Design Report
BNL - E951 15T Pulsed Magnet for Mercury Target Development
Neutrino Factory and Muon Collider Collaboration
(DRAFT)

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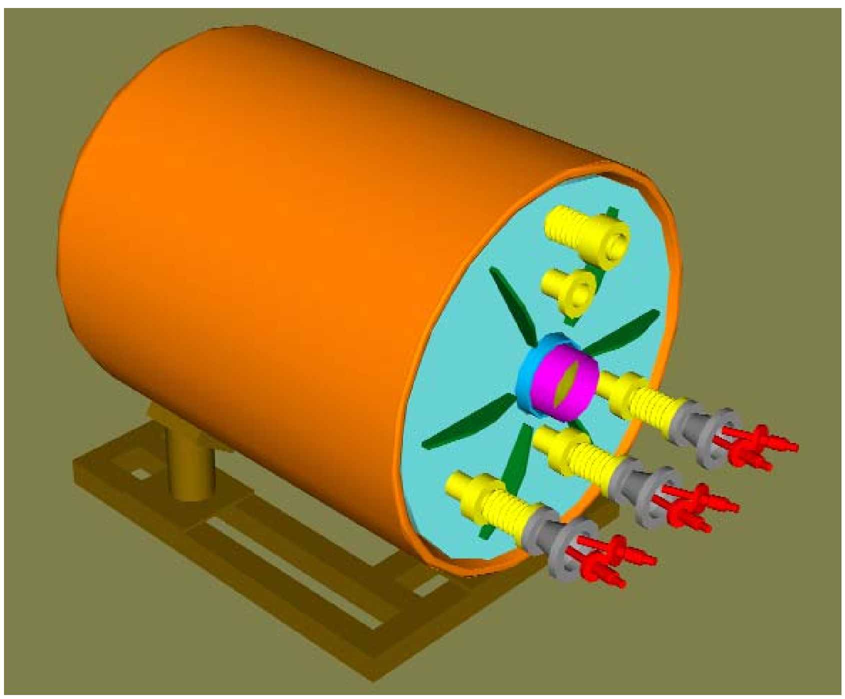

BNL Pulsed Magnet –Inertially Cooled , 30K He Gas Cooled Between Shots

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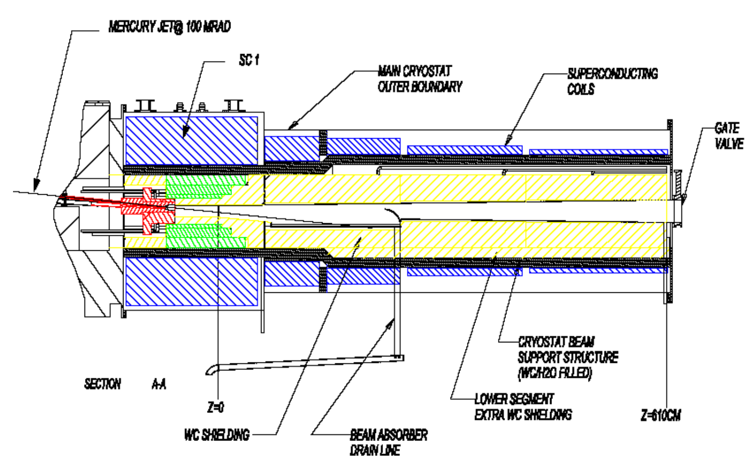
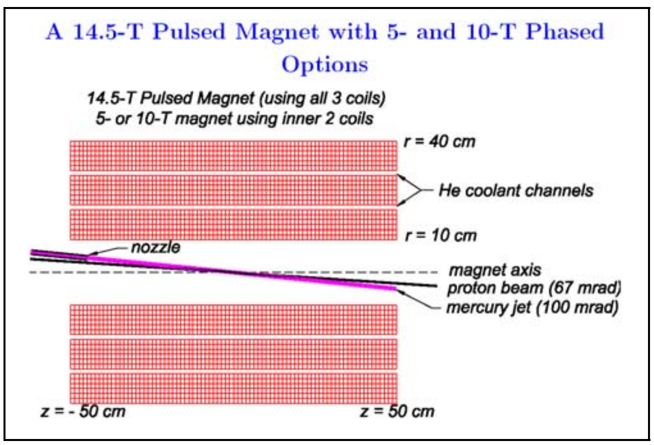
1.0 Introduction

The purpose of the experiment is to study mercury targets for neutrino beams and a muon collider source. In these experiments, a mercury jet intersects a proton beam in a high field. The particles that are produced are confined by the magnetic field. The behavior of the mercury jet in this environment needs to be understood before resources are committed to the larger experiments



The Neutrino Factory

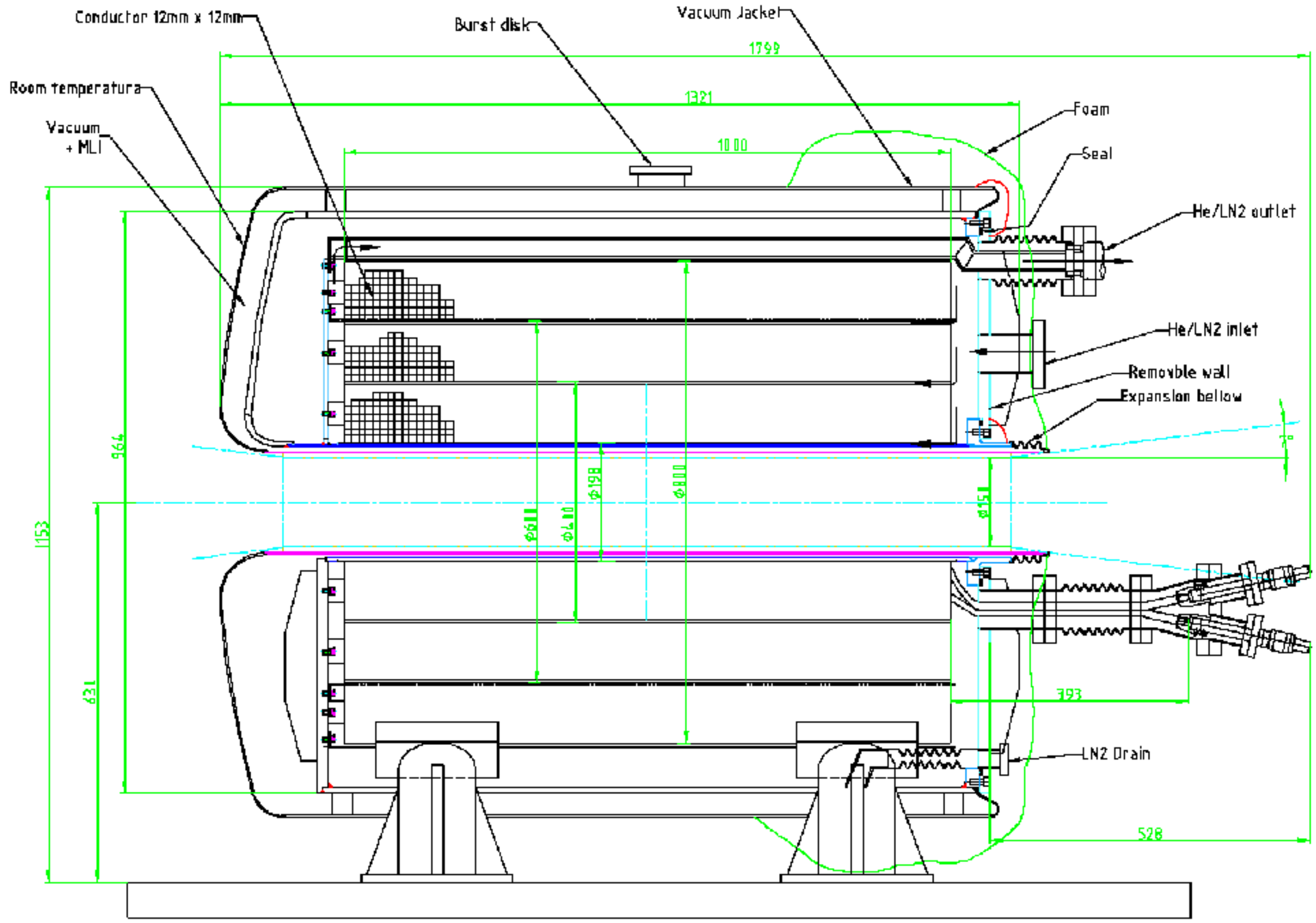
Cost issues dictate a modest coil design. Power supply limitations dictate a compact, low inductance, high packing fraction design. three segment, layer wound solenoid is proposed for the pulsed magnet. Phased manufacture is supported. The third segment may be purchased and installed in the cryostat later. 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. For the same packing fraction, a hollow conductor would have a 1.4mm diameter hole. This is judged difficult to manufacture and difficult to maintain helium flow over the conductor length, without intermediate gas connections. The coil will be epoxy impregnated. Wound coils of this small radius, using cold worked conductor, retain internal elastic stresses from the winding process, and if not impregnated, require elaborate clamping mechanisms to have the coil retain it's shape.



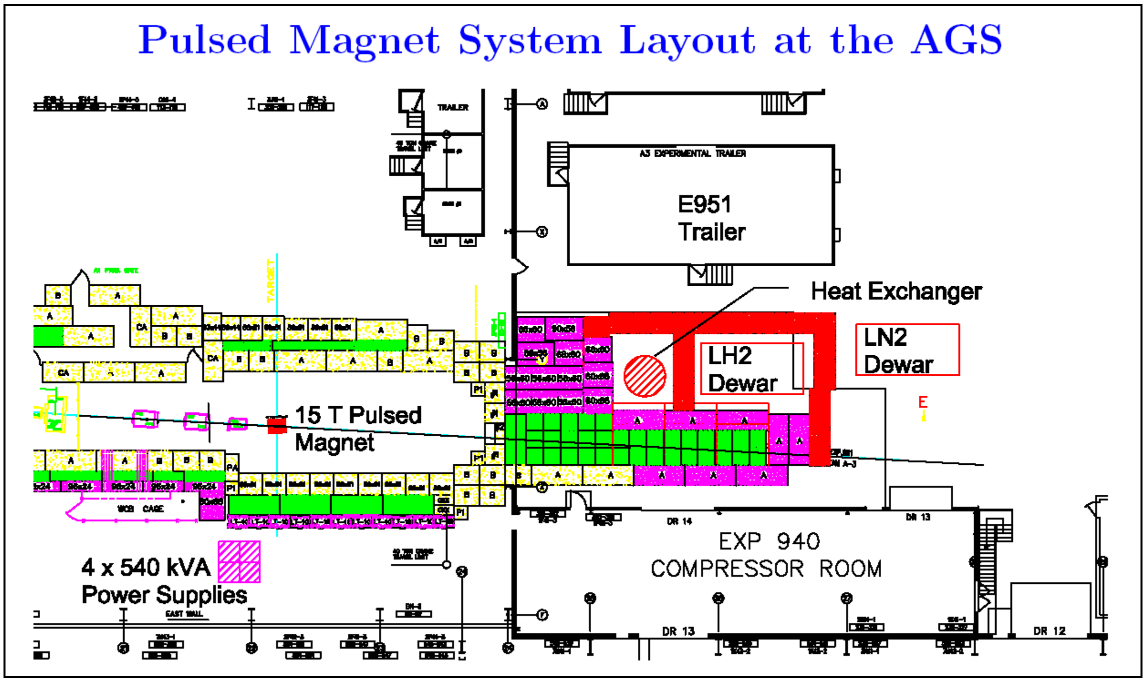
Simulations of the Mercury Jet interactions with the magnetic field, and proton beam.

Proposed Operational Scenarios:

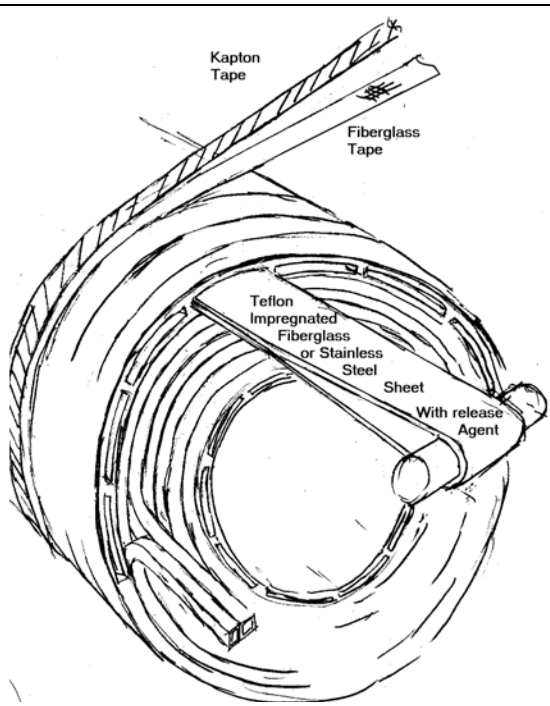
Case #	Peak Field	Coolant	T after pulse	T coolant	Start Bulk Temp
1	5T	Helium Gas	90K	66K	84K
1a	5T	LN2	90K	66K	84K
2	10T	Helium Gas	96K	66K	74K
2a	10T	LN2	96K	66K	74K
3	14.5T	Helium Gas	78K	22K	30K



Elevation/Assembly Drawing of the BNL - E951 15T Pulsed Magnet, used for mercury target development for the Neutrino Factory and Muon Collider Collaboration



Dual operational modes require special design of the cryostat/helium can. This is discussed in the section on cooldown behavior.



This is the original concept for forming the annular array of longitudinal coolant channels. Requirements for separately powering the three coil segments raised the likelihood that the channel ribs would have to support large shears due to differential thermal expansion of the inner segments vs. the outer segments.

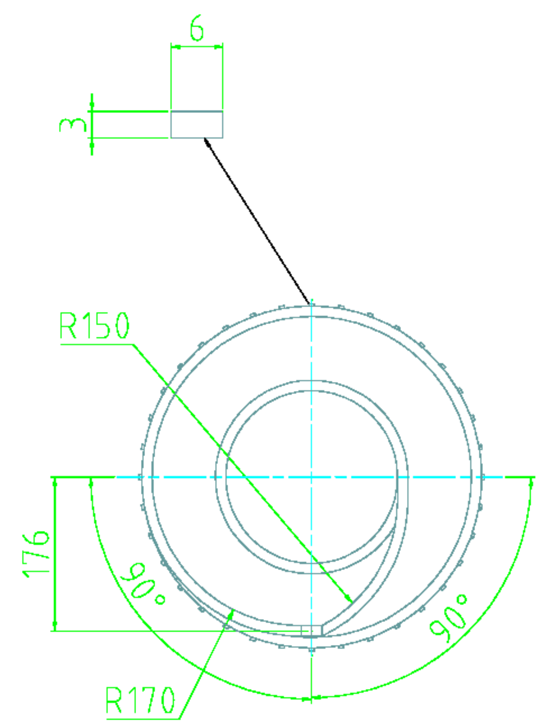
Insulation design impacts the conduction cooling behavior:

- Kapton is the limiting element in the thermal conduction through the coil.
- Kapton initially 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. Note that the He operating pressure is expected to be 15 atmospheres, the pressures inside the epoxy winding pack may be substantially lower, depending on Helium diffusion, making the 1 atm breakdown voltage for the conductor, reasonable.
- The layer to layer voltage exceeds this rule of thumb, 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 equivalent of 3 mils of Kapton rather than 5 if the conductor were wrapped individually. Every 6 to 8th layer some sort of preformed channel array would be layed on, then wrapped with glass/Kapton to hold it in place, and as the layer insulation for the next layer of conductors. .

Thermal contraction/shock of channel presents some reliability concerns. It was originally conceived that the channels might be preformed and the layer winding would be applied over them. Thermal differentials could produce separation and loss of conduction. In the final design each of the three coil segments is manufactures separately, and slipped over the next inner coil.

Experience with Alcator C-Mod indicates that for final magnet temperatures at or below 100K, the channels will not need "turbulators" or surface trips to break-up the film boiling layer. This will have to be reviewed during the design phase. If some form of surface roughness will be required in the 2mm channels, then the method of forming the channels with removable strips will have to be re-visited.



This is and end view of the inner coil. Ribs or stand-offs form the channels which allow sliding/parting planes to accommodate axial and radial motion between the coil segments. A few ribs bonded or formed with the ID of the next outward coil segement provide torsional registration.

2.0 Design Input/Specifications

It is important that we have the expected (design) operating conditions for, especially, the following parameters:

Mode	Field	T_0	Energy	T_2	?T	Cycle
Units >	T	K	MJ	K	K	minutes
LN_2	5.0	84	2.4	90	6	6
LN_2 Pumped	10.0	74	7.9	95	21	20
LH_2	14.5	30	13.5	78	48	20

LN_2	5.2	81	2.6	87	6	10
LN_2 Pumped	10.4	70	7.9	91	21	30
LH_2	15.0	26	15.0	80	54	30

Table 1. The initial temperature, energy deposition, final temperature, temperature rise and maximum rep rate for ca. 5, 10 and 15 T central field. The first set of three rows is for coils with 75 turns per layer. The second set is for coils of 78 turns per layer and a less conservative estimate of magnetoresistance. All coils can maintain a flat top of one second. Decreasing the flat top to about half a second would allow one to achieve full field from a starting temperature about 1 K higher. (From Bob Weggel, 7/16/02)

Builds used in the finite element models:

#	r	z	dr	dz	nx	ny
1	.15	0	.098	1.0	16	16
2	.2	0	.002	1.0	1	16
3	.25	0	.098	1.0	16	16
4	.3	0	.002	1.0	1	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 t	.0116698 m .45944 in	.0116698 m .45944 in	.0116698 m .45944 in
Conductor Axial t	.012516m .49274359 in	.012516m .49274359 in	.012516m .49274359 in
Max Operating Field Bore CL	5T	10T	15.0T
Max Field at Magnet			

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 - Initial Operating			15 atm
Cryostat Pressure – During Cooldown			20 atm max
Number of .54 MVA power supplies	1	4	4
Mode of Ganging Supplies	None	2 X 2	2 X 2
Charge Time	7.2	6.3	15.3 sec
Initial Temperature	84K	74K	30K
Temp Rise	5.8K	21.7K	48.3K
Final temperature			78.3
Cumulative heating at end of pulse	2.7MJ	9.1MJ	15.2MJ

1. Longevity goal for the magnet is ~1000 pulses of 15.0 T peak central field.
2. Magnet should be capable of operation in three modes: 1) 5 T at 3600 A, with inner windings (inner two shells) pulsed at 150 V from ≤84 K; 2) 10 T at 7,200 A, with inner windings pulsed at 300 V from ≤74 K; 3) 14.5 T at 7,200 A, with entire magnet pulsed at 300 V from ≤30 K.
3. All vessels and piping, including the bore tube, should satisfy ASME pressure and vacuum codes.

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

3.0 References

[1] Fusion Ignition Research Experiment Structural Design Criteria; Doc. No. 11_FIRE_-DesCrit_IZ_022499.doc; February, 1999
[2] "General Electric Design and Manufacture of a Test Coil for the LCP", 8th Symposium on Engineering Problems of Fusion Research, Vol III, Nov 1979
[3] Product Literature, Inco Alloys International, Inc Huntington West Virginia 25720, USA
[4] "Mechanical, Electrical and Thermal Characterization of G10CR and G11CR Glass Cloth/Epoxy Laminates Between Room Temperature and 4 deg. K", M.B. Kasen et al , National Bureau of Standards, Boulder Colorado.
[5] "US ITER Insulation Irradiation Report Program Final Report" August 31 1995 Reed, Fabian, Shultz
[6] Effect of Face Compression on Interlaminar Shear Strength of Polyimide/S2 Glass Laminate Insulators - Preliminary Report" H.Becker, T. Cookson (GDC) June 24 1985
[7] "Shear Compression Tests for ITER Magnet Insulation" Simon, Drexler, Reed, Advances in Cryogenic Engineering Materials Vol 40 (1994)
[8] "Case Studies in Superconducting Magnets" Design and operational Issues, by Yukikazu Iwasa , Plenum Press, New York and London 1994
[9] CryoCoat™ UltraLight™ Insulation presented by:Michael L. Tupper COMPOSITE TECHNOLOGY DEVELOMENT INC. 1505 Coal Creek Drive Lafayette, Colorado 80026 January 2001
[10] http://www.lakeshore.com/temp/sen/crtd.html
[11] CPC Cryolab Vacuum Tight Pressure Relief Discs PR-3 Series Data Sheet
[12] Mark's Standard Handbook for Engineers, Sevnth Edition, Pages 3-60 through 3-63, Pipe friction factors and entry/exit losses.
[13] Air Liquide Web Site http://www.airliquide.com - For some Helium and Nitrogen Properties
[14] MLI Specification from: "LHC Interaction Region Quadrupole Cryostat", Thomas H. Nicol, Fermi National Accelerator Laboratory December 3, 1998, P.O. Box 500, Batavia, IL 60510

Table 4.8: "Typical" Values of Radiation Heat Flux [4.14]

Material	$T_{cl} \sim T_{wm}$ [K]	$[e_r]_{cw}$	q_r [mW/m^2]
Copper			
as received	4∼20	0.03*	0.3
	4∼80	0.06	140
	80∼300	0.12	55,000
mechanically polished	4∼20	0.01*	0.1
	4∼80	0.02	46
	80∼300	0.06	27,000
Stainless steel			
as received	4∼20	0.06*	0.6
	4∼80	0.12	280
	80∼300	0.34	155,000
mechanically polished	4∼20	0.04*	0.4
	4∼80	0.07	160
	80∼300	0.12	55,000
electropolished	4∼20	0.03*	0.3
	4∼80	0.06	140
	80∼300	0.10	46,000
Aluminum			
as received	4∼20	0.04*	0.4
	4∼80	0.07	160
	80∼300	0.49	224,000
mechanically polished	4∼20	0.03*	0.3
	4∼80	0.06	140
	80∼300	0.10	46,000
electropolished	4∼20	0.02*	0.2
	4∼80	0.03	70
	80∼300	0.08	37,000
foil	4∼80	0.01	20
	80∼300	0.06	28,000

* One half of the 4.2∼80 K value.

From [8]: page 152 "Case Studies in Superconducting Magnets" Design and operational Issues, by Yukikazu Iwasa , Plenum Press,

4.0 Structural Design Criteria, Materials and Conductor Specifications

Lacking a specific design code jurisdiction, fusion project criteria are used for guidance in coil design [1] The referenced 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. However because the cryostat must be safely pressure tested at room temperature, stresses will be checked based on the room temperature properties. The room temperature physicals for the proposed 316 bolts are:

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

The cryostats are to be qualified in accordance with ASMEVIII. Qualification of all the weld details, shell thicknesses, nozzle reinforcements, and saddle or support details of these vessels will be done at the final design stage. The conceptual design sizing presented here is intended to ensure adequate space allocation and cold mass performance.

The magnet is to be seismically qualified in accordance with the Uniform Building Code.

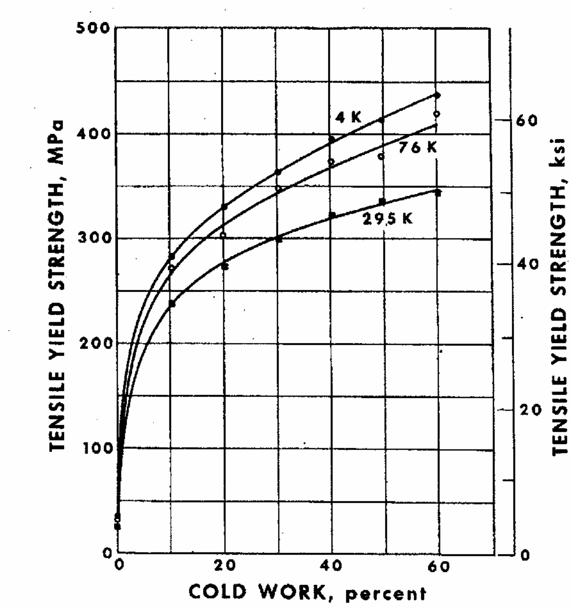


Fig 4-1 NIST Data – Oxygen Free Copper Tensile Properties (4-300K)- C10100 – C10700 Cold Worked

4.1 Conductor Properties and Allowables

Mechanical properties for some of structural materials and coil components are given in this section. Tensile yield strength for oxygen free copper is given in Fig. 1 at 4 K, 76 K and at 296 K. Yield and Ultimate strength data is given for several variants of copper at RT and 77K in Table 1.

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

The maximum stress in the three segment coil is 166 MPa. Half hard copper should satisfy this requirement at liquid nitrogen temperatures. In order to minimize the difficulties of winding the first layers of the inner solenoid, It is intended that the conductor physical properties and degree of cold work be selected to just satisfy a 166 MPa yield stress.

Table 4-1. Properties of Variants of Copper

Variant	Yield Mpa at RT	Yield Mpa at 77 K	Ult., Mpa at RT	Ult, Mpa at 77K

C10100/C10700 80%CW	380		420	500
C10100 Becker/C-Mod 60%CW	308	373	350	474

Table 4-2 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.

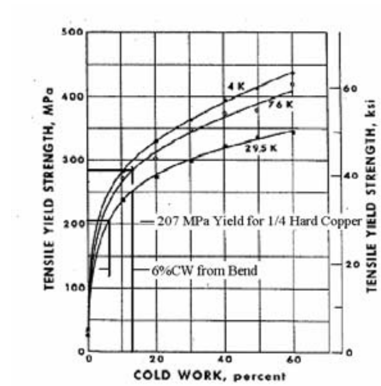


Figure 4.1 Marked-up with Expected Yields. For Segment 1 ID with CW at 100 K, about 270 MPa would be expected

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. From Table 4-3, ¼ hard copper would have a yield of 30 ksi or 207 MPa. From Figure 4-1 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. Figure 4-1 plots yield as a function of cold work. Full hard copper would have a yield of about 350 MPa at 77°K, and an ultimate of about 450 MPa which gives a primary membrane allowable (lesser of 2/3Sy or 1/2Su for externally supported coils) of about 200 MPa, At 4°K 30%CW reaches these levels.

Table 4-3 Room Temperature Properties of Copper, C10200 (OFHC)

Standard	Former	Yield Min	Yield Max	Tensile Min	Tensile Max	Elong %	Rockwell F
O25	Hot Rolled-Annealed	11 ksi (2) 76 MPa		34 ksi (2) 234 MPa(2)		45	
H00	Eighth Hard	28 ksi (2) 193		36 ksi (2) 248 MPa (2)		30	54-82 (1) 60 (2)
H01	Quarter Hard	30 ksi (2) 207		38 ksi (2) 262 MPa (2)	25	25	60-84 (1) 70(2)
H02	Half Hard	36 ksi (2) 248 MPa (2)		42 ksi (2) 290 MPa (2)		14	77-89 (1) 84(2)
H03	¾ Hard						82-91 (1) 85(2)
H04	Hard	40 ksi (2) 276 MPa (2)		45 ksi (2) 310 MPa (2)		6 to 20	86-93 (1) 87 (2)
H06	Extra Hard						88-95 (1)
H08	Spring	50 ksi (2) 345 MPa (2)		55 ksi (2) 379 MPa (2)		4	90-97 (1)

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

Table 4-4 Room Temperature Properties of Copper, C10100 (OFHC) (Identical to C10200)

Standard	Former	Yield Min	Yield Max	Tensile Min	Tensile Max	Elong %	Rockwell F
O25	Hot Rolled-Annealed	11 ksi (2) 76 MPa		34 ksi (2) 234 MPa (2)		45	
H00	Eighth Hard	28 ksi (2) 193		36 ksi (2) 248 MPa (2)	30	30	54-82 (1) 60 (2)
H01	Quarter Hard	30 ksi (2) 207		38 (2) 262 MPa (2)	25	25 to 35	60-84 (1)
H02	Half Hard	36 ksi (2) 248		42 ksi (2) 290 MPa (2)		14	77-89 (1)
H03	¾ Hard						82-91 (1)
H04	Hard	40 ksi (2) 276 MPa (2)		45 ksi (2) 310 MPa (2)		6 to 20	86-93 (1) 87 (2)
H06	Extra Hard						88-95 (1)
H08	Spring	50 ksi (2) 345 MPa (2)		55 ksi (2) 379 MPa (2)		4	90-97 (1)

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

It would be wise to do a tension test of the full copper channel section prior to soldering the superconductor. Surface hardness may not be a reliable indicator of the full section strength.

Typical values of mechanical strength for several different types of composite insulating materials is given in Table 2.

4.2 Insulation Allowable

Warp and Fill tensile allowable with a Factor of Safety F.S.=3 or 1/3 ultimate is 167 Mpa. Note that for tension normal to the reinforcement, there is no capacity listed. Normally primary tension in this direction is not allowed. Secondary or strain controlled tensile stresses are nearly unavoidable in bonded conductor arrays. Small cracks often develop near corners, and multi-layered insulations are used to limit the likelihood of through cracks. For MECO magnets, Kapton tape is specified to mitigate the effects of these cracks on electrical insulating integrity and this has the effect of reducing the tensile bond strength. It also reduces the winding pack modulus in the direction normal to the Kapton tape. The interplay between modulus and secondary displacement controlled strains will be resolved with measured properties and strengths of a representative impregnated array of conductors.

Table 4-5. Insulating Material Strengths (Ref 27)

	Mpa @4°K	Mpa @77°K	Mpa @292°K
Comp.Strength Normal to Fiber			
G-10CR	749(Ref 4)	693(Ref 4)	420 (Ref 4)
G-11CR	776(Ref 4)	799(Ref 4) 900(Ref 7)	461 (Ref 4)
CTD 101K AR irradiated	1260 (ave) (Ref 5)		
CTD-112P irradiated	1200 (ave) (Ref 5)	1150(Ref 5 p 47)	
Polyimide/S2 Glass Laminate			1033 Mpa, Ref [6]

Tensile Strength (Warp)			
G-10CR	862 (Ref 4)	825(Ref 4)	415 (Ref 4)
G-11CR	872(Ref 4)	827(Ref 4)	469 (Ref 4)
Tensile Strength (Fill)			
G-10CR	496(Ref 4)	459(Ref 4)	257 (Ref 4)
G-11CR	553(Ref 4)	580(Ref 4)	329(Ref 4)

Tensile Strain Allowable Normal to Plane

No primary tensile strain is allowed in the direction normal to the adhesive bonds between metal and composite. Secondary strain will be limited to 1/5 of the ultimate tensile strain. In the absence of specific data, the allowable working tensile strain is 0.02% in the insulation adjacent to the bond.

Table 3 provides modulus data for G-10 composite materials.

Table 4-6. Modulus of Elasticity for G-10 at several temperatures.

Temp Deg. K	G-10 Warp/Fill Gpa	G-10 Normal Gpa	Epoxy Only Gpa
295	27.8	14.0	3.81
250	29.5	16.5	5.25
200	31.3	18.8	6.69
150	32.5	20.5	7.84
100	33.0	21.5	8.54
76	33.5	21.8	8.68

4.3 Stainless Steel Properties and Allowable

Additional properties for materials used in the BNL magnet system conceptual design are provided in Tables 4-7 to 4-10.

Table 4-7. Tensile Properties for Stainless Steels and Aluminum

Material	Yield 4 deg K (MPA)	Ultimate 4 deg K, (Mpa)	Yield, 80 deg. K (Mpa)	Ultimate, 80 deg. K (Mpa)	Yield, 292 deg K (Mpa)	Ultimate, 292 deg K (Mpa)
316 LN SST	992	1379			275.8]	613]
316 LN SST Weld	724	1110			324	482
304 SST 50% CW			1344 (195 ksi)	1669	1089	1241
304 Stainless Steel (Bar,annealed)			282 (40.9ksi)	1522	234	640
Aluminum	362(20K	496(20K)	275.8		275 Mpa	310

6061T6	)				40ksi	Mpa 45ksi
Alum 6061 Weld	259(4K)	339(4K)				

Table 4-8. Coil 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
316 LN SST	183Mpa (26.6 ksi)	275Mpa(40ksi)
316 LN SST weld	160MPa(23.2ksi)	241MPa(35ksi)
304 SST 50% CW		
304 Stainless Steel (Bar,annealed)	156MPa(22.6ksi)	234 MPa (33.9ksi)
Aluminum 6061T6		

Table 4-9. Coil Structure Cryogenic (80 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

Material	Sm	1.5Sm
304 SST 50% CW	556 Mpa (80 ksi)	834 (120 ksi)
304 Stainless Steel (Bar,annealed)	188MPa (27ksi)	281 MPa (40.9ksi)

Table 4-10. Coil Structure Cryogenic (4 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

Material	Sm	1.5Sm
316 LN SST	459.6 Mpa (66.7 ksi)	689 (100 ksi)
316 LN SST Weld	366MPa (53.2ksi)	550 MPa (79.7ksi)
Alum 6061T6	165 MPa	248 MPa
Alum 6061T6 Weld	113 MPa	169.5 MPa

Inconel 718 was used in the C-Mod Drawbars and oblong Pins. Physical properties were measured from samples of the forgings used for these drawbars. This data is summarized in Table 8 . These values are representative of strengths expected for the 718 bolting specified for MECO.

Table 4-11. Inconel 718 Tensile data (hardening for 1 hr. at the most favorable temp, either 1750 or 1950deg F from ref[3])

	4 in. Bar	5/8in Bar	5/8in. Bar
	292 degK	292K	77degK
Yield	165ksi	180 ksi	173ksi
Ultimate	195ksi	208 ksi	237ksi
Modulus of Elasticity	29.8e6	29.8e6psi	31.e6 psi
Density	.296 lb/in^3	.296 lb/in^3	.296 lb/in^3

Used as bolting, 718 would have a 0.6*173=100 ksi maximum allowable operating stress

4.4 Conductor and Insulation systems design and packing fraction

Conductor Keystoning:

H/(2*r)= .012/.1/2=6% (elastic strain) For Plastic bending, (poisson=.5) the Keystoning contraction is 3%

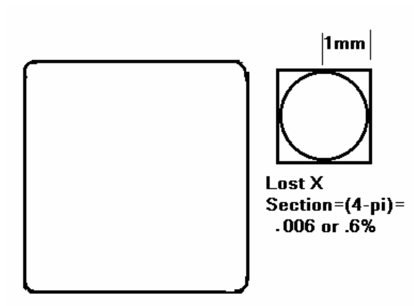
This is a function of radius. Three Keystone specs are suggested. The keystone geometry for the first segment should be .012/.15/2*.5=2%

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

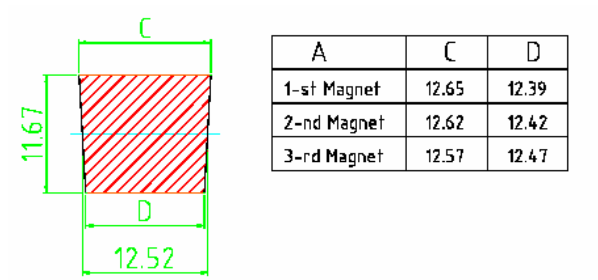
Keystone allowances in outer two segments are 1.2%, and .86%. Packing fraction losses in outer two segments are .15%, and .007%

Effect of Corner Radius:

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



Corner Radius



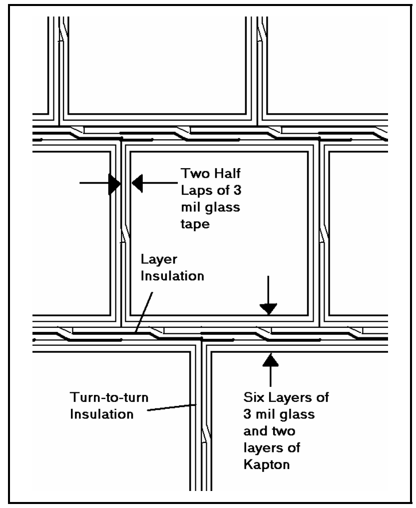
Keystone specifications from MIT-BNL-003.


During a March 9 2004 visit to Everson, This preliminary test bend test was shown, and Everson indicated that the keystoning was "about what was in the spec."

