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TD-04-002
1/21/2004

2D MAGNETIC AND MECHANICAL ANALYSIS OF THE SAMPLE HOLDER FOR Nb_3Sn CABLE TEST AT F.R.E.S.C.A. (CERN)

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Abstract:

A finite element analysis was performed in order to compute the stress distribution in the Nb_3Sn cables to be tested at CERN cable test facility (F.R.E.S.C.A.). The goal of this study was to check the design of the sample holder and to optimize the pre-stress. The stress in the cables was computed after pre-stress application, after cooldown and at maximum forces (32 kA and 10T). The magnetic forces were computed for three orientations of the self-field with respect to the background field: transverse, parallel and anti-parallel. The finite element models and the results are presented and discussed.

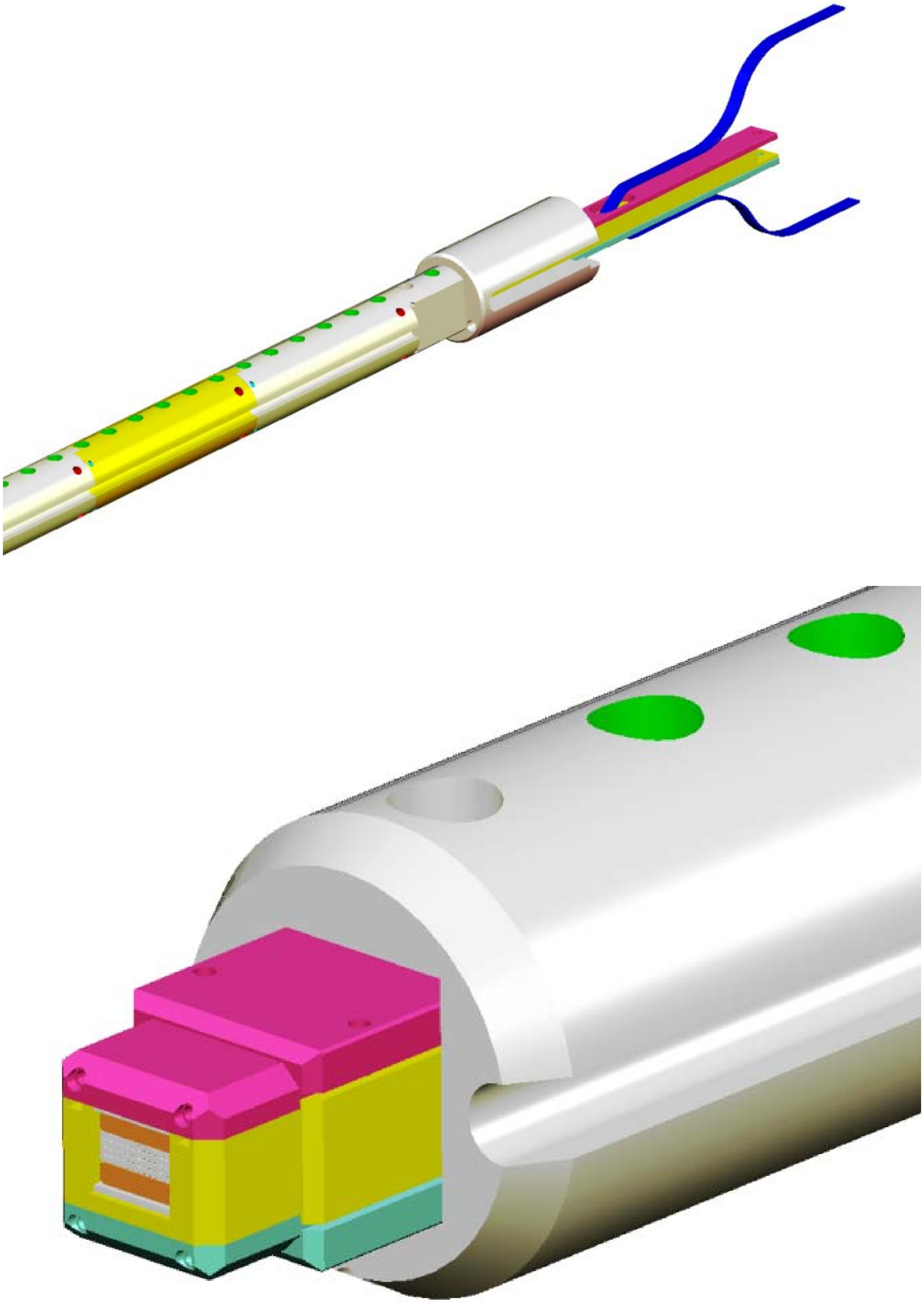


Fig. 1: Top and bottom of the sample holder for Nb_3Sn cables to be used at F.R.E.S.C.A.

1. SAMPLE HOLDER DESIGN

A solid model of the cable sample holder is shown in Figure 1. The external part of the sample holder "collars" (see Figure 2) is the same of the existing sample holder used for NbTi cable measurement at FRESCA [1]. The inner part of the holder has been redesigned for Nb_3Sn samples. It consists of a stainless steel case surrounding four cables. The two central cables are connected in series to the power supply and will be tested ("active" cables). The other cables ("dummy" cables) provide a magnet like environment and protect the active cables during assembly and pre-stress application. This concept was successfully used in the sample holder for Nb_3Sn cables designed by FNAL for tests at NHMFL and BNL [2-4].

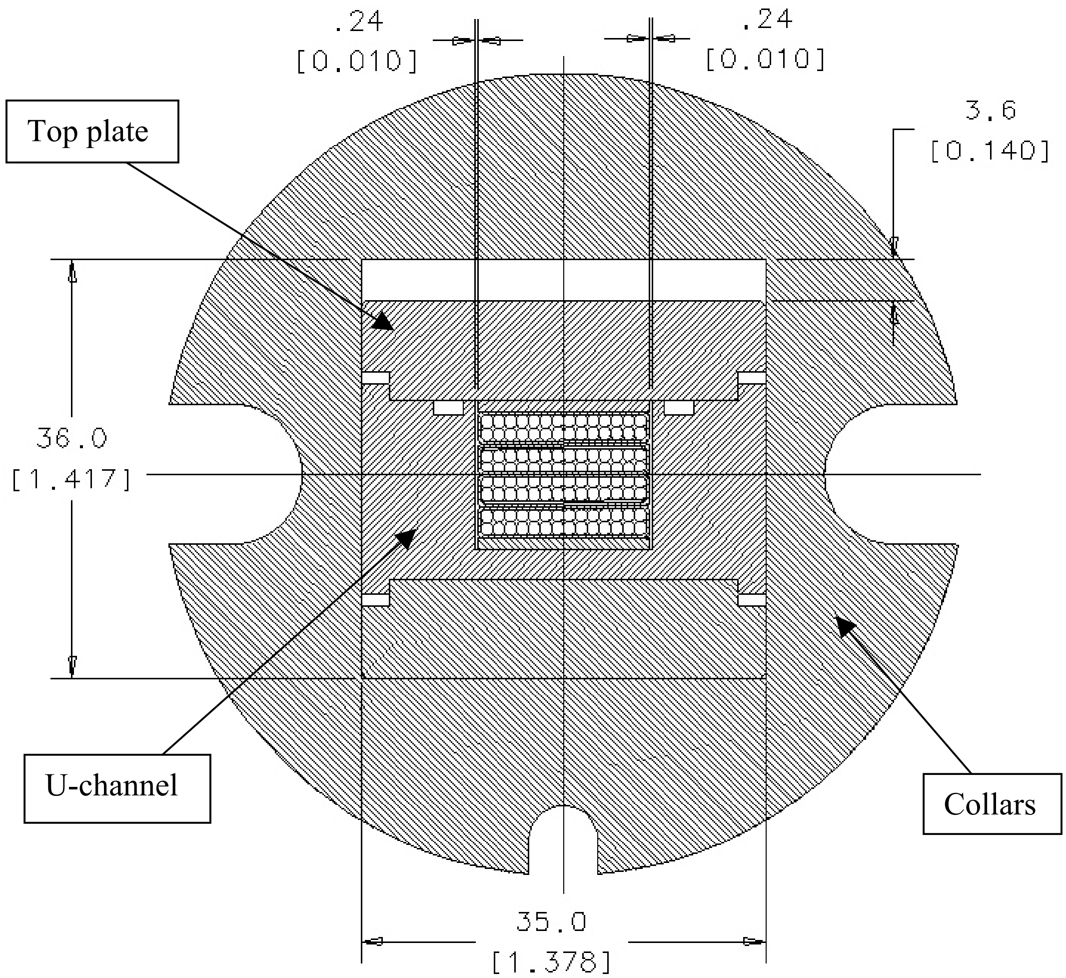


Figure 2: Cross-section of the holder. The innermost cables are active samples, the outermost cables provide a "magnet like" environment.

Pre-stress will be applied by means of interference between the coil and the top plate of the inner holder and by the bolts going through the collars. The interference will be created by inserting a Kapton film (50 μm thick) on the top of the cable stack after impregnation. The bolts will be used to push the top plate in contact with the U-channel, closing the gap created by the interference. In case of excessive load applied to the bolts the extra-load will be transferred to the sides of the U-channel, that is stiffer than the cable stack, reducing the risk of excessive pre-stress on the cables. More details about the design of this sample holder may be found in [5].

