

Structural analysis of coil and cold mass, choice of 2 support designs

Alexey Bragin, Vassily Syrovatin

Budker Institute of Nuclear Physics, Novosibirsk, Russia

November, 2019

The purpose of the calculations

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, mostly in 3D models.

The values of the forces were taken from other ANSYS magnetic field calculations to simplify the model.

Two designs of the support struts were calculated.

Criteria for the coil

- - 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 should 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

$$\sigma = p \cdot R / h \text{ (radius and radial thickness of the coils)}$$

$\sigma = 5 \cdot 0.7 / 0.16 = 22 \text{ MPa}$ – 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!

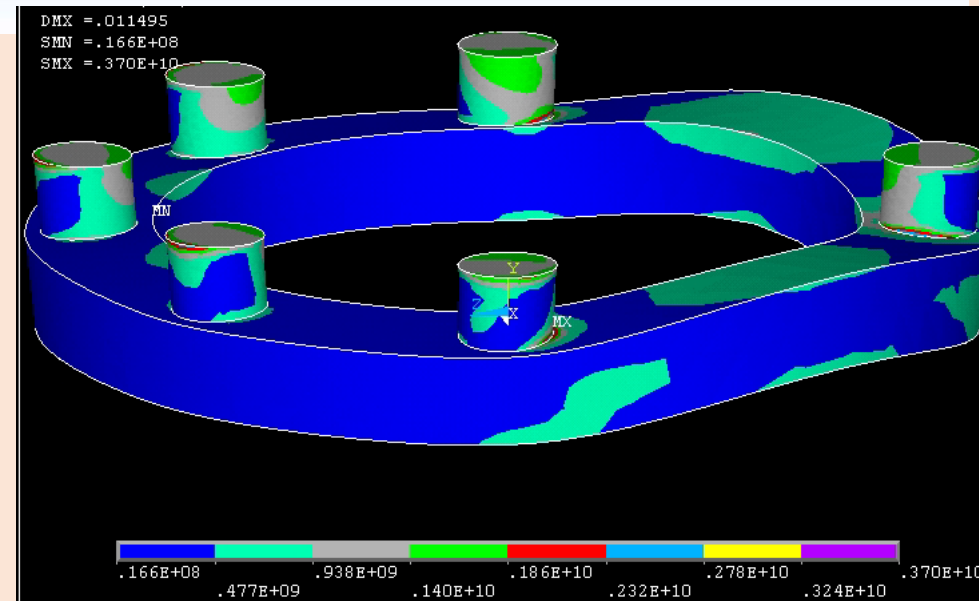
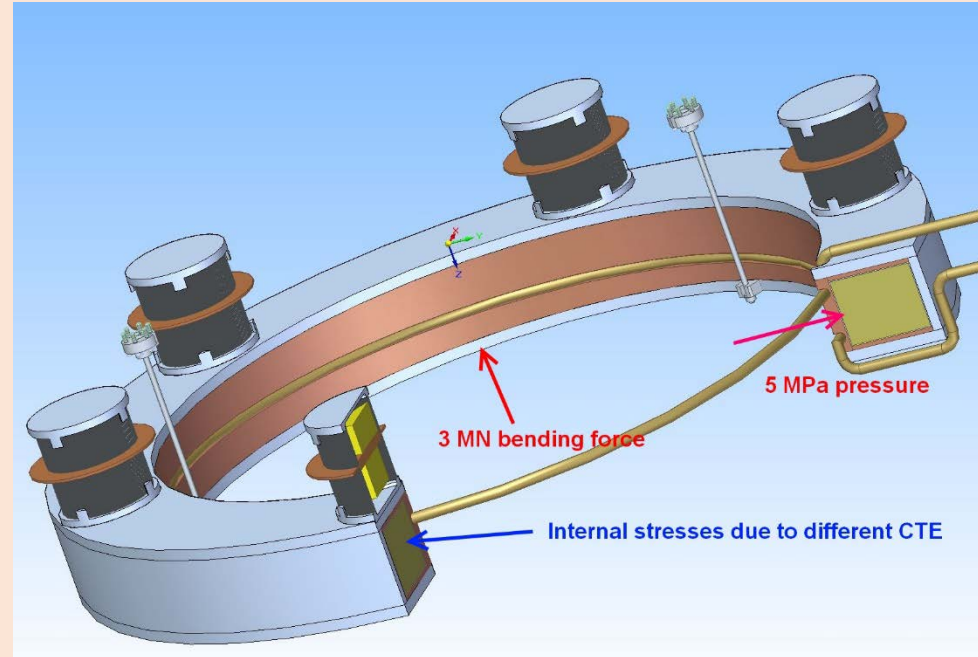
The direct application in the winding of this force gives $\sigma = F / (2\pi R \cdot h) = 3.3 / (4.87 \cdot 0.16) = 4.2 \text{ MPa}$ – very low value. **Large number of the struts.**

$$\sigma = \frac{M}{J_x} \cdot y \text{ evaluated according:}$$

, where M – force momentum [F*m], Jx – momentum of inertia [m⁴], 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:

$$\sigma = 4.4 \cdot 10^4 \cdot 0.1 / 1.33 \cdot 10^{-4} = 33 \text{ MPa. For the six struts.}$$

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



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.

Epoxy compound with powder

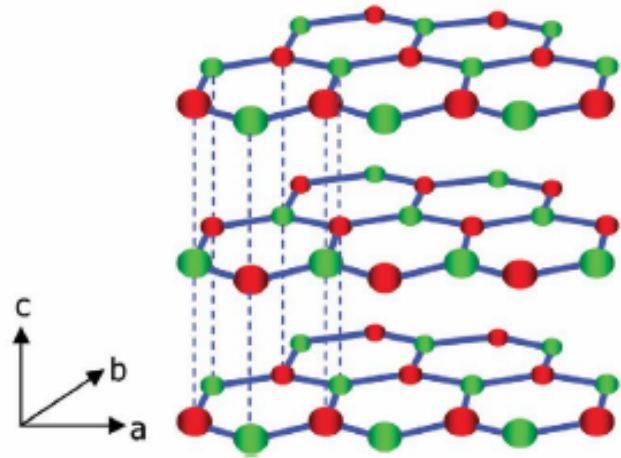


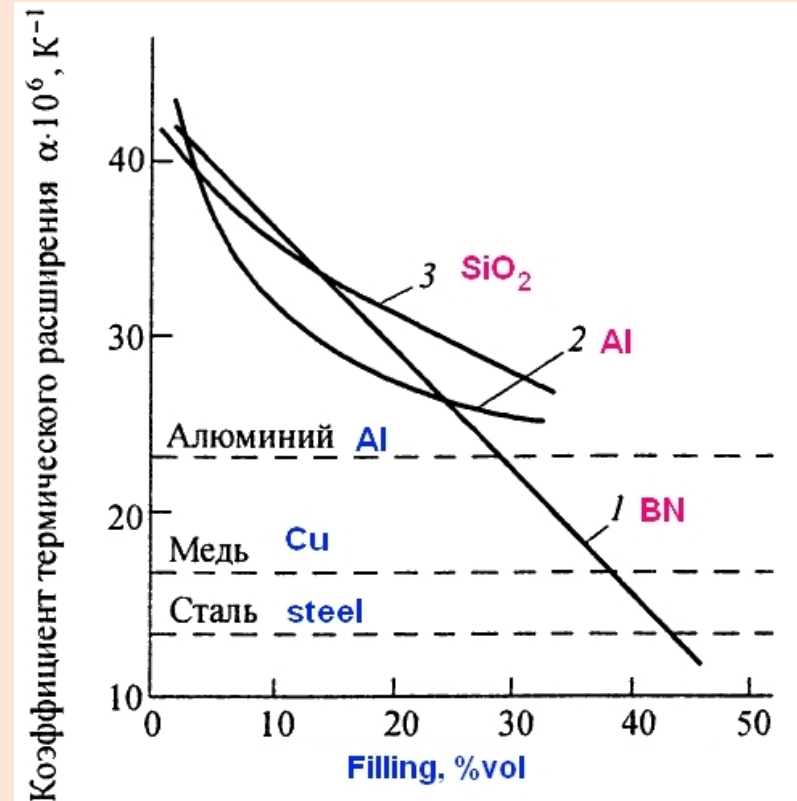
Figure 1: Structure of hexagonal boron nitride.

Table 1: Typical properties of various thermal fillers

	BN	AlN	Al ₂ O 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/mm ²)	11	1200	1500	500	387

“Boron nitride finds new applications in thermoplastic compounds.”

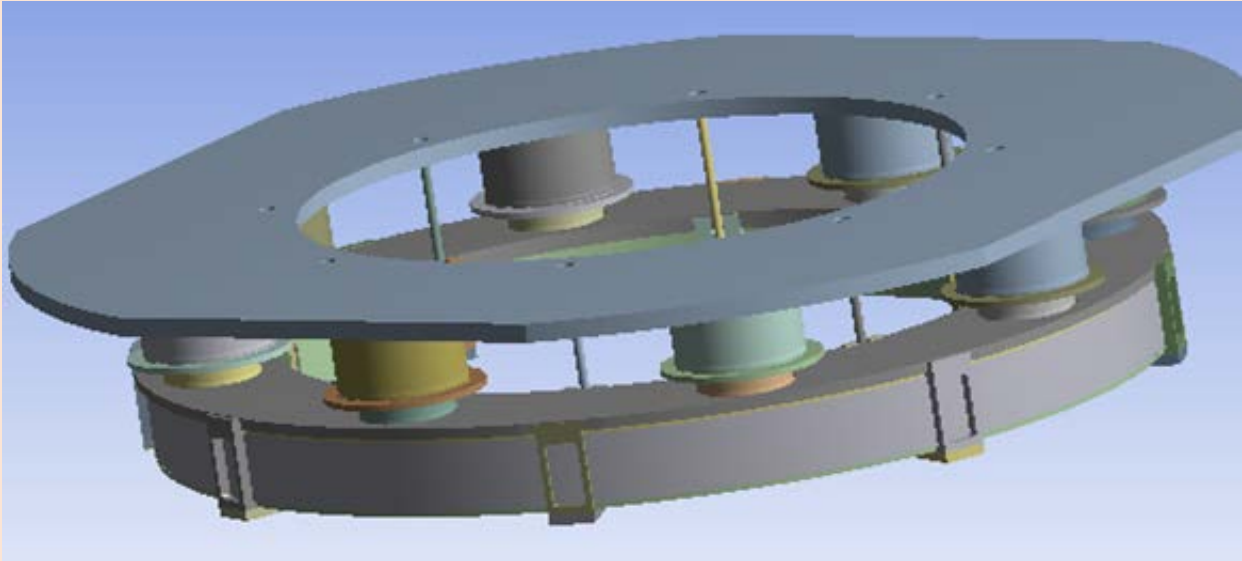
Plastics Additives & Compounding May/June 2008, p.26.



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.

