MIT PSFC Plasma Science and Fusion Center

fact νμ π Muon Collaboration

MC Collaboration Meeting June 11 - 12, 2003
Targetry Group Report FY04 R&D Plan – Pulsed Magnet Status
E951 15T Pulsed Magnet for Mercury Target Development

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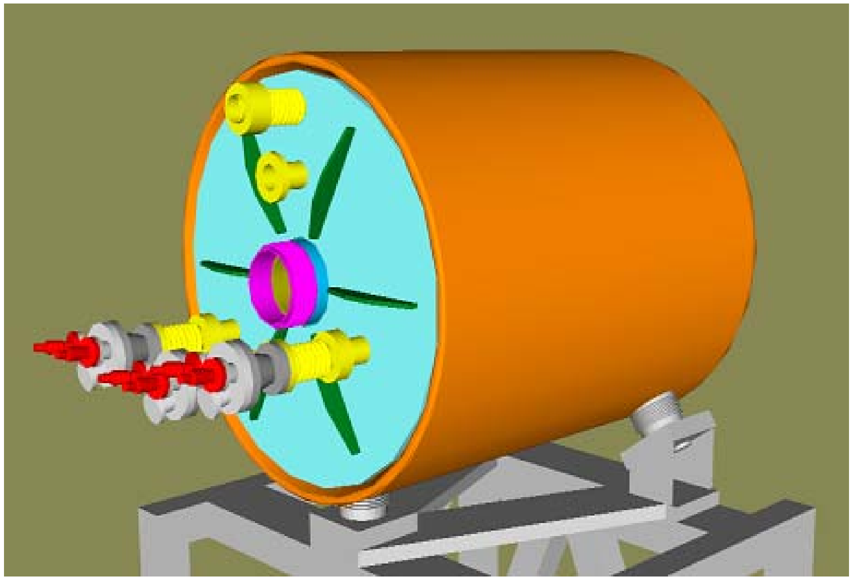
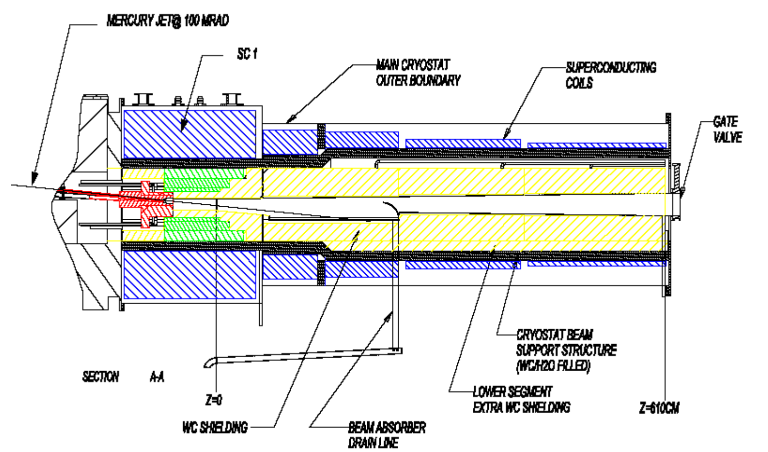


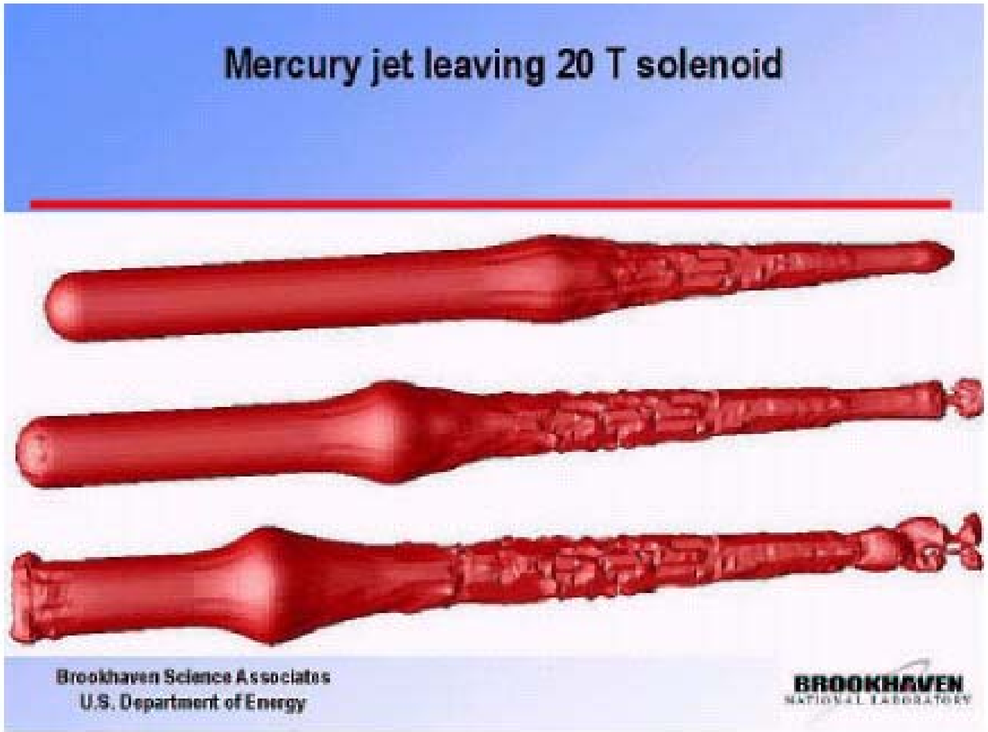
BNL Pulsed Magnet –Inertially Cooled , 72K He Gas Cooled Between Shots

MC Collaboration Meeting June 11 - 12, 2003 Pupin Laboratory Building - room 329 Columbia University, NY

The Purpose of the Experiment is to Study Mercury Targets for Neutrino Beams and a Muon Collider Source



The Neutrino Factory
SC-1 could be the ITER CS Model Coil



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

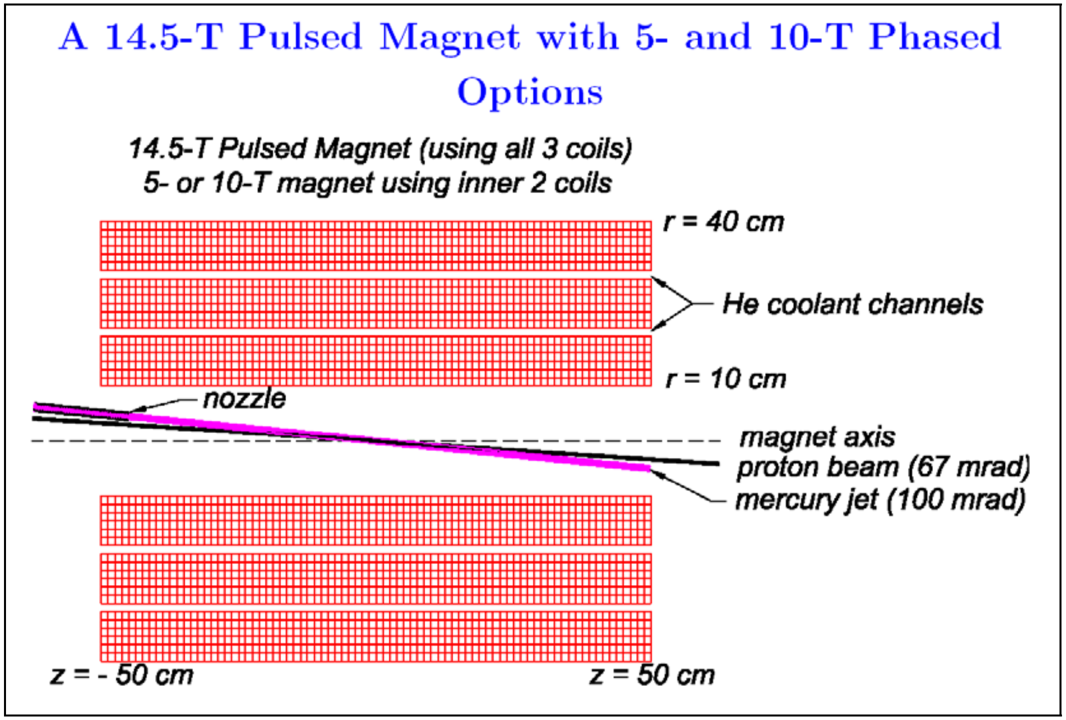
Cost issues dictate a modest coil design.

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

A three segment, layer wound solenoid is 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.

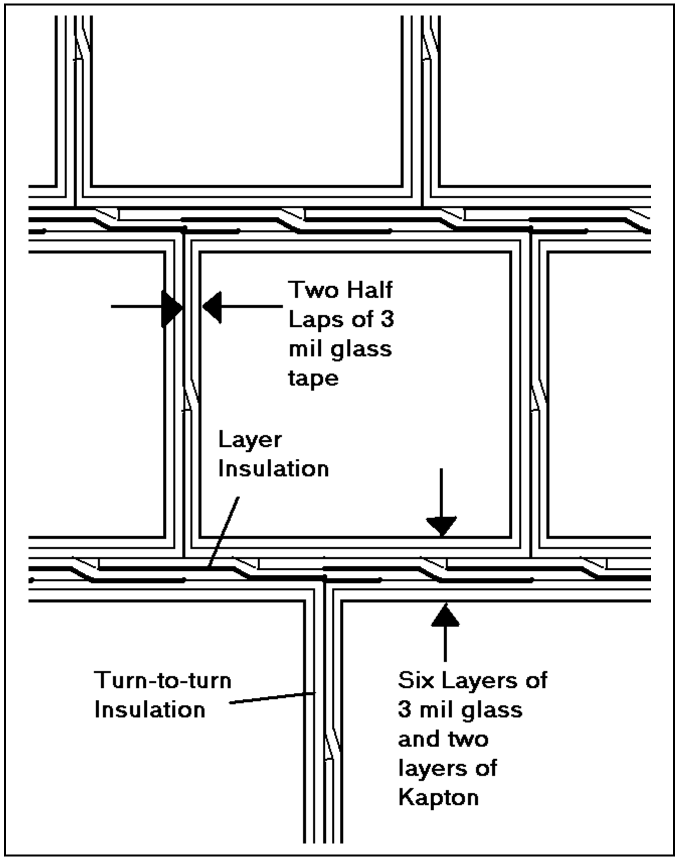
For the same packing fraction, a hollow conductor would have a 1.4mm diameter hole

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.

