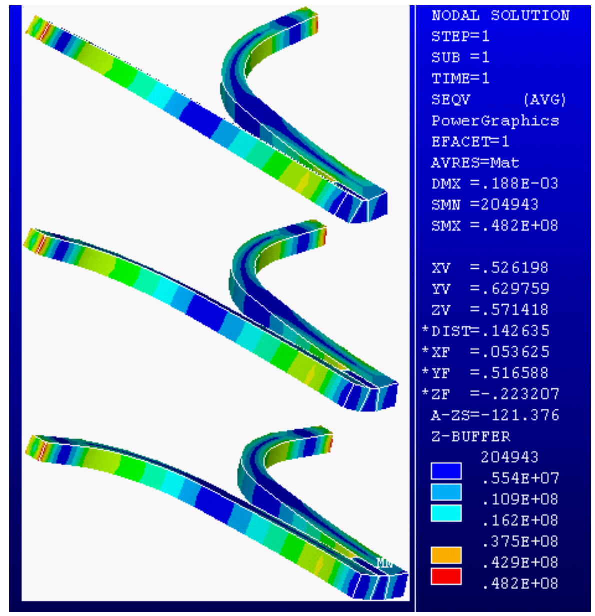


Joint Temperature

- **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

Status of Bus Bars / Leads

The leads are modeled as 1 X 3 inch bar/strap.

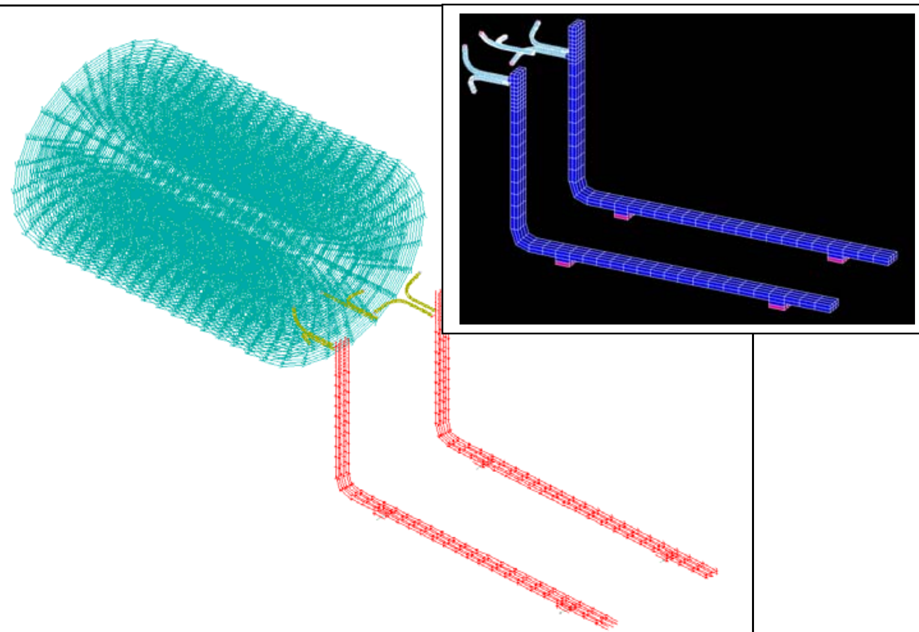
Loads on the Bus Bar Extensions

The total reaction for the 2 pads on the rear lead are:

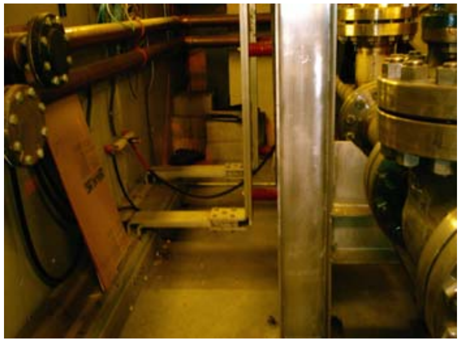
FX 113.73N
FY 1982N
FZ –24.5N

The total reaction for the 2 pads on the front lead are:

