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2D MAGNETIC AND MECHANICAL ANALYSIS OF THE SAMPLE HOLDER FOR CABLE TEST AT BNL

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Abstract:

A Finite Element analysis was performed in order to compute the stress distribution in the Nb_3Sn cables, made of 1-mm strand, to be tested at BNL cable test facility. The goal of this study was to choose the best orientation of the cable, with respect to the background field, for the first test. In the BNL cable test facility the sample can be oriented with the background field normal or parallel to the large face of the cables. Therefore there are three different set-ups: the background field may be transverse or parallel or anti-parallel to the cable self-field. The last orientation was chosen for the first test (with a very low prestress on the cables at room temperature) because it should give less training then the others. This note reports the models used for the analysis and the results.

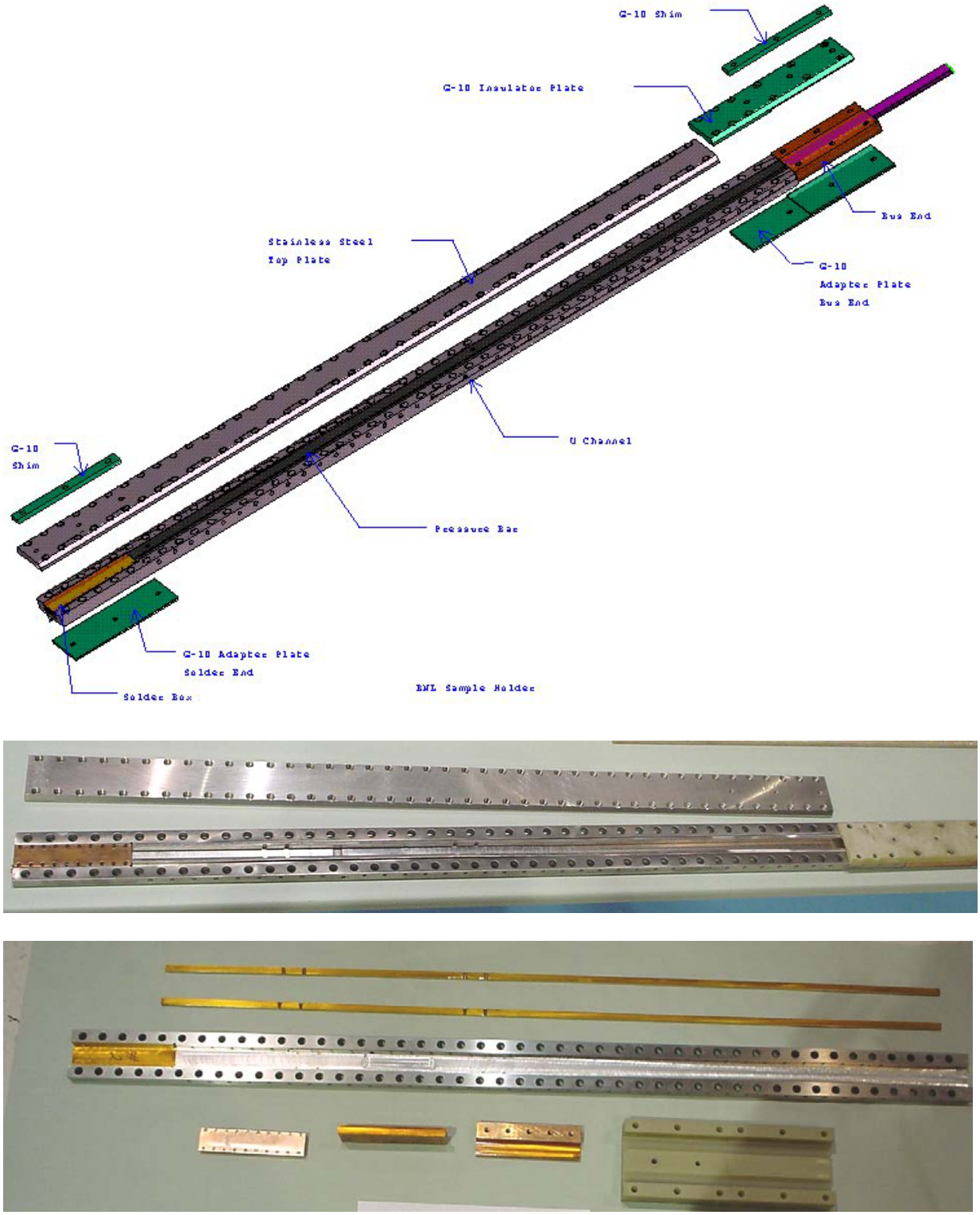


Fig. 1: Plot of the BNL cable sample holder (top) and parts of the sample holder before assembly.

1. SAMPLE HOLDER DESIGN

The cable sample holder is shown in Figure 1. It consists of stainless steel case surrounding four cables. The two active samples are in the center of the cable stack, while two dummy cables provide a magnet like environment and protect the active cables during assembly and prestress application. A detailed description of the sample holder may be found in [1].

2. MAGNETIC MODEL

The magnetic forces in the X-section were calculated by ANSYS ® at 15 kA without background field, and at 25 kA and 7.1 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 current is flowing in opposite direction in the cables so that the maximum self-field is in between them. The modulus of the field and the direction of the magnetic force in the coil cross-section are shown in Figures 4 to 11. The peak field in case of parallel orientation is 9 T. The symmetry was used to model only half coil in case of parallel and anti-parallel orientation of the background field. The whole coil had to be modeled to study the case of transverse background field.

3. STRUCTURAL MODEL

Also in this analysis the symmetry was used to model only half sample holder in case of parallel and anti-parallel orientation of the background field. The whole sample holder had to be modeled to study the case of transverse background field. The mesh of the finite element model used in this case is shown in Fig. 2. The same subroutine was used to generate the mesh of the coil area in the magnetic model and 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 area (mold-release was used to prevent the coil from being glued to the case), between the top cover and the U-channel of the sample holder, and between the epoxy layer and the inner sides of the U-channel (see Fig. 3). The bolts used to apply prestress were simulated by link elements with the same effective cross-section of the bolts per unit length. During the assembly of the first sample holder the prestress was applied by adding a 1-mil Kapton layer on the top of the cable stack after impregnation. This prestress was simulated by modeling an interference on the top of the cable stack and by applying an initial strain to the bolts in order to close the gap between the top cover and the U-channel of the sample holder at room temperature. Because of the contact elements the analysis is non-linear. Therefore the analysis of the cooldown effect was initiated from the solution of the analysis simulating the application of the prestress. In the same way the analysis of the effect of the magnetic forces was initiated from the results after cooldown.

4. MATERIAL PROPERTIES

Table 1 lists the material properties used in the finite element 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 insulation	13	10	18.2	13	3.3	4.5	11.5	15.6
Epoxy layer	Epoxy	27	27	28	28	13	13	49	49
Structure and bolts	Stainless Steel 316	210	210	225	225	3	3	10.3	10.3

Table 1: 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. In the first case (Fig 4-5) field modulus and magnetic forces are computed with 15 kA in each cable and no background field. The maximum self-field is about 1 T. In the second case the current is 25 kA and the background field of 7.1 T is oriented parallel to the self-field between the cables. The resulting maximum field is 8.96 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 (5.75 T) and the maximum is on the outer surfaces of the cables (7.48 T). 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 11 to the end. Each page contains the results of a run. The first two plots of each run regard the contact elements: the first shows the status of the contact elements (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 whole coil package (i.e. active and dummy cables). The following lines give the status of the bolts (first the main bolts used to close the sample holder, then the small bolts used to push the side shims).
Page 11 shows the results of the analysis of the half-holder model at room temperature after pre-stress application (1-mil interference). The average prestress in the direction normal to the cables (SY) is about 10 MPa. Page 12 shows the results after cooldown. Since the thermal contraction of the coil package is higher then the contraction of the holder the prestress goes down to 6 MPa and there is only a partial contact between the coil and the side pushers. Page 13 shows the results at 25 kA with 7.1 T of background field oriented parallel to the self-field. The insulation layer between the cables goes under tension (7.6 MPa max) and the bolt load increases by about 10%. The epoxy-impregnated insulation should withstand this small tension, 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 should be avoided, when the prestress is so small, because of the long training that may occur.

Page 14 shows the results in case of anti-parallel orientation of the background field. In this case the whole coil package remains under transverse compression. This is the most favorable orientation for the first test.