Bob Weggel has performed the coil/power supply simulations. He has picked operating temperatures, and basic coil build.

Coil Description:

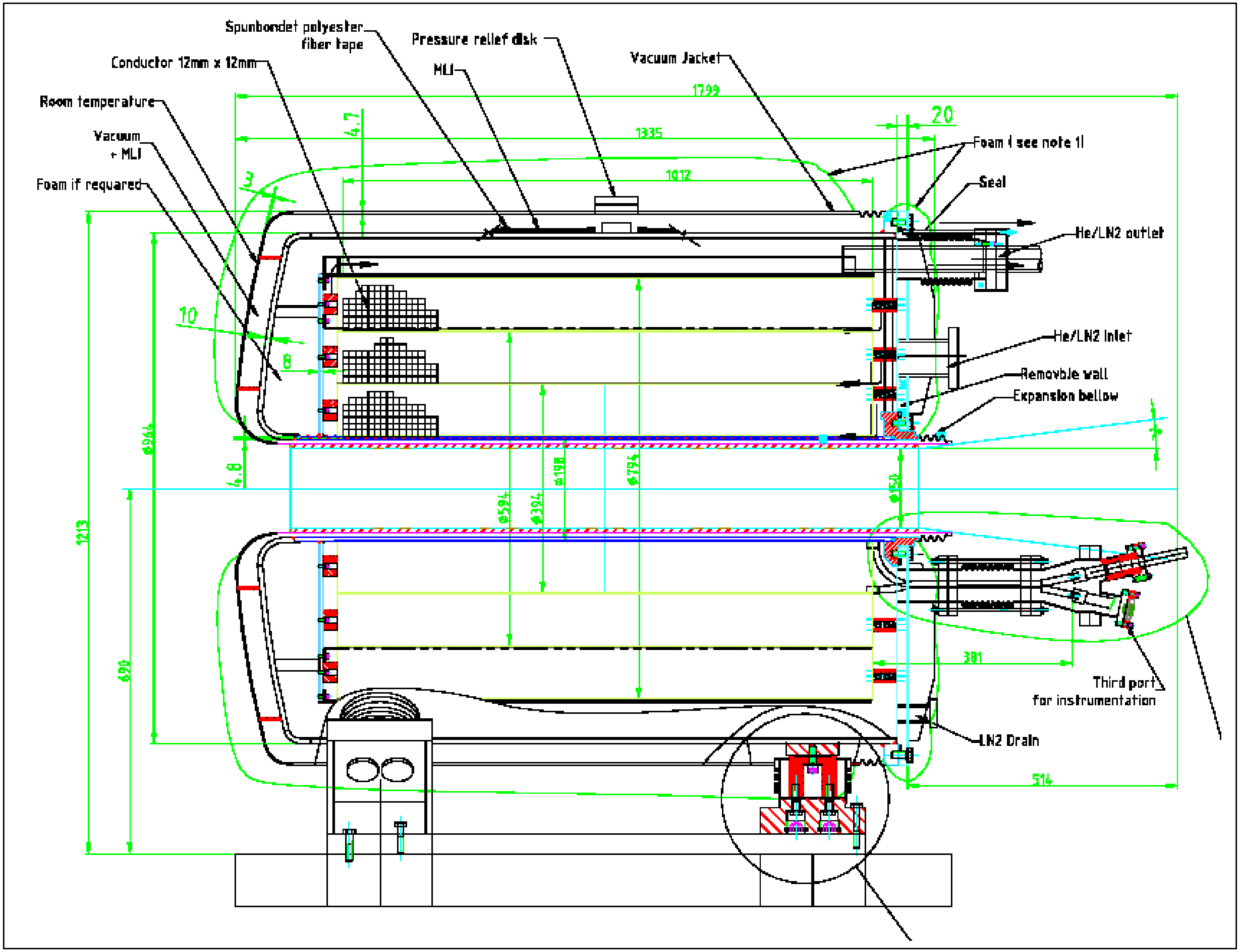
	Mode 1	Mode 2	Mode3
Number of Segments operating:	2	2	3
Number of turns per segment	624	624	624
Total number of turns active	1248	1248	1872
Layers in each coil segment	8	8	8
Turns per layer	78	78	78
Conductor radial thickness	.0116698 m .45944 in	.0116698 m .45944 in	.0116698 m .45944 in
Conductor Axial thickness	.012516m .49274359 in	.012516m .49274359 in	.012516m .49274359 in
Max Operating Field Bore CL	5T	10T	15.0T
Max 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			12 atm
Cryostat Pressure – During Cooldown			15atm 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 sec	6.3 sec	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



Coil Builds used in the Finite Element Models:

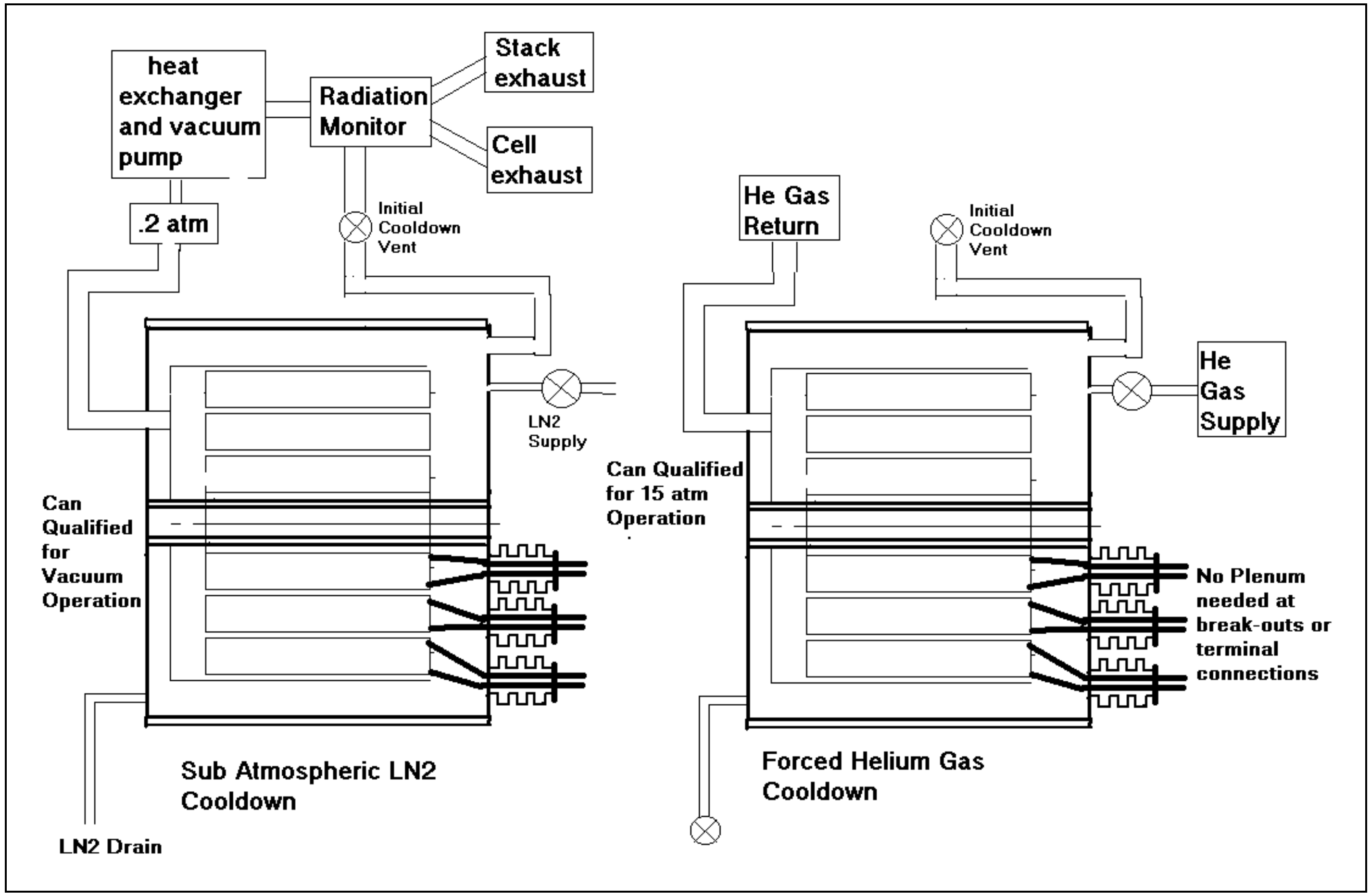
#	r	z	dr	dz
1	.15	0	.098	1.0
3	.25	0	.098	1.0
5	.35	0	.098	1.0

http://198.125.177.77/bnlpulsed/assemnote.pdf



Proposed Operational Scenarios

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



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

Structural Design Criteria

Magnet

Lacking a specific design code jurisdiction, fusion project criteria are used for guidance in coil design

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.