Insulation System:

In the axial or "Z" direction, there are four thicknesses of 3 mil glass tape between each conductor. In the radial direction, there are an additional two layers of glass tape, interleaved with Kapton tape.

```
_ data 1,.15,0,.098,1.0,16,16
_ data 2,.2,0,.002,1.0,1,16
_ data 3,.25,0,.098,1.0,16,16
_ data 4,.3,0,.002,1.0,1,16
_ data 5,.35,0,.098,1.0,16,16
_ read n,r,z,dr,dz,nx,ny
_ print "current Densities"
_ print 4.5e6/dr/dz
_ print 4.5e6/dr/dz/100/100
_ clear
let ntpc=624
 print "conductor dimensions"
 let rdim=(dr-(.003*2+.001*2)/39.37)/8-.003*4/39.37
 let zdim=dz/(ntpc/8)-.003*4/39.37
 print "radial dim";rdim;"m";rdim*39.37;"in"
 print "Axial dim";zdim;"m";zdim*39.37;"in"
 print "packing fraction=";ntpc*rdim*zdim/dr/dz
 print
 print "conductor dimensions with 2 millimeter channel tolerance"
 let dr=dr-.002
 let rdim=(dr-(.003*2+.001*2)/39.37)/8-.003*4/39.37
 let zdim=dz/(ntpc/8)-.003*4/39.37
 print "radial dim";rdim;"m";rdim*39.37;"in"
 print "Axial dim";zdim;"m";zdim*39.37;"in"
 print "packing fraction=";ntpc*rdim*zdim/(dr+.002)/dz
 end
```




```
conductor dimensions
radial dim 1.1919799e-2 m .4692825 in
Axial dim 1.2515712e-2 m .49274359 in
packing fraction= .94991124

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.

5.0 Coil Stress Analysis

The coil stress has been analyzed using ANSYS. Fields and forces are computed using Elliptic integrals in a code external to ANSYS. The model is axisymmetrric. The figures show a 3D representation from a symmetry expansion.

Table 5.1 Coil Build used in the Stress Analysis

Seg#	r	z	dr	dz	nx	ny
1	.15	0	.098	1.0	16	16
chan	.2	0	.002	1.0	1	16
2	.25	0	.098	1.0	16	16
chan	.3	0	.002	1.0	1	16
3	.35	0	.098	1.0	16	16

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. The allowables are discussed in more detail in section 4.

Table 5.2 Stress Summary for ¼ Hard Copper Specified by Everson/Tesla

Location	Load Case	Peak Von Mises Stress	Allowable	Factor of Safety @100K
ID Segment 1	3 Coils fully energized No Gaps	166(Tresca)	270 MPa at 100K 1/4 Hard Copper w/ID CW	1.6
ID Segment 2	3 Coils fully energized w/ Gaps	107	207MPa RT ~250 MPa at 100K, 1/4 Hard Copper	2.33
ID Segment 3	3 Coils fully energized w/ Gaps	40	207MPa RT ~250 MPa at 100K, 1/4 Hard Copper	6.25

If the highly cold-worked copper is chosen for the winding, the conductor allowable near the inside radius of the coil would be 365MPa. The max stress in the three segment coil is 166 MPa. With this stress level, it is expected that half hard copper could be used, simplifying the winding process. The three segment coil has three operational modes, two of which are structurally significant. The full performance configuration is limiting in terms of hoop stress and equivalent stress. It also has some radial stresses that will have to be mitigated with parting planes at the segment boundaries, or within the winding.

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

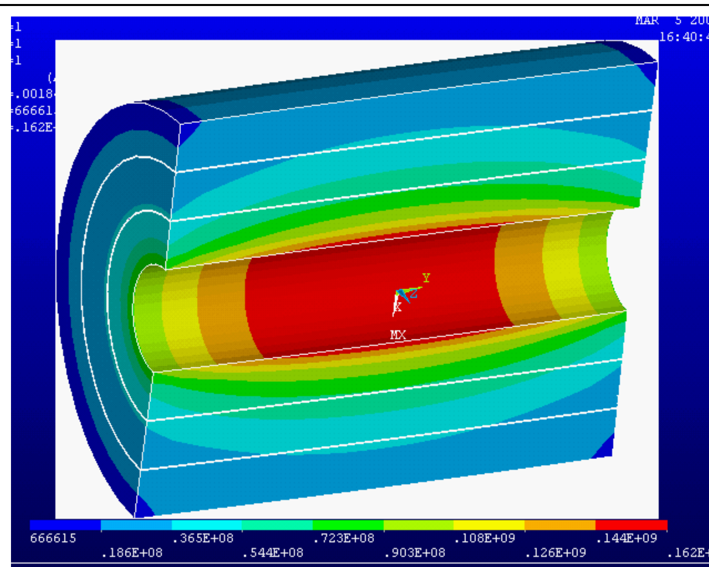


Figure 5.1 Hoop Stress, all coil segments fully energized. The Von Mises stress plot is similar with a peak of 165 MPa, Tresca is 166 MPa.

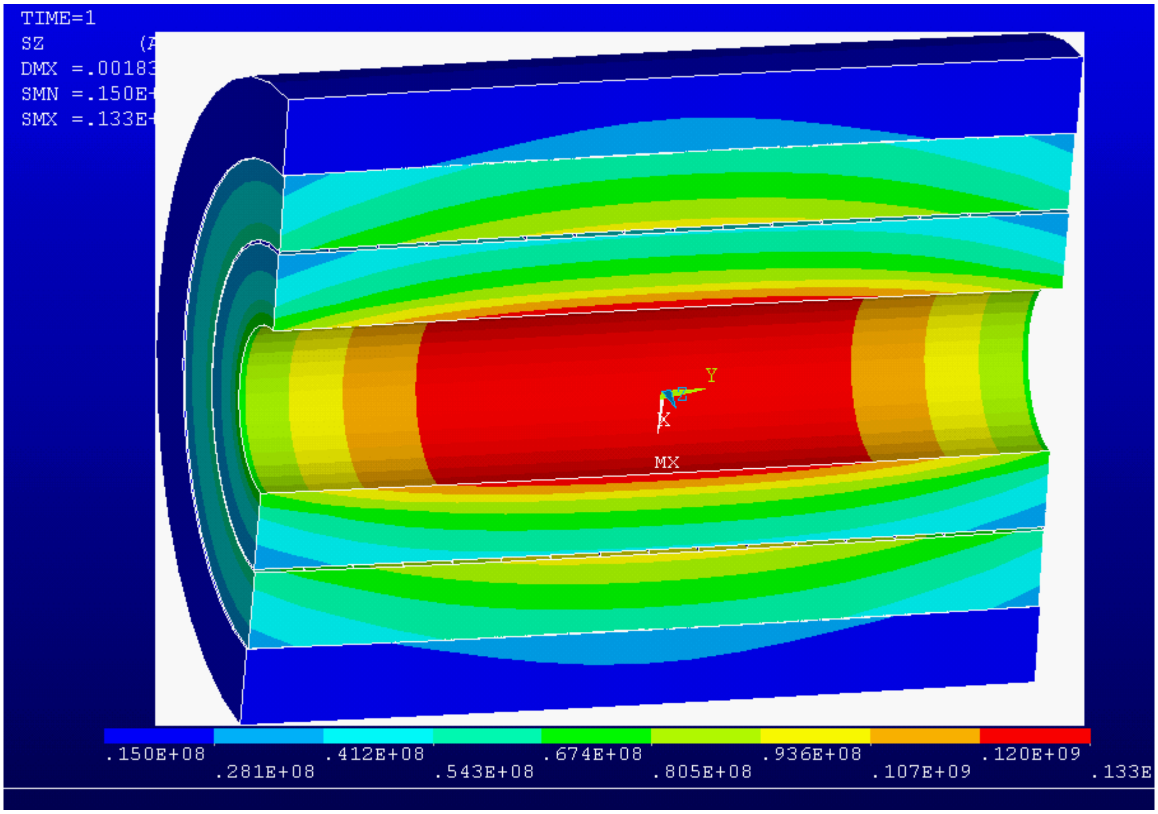


Figure 5.2 Re-run with gap elements the hoop stress went down to 133 MPa

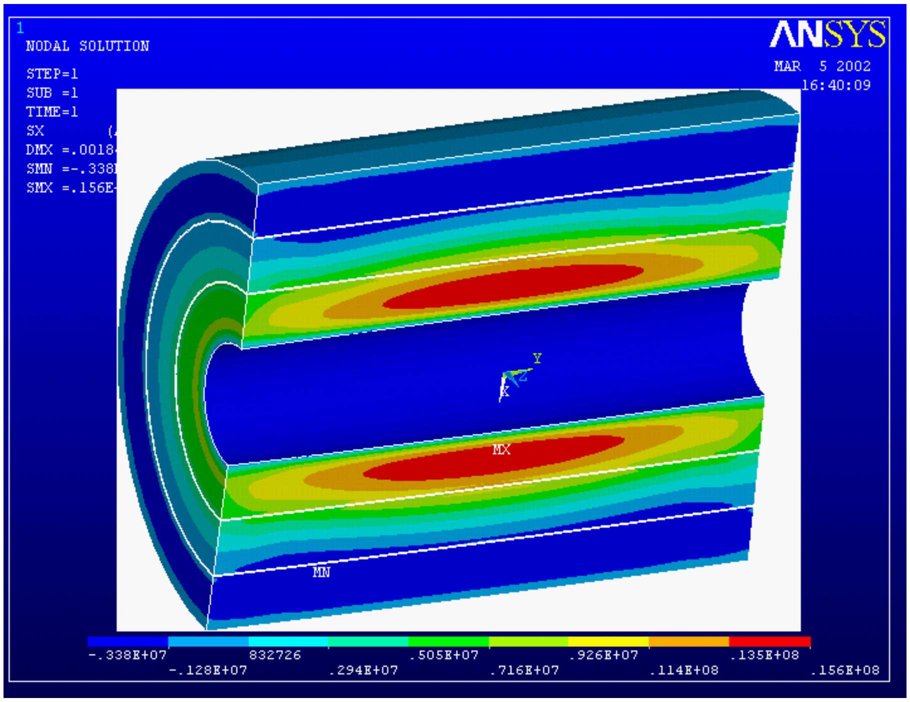


Figure 5.3 Radial tension stress, all coils fully energized. There is about an MPa of tension at the boundary between the first and second module. To avoid damage to the channel ligaments, a parting plane will be incorporated in the channel detail. This needs to occur in the ligament to retain thermal connection with the coolant in the channel.

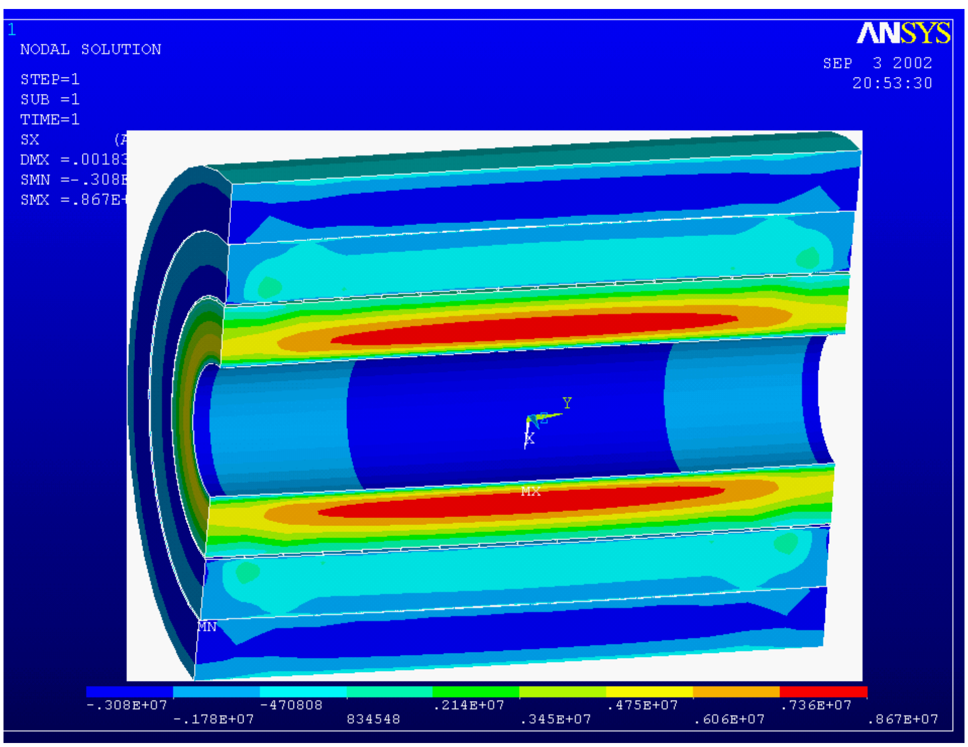


Figure 5.4 Radial Tension in the winding of the first segment is reduced by about A half with gap elements modeling the interactions of the three coil Segments.

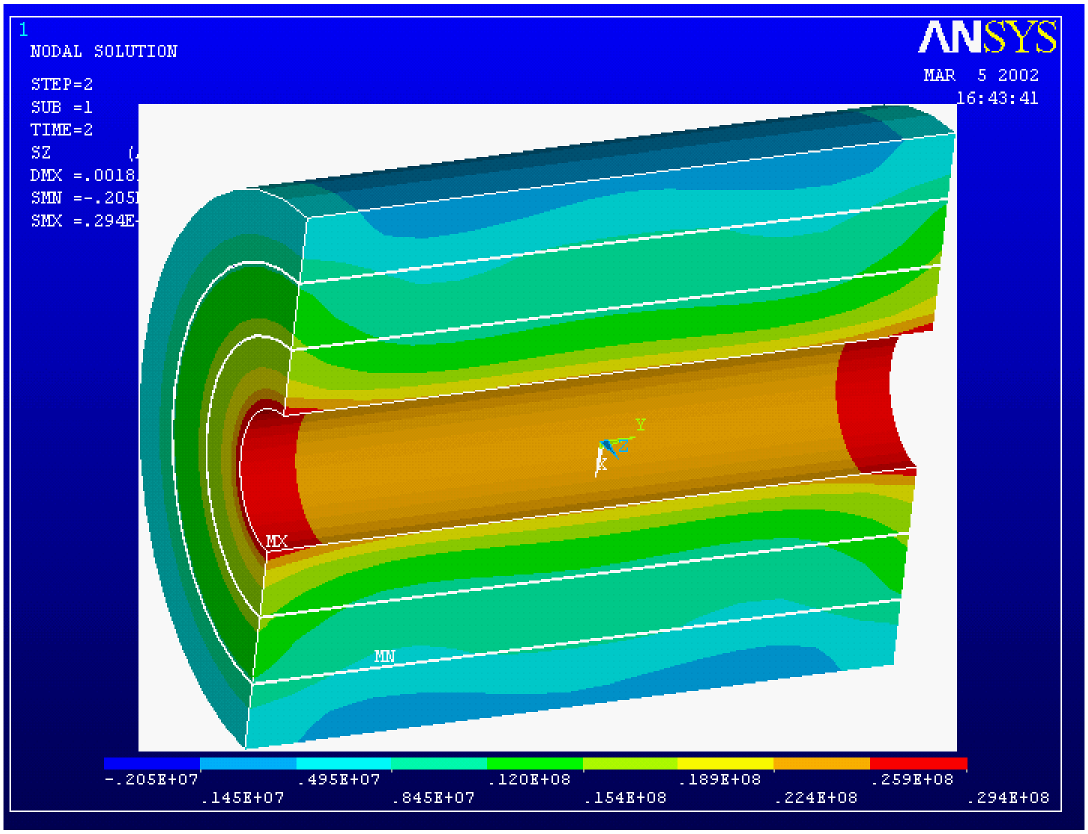


Figure 5.5 Hoop Stress with only the inner two segments energized.

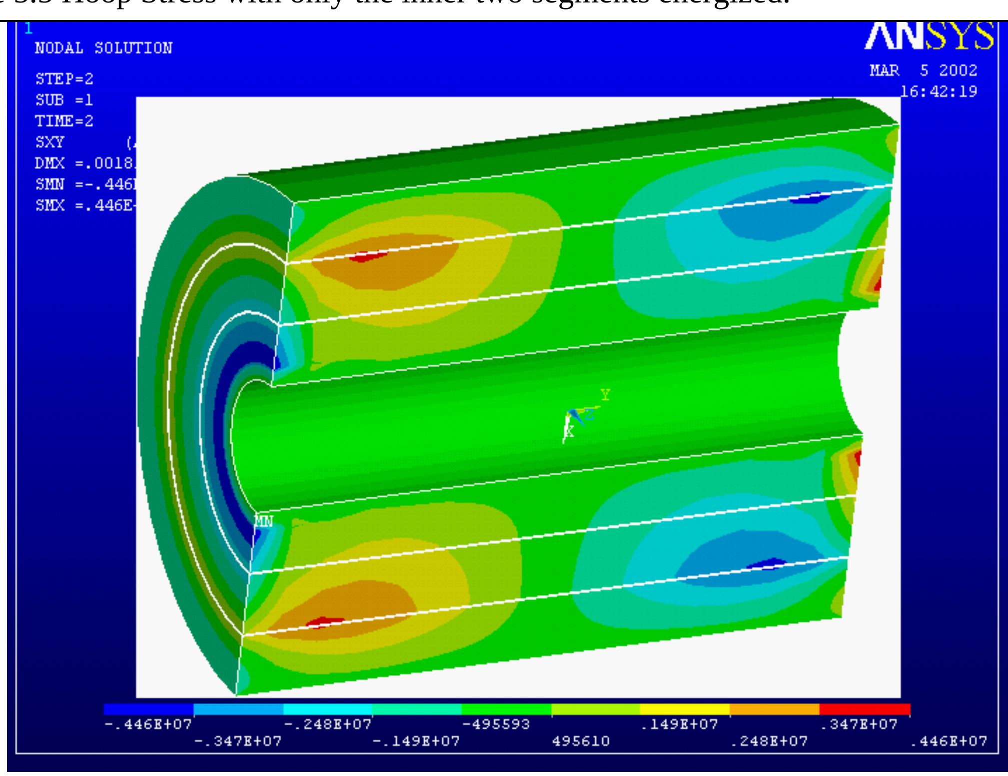


Figure 5.6 Smeared radial-axial shear stress with the inner two segments energized. This is a peak at the interface between the second and third modules. It must be carried across the thin ligaments between the channels, or relieved via a slip plane.

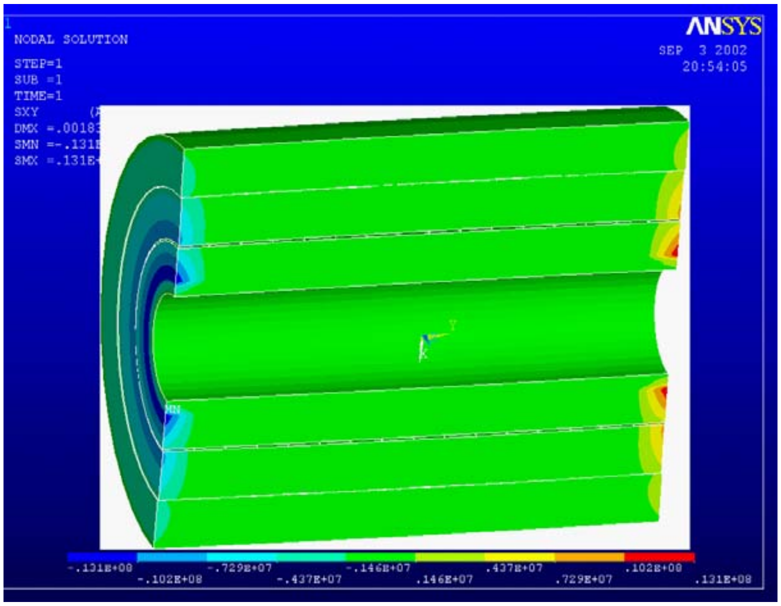


Figure 5.7 With gaps modeling the interfaces between segments, only inner segment shears remain.

Optional Purchase of only the Inner Two Segments

It may be desirable to build only the initial two inner segments and add the outer segment at a later time. The coil was analyzed with the outer segment removed, and the same current density in the other two segments. The max stress for this case is 85.3 MPa, which is a bit more than with the outer segment in place, but less than for the fully energized three segment coil. In all cases the stresses are lower than the expected allowable for the conductor. It is expected that the degree of cold work can be relaxed from the full hard condition. The final choice of the degree of cold work for the conductor will be determined during detailed design.

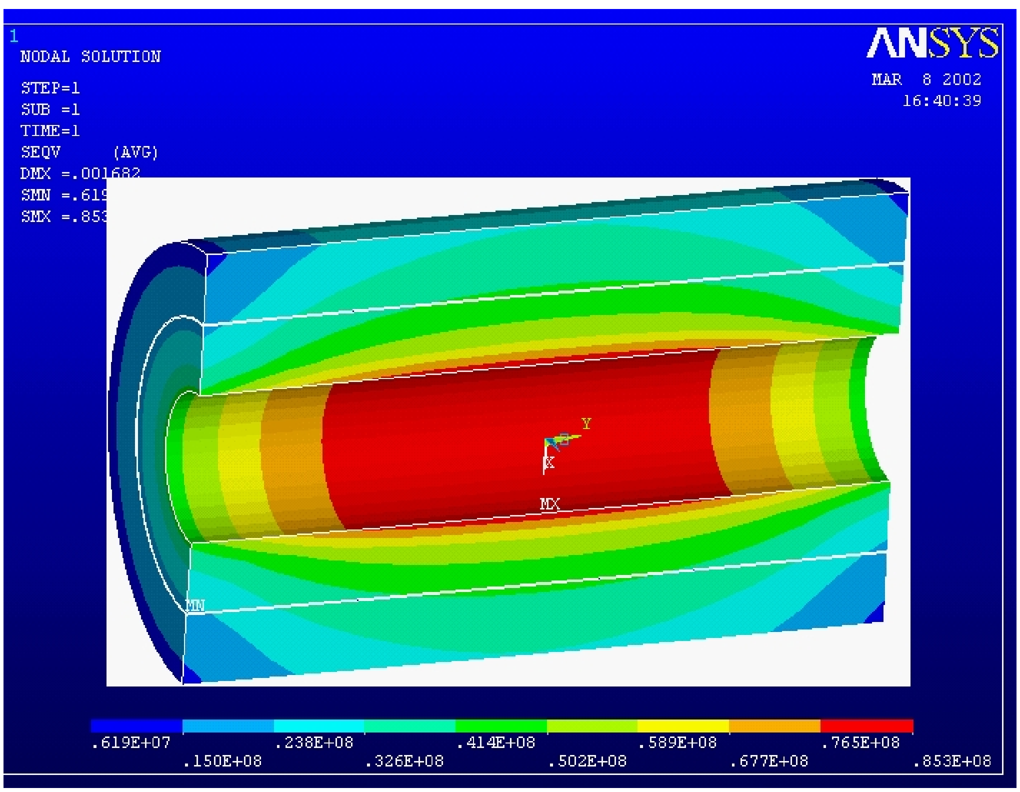
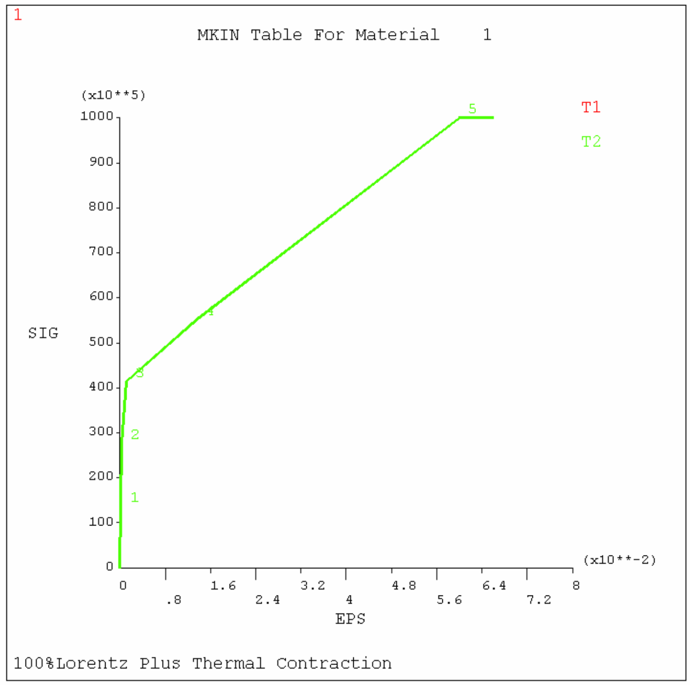


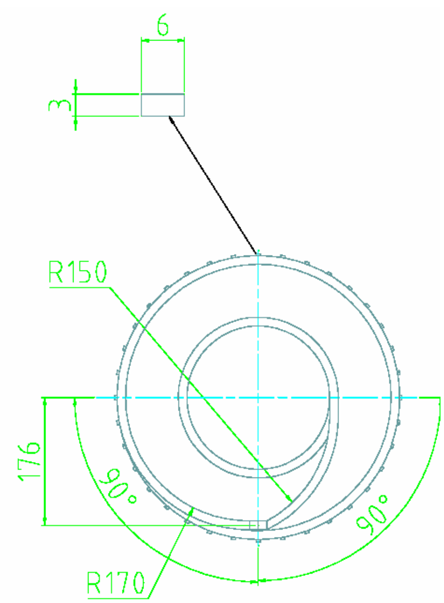
Figure 5.8

Elastic Plastic Analysis

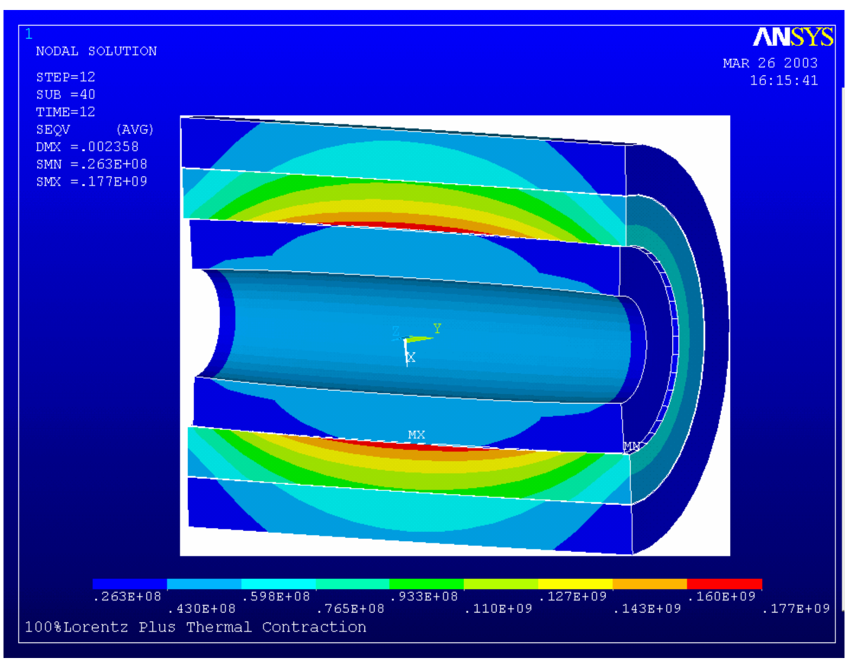
There is a concern that the tight inner radius of the coil will be difficult to wind with full hard copper. Fiberglass tape and Kapton tape cutting/crushing are possible. Relaxing the cold work specification, while still meeting the normal allowables is one approach, but may not ease the winding process sufficiently. A "fall-back" approach is to wind the inner module with annealed copper and allow it to yield and "lean" against the second coil segment. This was analyzed using elastic-plastic properties in the inner segment. The results show acceptable stress levels in the outer segments, but the strains in the inner turns may exceed the capabilities of the bonded insulation.



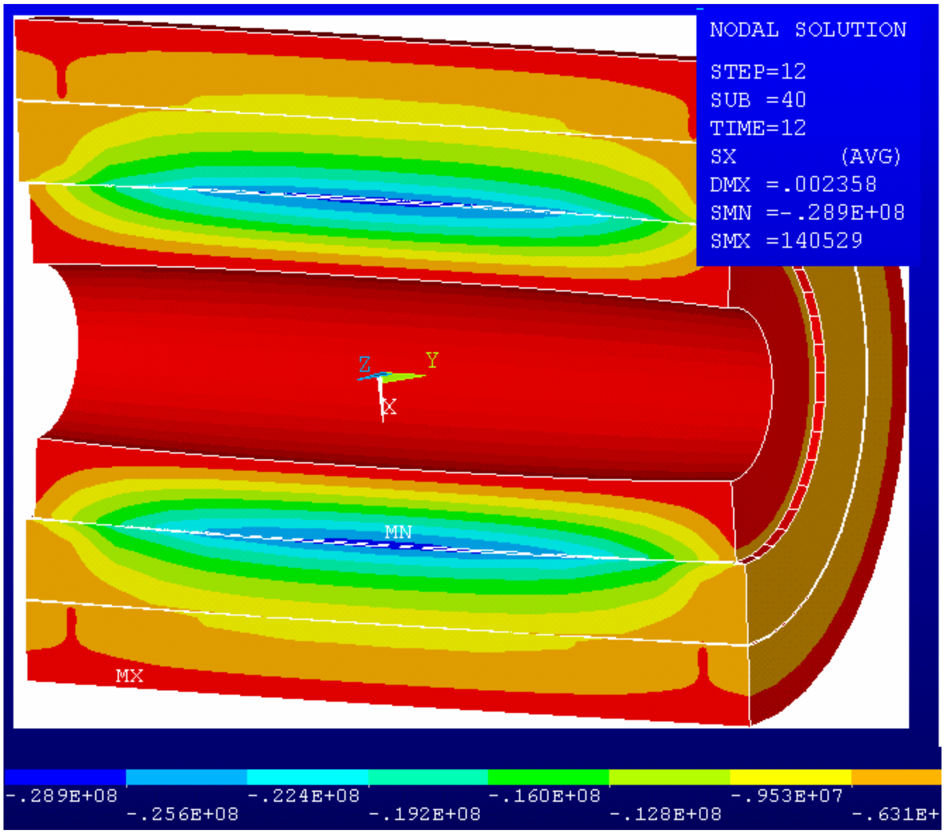
5.9 Stress Strain Curve for Annealed Copper.



5.10 Radial compressive stress between segments one and two must be supported by the ribs that form the cooling channels. The baseline design has almost no load across this gap. If annealed copper is used in the inner segment, compressive loads across this space could be significant near in the ribs.The radial stress multiplier is 200*pi/(24*6)= 4.36



5.11 Von Mises Stress. The Inner Segment is annealed copper, and the middle segment of the coil supports most of the Lorentz Forces. The Von Mises stress at the ID of segment number two is 177 MPa, which would be acceptable, but there is a multiplier on the radial compressive stress that will increase the local Von Mises under the ribs significantly.



5.12 With an annealed inner segment, The radial multiplier due to the rib projected area is 4.36, and the compressive stress under a rib is 28.9*4.36=126 MPa, acceptable by itself, but unacceptable when added to the hoop tension in the second coil segment.

6.0 Coil Thermal Stresses.

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's. This may have been a result of using the average data from the NIST Kohler plot that the upper bound. To make some progress on the stress calculations the time scale was stretched to come closer to Bob's temperature distribution. The stresses from this analysis are small, less than 5 MPa, The cooldown stresses will require more work. These are discussed on the next page.

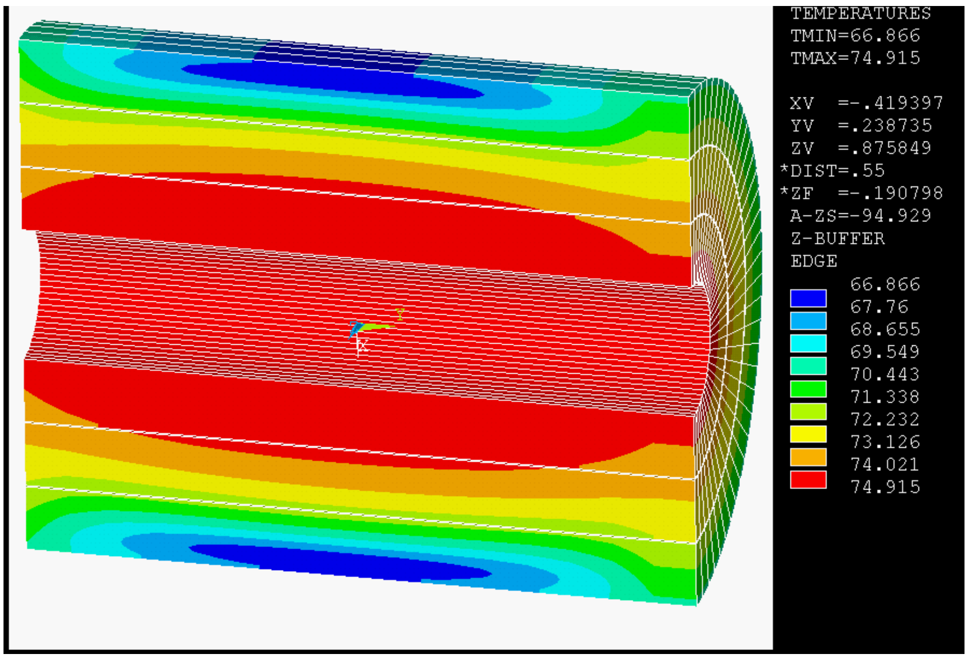
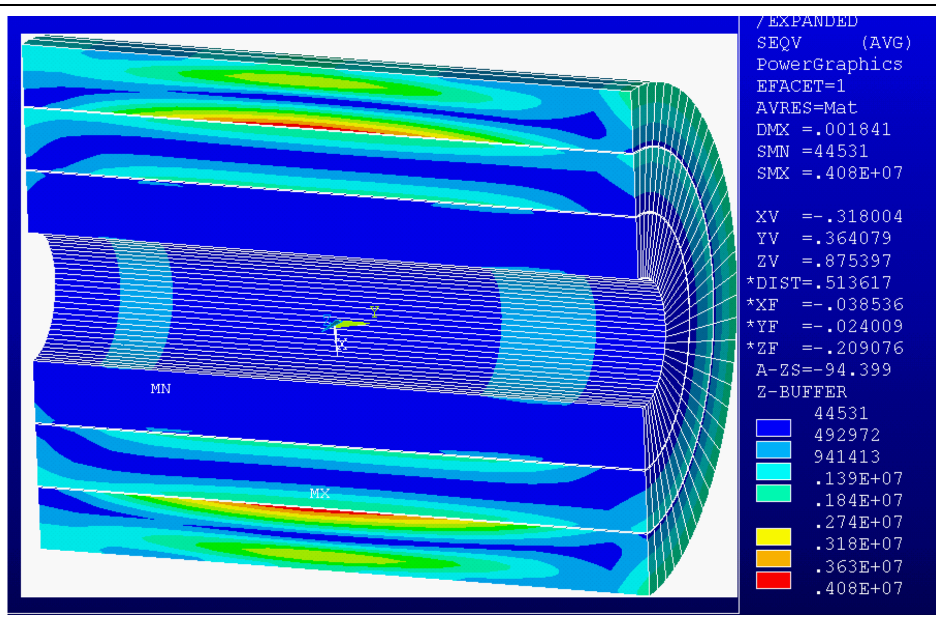
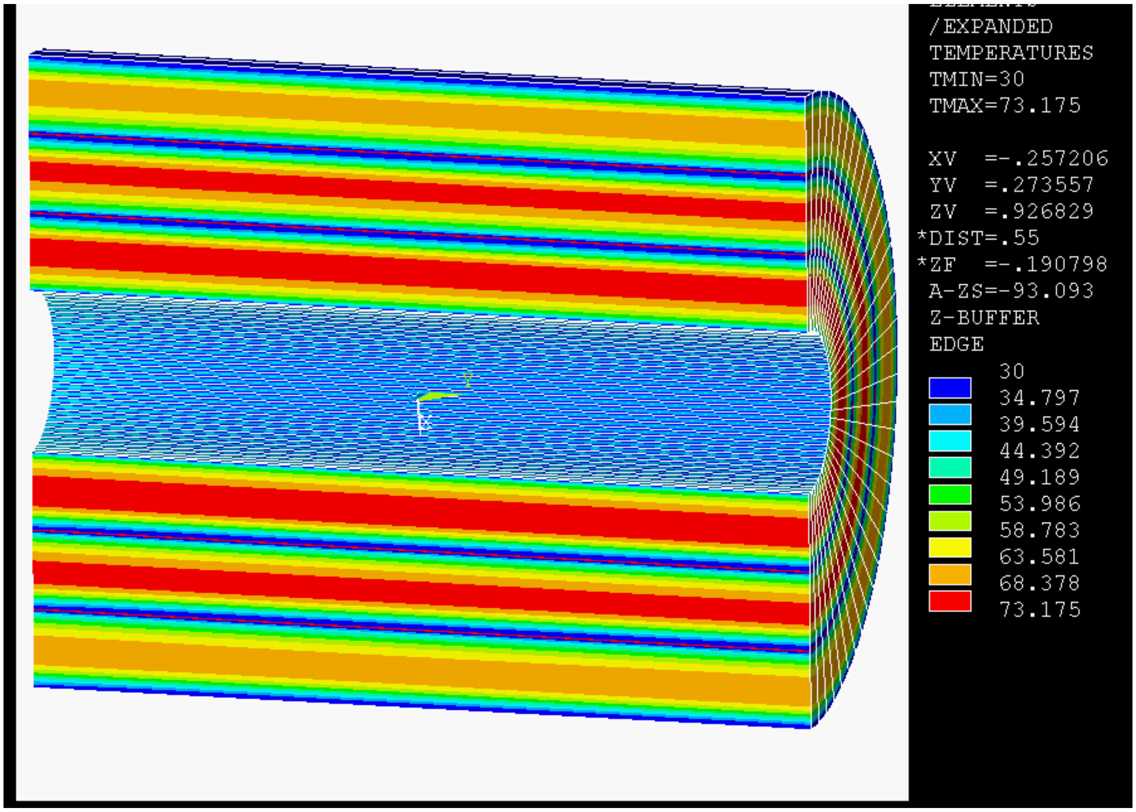


Figure 6.1 Temperatures with magneto-resistive effects, 14.5T



Resulting VonMise Stresses due to Temperature includint the magneto-resistive effects, 14.5T.

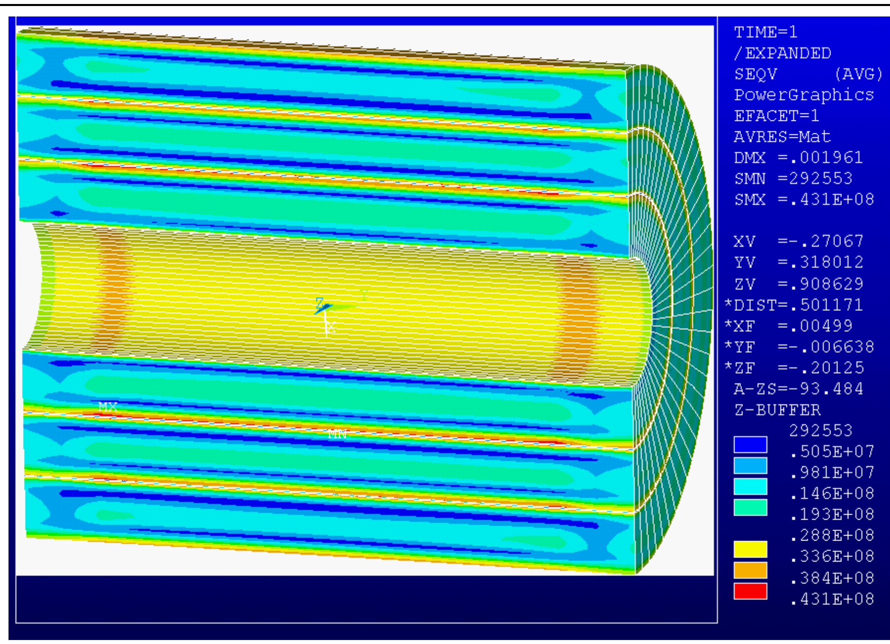
Cooldown Stresses



Cooldown Temperature distribution

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.

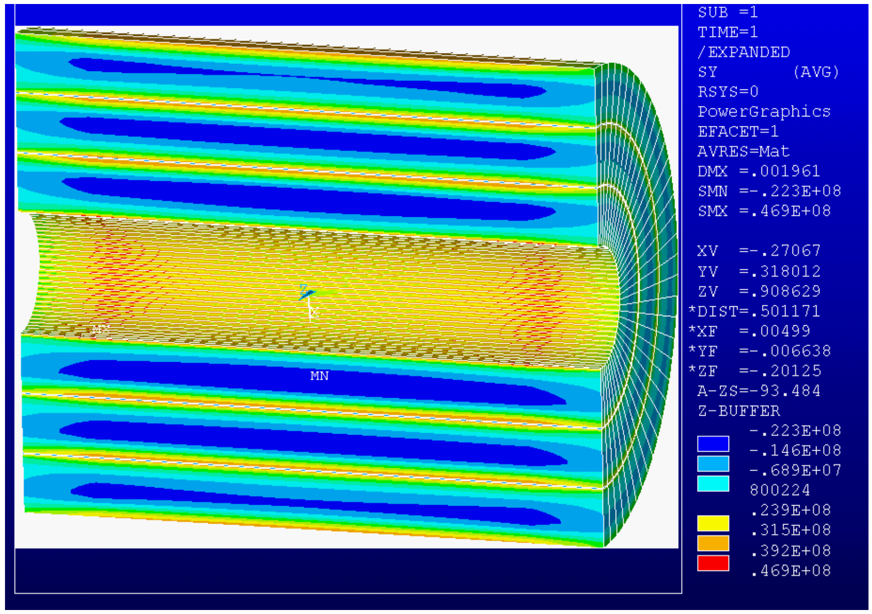
The Von Mises stress is relatively modest, at 43MPa



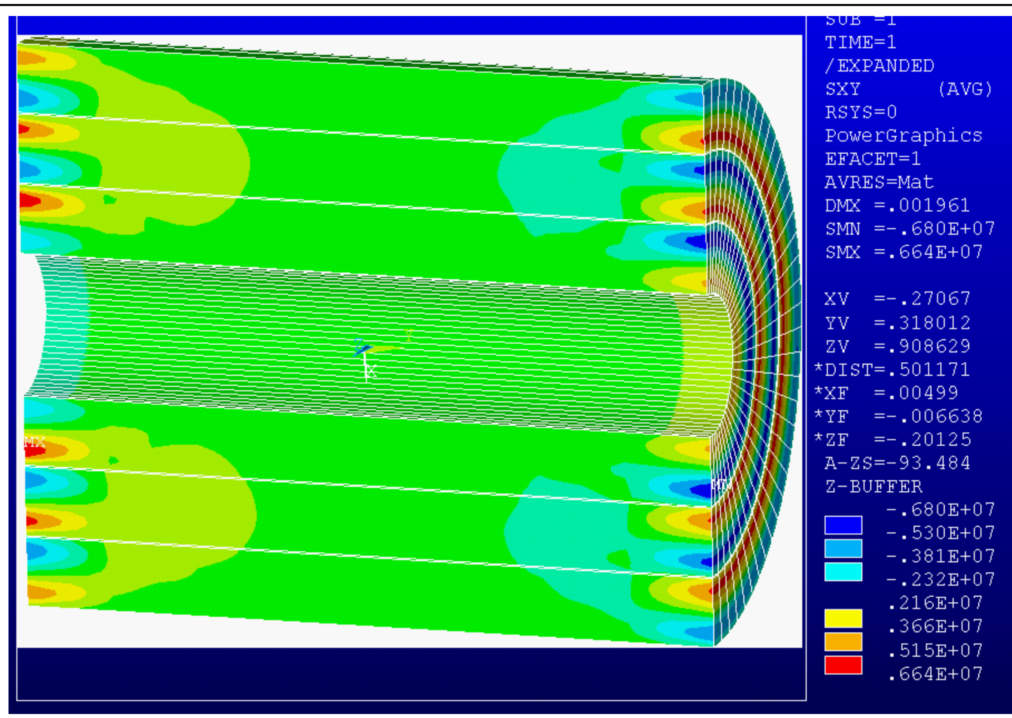
“Smeared” VonMises stress

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)



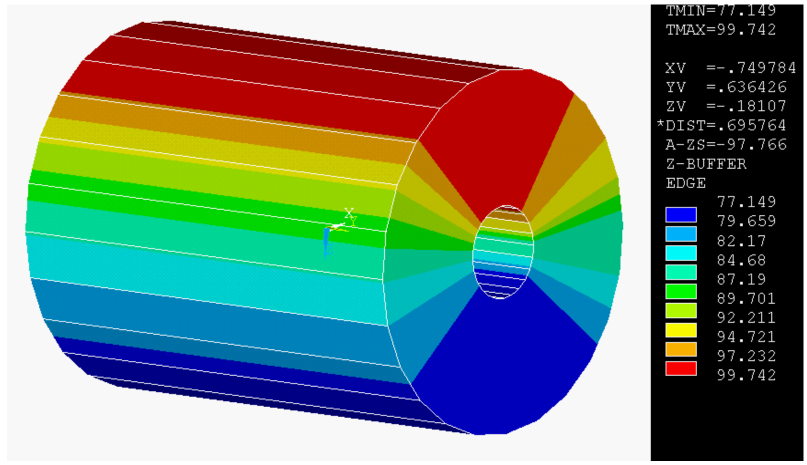
Axial tension



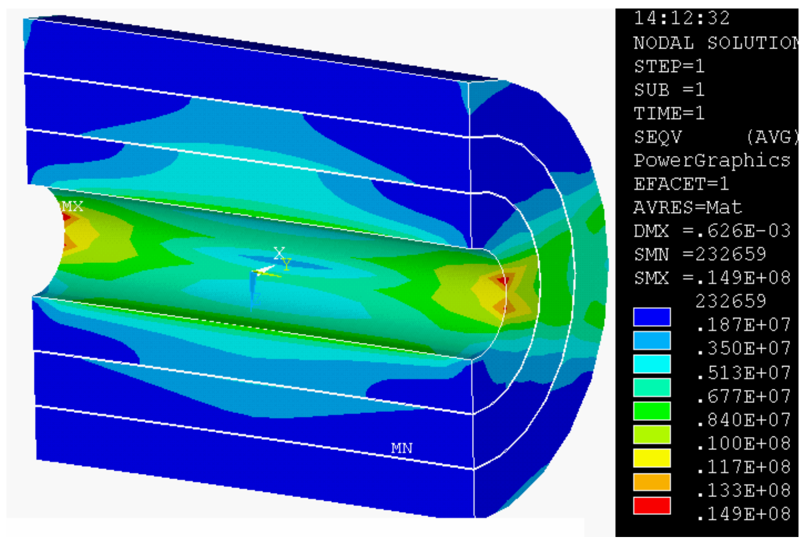
Shear stresses due to the cool down temperature distribution

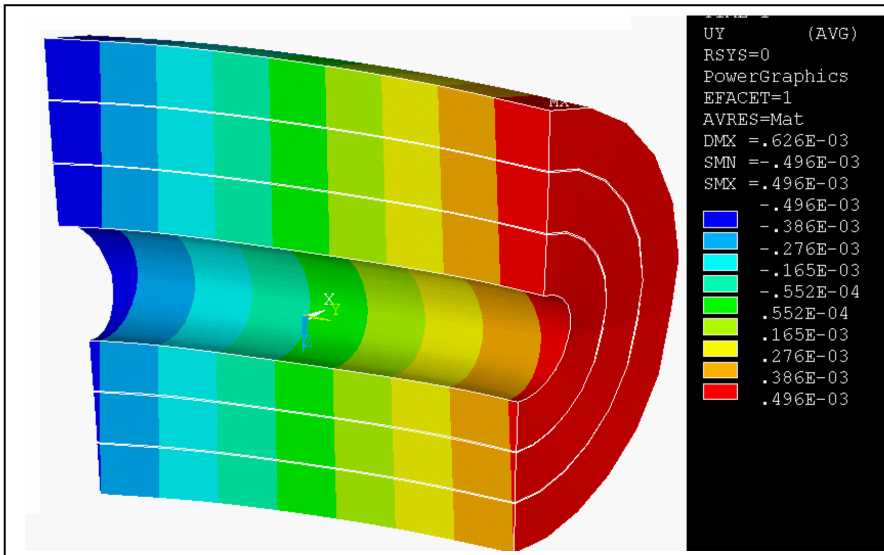
Cooldown Stress, Global Thermal Differential.

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 77 to 100 K variation is assumed. The resulting 15 MPa stress is Acceptable



Assumed temperature variation

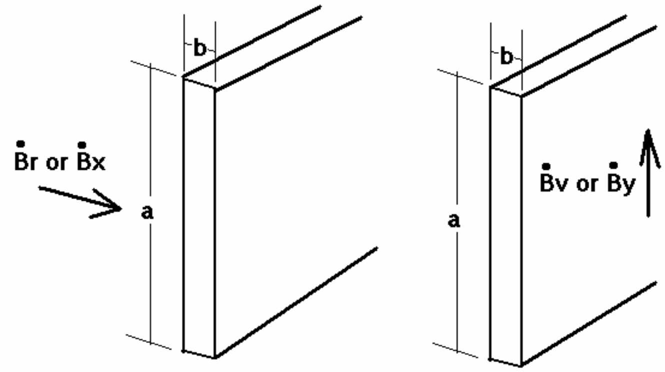




Resulting Displacements

Eddy Current Temperatures – A Non-Problem

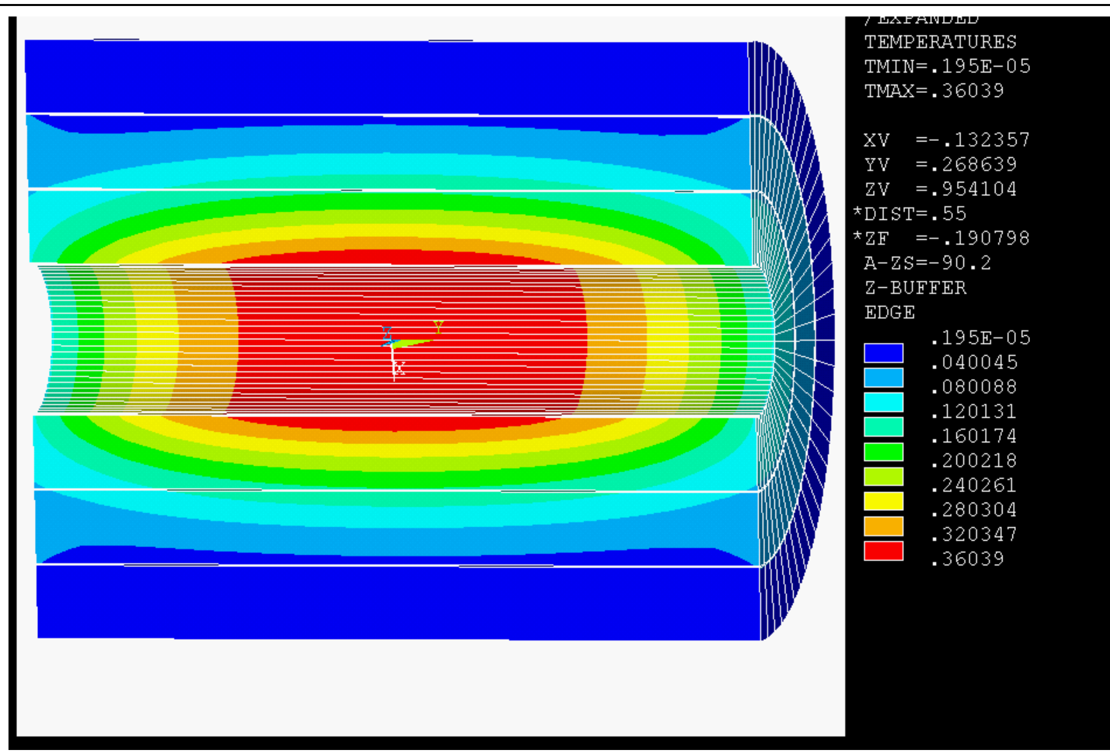
Transient fields induce eddy currents in the conductors as well as in the cryostat plates. This has been investigated for a strip wound solenoid used for FIRE, a fusion experiment. Eddy current heating has been evaluated for the BNL pulsed magnet using the same procedure. The conductor cross section is much lower for the BNL conductor, and the eddy current heating is less than one degree. – a non-problem.



$$P_e = \frac{a^3 * b * \dot{B}x^2}{12 * rho} \qquad P_e = \frac{b^3 * a * \dot{B}y^2}{12 * rho}$$

Eddy Current Power Losses, R.L Stoll, Clarendon Press, Oxford, 1974, and Stoll et. al. IEE Vol 116 No 6 1969 1003

Power is in Watts/m for dimensions in meters, rho in ohm-m, and B-dot in Tesla/sec. Note that the strip orientation is actually advantageous for resisting eddy currents resulting from the vertical field.