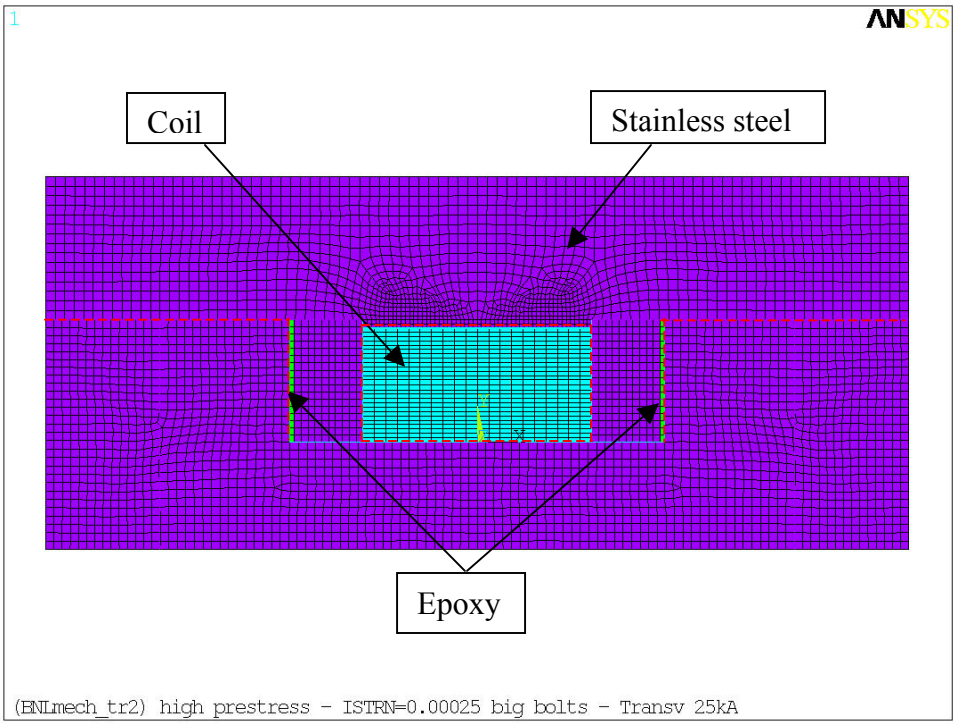
Page 15 shows the results of the magnetic forces at 15 kA without background field. The transverse compression is only slightly lower than after cooldown and the coil is still completely under transverse compression.

Pages 16 to 18 show the analysis of the full model used to study the case of transverse background field. The results after prestress application and after cooldown show symmetric solutions and values very similar to those obtained using the half-holder model. The symmetry is broken when the magnetic forces are applied. The last two plots of page 18 show the share stress in the whole cable stack (left) and in the active cables only (right). The maximum share stress on the edge of the active cables is 11 MPa. The epoxy-impregnated insulation can withstand this share stress, but a possible weak spot (as for parallel background field) is the boundary between the bare cable and the insulation. Therefore this sample orientation should be avoided, especially for tests at high current and high field, because of the long training that may occur.

6. REFERENCES

1) P. Bauer, K. Ewald, J. Ozelis "Design of a Sample Holder for Measurement of Nb_3Sn Cable Critical Current Under Transverse Loading Conditions", TD-99-051

APPENDIX - PLOTS



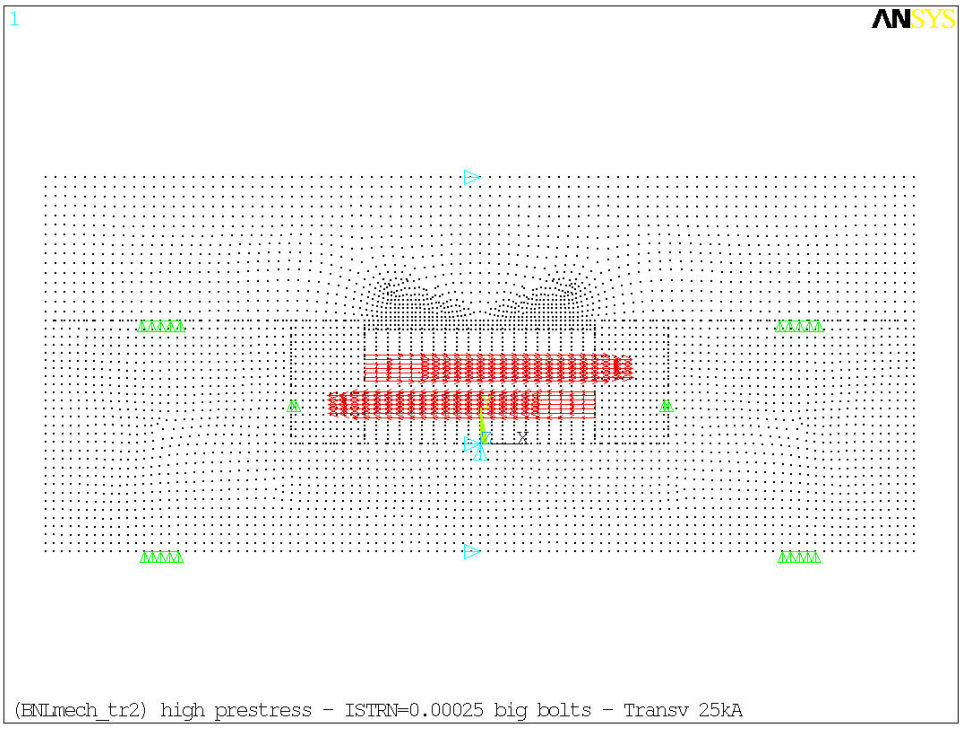
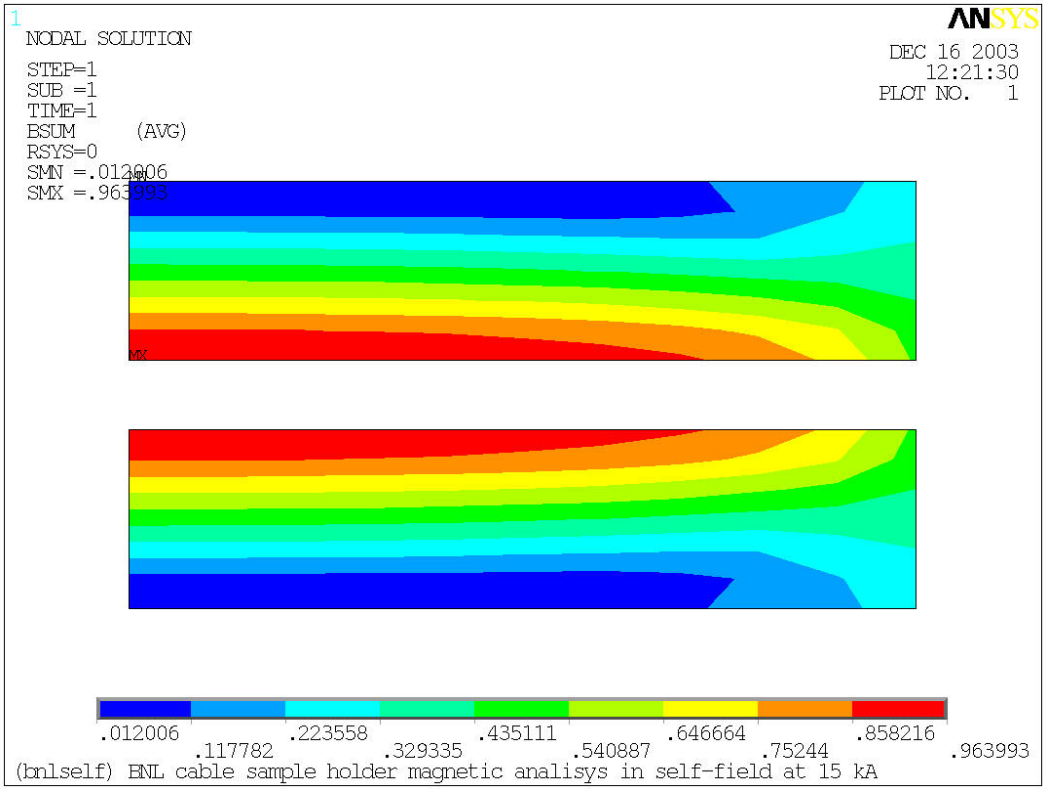


Fig. 2-3: Finite element model of sample holder. Different colors indicate different materials. Red dashed lines in Fig 2 show the contact elements. In Fig.3 the red arrows represent the magnetic forces in case of transverse background field, the green marks show the ends of the link elements used to simulate the bolts.