2. MAGNETIC MODEL

The magnetic forces in the X-section were calculated by ANSYS ® at 32 kA and 10 T in three orientation of the sample self-field with respect to the background field: transverse, parallel and anti-parallel. The background field was simulated by setting boundary conditions on the vector potential (z-component only because of the 2D symmetry). The error caused by these boundaries in the field distribution on the cables is lower than a few percents. The same technique was adopted for the FEM analysis of cable sample holder for tests at BNL [6]. The sample holder has right/left symmetry, but symmetry conditions couldn't be used to model the transverse background field. Therefore a full model (i.e. without using symmetry conditions) was created and used in all cases. The current is flowing in opposite direction in the cables so that the maximum self-field (2.2 T at 32 kA) is in between them. The modulus of the field and the direction of the magnetic forces in the cross-section of the active cables are shown in Figures 4 to 11. Table 1 reports the total magnetic force on the top cable in each case.

Force Field	Horizontal (kN/m)	Vertical (kN/m)
Self-field	0	31
Parallel	0	361
Anti-parallel	0	-300
Transverse	320	31

Table 1: Magnetic force on the top cable at 32 kA and 10 T (except self-field case). Directions refer to Figure 2.

3. STRUCTURAL MODEL

The mesh of the finite element (FE) model used for the structural analysis is shown in Fig. 3. Since symmetry couldn't be used in case of transverse background field, the same model (without using symmetry conditions) was used for all cases. The same subroutine used to generate the mesh of the coil area in the magnetic model was used also in this model. This procedure allowed the automatic uploading of the forces generated by the magnetic model on the structural model. Contacts elements (see Fig. 3) were set all around the coil (mold-release should prevent it to be glued to the case), among the three parts of the stainless steel case and between the case and the "collars". The bolts used to apply pre-stress were simulated by a shim with the same width of the bolt diameter. The material properties of this shim were trimmed in order to simulate the bolts: the elastic modulus used was the one of stainless steel divided by the filling-factor (0.314) of the bolts with respect to the shim. The pre-load was applied by means of two interferences. The first (50 μm) modeled the Kapton layer inserted after impregnation; the second (50 or 100 μm) generated the load in the bolts (see Figure 3).
Because of the contact elements the problem was non-linear. Therefore the analysis of the cooldown effect was initiated from the solution of the analysis simulating the application of the pre-stress. In the same way the analysis of the effect of the magnetic forces was initiated from the results after cooldown.

4. MATERIAL PROPERTIES

Table 2 lists the material properties used in the FE calculations presented in this note.

Parts & Materials		Elasticity Modulus				Thermal Contraction Coefficient			
		300 K [GPa]		4.2 K [GPa]		300–4.2K [mm/m]		per 1 K [μm/m/K]*	
		X	Y	X	Y	X	Y	X	Y
Coil	Impregn. Cu/Nb_3Sn, ceramic ins	13	10	18.2	13	3.3	4.5	11.5	15.6
Shims	G10	18	14	18	14	2.75	7.62	9.5	26.4
Case & collars	Stainless Steel 316	210	210	225	225	3	3	10.3	10.3
Bolts	S. Steel 316 E scaled by fill fact.	66	66	71	71	3	3	10.3	10.3

Table 2: Material Properties used in the analyses presented in this report (*calculated from integrated contraction between 300 and 4 K, assuming a linear contraction coefficient)

5. RESULTS

Figures 4 to 11 show the results of the magnetic analysis with 32 kA in each cable. In the first case (Fig 4-5) field modulus and magnetic forces are computed with no background field. The maximum self-field is about 2.2 T. In the second case the background field (~10 T) is parallel to the self-field between the cables. This orientation gives the maximum total field on the cables (12.5 T). In the following case the background field is oriented anti-parallel to the self-field. In this configuration the minimum field is located between the cables (8 T), the maximum is on the outer surfaces of the cables (10.5 T) and the magnetic forces are pushing the cables one against the other. The results with the background field transverse to the large face of the cables are shown in Fig. 10 and 11.

The results of the mechanical analyses are shown from page 12 to the end. Each page contains the results of a run. The first two plots of each run give information about the contact elements: the first plot shows their status of the (1=open, 2=closed), the second shows the gap dimension (m) if the contact is open. The third and fourth plots show the stress in Y (transverse to the large face of the cables) and X direction in the active cables. The last plot shows the Von-Misses equivalent stress in the whole model. The line at the end of each page reports the vertical stress on the bottom edge of the shim simulating the bolts: shim width (m), stress integral (Pa), stress average (Pa) and the force (N) that should be applied to each bolt of the collars in order to have the same force/meter on the top plate.

Pages from 12 to 14 show the results of the analysis in case of a moderate pre-stress (50 μm interference over the coil and for the bolts). At room temperature (pag. 12) the average pre-stress in the direction normal to the cables (SY) is about 40 MPa and the bolt load is 25 kN. Page 13 shows the results after cooldown. Since the thermal contraction of the coil package is higher then the contraction of the holder the pre-stress decreases to about 24 MPa. Page 14 shows the results with 32 kA and 10-T background field parallel to the self-field. The active cables are still completely under transverse pressure (from 5 to 28 MPa) and the bolts see a small load increment (2%).

Pages from 15 to 18 show the results of the analysis in case of a higher pre-stress (50 μm interference over the coil and 100 μm interference for the bolts). At room temperature (pag.15) the average pre-stress in the direction normal to the cables (SY) is about 45 MPa and the bolt load is 53 kN. The last plot shows that large part of the load applied by the bolts is transferred to the U-channel avoiding to overload the coil package. During the cooldown the transverse stress in the coil decreases to about 30 MPa. Page 17 shows that with 32 kA and 10-T background field parallel to the self-field, the active cables are under transverse pressure in the range 13 to 35 MPa.
Page 18 shows the results in case of transverse background field and the same pre-stress of the previous case. The fifth plot shows the share stress in the active cables and in the insulation between them. The maximum share stress is 19 MPa. The epoxy-impregnated insulation should withstand this shear stress, but a possible weak spot is the boundary between the bare cable and the insulation. Residues deposited on the strand surface during the heat treatment (ceramic binder, oil used during cabling, other) weaken the bonding between the epoxy and the copper surface of the strands (as shown by the easiness in pealing off the impregnated insulation). Therefore this sample orientation with respect to the background field may cause a long training.

6. REFERENCES

1) A.P. Verweij, et al., *"1.9 K Test Facility for the Reception of the Superconducting Cables for the LHC"* IEEE Trans. on Applied Superconductivity Vol. 9, No 2, p. 153-156 (1999).
2) P. Bauer, K. Ewald, J. Ozelis *"Design of a Sample Holder for Measurement of Nb_3Sn Cable Critical Current Under Transverse Loading Conditions"*, Fermilab Technical Division note TD-99-051*.
3) P. Bauer, et al. *"Fabrication and Testing of Rutherford-type Cables for React and Wind Accelerator Magnets",* IEEE Transactions on Applied Superconductivity, vol. 11, no. 1, pp. 2457-2460, (2001).
4) P. Bauer, et al., *"Results of the Third Series of Measurements of the Critical Currents of Nb_3Sn Cables for the React & Wind Cable Development Program"*, Fermilab Technical Division note TD-01-069*.
5) G. Ambrosio, et al., *"Design of a Sample Holder for Nb_3Sn Cable Test at F.R.E.S.C.A."* Fermilab Technical Division note under preparation.
6) G. Ambrosio *"2D Magnetic and Mechanical Analysis of the Sample Holder for Cable Test at BNL"*, Fermilab Technical Division note TD-04-001*.

