Structural analysis of the CBM magnet coil

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The purpose of analysis

The coil consists of several different materials

The coil is subject by Lorentz forces coming from vertical and radial components of the magnetic field

The internal stress will appear after cooling down and magnetic forces application. The purpose of the calculations is to obtain stress and deformation of the CBM coil structure under the following loads:

- stress after cooling down from room temperature to 4.5 K temperature;
- stress after application of the Lorentz force, which were taken as 2.5 or 3 MN of axial direction, and of 5 MPa pressure on the inner radius of the coil. These values were taken from the magnetic field calculations.

The ANSYS code was used for these calculations. The available ANSYS package not included the magnetic field analysis, so the magnetic forces were applied as external forces on the coil. The values of the forces were taken from other ANSYS magnetic field calculations.

Criteria

- - the stress in the stainless steel is below 600 MPa that is the yield stress at low temperatures;
- - the stress in the copper is below 450 MPa that is the ultimate stress at low temperatures;
- - the stress in the SC cable is below 350 MPa that is the stress of degradation of superconducting property of NbTi by ~ 5%;
- - the stress in the winding structure is desired to be below 100 MPa that is the ultimate stress of epoxy compounds. Such stress beyond this value may produce epoxy cracking causing premature quenches. If such stress is exceeding the 100 MPa value but of compressive quality or not making movements of the SC cable then it may be treated as an acceptable stress.

Preamble – the stresses evaluated by formulas

Origins of mechanical stresses in the CBM magnet winding

1. The pressure from the Lorentz force (vertical Bz)

This pressure gives hoop stress in the coils which is estimated as

σ = p*R/h (radius and radial thickness of the coils)

σ = 5*0.7/0.16 = **22 MPa** – the hoop stress without Cu and stainless steel cases.

2. The vertical force bending the magnet (axial Bx and By) It depends on numbers of support struts!

The direct application in the winding of this force gives σ = F/(2πR*h) = 3.3/ /(4.87*0.16) = **4.2 MPa** – very low value. **Large number of the struts.**

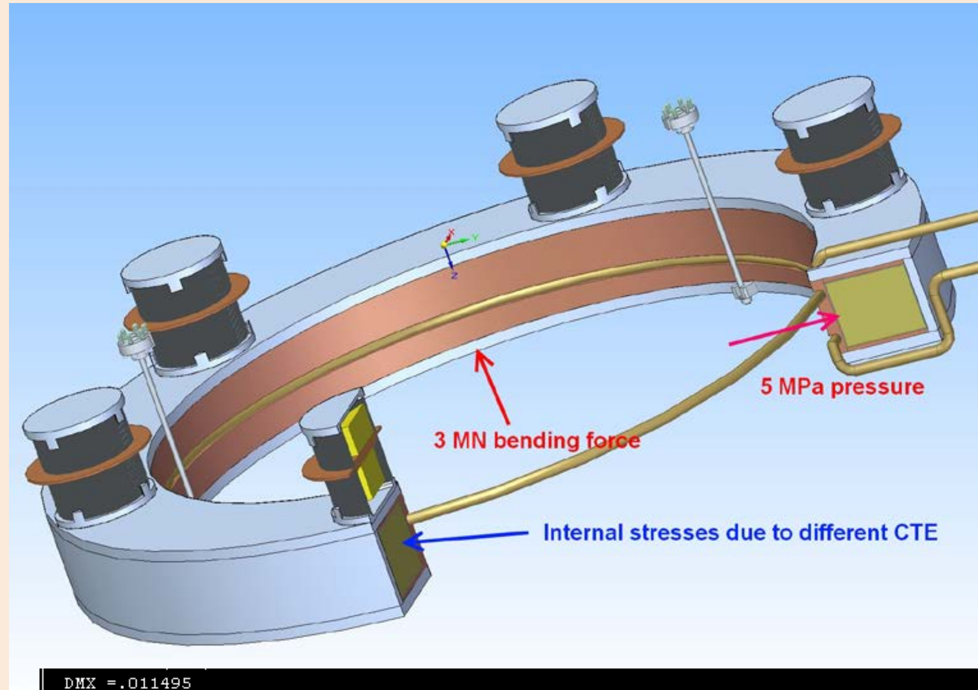
This stress is evaluated according:

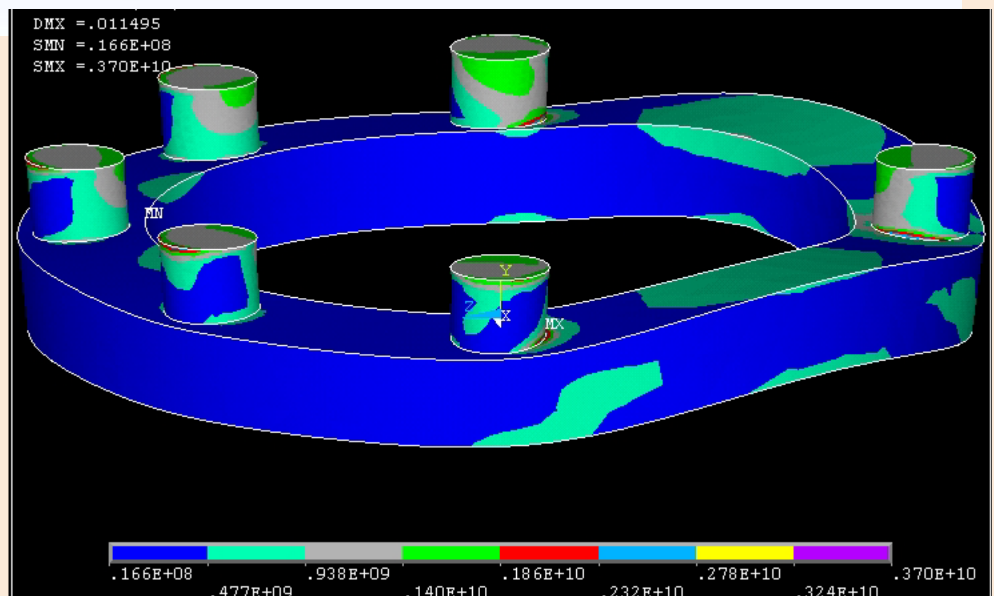
$$\sigma = \frac{M}{J_x} * y$$

, where M – force momentum [F*m], Jx – momentum of inertia [m^4], y – half length of the coil axial size. For a rectangular shape beam the Jx = a*b3/12, as a ~ b = 0.2 m, then Jx = $1.33*10^{-4}$ m4. M = F/24 * 2πR/12 = 4.4*104 H*m. The half length y ~ 0.1 m. The result is:

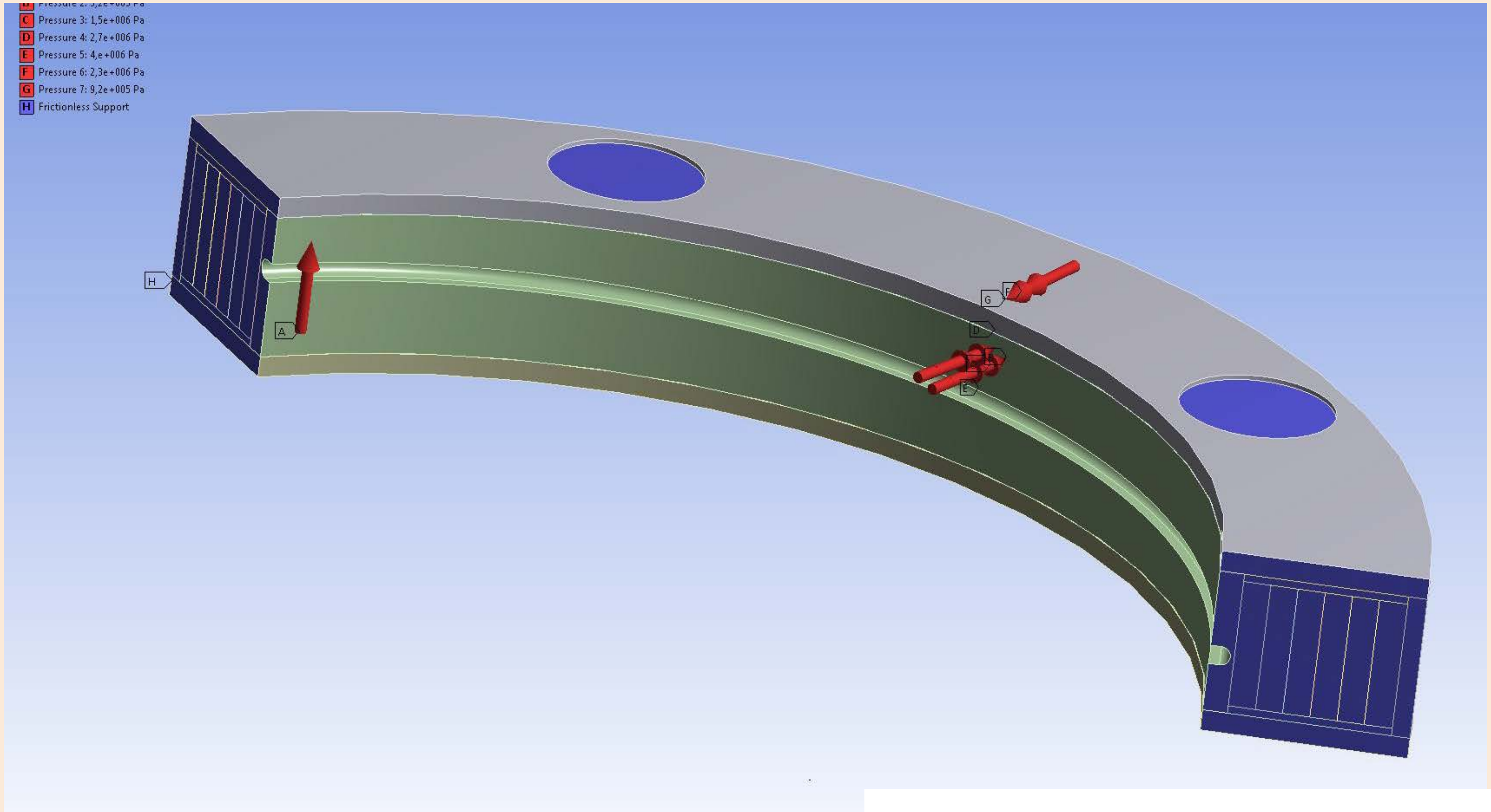
σ = 4.4*104*0.1/1.33*10-4 = **33 MPa. For the six struts.**

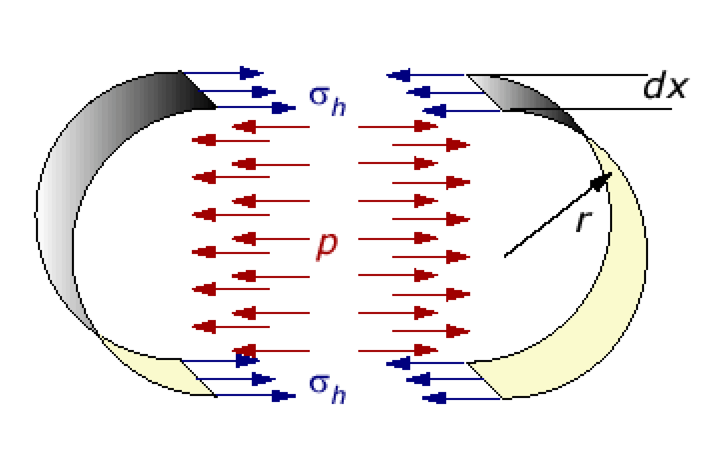
3. The stresses due to different coefficient of thermal expansion is calculated by ANSYS





The 3D ANSYS model





The pressure was applied as:
-simple 5 MP
-distributed pressure of +4.0, +2.7, +1.5, +0.32, -0.92, -2.3 MPa
- three times higher 15 MPa

Material properties in the calculations

The coil consists of the following materials:

- stainless steel

- copper

- SC winding

- G-10 sheets of 2 mm thickness by the perimeter of the SC winding

SC winding consists of:

- copper 47.0% vol;

- NbTi 6.4% vol;

- Insulation (glass fibre, Kapton, epoxy compound) 46.6% vol.

At the beginning it was unclear who to average the parameters for the winding. In the first calculations the insulation was treated as G-10, so the next slides are marked as G-10 with value of CTE with 40 GPa of YM.

The next calculation were made with insulation CTE and Young modulus close to real, it was named as close to copper parameter of CTE.

G-10 itself has two different CTE and Young modulus depending on directions.