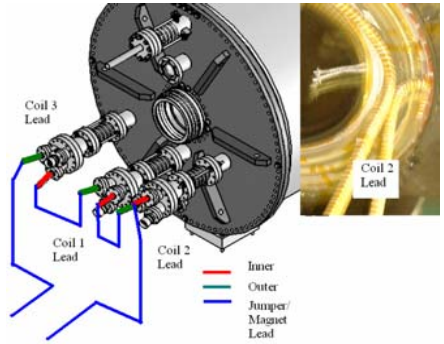
FX 627N
FY 1714N
FZ –17.25N



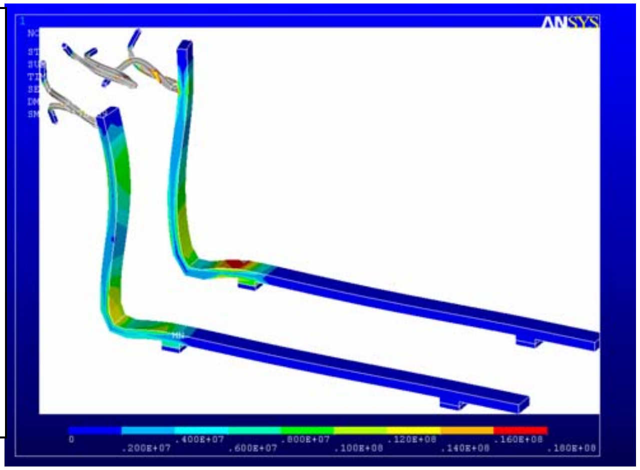
Biot Savart Model of leads and Bus Bar Extensions



Bus connection to the PTF Split Pair



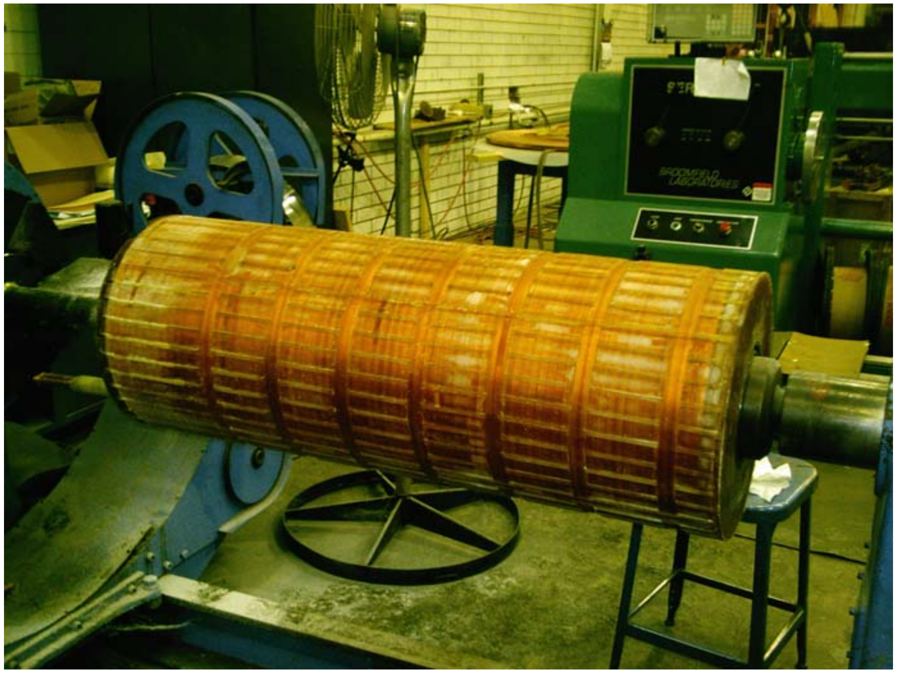
MIT-PSFC will Fabricate Jumpers ,Leads and supports.



Strap Stress is only 18 MPa.

Cooldown

- **LN2 Cooling is now the Baseline. Helium Gas Cooling is retained as a Possible Upgrade**
- **The magnet was initially designed as an axial flow cooled system.**
- **Annular flow channels between coil segments provided coolant flow**
- **Present design is based on pool boiling LN2 cooling, for which circumferential channels were added**



Segment #1 with it's OD machined.