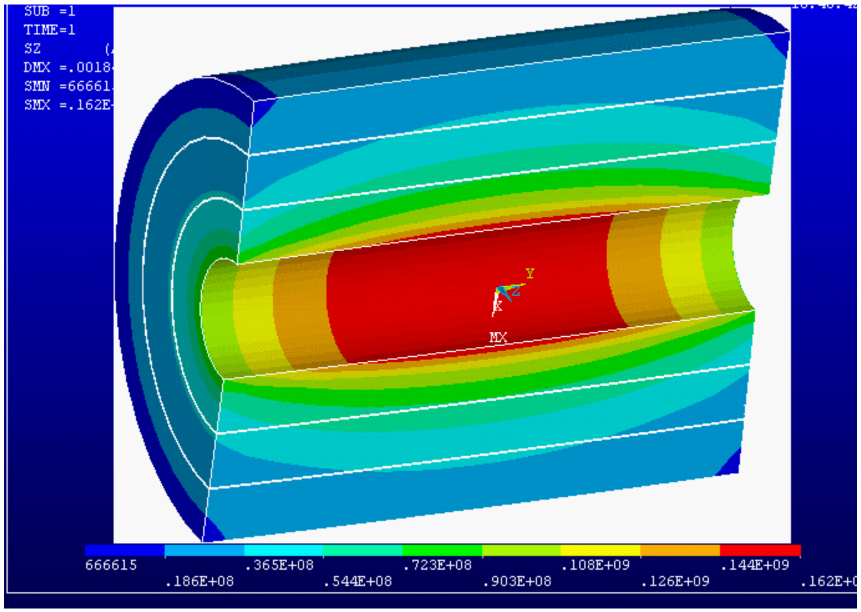
Guidance for bolting and column buckling is taken from AISC, with average net section bolt stresses kept below 0.6*yield. Yield Strength and Tensile Strength properties are taken at the loaded temperature.

Vessels

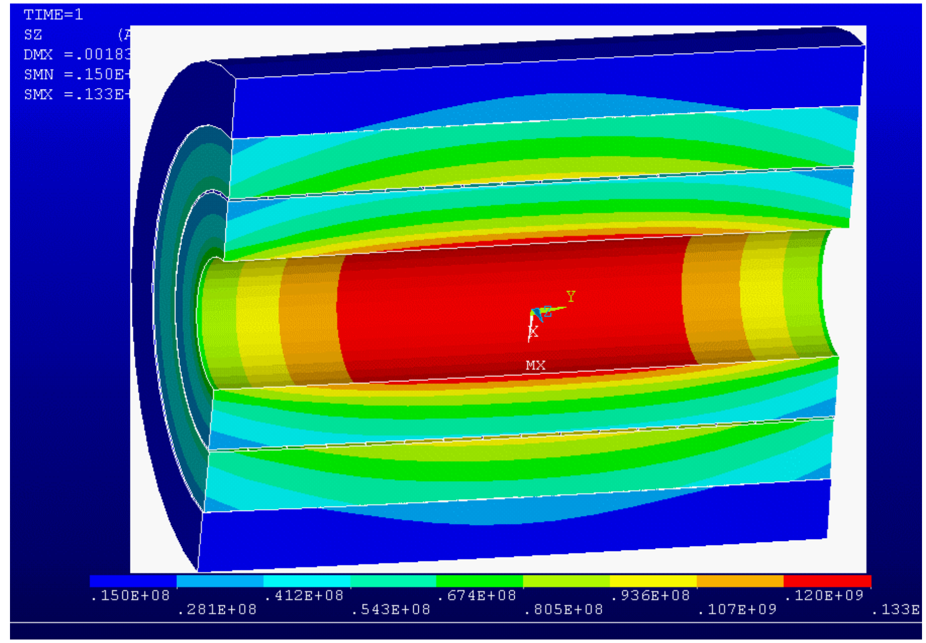
The cryostat and vacuum jackets are to be qualified and manufactured in accordance with ASMEVIII. –But Not Stamped

The magnet Assembly is to be seismically qualified in accordance with the (Uniform Building Code?).

Coil Stress Analysis



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



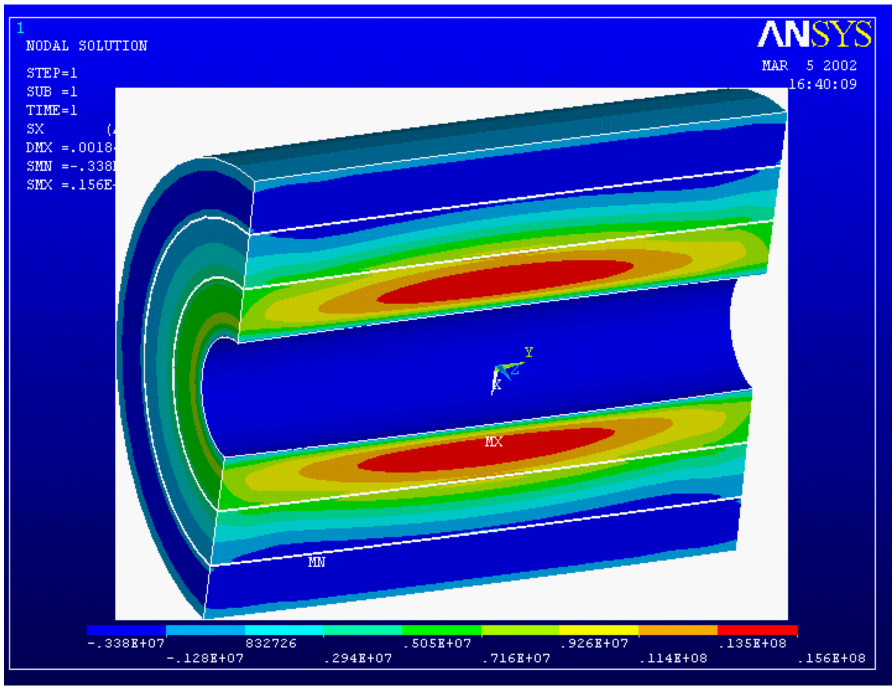
Re-run with gap elements the hoop stress went down to 133 MPa

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

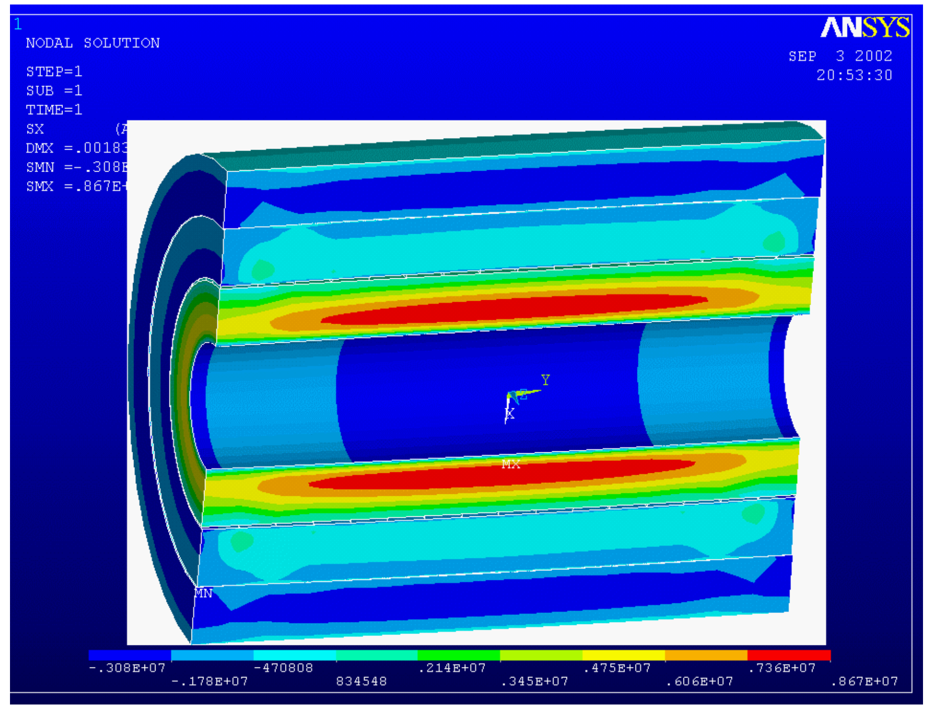
In the initial operating mode the outer coil segment is not energized. This induces some differential Lorentz forces and differential temperatures, that cause shear stresses between segments.

Design Must Accommodate All combinations of Coils Energized.

Radial Tension Stress, All Coils Fully Energized.



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



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

Conductor Allowable and Cold Work Spec

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

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

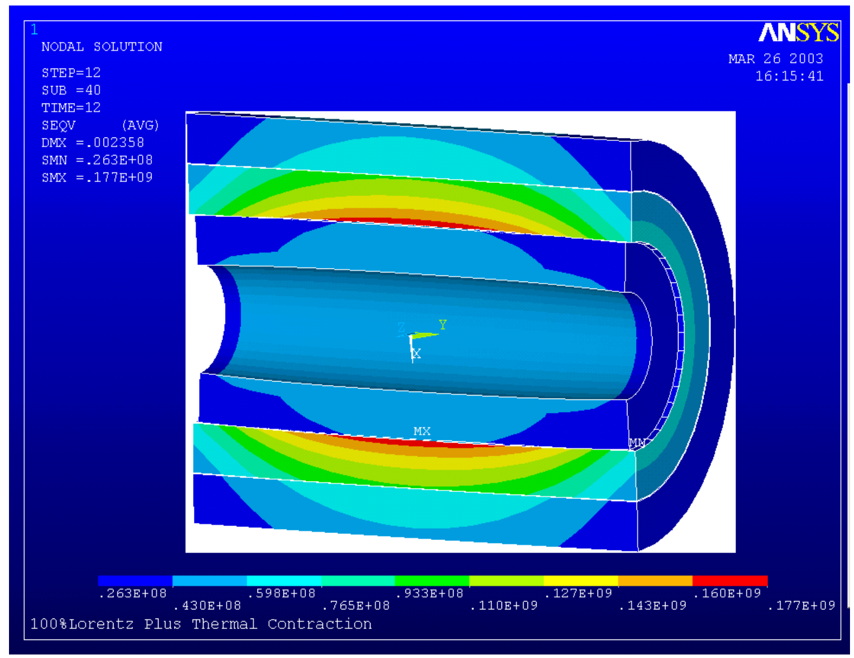
temp deg k	77	90	100	125	150	200	250	275	292
yield	374	369.	365.	356.	347.	328.	317.	312.	308.
ultimate	476.	466.	458.	439.	420.	383.	365.	356.	350.