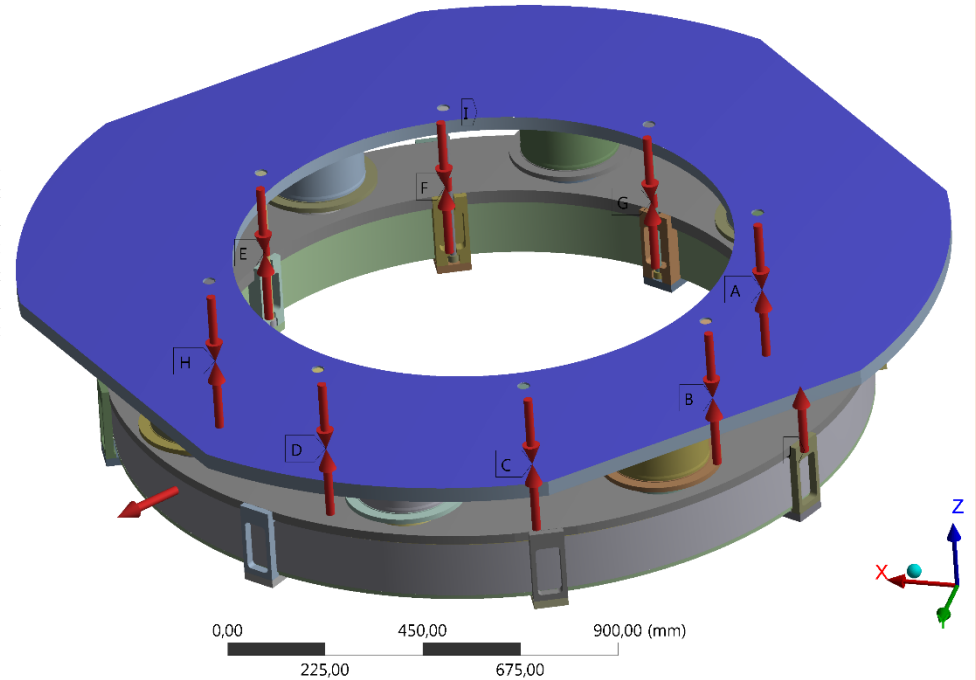
The 3D ANSYS model – eight struts design



The loads applied to the model. The vertical force is 360 tons, the pressure is 6 MPa.

E: G10 warp Z frictional
Static Structural
Time: 3, s
Items: 10 of 11 indicated
26.09.2018 10:23

- A** Bolt Pretension: Lock
- B** Bolt Pretension 2: Lock
- C** Bolt Pretension 3: Lock
- D** Bolt Pretension 4: Lock
- E** Bolt Pretension 5: Lock
- F** Bolt Pretension 6: Lock
- G** Bolt Pretension 7: Lock
- H** Bolt Pretension 8: Lock
- I** Frictionless Support
- J** Force: 3,6e+006 N



The boundary conditions:

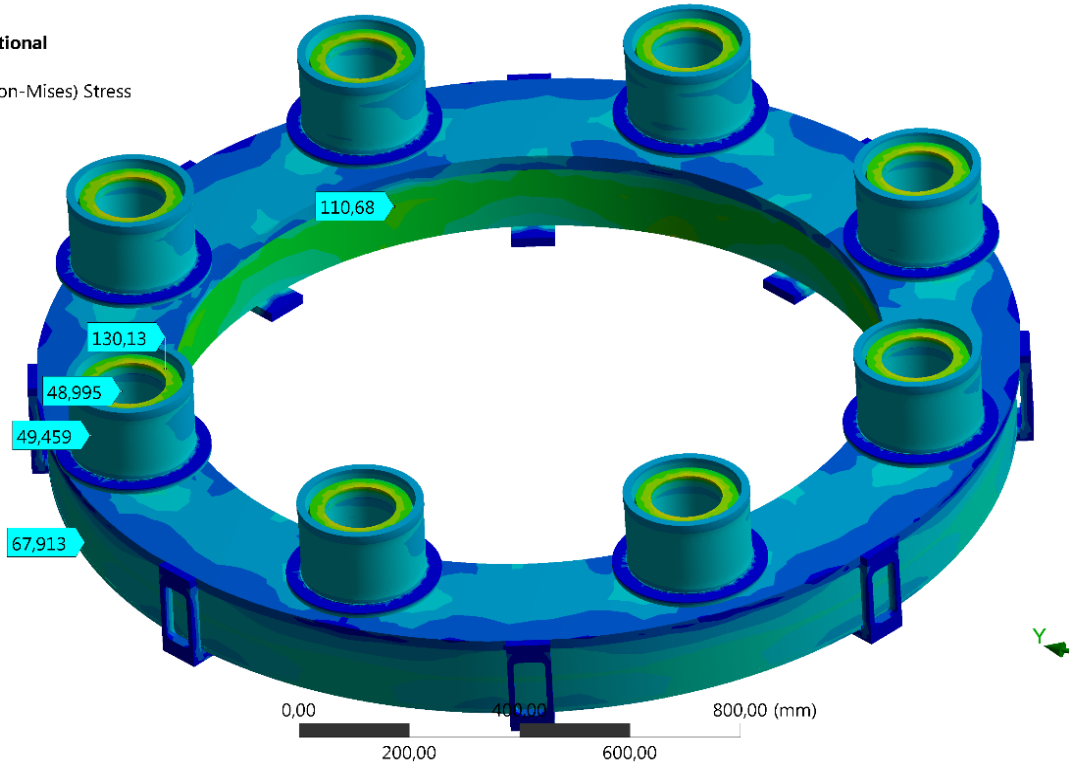
The outer surface of the stainless steel vessel is fixed in all directions.

The cable pretension was not accounted, because this value is not much 10-20 kg, about 30 MPa without insulation. In all volume ~ 15 MPa. The copper case has the contraction coefficient more than wire, so the influence is negligible.

Results

E: G10 warp Z frictional
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 3
26.09.2018 9:39

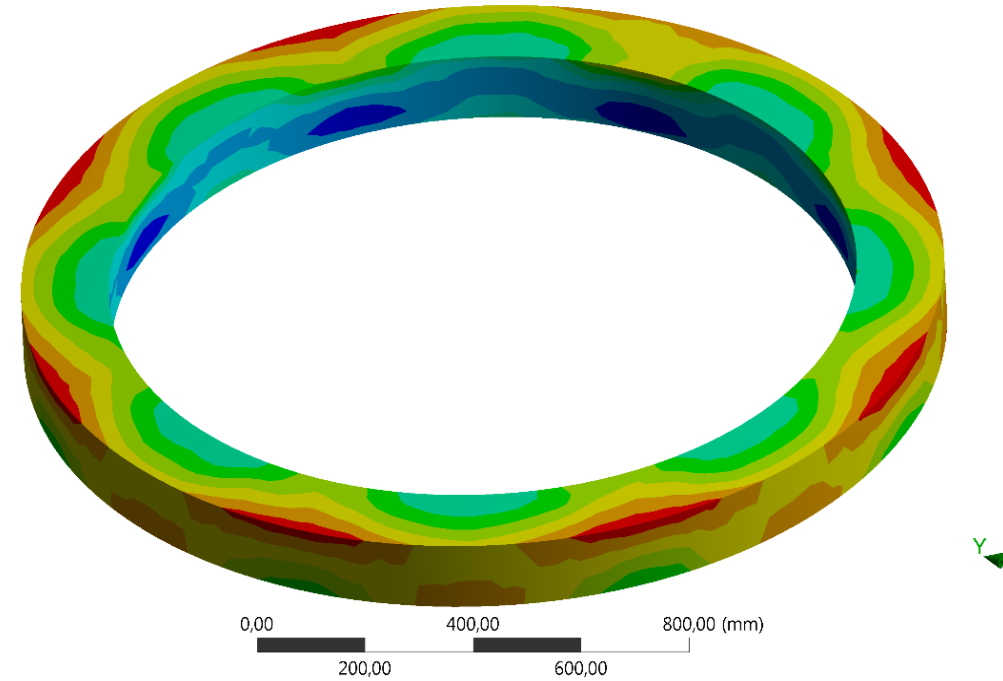
217,17 Max
201,67
186,16
170,66
155,15
139,65
124,14
108,64
93,135
77,631
62,126
46,622
31,118
15,613
0,10875 Min



Von-Mises stress, total model. Max. 217.2 MPa

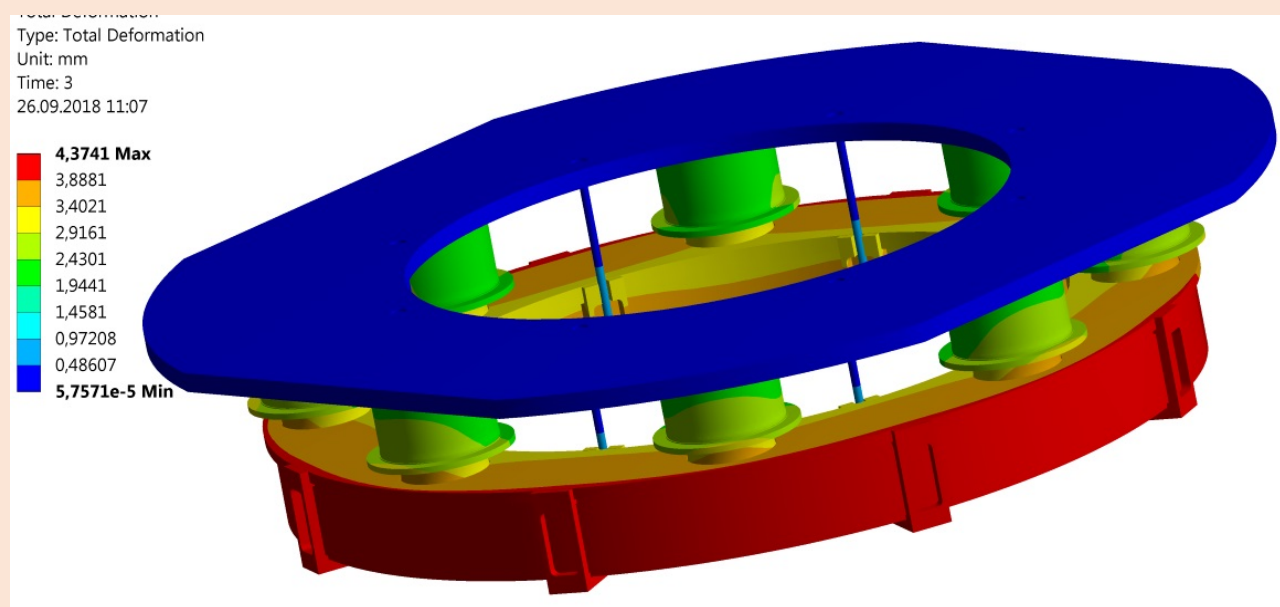
E: G10 warp Z frictional
Equivalent Stress 2
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 3
26.09.2018 9:45