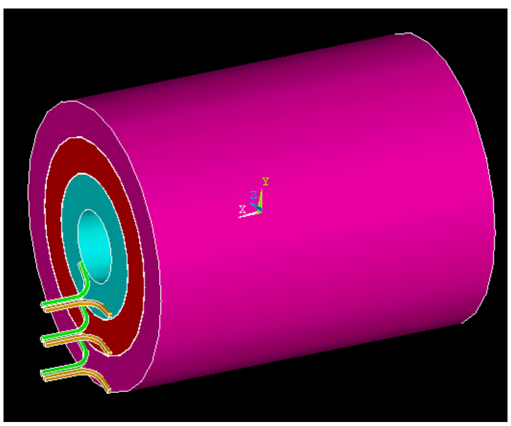
Temperatures due to conductor eddy currents in .5in square conductors subjected to a 14.5T/7sec transient (rampdown)

7.0 Break-Outs, Leads, and Penetrations

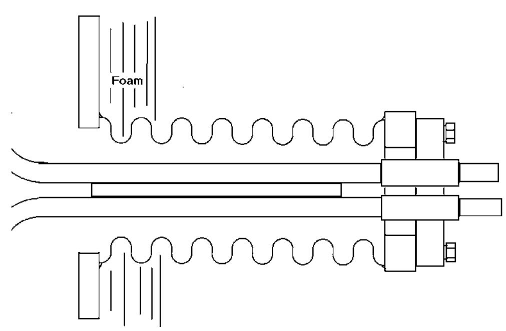
The choice of modular design favors duplicating the break-out and lead design for all three segments, even though two of the segments are connected in series. The current leads from each coil segment can be accessed from outside the cryostat, and can be re-wired without removal of the cover. In the case where 3 segments are purchased initially, the re-wiring to accommodate the power supply changes is done without opening the cryostat. This feature comes at the expense of the heat leak of the extra terminals connected to room temperature.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. This is similar to a coax, but because the conductors are side-by-side, and not concentric, there is a small torque. To achieve the interconnection of the leads, they cross the face of the winding. An alternate is to wind an end pancake. The mandrel design may dictate one over the other. At this time only one lead arrangement has been modeled. 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 lead must penetrate the end plate of the cryostat, and because of the differential thermal motions, and flexure of the end cap under pressure loading, a bellows extension is used. This also has the effect of lengthening the cold length of the lead, reducing the heat gain.

At this time, the analysis includes the Lorentz forces on the leads, and thermal stresses due to the temperature gradient. The displacement induced stress due hoop expansion has not been modeled.

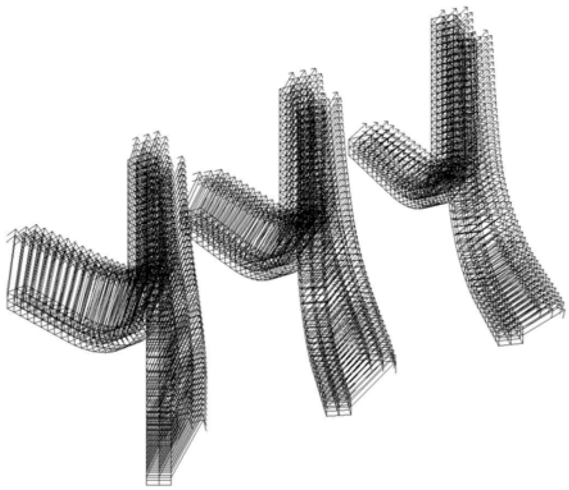
. The magnetic model includes the coil as a “smeared” volume, with the detailed break-out models added. The fields and forces in the leads are calculated with 7200 amps in the leads, and the appropriate solenoid end field solution is applied.



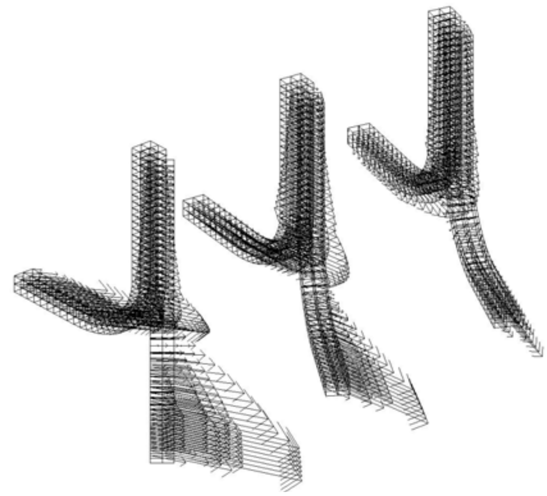
The electromagnetic model.
 The fields and forces in the leads are calculated with 7200 amps in the leads, and the appropriate solenoid end field solution is results.



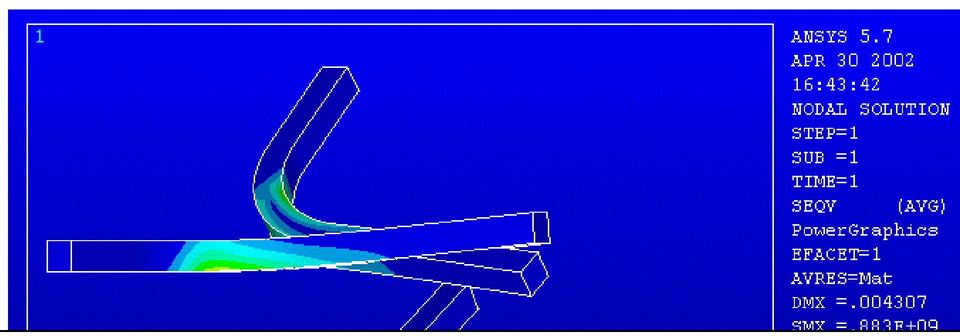
Lead penetration

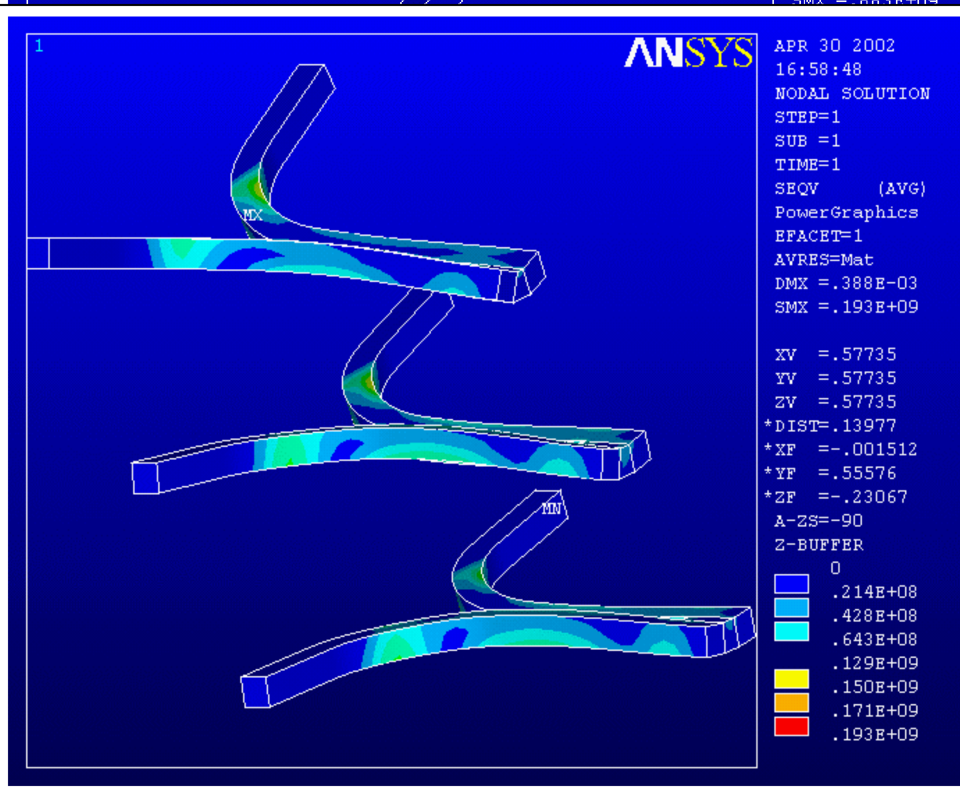


Fields at the break-outs, 14.5T Full field operation.

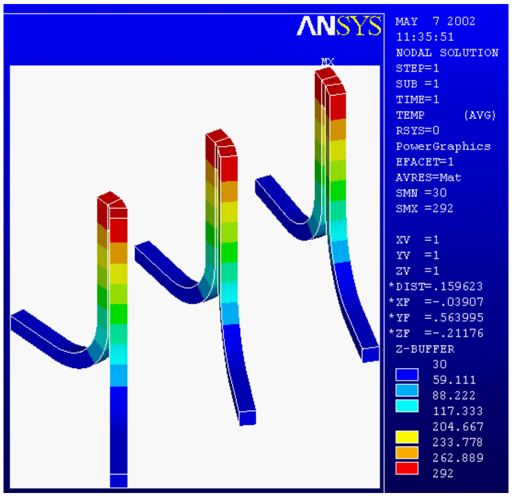


Lorentz Forces at the break-outs. 14.5T Full field operation.

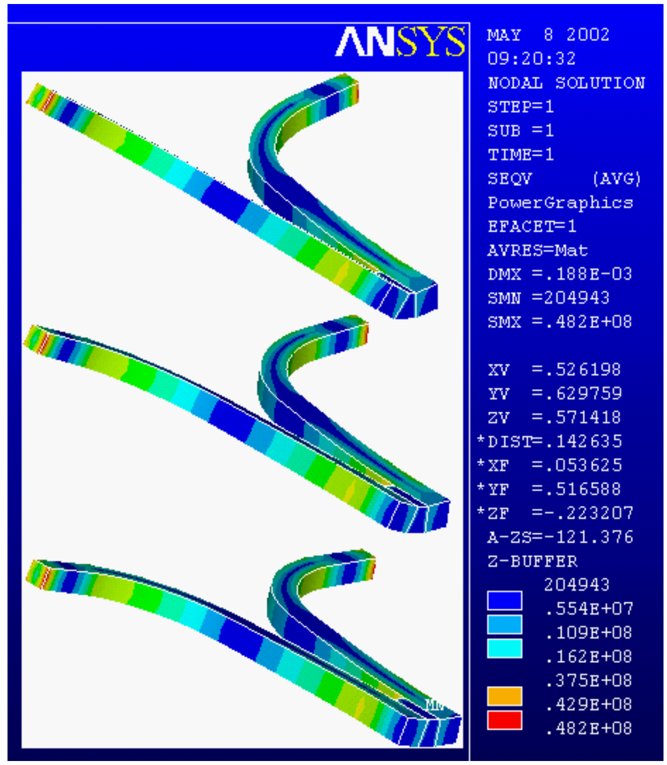




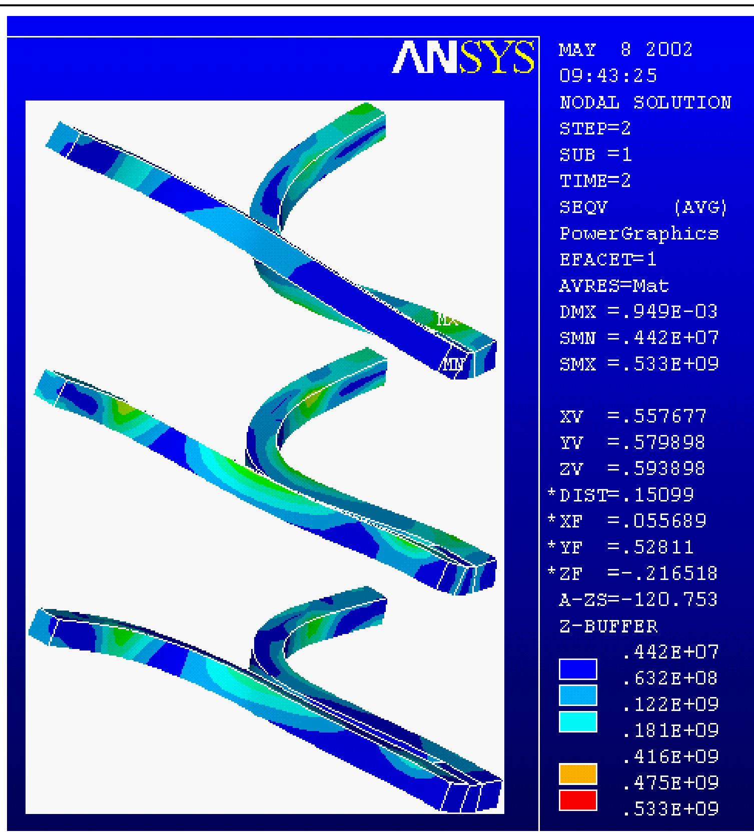
Winding ends well supported, Terminal ends interconnected at the end of the lead pair. Lorentz Forces Only



Joint Temperature from conduction solution

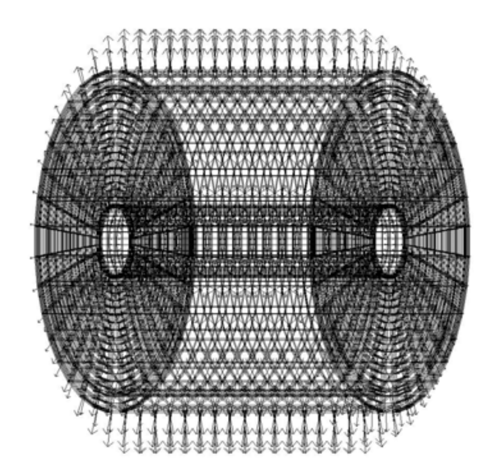


Joint thermal stress. Winding ends well supported at extreme of the radius, where the thermal constraint was applied



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.

10.0 Helium Cryostat Stress



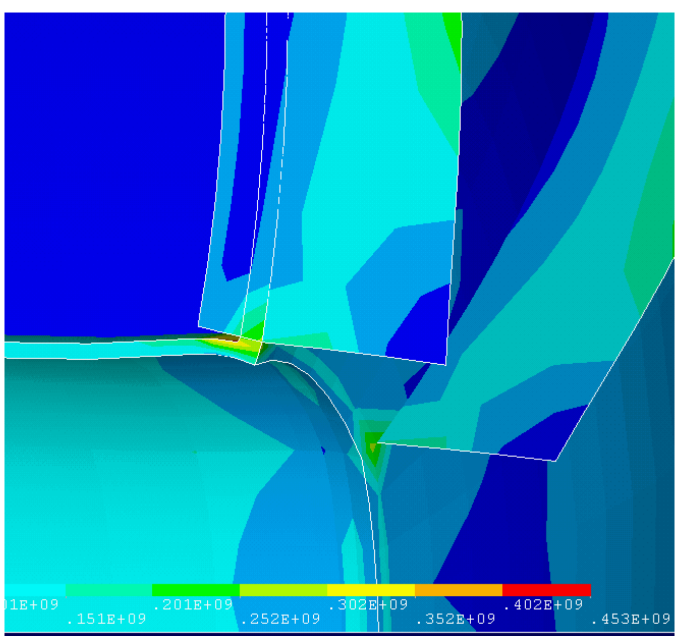
He Can pressure forces.

The normal operating pressure of the cryostat is 15 atm. In one of the considered cryogenic systems, there was a possible pressure excursion during cooldown to 20 atm. This resulted from the expansion of the warm He gas on the downstream side of the magnet. Other systems The relief valves will be set based on a 15 atm design pressure. The cryostat has a flat head at the side where the penetrations are made. This is bolted to the cryostat shell. Mechanical seals are used. The flat head thickness is 2 cm. ID and OD shell thickness is 5mm. The p*r/t stress is 20*14.7*6895*.5/.005/1e6= 202.713MPa
If ¼ inch plate stock is used the thickness is 6.35mm and the p*r/t stress is 159 MPa. The 316 SST is recommended. Cold worked 304 SST starts to lose it's ductility below liquid nitrogen temperatures. The ¼ inch plate stock meets the membrane stress requirement. . (present finite element analyses are based on 5mm)
Flat head thickness is 2 cm, Dished head is .5 inch thick, Vacuum Jacket Dished head is .125 in.

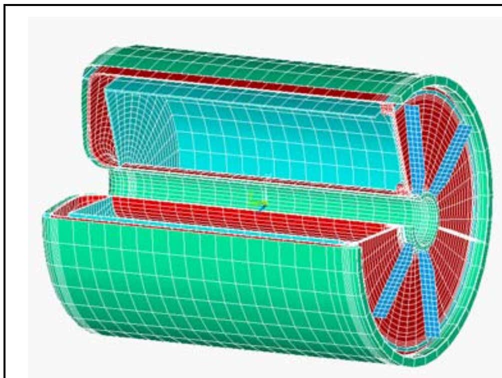
Structure Room Temperature (292 K) Maximum Allowable Stresses, Sm = lesser of 1/3 ultimate or 2/3 yield, and bending allowable=1.5*Sm

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

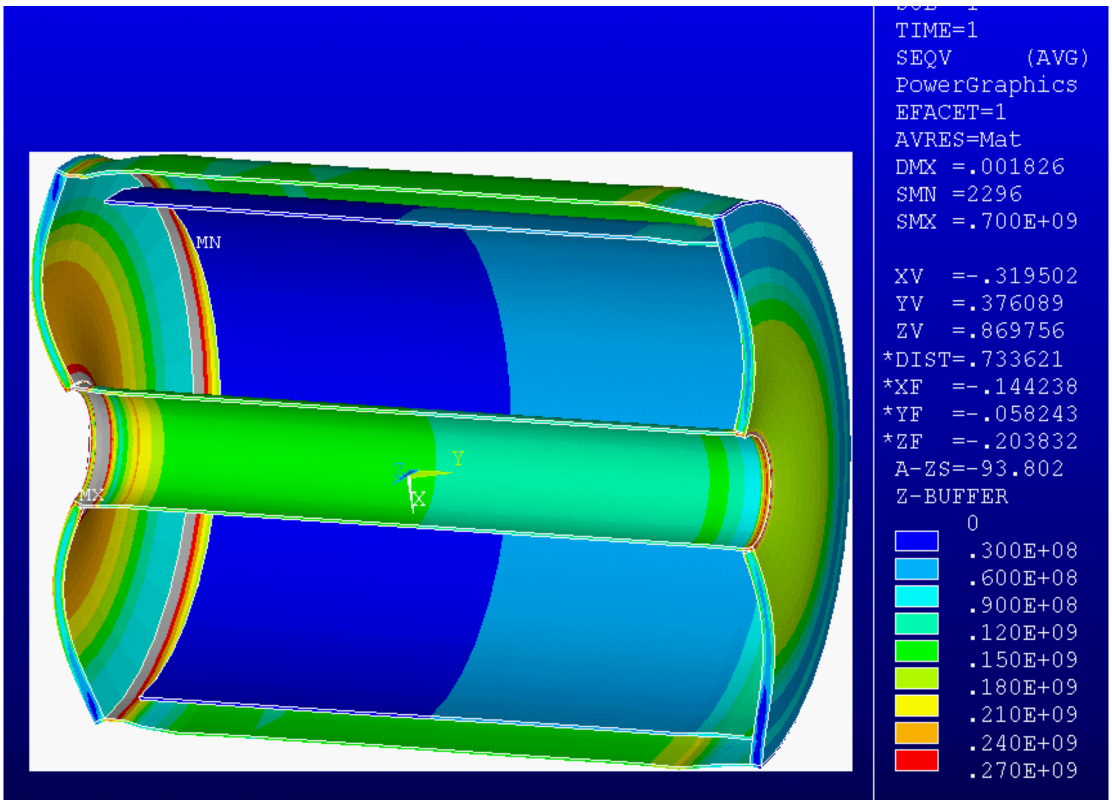
Without stiffeners on the flat head, local (corner) stresses are high – 700 MPa. After the addition of six 1cm thick stiffener ribs , the peak stress went down to 448 MPa. This occurred in the ribs, and the weld and head stress is much improved, but is still above 300 MPa further reductions are needed to meet the weld allowables, although the plate allowables summarized above are for room temperature, and are much below the cryogenic capability of 304 or 316.. Increasing the depth of the ribs from the 6cm modeled, is indicated



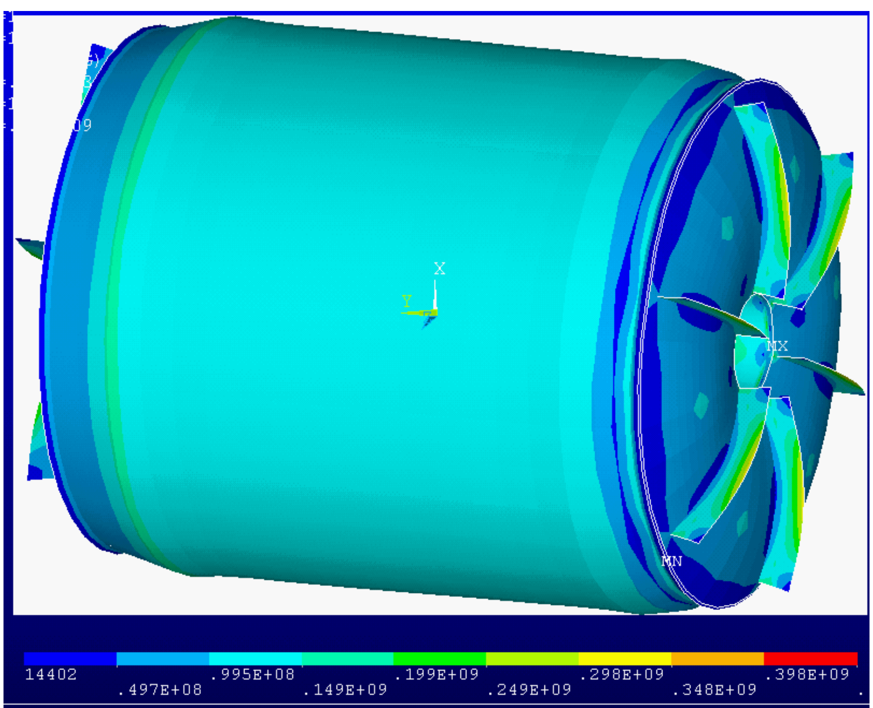
Local stress in the shell to head weld. 6cm high, by 1cm thick ribs are modeled.



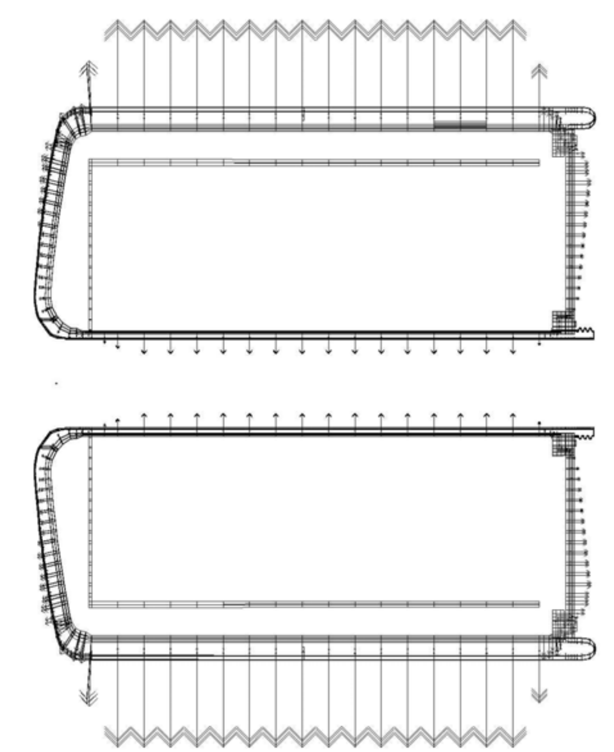
Early model before the bellows were modeled in more detail.

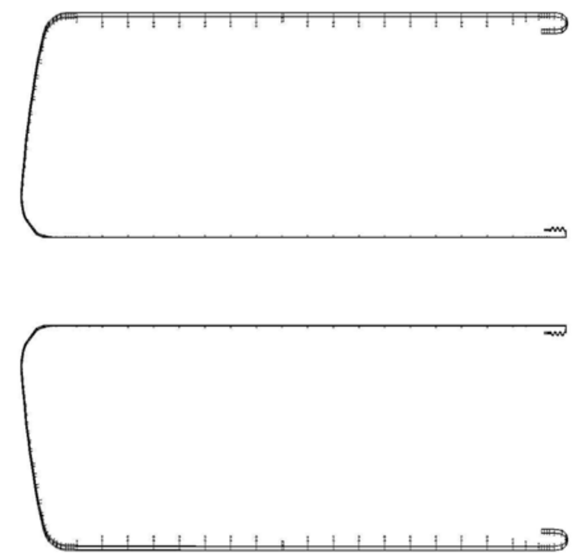


VonMises Stress without ribs



Pressure Load Vectors – Nodal Forces, Pressure times element area


Whole model –20 atm loads on the Cryostat dominate


Vacuum loads on vacuum jacket

Shell Stresses

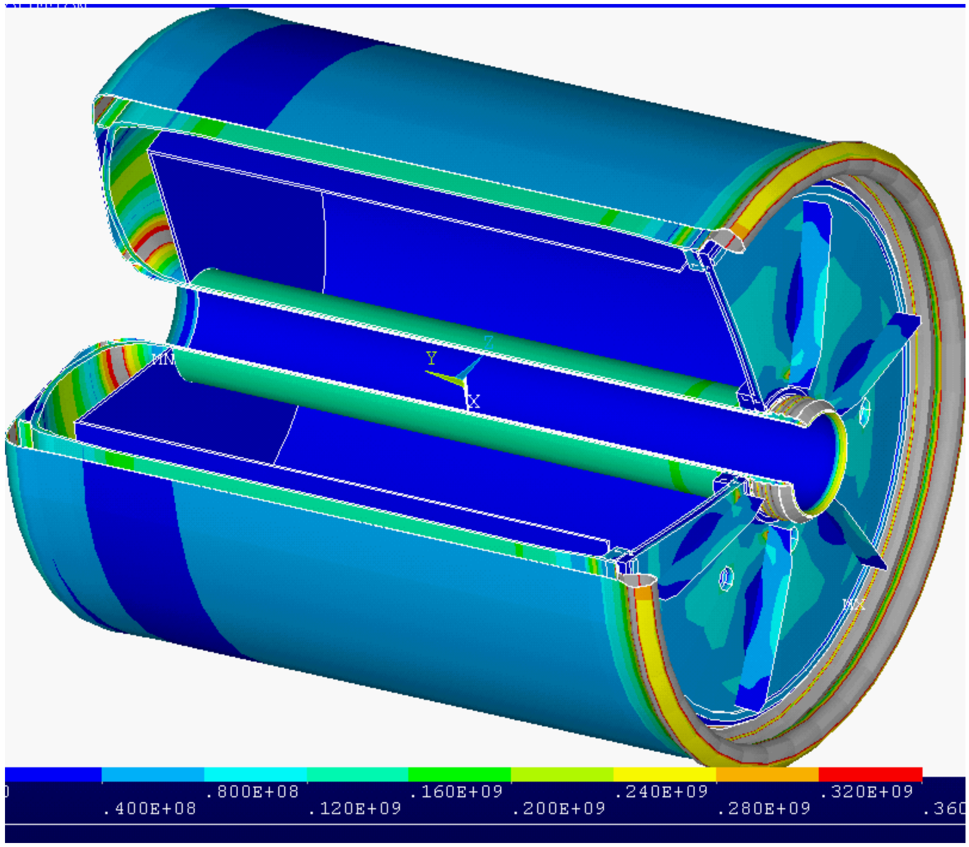
Note that the ASME VIII sizing equations (UG27 and UG28) don't apply to the annular geometry. The inner bore tube of the cryostat is loaded in hoop compression and axial tension. It also supports the weight of the magnet. The axial stress contribution to the stress intensity is different than a normal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

.

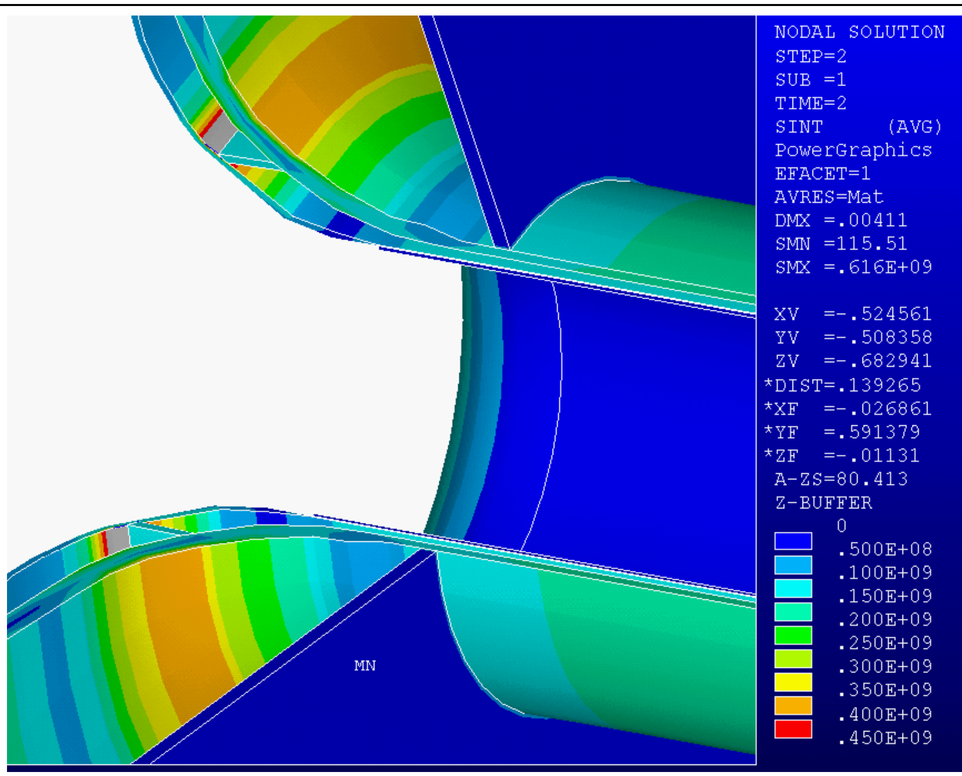
	IR	OR	t	Pressure atm	pressure MPa	P*r/t Stress	E*	Hoop σ/E	Axial σ	Tresca	Sm	F.S.
	.09424	.1	.00476	21	2.128	-44.7	.7	-64	78.2	142	183	1.29
	.472	.482	.01	21	2.128	101.5	.7	145		145	183Mpa	1.26
	.523			1.0								

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

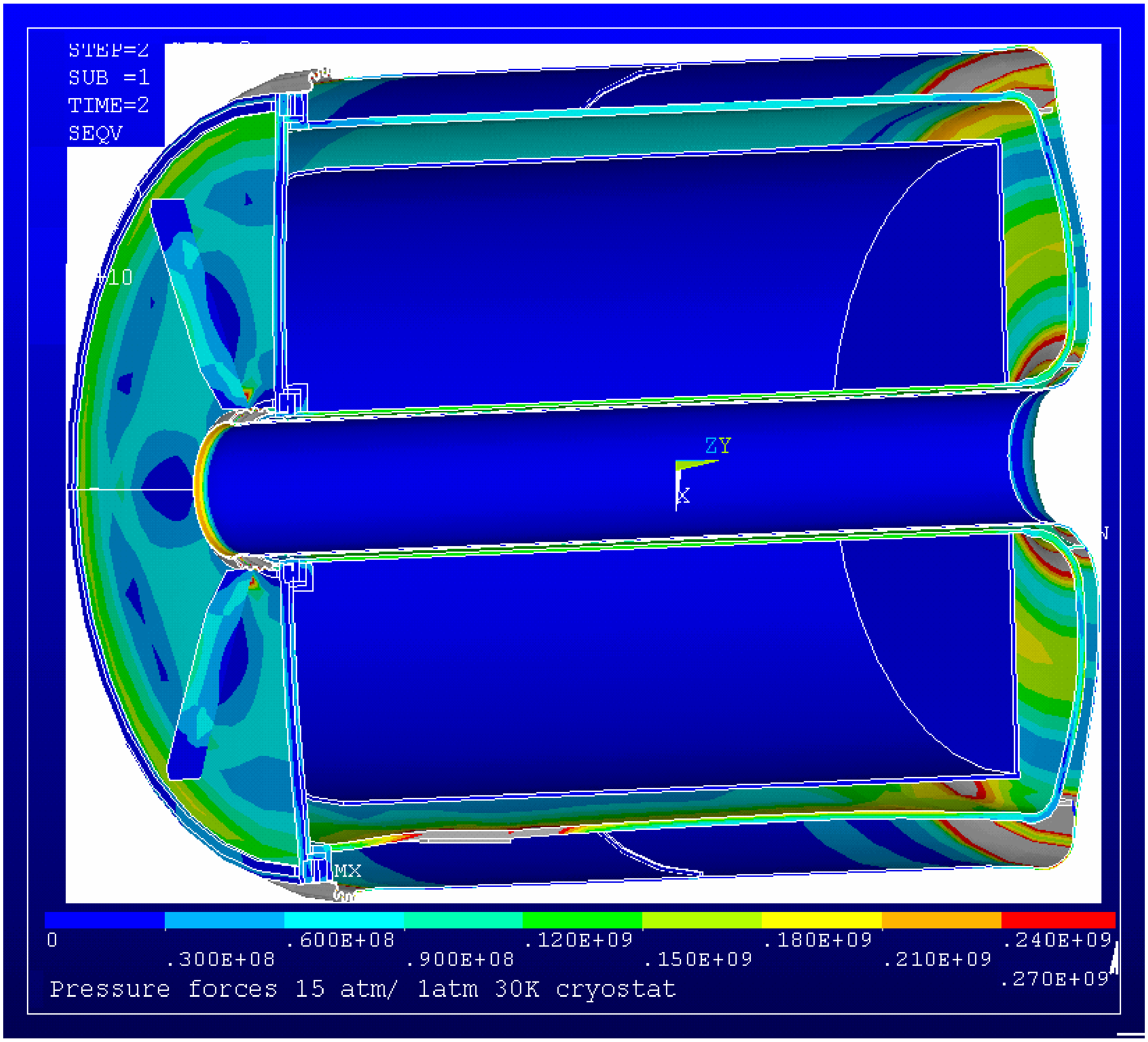
All Cryostat and Vacuum Jacket Stresses (with the exception of the bellows details) satisfy the primary membrane stress of 183 MPa



In this plot, light blue is 120 to160 MPa



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

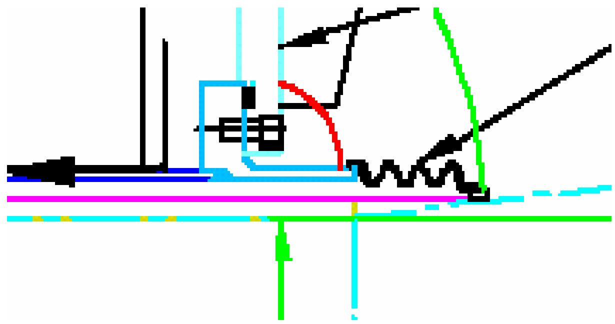


Cryostat Analysis Results for 15 atm cryostat pressure and vacuum in the vacuum jacket

Cryostat/Helium Can Stress – Head Closure Detail

Without stiffeners on the flat head, local corner weld stresses are high - 700 MPa. After the addition of six 1cm thick stiffener ribs , the peak stress went down to 448 MPa. This occurred in the ribs, and the weld and head stresses are much improved, but are still above 300 MPa. Further reductions were needed to meet the weld allowables, although the plate allowables summarized above are for room temperature, and are much below the cryogenic capability of 304 or 316. 2 cm thick ribs have been specified.

Cryostat Bolting Calculations



Bolted Head Closure detail

Bolts are used at an inner radius, and an outer radius of the cover flange of the Helium/LN2 cryostat. The cover area is large, and when the cryostat is pressurized to the nominal 15 atm for Helium gas operation, the axial load supported by the cover is quite large, approximately 250,000 lbs, which is reacted by an inner and outer bolt circle totaling 120 ½ inch bolts. A Basic program is used to calculate stresses in these cryostat cover bolts. First a reasonable method of apportioning the pressure load to the inner and outer array of bolts is needed. In the Basic program, moment equilibrium is applied to a strip section, and a mean radius of the pressure load is calculated. The inner and outer reaction loads are calculated from the contributory areas. Because the axial pressure load path is redundant, the finite element model may give a better idea of how much axial load is picked up in the bore tube and how much appears in the outer shell. This showed the Basic calculation to be conservative by 50%. 316 Stainless Steel properties improve at low temperatures, but due to the anticipated pressure test at room temperature, RT bolt and flange properties are assumed. This adds more conservatism for normal operating conditions. .

High strength 316 Stainless Steel bolts are used for the cover bolting. These have been specified as ASTM A193 Grade B8M - Class 2 - Type 316. For bolts 3/4" and under, the ultimate strength, fu is = 110,000 psi. and the yield strength, fy = 95,000 psi. Thread shear failure is a possible concern, given that the bolts are stronger than the flange- This is only true at room temperature. At cryogenic temperatures, both the bolting and flange materials have a high yield stress. Direct tension on the bolt stress area is the limiting stress. The Basis program yield a factor of safety of 1.12 against the RT allowable for the cold worked 316 bolts chosen for the design. Because of space constraints, and uncertainty in the bolt tightening needed to seat the mechanical seal, the thread engagement will be less than the 1.5 diameter rule of thumb. In the calculation, one bolt diameter is assumed. This still may be optimistic, but it provides a factor of safety for thread shear on the inner bolt circle of 1.8 against the RT allowable of annealed 316. The length of thread engagement will need to be evaluated during detailed

Bolt Analysis

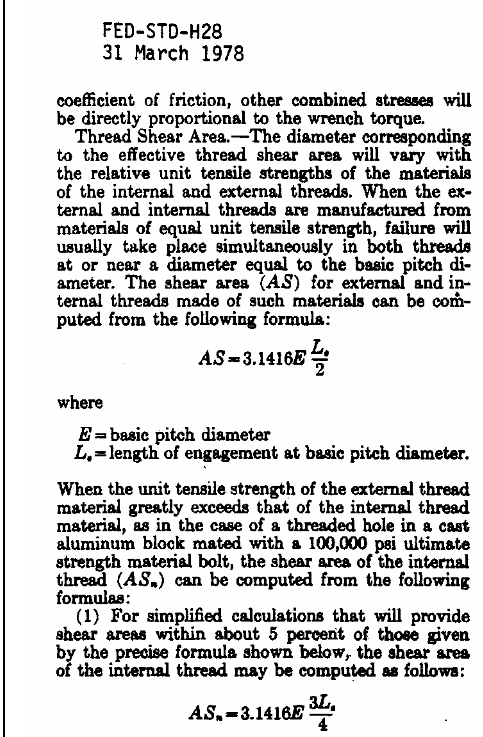
```
clear