* Available on line at: http://www-td.fnal.gov/info/td_library.html

APPENDIX - PLOTS

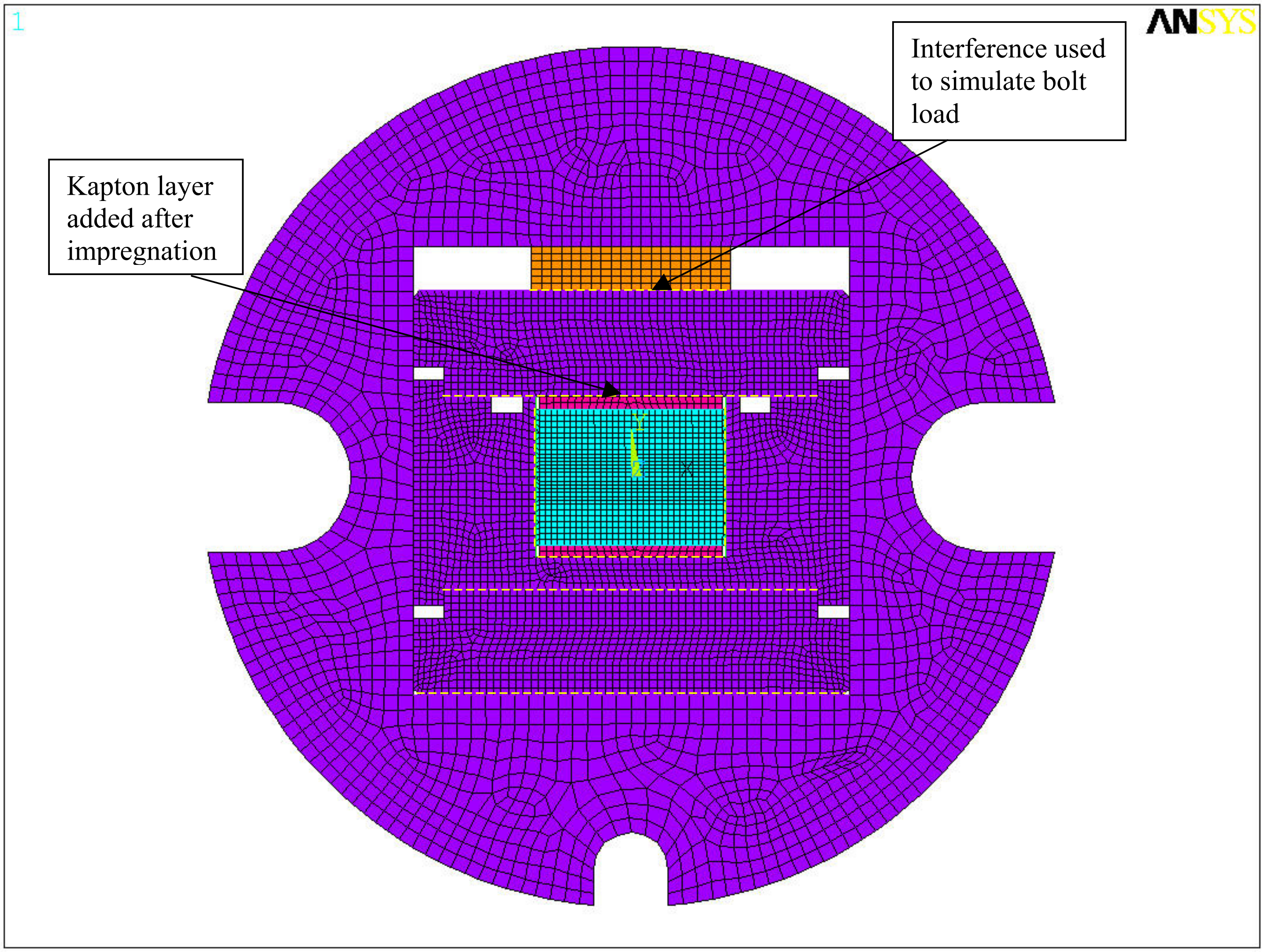
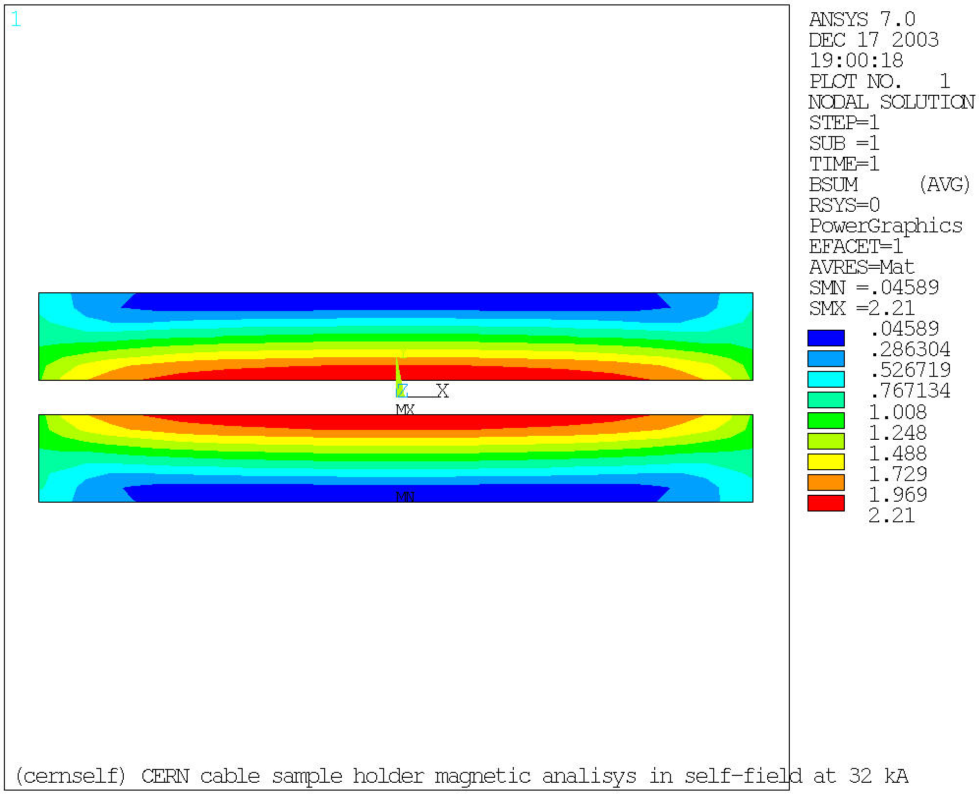


Figure 3: Finite element model for mechanical analysis. Different colors indicate different materials. Yellow dashed lines show the contact elements.



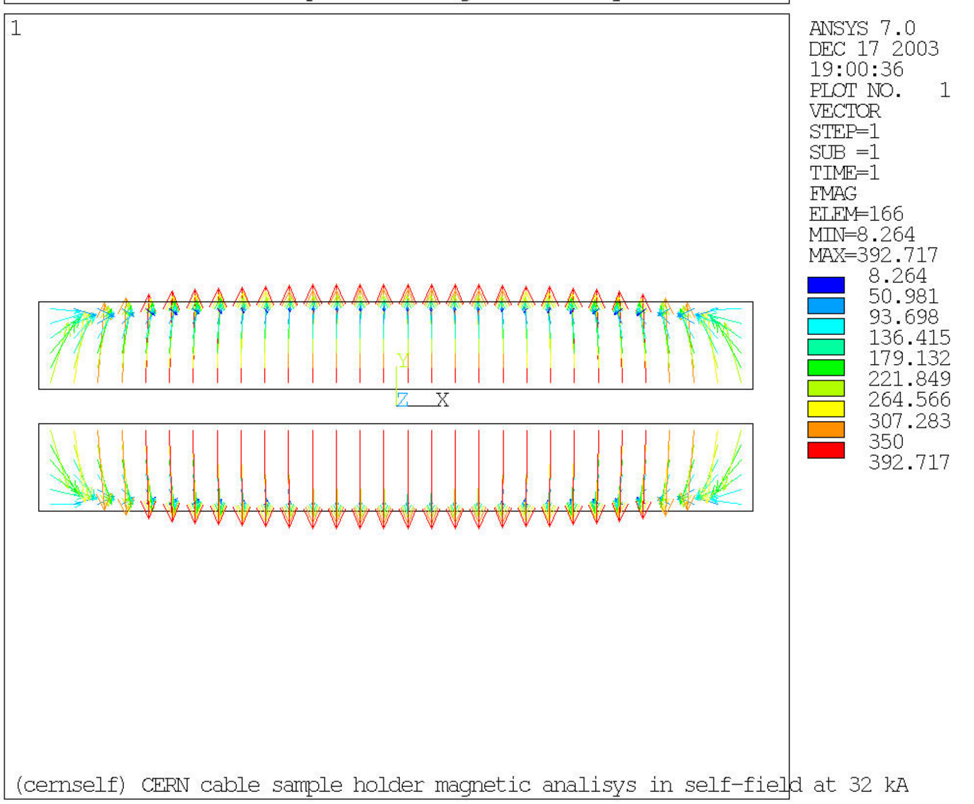


Figure 4-5: Field modulus and magnetic force distribution in the cables at 32 kA without background field.