Materials data

Uniformed data

Table A3.4: Mean Linear Thermal Expansion Data of Selected Materials
$[L(T) - L(293\,K)]/L(293\,K)$ [%]

Material	*T* [K]				
	20	80	140	200	973†
Aluminum	−0.415*	−0.391	−0.312	−0.201	—
Brass (70Cu-30Zn)	−0.369	−0.337	−0.260	−0.163	+1.30
Bronze	−0.330	−0.304	−0.237	−0.150	+1.33
Copper	−0.324	−0.300	−0.234	−0.148	+1.3
Nickel	−0.224	−0.211	−0.171	−0.111	—
Silver	−0.409	−0.360	−0.270	−0.171	+1.50
Stainless steel 304	−0.306	−0.281	−0.222	−1.40	+1.32
Epoxy	−1.15	−1.02	−0.899	−0.550	—
G-10 (warp)	−0.241	−0.211	−0.165	−0.108	—
G-10 (normal)	−0.706	−0.638	−0.517	−0.346	—
Phenolic (normal)	−0.730	−0.643	−0.513	−0.341	—
Teflon (TFE)	−2.11	−1.93	−1.66	−1.24	—
Nb_3Sn	−0.171	−0.141	−0.102	−0.067	+0.55
Cu/NbTi wire	−0.265	−0.245	−0.190	−0.117	—
Solder (50Sn-50Pb)	—	−0.510	−0.365	−0.229	—

Property	Stainless steel	GFRP material	Coils	Epoxy	Copper
CTE, K^{-1}	1.11 10^{-5}	1.2 10^{-5}	1.2 10^{-5}	1.2 10^{-5}	1.25 10^{-5}
Shear modulus in xz plain, Pa	7.5 10^{10}	4.0 10^{9}	1.9 10^{10}	4.0 10^{9}	4.0 10^{10}
Young modulus y direction, Pa	2.0 10^{11}	1.8 10^{10}	4.1 10^{10}	9.0 10^{9}	1.2 10^{11}
CTE, K^{-1}	1.11 10^{-5}	1.0 10^{-5}	1.57 10^{-5}	6.0 10^{-5}	1.25 10^{-5}
CTE, K^{-1}	1.11 10^{-5}	1.6 10^{-5}	9.2 10^{-6}	1.6 10^{-5}	1.25 10^{-5}
Young modulus xz direction, Pa	2.0 10^{11}	2.2 10^{10}	7.5 10^{10}	1.8 10^{10}	1.2 10^{11}

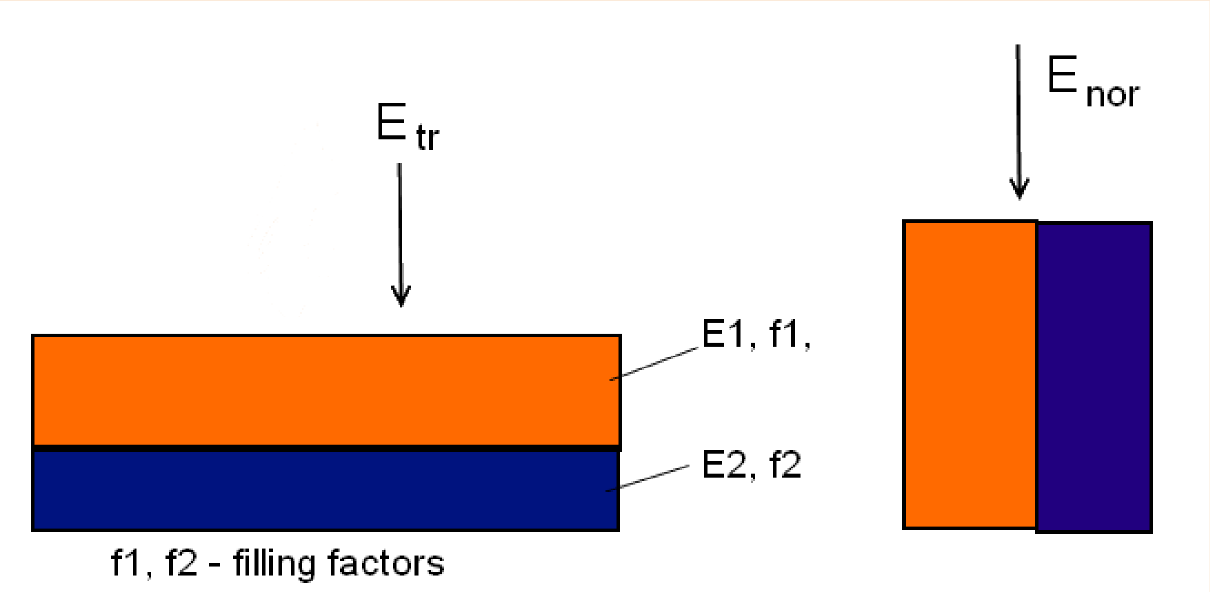
Table A3.3: Mechanical Properties of Selected Materials

Material	σ_U [MPa]		σ_Y [MPa]		*E* [GPa]	
T [K]	295	77	295	77	295	77
Aluminum 6061 (T6)	315	415	280	380	70	77
Copper (annealed)	160	310	70	90	70	100
Copper (1/4 hard)	250	350	240	275	130	150
Copper (1/2 hard)	300		280		130	
Nickel	345→2000		51	58	60	70
Silver	190	295	40–60	45–70	82	90
Stainless steel 304	550→ 1030	1450→ 1860	200→ 620	260→ 1400	190→ 190	200→ 200
Stainless steel 316LN	1290	1790	1100	1400	185	195
Epoxy	40	100	—	—	27	28
G-10 (warp/normal)	280/240	—	—	—	18/14	—
Mylar	145	215	—	—	7	13
Teflon	14	105	—	—	0.4	5

TABLE 3.2. Typical properties at 4 K and characteristics of glass–epoxy composites used in superconducting coils (50 vol.% glass content)

Property	Type of composite: HPL (G-10CR)	PP (TGDM–glass–Kapton)	VPI (epoxy–glass)
Density (g/cm^3)	1.8	1.8	1.8
Young's modulus (GPa)			
in plane	35	22	22
through thickness	22		
Shear modulus (GPa)			
interlaminar	9.0	4.4	7.6
Shear strength (MPa)			
interlaminar	80	40	70
Compressive strength (MPa)			
through thickness	800	800	800
Thermal contraction 295 K → 4 K (%)			
in plane	0.24	0.20	0.20
through thickness	0.72	0.70	0.73
Thermal conductivity [W/(m K)]			
through thickness (4 K/300 K)	0.030/0.55	0.064/0.47	0.062/0.50
Inspection	Complete visual Detailed electrical	Complete visual Detailed electrical	No visual General electrical
Repair	Complete exchange of parts	Defect cut/grind followed by replacement PP	Not possible
Manufacture	Independent of coil fabrication Industrial laminate	Wrap around conduit/conductor Off line Under pressure, cure at 150–300 °C	On line Final stage Complete coil resin cure at 110–150 °C

Young modulus for composite materials



$E_{tr} = E1*E2/(E1*f2+E2*f1)$

$E_{nor} = E1*f1 + E2*f2$

The winding has copper E1 = 117 GPa, f1 = 0.564;

for G-10 E2 = 14-22 GPa for transverse, 18-35 GPa for normal, f2 = 0.436.

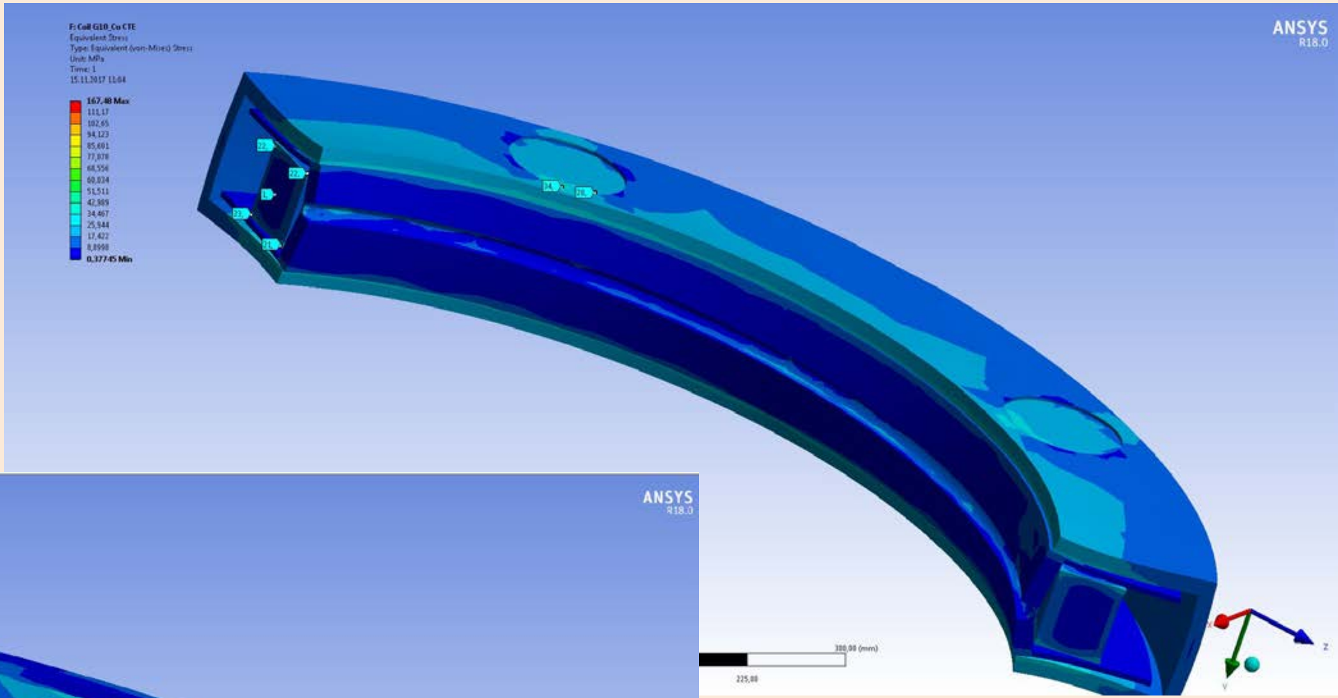
For E1= 117, E2=20 GPa E_{tr} **= 37.5 GPa;**

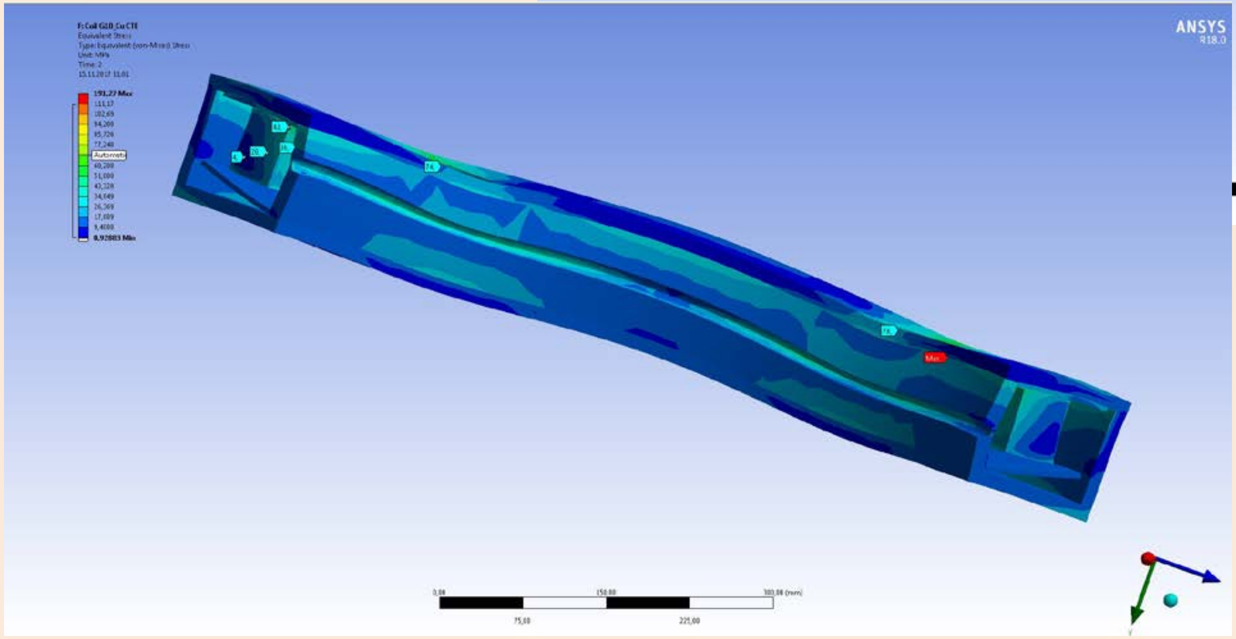
For E1= 117, E2=30 GPa E_{nor} **= 79.1 GPa**

E2 values here are for G-10 material only! The real insulation has lower values of E2.

Stresses in the coil, 3 MN and 5 MPa
G-10 with high value of CTE

The total stress in the structure after cooling.
The maximal value is about 167 MPa in the stainless steel case. The mesh is not fine enough.