!room temp bolt properties ASTM A193 B8M
class 2
let fy=95000
let fu=110000
let sshear=.4*275.8e6/6895 !316 RT annealed
let dpres=15   !atm
let dpres=15   !atm
print "Design Pressure=";dpres;" atm"
let sm1=2*95000/3
let sm2=110000/3
let sm=sm1
print "Allowable Stress=";sm
if sm2<sm1 then let sm=sm2
!let sm=.6*fy   !AISC)
print "Bolt Ultimate Strength=";fu
print "Bolt Yield Strength=";fy
let numin= 24
let numout=6*16
print "Number of Inner Bolts:";numin
print "Number of Outer Bolts:";numout
let p=dpres*14.7
let ro=(1.007)/2
let ri=(.248)/2
let ro=(.964+1.007)/4
let ri=(.291+.248)/4
let rm=((ro^3-ri^3)/3)/((ro^2-ri^2)/2)
let f=p*pi*(rm^2-ri^2)*39.37^2
let ba=.375^2*pi/4
let ba=.5^2*pi/4
let bsa=.5^2*pi  !pull out shear area
let bsa=pi*.5*.45*3/4  !pull out shear area
according to FED-Std-h28
let ba=.1416   ! 1/2 inch coarse thread
stress area
print "Bolt Tensile Area=";ba;"  Bolt
Thread Shear Area=";bsa
print "Tensile Load on inner Cyl:";f;"lbs"
print "Tensile Load on inner
Cyl:";f/.2248;"N"

print "Inner Bolt Tensile
Stress";f/ba/numin
print "Inner Bolt Pull Out Shear
Stress";f/bsa/numin
print "Inner Bolt Tensile Factor Of
Safety";sm/(f/ba/numin)
print "Inner Bolt Shear Factor Of
Safety";sshear/(f/bsa/numin)
print "Inner Cylinder Stress Based on Bolt
Loading";f/.2248/(pi*.184*.004763)/1e6;"MPa
"
let f=p*pi*(.5^2-rm^2)*39.37^2

let ba=.375^2*pi/4
let bsa=.5^2*pi   !pull out shear area
let ba=.0773     ! 3/8 inch coarse thread
stress area
let ba=.1416   ! 1/2 inch coarse thread
stress area
print "Tensile Load on outer Cyl:";f;"lbs"
print "Tensile Load on outer
Cyl:";f/.2248;"N"
print "Outer Bolt Tensile
Stress";f/ba/numout
print "Outer Bolt Pull Out
Stress";f/bsa/numout
print "Outer Bolt Factor Of
Safety";sm/(f/ba/numout)
print "Outer Bolt Shear Factor of
Safety=";sshear/(f/bsa/numout)
print "Outer Cylinder Stress Based on Bolt
Loading";f/.2248/(pi*.966*.01)/1e6;"MPa"
end
```

manufacture. Use of studs instead of bolts would eliminate the uncertainty in the engagement, and can be considered, once the dimensions and seating requirements of the seal are certain. In the Basic program, the ASME tensile allowable of the lesser of 2/3 yield or 1/3 ultimate, is used. If the AISC allowable of.6*fy is used the factor of safety goes up.


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:

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

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:

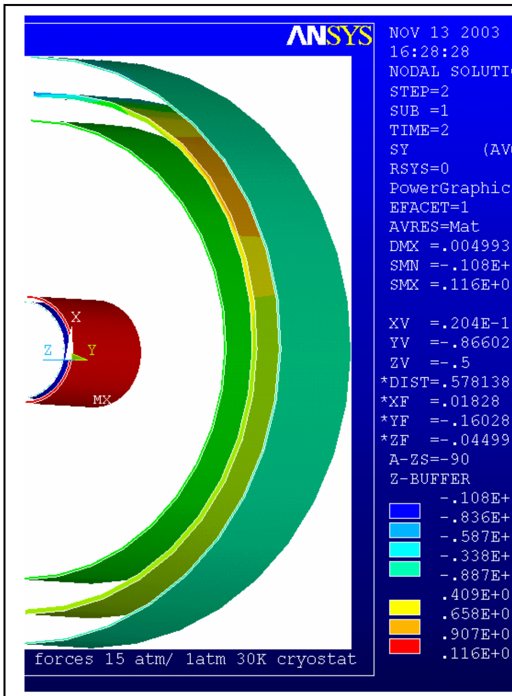
(1) For simplified calculations that will provide shear areas within about 5 percent of those given by the precise formula shown below, the shear area of the internal thread may be computed as follows:

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

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

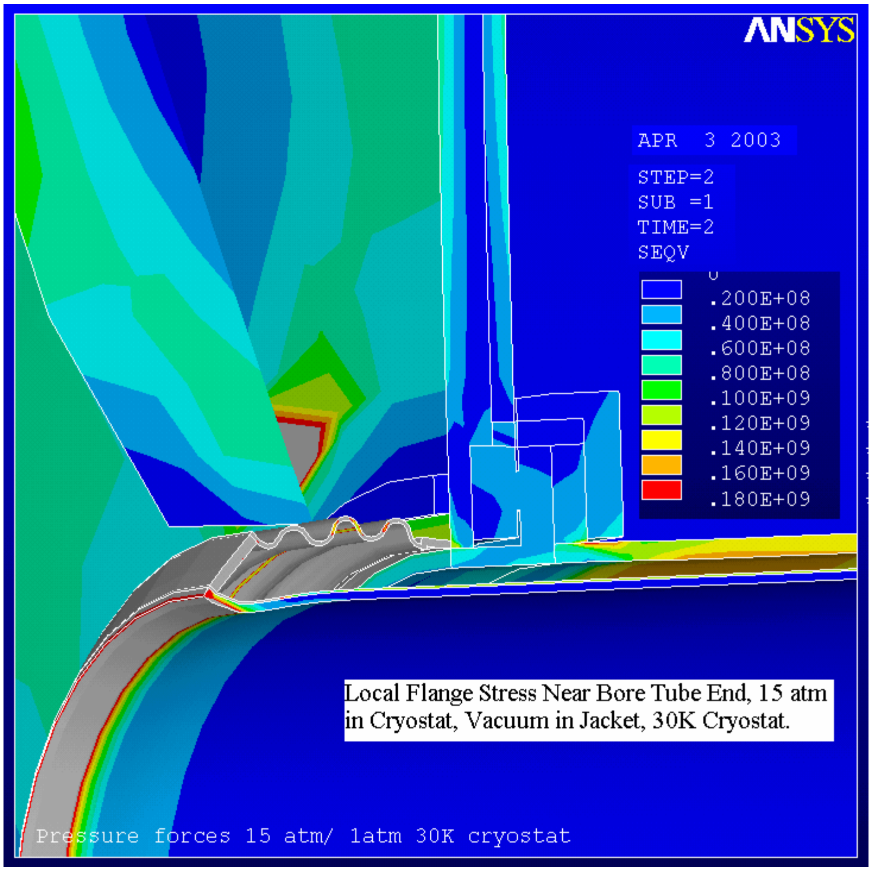
Design Pressure= 15 atm

```
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
```

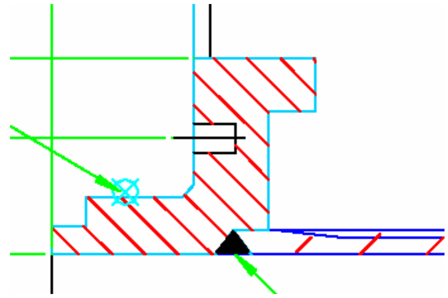


The axial tension in the bore tube is 116 MPa, which is lower than the bolt Basic program calculations predict (178 MPa). The reported inner bolt tension