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.

Half hard copper may still be too difficult for the Inner coil winding radius.

Elastic-Plastic analysis of the tight radius bending operation may introduce sufficient cold work to satisfy the stress allowables. H/2/R is 6% at the ID turn of the inner magnet section

Allowing Inner Segment to Yield is Not attractive Because of Compressive Pressure on Annular Coolant Channel Spacer Ribs.



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.

Operational Thermal Stresses.

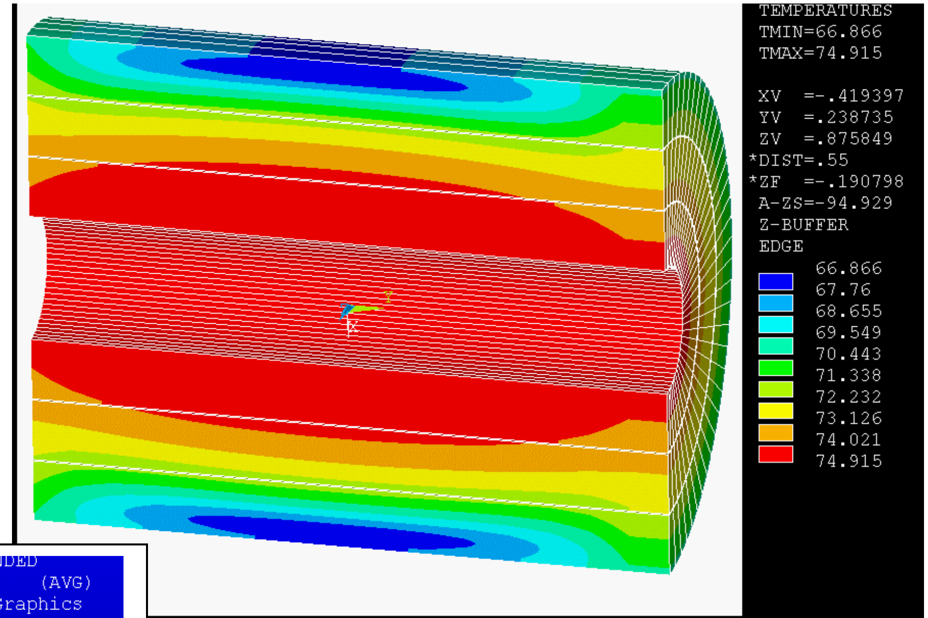
Although a constant current density coil, heat-up during a pulse is not uniform due to the magneto-resistive effects.

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

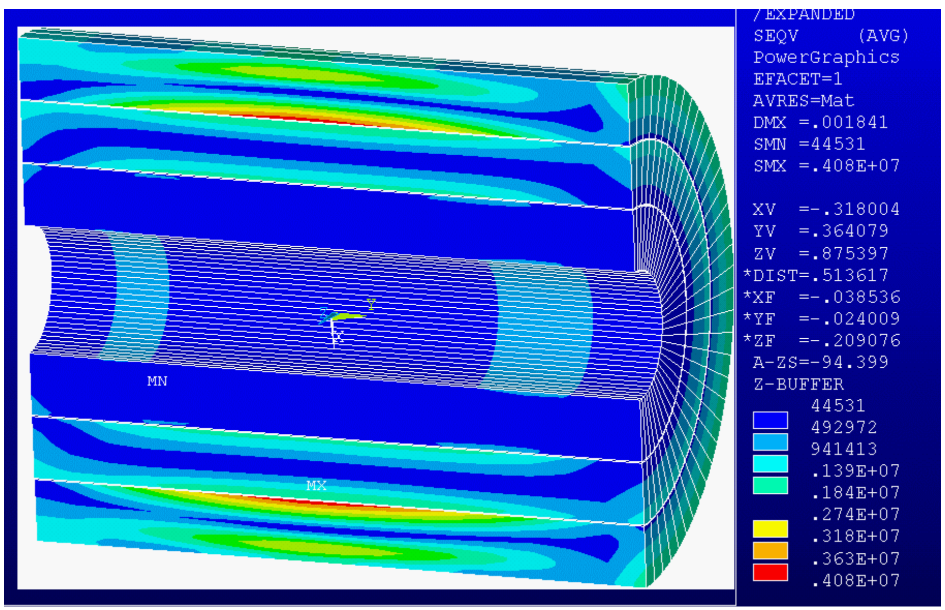
In my calculations, the temperatures were low compared with Bob Weggel's. The difference was the conservatism the Bob applied to his analysis from the scatter of the Kohler plot.

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

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



mperatures with magneto-resistive effects, 15.0T

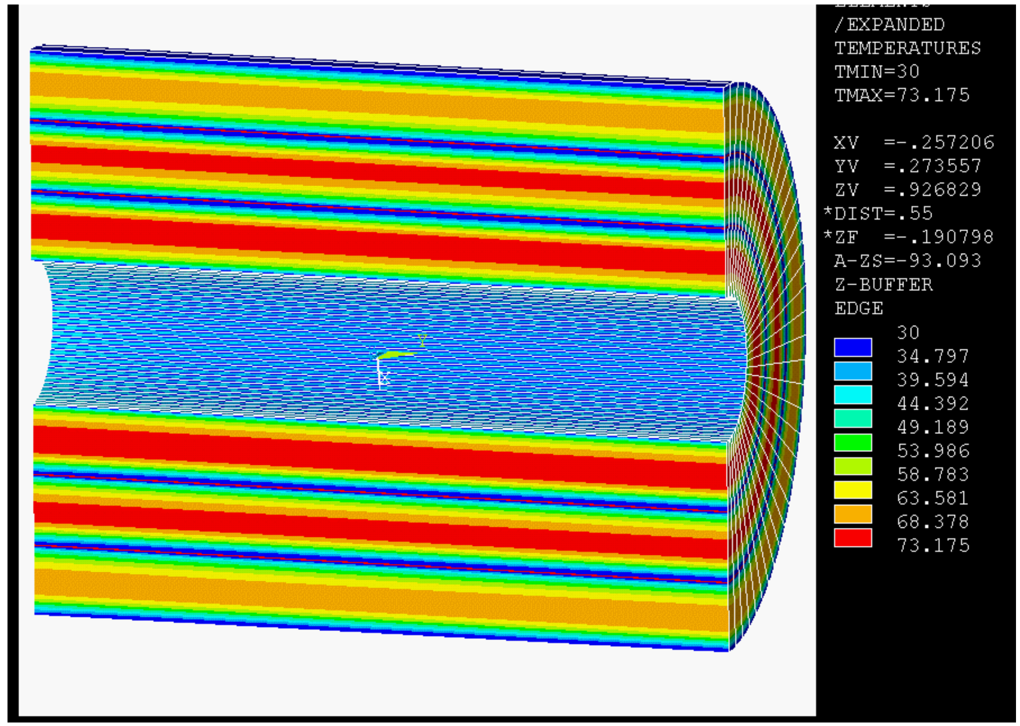


Resulting VonMise Stresses due to Temperature including the magneto-resistive effects, 15.0T.

Cooldown Stresses –Von Mises

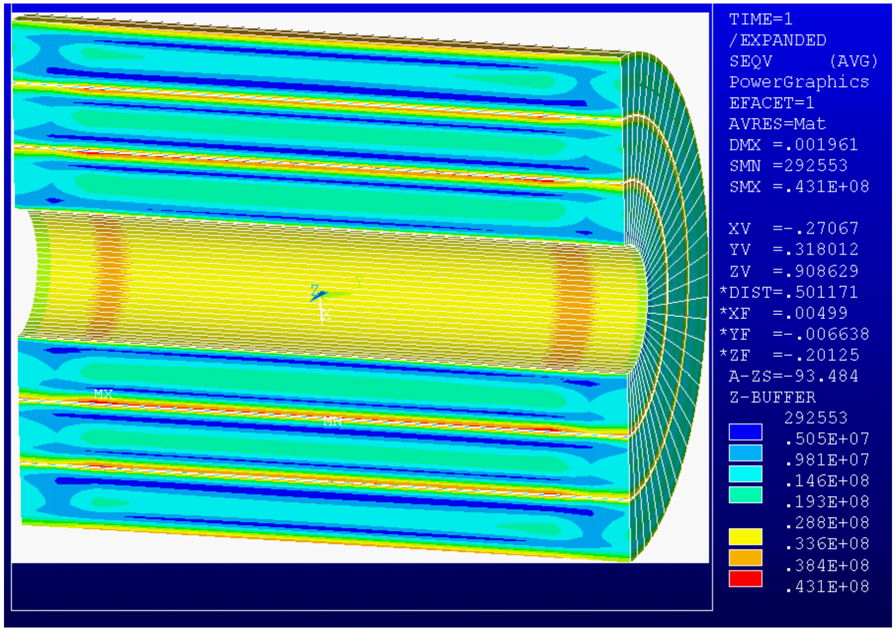
The channels were held at 30K and the temperature distribution was obtained by averaging nodal temperatures with the final temp distribution from the heat-up calculations. This is not rigorous, and is essentially assumed, but it is representative of temperature distribution, and will serve to provide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