Cooldown Calculations:

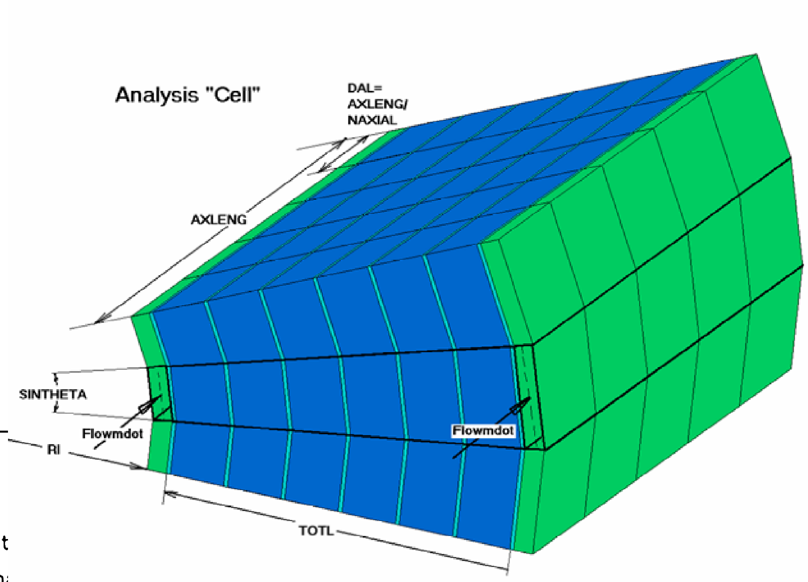
Finite Difference Model is Used.

Axial Channel Flow and

Transient Heat Conduction

Reducing the Kapton between Layers Allows 8 layers to be cooled from axial channels.

Two Phase N2 Cooling



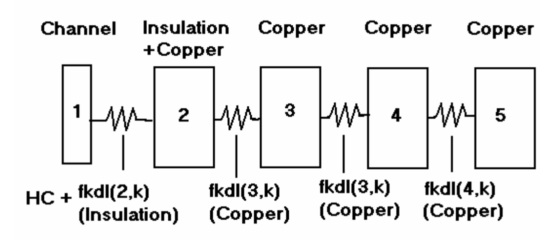
2.1.3 Convective Heat Transfer

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

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

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

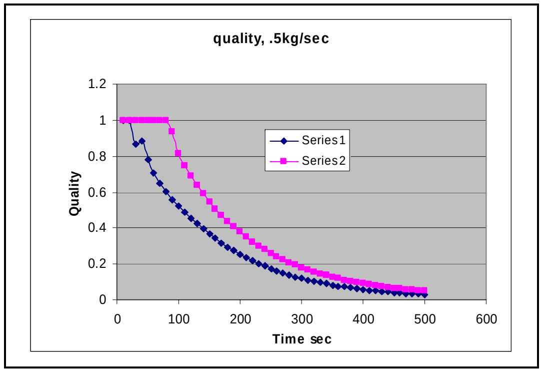
Axial Flow Is Still Assumed in the Analysis.

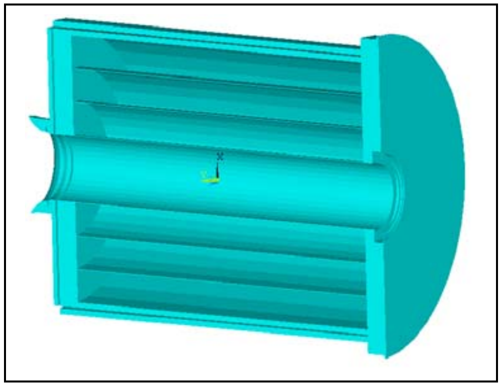
Design Features are Being Added to Encourage Vertical Natural Convection.