```
Pressure= 20  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: 147171.99 lbs
Tensile Load on inner Cyl: 654679.67 N
Inner Bolt Tensile Stress 43306.259
Inner Bolt Pull Out Shear Stress 11566.987
Inner Bolt Tensile Factor Of Safety .84668286
Inner Bolt Shear Factor Of Safety 1.3832469
Inner Cylinder Stress Based on Bolt Loading 237.78288 MPa
Tensile Load on outer Cyl: 184738.49 lbs
Tensile Load on outer Cyl: 821790.44 N
Outer Bolt Tensile Stress 13590.108
Outer Bolt Pull Out Stress 2450.1703
Outer Bolt Factor Of Safety 2.6980409
Outer Bolt Shear Factor of Safety= 6.5301582
Outer Cylinder Stress Based on Bolt Loading 27.079091 MPa
Ok. echo off
```



Local stress in the shell to head weld. 6cm high, by 2m thick ribs are modeled. The "leading edge weld is not modeled well but this will be a location of stress concentration. 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

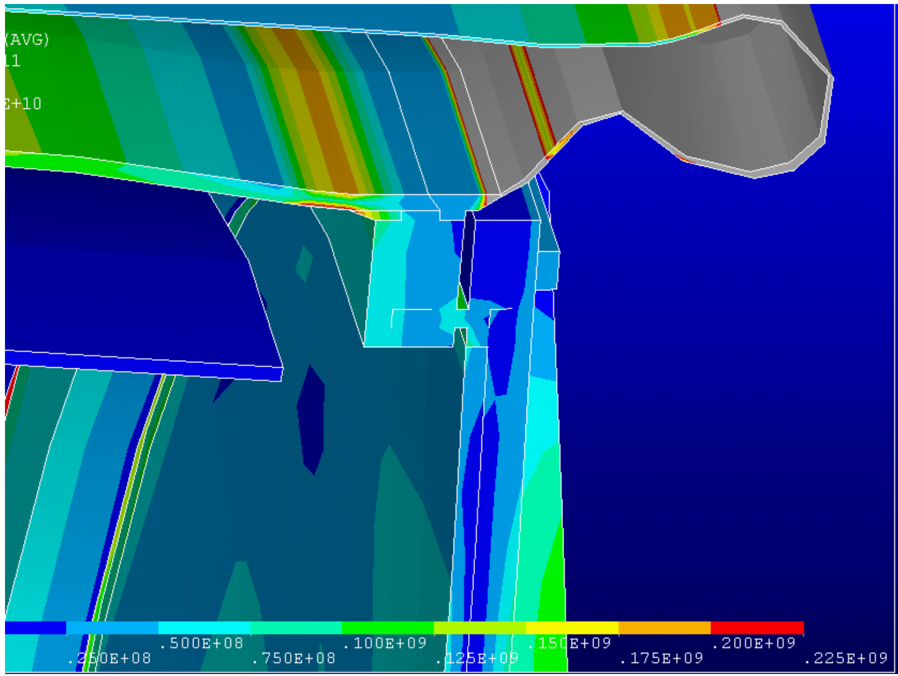


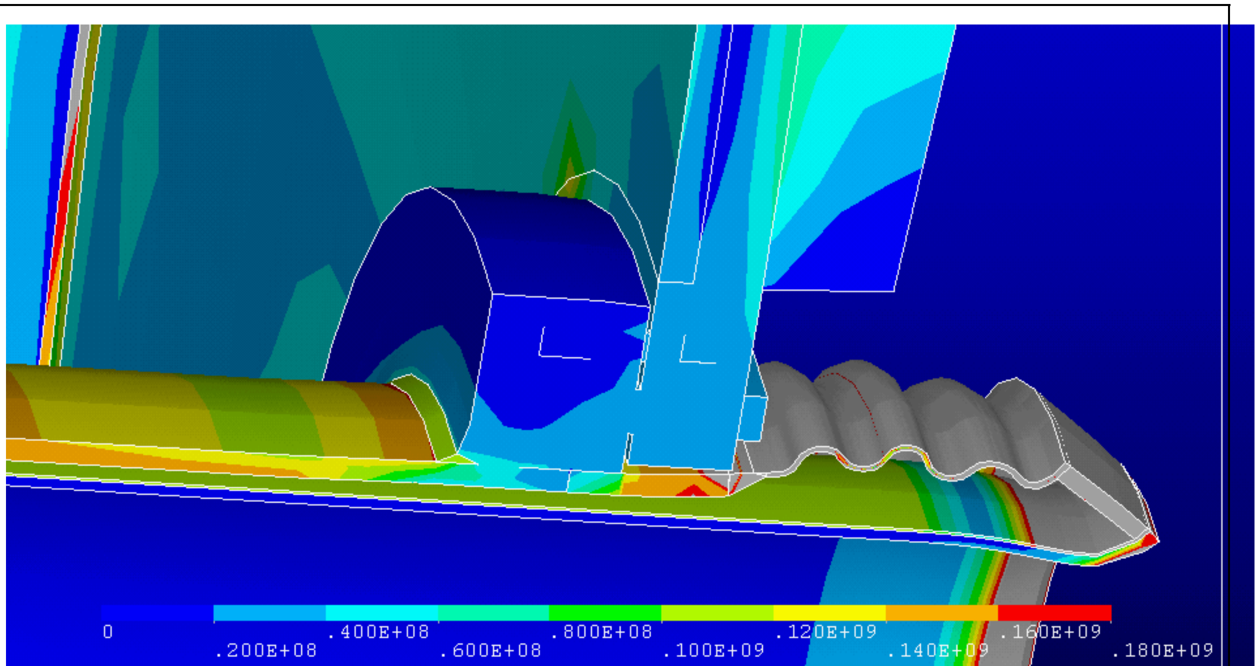
The weld between the bore support tube and flange is a full penetration weld backed by the flange step. The weld is made from the bore side after the magnet is assembled on the bore support tube.

Local Flange to Shell Connection

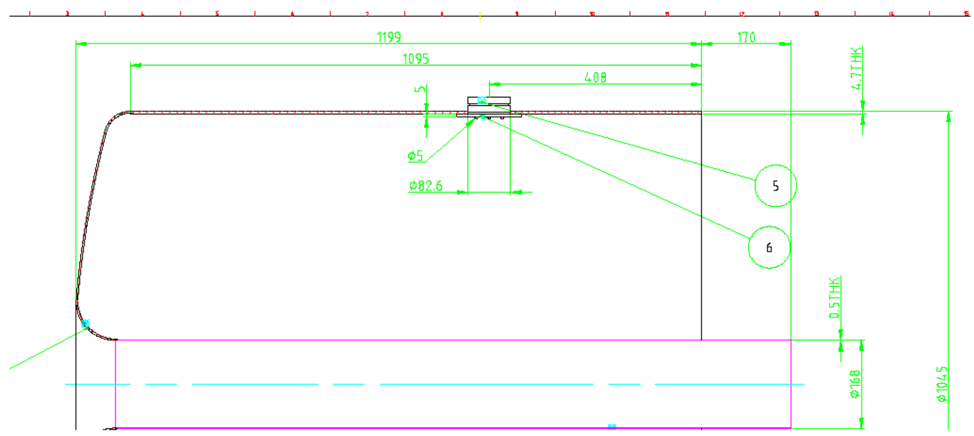
Bending stress allowable is 241MPa (room temperature weld allowable in bending) OD flange stress is at the allowable.
ID flange has a F.S. of 1.5

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



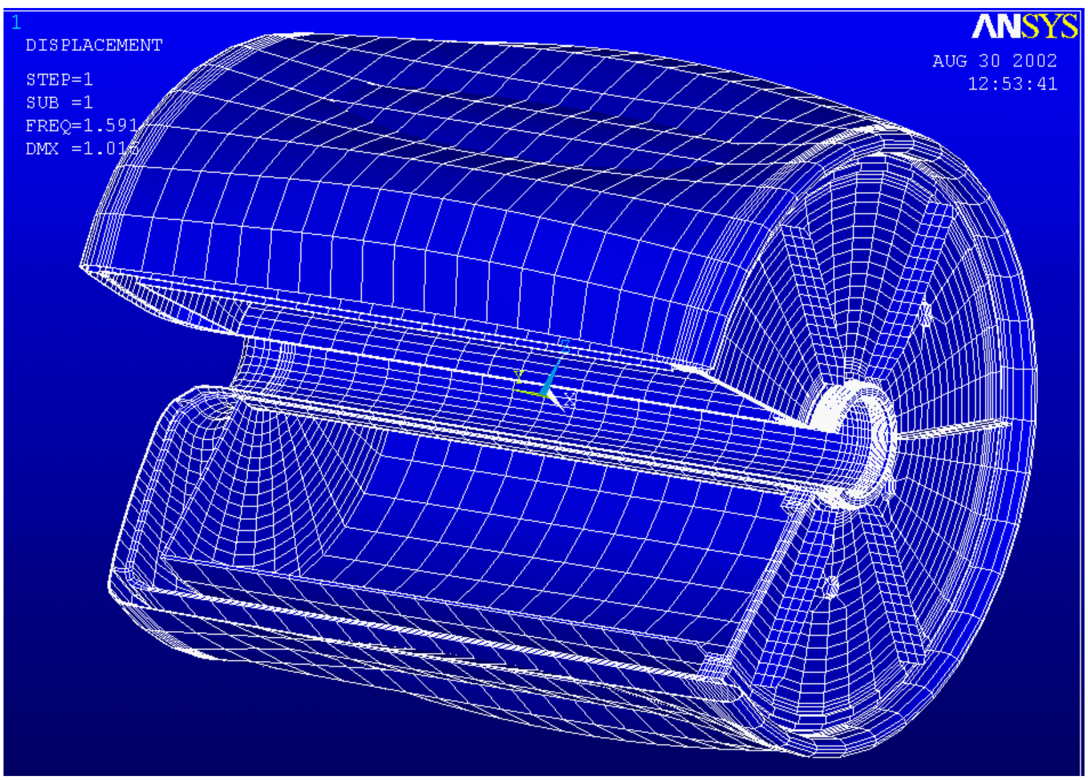


11.0 Vacuum Jacket Buckling

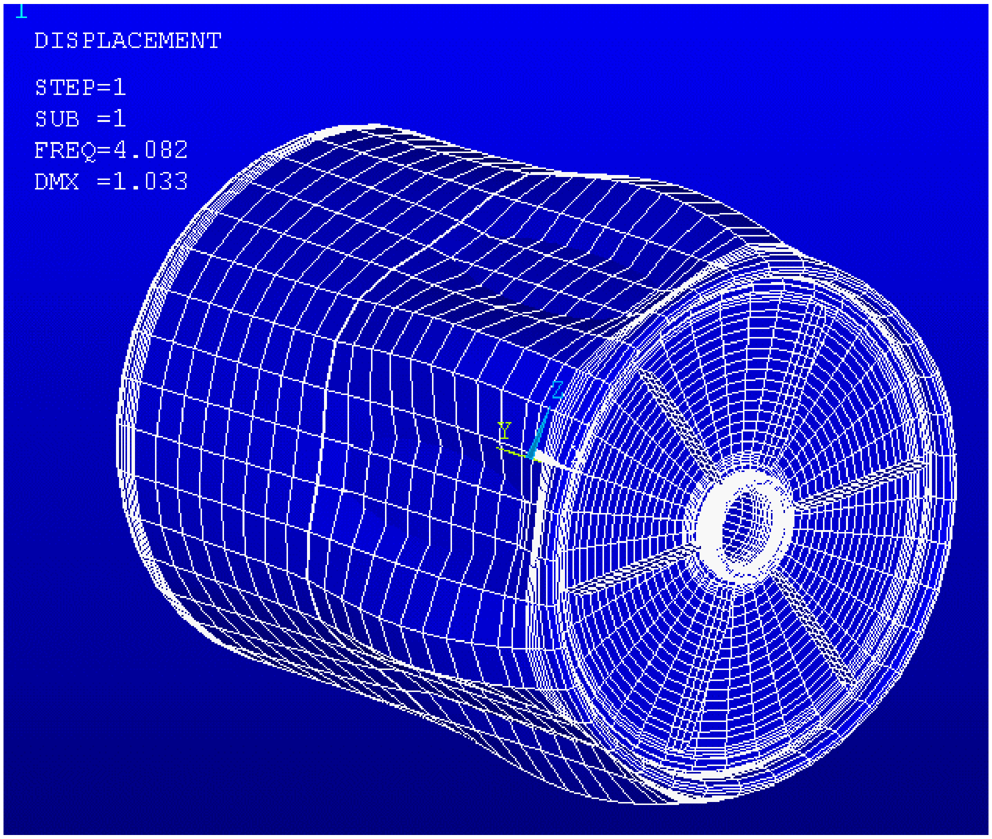


Excerpt from BNL-11. Vacuum Jacket and Bore Tube.

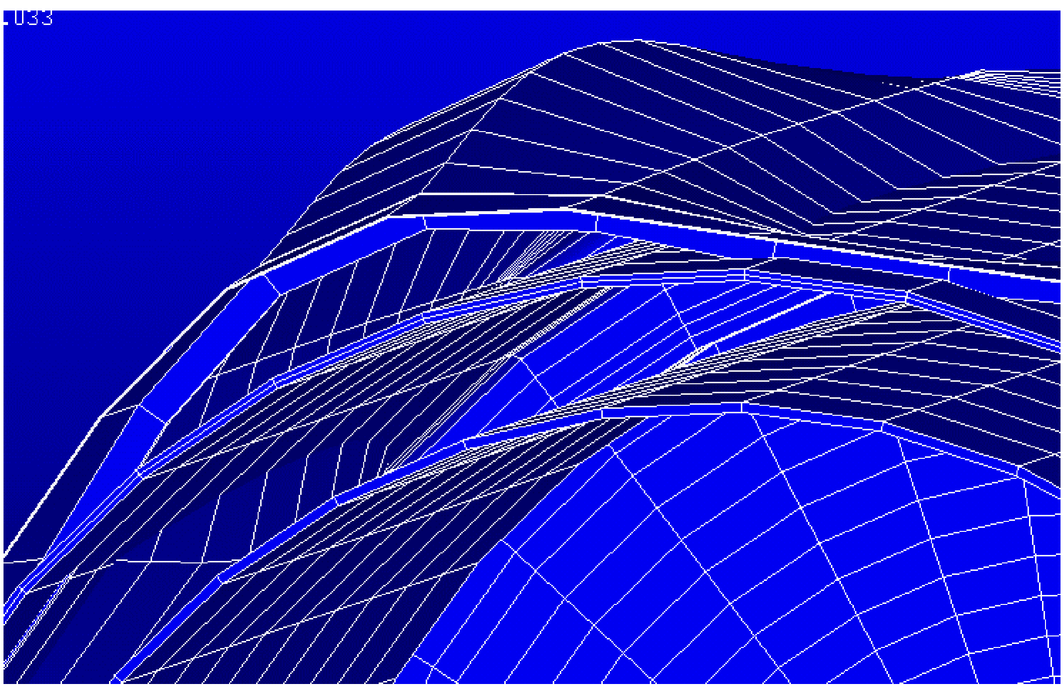
A 1mm thick vacuum jacket was analyzed. The 1mm thick vacuum jacket only has a margin of 1.5 against buckling. A factor of 5 is needed. Stiffeners were added in the analysis, and this was found to produce adequate buckling behavior. BNL drawing, BNL-011 shows 5mm walls for the vacuum jacket. This should be more that sufficient, and the stiffener will not be required.



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



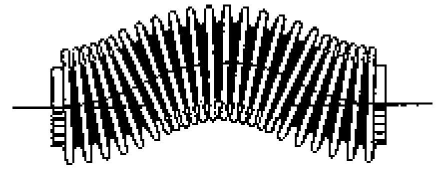
Factor against buckling is 4.08 with mid span stiffener.



Stiffener added to inside of cryostat.

12.0 Bellows Design

There are four areas where bellows are employed to allow thermal differential contraction, and to add thermal conduction length. All of these will be specified in terms of required operating pressure, and lateral and axial displacements. The stress analyses presented in this section are intended to be an "existence proof" for the bellows space allocation. The coil fabricator should consult with the bellows manufacturer for appropriate convolution details.



Bellows "squirm" is stabilized with tension rods for the lead and LHe/LN2 bellows.

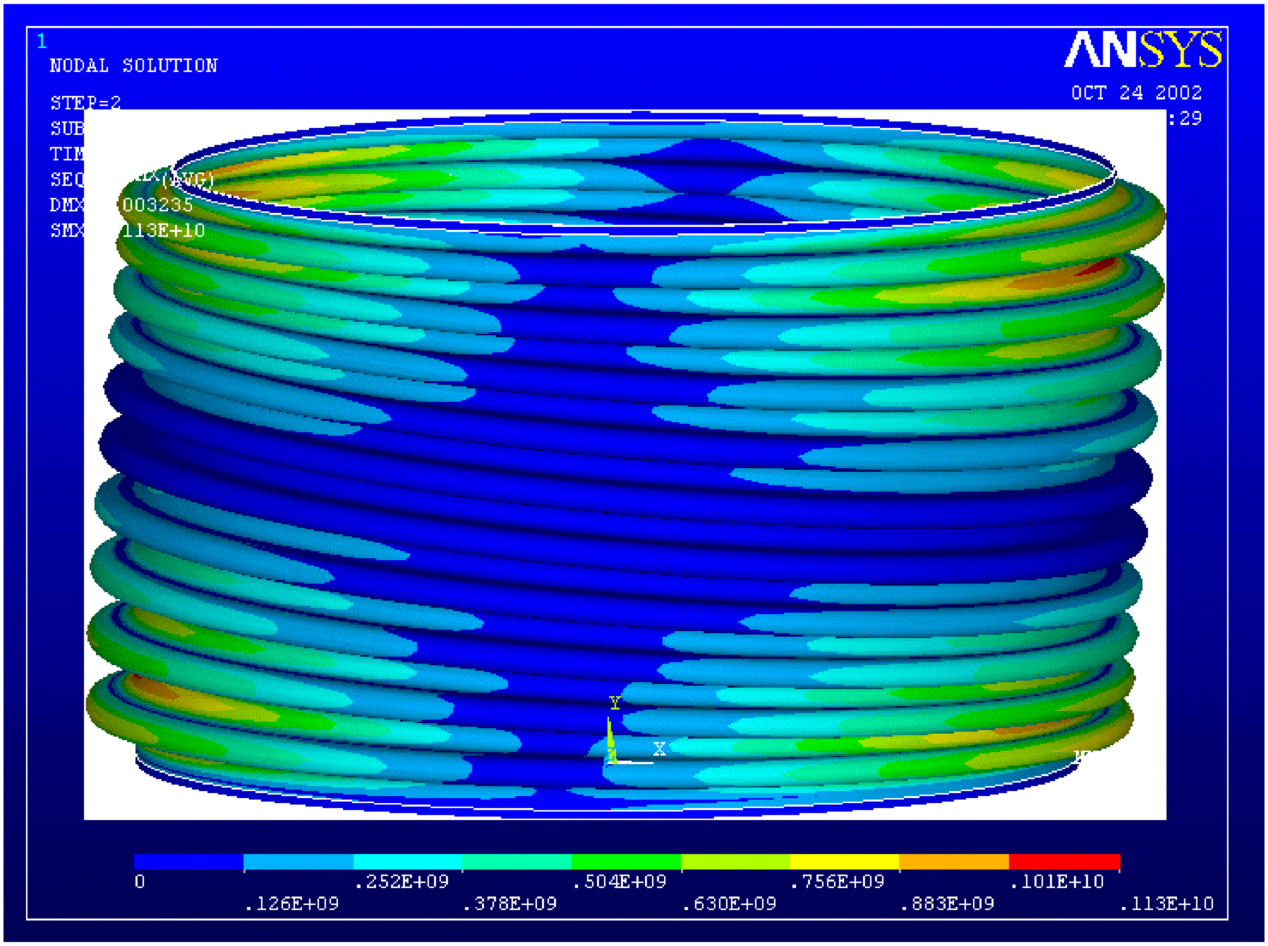
Table of Bellows Specifications:

Item #	Location	Operating Pressure	Axial Displacement	Lateral Displacement	Axial temp Gradient	Material
BNL-002 #27	End of Bore Jacket	Vacuum	.35mm	0 mm	30K-292K	316 SST
BNL-002 #24	Cover end of Vacuum Jacket	Vacuum	.35mm	0 mm	30K-292K	316 SST
BNL-002 #30	Leads (Normal Operation)	15 atm	0.7 mm	.25mm	30K-292K	316 SST
BNL-002 #30	Leads (extreme Thermal Differential)	15 atm	3mm	1mm	30K-292K	316 SST
BNL-002 #40	Gravity Support Pads	Vacuum	~2mm	2.2mm	Only 292K	304 or 316 SST
BNL-002 #21	He/LN Outlet	15 atm	~2mm	2mm	~0 K	316 SST

All bellows have a critical pressure at which they become unstable. Instability can occur in either of two modes, column instability (or squirm), or inplane deformation of the convolution side wall.

Squirm is the phenomena whereby the centerline of a straight bellows develops a sideways or lateral bow.

The critical pressure at which this instability occurs is a direct function of the diameter and spring rate, and an inverse function of the length. If the bellows is bent, or angulated, the centerline can begin to move away from the center of curvature. In each case, the effective length of the bellows increases, lowering the material available to withstand the pressure, thereby increasing the hoop stresses. As the length increases, the tendency to squirm increases and the stresses become higher and higher until catastrophic failure occurs. A simple way to visualize this phenomena is to remember that the bellows is a cylinder of given volume. Internal pressure tries to increase a vessel's volume. Since a bellows is flexible in the axial direction, it can increase its volume by increasing the length of its centerline. With the ends fixed, it does so by simulating the appearance of a buckling column. In the BNL Pulsed Magnet, bellows "squirm" is stabilized with tension rods for the lead and LHe/LN2 bellows.

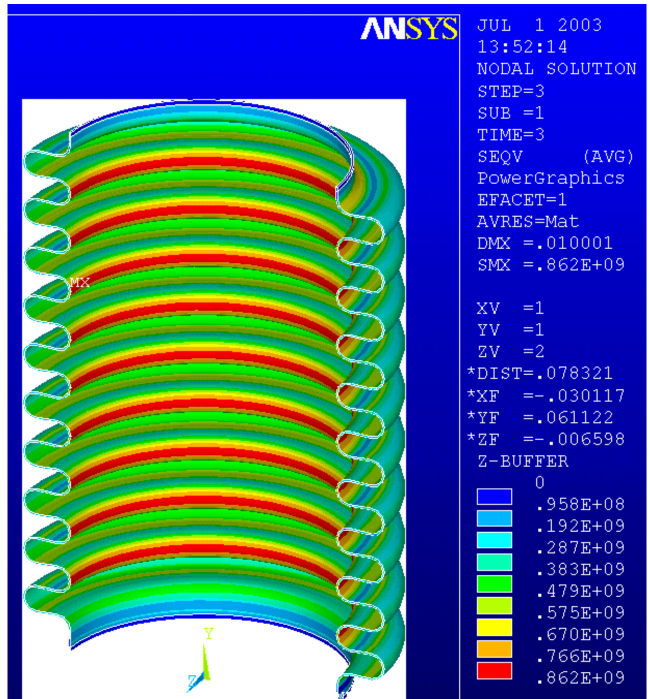


.Gravity support bellows, Stress due to cooldown. 008” thick stock. 4.0 inches in inner diameter, 6mm convolution pitch with 2.5mm flats, 2.2mm lateral displacement due to cryostat cooldown.

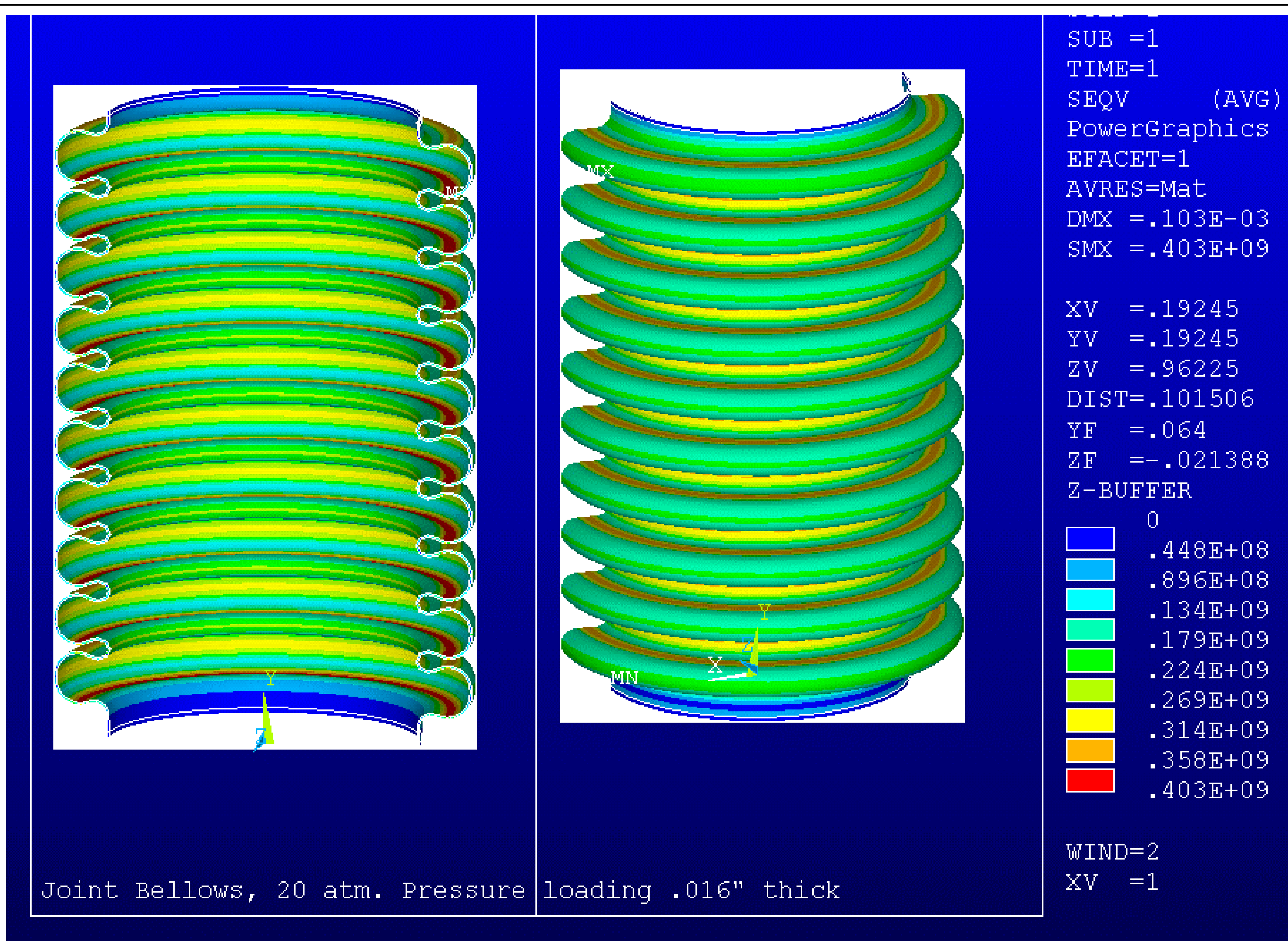
Bellows materials are specified as 316 for sub- LN2 temperature service, and 304 for RT service. Room temperature yields of highly cold worked materials should be in the range of 500 MPa for 316 and 1000 MPa for 304. All the bellows must see their pressure service at room temperature. The gravity support bellows worst loading is due to a lateral displacement due to cryostat contraction.

Joint and LN2/He Bellows.

These bellows must accept the axial differential thermal motions between the 30 K cryostat and the magnet. Nominally this is the difference between cryostat, and the coil at 100K. Both Copper and Stainless Steel have coefficients near 10e-6, and the magnet/cryostat assembly is about 1 m. long. The intention is to have the plenum inlet side of the magnet and plenum to be held to the same displacement via spacer blocks, and the joint end of the magnet is spaced off the cover with a Belleville spring stack. The differential displacements thus appear in the joint bellows. Nominal differential motion is 1m*10e-6*70K=.0007m or 0.7mm. A worst case differential axial motion might occur if the cryostat was at 30 K and the magnet accidentally was heated beyond it's normal high temperature, to RT. The system interlocks should shut down the magnet current well before this. This would yield a differential axial motion of 2.62 mm. There is a radial differential motion. The outer joint at a radius of .35m would see a little over 1/3 the axial motion or about 1mm. Early in the design a large axial compression was needed to expose joint connections but the gland nut- penetration design does not require this.



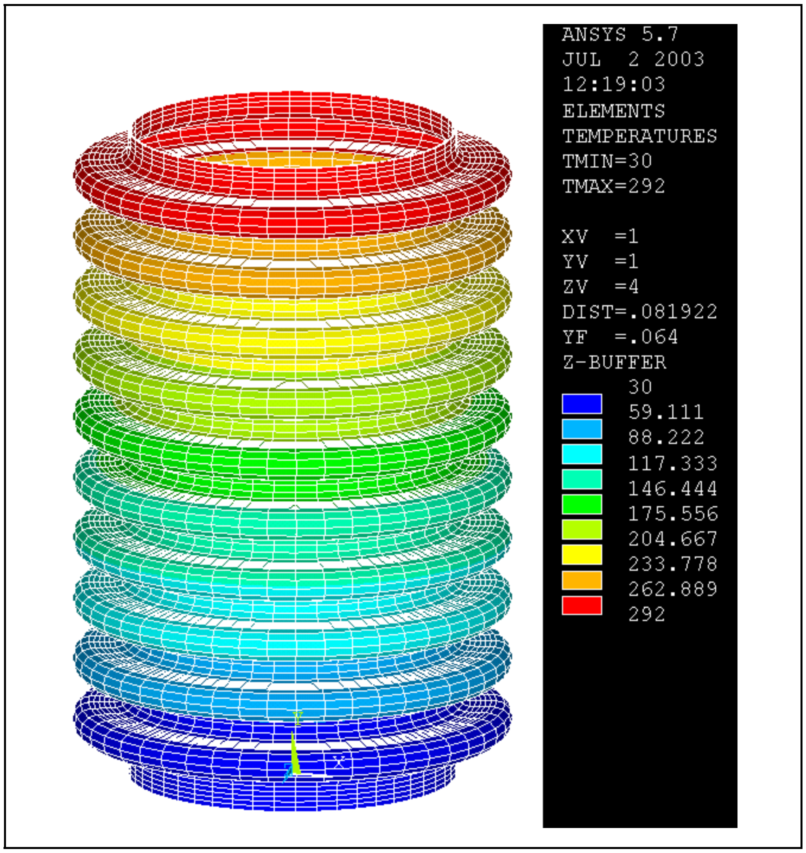
Stress in the joint bellows for one cm axial displacement.

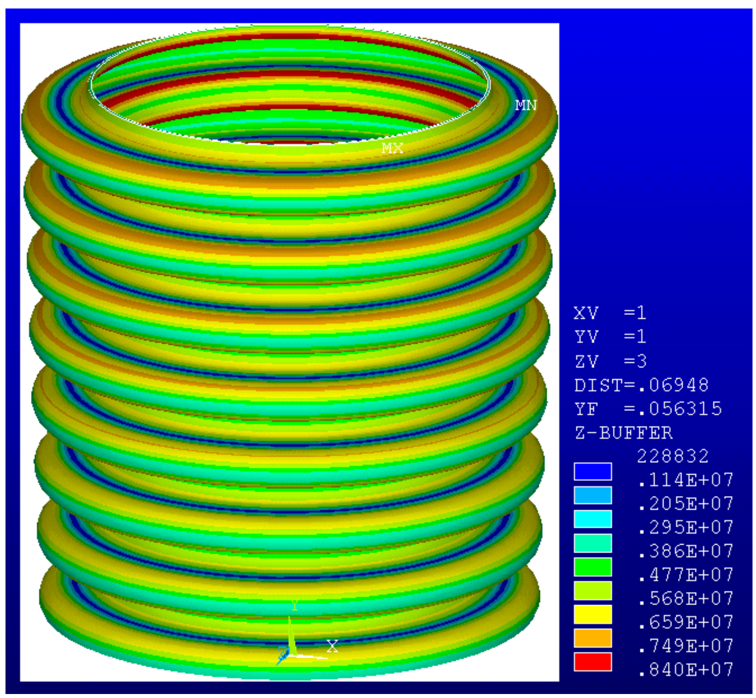


Bellows used for the Joint penetration. The overall length of this model is .127m or 5 inches. The convolution pitch is 12mm with 5mm flats. The inner diameter is 6.25 cm or about 2.5 inches. The stock thickness is .016"

Joint Bellows Thermal Stresses

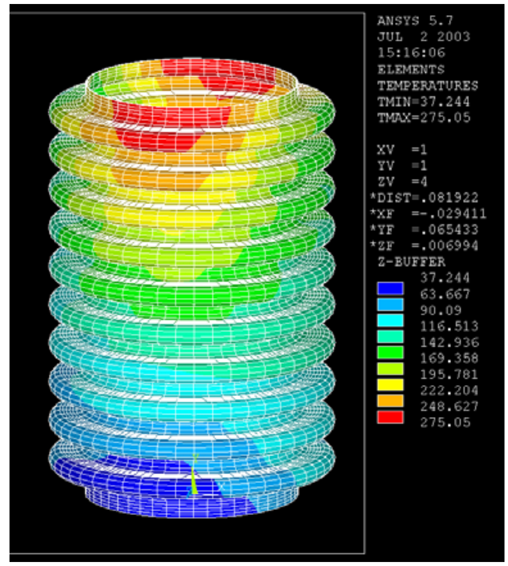
The bellows are used to absorb differential motions, and also to provide long thermal paths to minimize heat leaks – See section 14.0. The joint bellows model was analyzed with a 30K to RT (292K) axial gradient. With this linear axial thermal gradient, appropriate for conduction from the 30K cryostat cover to the LN2 or RT end of the joint break-out, the stresses are minimal.

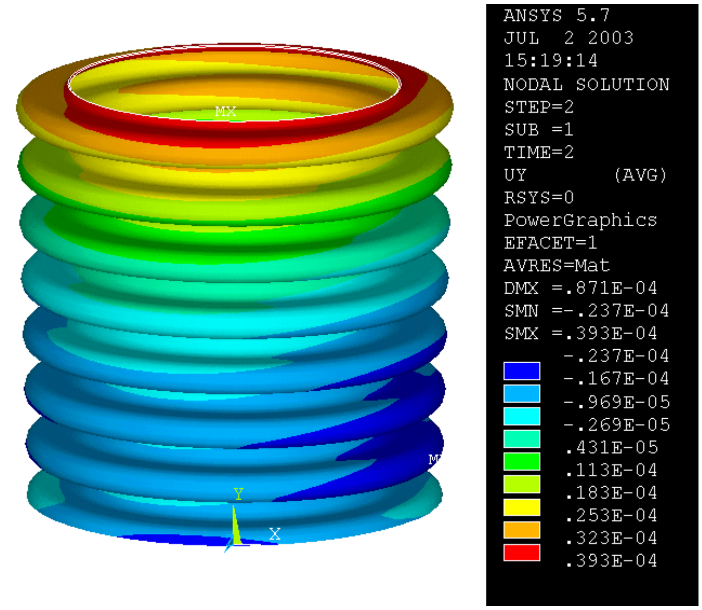




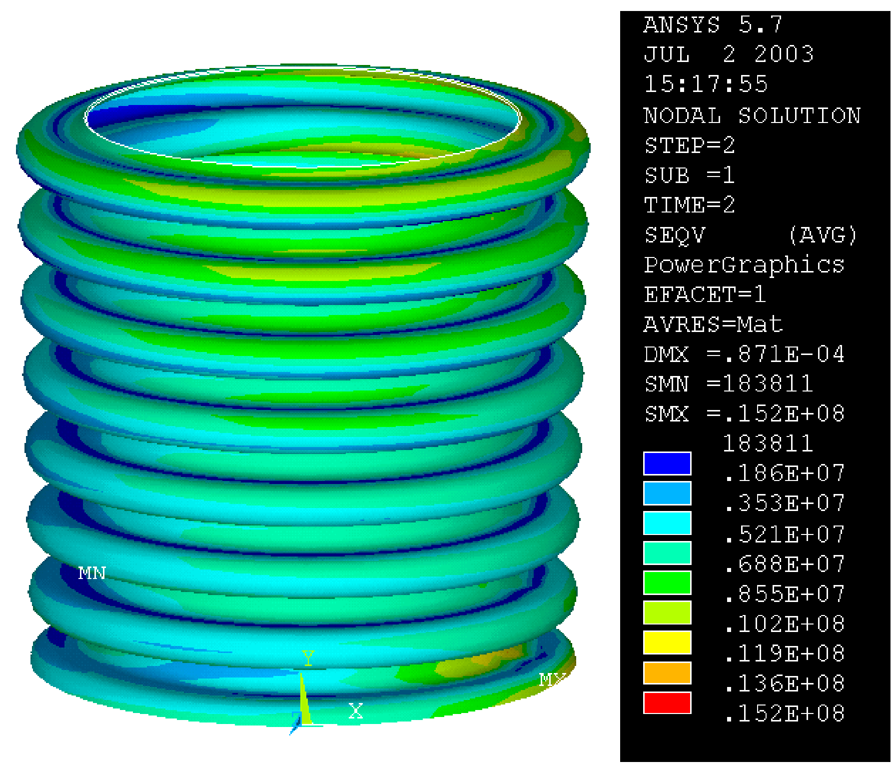
Von Mises Stress of the bellows convolutions with the axial temperature gradient applied. The peak stress in this analysis is 8.4 MPa

An attempt was made to "invent" a temperature distribution that wasn't quite so uniform. This is shown at right. The axial (vertical in these plots) displacement is not uniform. . The peak stress for this non-ideal temperature gradient is 15.2 MPa, up from the previous 8.4 MPa, but it is clear that thermal stresses are not critical for the temperature gradients we expect at the joint penetrations.

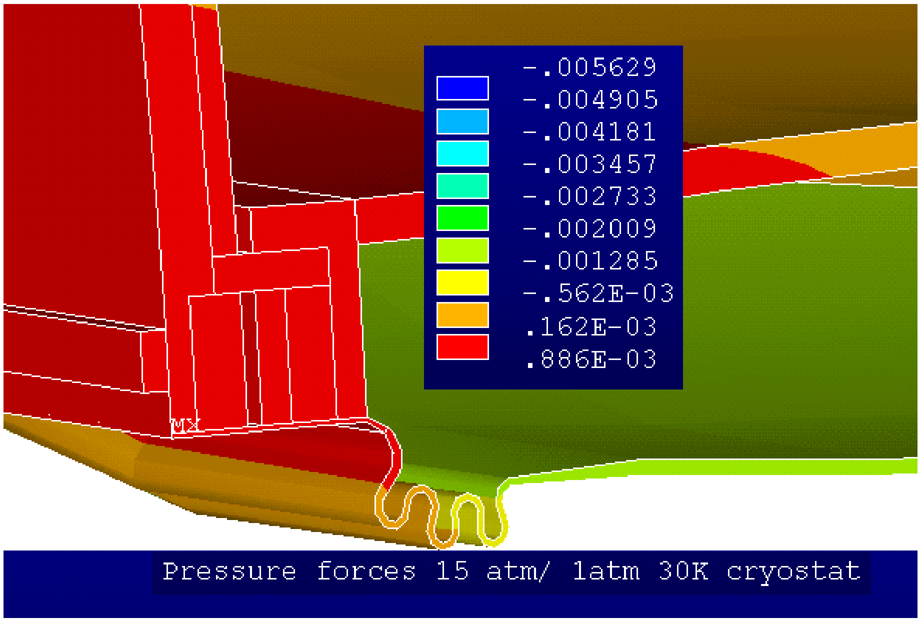




Axial thermal displacement in meters.



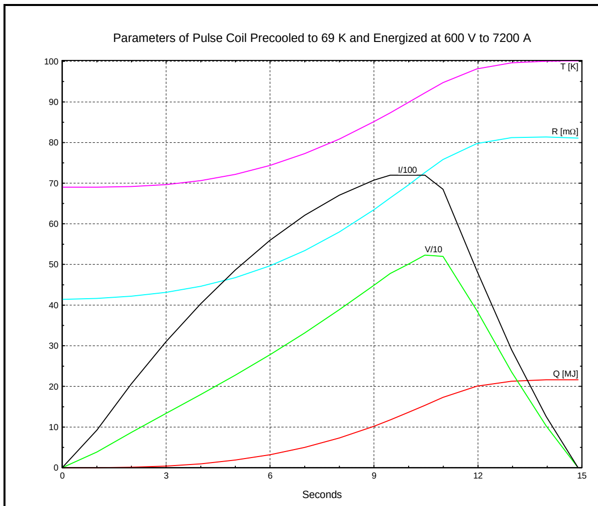
The peak Von Mises stress is 15.2 MPa



Vacuum Jacket Outer Flange Axial Displacements.

13.0 Cryostat Eddy Current Analysis

There is a concern that pulsing the magnet can induce eddy currents in the shells sufficient to cause a significant load. The eddy currents coupled with the large bore field, may significantly load the bore vacuum jacket. In addition the flat plenum plate does not have a curvature to stabilize it and would see bending stresses rather than hoop membrane stresses. To address this concern, an electromagnetic transient analysis was performed. The solution is a vector potential solution, That traces the current history at the right. The wors point will be the beginning of the ramp-down An additional concern is the field loss due to the opposed currents in the bore shells, but this field loss is of the order of a few milli-Tesla. Stress Levels also turned out minor – of order 2 MPa.The ANSYS Input listing is included at the end of this section.

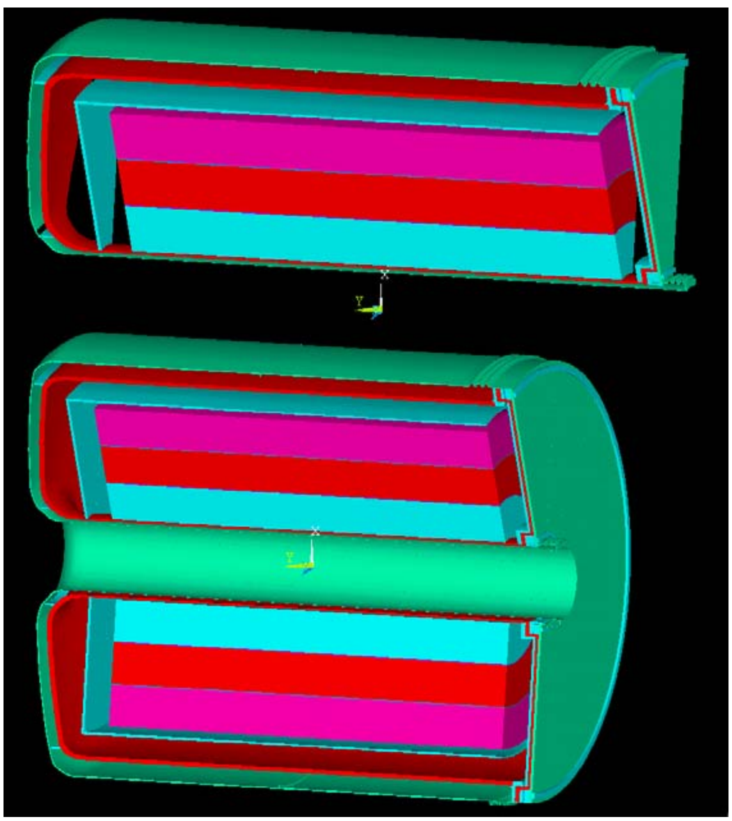


Bob Weggel's 10-14 analysis of the LN2 magnet operation

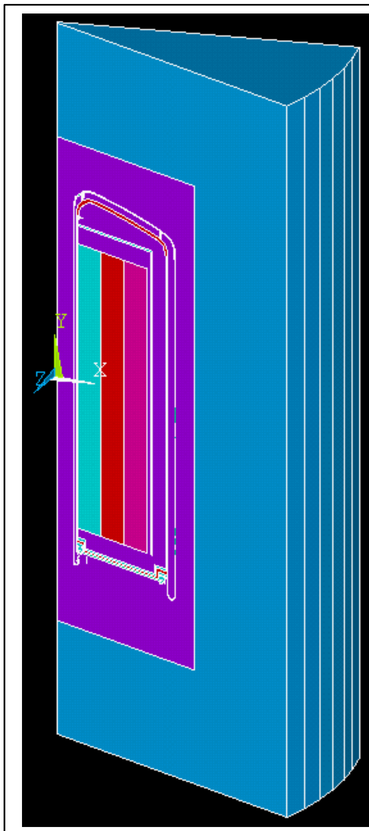
Resistivity Values for Metals

	%IACS		Ohm-m	Reference
OFHC Copper	100		1.7074e-8	
Stainless Steel 316			74e-8	MHASM1
Inconel 625, at T=292 deg. K			103e-8	

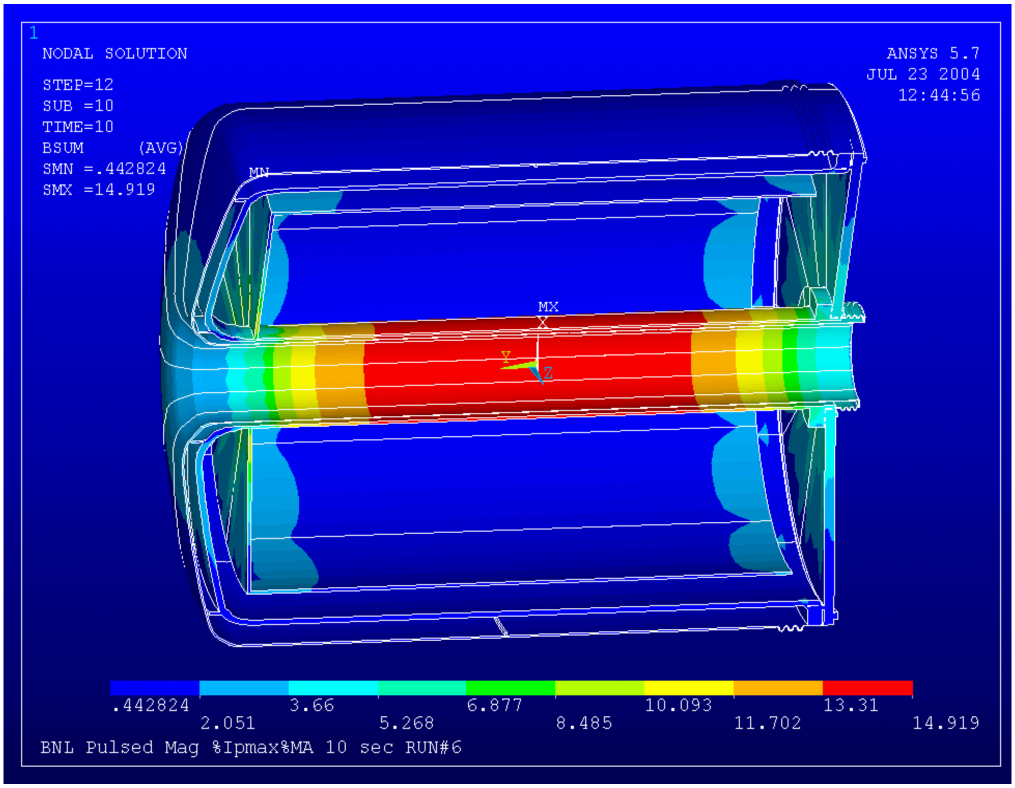
MHASM2=ASM Metals Handbook--Volume 2, Tenth Edition



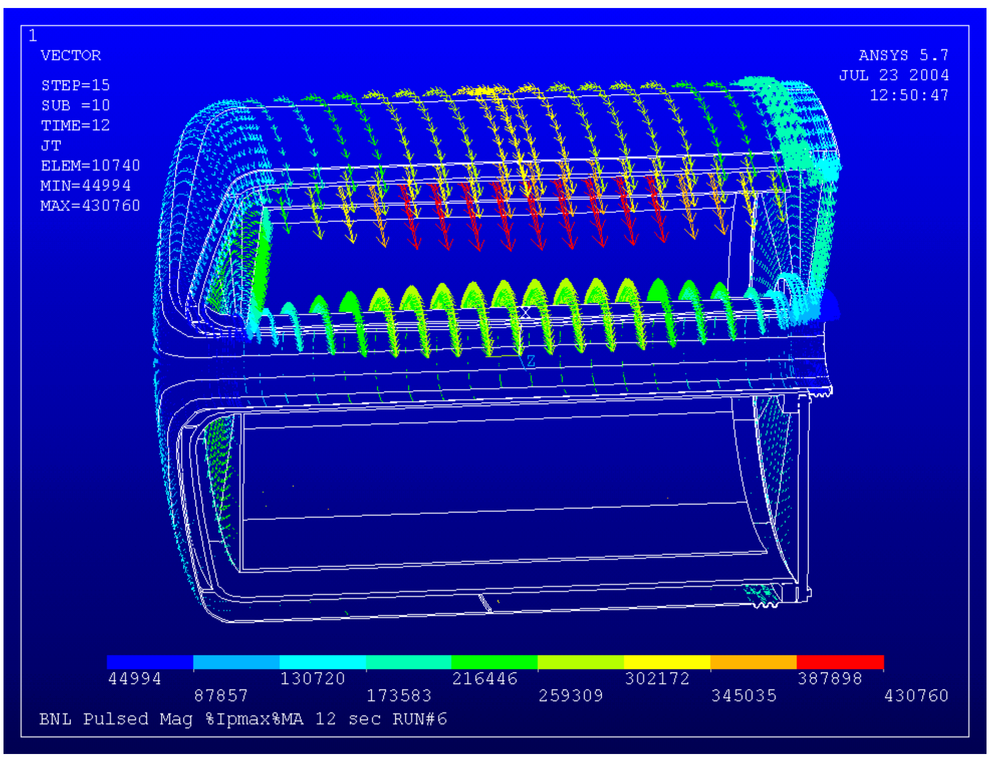
Structural Mode (Sub-Set of E-M Model)l Shown with Coils that are removed for structural analysis. The upper plor is the 30 degree cyclic symmetry model, below is a 7 segment symmetry expansion.



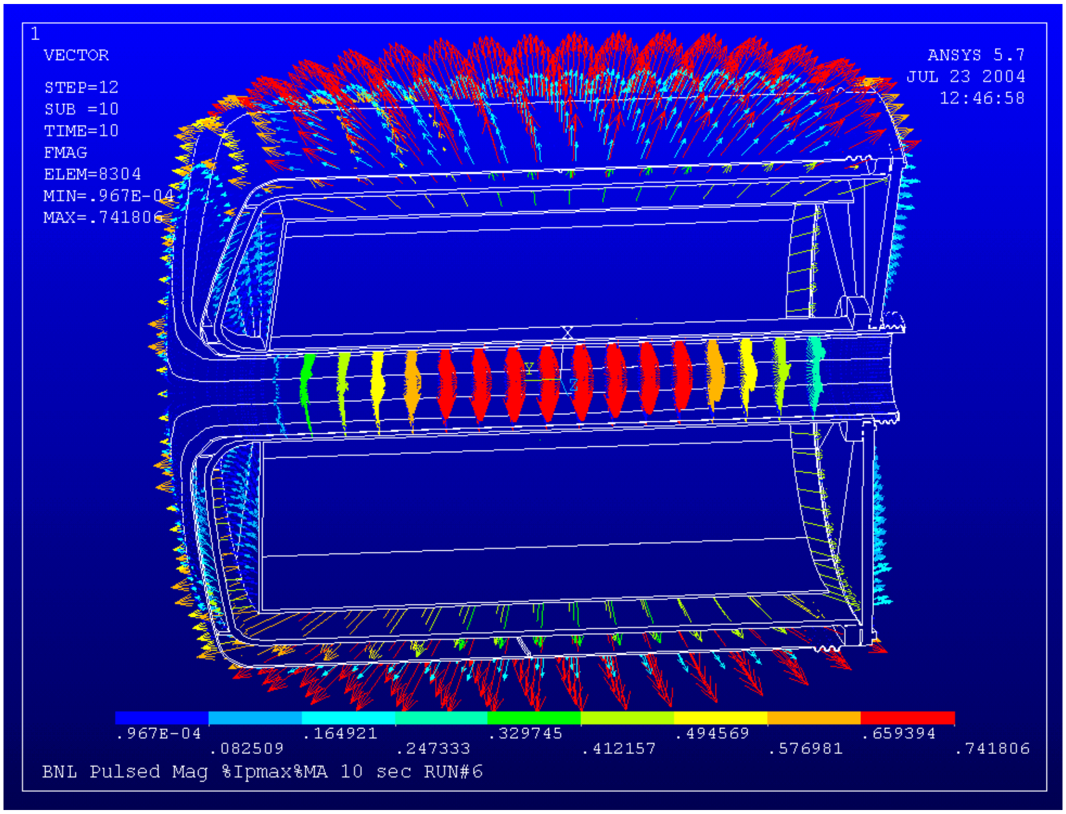
Electromagnetic Model with Air



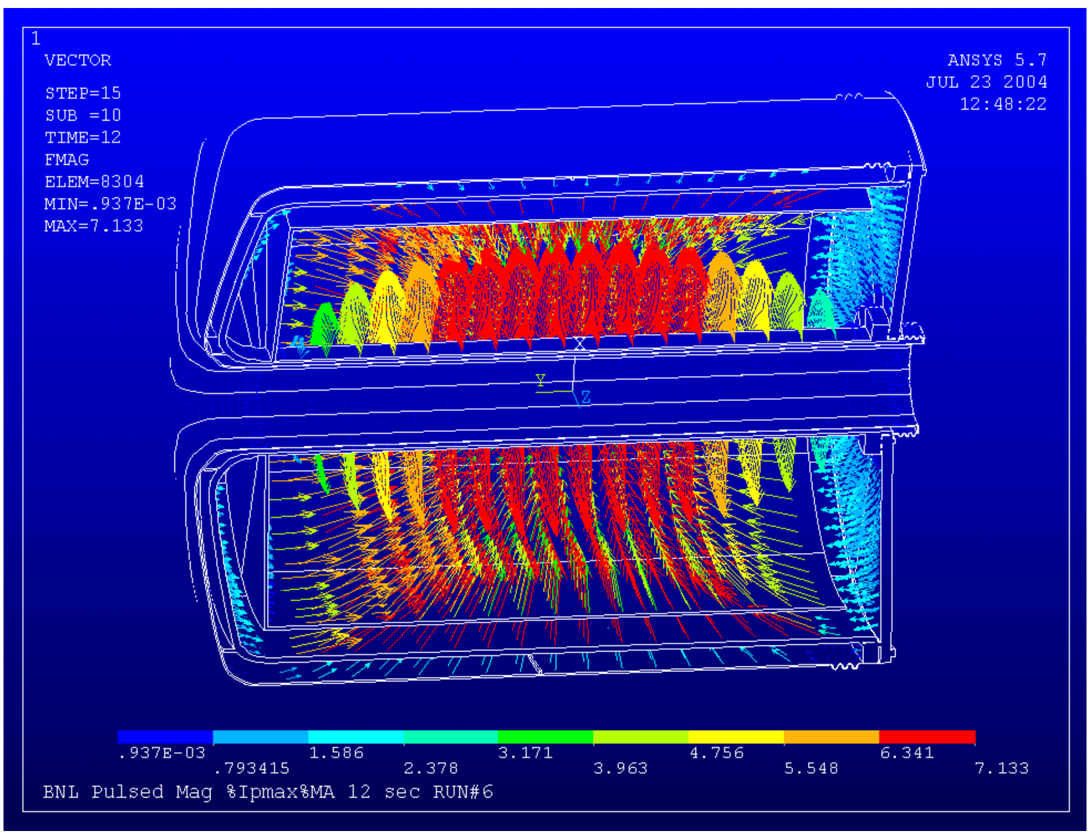
BSUM (Total Field) through Structural Elements



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



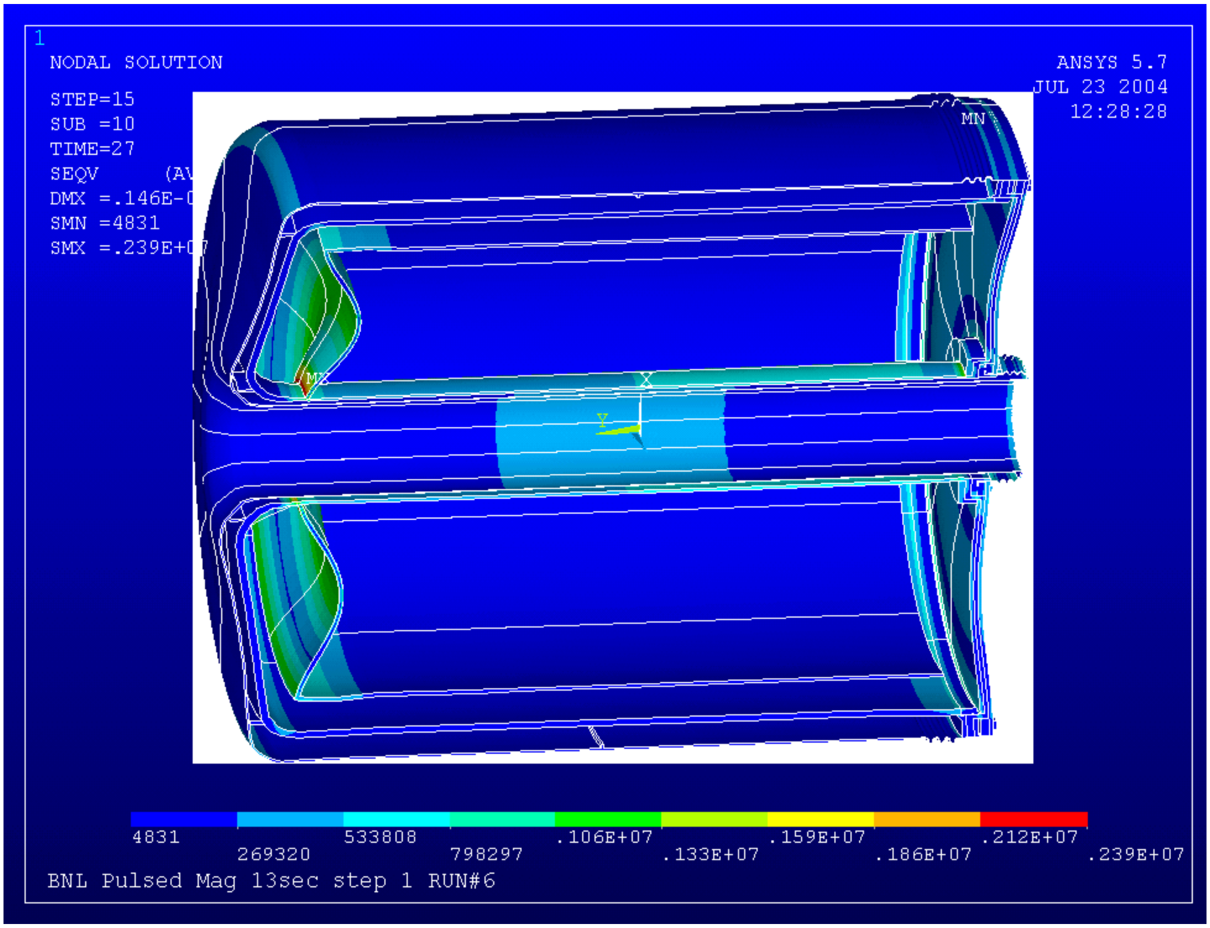
Eddy Current Forces During Ramp-Up



Eddy Current Forces During Ramp-Down

Cryostat Eddy Current Analysis – Stress Pass

The nodal Lorentz forces are produced in the electromagnetic run and can be read into the structural model with an LDREAD ANSYS command. This was done. j*B*r should give an estimate of the hoop stress in any of the cryostat shells. With current densities of .2MA/m^2 and fields of 10 Tesla, and radii of .1 to .5 meters, the hoop stress should be only .2MPa. The peak stress is a bending stress and occurs in the plenum plate.



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

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/com
/com

! CREATE BASE ELECTROMAGNETIC SOLUTION
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/PREP7
antype,trans
/COM   11-25-98   Electrical/Thermal
analysis
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current regions
ET,2,97,0    ! (Ax, Ay, Az) EM for air
ET,3,97,0    ! (Ax, Ay, Az) EM for air
TREF,292.0
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/COM   MAT,5  Coil
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/com   MAT,6  Channel
/com   MAT,7  Bore tube
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*end
*use,matt
/com
/input,vma6,mod
/com
nall
eall
LOCAL,12,1,0,0,0,0,-90.0,0.0
CSYS,12  $NROTAT,all
esys,12
/com Coupled Flux Condition

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nsel,z,1.75,2
nasel,z,-2.0,-1.75
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eall

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nelem
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nall
eall
csys,0

Wsort,x
wsort,y
```

```
wsort,z
tunif,80

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easel,mat,3
easel,mat,5
nelem
bfe,all,js,1,0,0,curd
eall
nall
save
fini

/solu
           Transient Current Parameters
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/com Elecromagnetic Solution
estep=estep+1
solve
save



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*create,load
/com solve electromagnetic problem
time,timpt
csys,0
curd= i%ls%*6375
esel,mat, 1
easel,mat, 3
easel,mat, 5
bfe,all,js,1,0,0,curd
eall
nall
solve
save
*end

!   START TRANSIENT

*do,ls,1,15,1
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curamp=i%ls%
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sec RUN#%runn%
*use,load
*enddo
fini

/filnam,stru
/prep7
antype,static
/TITLE, BNL Pulsed Mag %timpt%sec step
%estep% RUN#%runn%
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ex,7,70e9
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ex,14,200e9
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nasel,y,14.99,16
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eall
save
fini
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eusel,mat,91
eusel,mat,92
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eusel,mat,3
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eusel,mat,7
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solve
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fini

/exit
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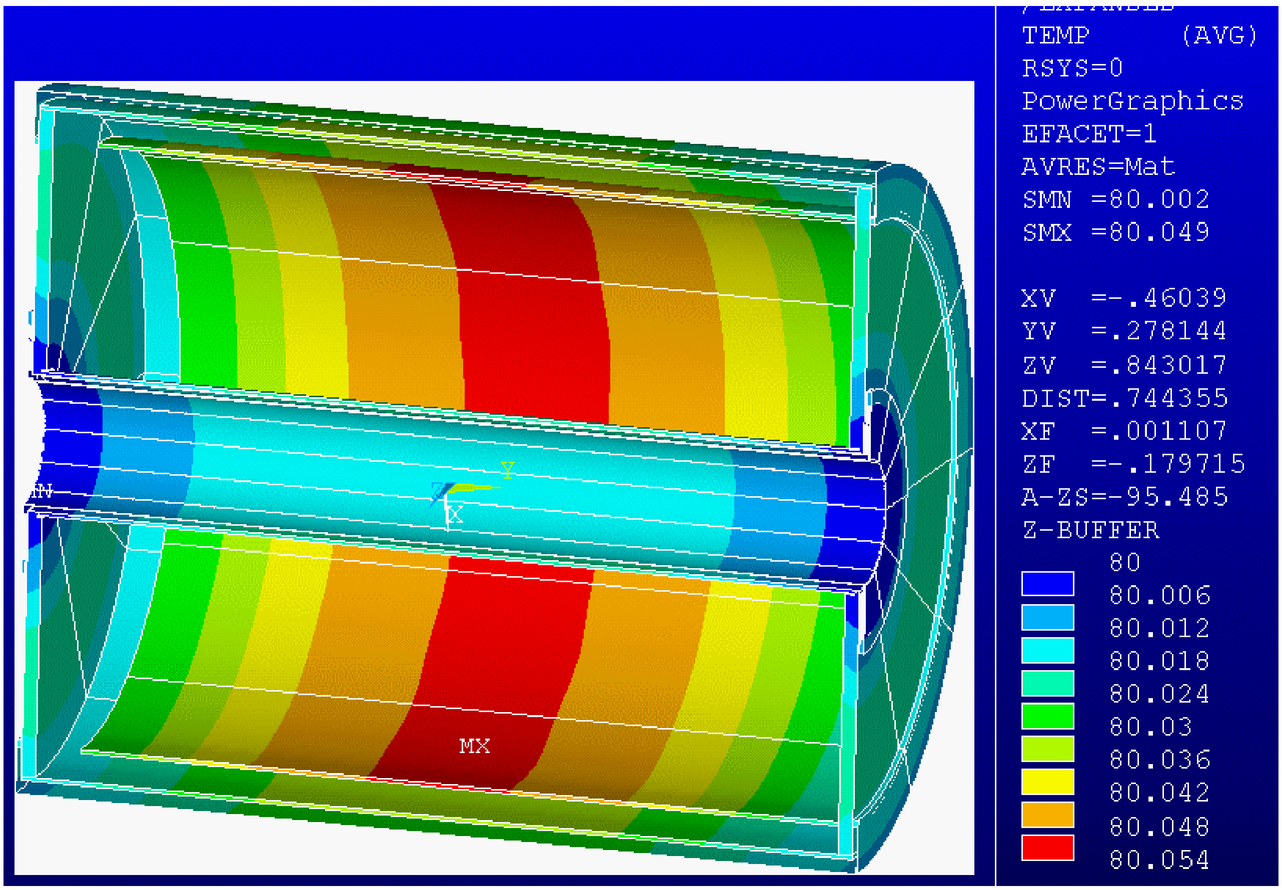
Cryostat Eddy Current Analysis – Temperature Pass

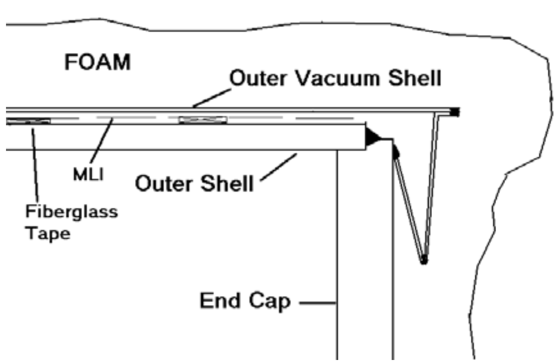
Heat-up due to the eddy current loading on the cryostat produces less than 1 degree K



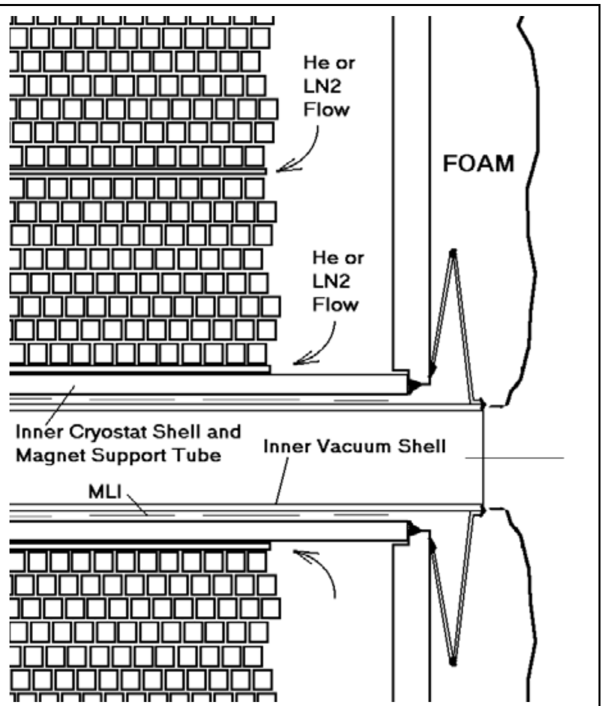
14.0 Steady State Heat Gain.

The specification requires that the cryostat heat gain should be <200 W at 22 K; i.e., it should boil off no more than ~500 liters/day of liquid hydrogen. The specification also states that liquid nitrogen is available for cooling the leads to the magnet. –This implies that the 200 watt limit for the cryostat excludes the leads. A concept which has a 234 watt heat gain has been developed that employs vacuum at the outer and inner shells and foam at the ends around fluid and electrical penetrations. This can be reduced to the required heat leak by adding vacuum jackets to the end flanges and/or increasing the foam thickness beyond 10 cm.

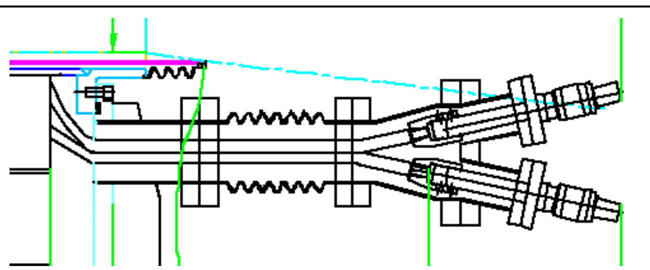
Because of the space limitations at the bore, only a vacuum insulation system has been considered here. The possibility of using foam insulation has been investigated on the remaining surfaces of the cryostat. Initial estimates of the heat gain on the outer shell of the cryostat were excessive if only foam were used, so a vacuum shell is proposed on the OD as well. If piping penetrations are moved to the end plates, it is relatively easy to add vacuum shells on the ID and OD. The connection between the room temperature vacuum shell and the 22 to 30K end caps also conducted too much heat, so the foam has been extended to the outside shell. To clear the experimental bore volume foam can't be used at the ID so here the connection must bridge between room temperature and the cold



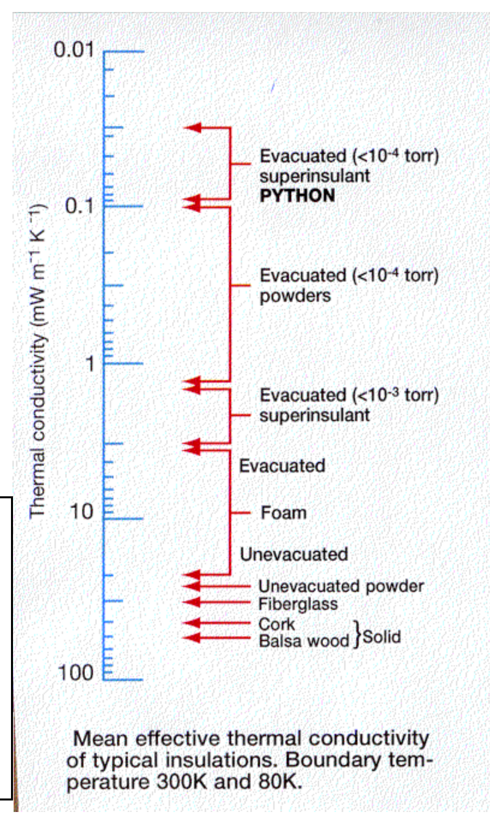
Outer Vacuum Shell to Cover Connection



Inner Vacuum Shell to Cover Connection



Lead with bellows



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

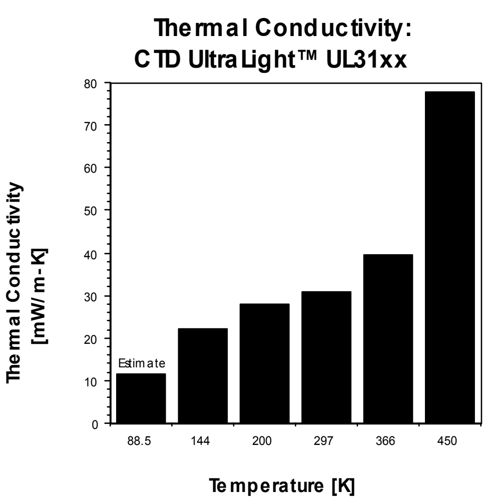
Helium/LN2 can. One virtue of this arrangement is that the magnet can be supported off the inner cryostat shell, and the system gravity supports can reach through the foam or vacuum boundary. In the heat gain calculations the gravity support is simply modeled as four G-10 columns or straps. With the magnet supported off the inner tube, the annular gap used for coolant flow will be readily maintained. If the magnet was supported independent of the inner cryostat tube, the alignment of the magnet to cryostat would be critical to maintain the 2mm annular space. For the heat transfer calculations, the cryostat is assumed to be a cylindrical geometry about 1.2m long and a meter in diameter.

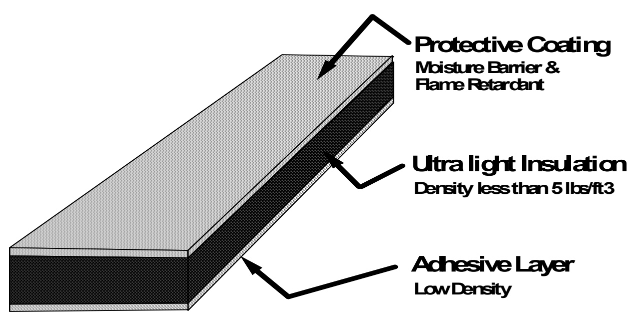
Heat Gain Summary

Component	Material	Thermal conductivity W/m/degK	Area m^2	Length m	delta T	Heat rate watts
Inner shell vacuum with mli	Vacuum/MLI	*	.75398224	*	292-22	**<20**
Inner shell vacuum extensions	.0005m thick sst	16.27	6.283e-4	.2	292-22	**13.8**
Outer shell (foam option)	CTD Cryo foam insulation	.03	3.77	.1	292-22	303
Outer shell foam in series with vacuum+mli	Cryo foam insulation	.03		.1	292-220	**49****