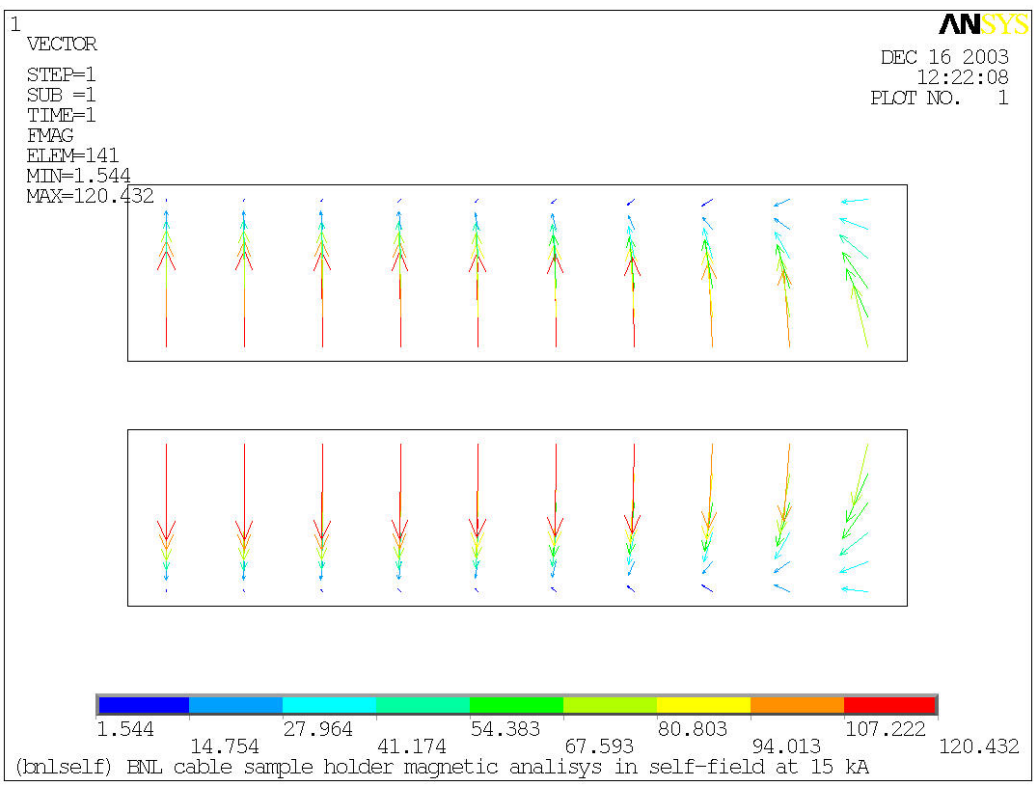
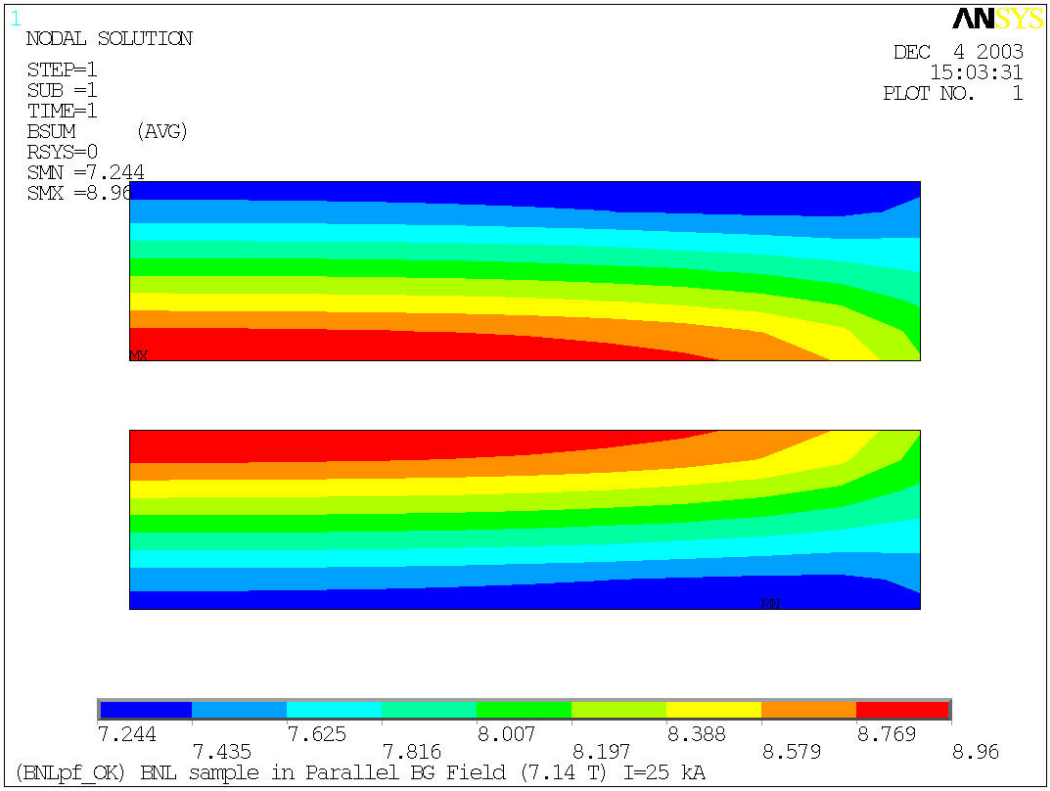


Fig. 4-5: Field modulus and magnetic force distribution in the cables computed at 15 kA without background field.



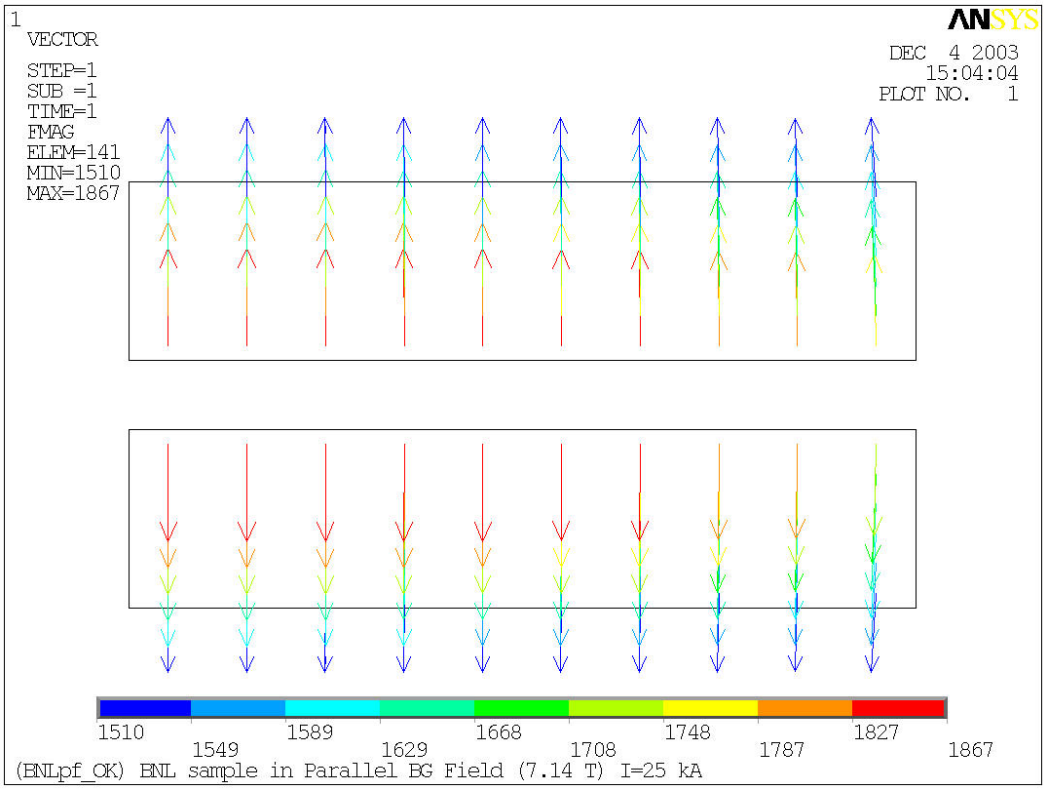
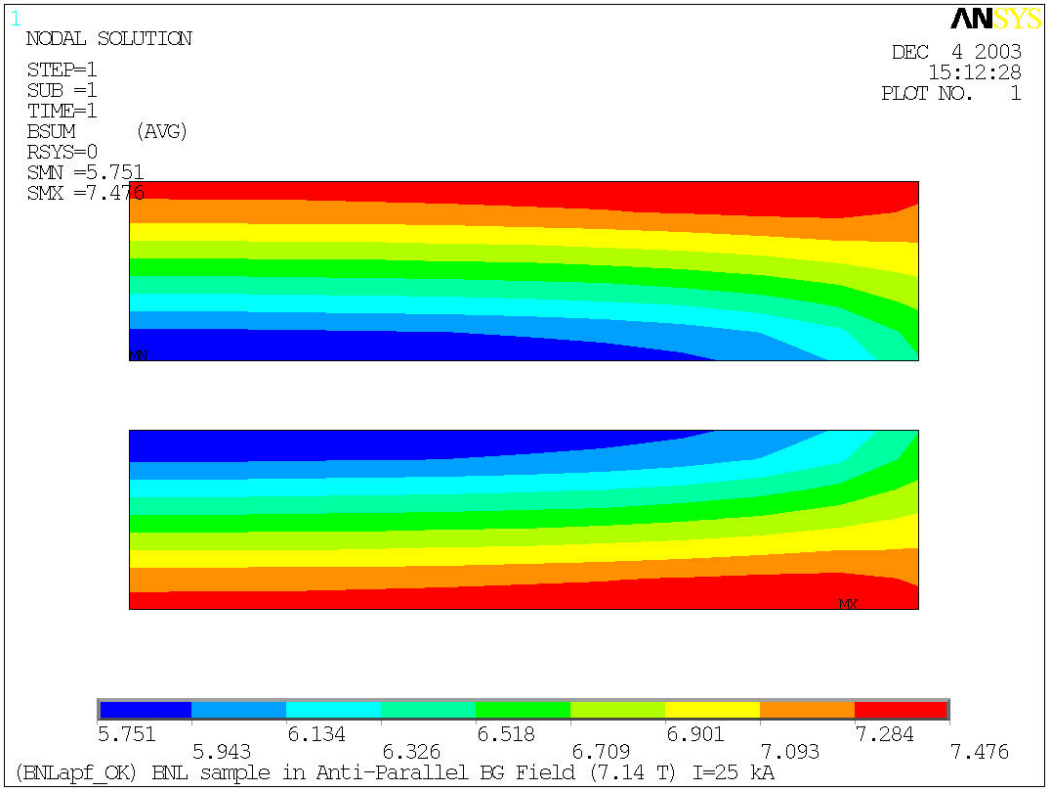


Fig. 6-7: Field modulus and magnetic force distribution in the cables computed at 25 kA with 7.1 T parallel background field.