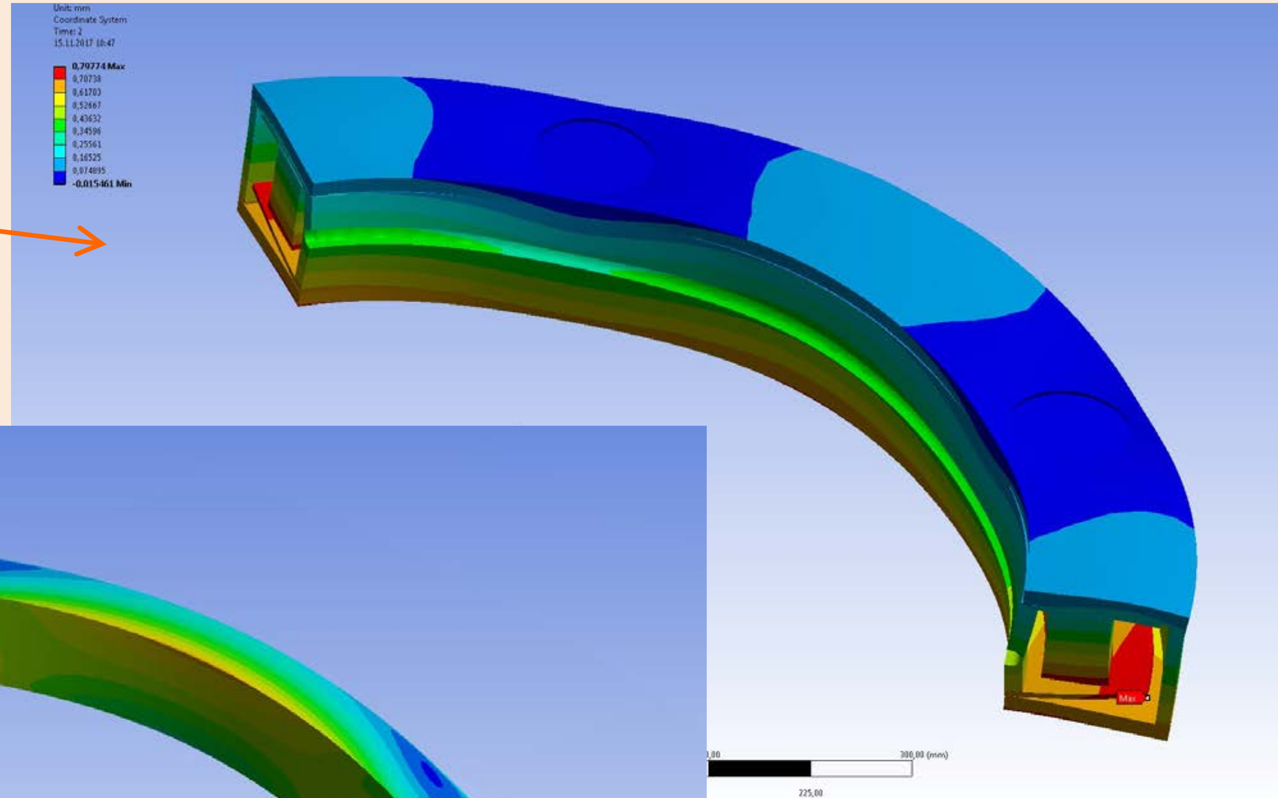


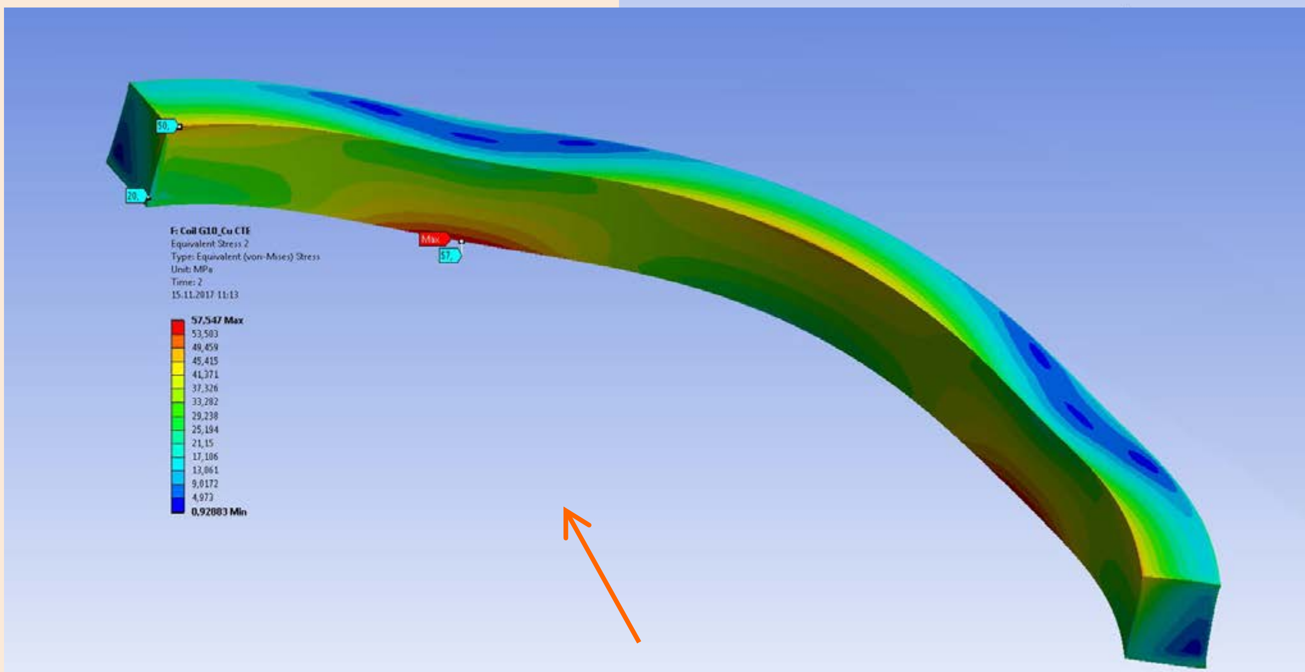


The total stress in the structure + forces.
The maximal value is about 191 MPa in the stainless steel case.

Deformation and stress, 3 MN and 5 MPa
G-10 with high value of CTE

The vertical deformation of in the structure after cooling and application of the forces. The maximal value is 0.9 mm.

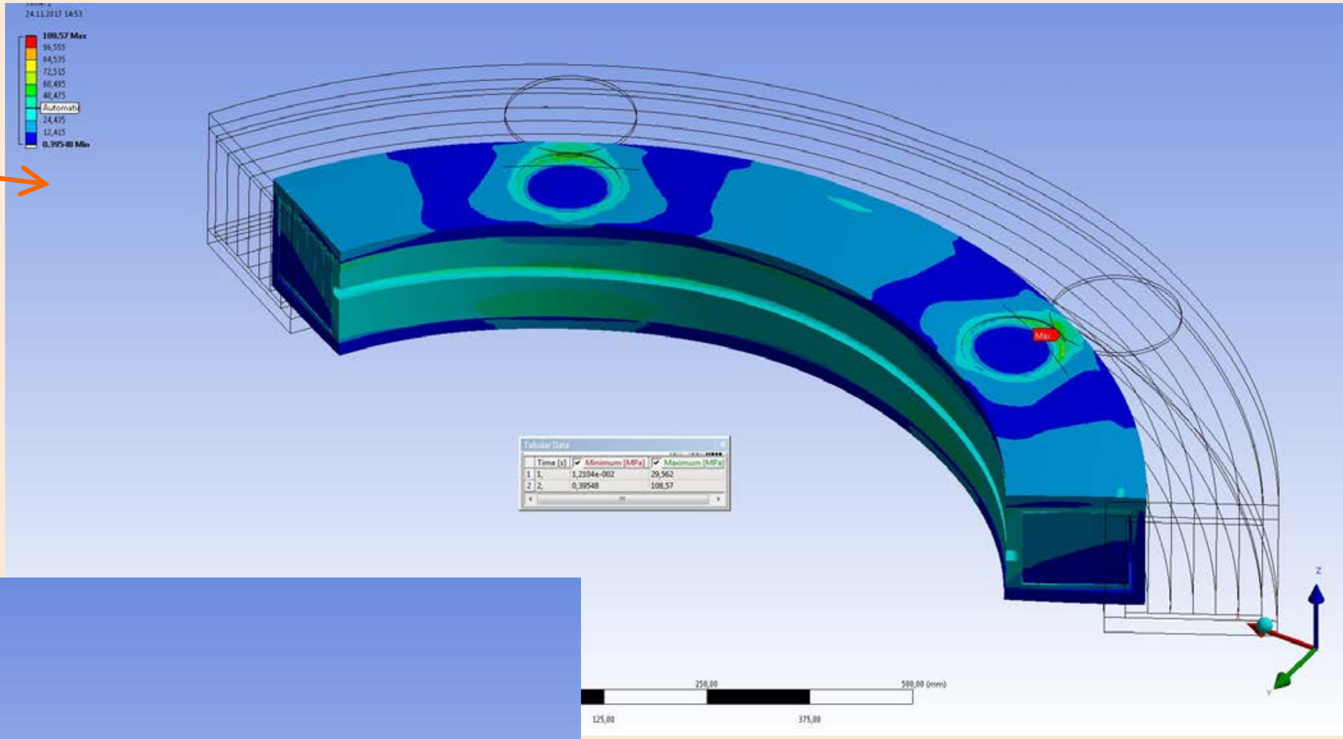


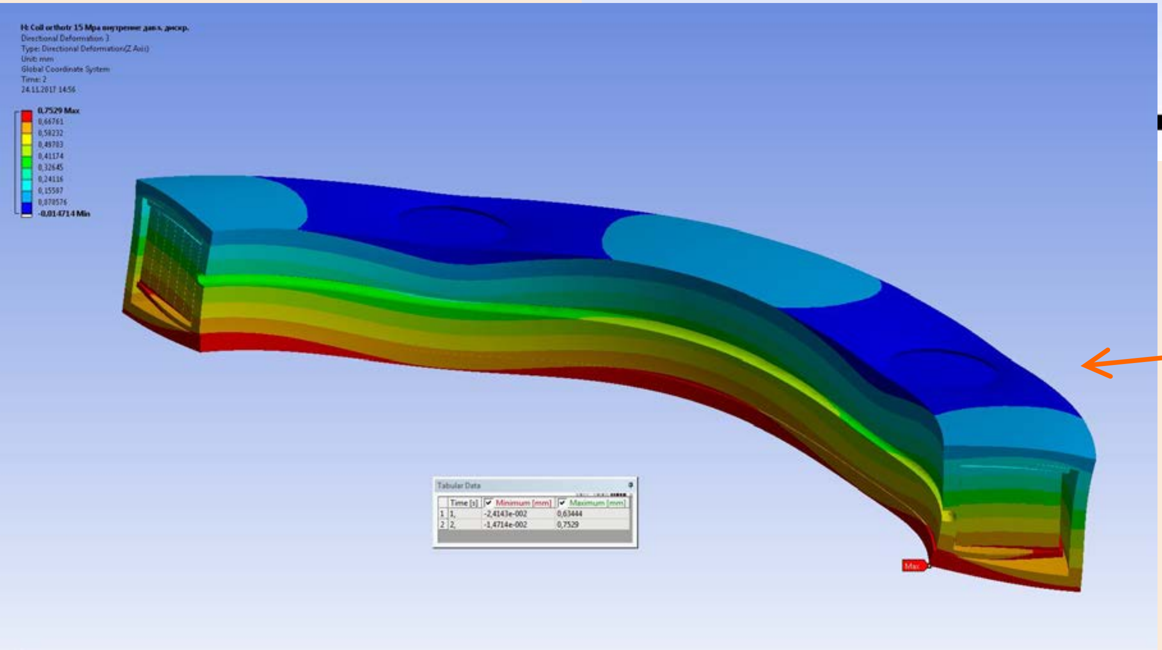


The coil total stress after cooling and application of the forces. The maximal value is 58 MPa.

Stresses in the coil, 2.5 MN and 5.3 MPa distributed
CTE of the winding is close to the copper – epoxy composite

The von Mises stress in the whole model.
The maximal value is 108 MPa.