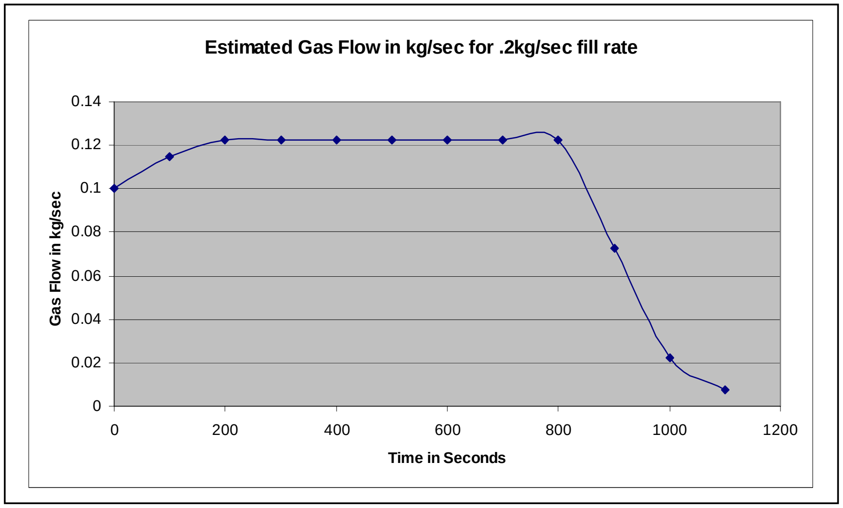
Fill Rate Effect on Cooling Time

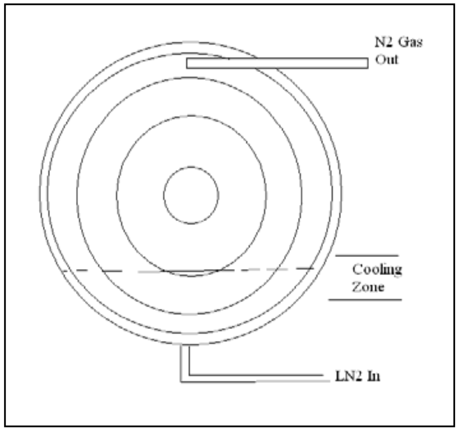
A fully submerged coil could vaporize .5g/sec and cool in 500 seconds

Rate of submergence limits the active cooling zone, extends the cooling time, and limits gas generation.









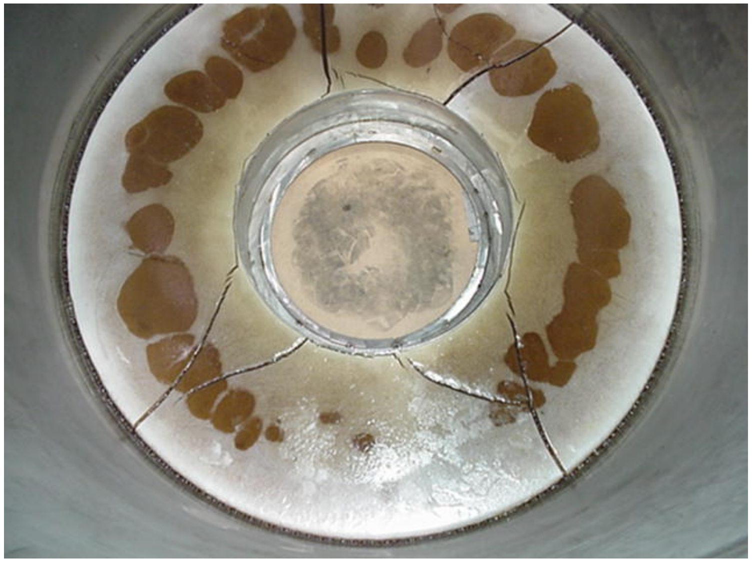
Total Kg of gas generated:	116.75	Resulting fro an assumed 1000 sec, 16.7min cool
Total Ilet Flow at .2kg/sec	200	