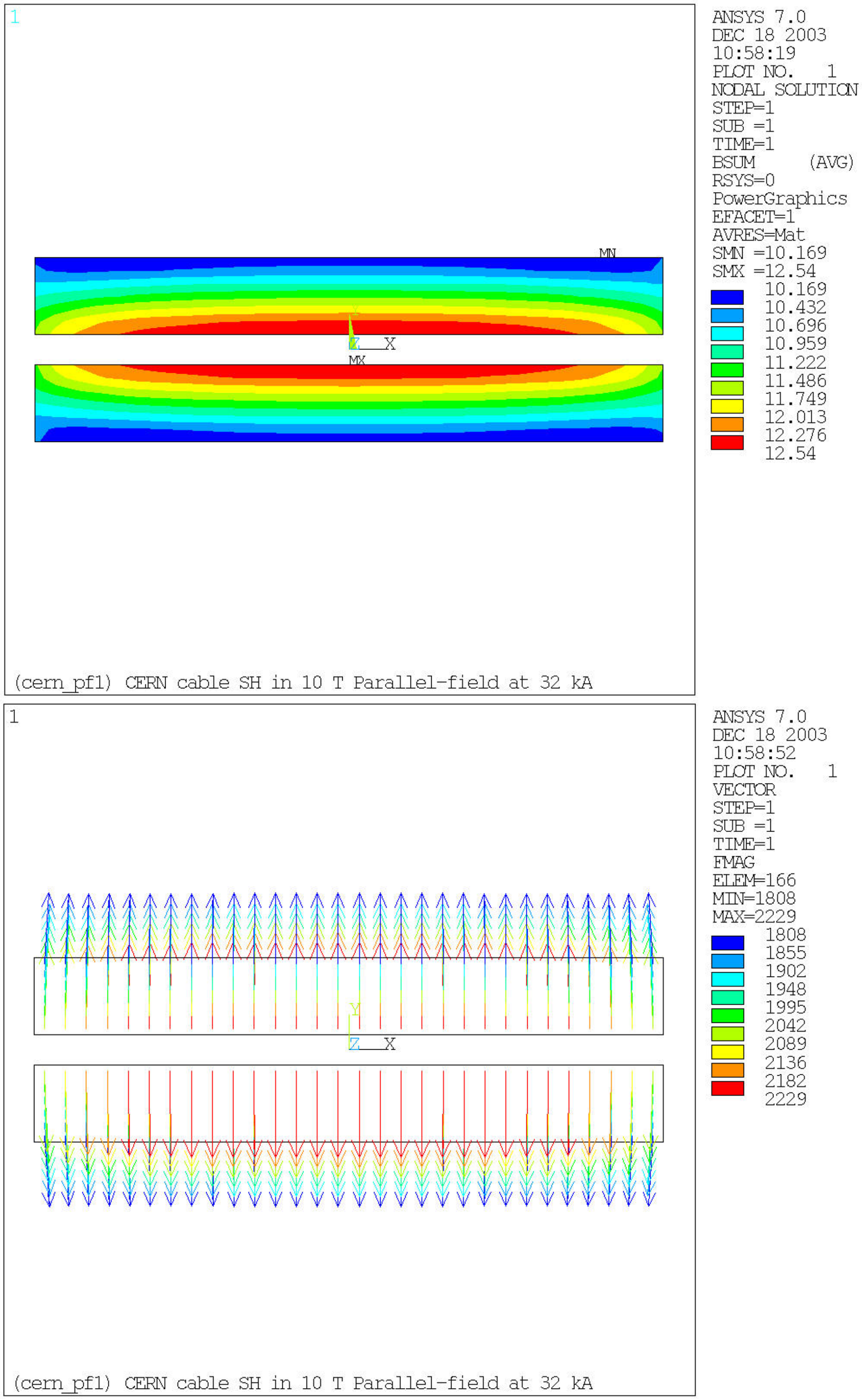
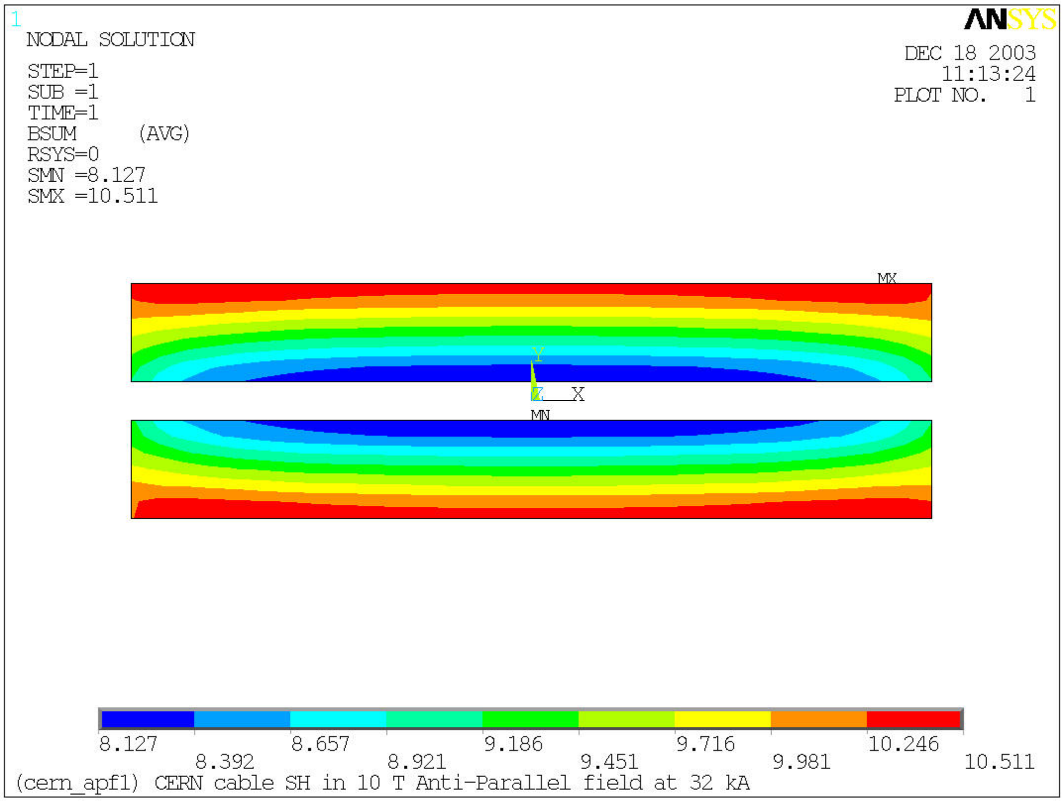


Figure 6-7: Field modulus and magnetic force distribution in the cables at 32 kA with 10T parallel background field.



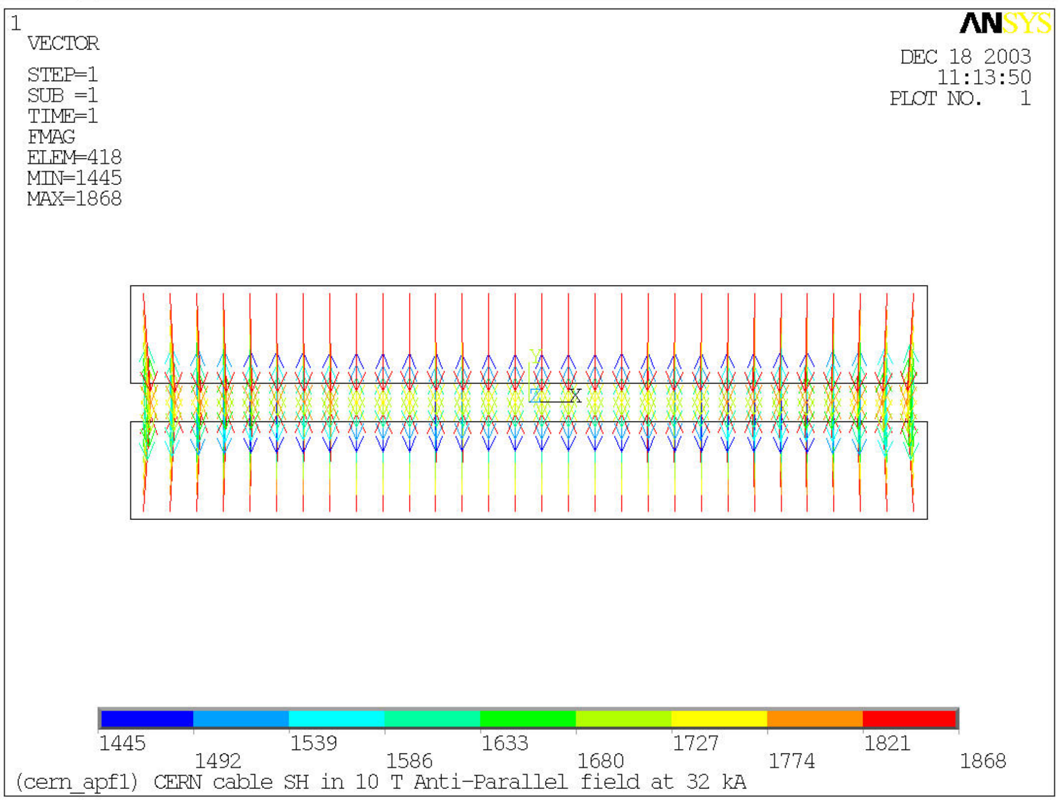
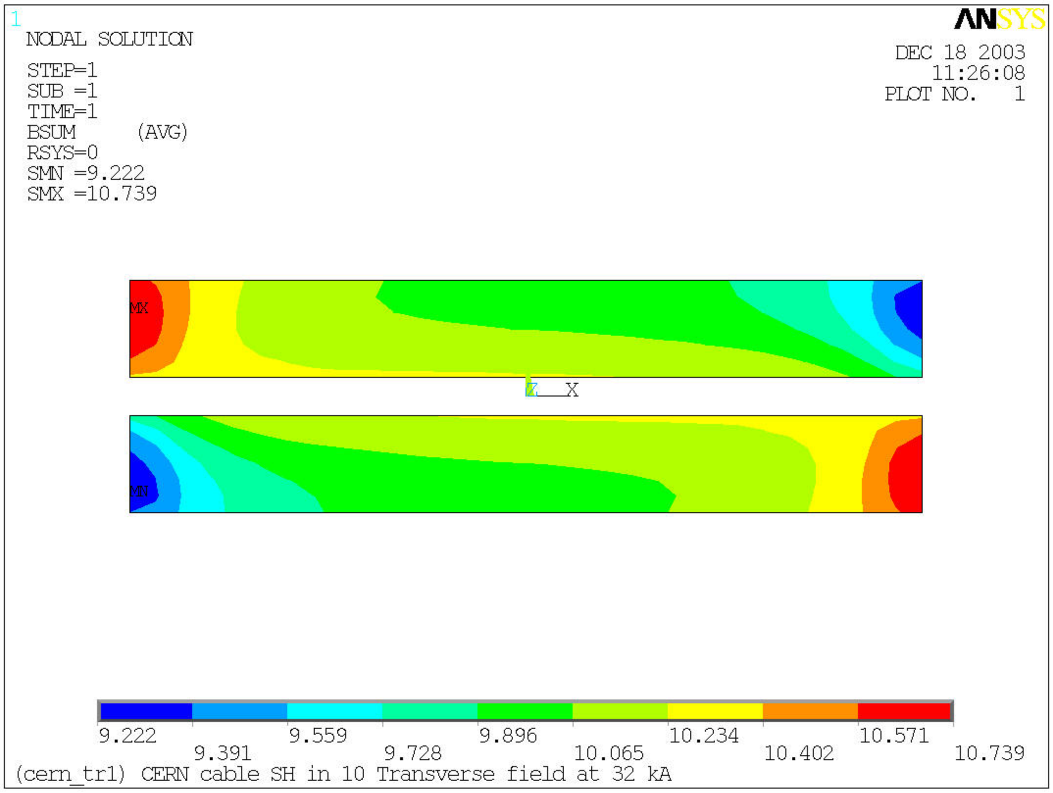


Figure 8-9: Field modulus and magnetic force distribution in the cables at 32 kA with 10T anti-parallel background field.