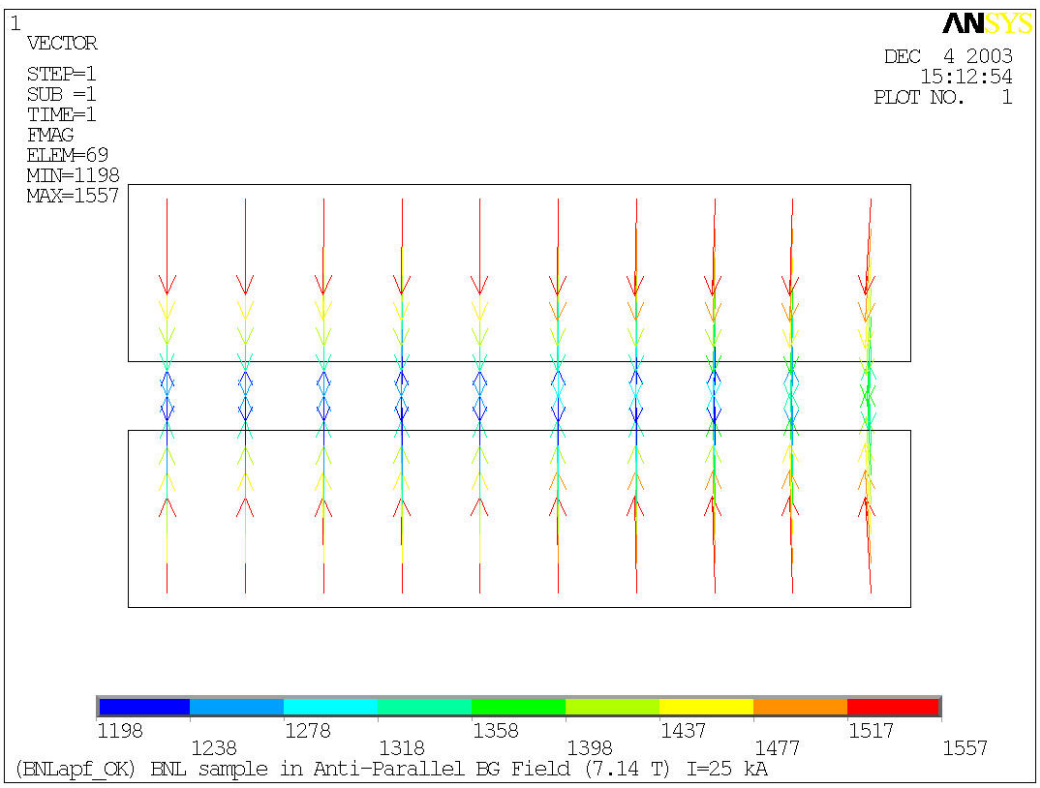
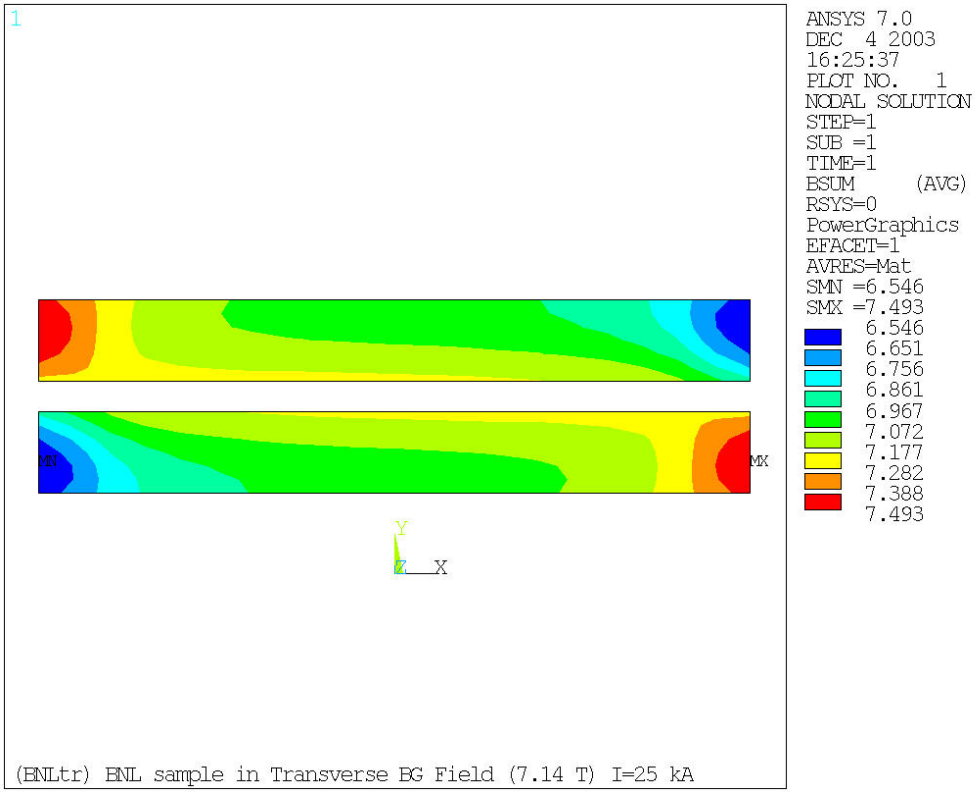


Fig. 8-9: Field modulus and magnetic force distribution in the cables computed at 25 kA with 7.1 T anti-parallel background field.