The VonMises stress is relatively modest, at 43MPa

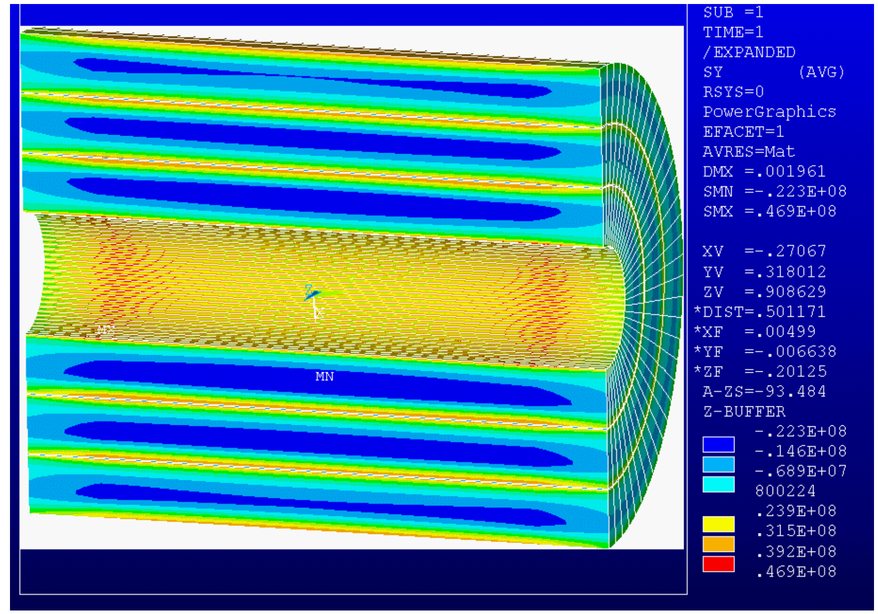


Cooldown Temperature distribution

Cooldown Stresses –Shear and Axial Tension



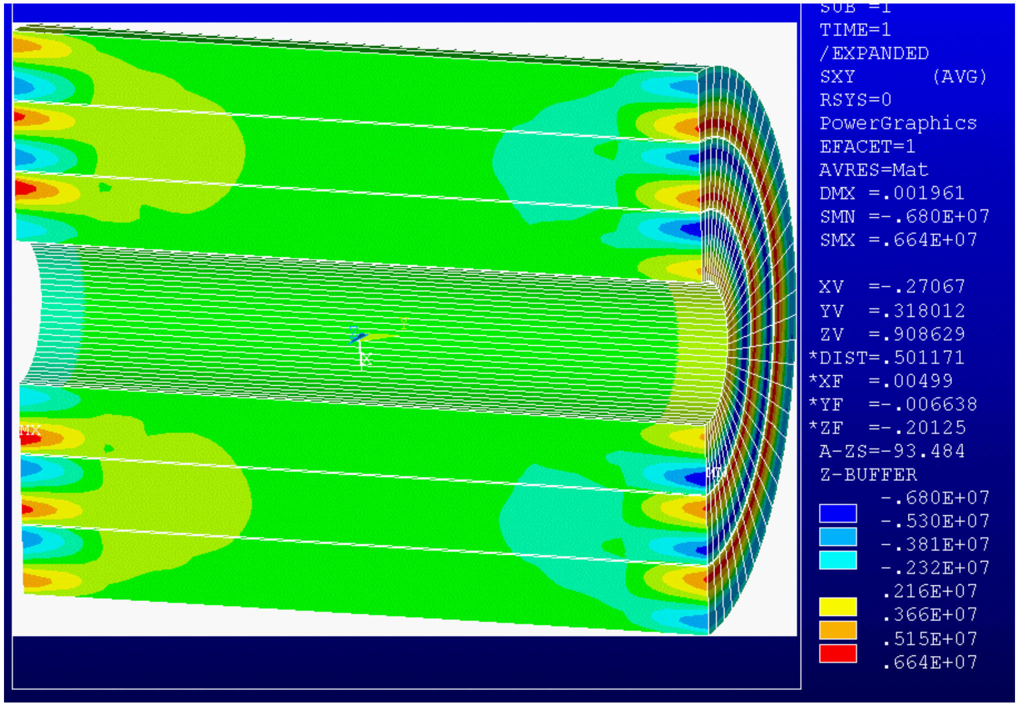
“Smeared” VonMises stress



Axial tension

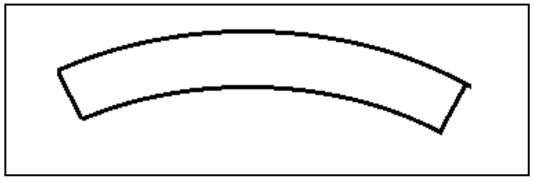
The axial tension near the channels is approaching 50 MPa, beyond the design capacity of epoxy bonded systems. Some provision will have to be made to either throttle the cooling gas to limit the channel temperature or design to allow the bond failure.

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



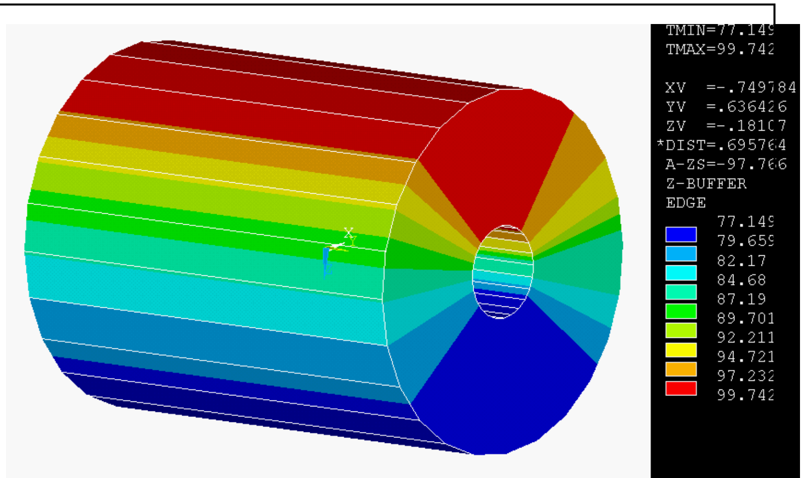
Shear stresses due to the cool down temperature distribution

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

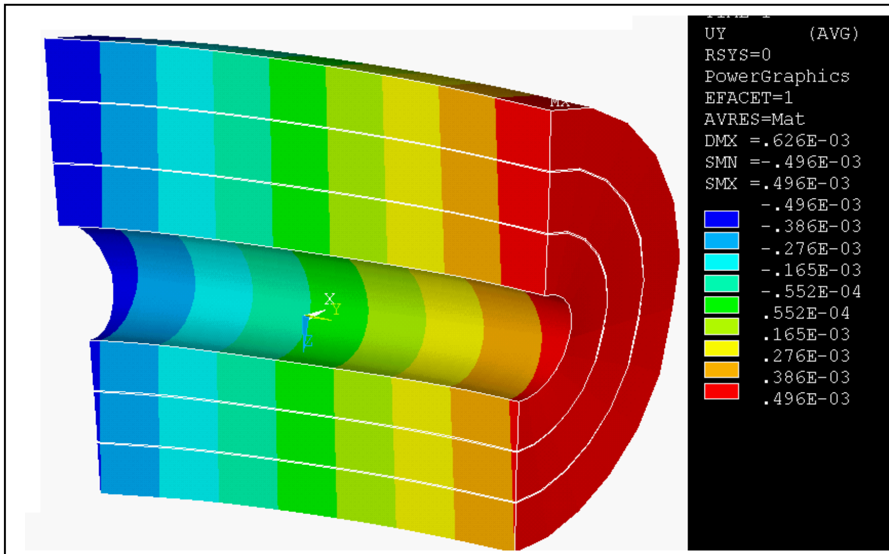


Cooldown Stress, Global Thermal Differential.

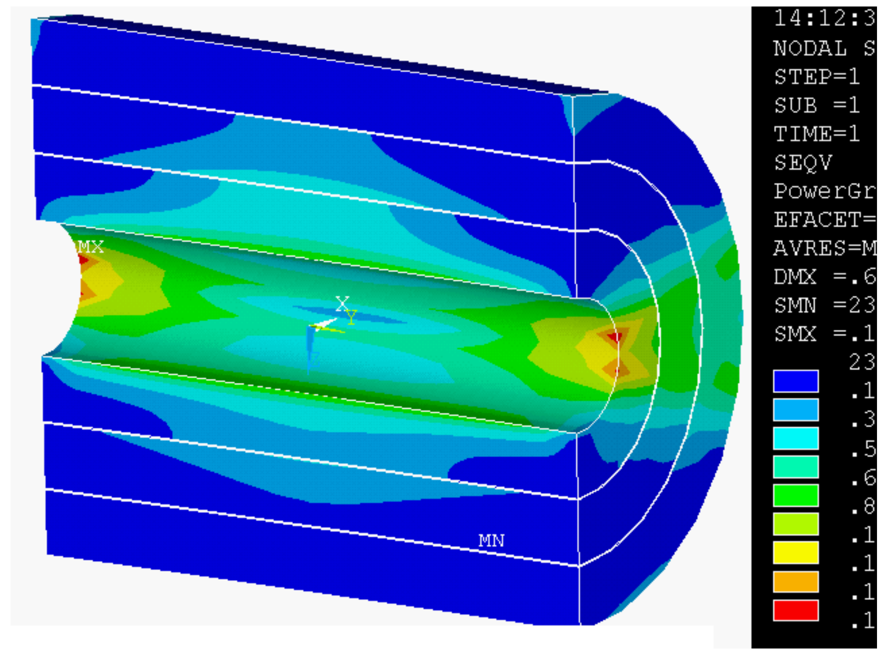
If there is stratification of He gas or if LN2 floods the bottom of the cryostat there could be a significant thermal differential between top and bottom of the coil. A 77 to 100 K variation is assumed. The resulting 15 MPa stress is Acceptable