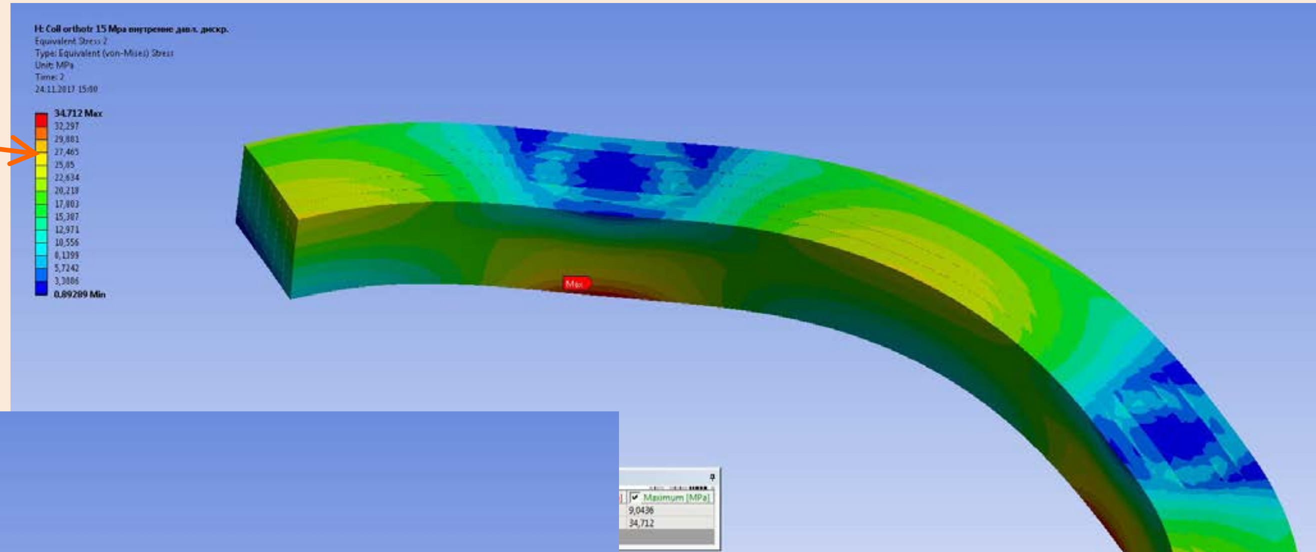


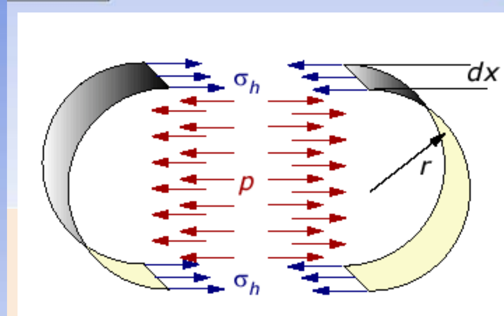


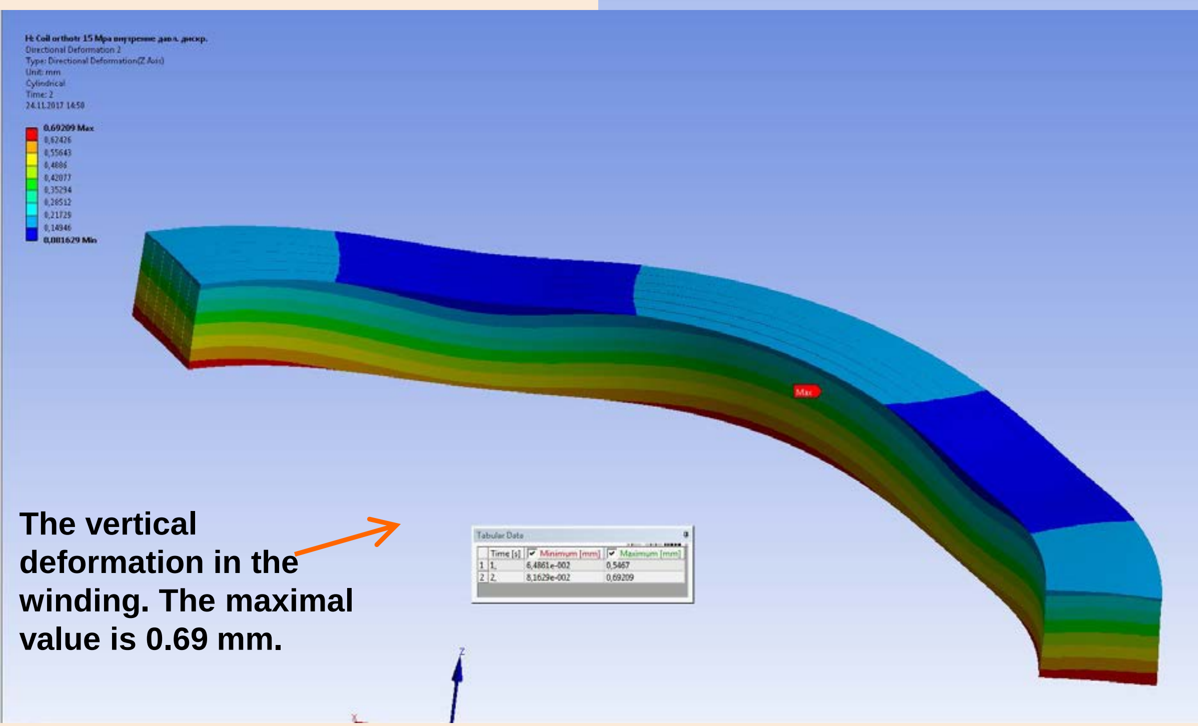
The vertical deformation after cooling down and forces application.
The deformation after cooling down is 0.63 mm and resulting deformation is 0.75 mm.
The deformation from the axial force is 0.12 mm that is slightly less than in the TDR design.

Stresses in the coil, 2.5 MN and 5.3 MPa distributed
CTE of the winding is close to the copper – composite epoxy

The von Mises stress in the winding. The maximal value is 34 MPa.
The maximal stress after cooling down is 9 MPa – the effect of epoxy compound with powder.



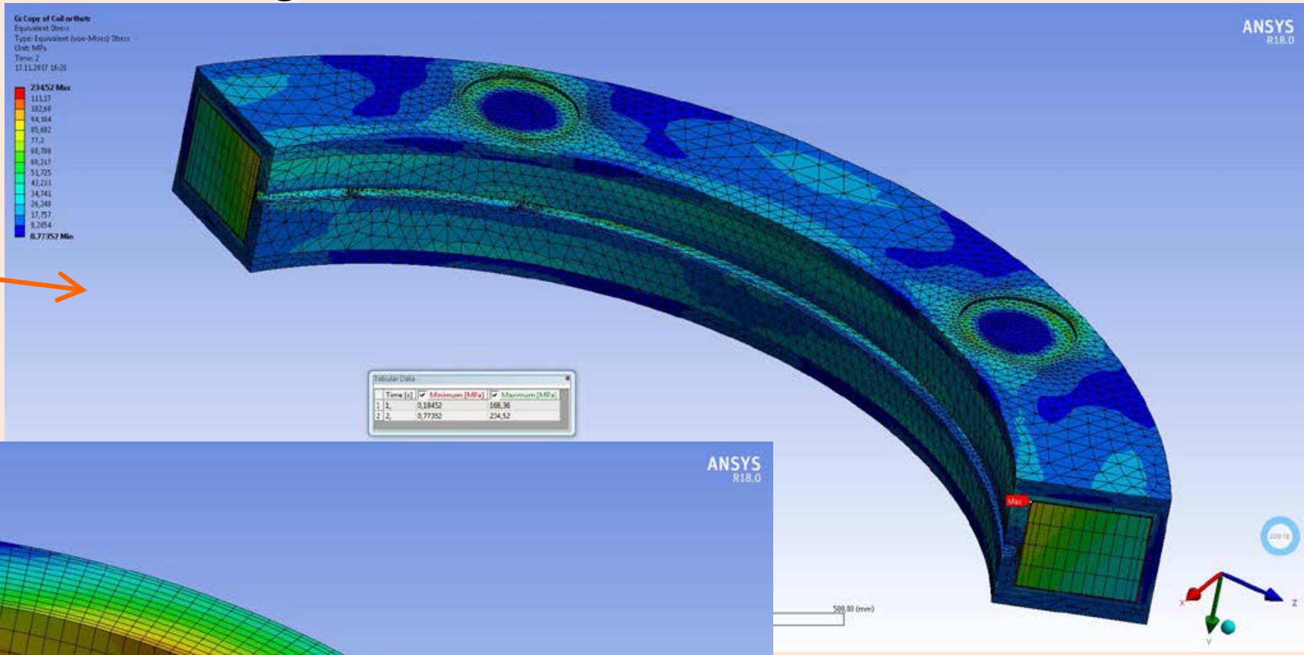


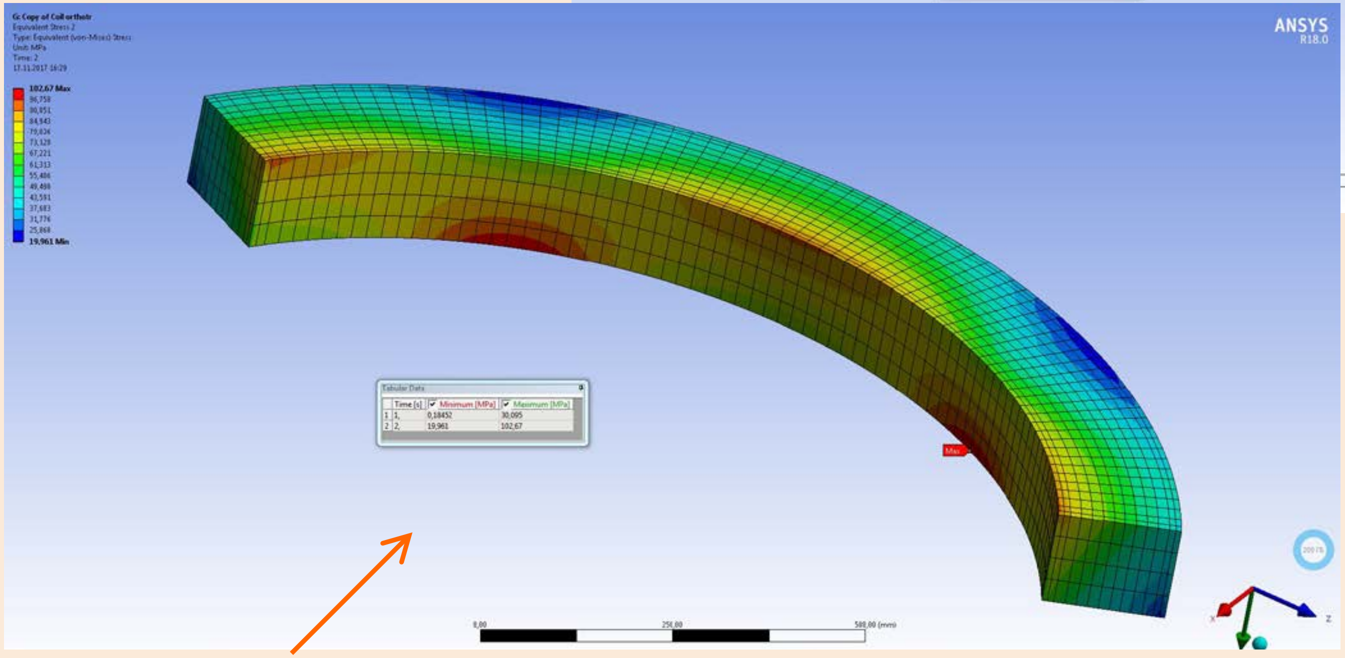


The vertical deformation in the winding. The maximal value is 0.69 mm.

Stresses in the coil, 3 MN and 15 MPa
CTE of the winding is G-10 worse value

The von Mises stress in the total model after cooling and application of forces, 15 MPa of radial pressure was applied. The inner table shows the maximal and minimal stresses after cooling and application of forces.





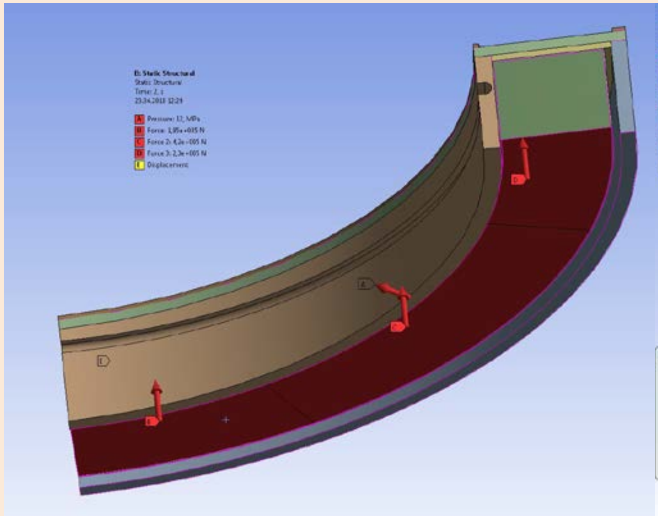
The von Mises stress in the total model after cooling and application of forces, 15 MPa of radial pressure was applied.
The inner table shows the maximal and minimal stresses after cooling and application of forces.
The maximal final stress is 103 MPa

Calculations of the model with 8 support struts and non uniform distribution of forces

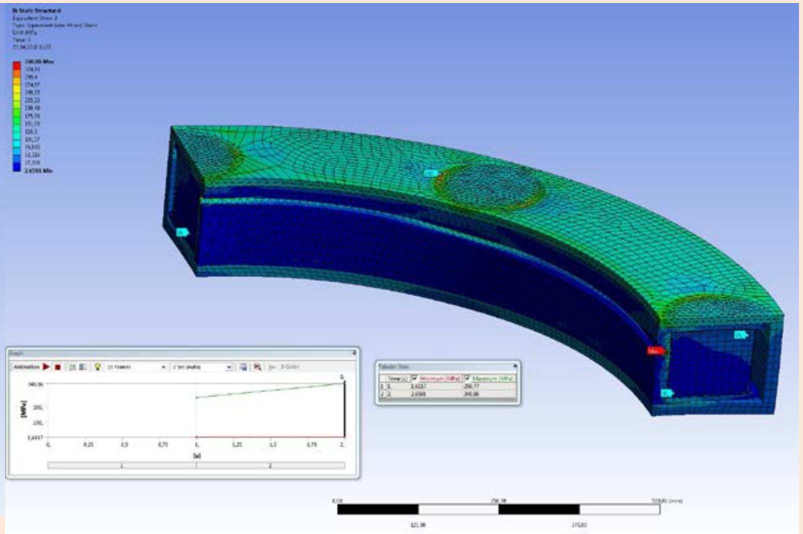
Only very preliminary results are presented here.