61,72 Max
55,933
50,147
44,361
38,574
32,788
27,001
21,215
15,429
9,6423 Min

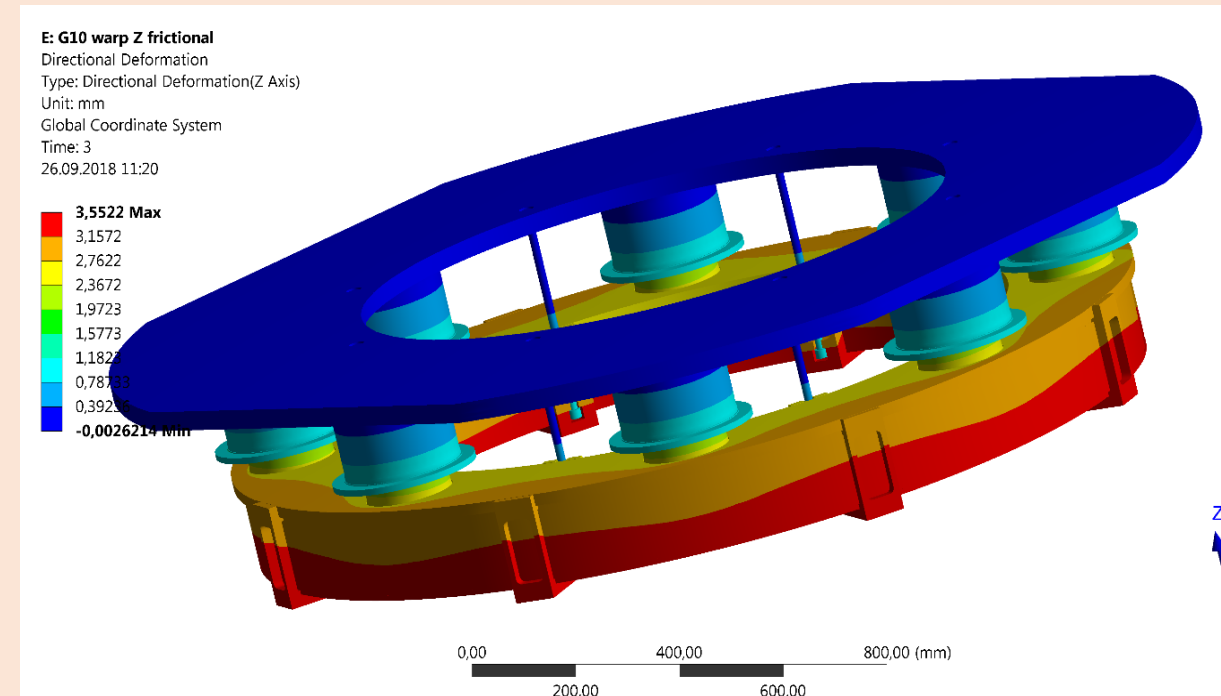


Von-Mises stress, in the coil. Max. 61.7 MPa

Results



Total deformation. Max. 4.37 mm



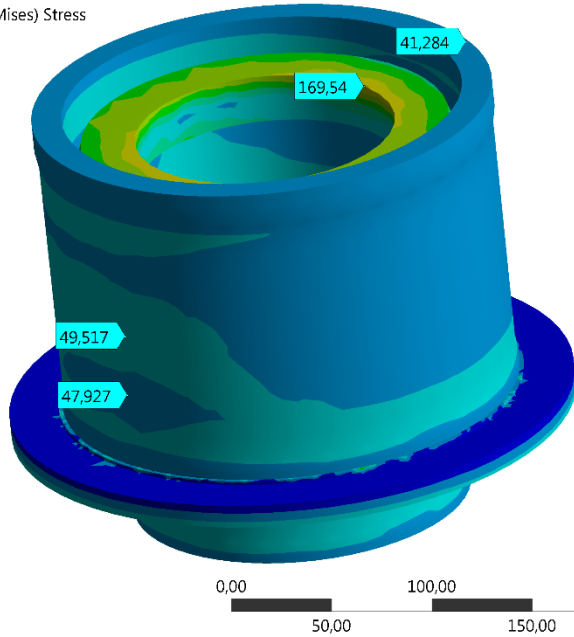
Total deformation in Z direction. Max. 3.55 mm

Results

E: G10 warp Z frictional

Equivalent Stress 3
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 3
26.09.2018 9:49

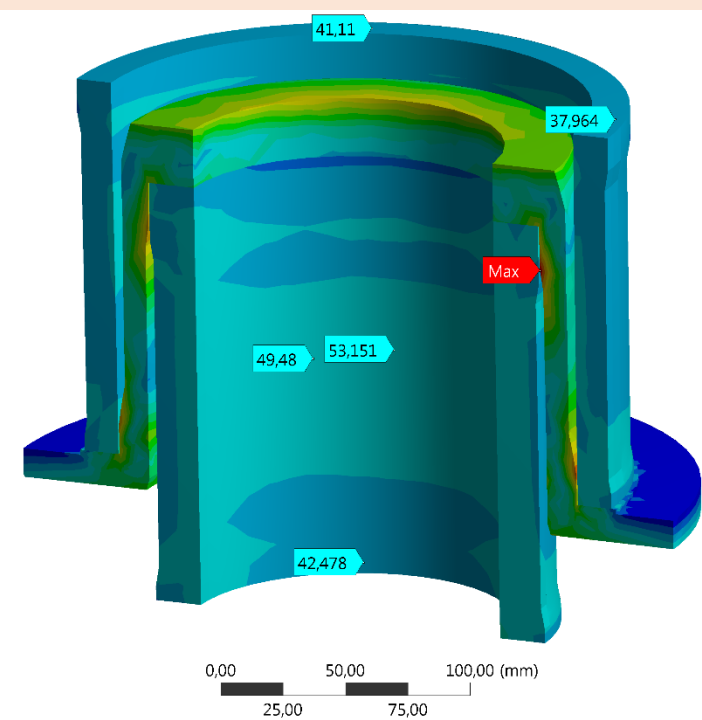
213,73 Max
190,18
166,63
143,08
119,52
95,973
72,423
48,872
25,321
1,7696 Min



Von-Mises stress.
Max. 213.7 MPa

E: G10 warp Z frictional
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 3
26.09.2018 10:01

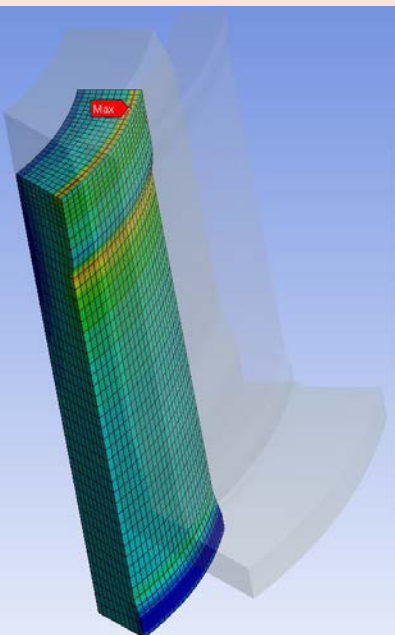
209,73 Max
193,75
177,76
161,77
145,78
129,8
113,81
97,82
81,832
65,844
49,856
33,868
17,88
1,8926 Min



Von-Mises stress. Max. ~ 53.2 MPa, not uniformly loaded

B: Static Structural
Maximum Shear Stress
Type: Maximum Shear Stress
Unit: MPa
Time: 2
20.08.2018 8:50

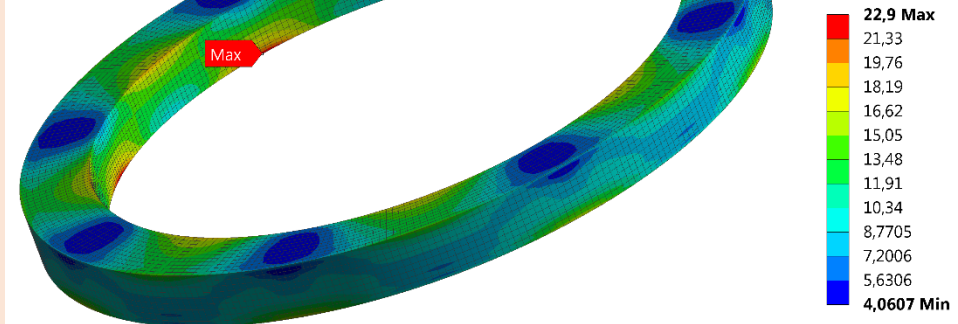
58,89 Max
55,815
52,74
49,665
46,59
43,515
40,44
37,365
34,29
31,215
28,14
25,065
21,99
18,915
15,84 Min



Shear stress in the G-10
Max. 58.9 MPa

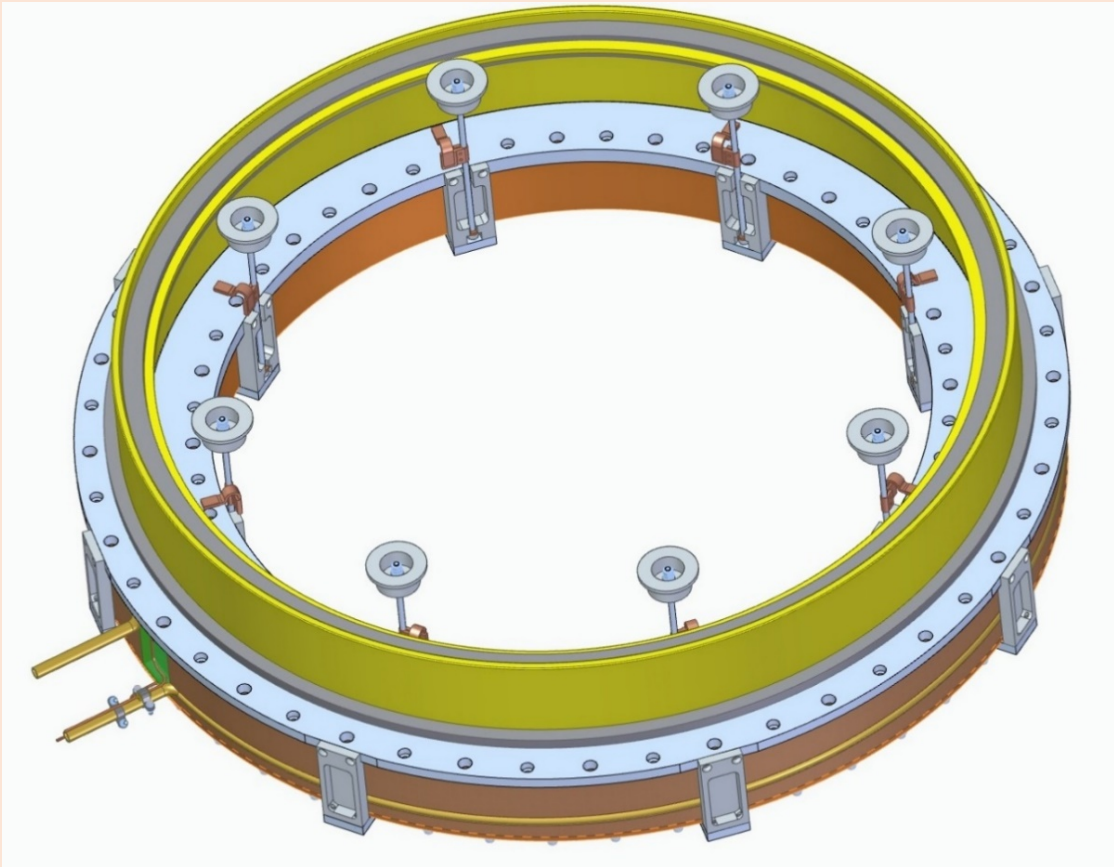
Time [s]	Minimum [MPa]	Maximum [MPa]
1	3,4261e-007	1,7618e-005
2	15,84	58,89

E: Coil KTR 1.3 br
Maximum Shear Stress 2
Type: Maximum Shear Stress
Unit: MPa
Time: 2
14.09.2018 14:07