Outer shell Vacuum Extension	sst	16.27	3.14159e-3	.2	292-220	**18.4**
End Cover foam (1 ends)	CTD Cryo foam insulation	.03	1.508	.1	292-22	**62.85**
Dished head End Cover	Vacuum/mli					
Leads	Copper (22 to 80K)	396.5	8.64e-4	.4	22-80	**49.6 (3 pairs)**
Leads	Copper (80 to 292K)	396.5	5.4569e-4	.4	80-292	**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. – See the mli specification at the end of this section.

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





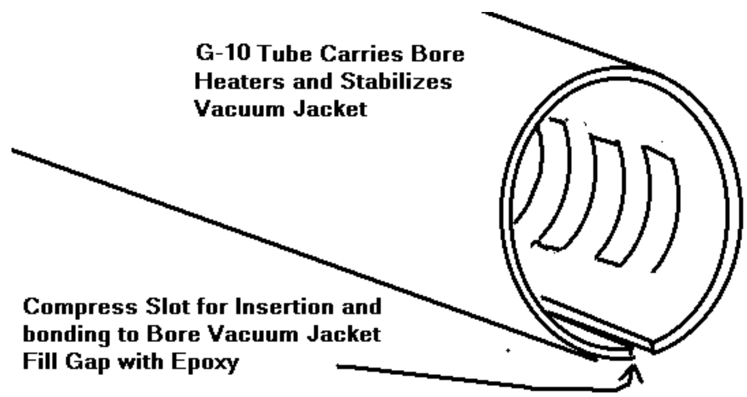
Cryostat Bore Tube Geometry

From the specification: “The Cryostat bore, including heater wire or tubing to keep it warm, should be at least 15 cm. If the bore tube is so long that its upstream end is >60 cm from magnet midplane, flare it conically at half angle of 125 mr.”.

Building from the Magnet ID and working towards the centerline:

Component	thickness	radius
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, well above the .15 m required. These dimensions may be optimistic. More thickness may be required for the MLI or for the cryostat tube that supports the magnet weight.



A bore tube heater is employed to ensure that the experimental volume is kept at room temperature.

MULTI-LAYER INSULATION (MLI) Specification from: “LHC Interaction Region Quadrupole Cryostat”, Thomas H. Nicol, Fermi National Accelerator Laboratory December 3, 1998, P.O. Box 500, Batavia, IL 60510, ref [14]:

“The stack height of each 32-layer blanket is 8.86 mm, with a mean layer density of 3.61 layers per mm. The blanket design incorporates 32 reflective layers of double-aluminized polyethylene terepthalate (PET) film. The reflective layers consist of flat polyester film aluminized on both sides to a nominal thickness not less than 350 angstroms. The spacer layers consist of randomly oriented spunbonded polyester fiber mats. The mean apparent thermal conductivity of an MLI blanket comprised of these materials has been measured to be 0.52 x10-6 W/cm-K.”

MLI insulation should be applied to the outside of the BNL Helium cryostat. 32 layers is overkill. A few (5 to 10) is sufficient. A stainless steel screen ring

15.0 Cooldown

15.1 Initial Cooldown

Magnet Quantities

	Segment 1	Segment 2	Segment 3	Total
Volume (m^3)	9.2362824e-2	.15393804	.21551326	.4618
numturn	624	624	624	
weight (kg)	748.04651	1246.7442	1745.4419	3740.232

The specific heat of copper at 100K is 2183978 Joule/m^3.

The initial cooldown to 77K requires:

(292-77)*.4618*2183978/(199000+2042*(180K-77)) -= 530 Kg of LN2 assuming an exhaust gas temperature of 180K

15.2 Cooldown Between Shots

Phased implementation of cooling systems is expected for the project. Within the coil, two cooldown methods are being investigated: an option using liquid nitrogen is discussed in section 15.3 and an option

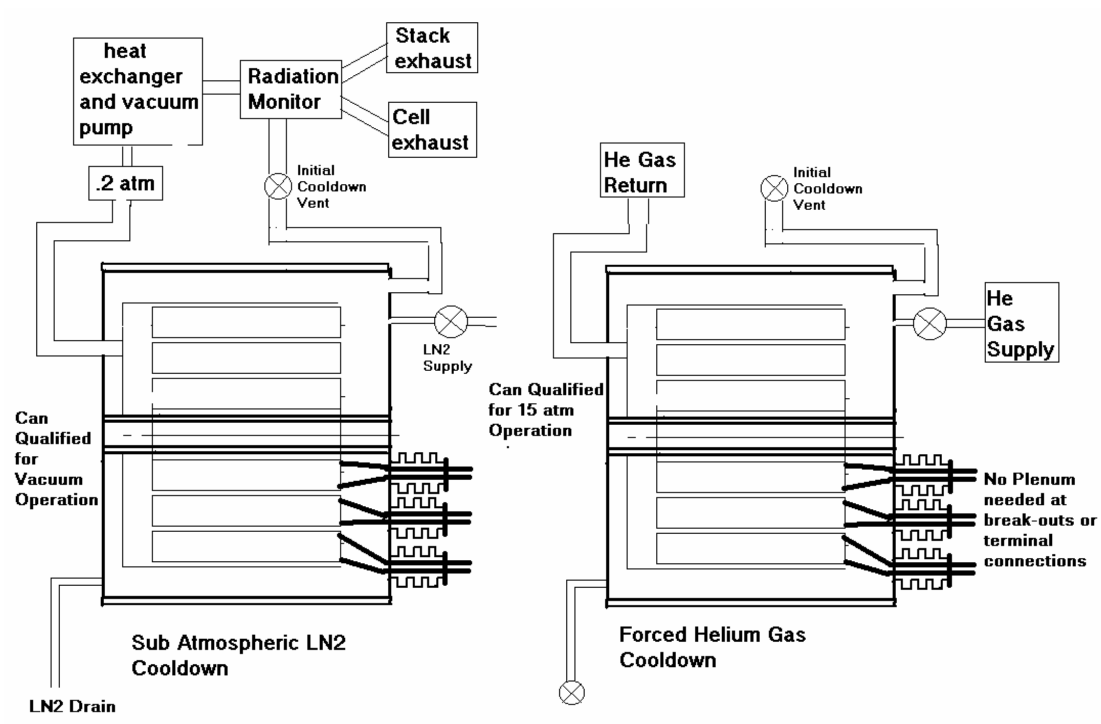
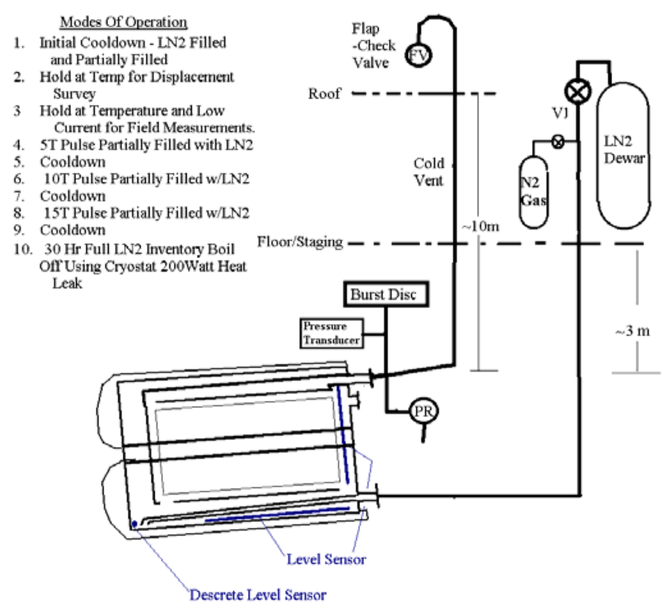
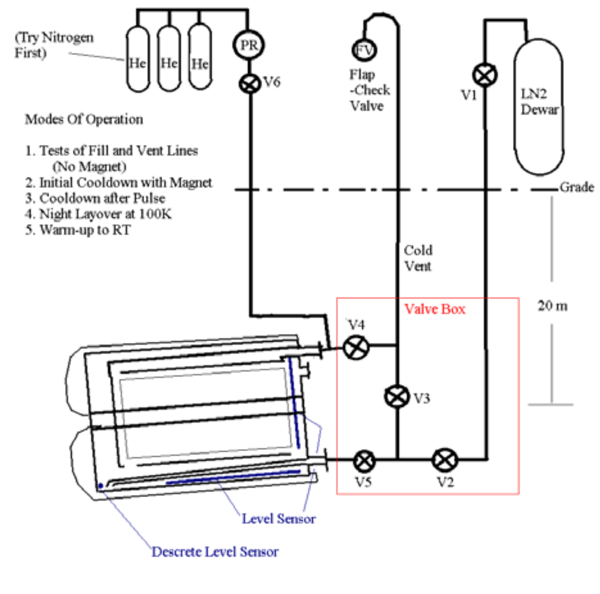


Figure 15.2-1 Early Operational Mode Concepts. The coil and can are designed for either cooling modes

which uses helium gas is discussed in section 15.2. It is expected that design of the magnet and cooling channels will allow either working fluid. Use of liquid nitrogen as the only coolant is contemplated for the initial operation of the magnet. It is possible to use the inner vessel around the magnet as a vacuum vessel, and sub-cool liquid Nitrogen to 66K. Helium gas operation uses liquid nitrogen to cool the helium gas in a heat exchanger, and later allows use of liquid hydrogen to cool the helium and obtain improved fields and/or pulse lengths. The heat transfer characteristics of liquid nitrogen operation have only been conceptualized. Heat transfer calculations using gaseous helium will be presented here.



Cryogenic System Planned for Use at MIT as of December 2004



Cryogenic System Planned for use at CERN – As of November 23, 2004

Working Fluid Properties

Fluid	Sensible Heat, Liquid Phase	Sensible heat Gaseous Phase	Heat of Vaporization
Units	Joule per Kg degK	Joule per Kg degK	Joule per Kg at 77Kat1atm
Helium	4545 at boiling pt.	5190	20280
LN2		2042	199000 (77K,1atm)
Gaseous N2		1040	

Magnet Flow Area Properties:

The coolant channel flow area is (.1+.2+.3+.4)+*2*pi*.002= .0126m^2 or about 39 square inches
The wetted perimeter of the channels is (.1+.2+.3+.4)*2*2*pi=12.6 m (ignoring the 2mm ribs)
The channel surface area is 12.6 multiplied by the one meter length of the coil or 12.6m^2
The magnet surface area is .(1+.2*2+.3*2+.4)*2*pi=9.42m^2
The Hydraulic diameter of the channels is 4*.0126/12.6=.004

15.3 Finite Difference Transient Conduction Model Used in Cooldown Calculations

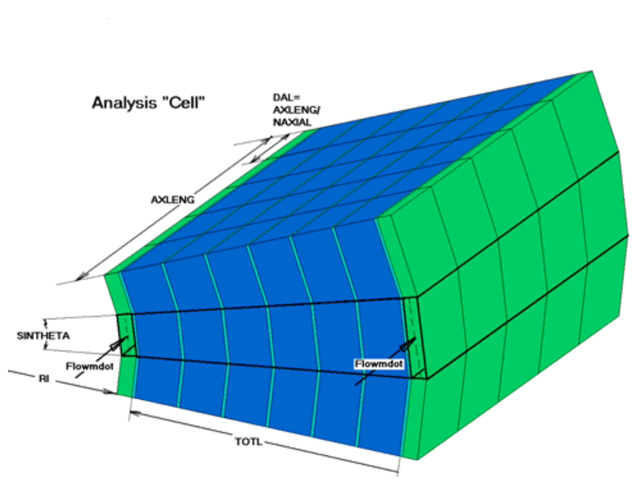
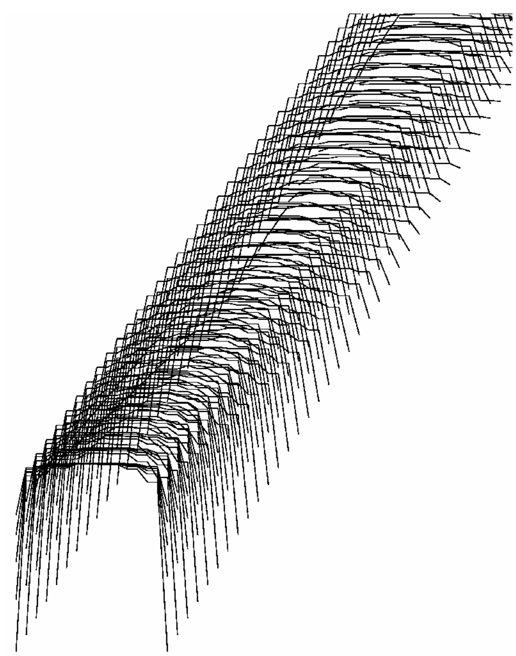


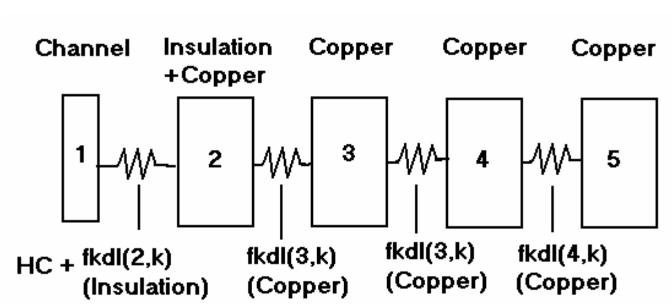
Figure 15.3-1

Initially the magnet was to be cooled via axial flow of cold Helium gas. At the end of the design process this was changed to LN2 pool cooling. The simulations available, however are for axial flow of coolant, and have been adjusted to address axial flow of LN2 and then circumferential flow of LN2 as in a pool boiling configuration.

The solenoid has three groups of 8 layers of 1/2 inch square conductors separated by set of annular cooling channels. The model employed, could model any linear stack of .5 inch square conductors cooled from the ends of the stack whether layer wound - then there would be a layer of channels every eighth layer of conductor, - or pancake wound, where there would be radial channels every sixth pancake. The solution is a simple finite difference transient analysis. Cracked conductor/Kapton tape interfaces have not been modeled. There is some effort to “encourage” cooldown crack formation that is parallel to the heat flux and delaminated insulation layers should not degrade radial conduction. This is discussed in the thermal stress section 6.0 of this report. The analysis starts with a specified mass flow which is apportioned to the 4 coolant channels based on the flow area of each channel. Coolant flow characteristics are modeled, including velocity Reynolds number, and surface heat transfer characteristics.



"Cell " Temperature profiles. Time progresses towards the upper rright. The groups of plots are temperature profiles for the five axial stations for which the temperatures are calculated.



Channel Edge Thermal Model

The insulation layer is modeled three, .001" thicknesses of Kapton tape. The thermal conductivity of the tape is about .14 W/(m-K) at 100 k and was taken from " Thermal Conductivity of Polymide Film between 4.2 and 300K With and Without Alumina Particles as Filler" Rule, Smith, and Sparks, NISTIR #3948. August 1990.

The surface heat transfer coefficient at the channels was initially taken as 170 W/m^2 for nitrogen gas at 100K flowing at 40 m/s in a channel with a 2cm hydraulic diameter. This comes from an Oak Ridge CIT report # ORNL/FEDC-85-10 Dist Category UC20 c,d October 1986. The Helium gas coefficient has been calculated from the Nusselt, Reynolds, and Prandle Numbers using the relation quoted in the Oak Ridge document, which is a more generic heat transfer coefficient correlation, and is good for ideal gasses.

2.1.3 Convective Heat Transfer

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

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

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,d October 1986

15.4 Cooling Time with Helium gas as a Working Fluid

Estimate of Cooldown time vs. deltaT for Helium Cooling Mode

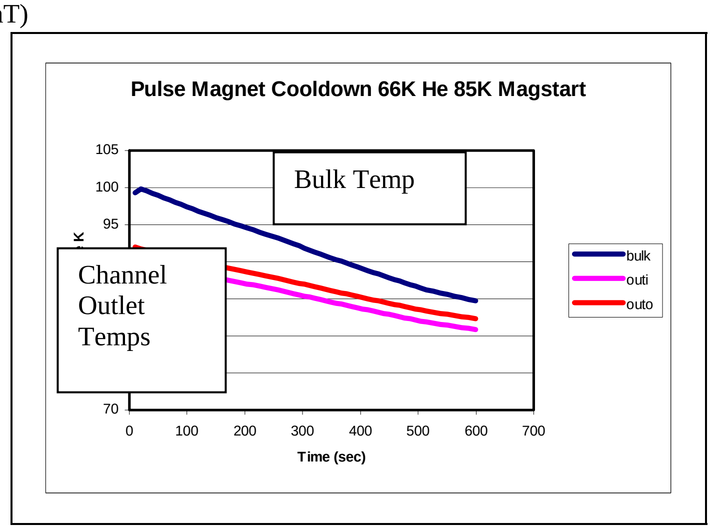
A simple check of the behavior of the magnet is available from the fluid mass flow. The power removed in a flow of fluid is Mdot*specific heat* delta T. Mdot is .1 kg per second, the specific heat of Helium gas is 5190 Joules per kg. The magnet energy change from a post pulse temperature of 78.3 to 30K is 15.2 MJ. The estimate of the energy for the 100K example is 15.2*70/48.3 or 22 MJ. The time to remove the heat from the magnet is:

Cooldown time = 22e6/(.1*5190*deltaT)

Or, the temperature change from inlet to outlet is:

DeltaT=22.05e6/(.1*5190*cooldown time)

The deltaT required for a 20 minute, 1200 sec cooldown time is 35 degrees. This is the difference between the inlet and outlet temperatures, so a 24K inlet yields a 59 degree outlet. This is for a steady state flow. To meet the 1200 seconds, much of the time the delta t must be higher than that.



Operational Scenarios:

Case #	Peak Field	T after pulse	T coolant	Start Bulk Temp for Next Shot	Guestimated Time
I	5T	90K	66K	84K	~200 sec
II	10T	96K	66K	74K	~800 sec
III	15T	78K	22K	30K	~1500 sec

Requested Simulations, Start Temperature, 100K, 100 g/sec He Gas flow rate at 20 atm.

Case #	Peak Field	T after pulse	T coolant	Start Bulk Temp for Next Shot	Cooldown Time (sec)	Initial delta T through the Magnet	Pressure drop
I	5T	90K	79K	84K			
II	10T	96K	68K	74K			
III	15T	78K	24K	30K			

Typical results for 66K He cooling, .1kg/sec, 100 K end of pulse temp. 85K target Magnet start temp. The cooldown time is 600 sec. to reach 85K bulk temp, but not thermal equilibrium.

Number of Atmospheres Operating Pressure ;10
Enter Channel Heigth in mm ;2
Rinner, radial build 0.1000000 7.6200157E-02
inner coil start temp 100.0000
outer coil start temp 100.0000
inner coil radius 0.1000000
model cell energy 1644.685J (100 to 85K bulk)
model cell volume 5.5099601E-05
volume cpp 1989954.
nlength, naxial, 120 5
Mass flow rate= 4.1666666E-05kg/sec
Volume flow rate= 5.5507730E-06
flow velocity= 2.120239
Hydraulic Diameter= 2.8944151E-03m
Velocity Head= 1.721665 Pascal
Pressure Drop= 31.46283 Pascal
Pressure Drop= 3.1041747E-04Atmospheres
Helium density= 7.506462 kg/m^3
Helium viscocity= 2.6448268E-07
Prandl #, Reynolds # 4.0756337E-02 174174.1
Heat transfer coefficient 115984. 9

From mdot*cp*deltaT for a 20 deg inlet-outlet difference the cooldown time is about 950 sec. The simulation with a finer time step (dtime=.0001 rather than .001) yields a 600 sec cooldown . The inlet outlet delta T ranges from 26K to 16K. The Energy balance or difference between the conduction heat flux and the channel heat flux. Is good at the finer time step

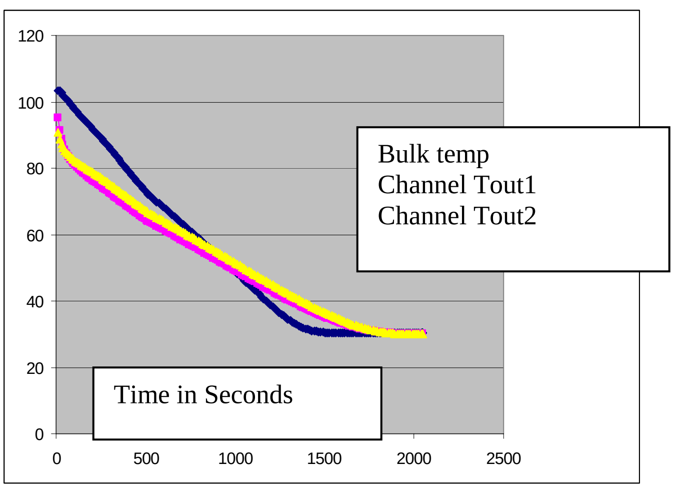
Helium Coolant, Simulation Results

Initial Analyses : Time to target bulk temp from 100K. ½ inch Copper Conductor.

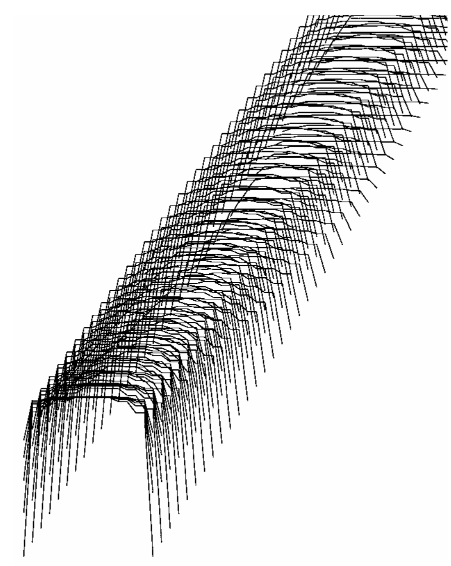
	T after pulse	T coolant	Cond Layers	Time to 85K sec	Time to 30K sec
Equiv 5 Kapton .001in wrap	100K	66K	6 layers	600	

Equiv 5 Kapton .001in wrap	100K	66K	8 layers	>850	
Equiv 3 Kapton .001in wrap	100K	66K	8 layers	450	
Equiv 5 kapton .0001in wrap	100K	30K	6 Layers		2000

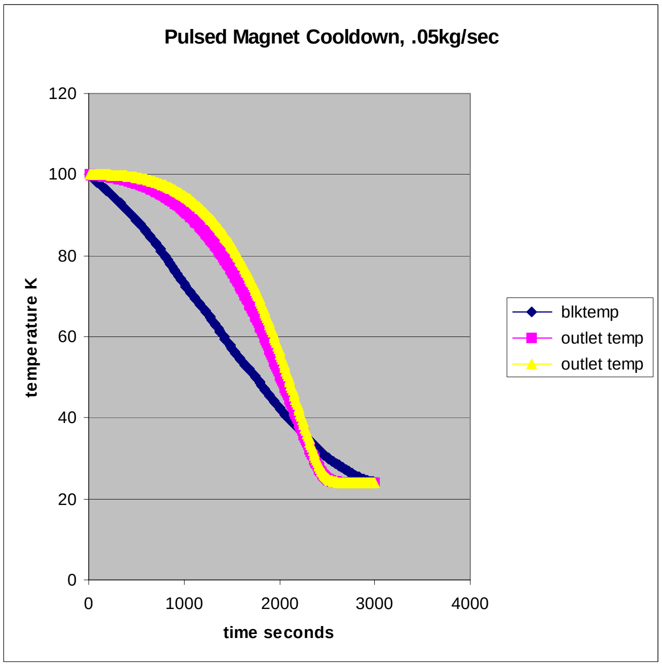
M dot	Time Step (sec)	Initial Temp	Final Temp	Tcool	Time to cool down (sec.)	Tend-Tstart	Excel File
.1		30	100	30	2000	70	(early#1)
.1	.001	74	100	67	2100	26	hegas1.xls
.1	.0001	53	78	20	570	25	Hegas7.xls
.1	.001	53	78	20	790	25	
.1	.001	84	90	77	1000	6	hegas3.xls
.1	.001	74	100	67	2100	26	hegas1.xls
.1	.0001	74	100	67	2100	26	Hegas8.xls
.1	.0001	80	100	67	1470	20	Hegas8.xls
.1	.0001	30	78	20	1100	48	Hegas7.xls
.1666	.001	84	90	77	650		Hegas9.xls
.1666	.001	74	96	70	1600		Hegas10.xls
.1666	.001	74	96	70	1670	22	hegas5.xls
.1666	.001	74	100	67	1600	26	hegas2.xls
.1666	.001	84	90	77	660	6	hegas4.xls



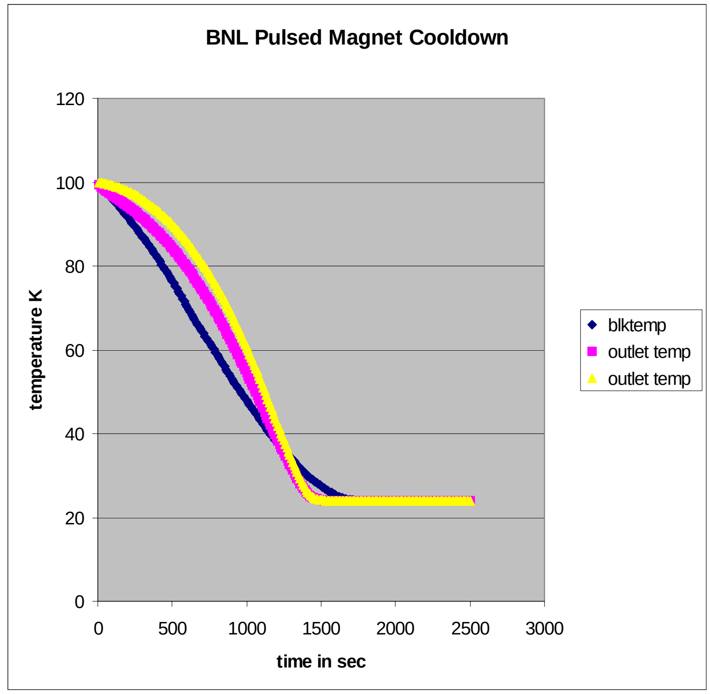
Early run, when bulk temp was approx at a slice mid axial build. In this simulation, Initial outlet temperatures start at only a fraction of a degree below the bulk temp. The magnet temperature at the outlet end is higher – near the channel outlet temps. With the bulk temp estimated mid axial build, the bulk temperature could drop below the channel outlet temp. the channel outlet temperatures are better indicators of when the magnet reaches 30K. tout 1 and tout2 are Outlet Temperatures



"Cell " Temperature profiles. Time progresses towards the upper rright. The groups of plots are temperature profiles for the five axial stations for which the temperatures are calculated.



Cooldown with half the flow.

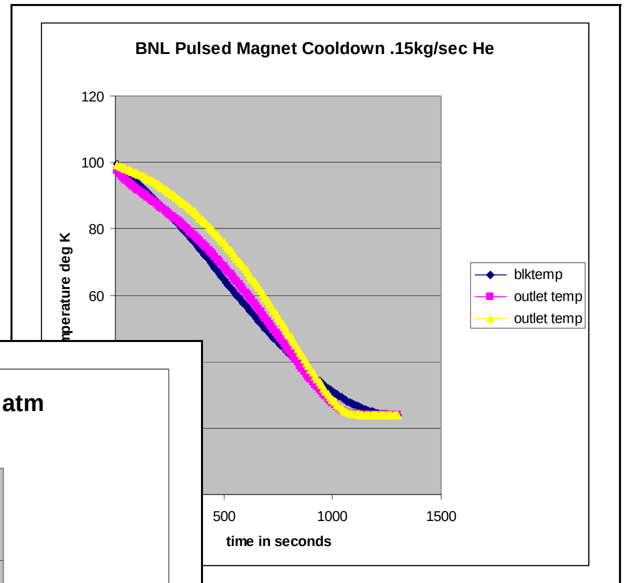


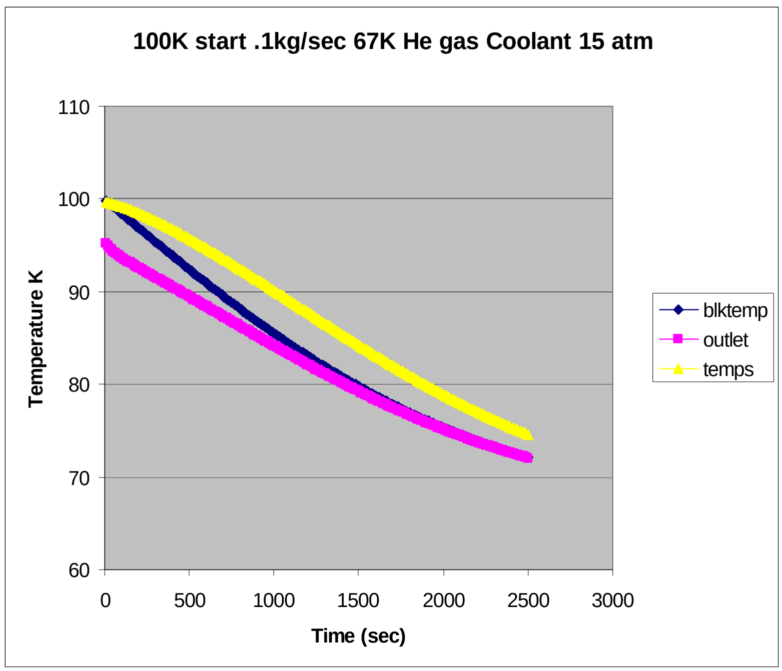
Nominal .1 kg/sec

Another Check Calculation (To Be Added Later)

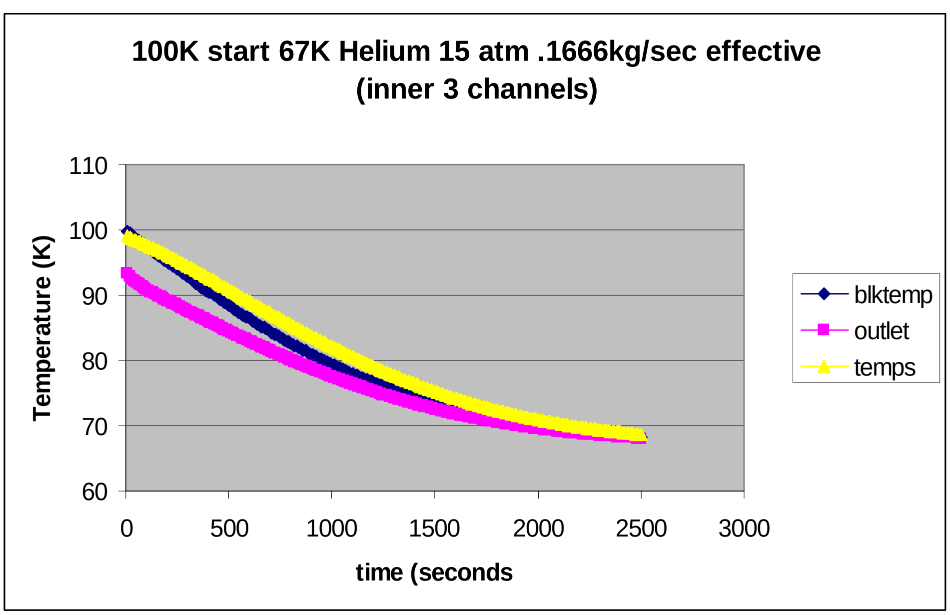
An FTM model with 1 mm elements modeling the kapton was run. 14 W/(m-K)
The effective thermal conductivity for 1mm modeling three Kapton layers is:

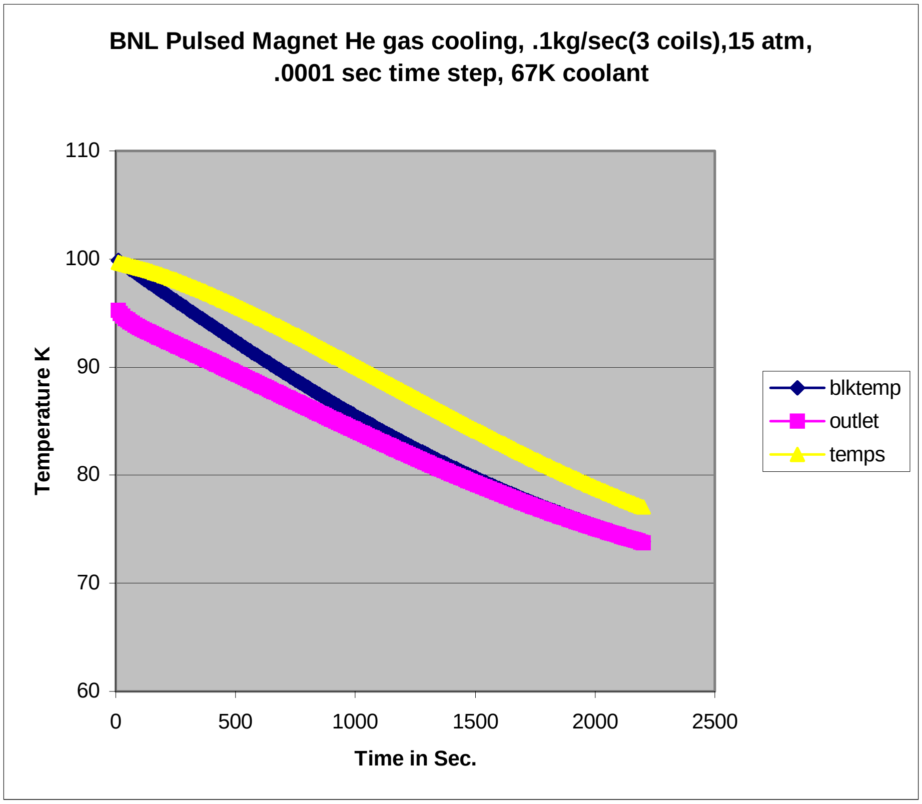
.14*AREA(I)/(numkapt*.001/39.37)*.001=1.83
7



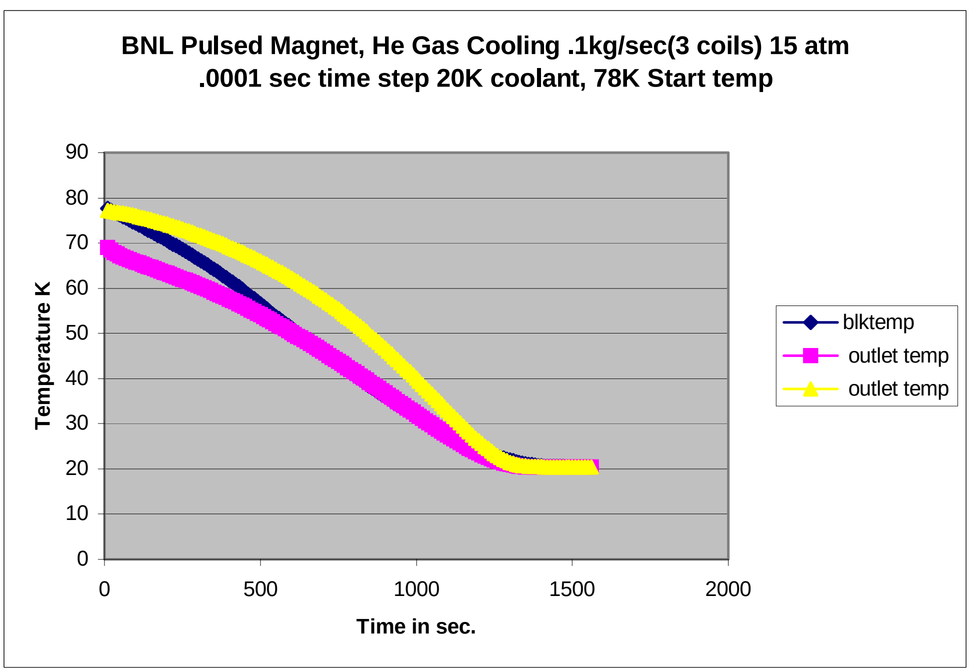


hegas1.xls

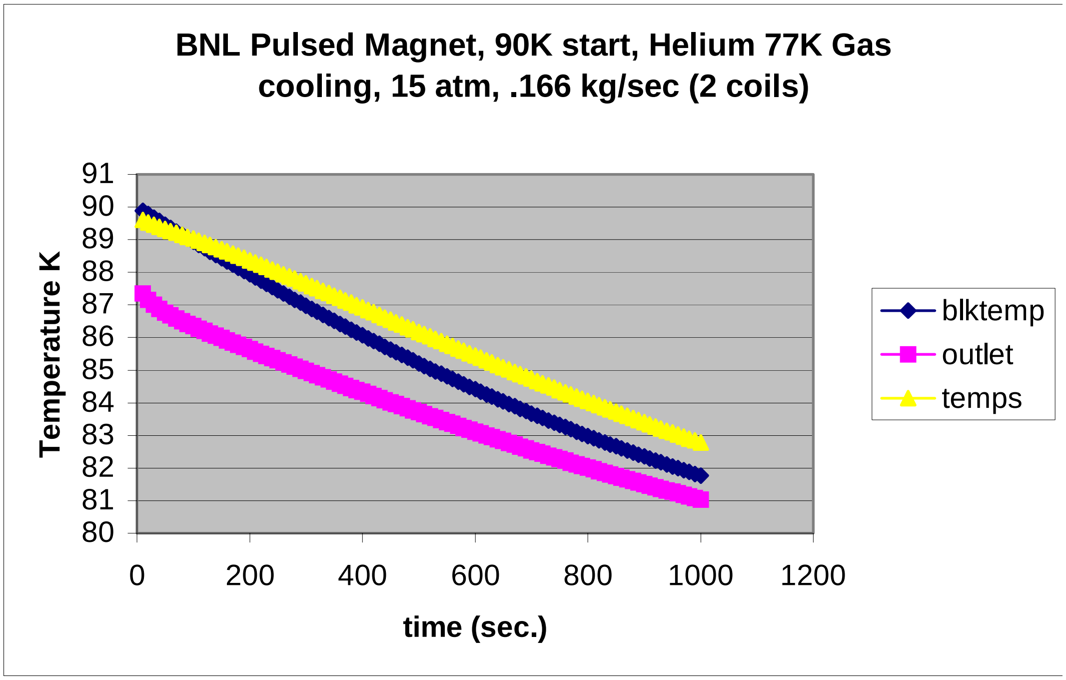




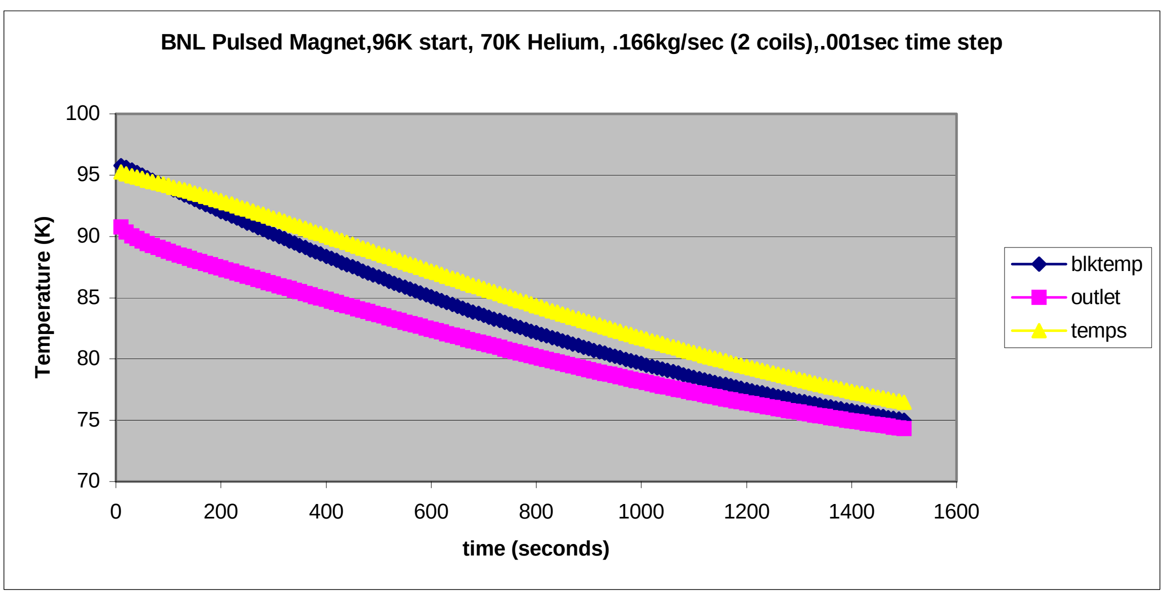
Hegas8.xls



Hegas7.xls



Hegas9.xls

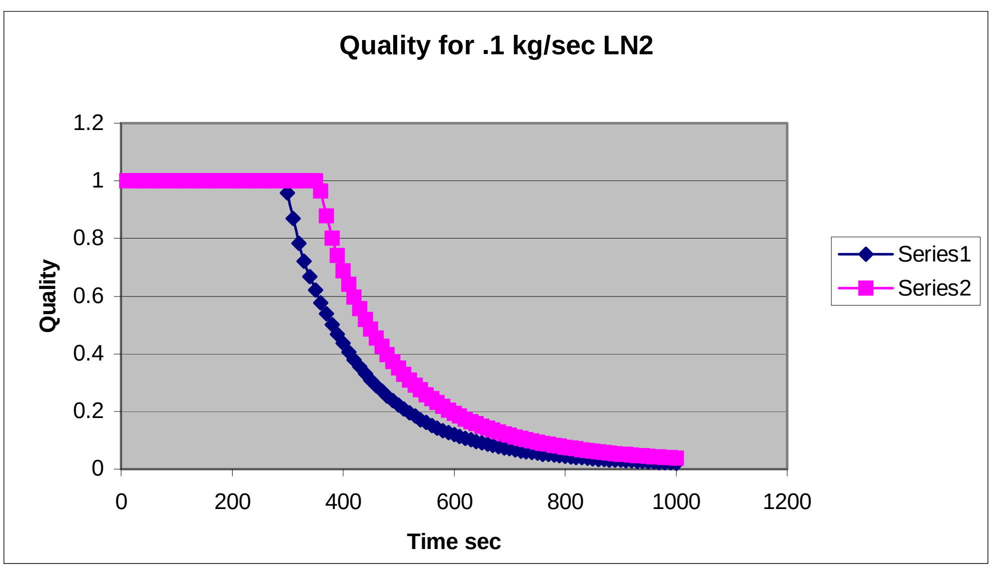


Hegas10.xls

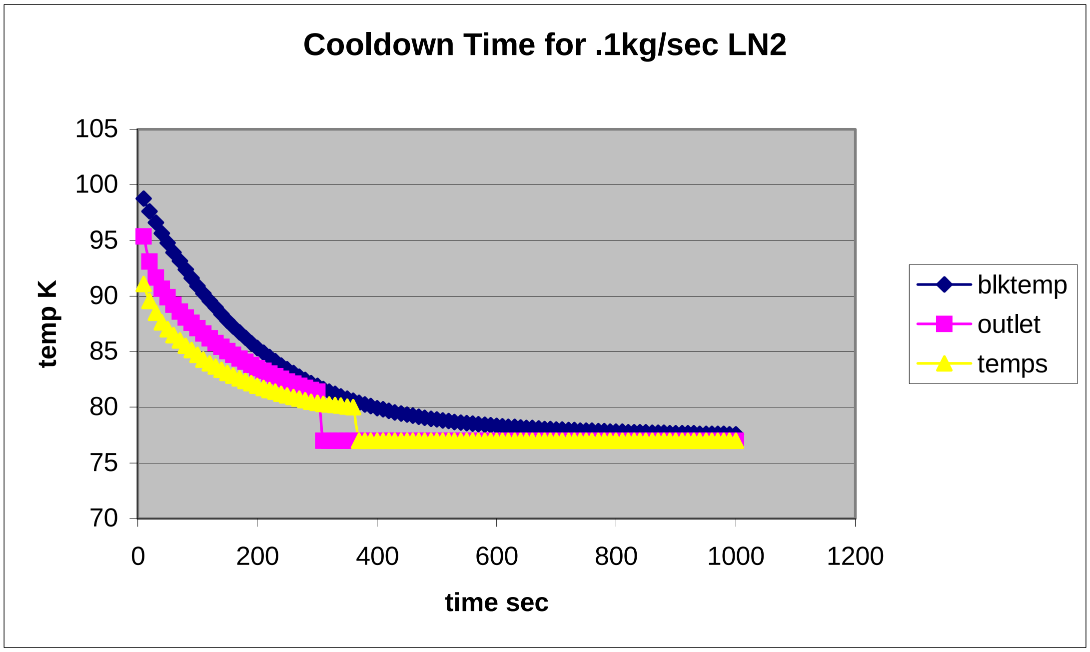
15.5 LN2 Two Phase and Metered Flow Options.

A simplified LN2 cooling system is being considered for the pre-operational tests, and This may be an operational mode as well. The system is much simplified over the Helium gas system. The heat exchanger is not required, and LN2 is cheaper and easier to handle.

npro	Project number	1.000
dtim	Intergration time step	0.001
tend	End time	1000.000
tinc	Print-Out Time increment	10.000
wflu	Coolant	3.000
comd	coolant mdot	0.100
nlen	Number of Nodes in conduction length	0.000
npll	Number of Nodes in a layer	10.000
naxi	Number of Nodes axial or channel direction	10.000
sint	Sin theta in Radians -Model slice angle	0.175
chan	channel height (halfheight in meters)	0.001
rein	reinforcement thickness (in meters)	0.000
numk	number of .001 in. Kapton wraps per layer	3.000
tini	inner channel start temp	100.000
tino	outer channel start temp	100.000
tcoo	Coolant inlet temperature	77.000
riii	inner channel radius	0.100
totl	conduction length between channels	0.098
axle	channel/coil axial length	1.000
nmat	Coil Material	1.000
numa	Operating Pressure (atmos)	1.000
curo	Current Distribution computation option	1.000
cooo	Cooling side option	2.000



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



In this simulation, gas generation ceases at around 350 seconds, and the

Pressure Drop Through the Magnet

The maximum flow is .1 kg/sec.

The density of LN2 at 73.13K is .8265 g/cm^3 = 826.5 kg/m^3 ref [16] page 283 table 9.13
The density of LN2 at 74K is 1/(1.214e-3 m^3/kg) = 823.7kg/m^3 ref [17]

The Liquid Volume flow into the magnet is (.1 kg/sec)/(825kg/m^3)=1.212e-4 m^3/sec.

The density of Nitrogen gas at 74K is 1/(317.8e-3 m^3/kg) = 3.1466 kg/m^3 (This is sub atmospheric, about .6 atmospheres)

The density of Nitrogen gas at 77K is 1/(225e-3 m^3/kg) = 4.44kg/m^3 (This is one atmosphere)[17],table 3

The density of Nitrogen gas at RT is 1.2506 kg/m^3 (This is at one atmosphere)

If fully vaporized the gas flow at the exit of the magnet is .1kg/sec * .3178m^3/kg = .03178 m^3/sec for the sub cooled condition, and .0225 m^3/sec at atmospheric, and 77K

The coolant channel flow area is (.1+.2+.3+.4)+*2*pi*.002= .0126m^2 or about 39 square inches

The flow velocity of 74K gas at the magnet exit is .03178/.0126 = 2.252 m^sec.
The flow velocity of 77K gas at the magnet exit is .0225/.0126 = 1.7857 m^sec.

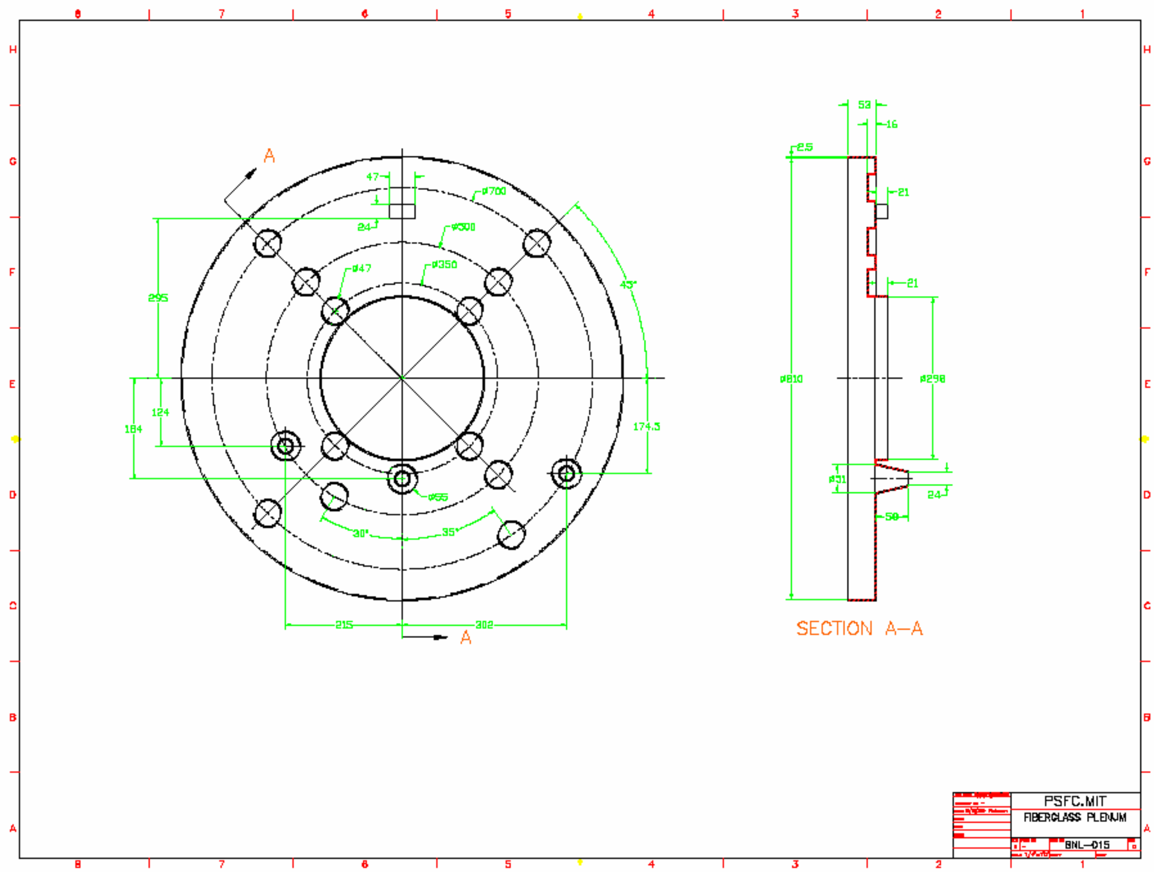
The velocity head is 3.1466 kg/m^3 *(2.252m/sec)^2/2 =7.97 N/m^2 at the subcooled temperature of 74 K ,sub atmospheric

The wetted perimeter of the channels is (.1+.2+.3+.4)*2*2*pi=12.6 m (ignoring the 2mm ribs)
The Hydraulic diameter of the channels is 4*.0126/12.6=.004 m

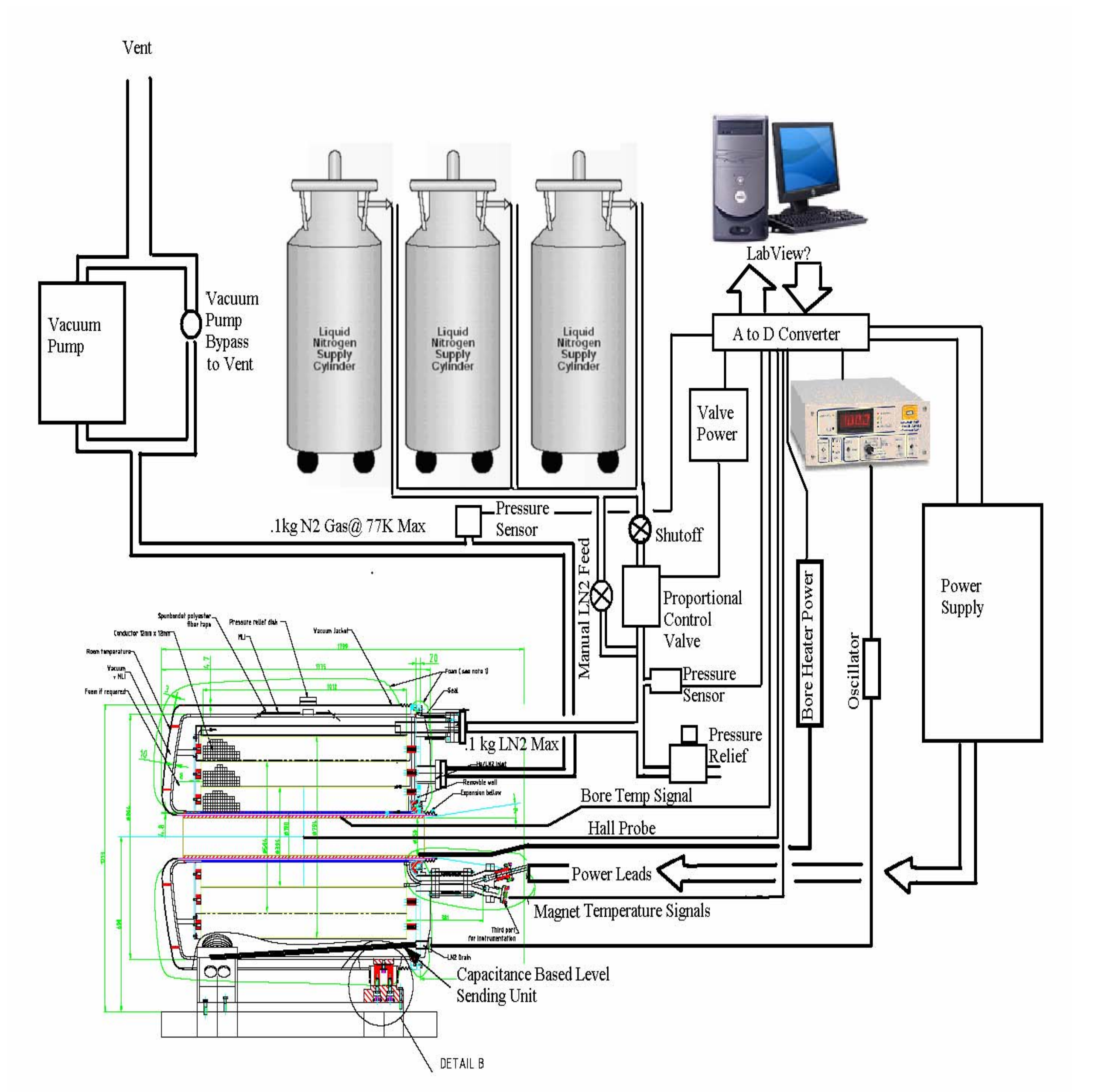
The length of the magnet is 1m

The pressure drop in the channel=7.97*1/.004*.02=39.95 Pascal

This is too low to expect uniform flow from top to bottom of the magnet. If LN2 cooling is to be employed, and it is not desired to fill the full volume of the cryostat, then a way to reduce the volume of the trapped LN2. A dam at the joint/lead end is proposed to accomplish this.

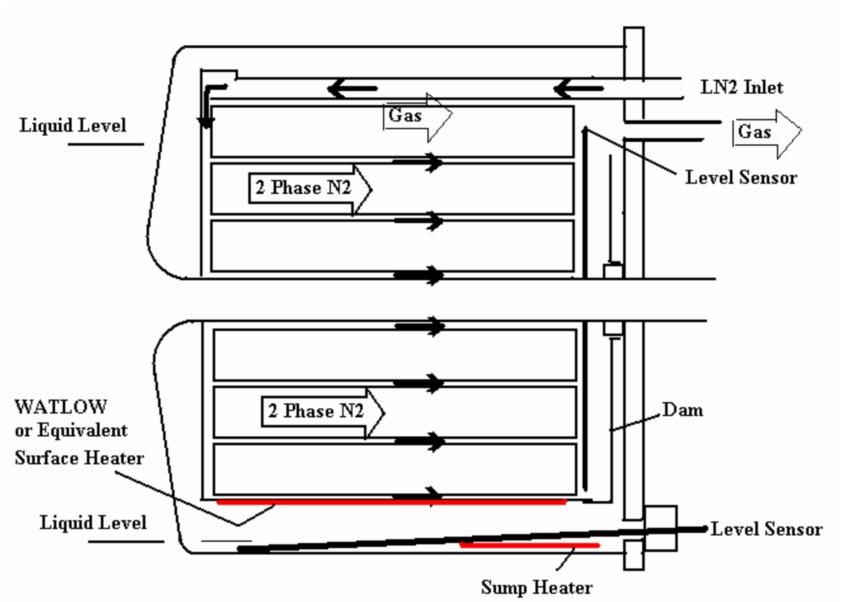


Fiberglass dam Concept – Not planned for use as of December 2004



Proposal for "complex", drainless cyyogenic system for pre-operational Tests at MIT. Tests will employ only LN2 cooling. Gravity fed flow is being considered, with a proportional control valve to meter the LN2 into the magnet at a flow which as nearly matches the amount of LN2 vaporized as possible. The cooling surface heat flux from the two phase flow simulation sets the flow needed to completely vaporize the LN2. It is assumed that quality calculated in the simulation can be used to compute the required flow.