Assumed temperature variation

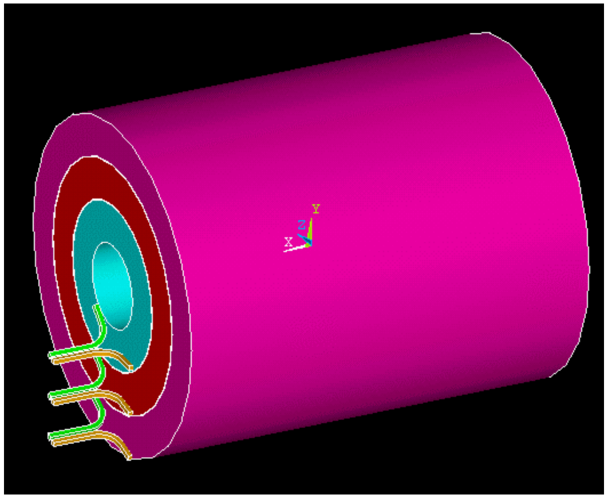


Resulting Displacements

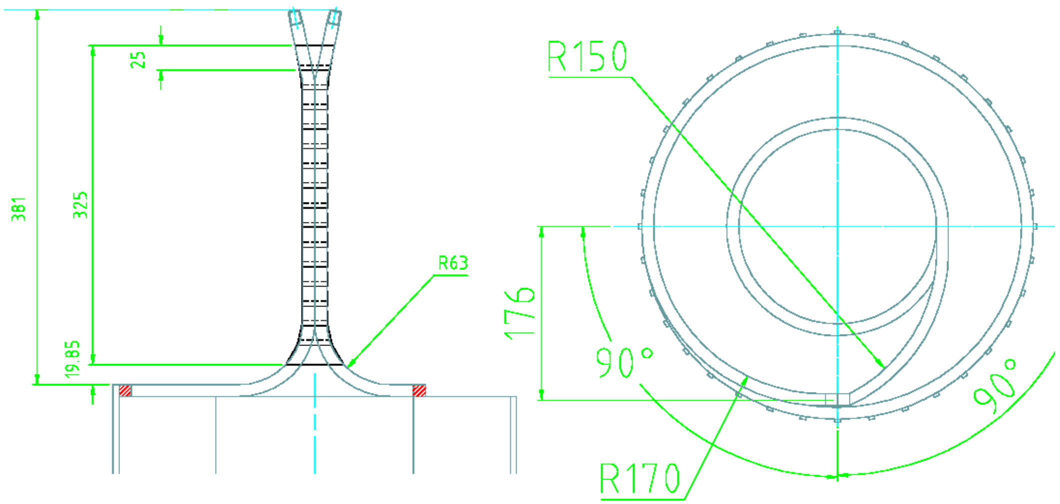


Break-Outs, Leads, and Penetrations

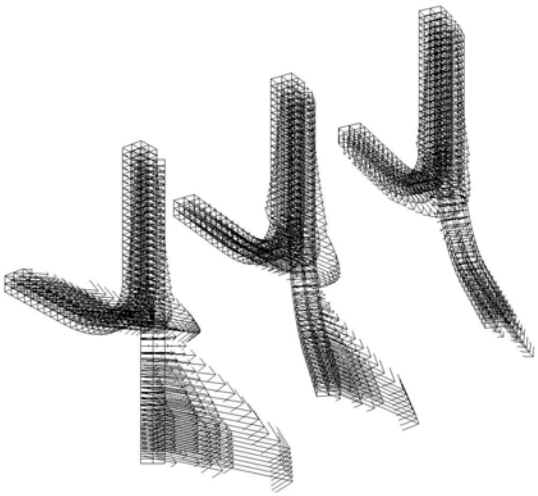
- The choice of modular design favors duplicating the break-out and lead design for all three segments, even though two of the segments are connected in series.
- The break-out concept structurally connects the inner layer break-out with the outer layer break-out.
- The leads are closely coupled to cancel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



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

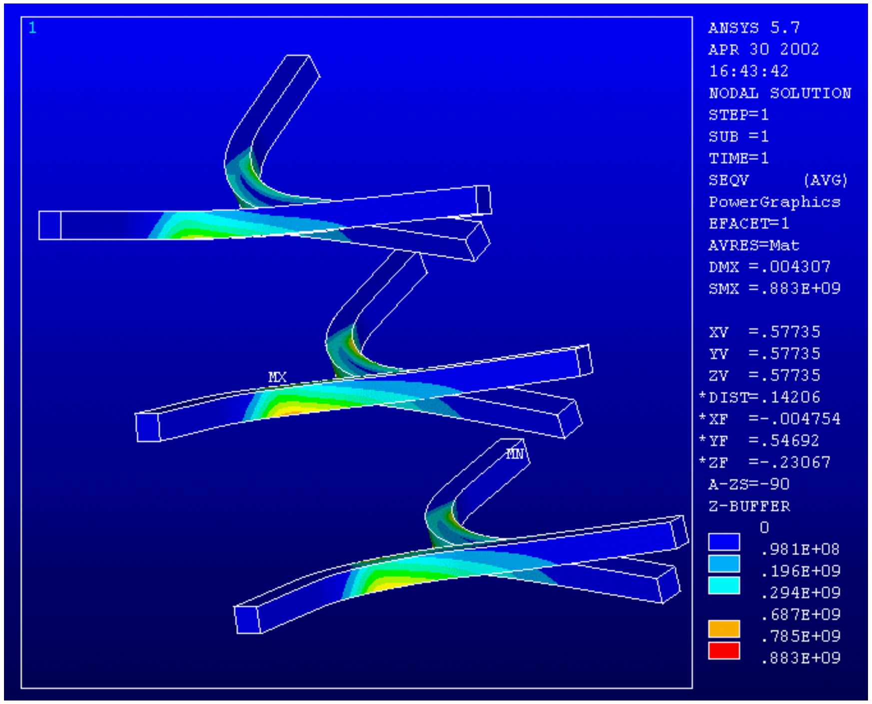


Inner Segment Break-Out Showing Structural Wrap

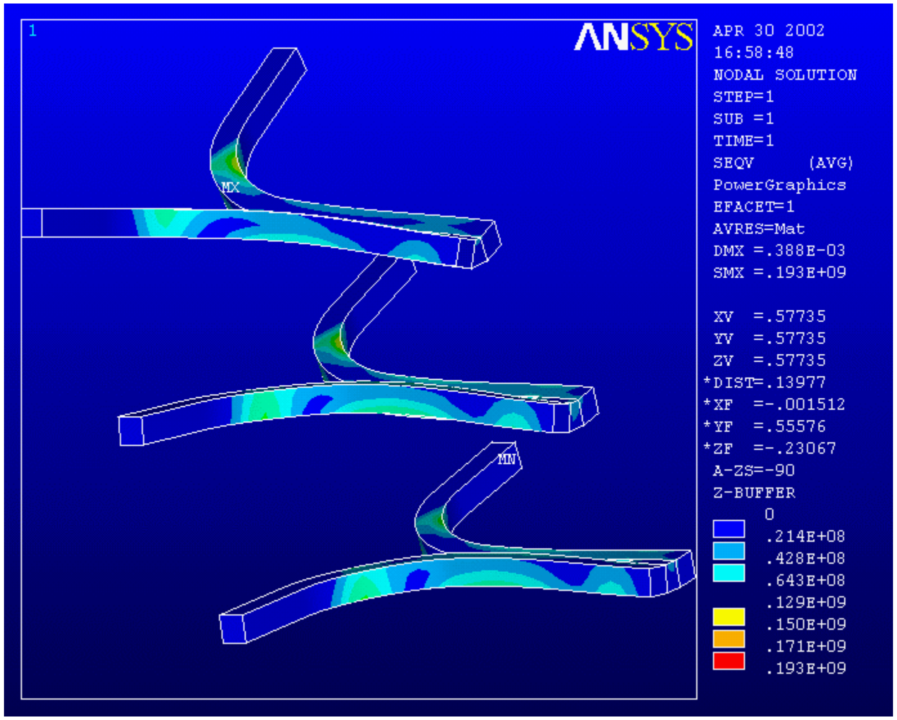


Lorentz Forces at the break-outs. 15.0T Full field operation.