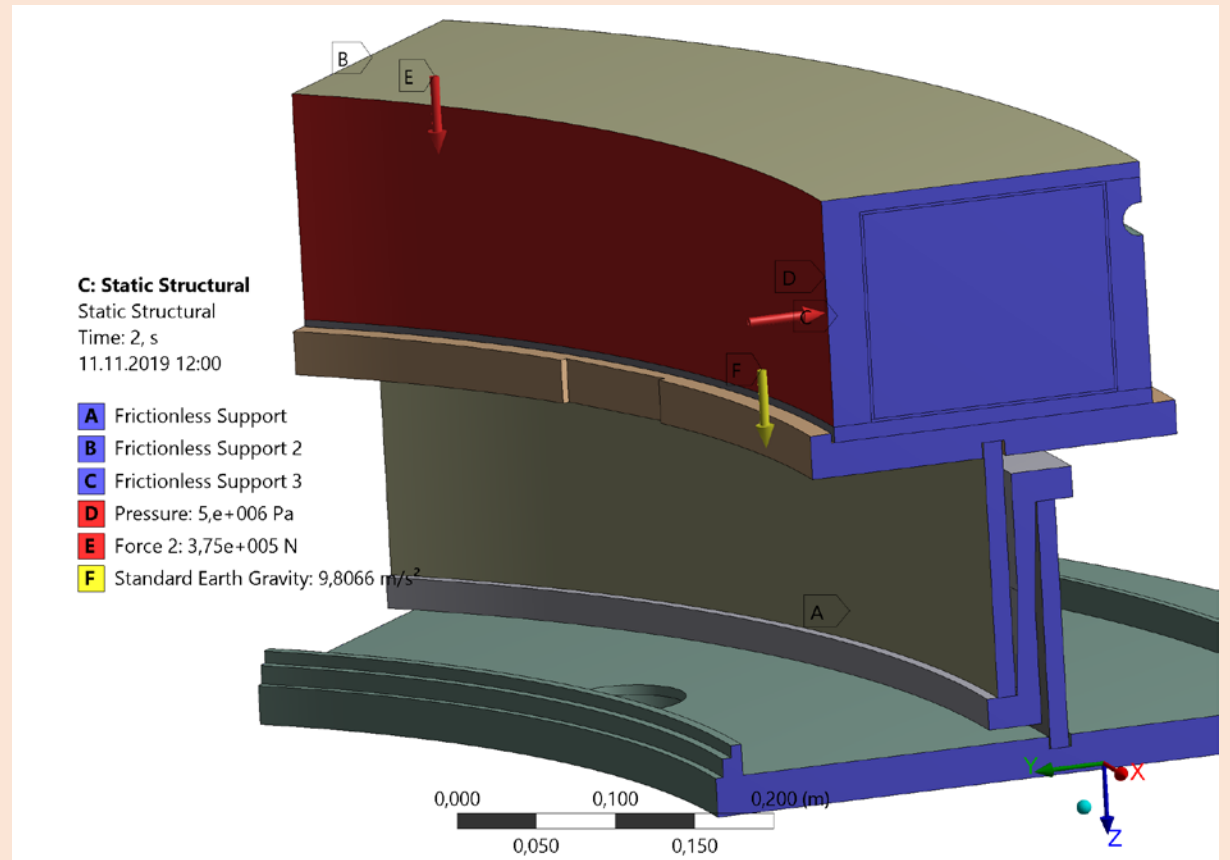


Shear stress in the coil. Max. ~ 22.9 MPa

The 3D ANSYS model – single strut design

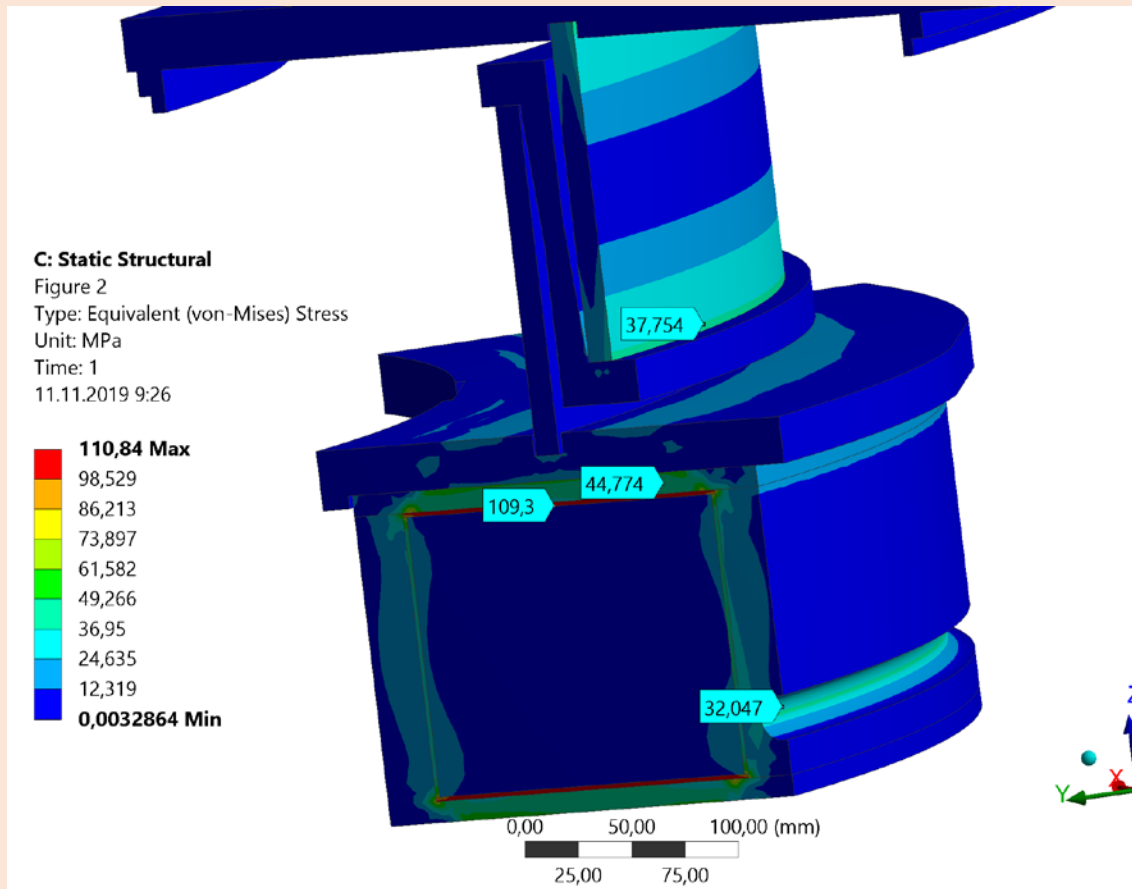


Main idea of this design is the ratio of total cross-section area to length is the same as for 8 struts as for single strut.

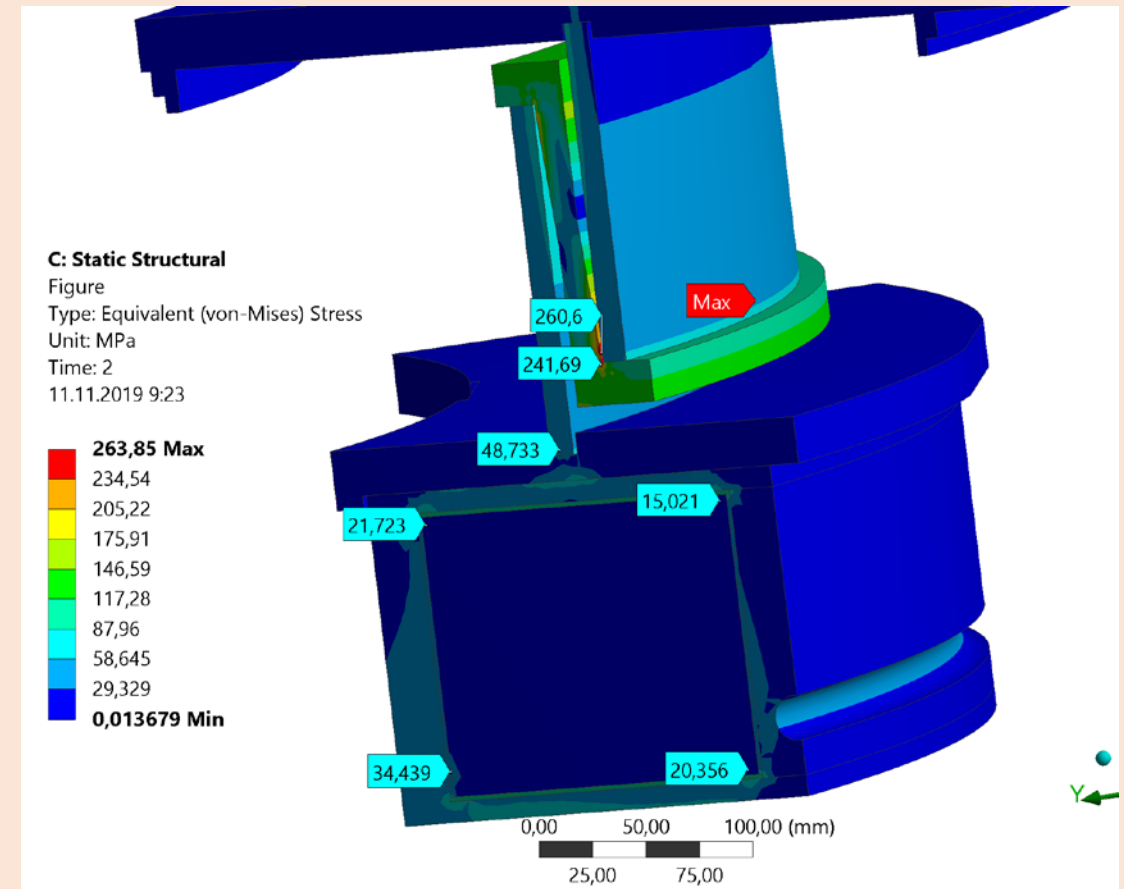


The model is 1/8th part (45 deg.). The loads are $F = 3$ MN, $p = 5$ MPa, gravitation, frictionless contact

Results

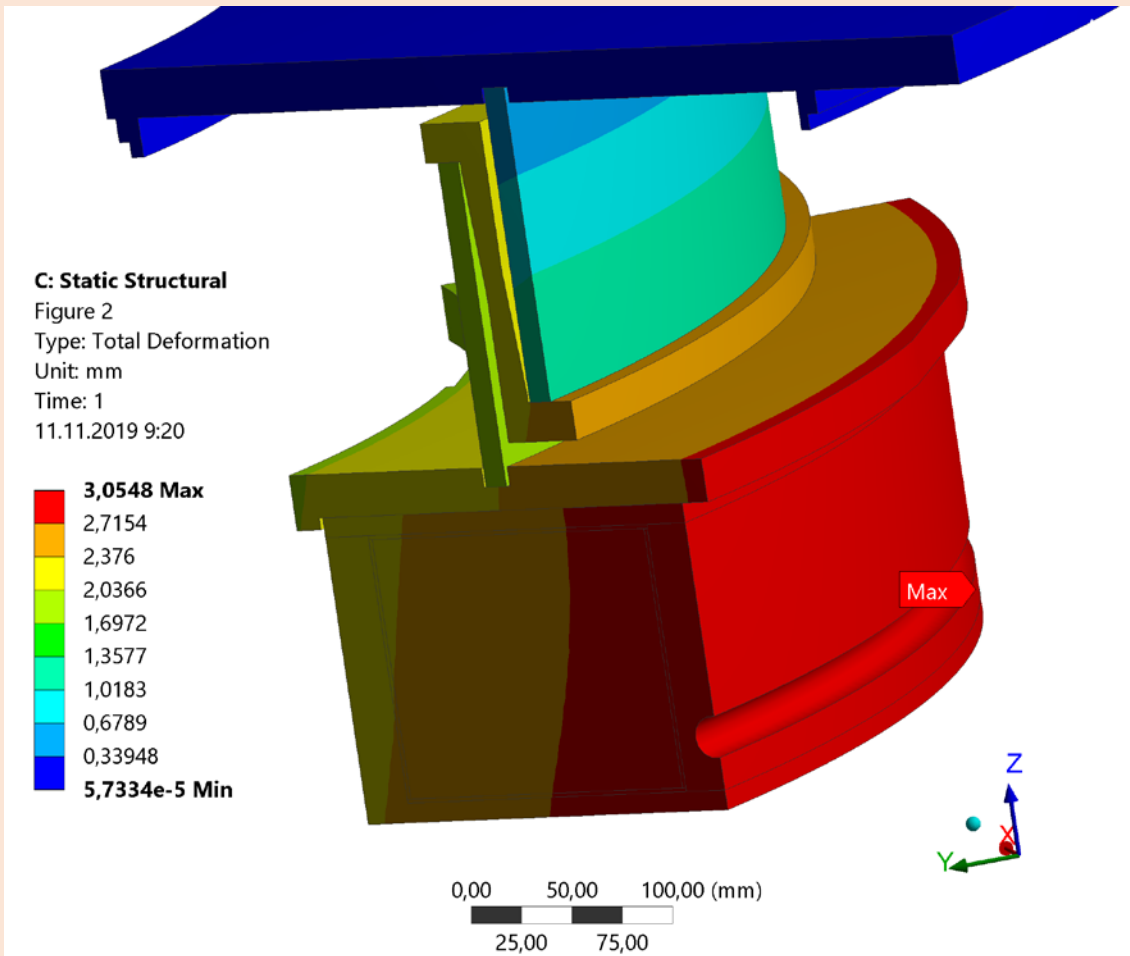


Von-Mises stress, total model, after cooling down.
Max. 110.8 MPa in G-10.