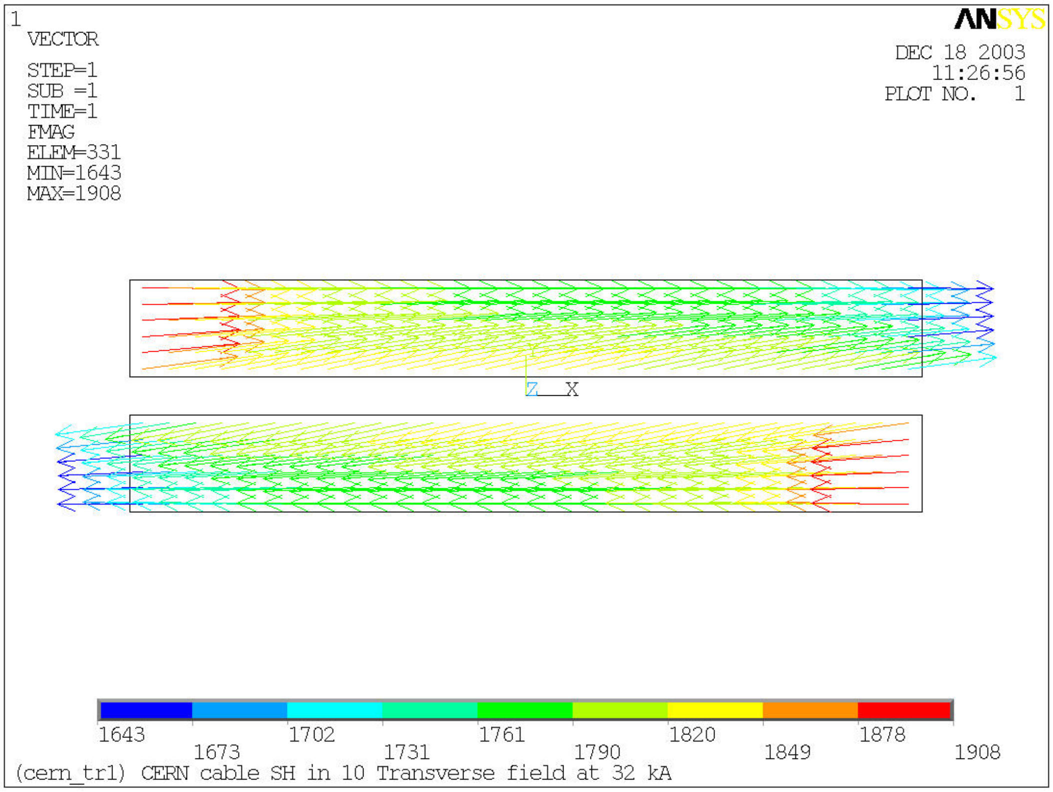
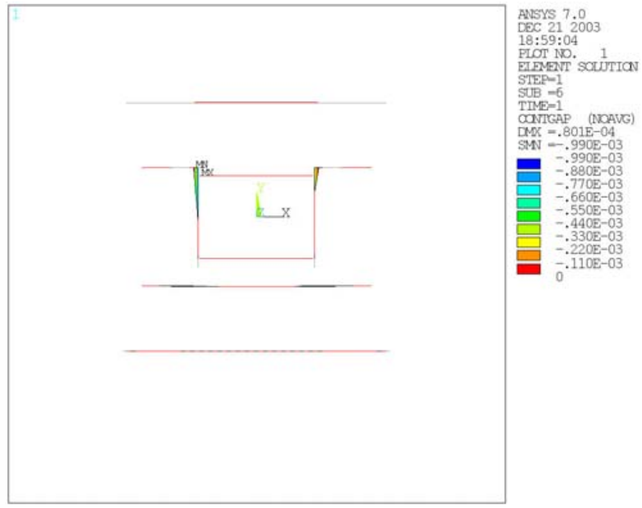
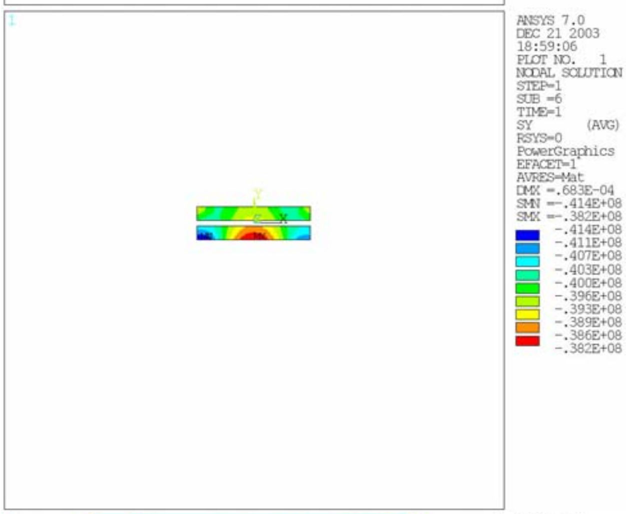
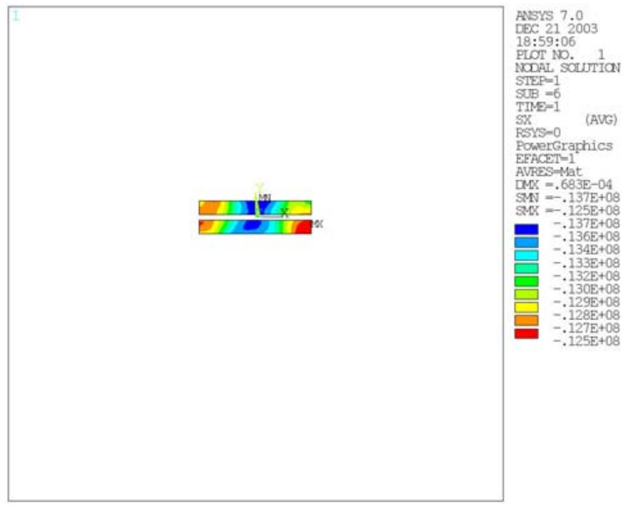


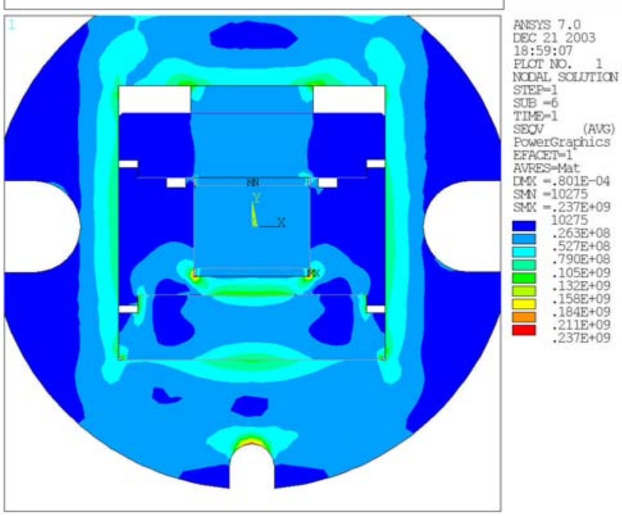
Figure 10-11: Field modulus and magnetic force distribution in the cables at 32 kA with 10T transverse background field.

Pre-stress at room temperature (2 mil coil interference – Low bolt load)
(File: CERNmech_p2) ***Bolt_interf.: 50 µm Coil_interf.: 50 µm***