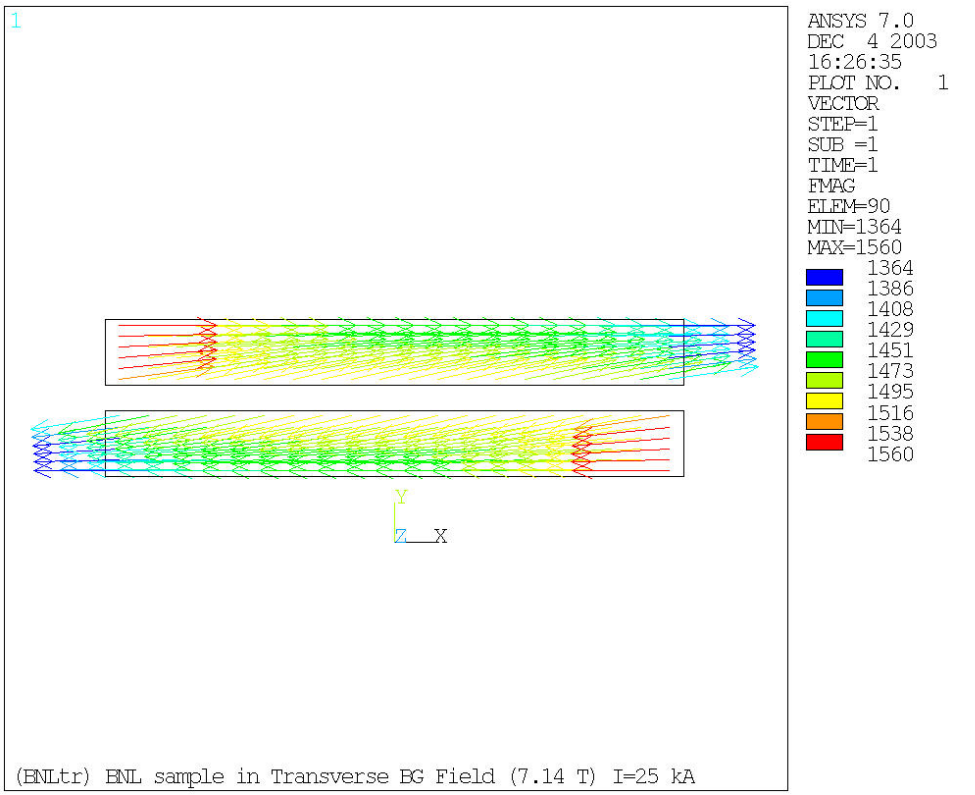
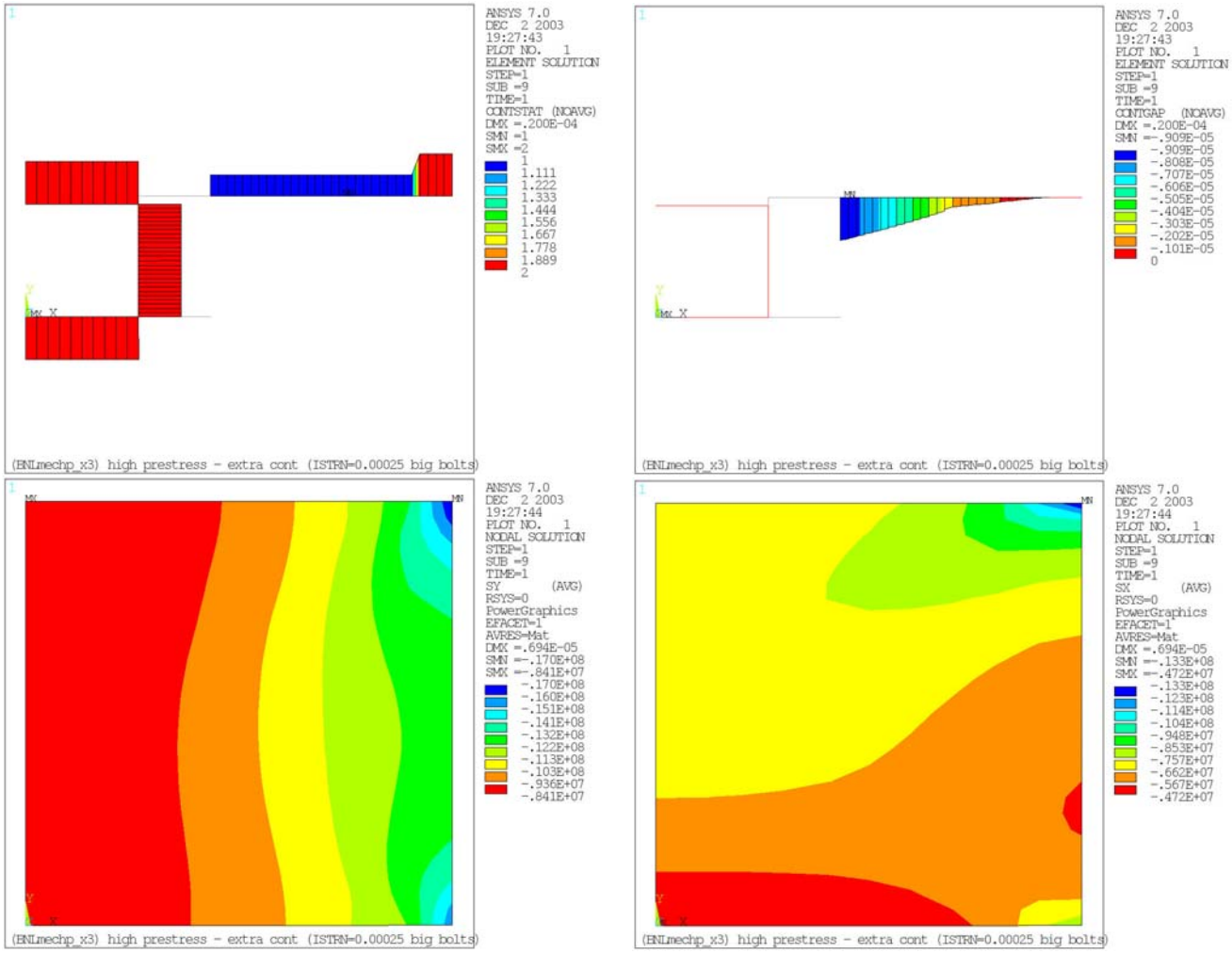


Fig. 10-11: Field modulus and magnetic force distribution in the cables computed at 25 kA with 7.1 T transverse background field.

Prestress at room temperature (1 mil interference)
(Files: BNLmechp_x3 and BNL_mech_p3) high prestrain of large bolts (=0.00025)

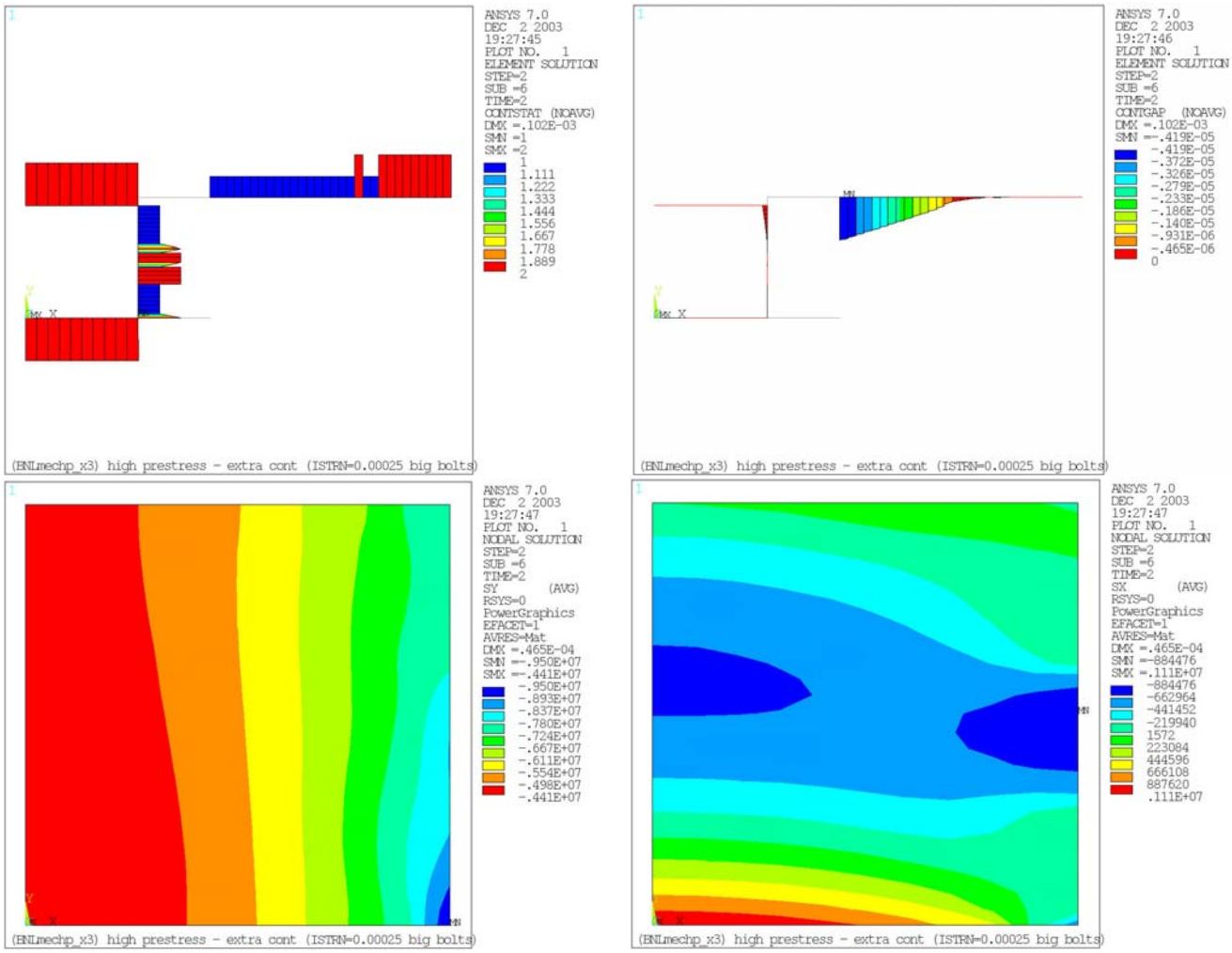



```
 LOAD STEP     1  SUBSTEP=     9
 TIME=    1.0000          LOAD CASE=  0

 TEMP =  293.00  293.00
MFORX= 0.14377E+06
SAXL= 0.60808E+08 EPELAXL= 0.000290 EPTHAXL= 0.000000 EPINAXL= 0.000250

 TEMP =  293.00  293.00
MFORX= -3795.9
SAXL=-0.57283E+07 EPELAXL=-0.000027 EPTHAXL= 0.000000
```

After cooldown (4.2 K)