The basic principle of operation with regard to handling excess LN2 is to use the magnet to vaporize the LN2 so that no external vaporizing is needed, The intended operation is to run through the metered cooldown with an effort to trail-off flow towards the end of cooldown, to limit the accumulation within the dammed volume and sump volume. The heaters are used to vaporize the LN2 that remains.



Internal Configuration for a “Drainless” LN2 system

The dammed volume is

The coolant channel flow area is .098*(.1+.2+.3+.4)+*2*pi*.002= .0123m^3
The left hand plenum volume is (.4^2-.1^2)*pi*.025 =.01178m^3
Assuming the plenum at the dam is comparable to the plenum at left, then the total “full” volume is .0123*2+.01178= .03647m^3. If the liquid height is set at 80%volume then the dammed volume is .03 m^3. or about 30 liters. A typical Cooldown takes only 110 –120 kg LN2

One solution is to shut-off flow at 70 kg and rely on residual energy in the coil to remove the last 20 to 30 Kg of LN2, but this would take a great deal of time to conduct all of the heat to the bottom of the plenum. A better solution is to add a heater

Flow Scenario Using Heaters:

The target time-temp profile is one in which the bulk of the twenty-sum MJ is extracted in the first 300 seconds. This leaves 4 or 5 degrees K in the magnet to be removed or 3.6MJ – and this amounts to just about the inventory of LN2 in the dammed volume (about 23 liters now with the reduction in plenum gaps).

At this point the heater can be turned on. This gives you 900 seconds to remove the trapped LN2, and the heat in the magnet. If you are only worried about removing the LN2, the size if the heater would be 4kw. – But you also have the remaining heat in the magnet, but once the dam volume is full, and you have shut off the LN2 supply, the heat transfer on the upper part of the magnet is poor. However the boiling action of the LN2 being heated by the heater can be used to drive mixed flow and cold gas to the top. To allow this, I would propose that we machine circumferential grooves in the G-10 stand-off ribs. Everson will have to machine the outer surface of these ribs anyway to fit the ID of the next segment. To uniformly heat the underside of the magnet I propose to mount the heater at the bottom of the metal shroud surface in the gap between the shroud and inner vessel wall. We use thin film heaters on C-Mod in LN2/gaseous N2 environment to heat the vessel shell to room temp. These might be a better form than the calrod type heater. Two loops on the outside of the shroud would allow the 4 m of calrod type heater if needed. The heater will produce 2 phase boiling conditions in the trapped volume of LN2. This will reduce the effective trapped volume of LN2. – At the 300 sec time point we will back off on LN2 flow, start cycling the heater, watching the level indicator (mounted in the face of the dam, and away from 2 phase conditions that might alter it’s reading). We may find that turning the heater on at the beginning of the cooldown will help the flow throughout the entire process. We will monitor the magnet temperatures. Currently, the Cernox temperature sensors are placed in the top of the magnet. I would propose shifting at least 2 to the bottom to monitor the temperature near the heater to ensure that the heater is not over-heating the shroud. Towards the tail end of the cooling cycle, while we are trying to extract the last couple of degrees from the magnet, there would be a nearly empty dammed volume. The flow a in the inner segments is going to be complex, and may not be as good as for the outer segment where LN2 flow is driven by the two phase flow. We might end up with less than ideal temperatures, by about 2 or three degrees. This might be 3 or 4 degrees at the end of a pulse. this is OK from a stress standpoint. Using sub-cooling, and higher initial flows (shortening the 300 seconds) can help.

This still requires some testing to find the best timing of flows and heating.

Flow Equalization

The simulations assume a constant pressure manifold feeding the four annular channels. Flow resistance of each channel should be comparable to produce a uniform cooldown.

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. "

Options Using a Drain, LN2 Dump Flow and Pressure Drop Calculations

There is a sheet metal plenum that surrounds the magnet for the 1, 2 or 3 segment configurations - but only on the outer segment. The down stream plenum side communicates with the vacuum pump/exhaust. After LN2 cooldown, the exhaust should be shut to minimize flow into the plenum. After the LN2 is dumped, the valve to the shuttle tank should be closed, and the exhaust/vacuum line re-opened to purge the exhaust plenum. This can be timed to provide a last bit of cooling before the next shot.

If the coils are purchased with three segments installed (assuming we can afford the three) the plenum will be installed on the outside of segment three. This means that during early operation with only two segments operating, there will be coolant flow through the third segment even though it remains cold -unless it is shipped with the outer channel plugged. In which case, the cover could be removed and the plugs removed prior to full performance operation. I think wasting one channel worth of cooling is preferable over opening the cryostat, but that can be Brookhaven's choice.

The coolant channel flow area is (.1+.2+.3+.4)+*2*pi*.002= .0126m^2 or about 39 square inches
Assuming a 1.5 inch line to the shuttle tank, the flow area is: ~.00115m^2 or 1.77 sq. in.
The wetted perimeter of the channels is (.1+.2+.3+.4)*2*2*pi=12.6 m (ignoring the 2mm ribs)
The Hydraulic diameter of the channels is 4*.0126/12.6=.004
the assumed pipe wetted perimeter is .119m, and the pipe hydraulic diameter is .0381m

The length of the magnet is 1m . assume the line to the shuttle tank is 2 m

The ratio of the pressure drop of the pipe to the channels is:
(.0126/.0015)^2*(.004/.0381)*(2/1)=25, assuming similar friction factors.

So the pressure across the plenum would be much less than the pressure differential between cryostat and shuttle tank if LN2 was allowed to flow freely out the exhaust. If the exhaust line valve is closed prior to the dump to the shuttle tank, there will be almost no flow through the channels, and no pressure drop.

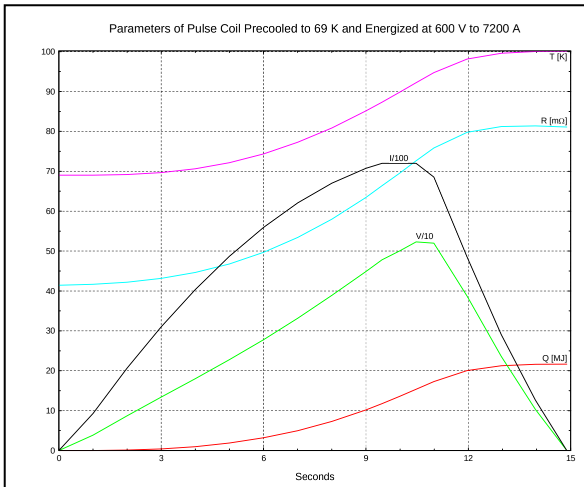
Estimating the pressure needed to vent .3m^3 in one minute, that is .005 m^3/sec. The flow velocity in the 1.5 in pipe is .005/.00115=4.35 m/sec. with a conservative friction factor of .1, the pressure drop is 857kg/m^3*4.35^2/2*.1*2/.0381=42563 Pa = 6.2 psi.

The shroud will rest on stand-offs the same as for the coil segments. I don't think we can maintain concentricity without the stand-offs. These are the strips bonded on the outside of the wound coil and machined to allow a slip fit of the shroud. We have 16 strips at the ID of segment 1, 32 between segments 1 and 2, 64 strips between segments 2 and 3 and a comparable (yet undetermined) number on the outside of segment 3. With 64 strips, the channel opening would be about 4cm wide. Assuming the shroud sheetmetal is a beam supported by the strips, and it actually sees the 2.0 atmospheres, the bending stress is w*l^2/12/(t^2/6)=14.7*2*1.5^2/12/(.0625^2/6)= 8467 psi. At LN2 temperature the yield of the 316 will be over 100 ksi. This is assuming 1/16 inch sheet stock for the shroud. I think Val specifies thicker material. The stress is lower if the shroud supportsthe pressure in hoop compression.

The external pressure on the annular flat plate that forms the plenum on the downstream side of the magnet is thick, and is supported by blocks against the coil. If the downstream plenum volume becomes pressurized with respect to the cryostat pressure, this flat plate might bend, and the magnet might slide on the cryostat bore tube, but I can't think of a circumstance where this pressure could be higher than the cryostat pressure.

The present configuration is structurally adequate to take the likely pressures that might build up during the dump to the shuttle tank. I think we will need to add some stiffeners to the plenum annular plate because it needs to support the coil load during vertical assembly. Can you update me on your estimate of the pressure to achieve the 300 l/m?.

Estimate of cooldown time for LN2 Cooling Mode

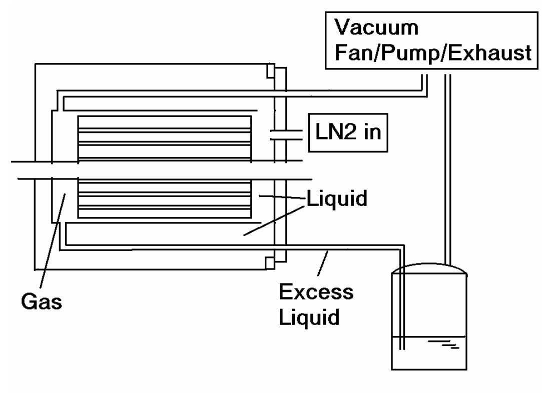


Bob Weggel's 10-14 analysis of the LN2 magnet operation

For the 100K to 69K cooling in the LN2 mode of operation, a 17 minute cooldown time between shots is possible with some forced circulation through the channels. Without circulation, the cooldown time could be longer than 40 minutes. It all depends on the behavior of the stagnant fluid/gas in the channels. Without clearing the bubbles with some forced circulation, I would envision a "blurp" mode in which a small amount of LN2 enters the channels, .flashes to gas and is expelled at the ends forcing fluid out as well. The channel geometry could be altered, but it will be difficult to obtain something like a pool boiling mode inside the channels which would require vertical free surfaces. An analysis of the coil cooldown with only conduction through the build of the coil yielded a 40 minute cooldown time, but this assumed conduction across the interior channels. If the interior channels act as thermal resistance because they are gas bound, the cooldown could be longer. Bubble clearing is an important issue in superconducting magnets. In MECO we have many flow channels cut into the mandrels in the production solenoid. These are vertically oriented. Channels in the BNL magnet are presently horizontal. In LN2 cooled Tokamaks, cooling is gravity fed with vertical channels or they have forced flow.

One option to get some flow is to pump gas on the exhaust side and cool with a mode where LN2 at the lower part of the magnet boils, and the upper part of the magnet is cooled by gas flow. An analysis of the Nitrogen gas forced flow yielded very long cooldown times. The analysis was similar to the helium cooling analysis with .1kg/sec coolant flow, but the specific heat of N2 gas is a fifth that of Helium gas. This approach doesn't look viable. The possible "fixes" are:

- Spiral channel ribs might offer some (difficult to quantify) bubble clearing behavior. This produces a bit of a complication in maintaining coil torsional registration – but may be the simplest approach. With this approach the plenum and shroud details could be removed.
- Forced flow with a circulator. The existing Helium pump could be used for this? This would potentially yield lower cooldown times than the 17 min quoted above, because true liquid forced flow would be substituted for natural convection.
- Forced flow via pressure differentials is also a possibility. A forced flow concept is presented here The existing drain line would be connected to the downstream side of the plenum to be used to drain LN2 that hasn't been vaporized in the magnet.



Forced flow Concept

Liquid fills the inlet plenum and passes through the channels forced by a pressure differential between the inlet and outlet sides of the magnet. The pressure differential is maintained by exhaust fans or vacuum pumps. The flow through the channels is needed to clear bubbles. Some LN2 is not converted to gas, and collects on the downstream side of the magnet. This is drained to the dump tank which is used as a phase separator. Ultimately a .2atm pressure is maintained by the vacuum pumps to reach the subcooled temperature of the LN2. Channel flow exiting to the outlet plenum enters as two phase flow. If the dump tank gets filled, the cooling process would be stopped, and the fluid in the dump tank would transferred to the LN2 supply tank by closing valves and pressurizing the dump tank. This process would not carry much more time penalty than the "flush" of Nitrogen that is currently planned. The inventory of LN2 below the drain in the cryostat could be minimized with fillers. A simulation has been done with the transient conduction code previously used for the Helium gas cooling mode. The code was modified to include forced N2 gas cooling, and pool boiling heat transfer coefficients.

Magnet Flow Area Characteristics:

The coolant channel flow area is (.1+.2+.3+.4)+*2*pi*.002= .0126m^2 or about 39 square inches
The wetted perimeter of the channels is (.1+.2+.3+.4)*2*2*pi=12.6 m (ignoring the 2mm ribs)
The channel surface area is 12.6 multiplied by the one meter length of the coil or 12.6m^2
The magnet surface area is .(1+.2*2+.3*2+.4)*2*pi=9.42m^2
The Hydraulic diameter of the channels is 4*.0126/12.6=.004

To cool the magnet down from 100 to 69 K, 22 MJ is required. This will be done using 66K subcooled LN2. Approximately, this will vaporize 22e6/199000 = 110 kg of liquid. At 66K, and 1 atm, the specific volume of the gas is .937 M^3/kg. 103.6 m^3 of 66K gas would be produced. If we want to cool down in roughly 20 min, then the flow velocity at the exit of the magnet would be: 103/.0126/(20*60) =6.85 m/sec with a mass flow of 110/(20*60) = .0916 kg/sec. The volume exiting the exhaust is 103/(20*60)=.086 m^3/sec at 66K, and .086*292/66=.38m^3/sec. after heating to room temperature.

The magnet surface area, exclusive of the ends, is 9.42 m^2. The ends are excluded because they will be thermally insulated with the transition filler pieces.

For a 20 minute cooldown, the heat flux will have to be:
22e6/9.42 m^2/1e4/1200=.194 W/cm^2

Using the pool boiling correlations for Nitrogen (the same as G. Mulhulland.) As George points out, The delta Temperature needed to obtain the required heat flux is quite small. Thermal conduction through the winding and insulation needs to be simulated. With LN2 wetting the surface of the channel, the channel wall may be at the LN2 temperature, making even the small deltaT needed for heat removal unachievable. The conduction/gas flow simulation was modified to incorporate the pool boiling correlations. This is only an approximation inside the channels. Some form of fluid motion will be required to match the convective heat transfer behavior.

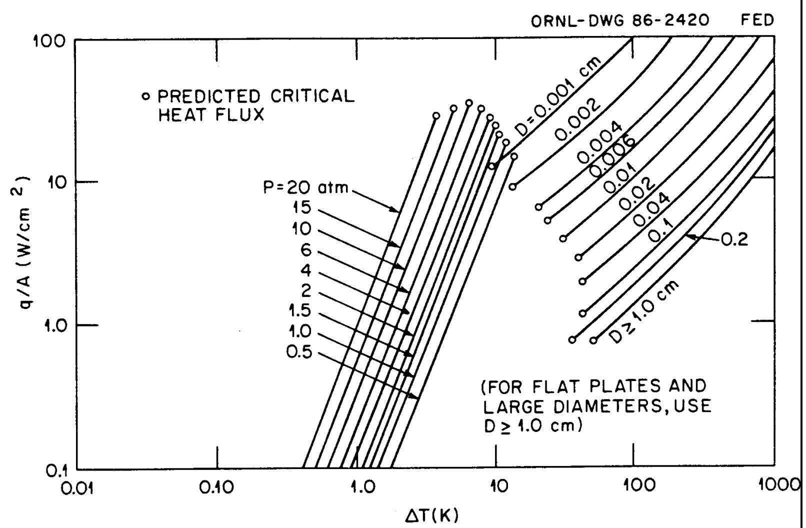


Fig. 4. Nucleate and film pool boiling correlations for nitrogen.

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

2.1.1 Pool Boiling Correlations

The following equations were obtained as a best fit for the correlation shown in Fig. 4, for the conditions of interest (coolant pressure = 1 atm, tube diameter > 0.2 cm). For the nucleate boiling regime,

$$\frac{q}{A} = 0.034\ \Delta T^{2.58} \quad (W/cm^2) \qquad 1 < \Delta T < 13\ K\ , \qquad (1)$$

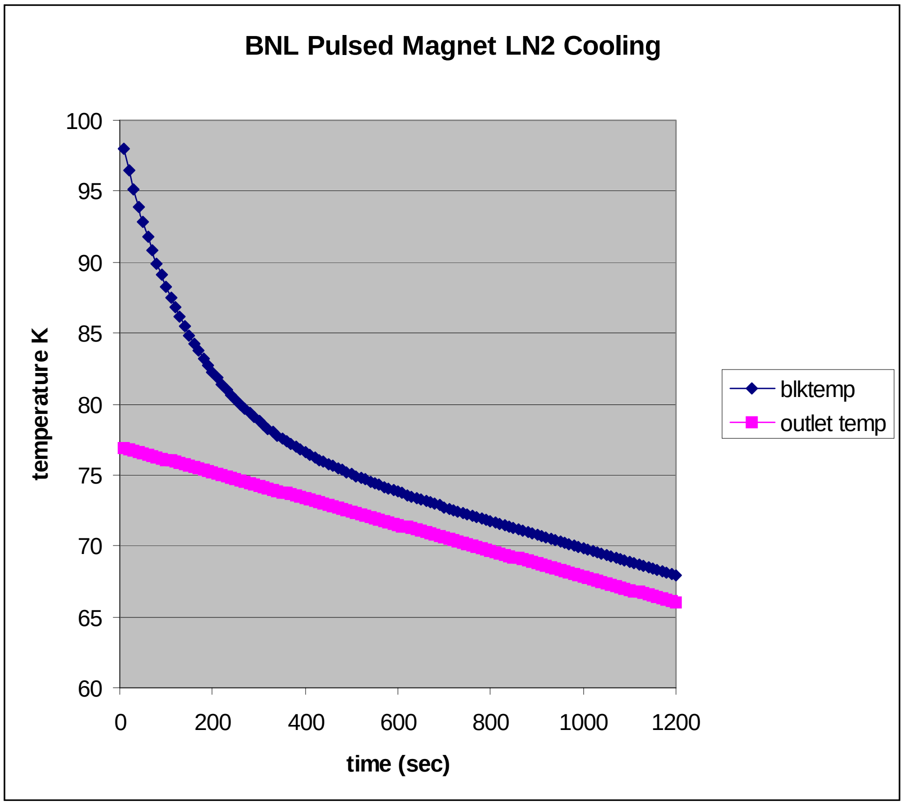
and for the film boiling regime,

$$\frac{q}{A} = 0.0143\ \Delta T \quad (W/cm^2) \qquad \Delta T > 53\ K\ . \qquad (2)$$

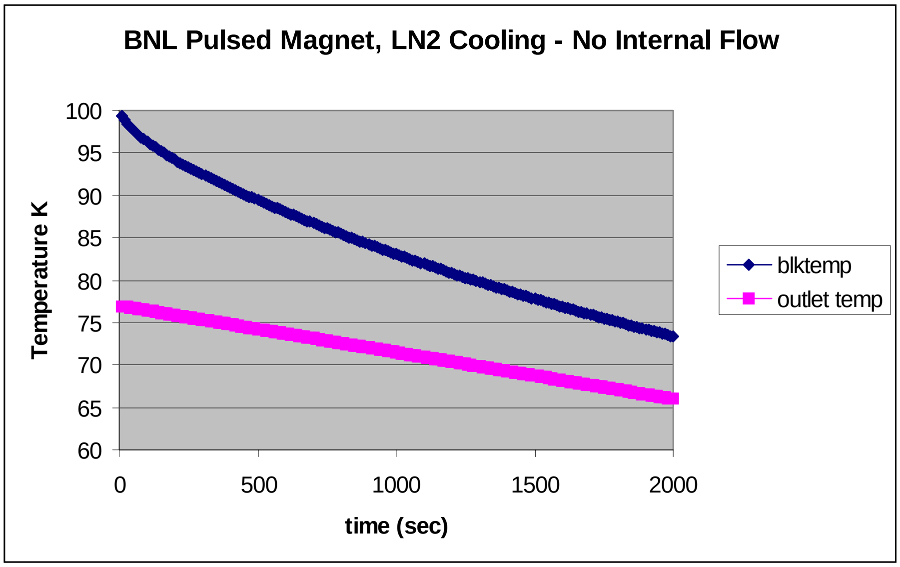
from: ORNL/FEDC-85-10 Dist Category UC20 c,d October 1986. Note that the correlations are not a function of the diameter in the nucleate boiling regime. Equation (1) above is used in the computer simulation. Channel hydraulic diameter was used to estimate the heattransfer coefficient in the film boiling regime.

Code Modification for Coolant Temperature Gradual Reduction:

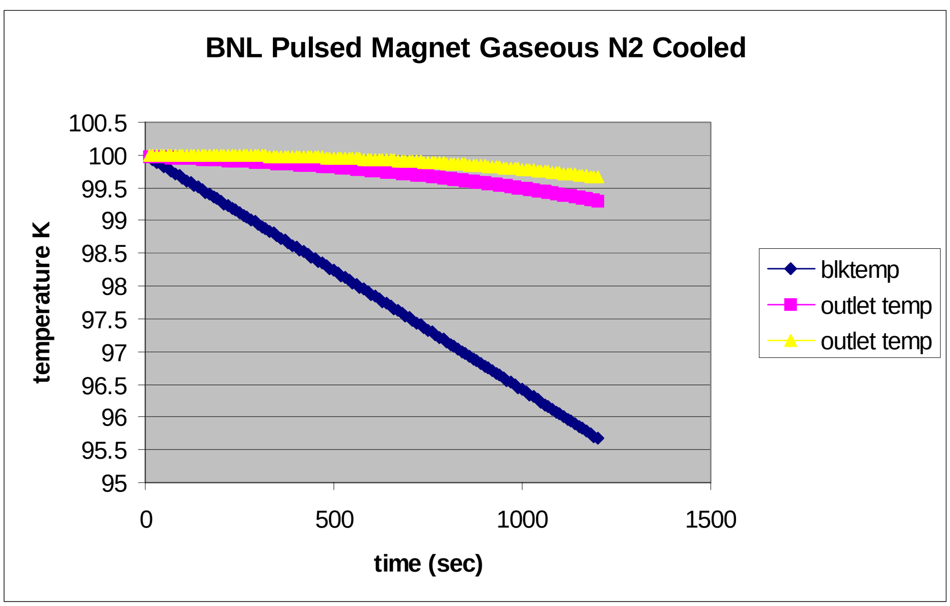
```
if (iwflu.eq.3) then
t(1,k)=77-11.0*etime/tend
t(nleng+2,k)=77-11.0*etime/tend
```



Cool down behavior, Fully immersed, but circulating LN2. LN2 pressure gradually reduced from 1atm to .2 atm. Time to 69 degree K bulk temp is about 1000 sec.



LN2 Pool Boiling Cooldown behavior Conduction through the full coil build – Interior channels are ignored. LN2 pressure gradually is reduced from 1atm to .2 atm. If after 2000 sec the LN2 temperature can be maintained at 66K a guestimate for the final coil cooldown to 69K would be about 2500 sec or 42 minutes. – But this assumes conduction across the interior channels



Excessive cooldown times would result with gaseous N2 flow.

15.6 Cryogenic System Peripherals – Vacuum Pump, Heater, Proportional Control Valve

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

Thermacast Heater

Vacuum Pump, and Inlet Heater