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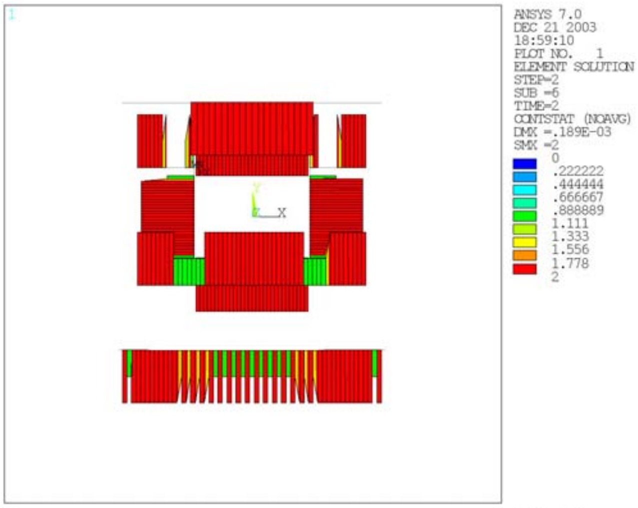
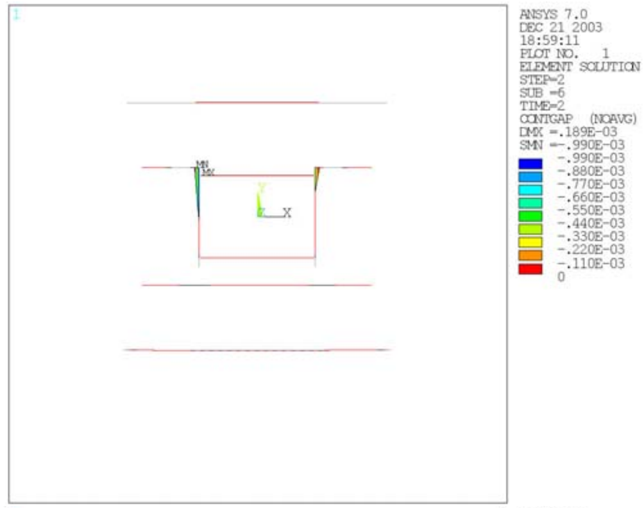
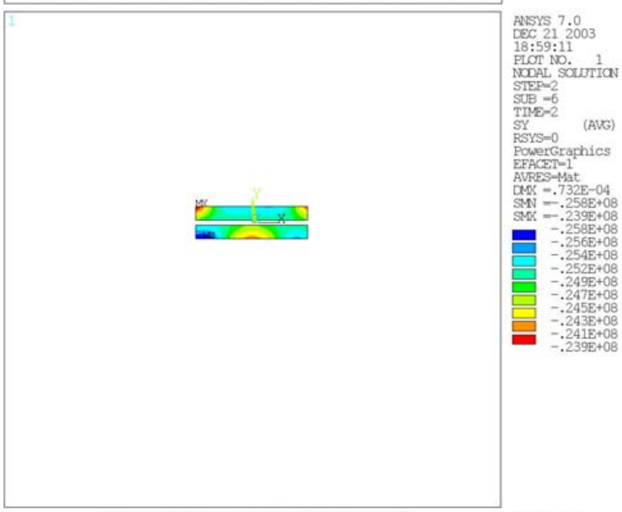
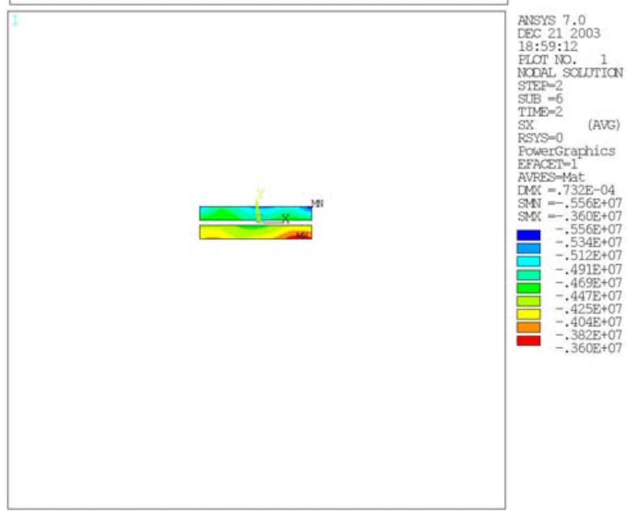
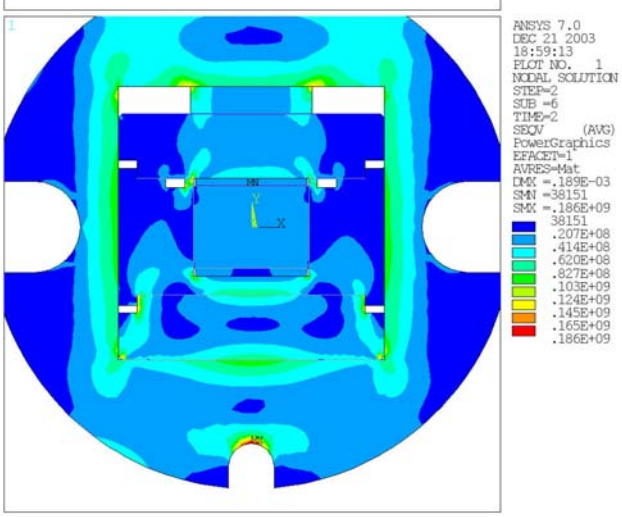
After cooldown at 4.2 K









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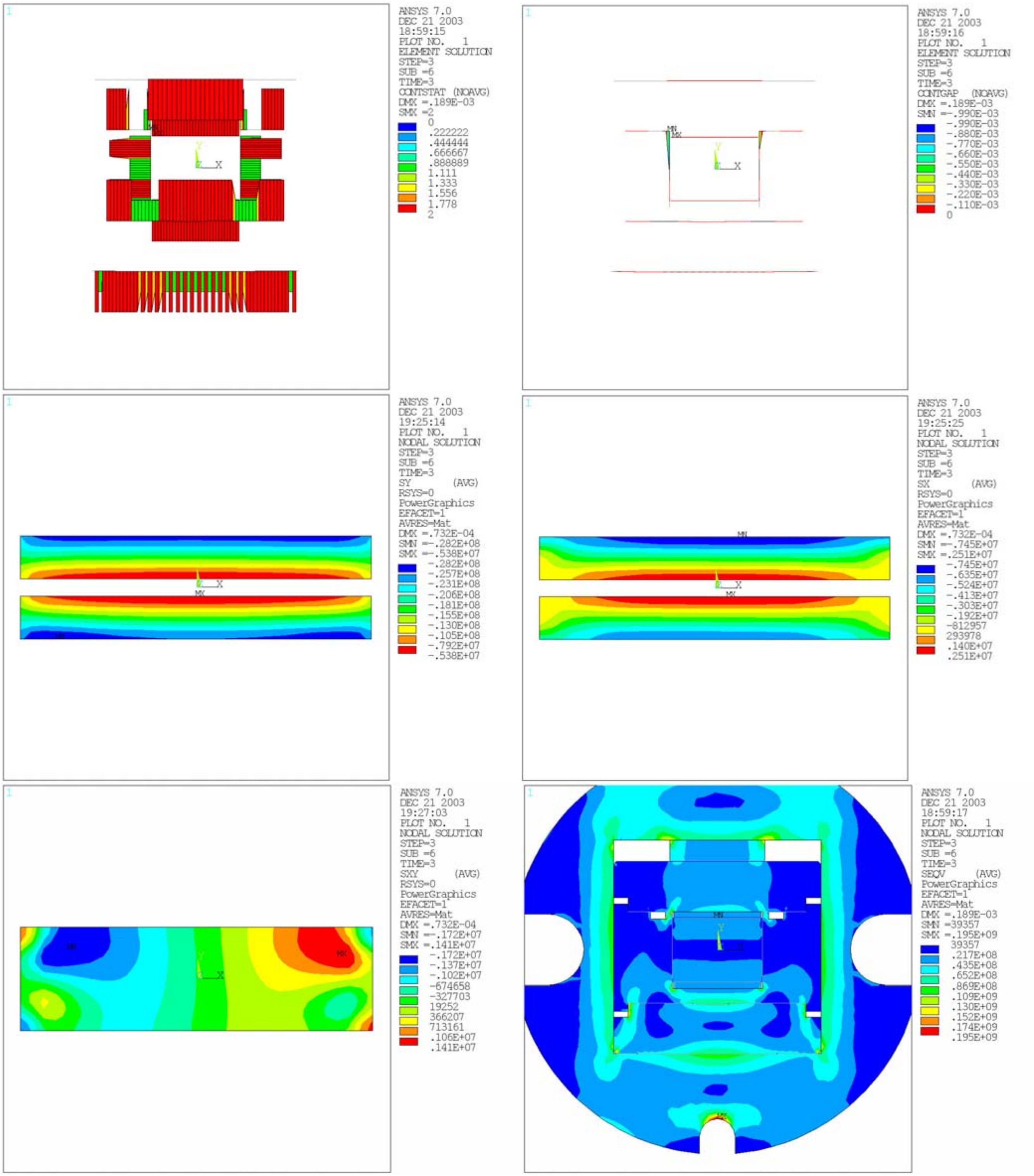
Magnetic Forces: Parallel field (10T) Max Current (32 kA)