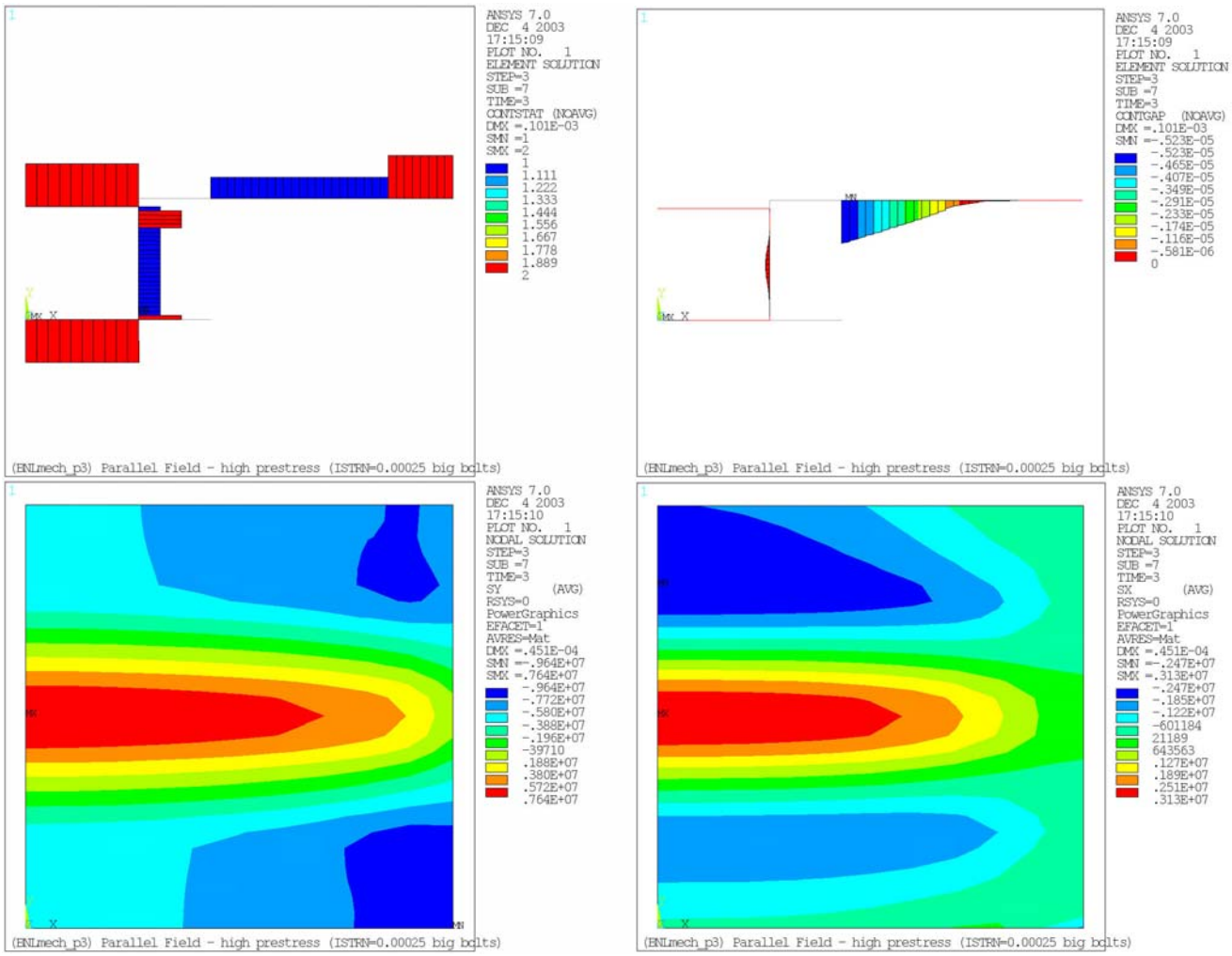



```
 LOAD STEP     2  SUBSTEP=     6
 TIME=    2.0000         LOAD CASE=  0

 TEMP =    4.20    4.20
MFORX= 0.11545E+06
SAXL= 0.48832E+08 EPELAXL= 0.000217 EPTHAXL=-0.002966 EPINAXL= 0.000250

 TEMP =    4.20    4.20
MFORX= -1957.2
SAXL=-0.29535E+07 EPELAXL=-0.000013 EPTHAXL=-0.002966
```

Parallel field B_{BG}= 7.1 T - I=25 kA

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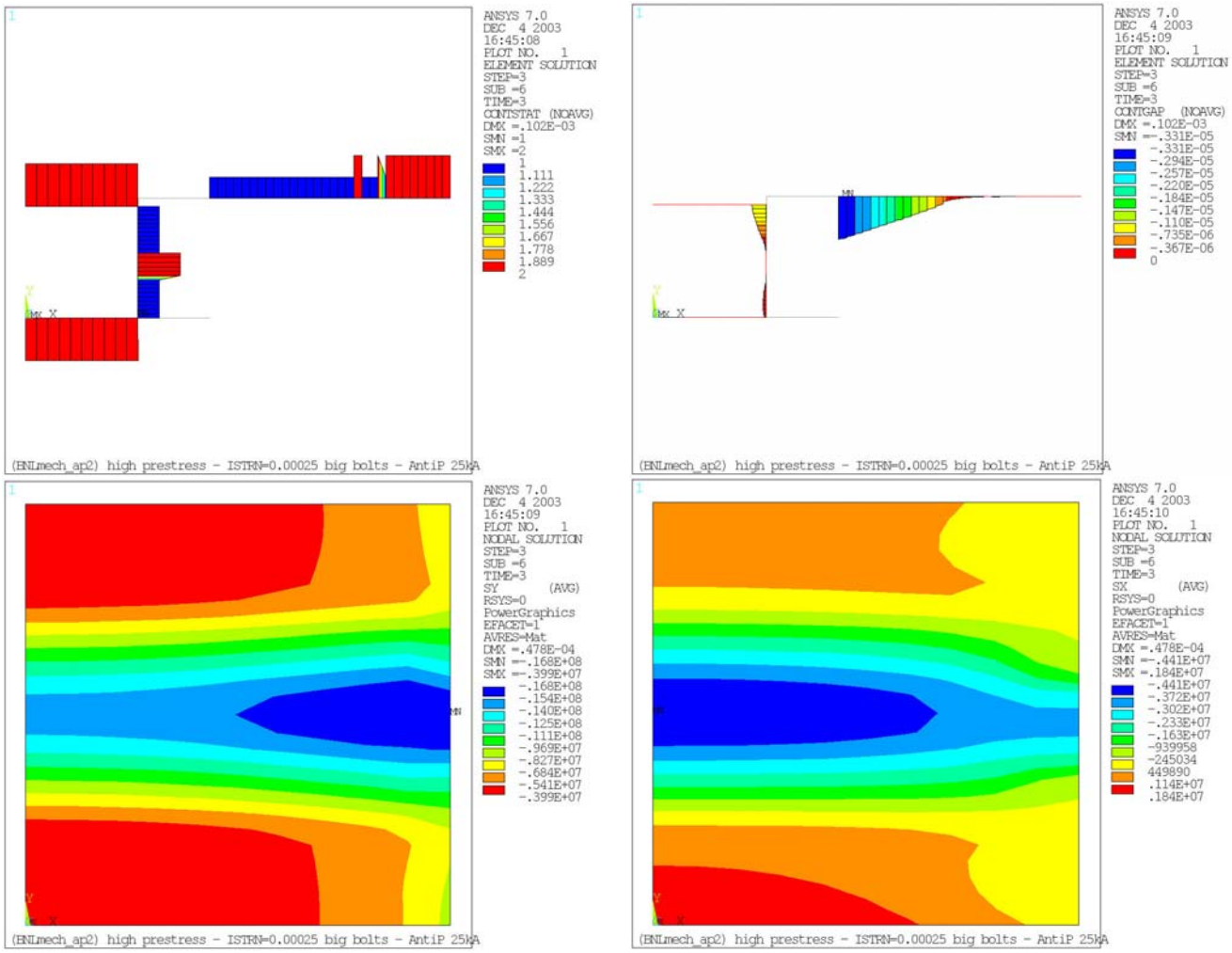
  LOAD STEP     3  SUBSTEP=     7
  TEMP =    4.20    4.20   MFORX= 0.12095E+06
 SAXL= 0.51158E+08 EPELAXL= 0.000227 EPTHAXL=-0.002966 EPSWAXL= 0.000000 EPINAXL= 0.000250