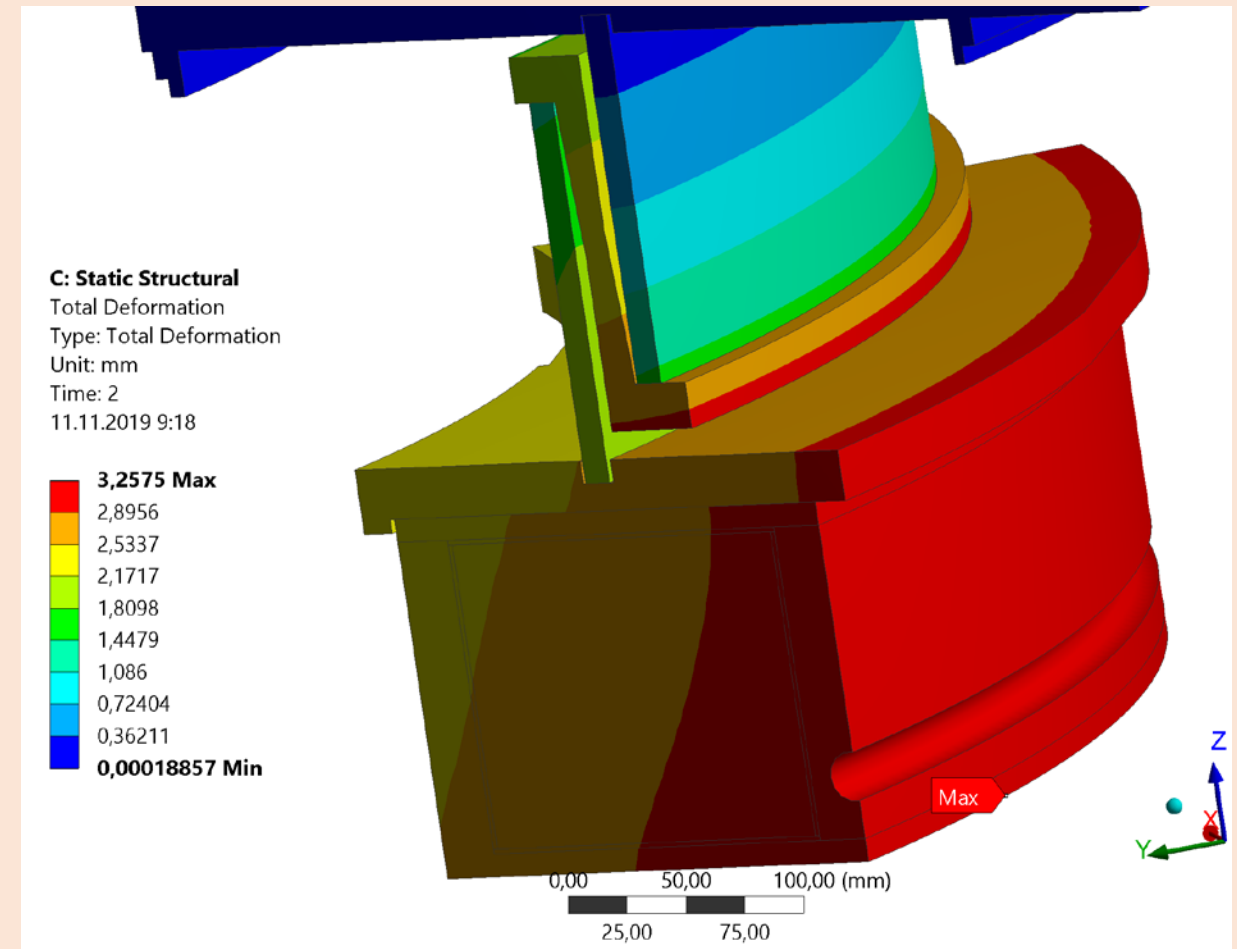


Von-Mises stress, total model, all loads. Max. 263.9 MPa
in the stainless steel

Results



Total deformation after cooling. Max. 3.055 mm

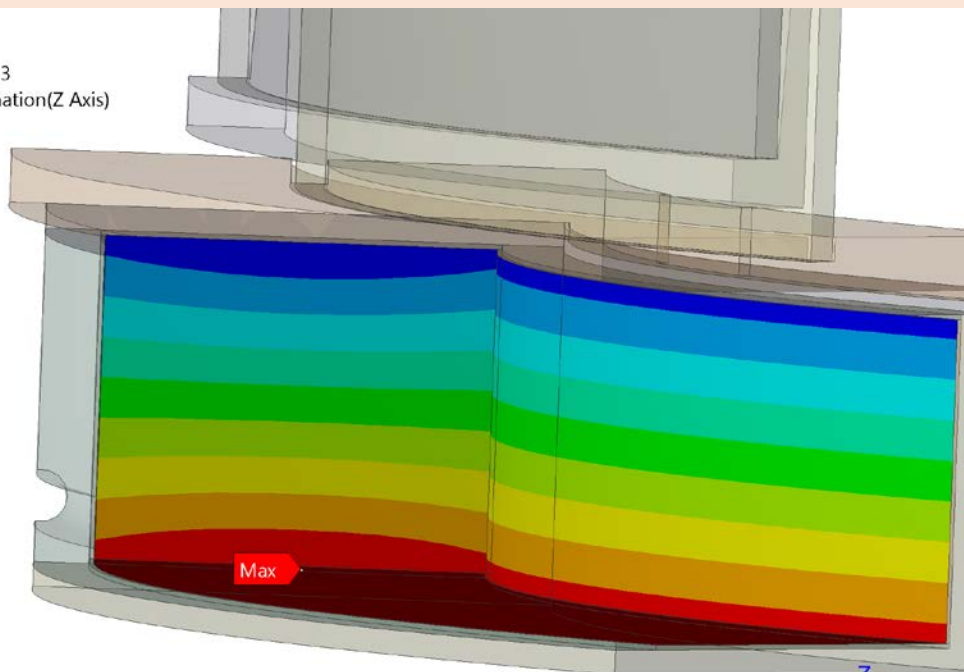


Total deformation after all loads. Max. 3.26 mm

Results

C: Static Structural
Directional Deformation 3
Type: Directional Deformation(Z Axis)
Unit: mm
cilindrical
Time: 1
11.11.2019 9:05

0,81214 Max
0,75414
0,69614
0,63815
0,58015
0,52215
0,46416
0,40616
0,34816
0,29016 Min

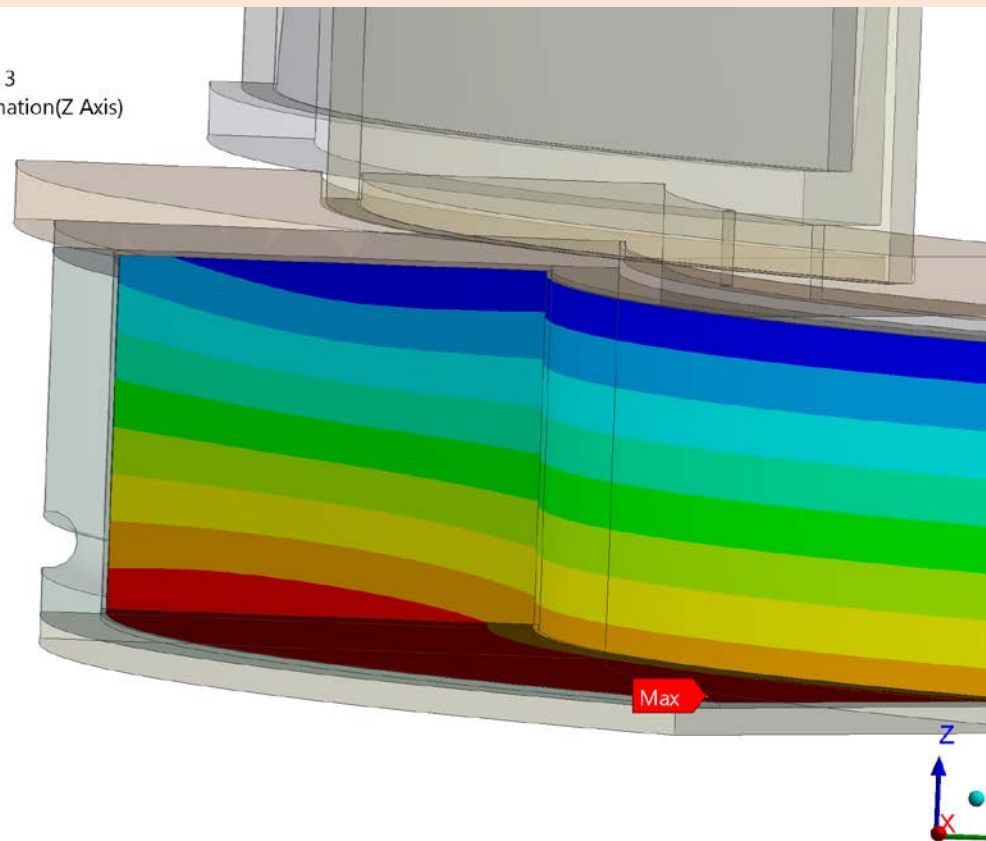


0,00 50,00 100,00 (mm)
25,00 75,00

Vertical (Z) deformation after cooling. Max. 0.812 mm

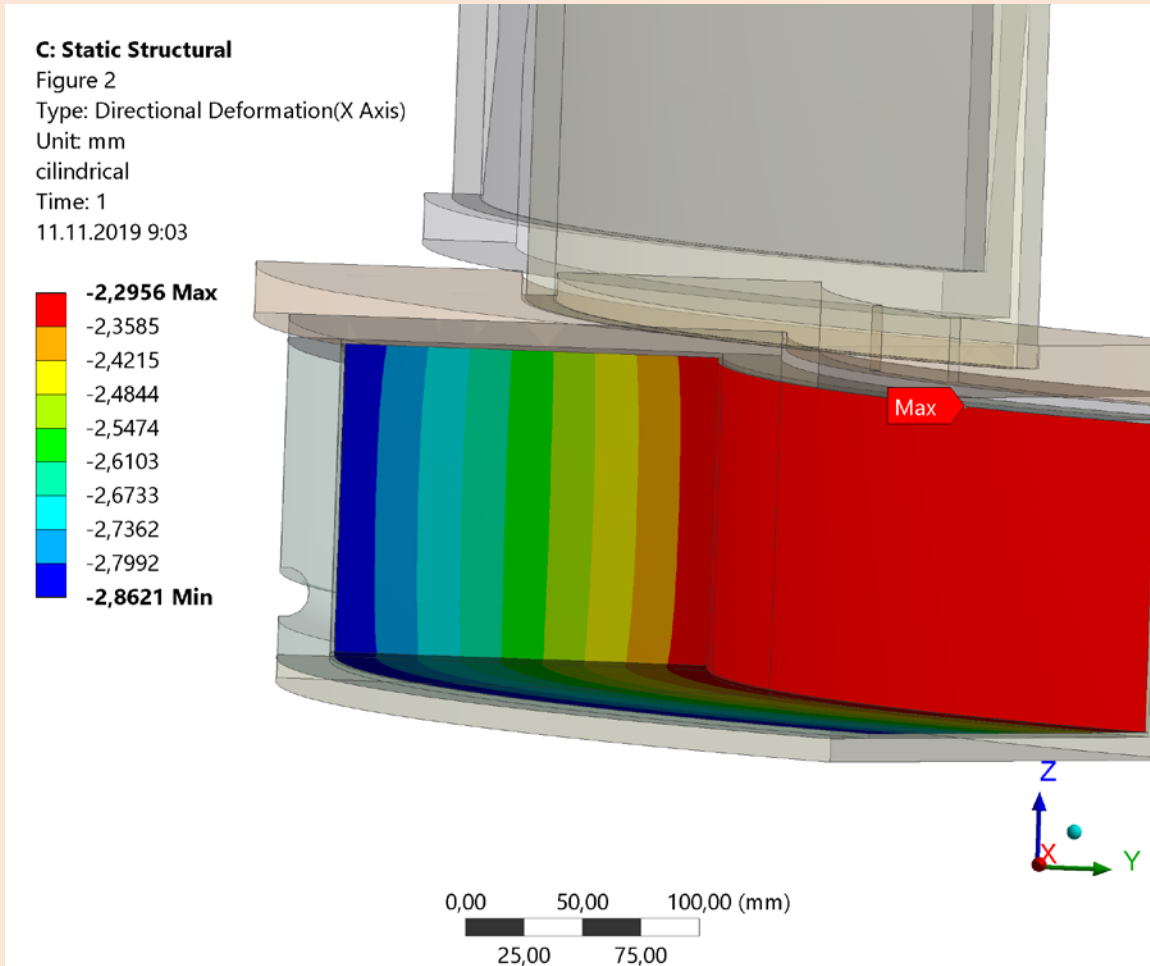
C: Static Structural
Directional Deformation 3
Type: Directional Deformation(Z Axis)
Unit: mm
cilindrical
Time: 2
11.11.2019 9:04