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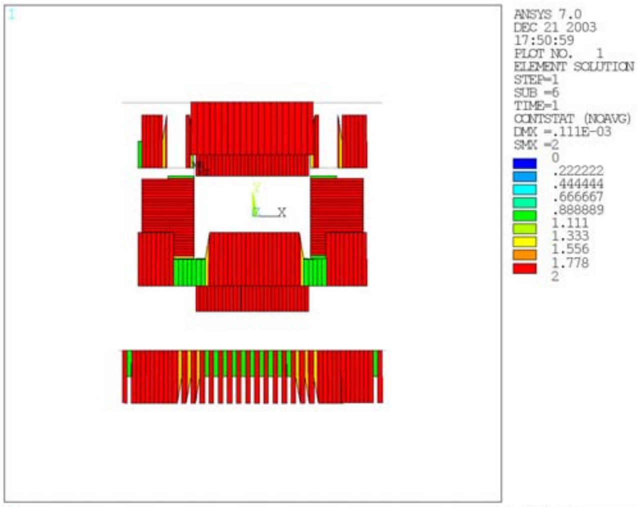
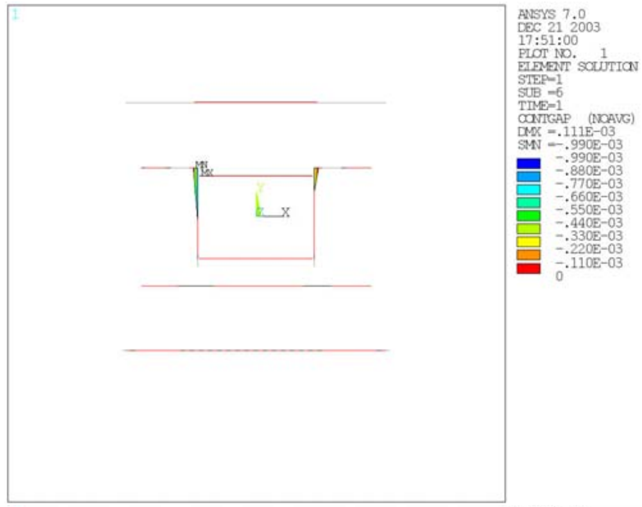
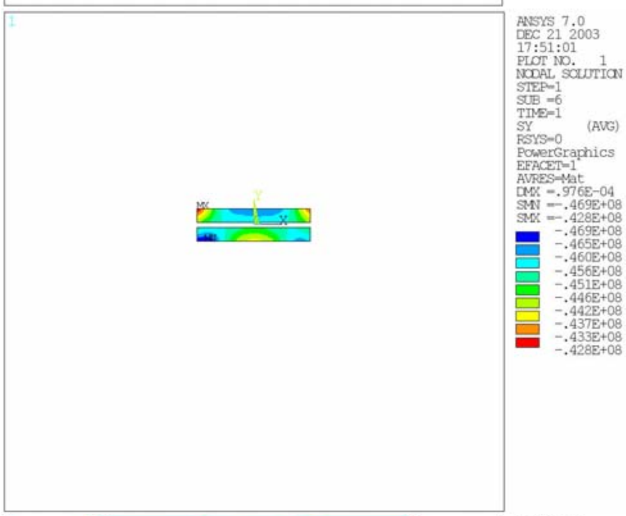
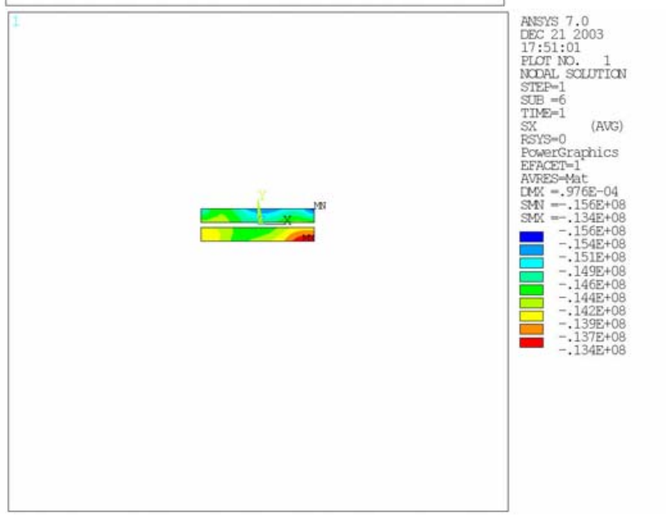
Pre-stress at room temperature (2 mil coil interference – High bolt load)

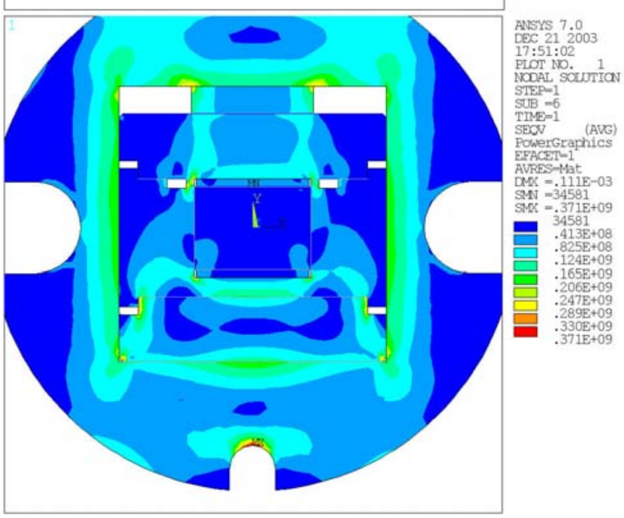
(File: CERNmech_tr1) ***Bolt_interf.: 100 µm Coil_interf.: 50 µm***









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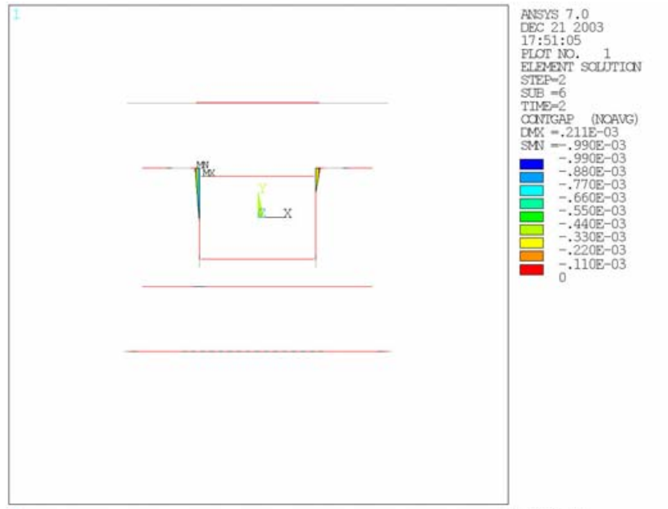
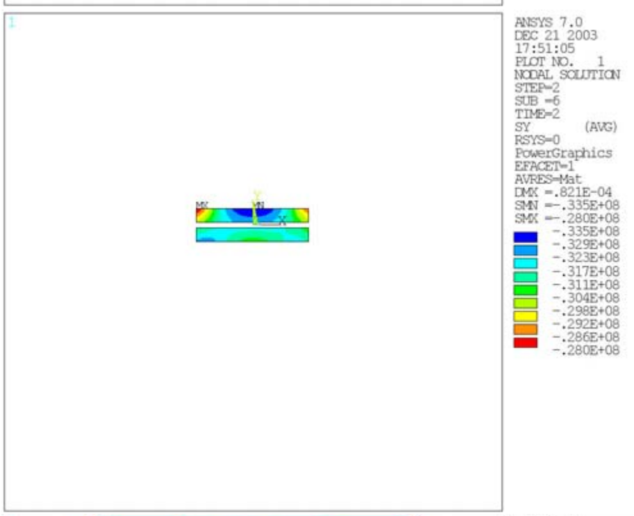
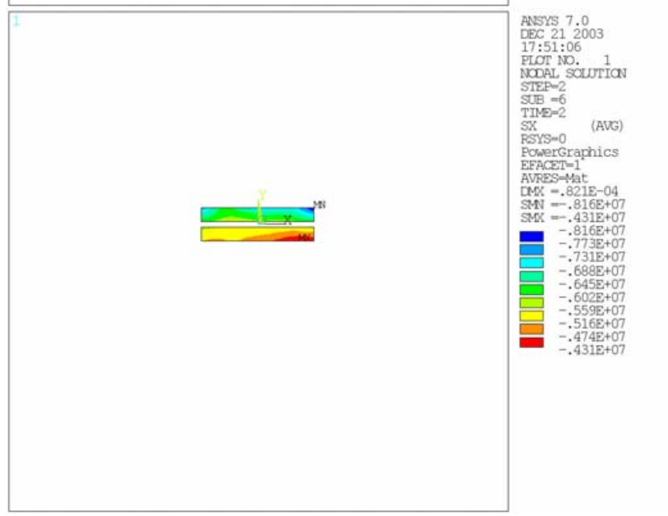
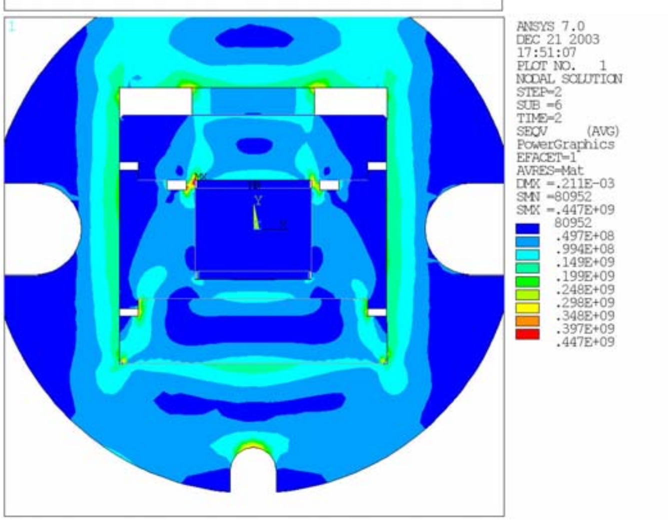
After cooldown at 4.2 K