 EL=    2612 NODES=     309     690 MAT=     2
LINK1
  TEMP =    4.20    4.20   MFORX= -715.70
 SAXL=-0.10800E+07 EPELAXL=-0.000005 EPTHAXL=-0.002966 EPSWAXL= 0.000000 EPINAXL= 0.000000
```

Anti-Parallel field B_{BG}=7.1 T - I=25 kA (file: BNLmech_ap2)

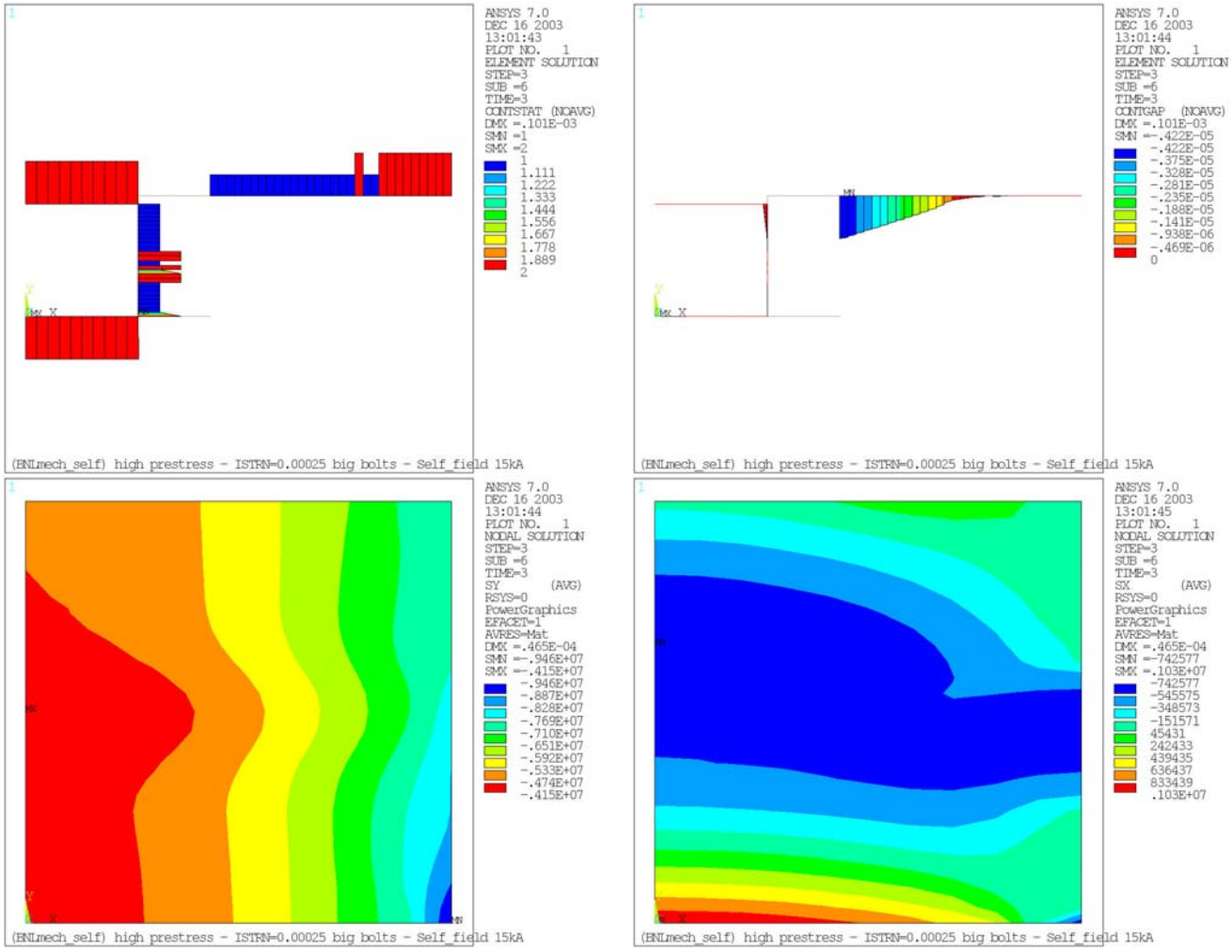



```
LOAD STEP      3  SUBSTEP=      6

 TEMP =     4.20     4.20    MFORX= 0.11112E+06
SAXL= 0.47001E+08 EPELAXL= 0.000209 EPTHAXL=-0.002966 EPSWAXL= 0.000000 EPINAXL= 0.000250

 TEMP =     4.20     4.20    MFORX= -3836.6
SAXL=-0.57898E+07 EPELAXL=-0.000026 EPTHAXL=-0.002966 EPSWAXL= 0.000000 EPINAXL= 0.000000
```

Self field only **B_{BG}= 0 T - I=15 kA** (File: BNLmech_self) high prestrain of large bolts =0.00025



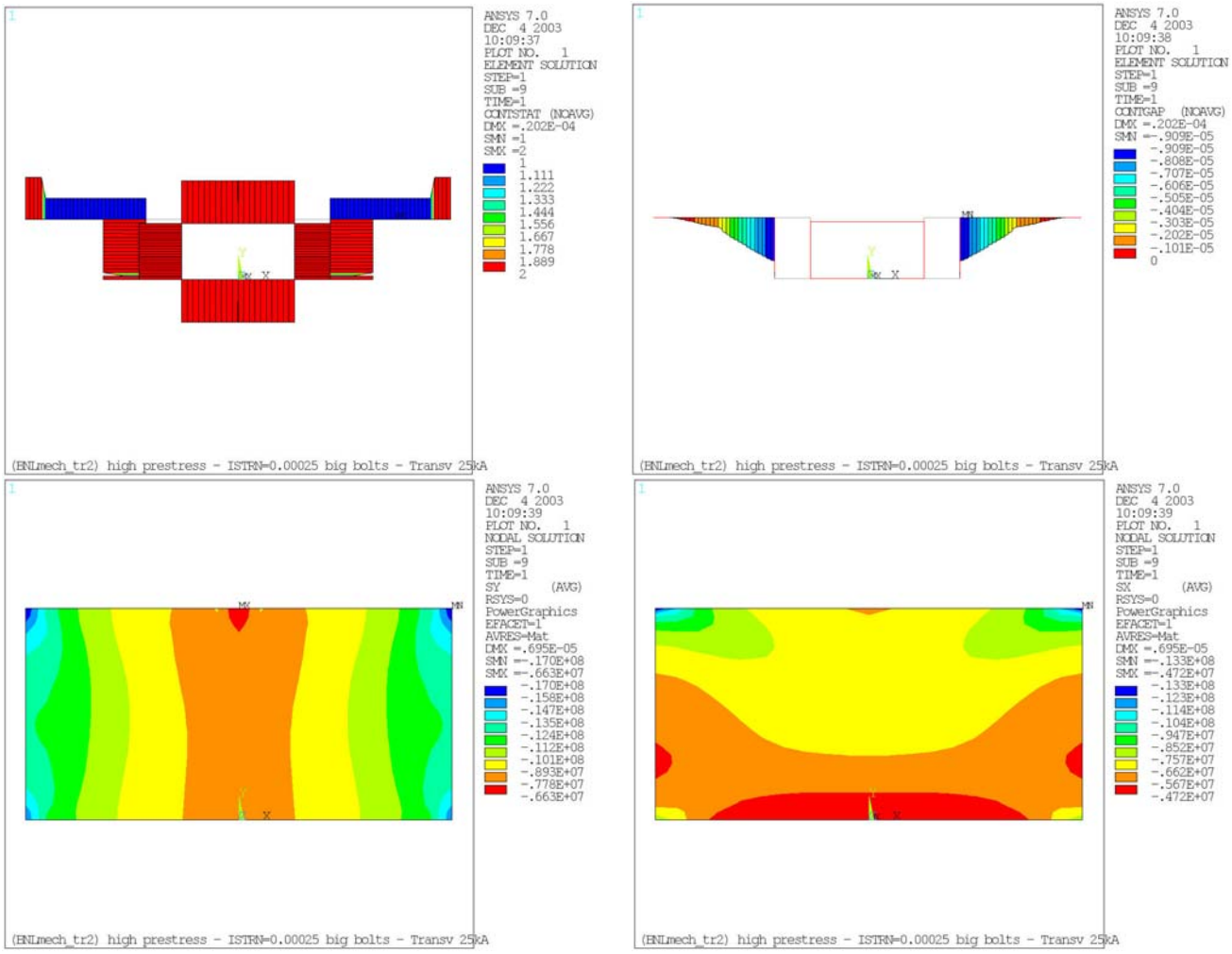