The model and the forces application will be improved.

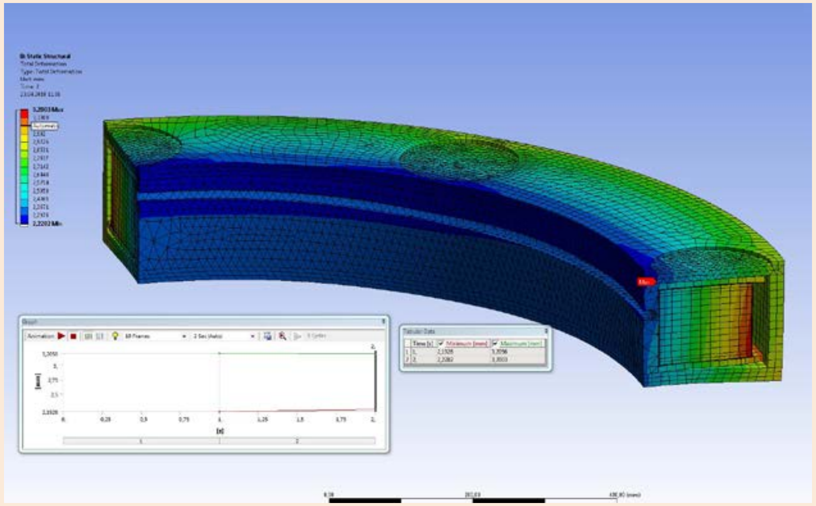
The model



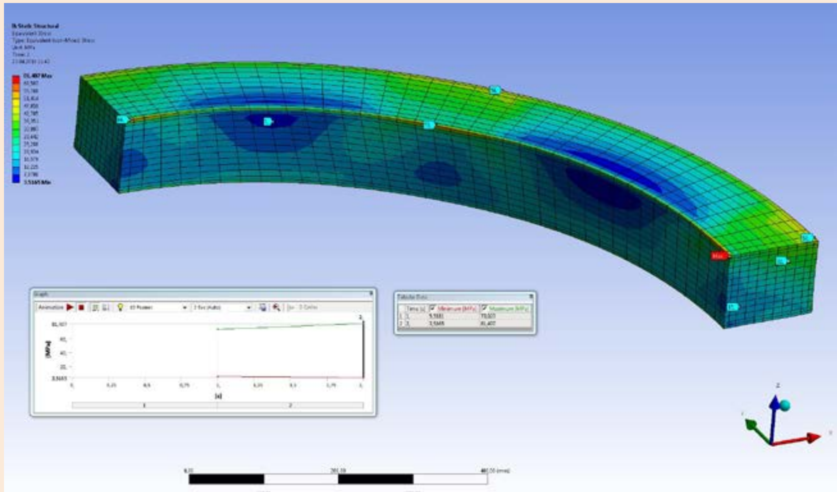
von Mises stress in the coil



deformation in the coil



von Mises stress in the winding



2D calculations

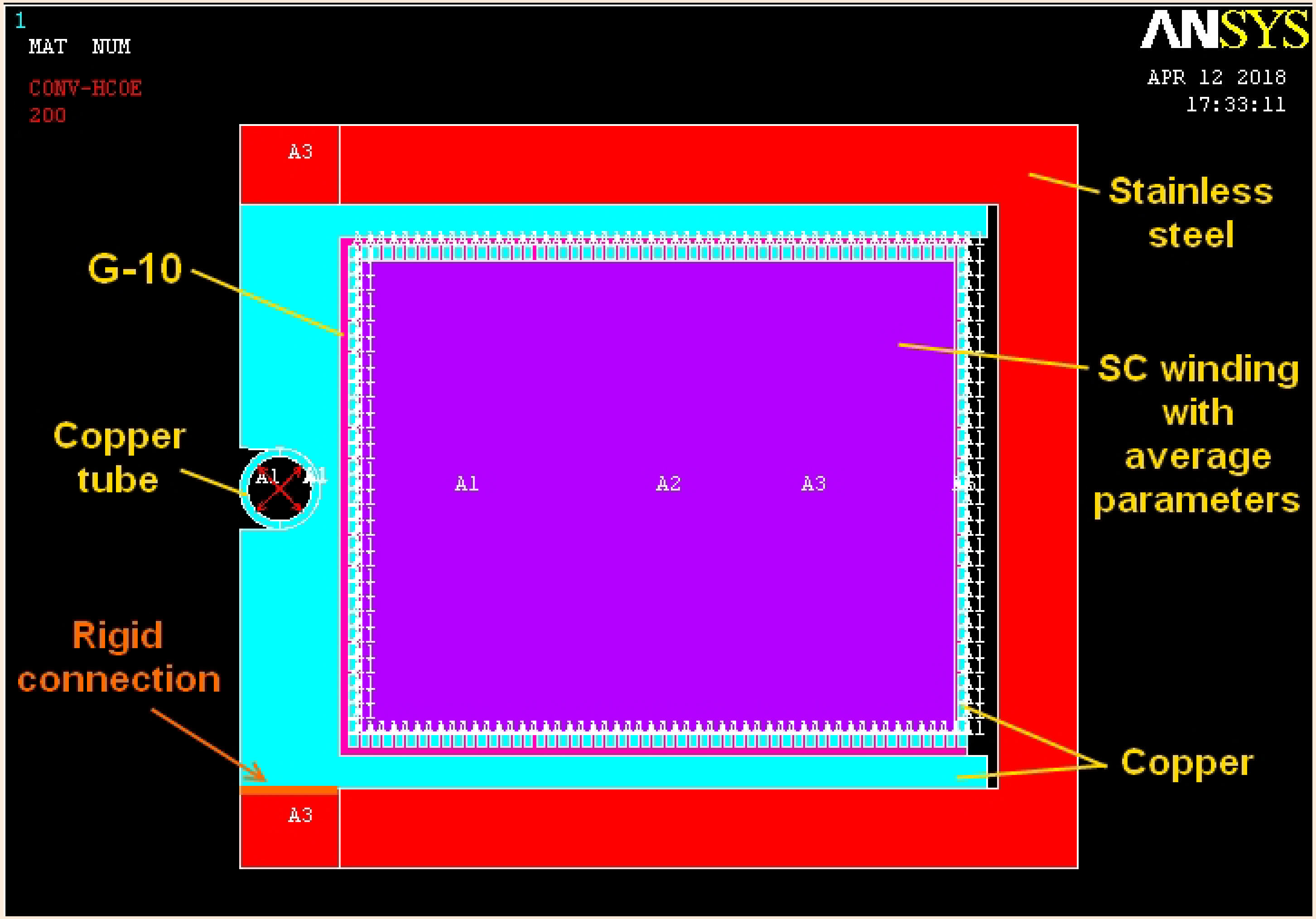
- The ANSYS 2D calculations were made to see detailed effect of different CTE of “G-10” material influence on the stress after cooling down. The SC cable was inserted into the model.

- Effect of faulty fast cooling down was presented in thermal-structural transient analysis in the same model.

ANSYS 2D model calculations with different coefficient of thermal expansion (CTE) of “G-10” material

The Young modulus of “G-10” in the following calculations was fixed at 40 GPa althoug the G-10 material is composed of G-10 itself, fiber glass and epoxy compound.

The model of axial symmetry



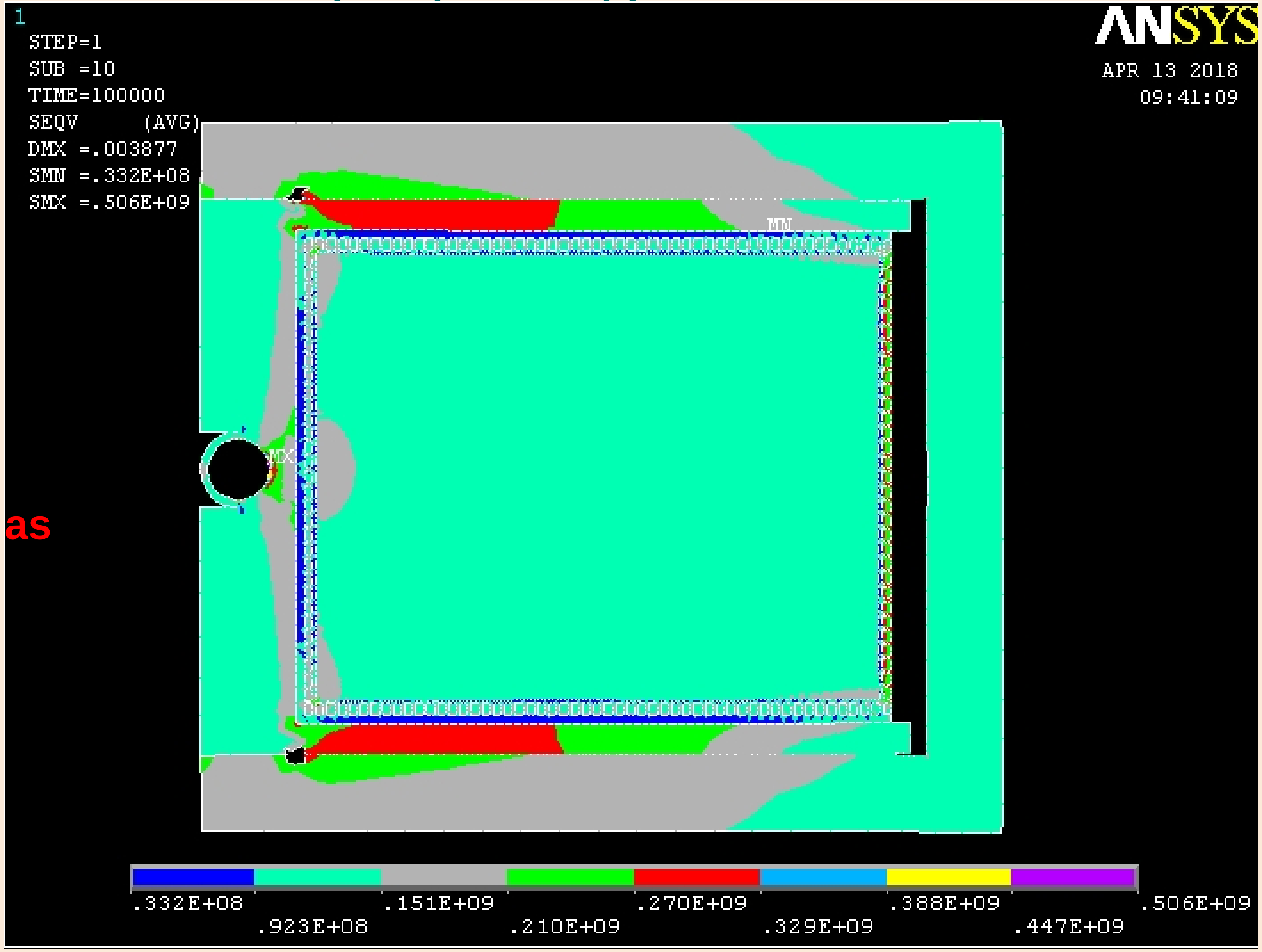
ANSYS 2D model – G-10 CTE. Result 1.

Coefficient of thermal expansion (CTE) for G-10 is like for normal direction ~ 0.7% (dL/L). For copper it is ~ 0.32%.