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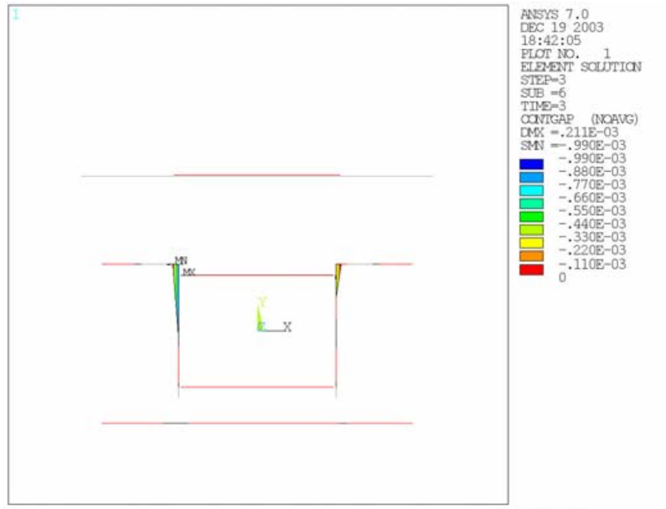
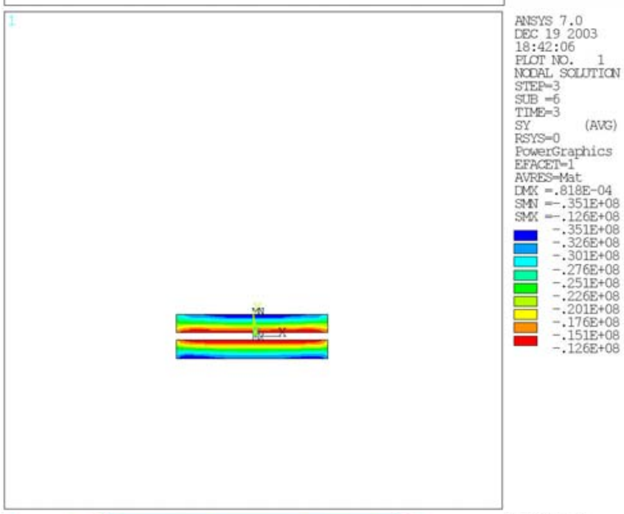
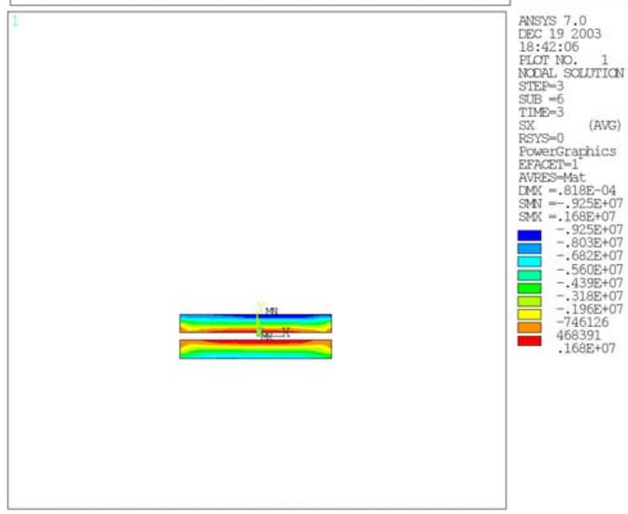
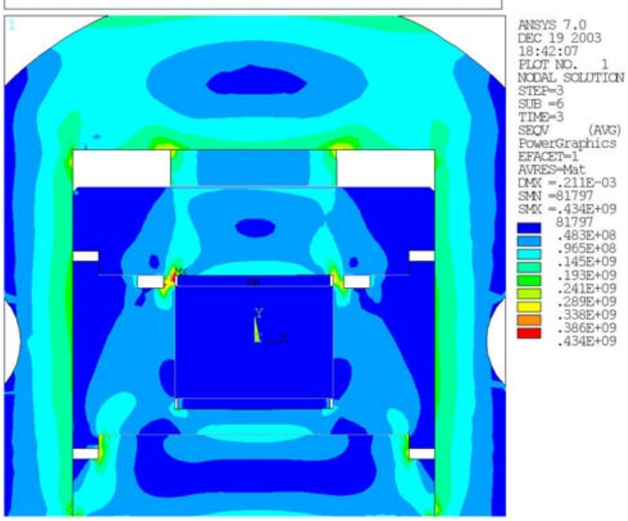
Magnetic Forces: Parallel Field (10 T) & Max Current (32 kA)







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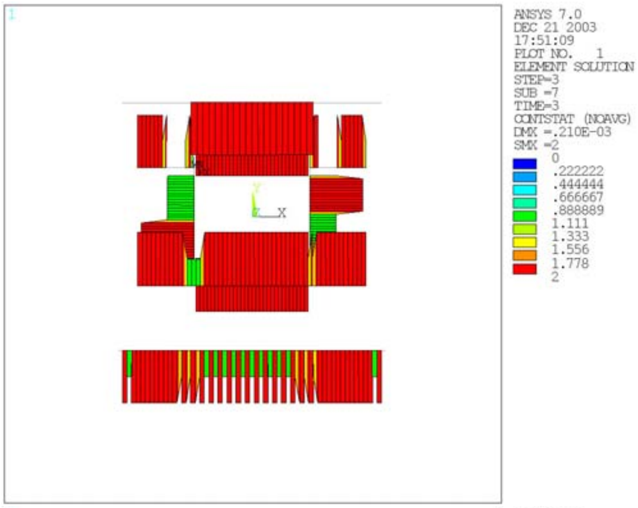
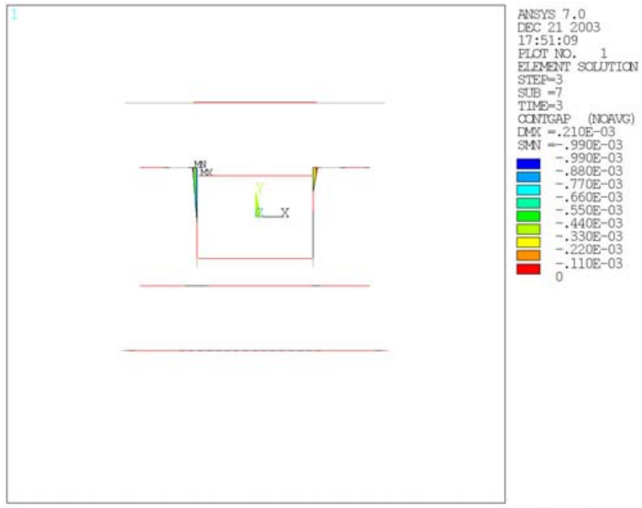
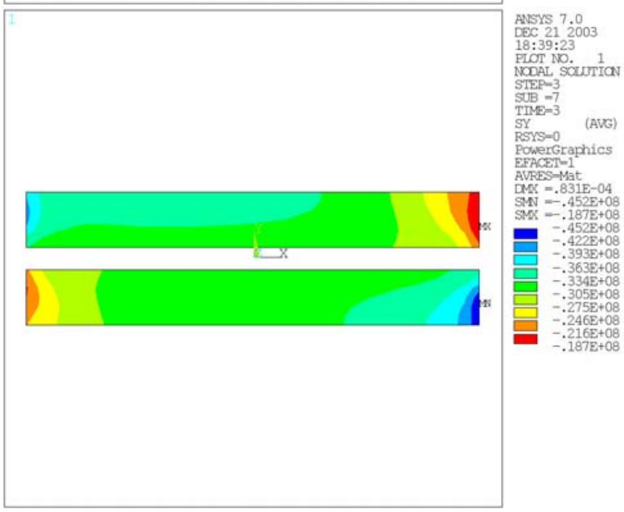
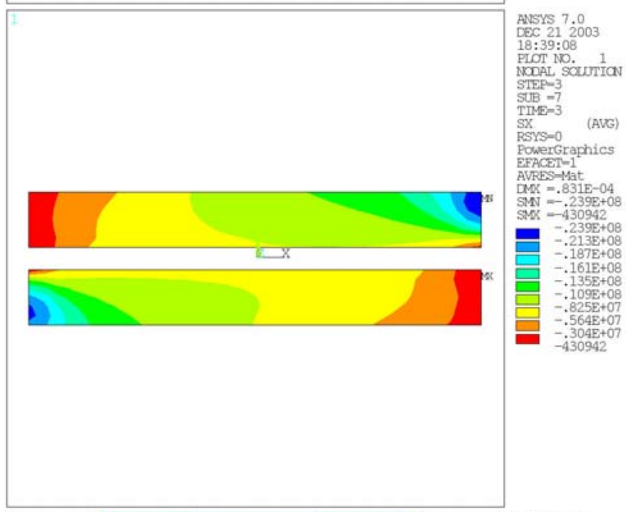
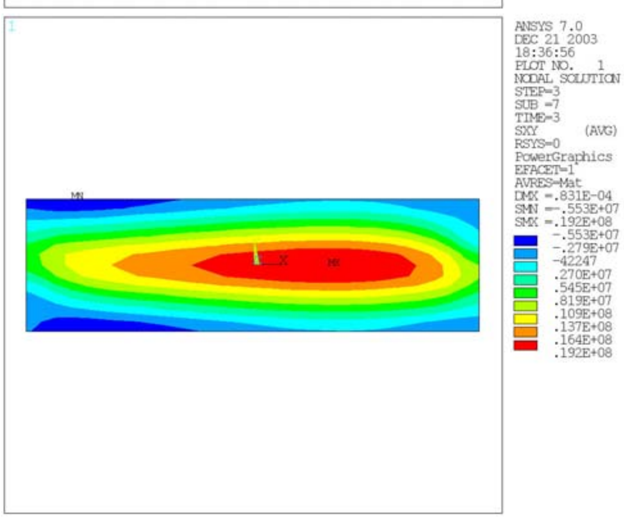
Magnetic Forces: Transverse field (10T) & Max Current (32 kA)

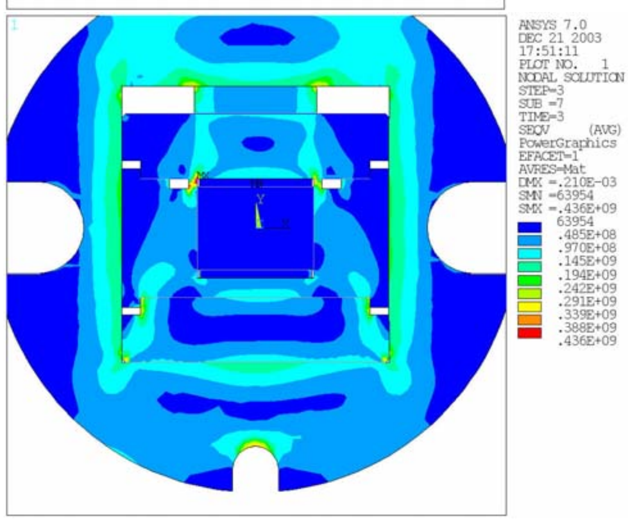










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