1,6561 Max
1,593
1,53
1,467
1,4039
1,3409
1,2778
1,2148
1,1518
1,0887 Min

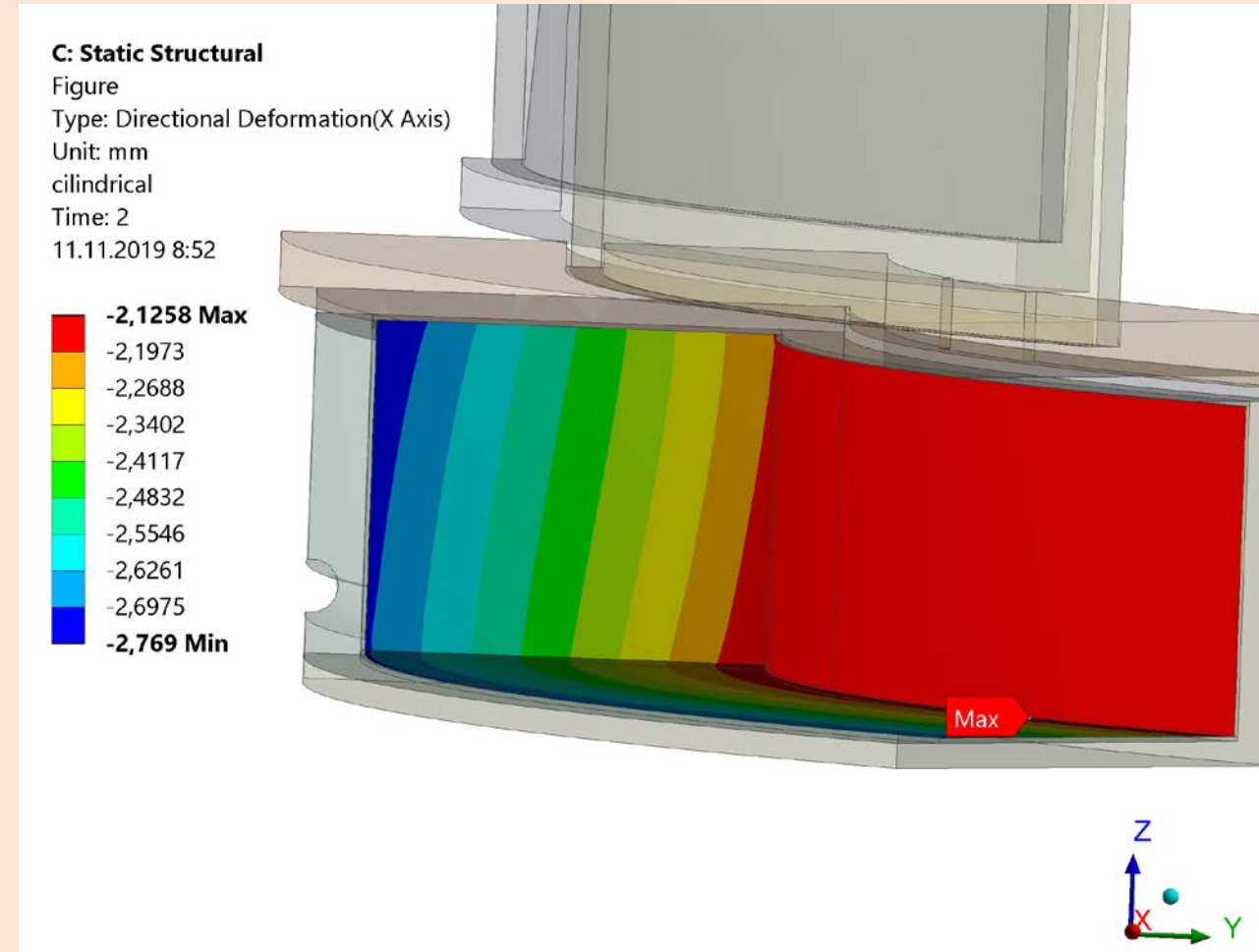


Vertical (Z) deformation after all loads. Max. 1.66 mm

Results



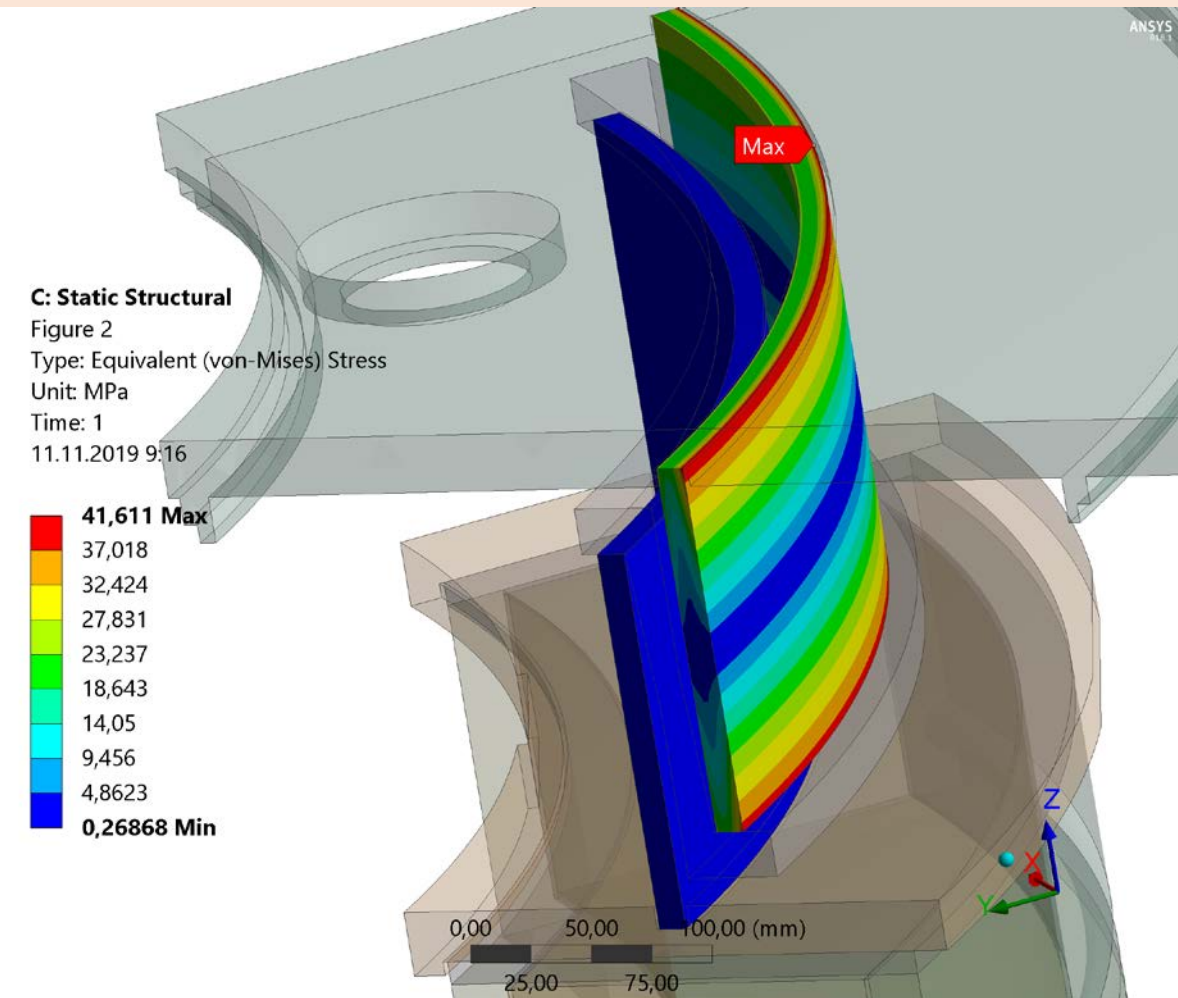
Radial (X) deformation after cooling. Max. - 2.8621 mm



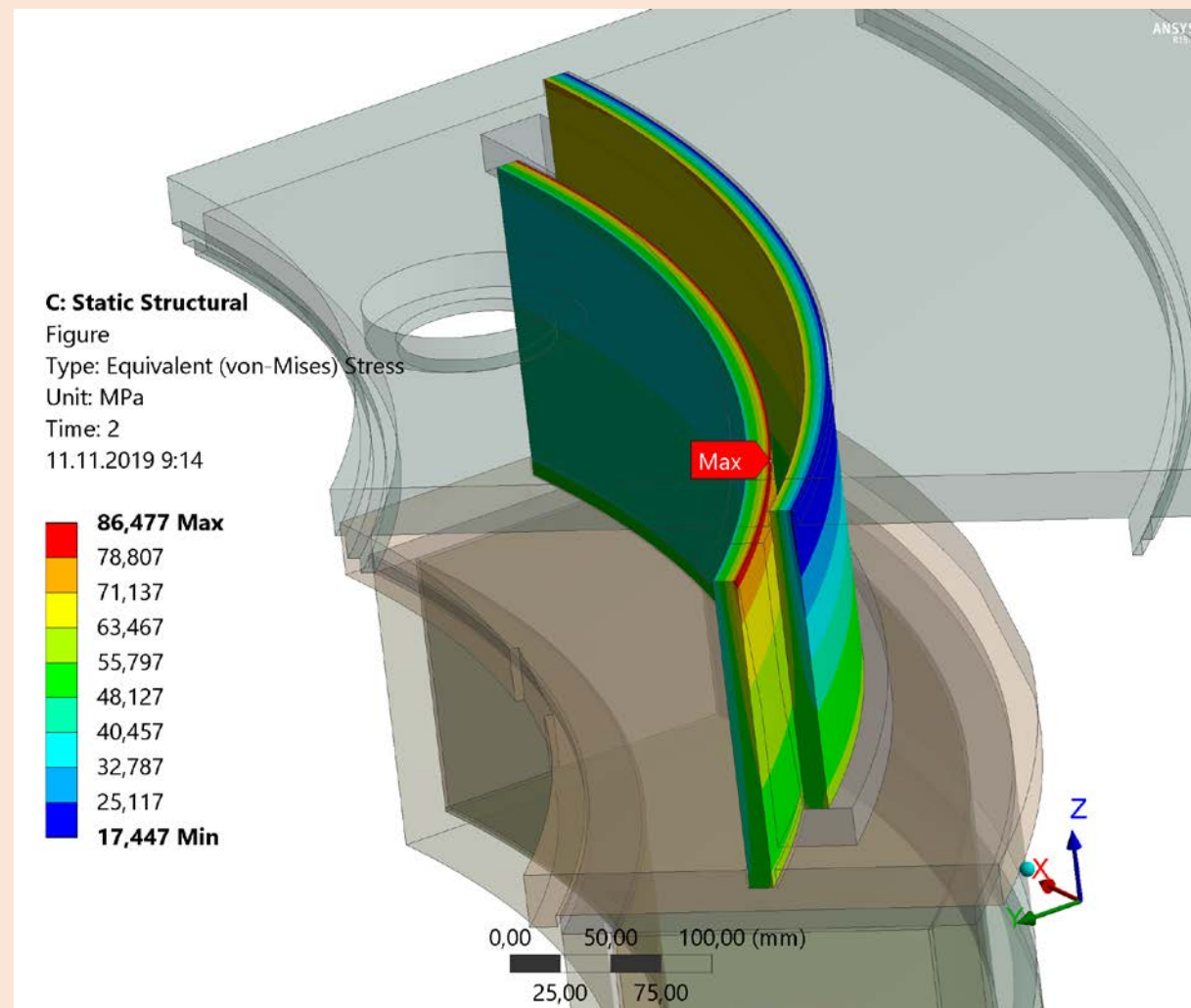
Radial (X) deformation after all loads. Max. - 2.769 mm

$dX = 2.8621 - 2.769 = 0.0931$ mm – radial expansion after powering. Stainless steel holds the winding!