```
  !   **  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
```

.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
```

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

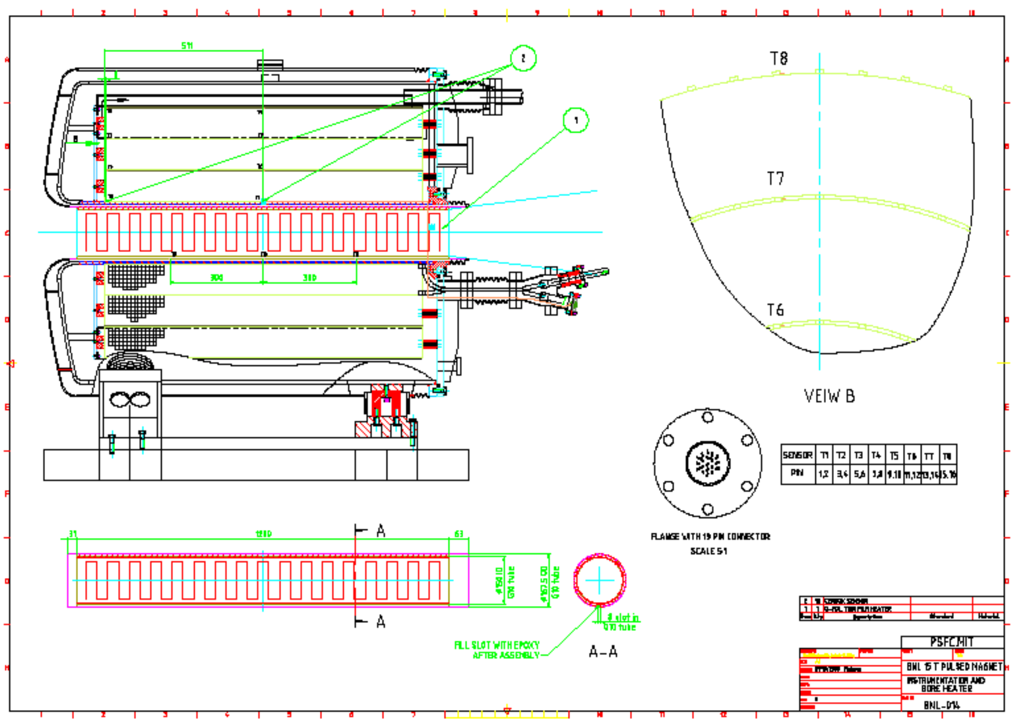
Thermacast™ Electric Vaporizers and Trim Heaters

16.0 Instrumentation

http://www.lakeshore.com/temp/sen/crtd.html

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. Instrumentation to read temperatures from these sensors may be found on the LakeShore site, above.

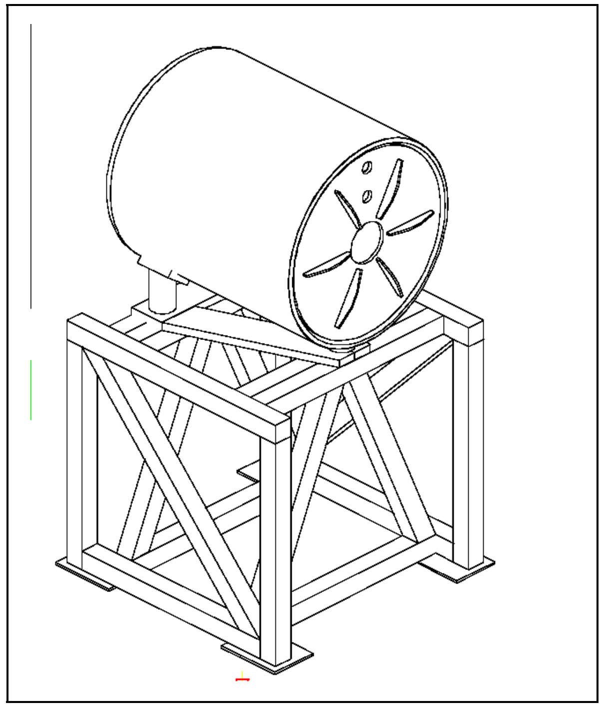
- Low magnetic field-induced errors
- High sensitivity at low temperatures and good sensitivity over a broad range
- Excellent resistance to ionizing radiation
- Fast characteristic thermal response times:
  1.5 ms at 4.2 K; 50 ms at 77K (in bare chip form in liquid)
- High Temperature Cernox offers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



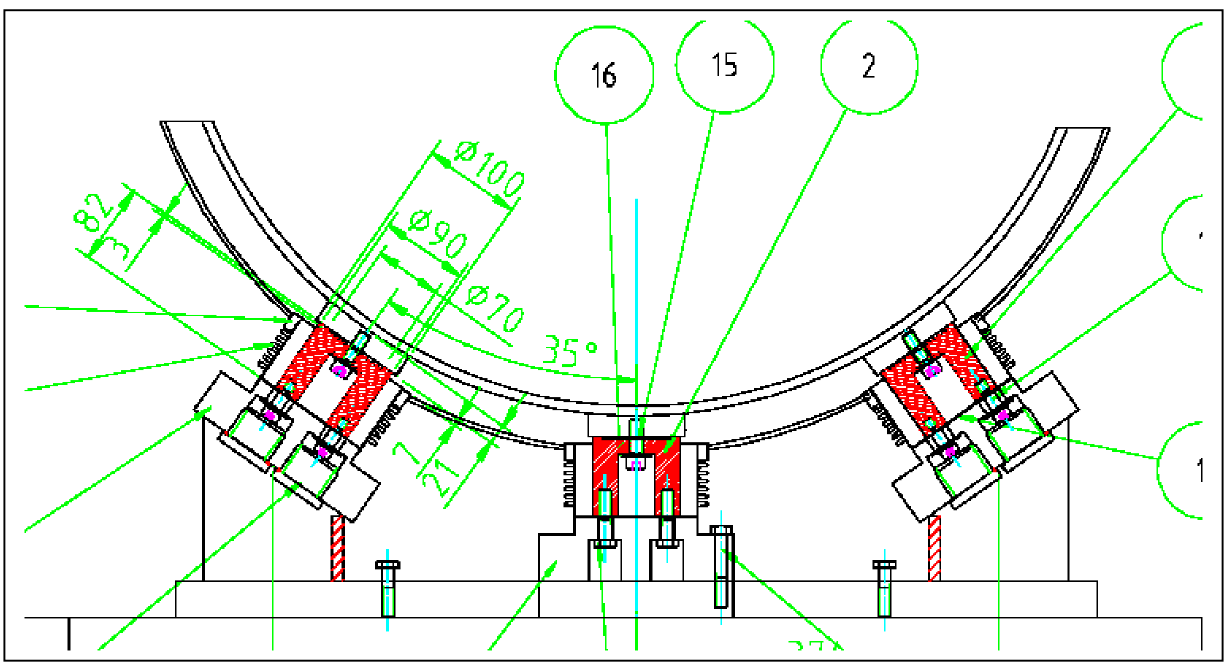
There are 8 Cernox temperature sensors inside the cryostat, requiring 16 pins of a 19 pin penetration. Three are "spares" T9 through T11 instrument the bore liner to allow control of the thin film bore heater. The bore is to be maintained at room temperature. These do not have electrrical connections that pass through the pressure boundary. BNL-002 shows two of Item #35, the instrumentation penetration. The second pin/instrumentation flange is a spare, and is intended to accommodate other possible instrumentation BNL may want to add at a later date. The pdf of the instrumentation flange layout in BNL-014, shows 19 labeled pins matching the pin-out specs in the table.

17.0 Support Frame and Gravity Supports

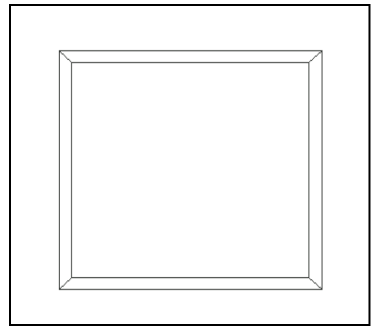
	Volume	Mass
Magnet Segment 1		748.04651
Magnet Segment 2		1246.7442
Magnet Segment 3		1745.4419
He Cryostat	.08727m^3	759kg
Vacuum Jacket	.01748m^3	152kg
Total	.	4651kg
		10253.6 lbs



The frame is made up of 4" square aluminum tubing. 4 verticals of 1.241m length, 2 diagonals of about 1.5m length, 4 longitudinal horizontal members of 1.168m length and 4 triangular legs supporting the center of about 1.0meter length, 6 horizontal transverse members of 1.168m length for about 24m of total length.



Element Group for which Section Properties are to be Calculated



Section Properties for Group Number: 0

AREA= 2.859375 IXX = 6.943665 IYY = 6.943665

MAX DISTANCE TO EXTREME FIBER, CX= 2.000000 CY= 2.000000

RINX= 6.943665 SNX= 3.471833 RAD OF GYR= 1.558328

RINY = 6.943665 SNY= 3.471832 RAD OF GYR= 1.558328

PRODUCT OF INERTIA ABOUT ORIGEN=RIXYT = -1.2011635E-07

PRODUCT OF INERTIA ABOUT NEUTRAL AXIS=IXYN = -1.2011635E-07

ROTATION ANGLE TO PRINCIPAL MOMENTS OF INERTIA = -13.36959

If only the four corner vertical posts supported the weight, the P/A Column Stress in the frame=10253.6 lbs/(4*2.859)=896 psi. Most of the vertical load however, will be carried by the inverted “V”’s . The frame is over built, but there may be unidentified side loads, for example attraction to iron nuclear shields, and there the frame can be used to mount fluid and electrical connections.

17.0 Manufacture and Assembly Approaches

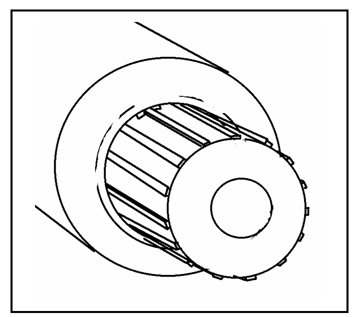
Winding Procedure Specification Content:

The seller is responsible for selecting the winding process that will best achieve the required coil geometry, insulation configuration, and impregnation quality. A possible winding method is described here. The bidder shall describe his proposed winding procedure, and any change to the purchaser's suggested procedure as a part of bid proposal. The Seller's winding procedure shall be submitted to the purchaser for review and approval. 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.

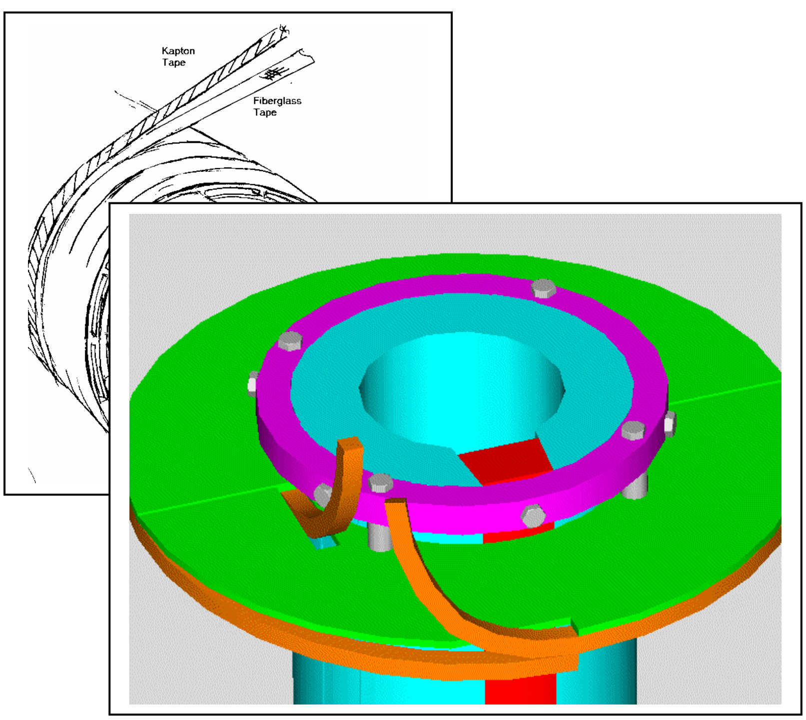
Options for "Resolution" :

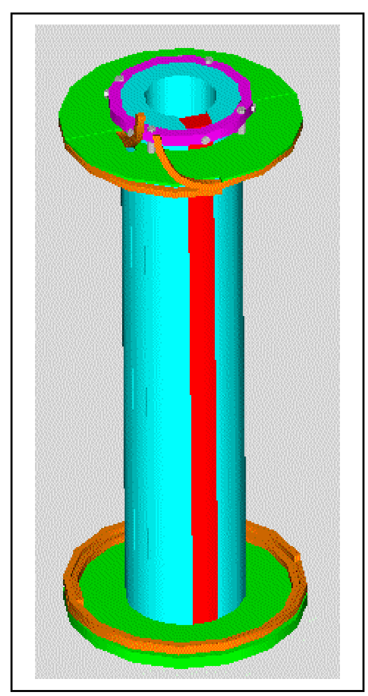
- Relax cold work
- Increase corner radius
- Pre bend over shaping rollers

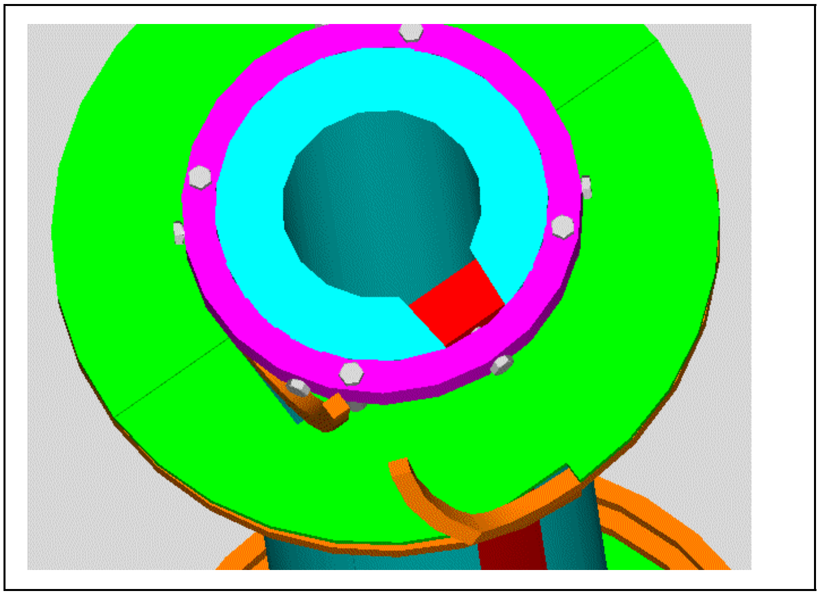
Assembly and Manufacture



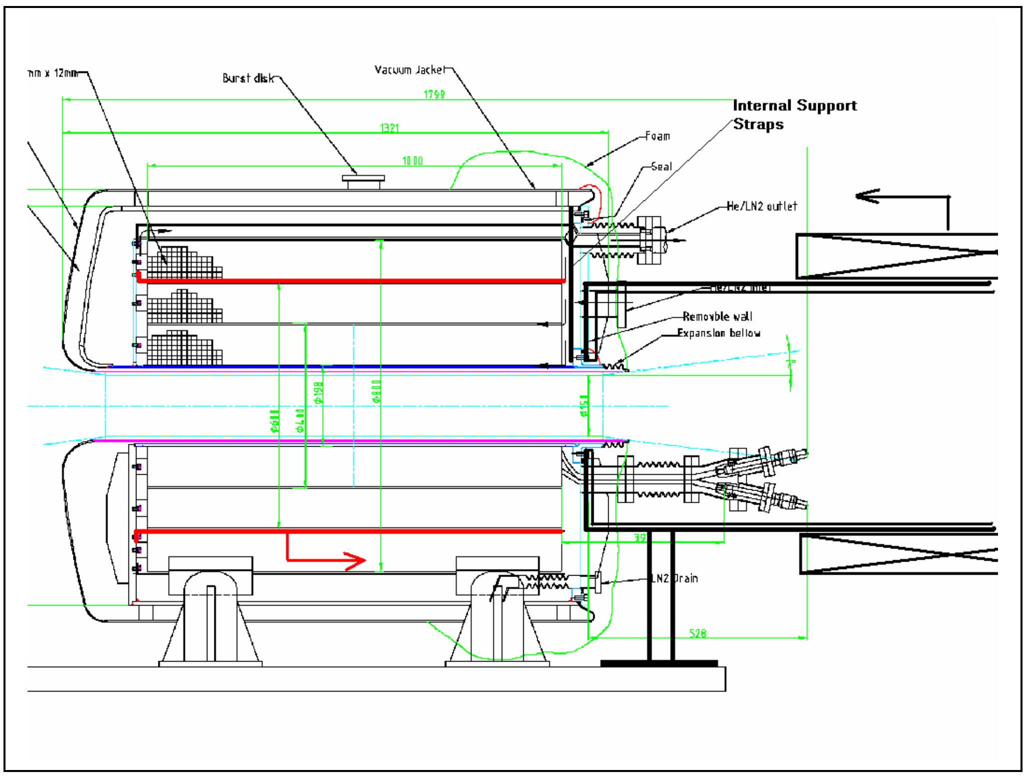
The Coil is layer wound
The Coil is made in three segments. Phased manufacture is allowed
Three separate mandrels are planned.
Mandrels maintain a precise bore geometry
Ribs are applied to outer surface of the wound and impregnated coil
Ribs are machined to match the ID of the next coil segment
Coils are slipped on to one another. – with a temperature difference if needed







Phased fabrication of the coil segments is the motivation for the mechanical head closure.



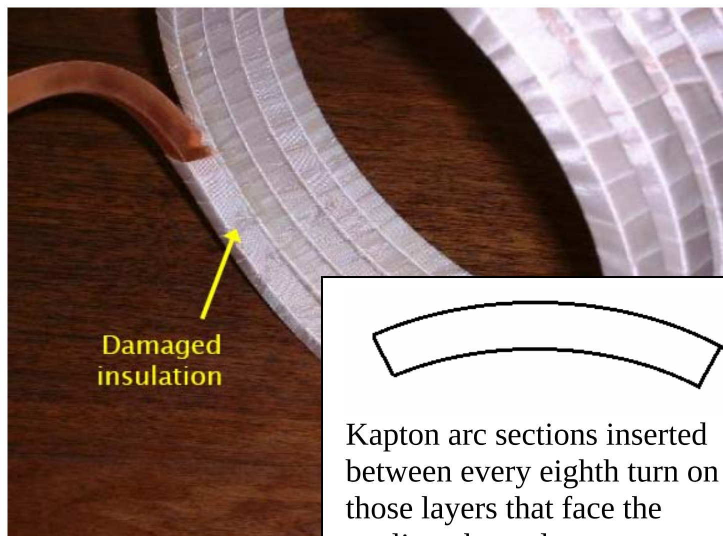
The joint flanges are loosened, bellows compressed, and ceramaseal penetration set screws are loosened.
The insulating penetration connections are removed
Head lip seal welds (if used) are cut.
The closure head is removed. Internal support straps hold the coil weight.
The assembly shell is installed, bolted to the inner head bolt circle, Temporary supports/cribbing support the shell and coil weight. The internal support straps are removed.
The coolant shroud (red) is removed swapping inner and outer temporary supports.
The third coil segment is then slipped into place.
The internal support straps are replaced. The assembly shell is removed.
The head is replaced, and bolts torqued. The lip seal welds (if used) are made. The ceramaseal connections are re-made.

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.



Kapton arc sections inserted between every eighth turn on those layers that face the cooling channels

Results of the test bend. … avoid fiberglass tape cuts.

BNL Pulsed Magnet Manufacturing Status Sept 8 2004

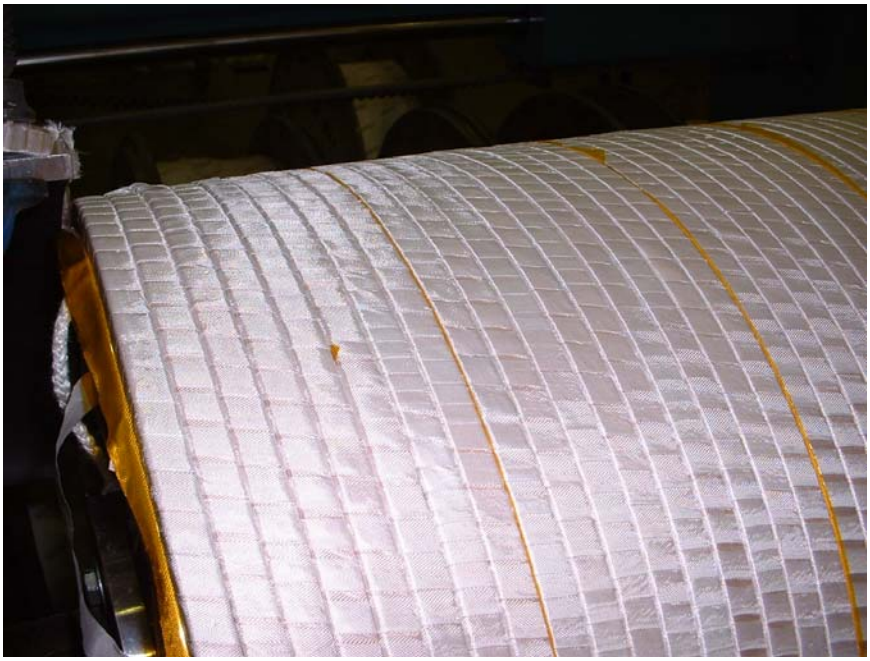
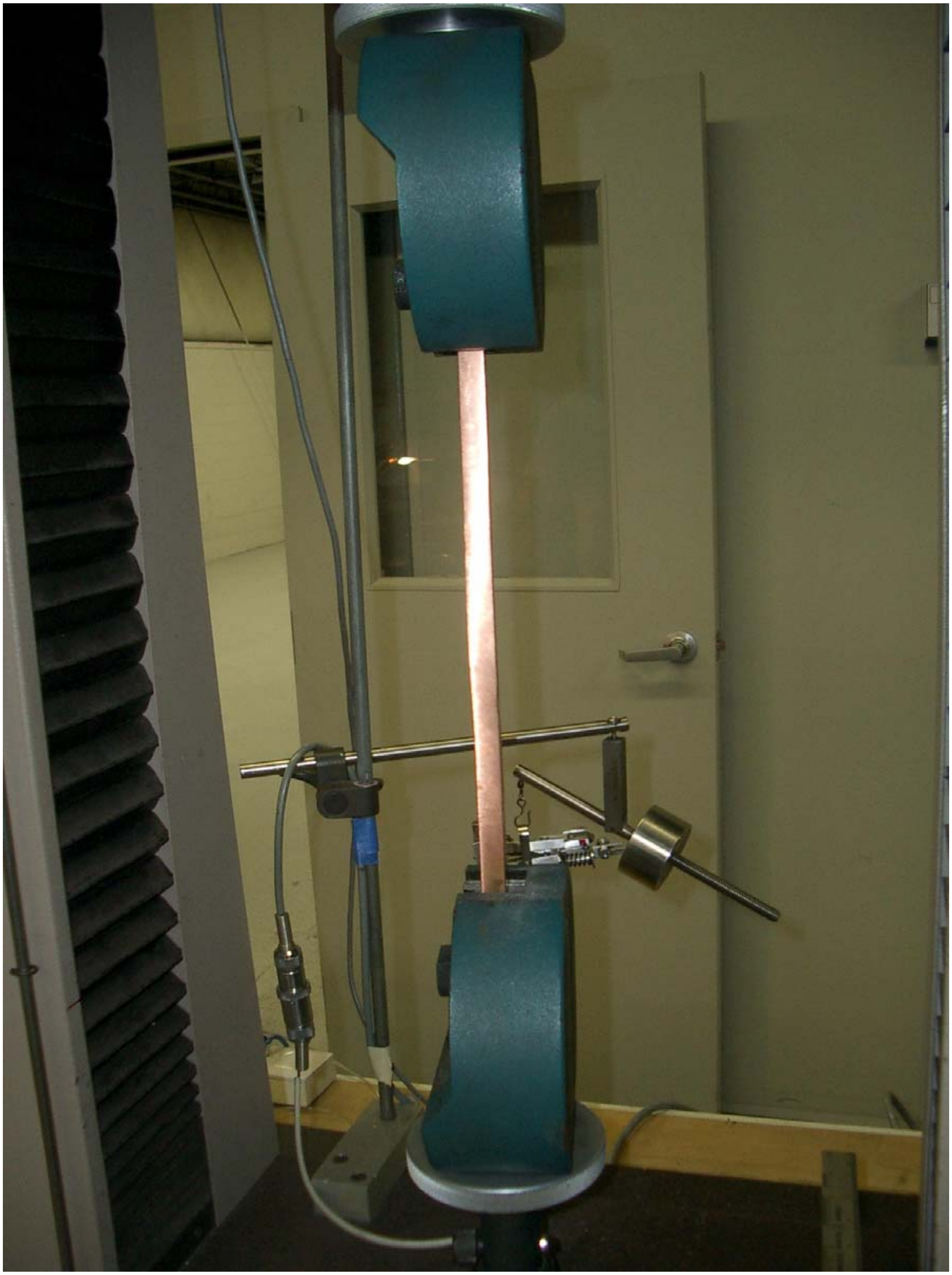
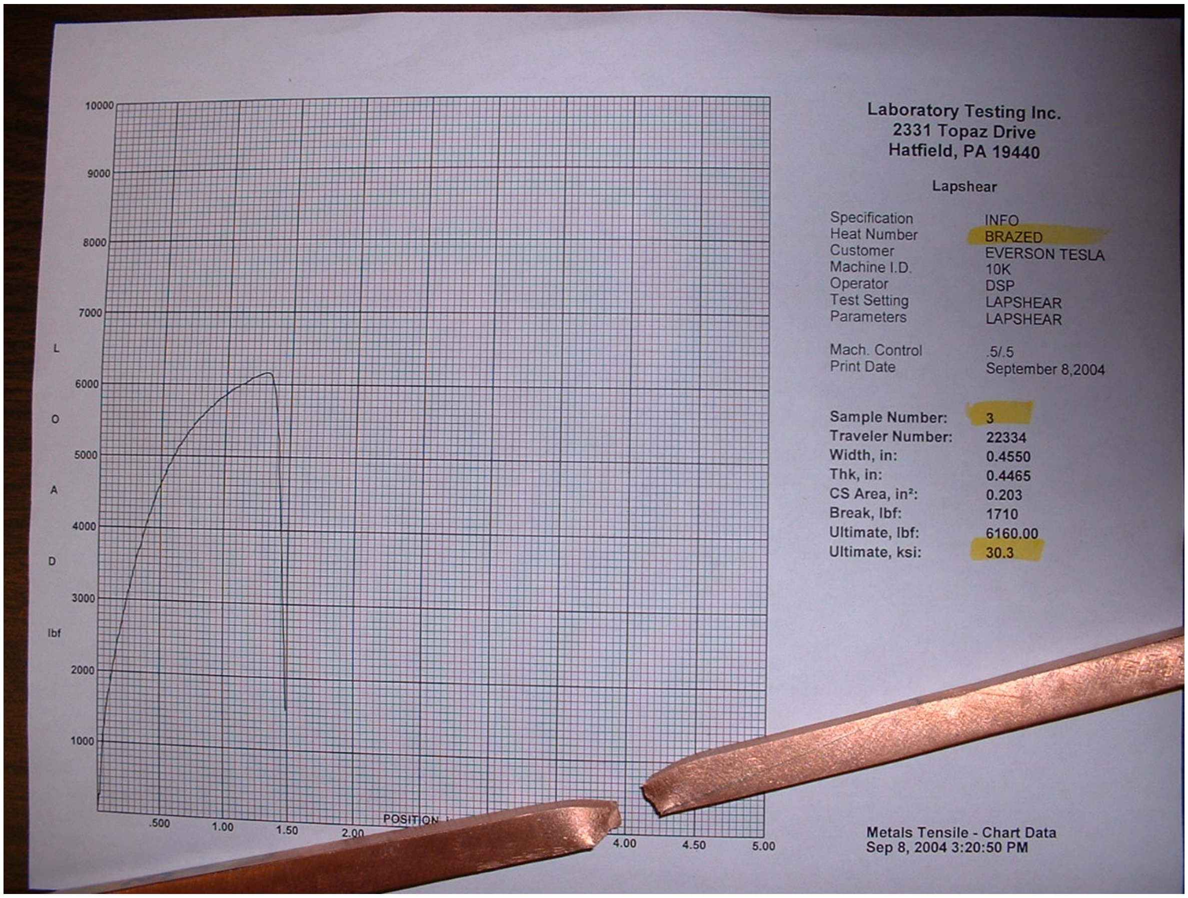


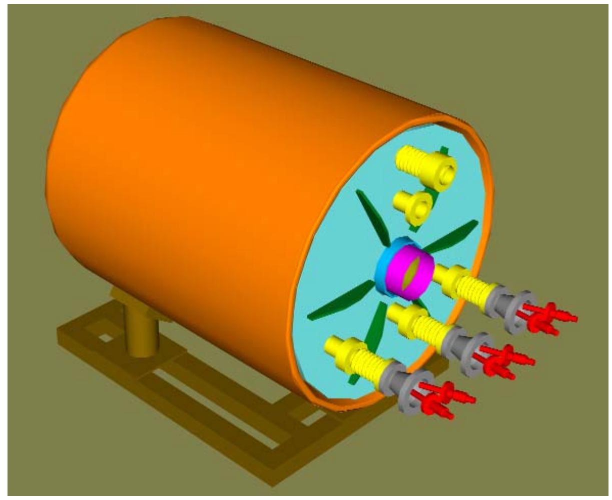
Photo taken by Dave Rakos at Everson 09-08-04. Kapton layer spaced at every eighth turn relieves axial tension in the layers near the cooling channels.

Faint indication of silver soldered scarf joint




Laboratory Testing Inc.
2331 Topaz Drive
Hatfield, PA 19440
Lapshear
Specification INFO
Heat Number BRAZED
Customer EVERSON TESLA
Machine I.D. 10K
Operator DSP
Test Setting LAPSHEAR
Parameters LAPSHEAR
Mach. Control .5/.5
Print Date September 8,2004
Sample Number: 3
Traveler Number: 22334
Width, in: 0.4550
Thk, in: 0.4465
CS Area, in²: 0.203
Break, lbf: 1710
Ultimate, lbf: 6160.00
Ultimate, ksi: 30.3
LOAD lbf
POSITION
Metals Tensile - Chart Data
Sep 8, 2004 3:20:50 PM

19.0 Safety and Fault Analyses



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

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

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.

He/LN2 Cryostat Leak

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

Mechanical Seal Failure

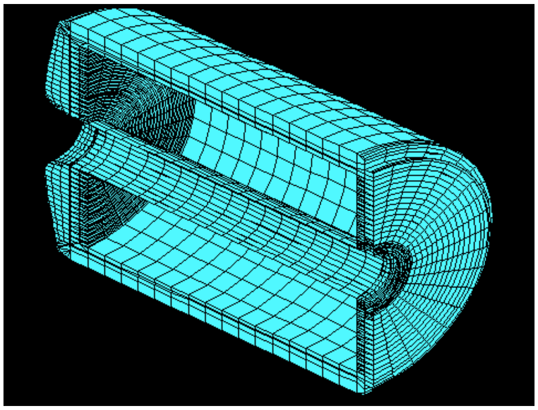
A redundant welded seal is available as a back-up. It can be applied if there are problems in-service? Or in the shop?

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)



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

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

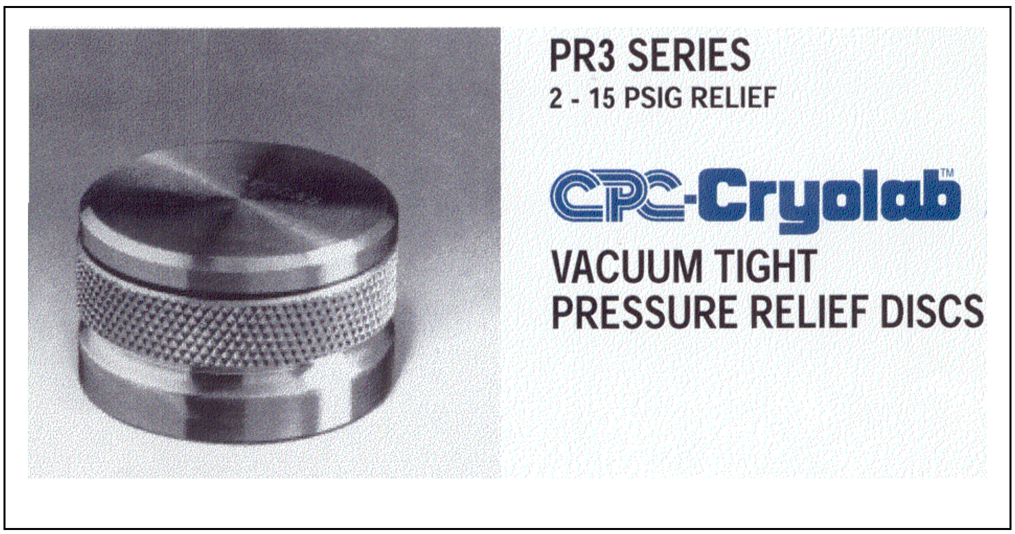
Loss of Vacuum in Jacket

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.



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.