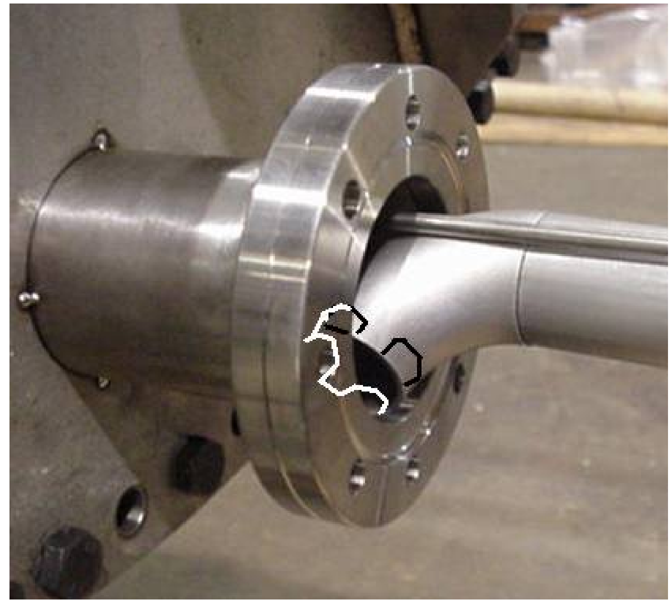
So a "Flat" Fill profile looks Viable in terms of Magnet Cooling

Total Gas Generation Needed:	126.0869 kg	
Fill Volume of Cold Vessel	104 kg	130 liters
Total LN2 Required:	230.0869	
Required Flow Rate 20 min Cool	**0.1917 kg/sec**	

-Consistent with Friedrich Haug's Calculations

LN2 Residual Volume Reduction - Fillers and Drain Details





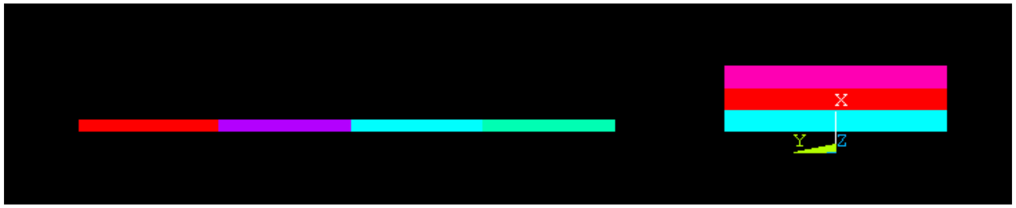
Fillers reduce LN2 inventory that needs to be blown out between shots. Tipped vessel needs drain tube extension.

Two separate instrumentation systems are used for level indication.

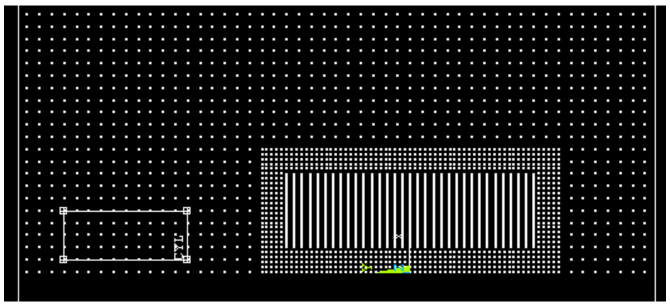
LN2 remaining in Cryostat may be activated of might accumulate Ozone.

There is a potential for particulate contamination in the LN2. Filters are needed.

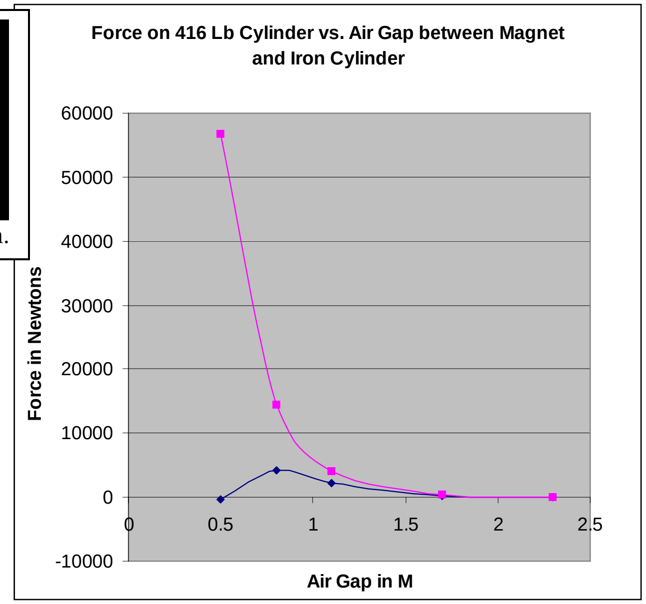
Loads on Iron Cylinders – And Any Other Fero-magnetic Components
Test Areas must be “Policed” for loose Magnetic Components