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

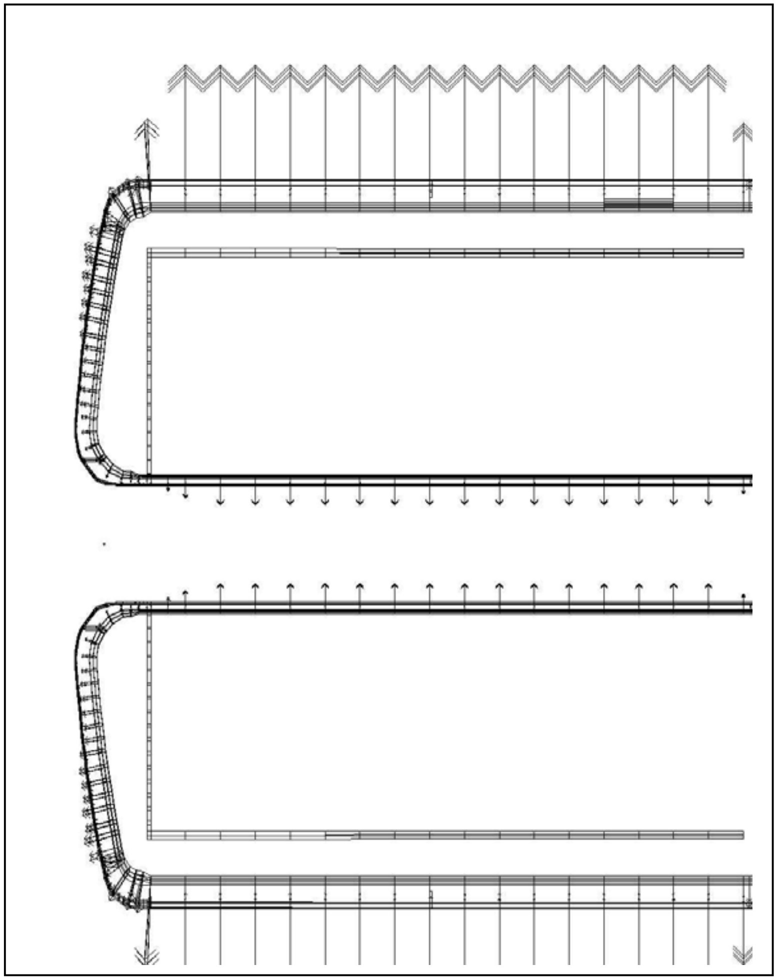


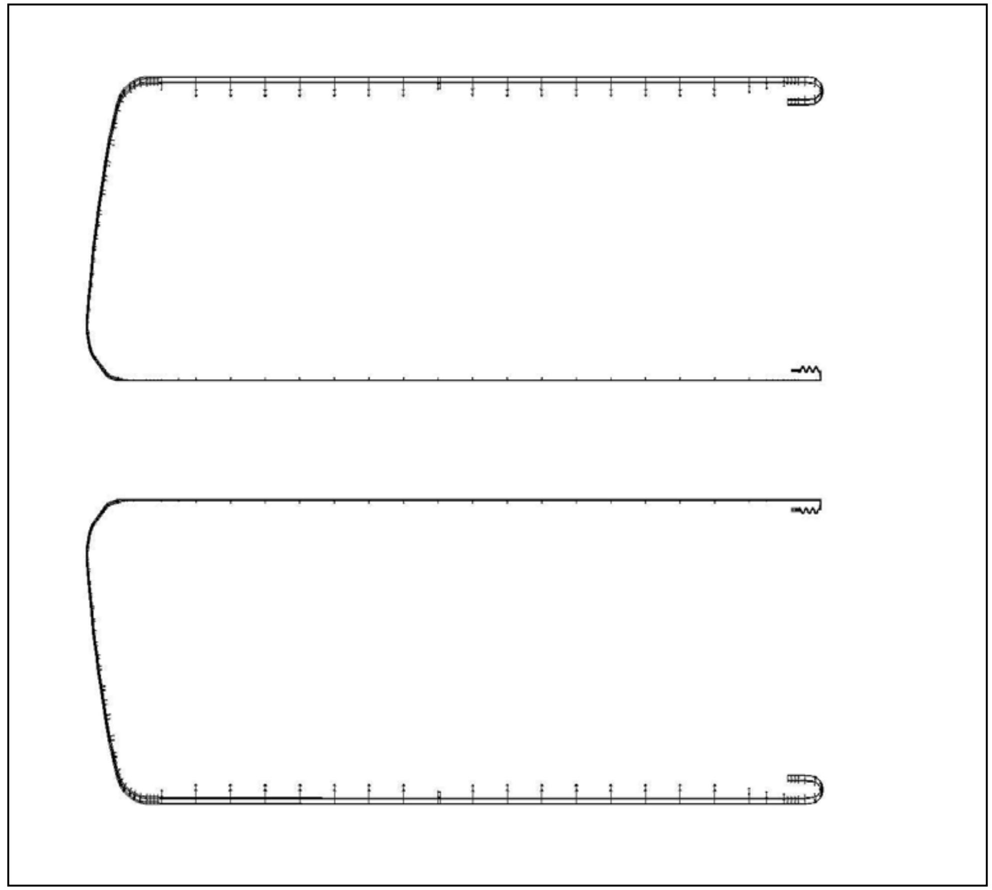
Winding ends well supported, Terminal ends Un-supported and not interconnected. Lorentz Forces Only



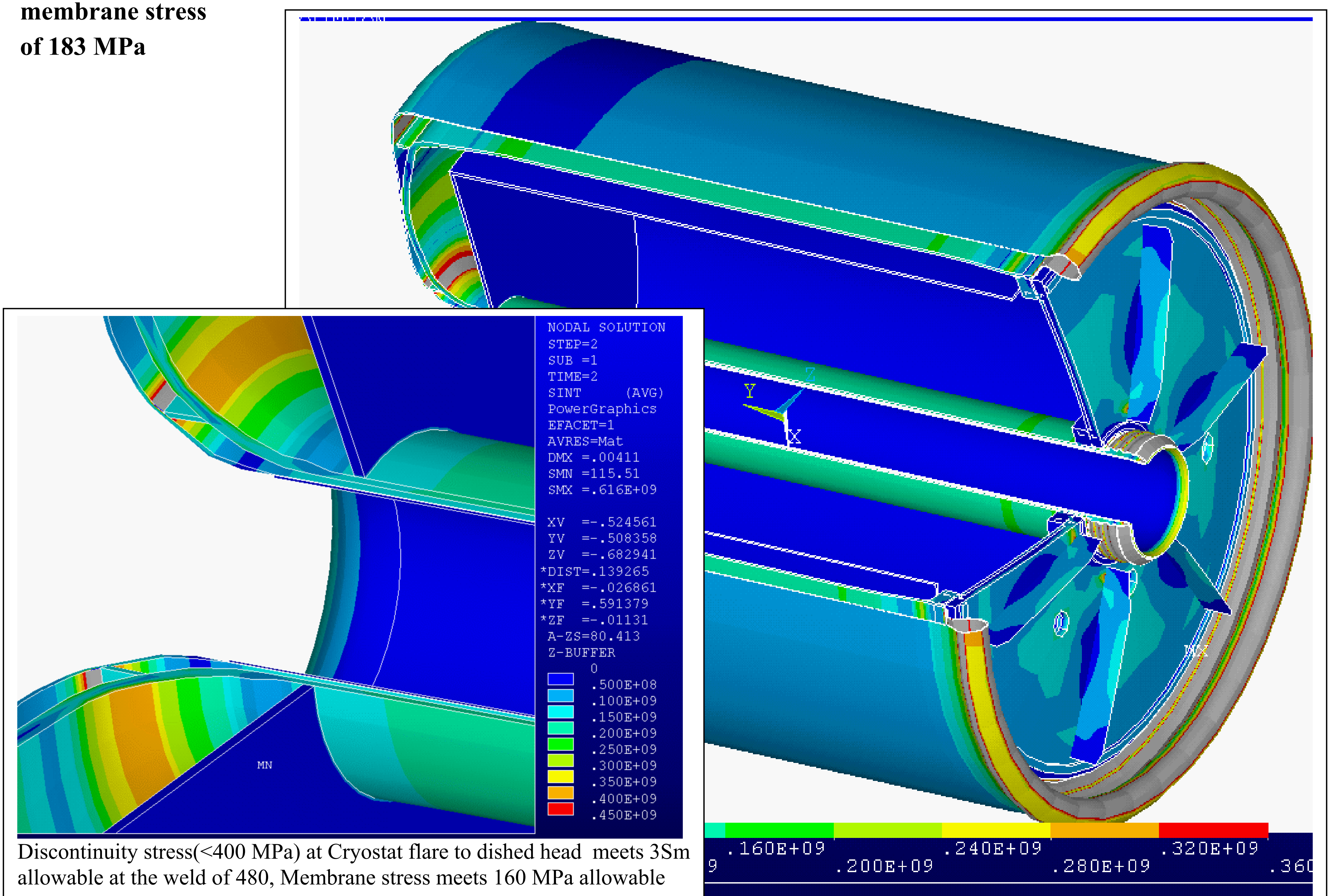
Winding ends well supported, Terminal ends interconnected at the end of the lead pair. Lorentz Forces Only

Cryostat and Vacuum Jacket Design:
Pressure Load Vectors – Nodal Forces, Pressure times element area