Results

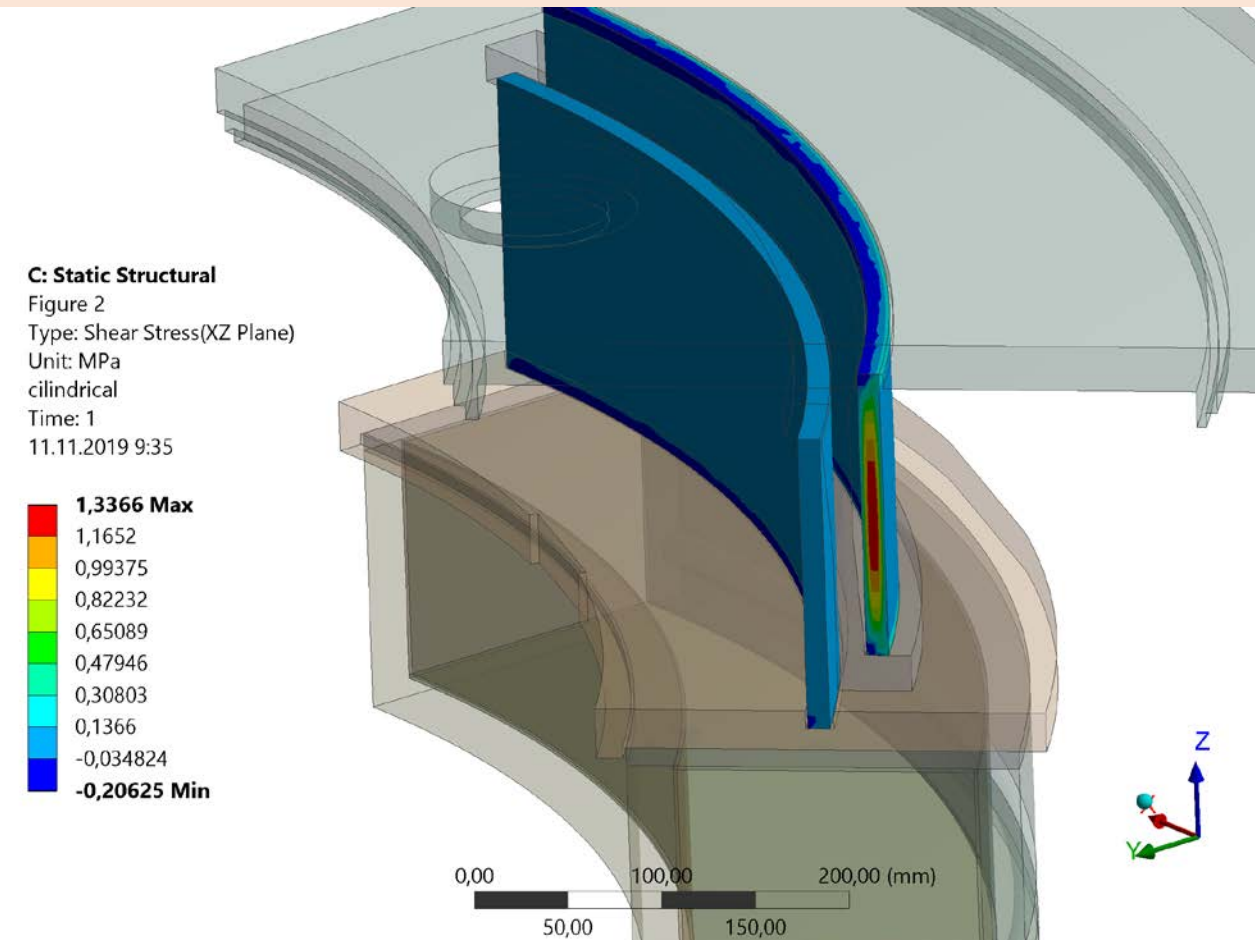


Von-Mises stress, after cooling. Max. 41.6 MPa

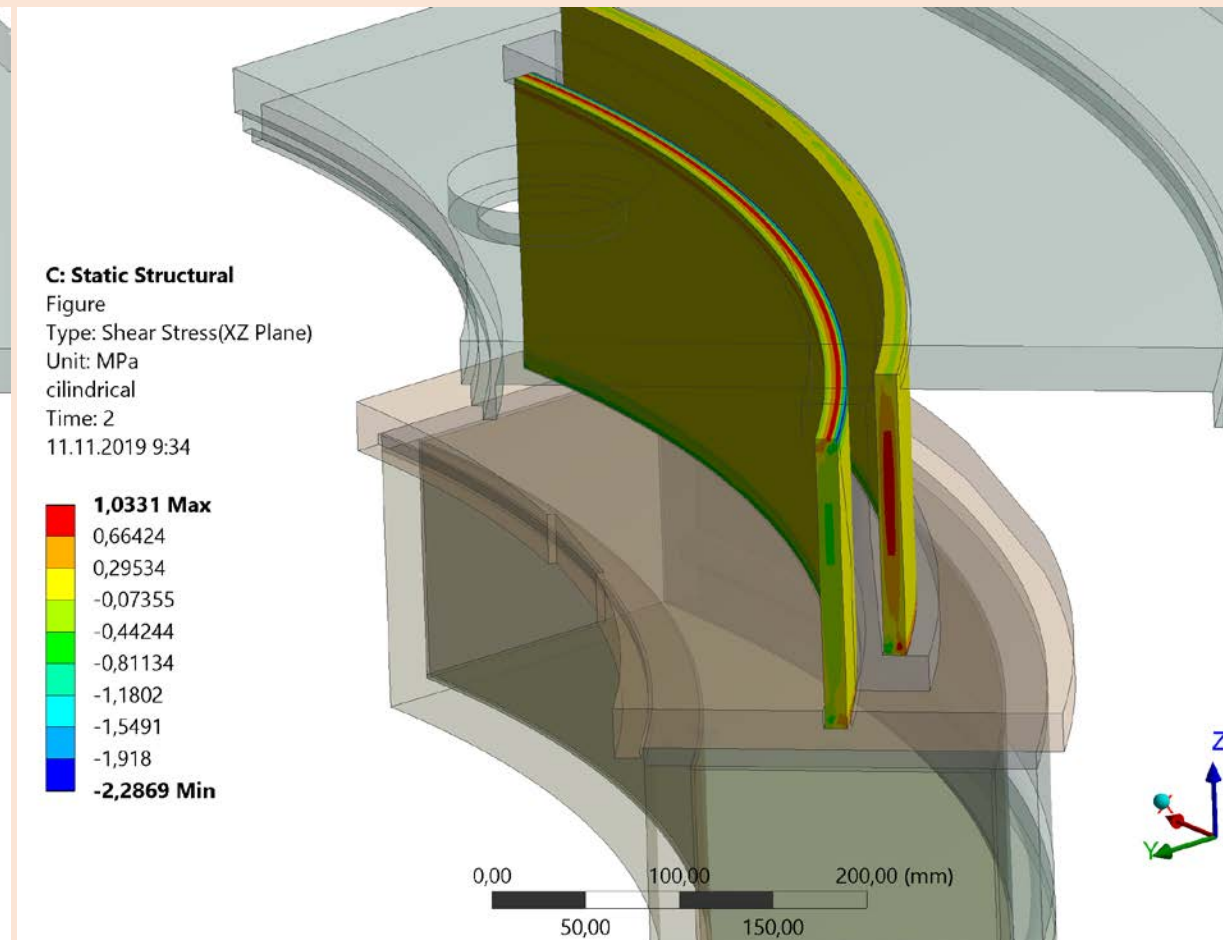


Von-Mises stress, after all loads. Max. 86.5 MPa

Results

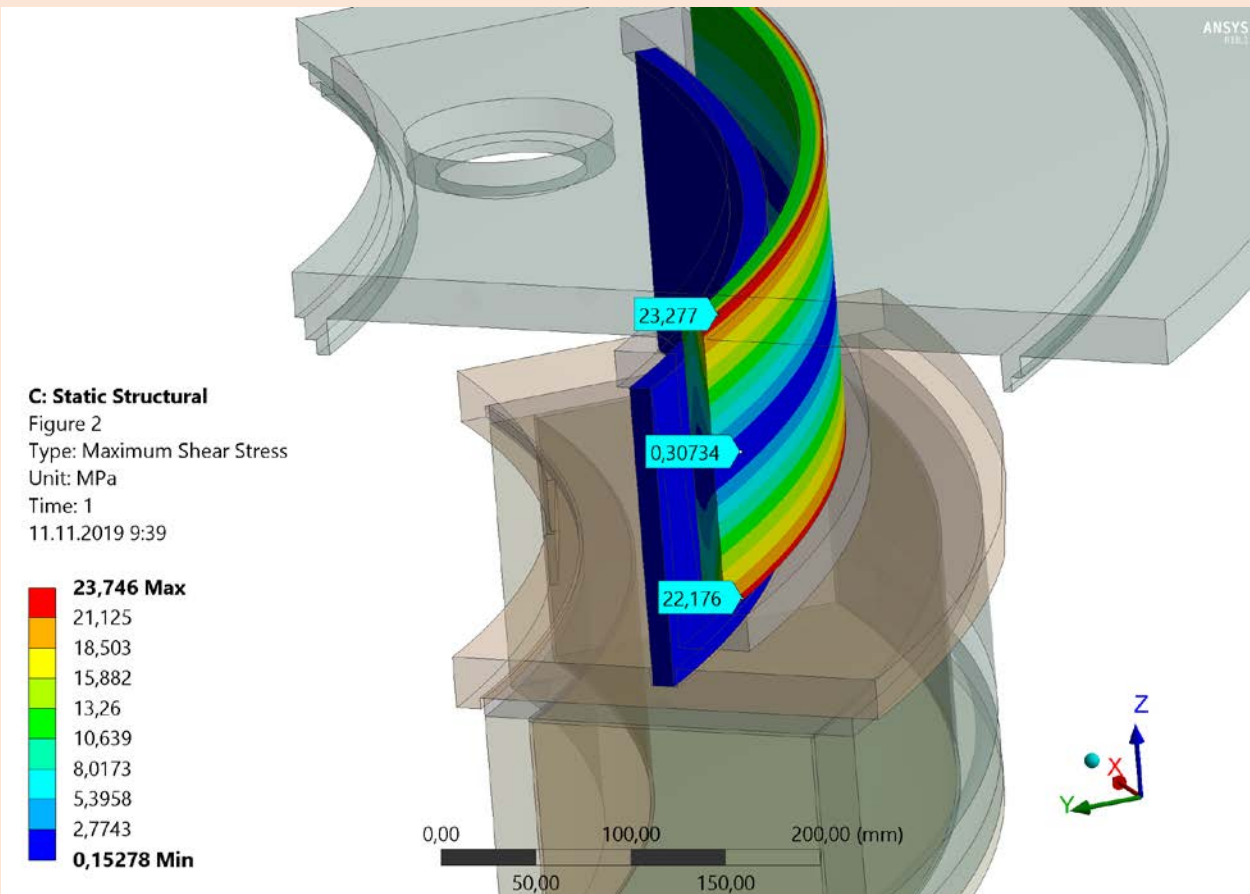


Shear stress in radial-vertical plane (XZ), after cooling.
Max. 1.34 MPa

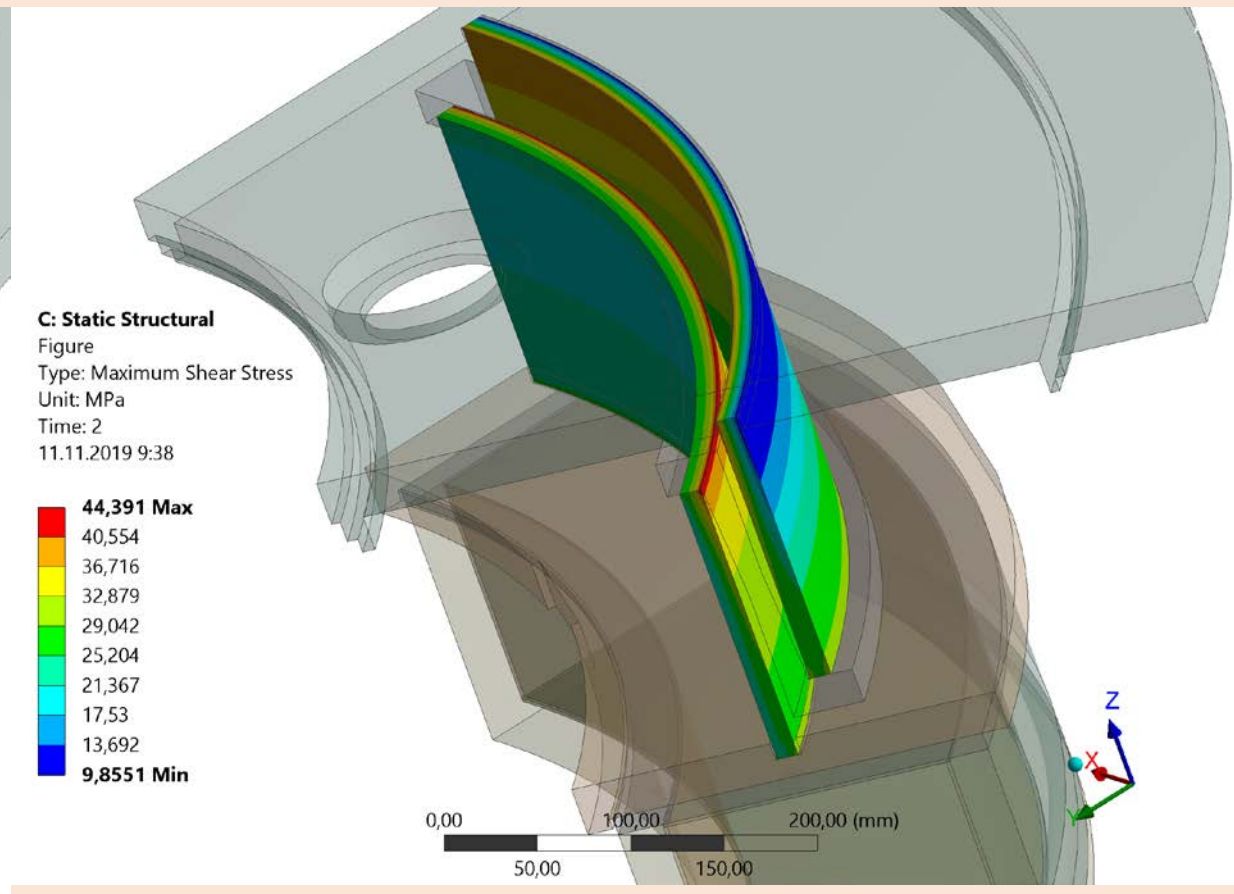