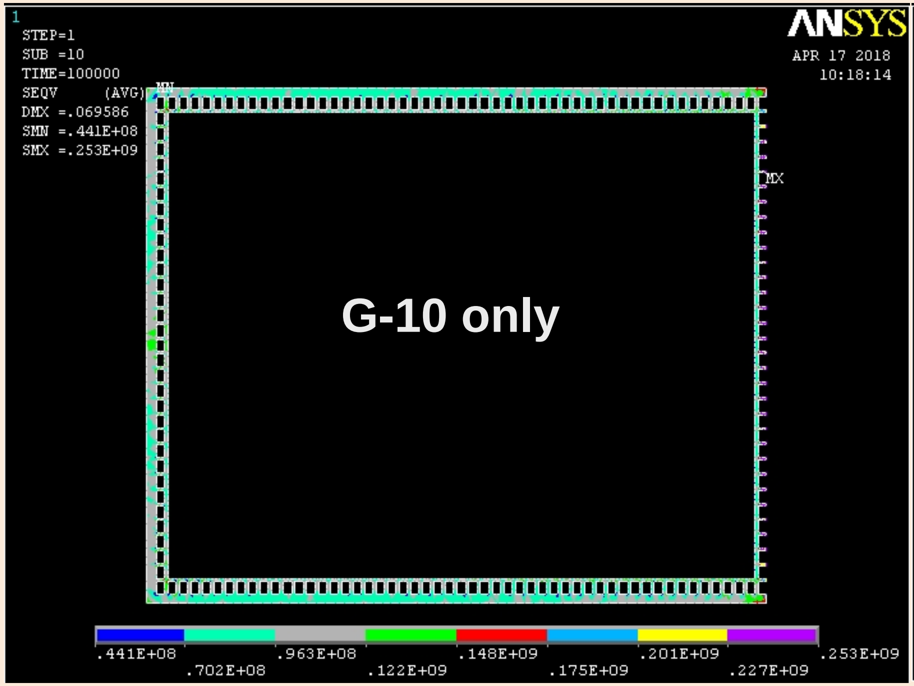
The von Mises stress after cooling down.

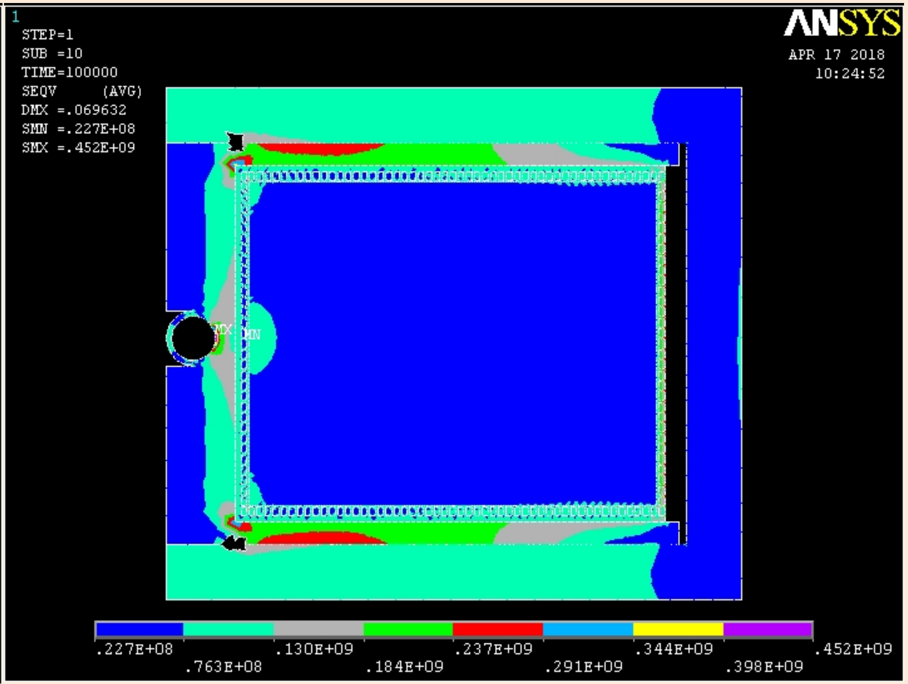
The values are HIGH even in the blue zone.

Young modulus of G-10 was here as 40 GPa (mistake) – too high



ANSYS 2D model – G-10 CTE. Result 1.



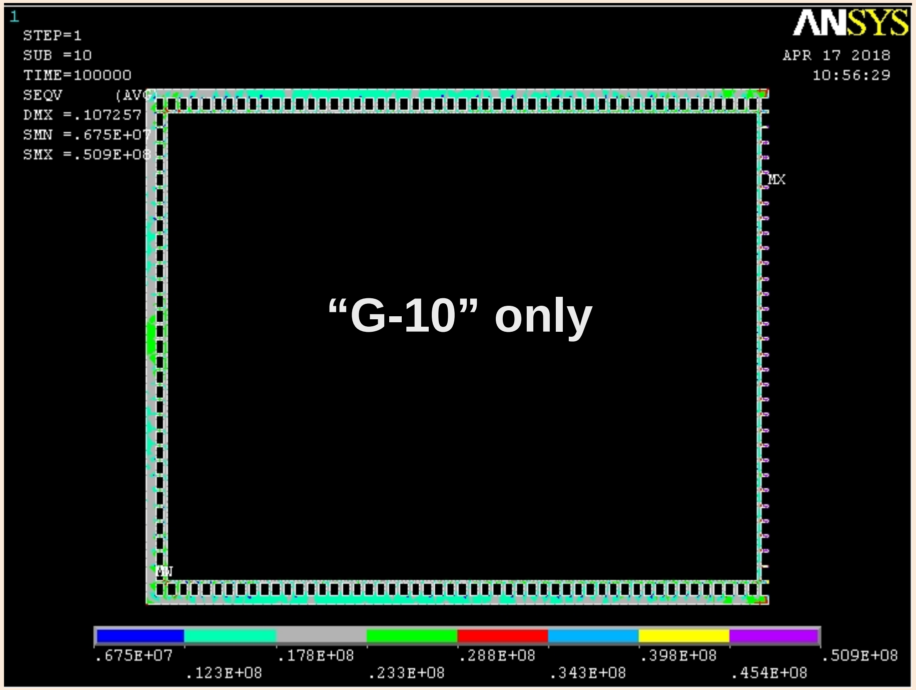


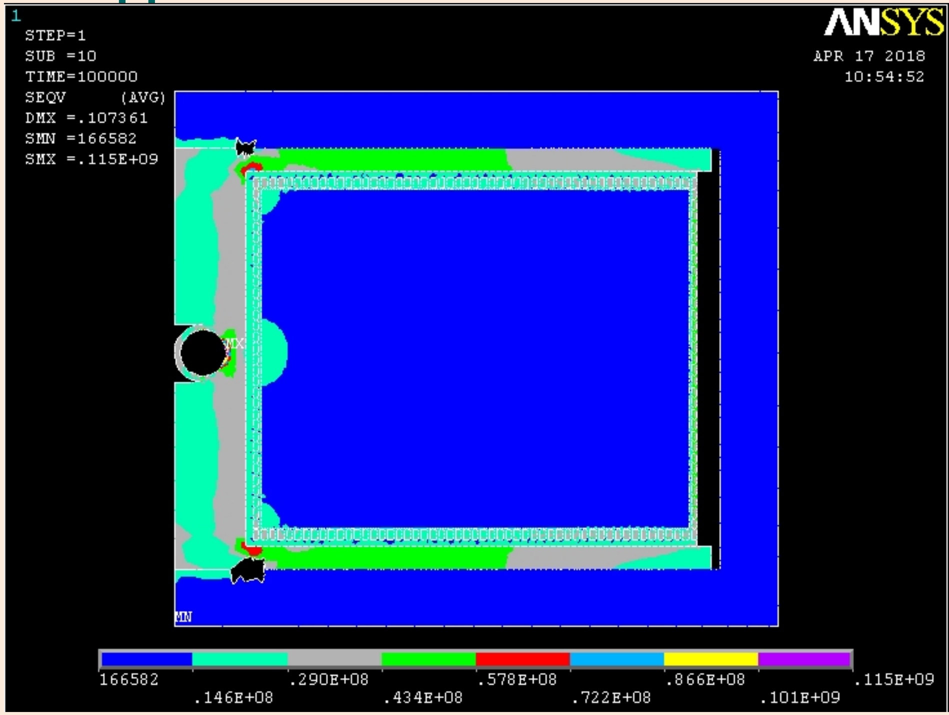
The von Mises stress after cooling down.
The values are close to the 100 MPa – epoxy cracking.

Young modulus of "G-10" was here taken as 20 GPa.
In literature YM for G-10 is ~ 22; 35 GPa at RT
for epoxy is 2-4 GPa at RT

ANSYS 2D model – G-10 CTE. Result 2.

Coefficient of thermal expansion (CTE) for G-10 is like for warp direction ~ 0.2% (dL/L). For copper it is ~ 0.32%.



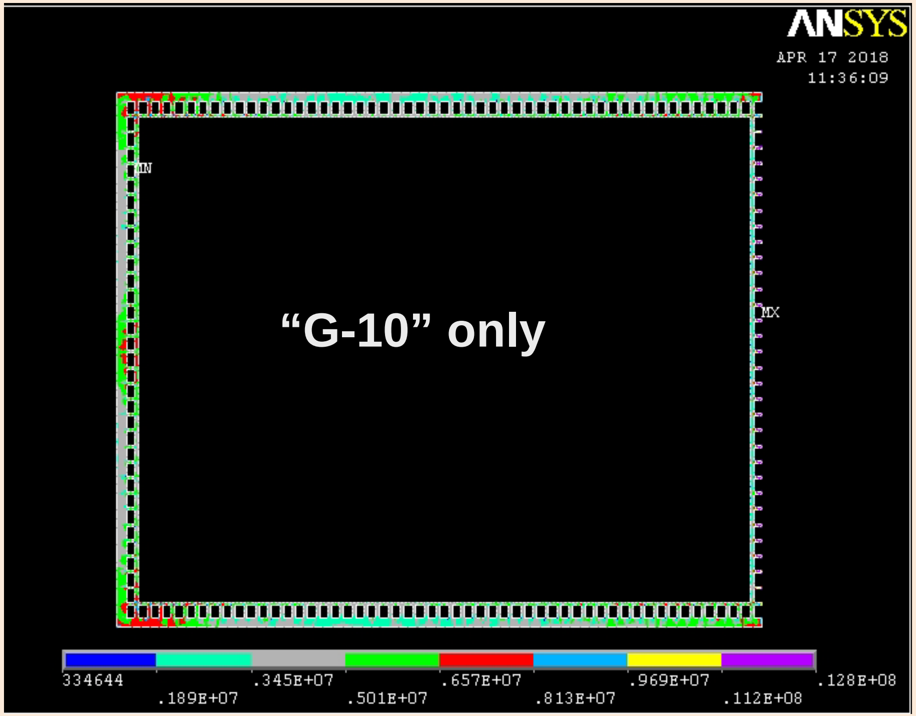


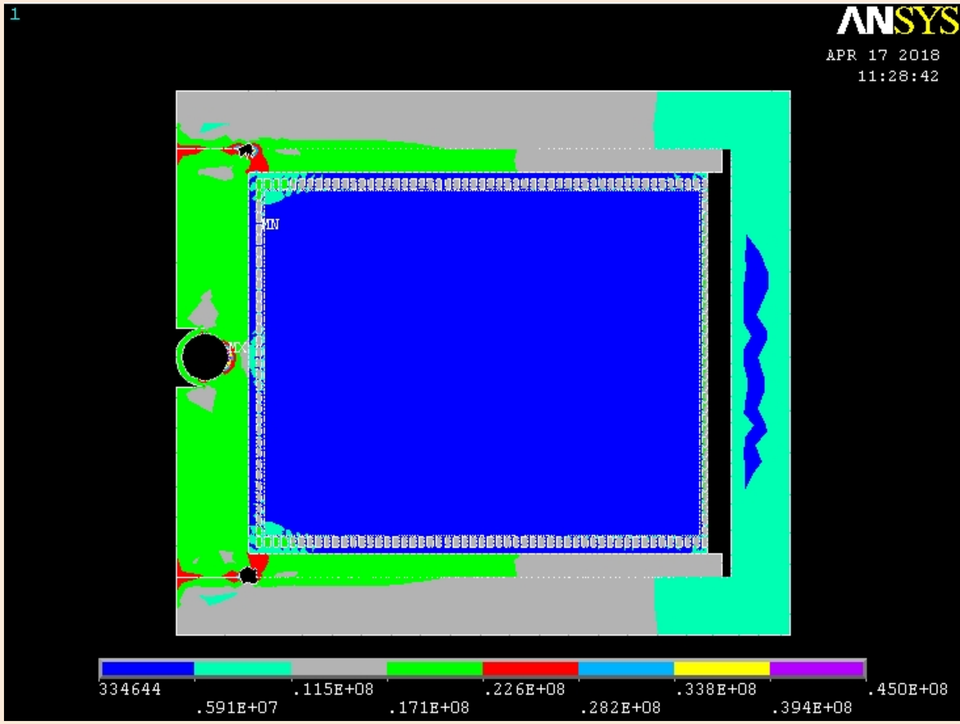
The von Mises stress after cooling down.
The values are acceptable.