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

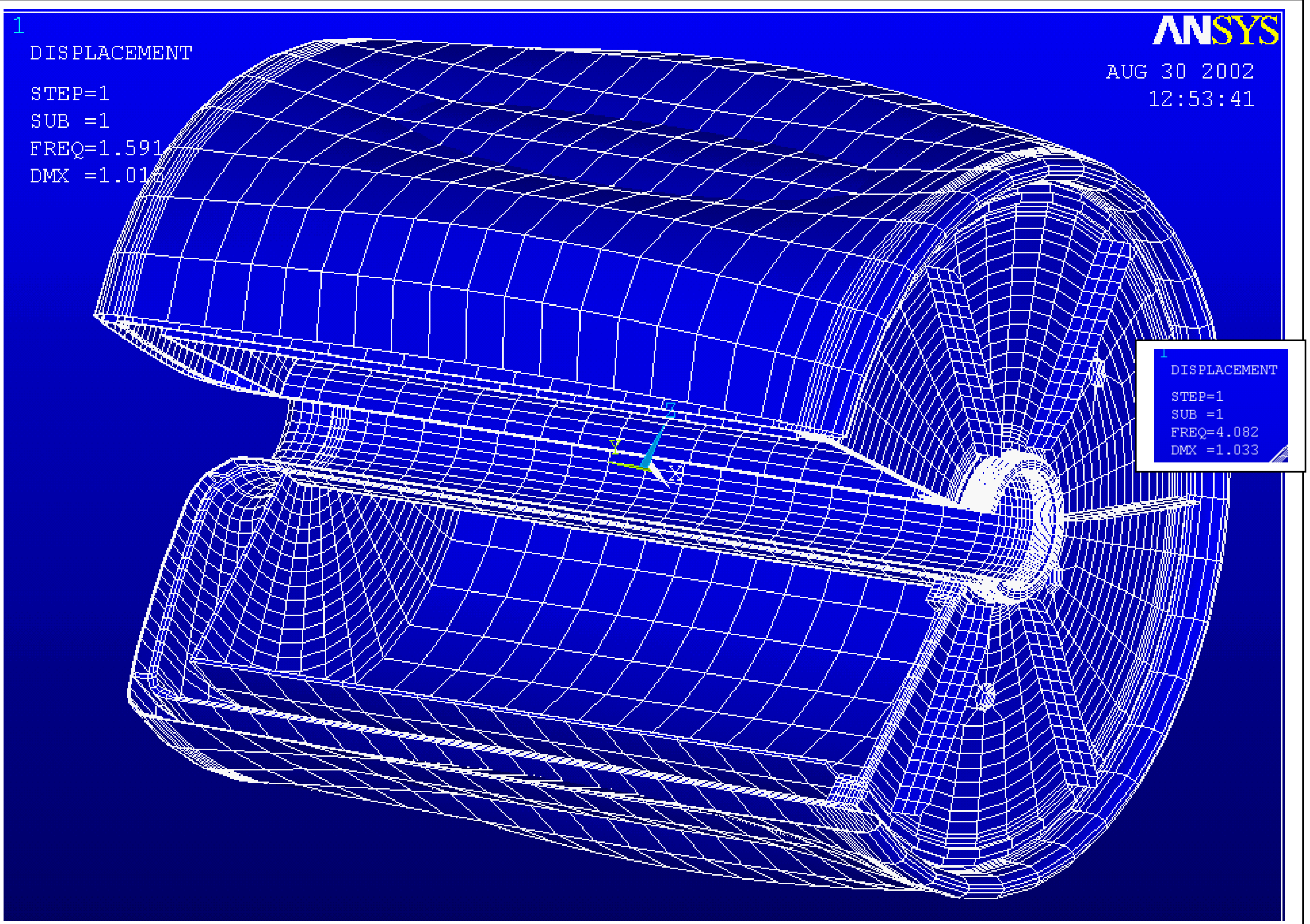


Discontinuity stress(<400 MPa) at Cryostat flare to dished head meets 3Sm allowable at the weld of 480, Membrane stress meets 160 MPa allowable

In this plot, light blue is 120 to160 MPa

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

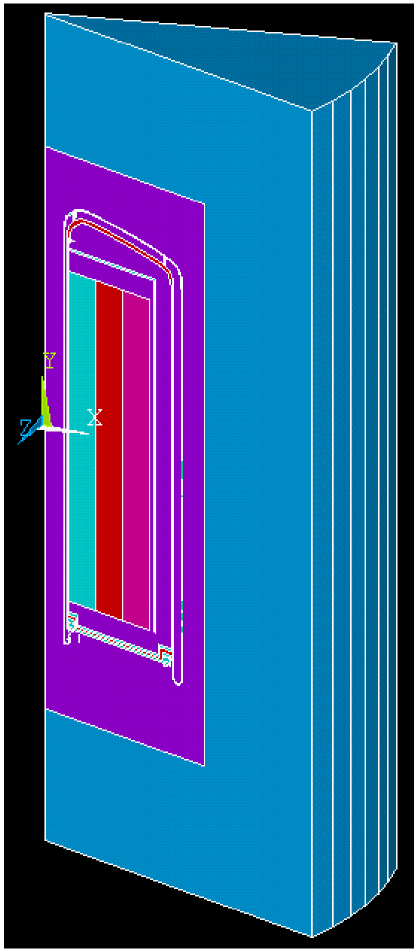
-Thicken or add stiffeners. – We thickened It



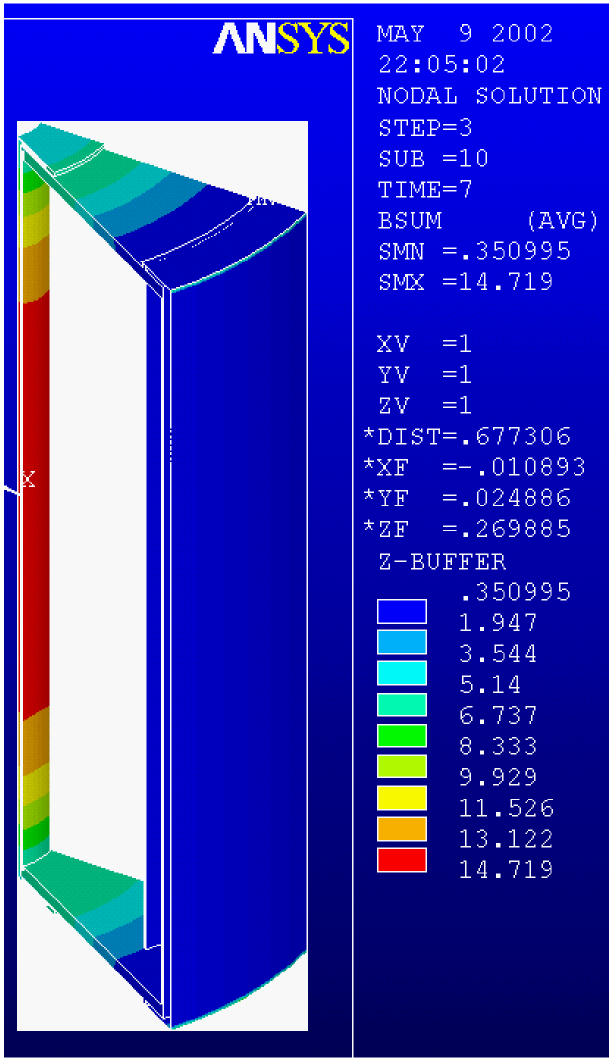
Eigenvalue Buckling Analysis, Load vector is 15 atm on cryostat and 1 atm on vacuum jacket. Analysis includes

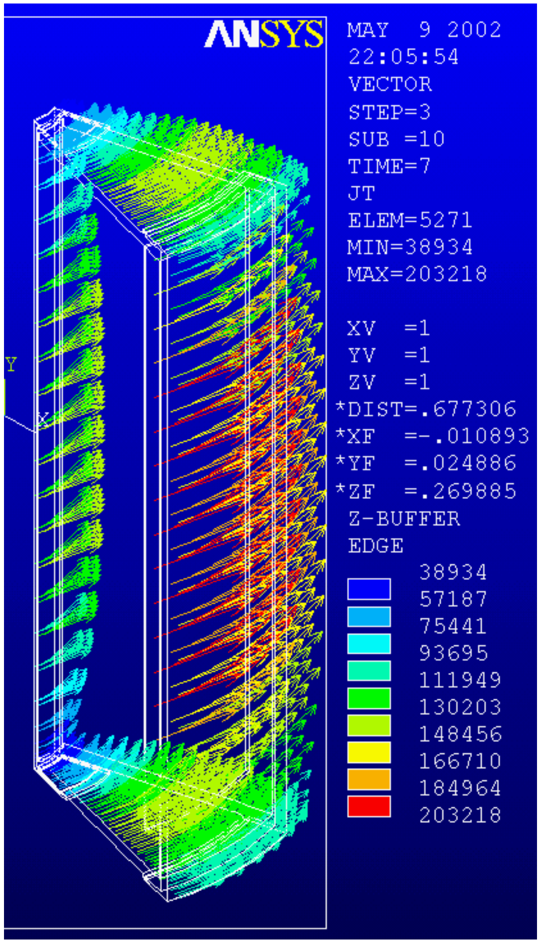
Cryostat Eddy Current Analysis

Vector Potential Solution, 7 sec Ramp-Up , (Envelopes ramp-up and ramp down)
Field Loss Due to Eddy's is of the Order of a few milliTesla. Bore tube eddys are not a structural issue.



Electromagnetic Model with Air

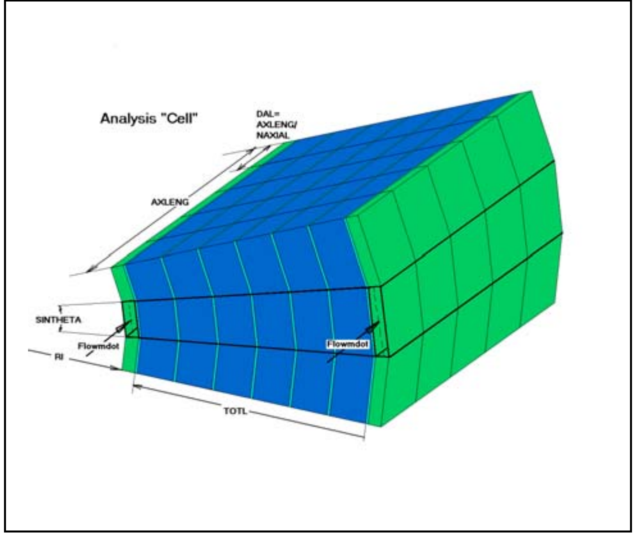


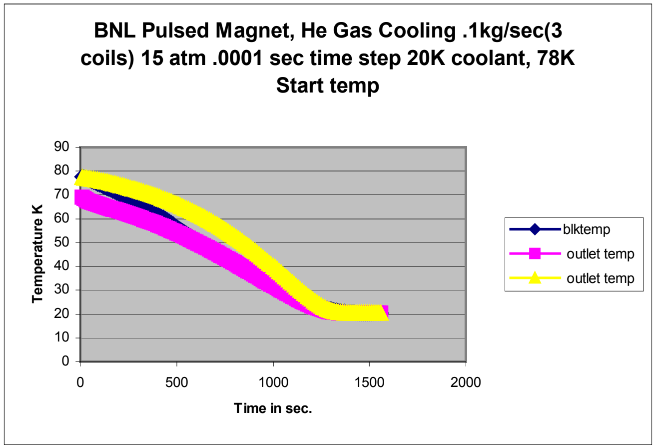


Cooling time with Helium gas as a Working Fluid

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.

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





Hegas7.xls

Status:

- ✓ **Design Drawings Complete**
- ✓ **Engineering Calculations Complete**
- ✓ **Manufacturing (Paper) Studies. Need Vendor Input on ½ Copper Inner Turn Bending.**
- ✓ **Cost Estimate Based on Recent Comparables and Bottoms-Up Estimate is Complete**
- ✓ **BNL Purchase Specification**
    - **BNL Purchasing Department Edit nearly complete**
    - **QA review Complete**
- ✓ **Formation of Source Committee Complete**
- ✓ **Bidders List – MIT Recommendations Complete**
- ✓ **Phased Purchase Strategy Being Worked Out**

RFP to go out any day???