```
 LOAD STEP     3  SUBSTEP=     6
 TIME=    3.0000          LOAD CASE=  0

 TEMP =    4.20    4.20   MFORX= 0.11562E+06
SAXL= 0.48902E+08 EPELAXL= 0.000217 EPTHAXL=-0.002966 EPINAXL= 0.000250

 TEMP =    4.20    4.20   MFORX= -1637.8
SAXL=-0.24716E+07 EPELAXL=-0.000011 EPTHAXL=-0.002966 EPINAXL= 0.000000
```

Full mechanical model for field normal to the large face of the cables
High prestrain of large bolts =0.00025 (File: BNLmech_tr2)

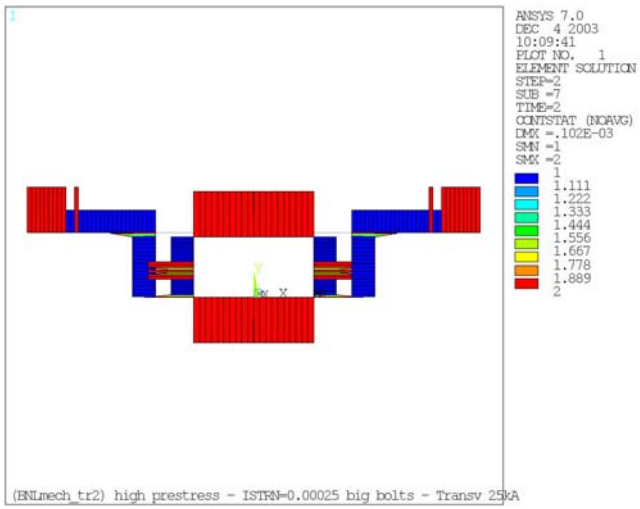
Prestress at room temperature (1 mil interference):

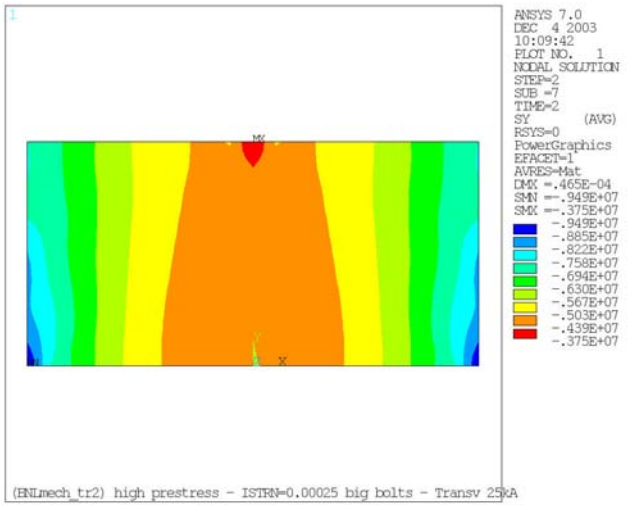


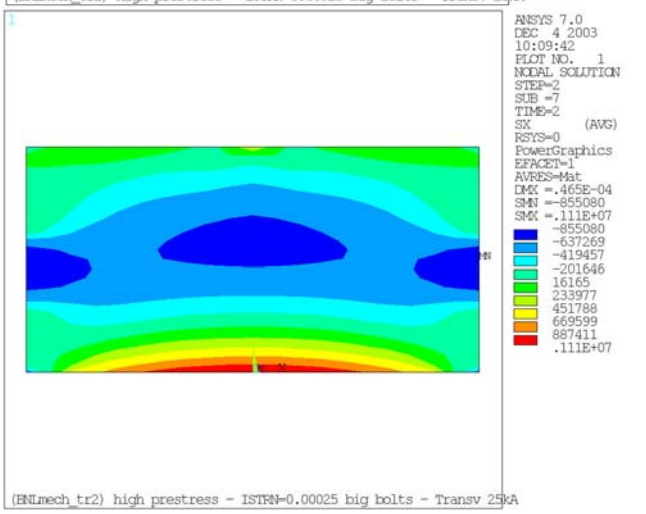
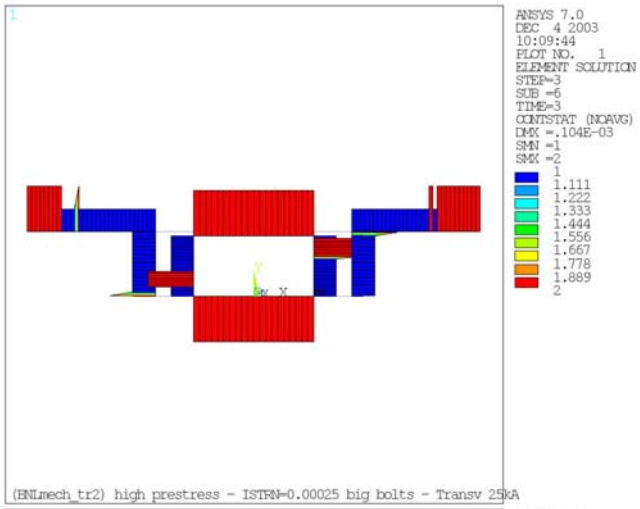
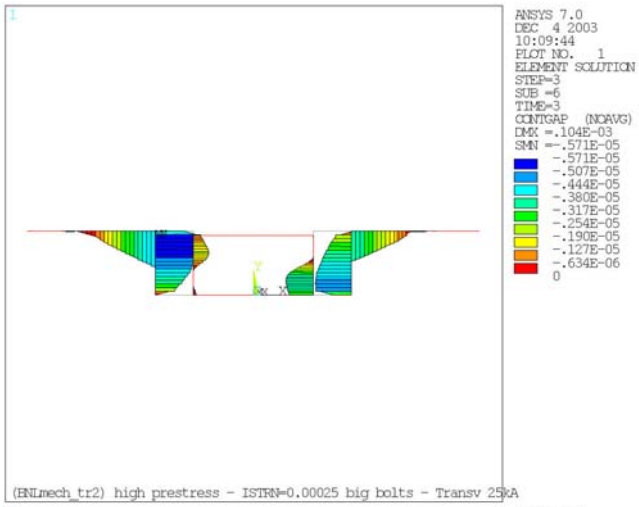
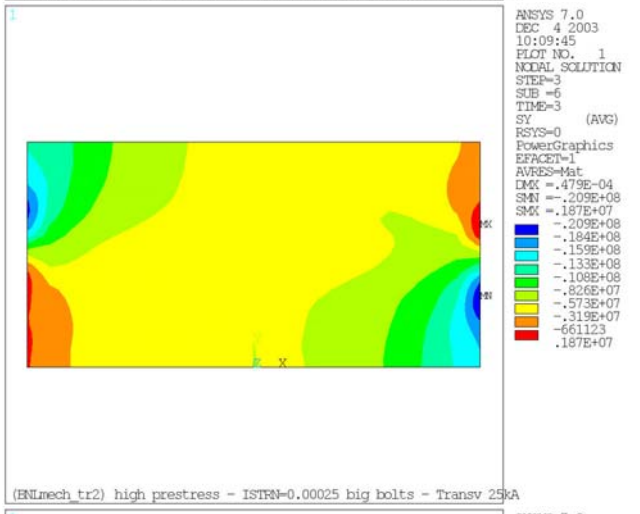
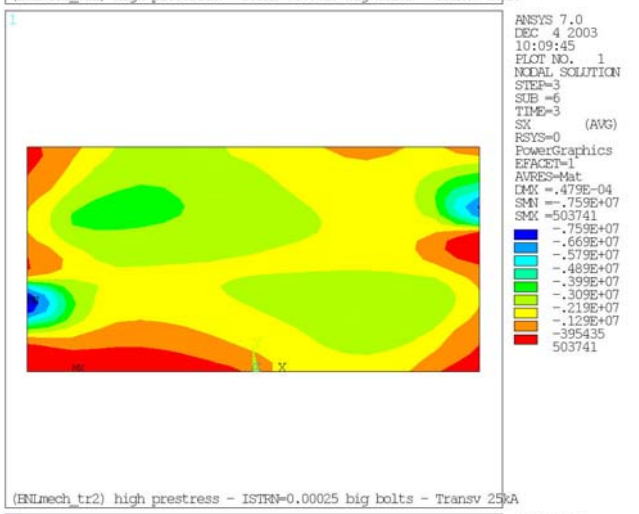
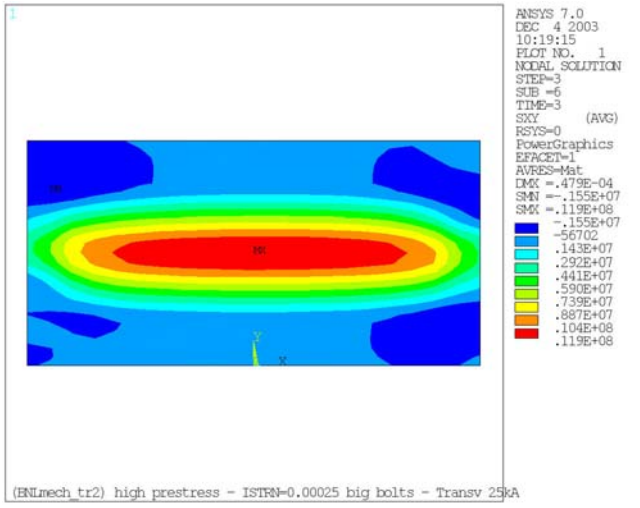
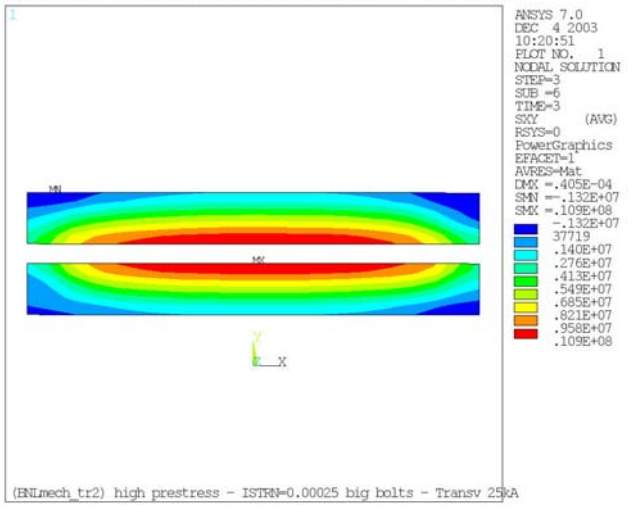
Bolt Summary:

Step	Bolt	MFORX=	SAXL=	EPELAXL=	EPTHAXL=	EPINAXL=
1	1	1.44E+05	6.08E+07	0.000289	0	0.00025
	2	1.44E+05	6.08E+07	0.000289	0	0.00025
	3	-3773.7	-5.69E+06	-0.000027	0	0
	4	-3773.7	-5.69E+06	-0.000027	0	0
2	1	1.15E+05	4.88E+07	0.000217	-0.002966	0.00025
	2	1.15E+05	4.88E+07	0.000217	-0.002966	0.00025
	3	-1868.6	-2.82E+06	-0.000013	-0.002966	0
	4	-1868.6	-2.82E+06	-0.000013	-0.002966	0
3	1	1.11E+05	4.69E+07	0.000208	-0.002966	0.00025
	2	1.19E+05	5.02E+07	0.000223	-0.002966	0.00025
	3	-6100.3	-9.21E+06	-0.000041	-0.002966	0
	4	-11062	-1.67E+07	-0.000074	-0.002966	0

After cooldown (4.2 K):







At Max Field and Current: B_{BG} = 7.1 T – I =25 kA