Young modulus of "G-10" was here taken as 20 GPa.
In literature YM for G-10 is ~ 22; 35 GPa at RT
for epoxy is 2-4 GPa at RT

ANSYS 2D model – G-10 CTE. Result 3.

Coefficient of thermal expansion (CTE) for G-10 is like for epoxy compound with powder ~ 0.3% (dL/L). For copper it is ~ 0.32%.





The von Mises stress after cooling down.
The values are very low.

Young modulus of “G-10” was here taken as 20 GPa.
In literature YM for G-10 is ~ 22; 35 GPa at RT
for epoxy is 2-4 GPa at RT

Epoxy compound with powder

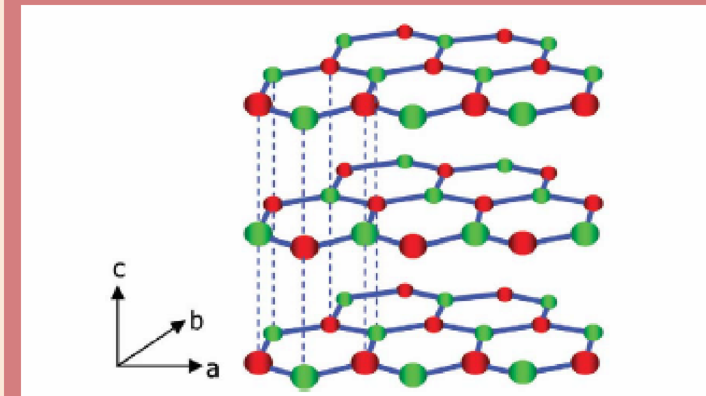
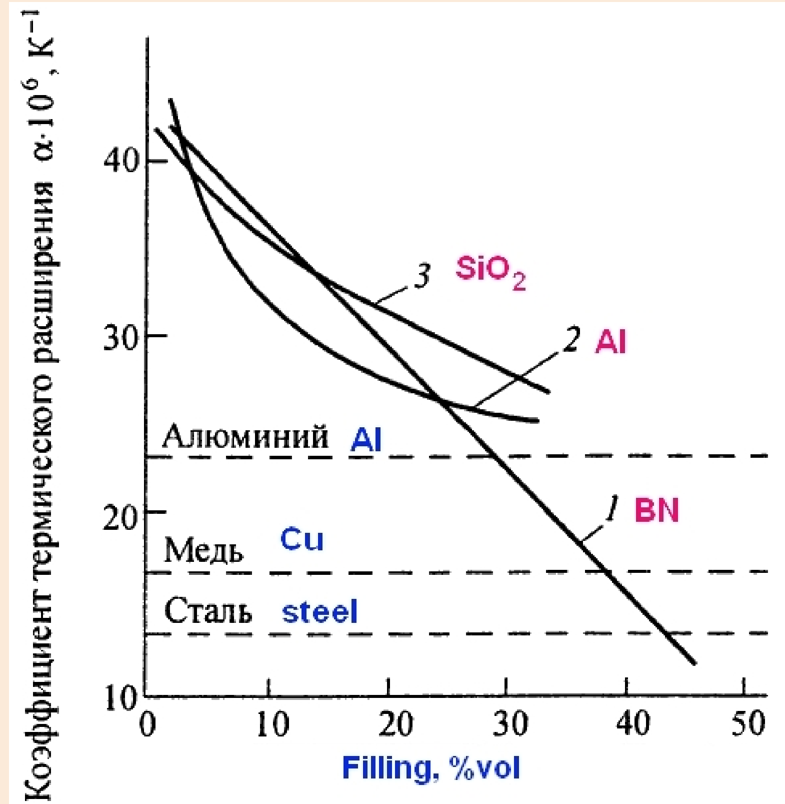


Figure 1: Structure of hexagonal boron nitride.

Table 1: Typical properties of various thermal fillers

	BN	AlN	Al_2O_3	SiO_2	ZnO
Thermal properties					
Thermal conductivity (W/mK)	300+	260	30	1.4	54
Specific heat (J/kg-K, 25°C)	794	734	798	689	523
Theoretical density (g/cc)	2.25	3.26	3.98	2.20	5.64
Electrical properties					
Dielectric constant	3.9	8.8	9.7	3.8	9.8
Volume resistivity	10^{15}	10^{14}	10^{14}	10^{14}	10^{7}
Mechanical properties					
Coefficient of thermal expansion (ppm/K)	< 1	4.4	6.7	0.5	0.7
Young's modulus (GPa)	40	400	340	72	12
Knoop hardness (kg/mm²)	11	1200	1500	500	387

"Boron nitride finds new applications in thermoplastic compounds."
Plastics Additives & Compounding *May/June 2008, p.26.*



Influence of filling components in epoxy on thermal expansion coefficient [Yu. Solntsev, "Materials for low and cryogenic temperatures", S.-Peterburg, 2008].
The dash lines are the thermal expansion coefficients for metals - for comparison.

Too fast cooling down. The model.

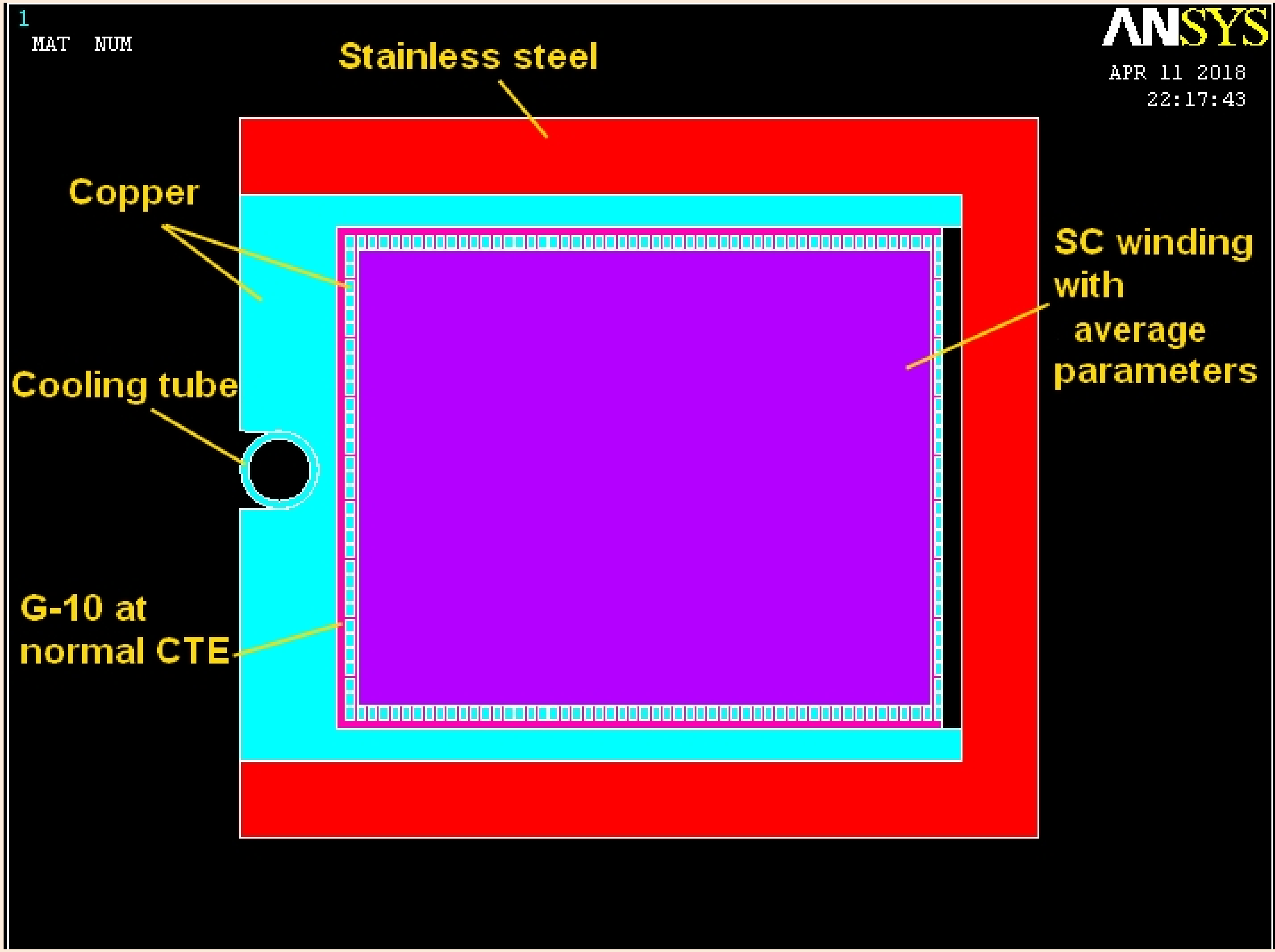
Problem: uncontrolled 50 K gaseous helium goes through the cooling tube. Possible delamination? Will it kill the magnet?

2D ANSYS analysis axial symmetry.

Conditions:
Uniform temperature 293 K

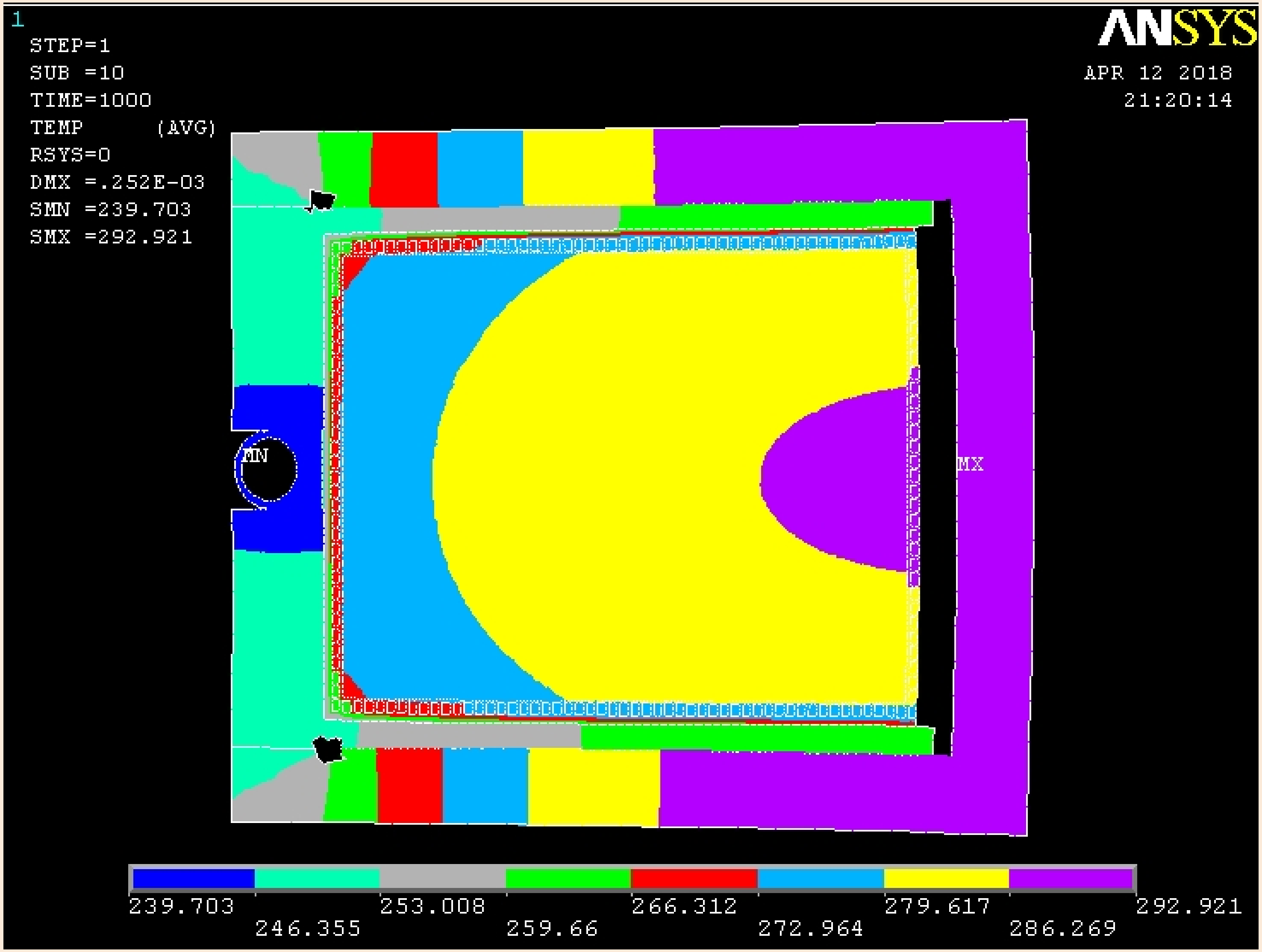
Heat transfer coefficient 200 W/(m²*K)

Bulk temperature 50 K – temperature of GHe is not changed in the tube!