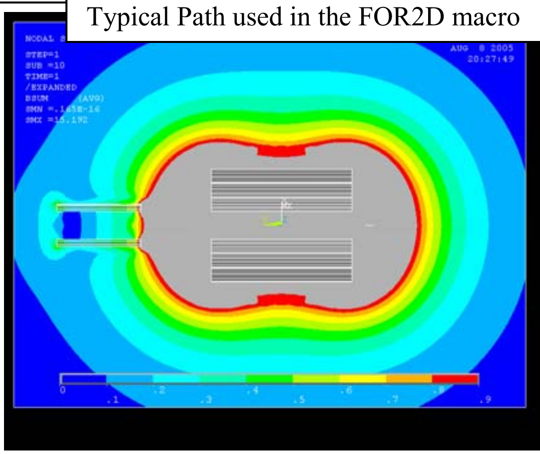


Model (shown without air) with 4 material regions used in the parametric study of cylinder position.

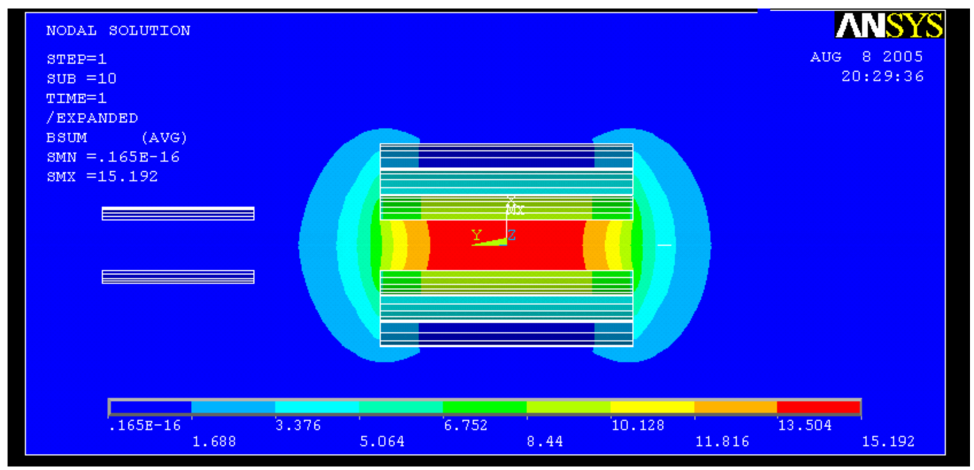


Typical Path used in the FOR2D macro





Field distribution for a .5m air gap between magnet and iron cylinder. The red contour is .9T