Too fast cooling down. Results after 1000 s

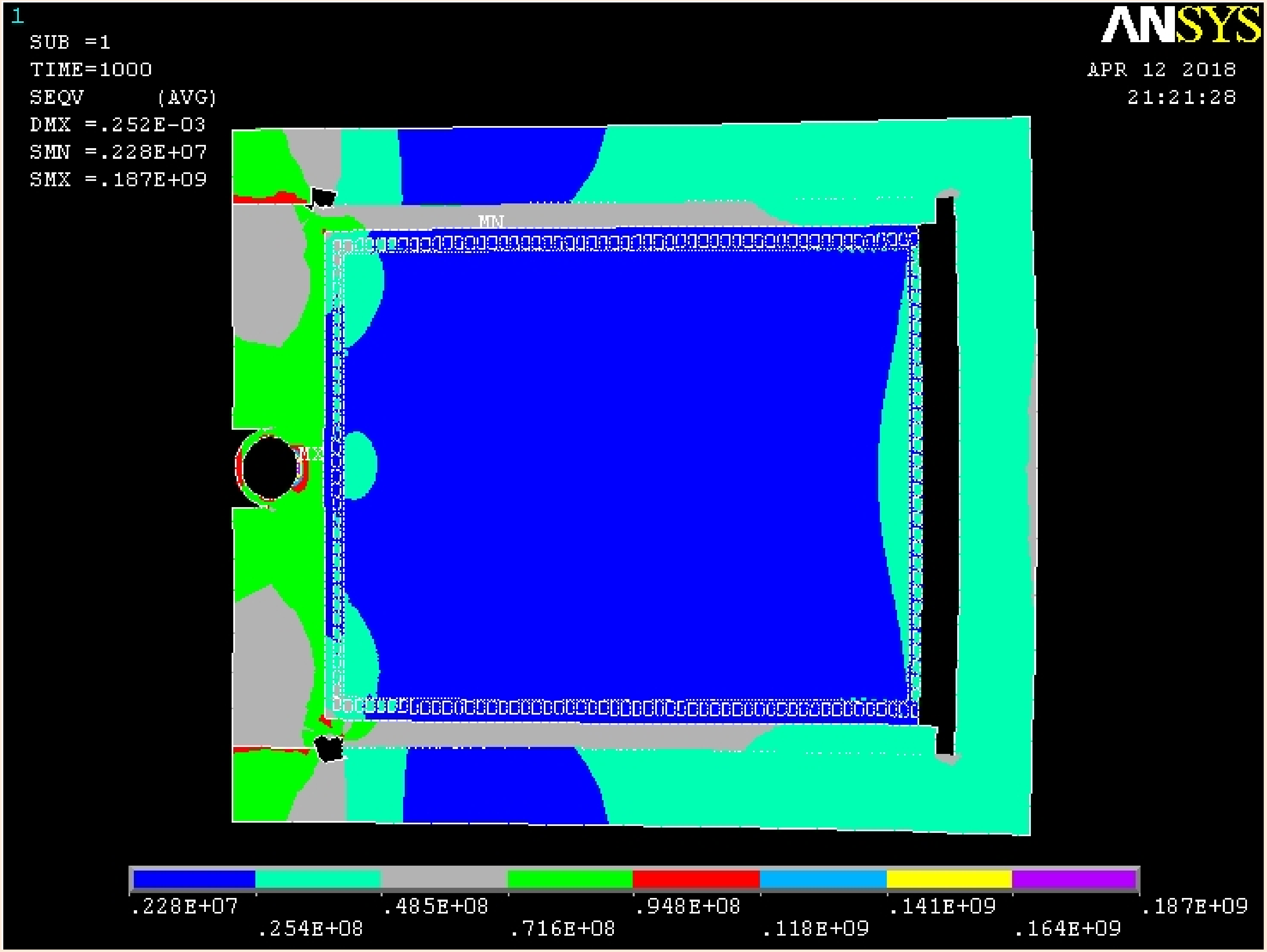
Temperature after 1000 s



Too fast cooling down. Results after 1000 s

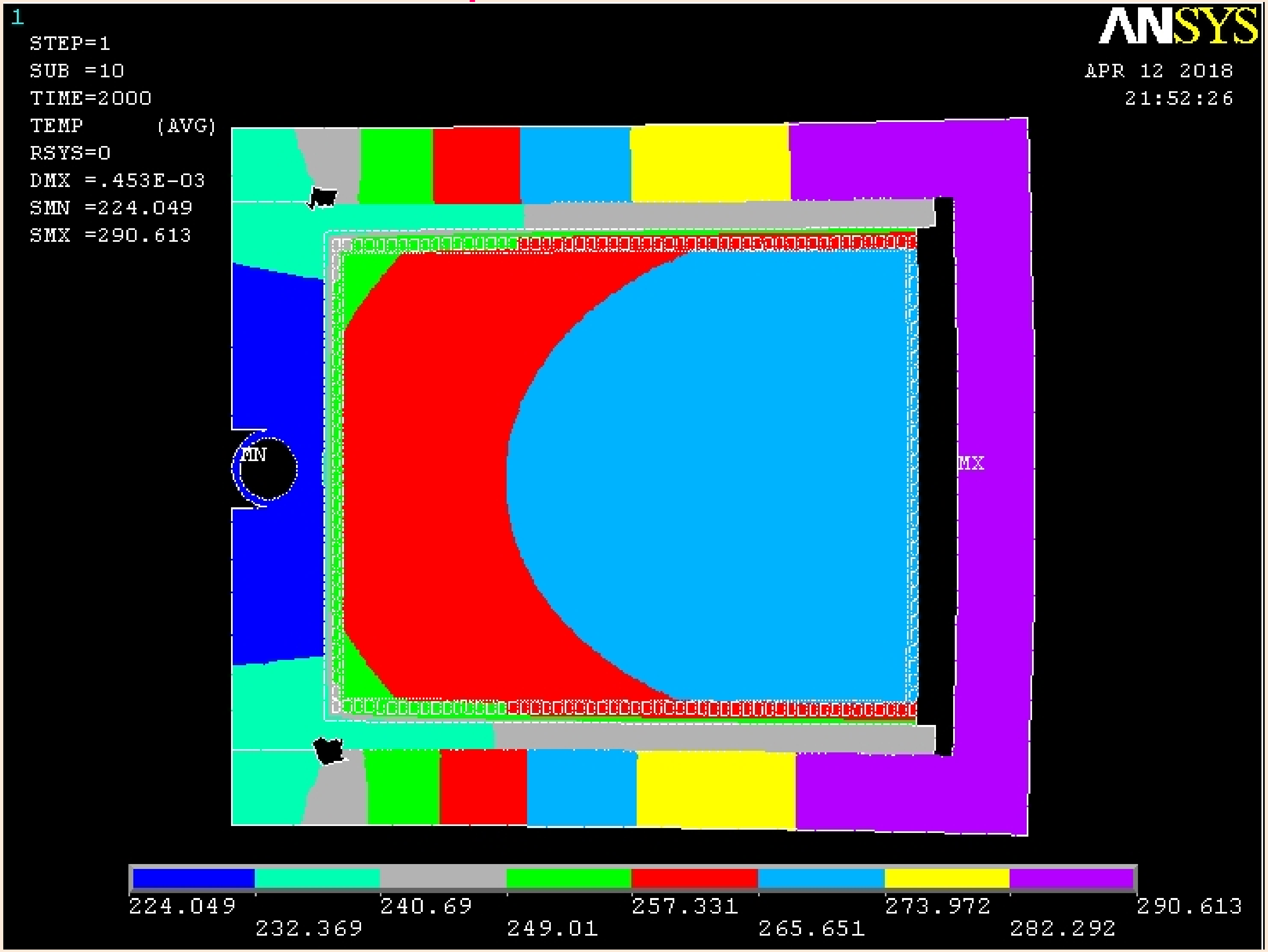
von Mises stress after 1000 s

The stress values are not
high in the
G-10
material.



Too fast cooling down. Results after 2000 s

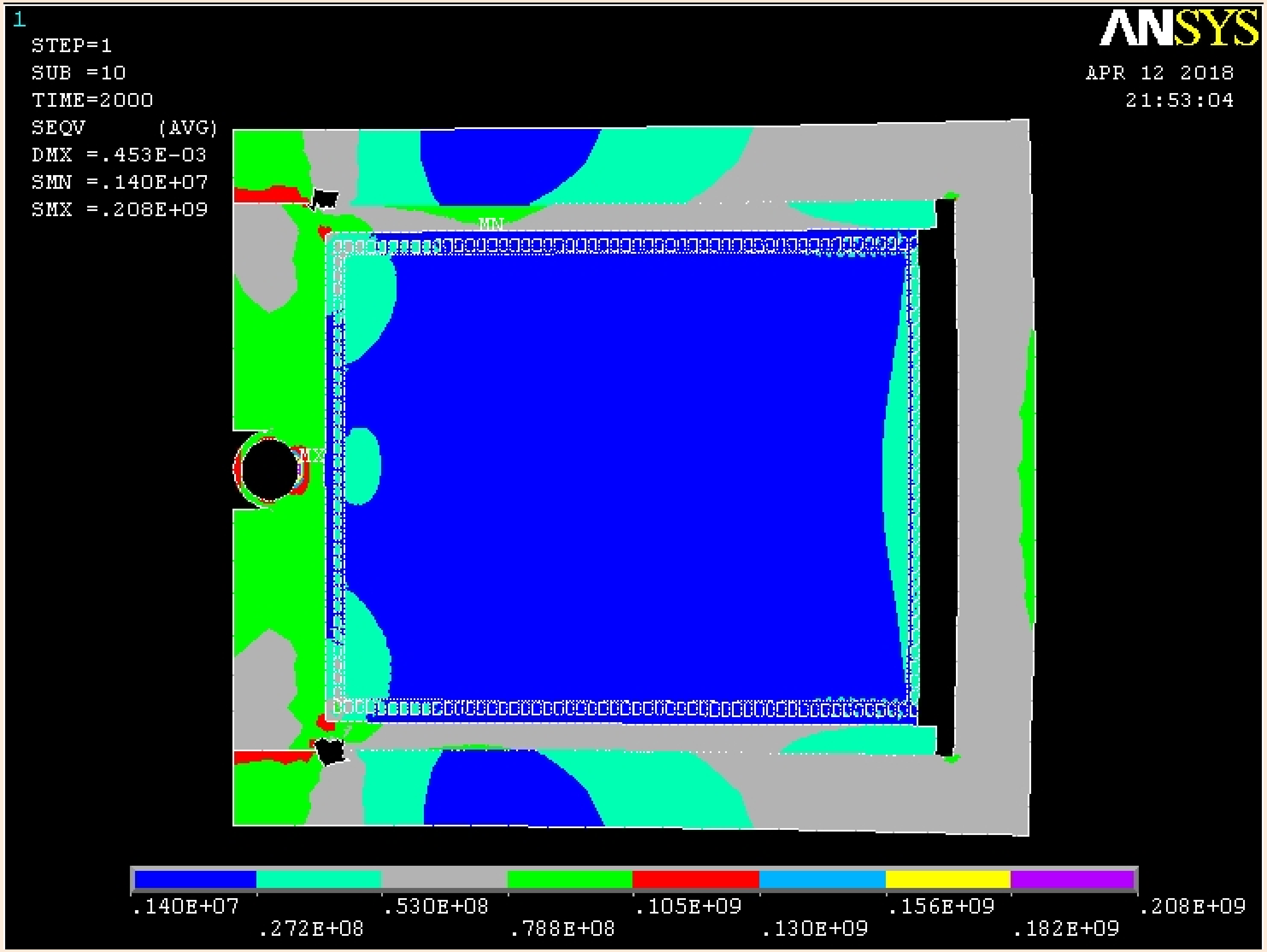
Temperature after 2000 s



Too fast cooling down. Results after 2000 s

von Mises stress after 2000 s

The stress values are not high in the G-10 material.



Conclusions

- The 3D model of the coil was calculated in ANSYS. The main stresses in the coil appears from different CTE of the materials and from bending around the supports.
- It is important to have materials of close CTE especially for the insulating and filling materials.
- The 2D model was calculated in ANSYS to show the stresses in the coil after cooling down to see if the specific pretension will work. Importance of proper CTE of epoxy compound was demonstrated. Application of specific pretention is unclear, it will be dependent by winding process (condition of winding machine and insulation). The Young modulus was 20 MPa for “G-10”, it will be much less for epoxy compound.
- The transient process of too fast cooling down was performed to see any harmful stresses in the coil. The stresses around the winding are not high. The cooling tube may be under large stresses.
- In total the performed analyses have not shown principal problems in the design.