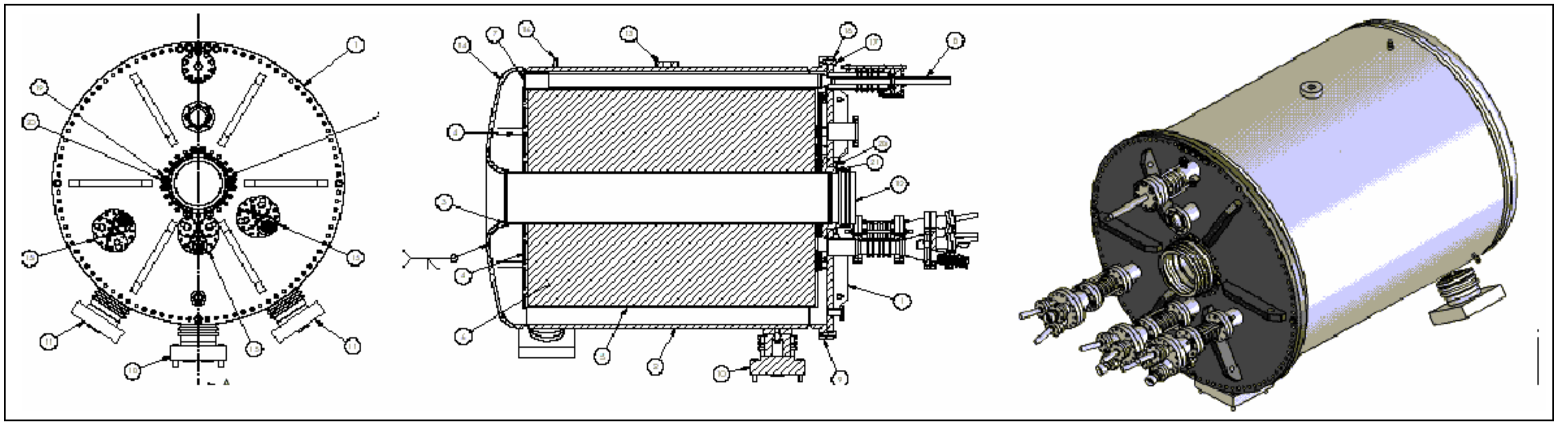
Field Distribution Near the Magnet with a .5 m air gap between magnet and cylinder.

Lateral Load Capability - Seismic and Lateral Magnetic Loads

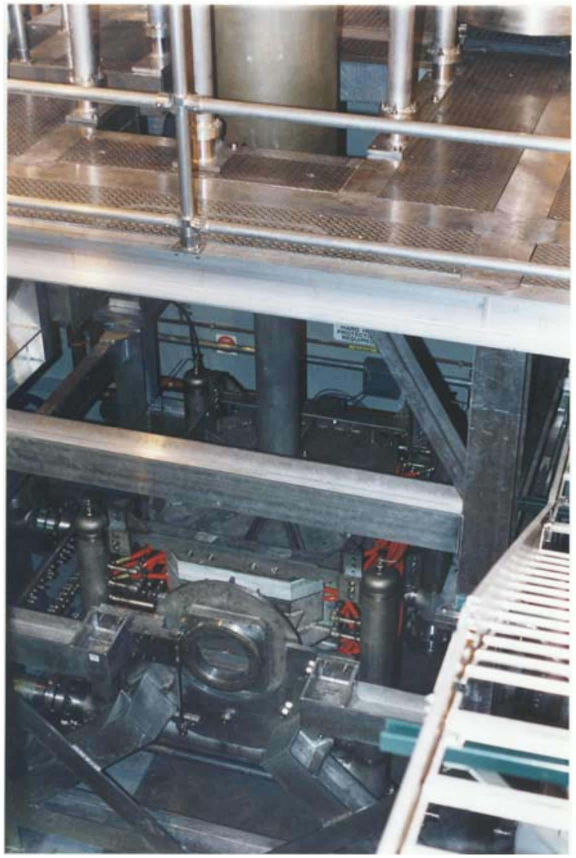
The magnet is supported on three legs. One is fixed and two are sliding. The sliding block feet have tensile capacity to ensure magnet stability against side loads.

At MIT-PSFC Rebar, Unistrut, Circulating Pump Components will produce loads on the magnet. Everything significant is more than 1 meter away. – But projectiles are still a concern.

Supports are robust otherwise – not as delicate as superconducting magnets supports.



The Magnet System will undergo Pre-Operational Testing 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

Conclusion

CERN will receive an extensively analyzed and tested magnet system for use in the MERIT Experiment. It has been qualified in accordance with the best practices available for unique magnet systems.

Testing Procedures, Results; Drawings, and Calculations are available at:

http://www.psfc.mit.edu/people/titus/#BNL%20Memos