Shear stress in radial-vertical plane (XZ), after all loads.
Max. -2.29 and 1.03 MPa

Results

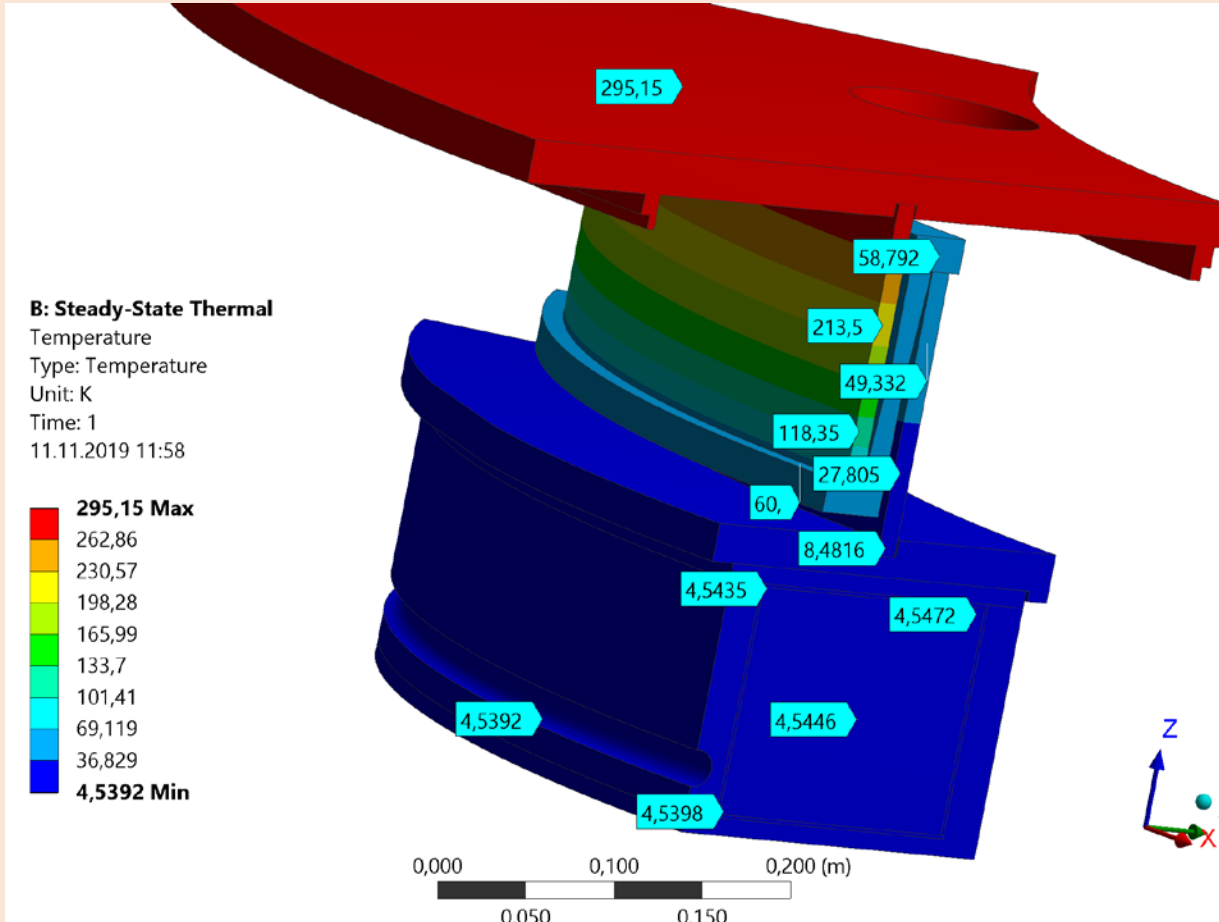


Maximum shear stress, after cooling. Max. 23.75 MPa

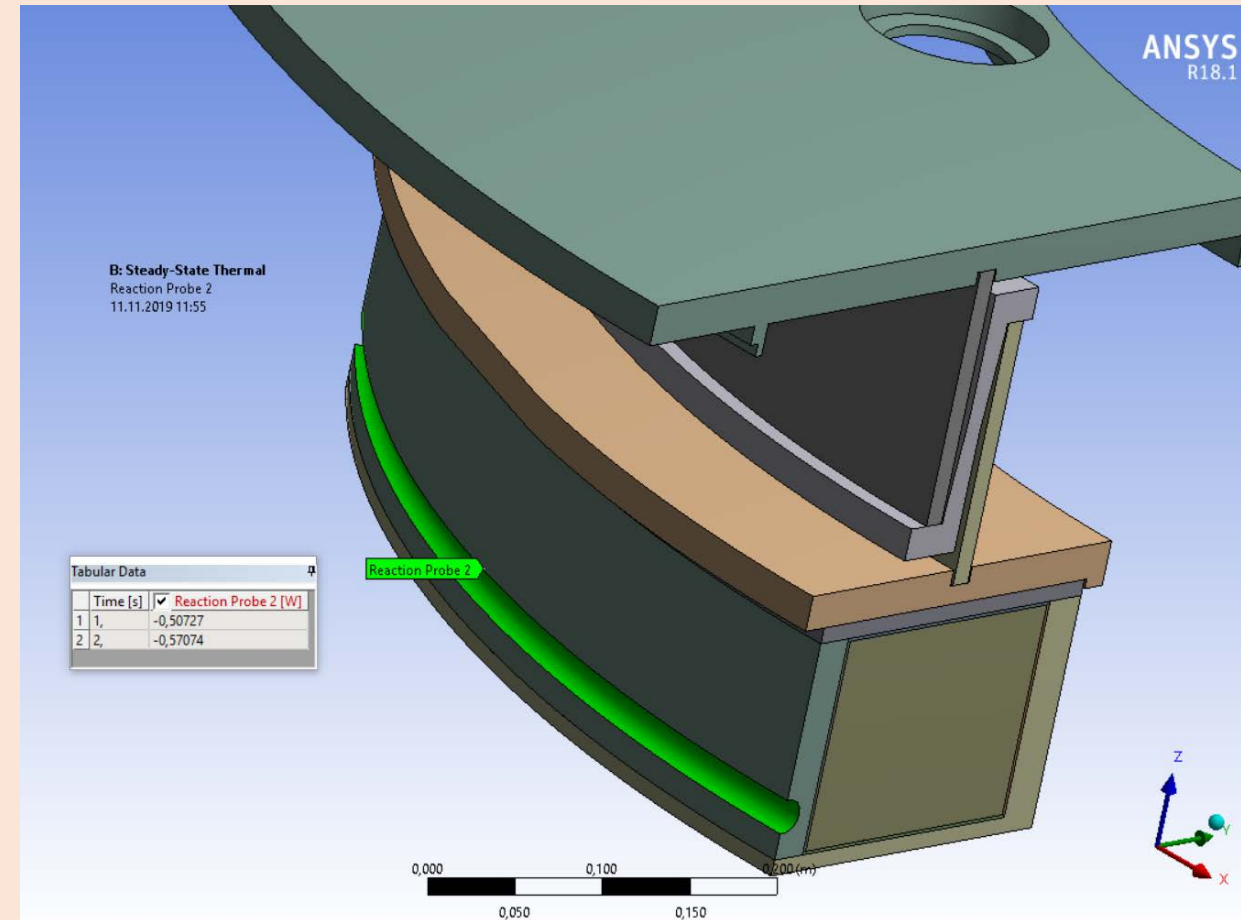


Maximum shear stress, after all loads. Max. 44.4 MPa

Thermal distribution



Temperature distribution

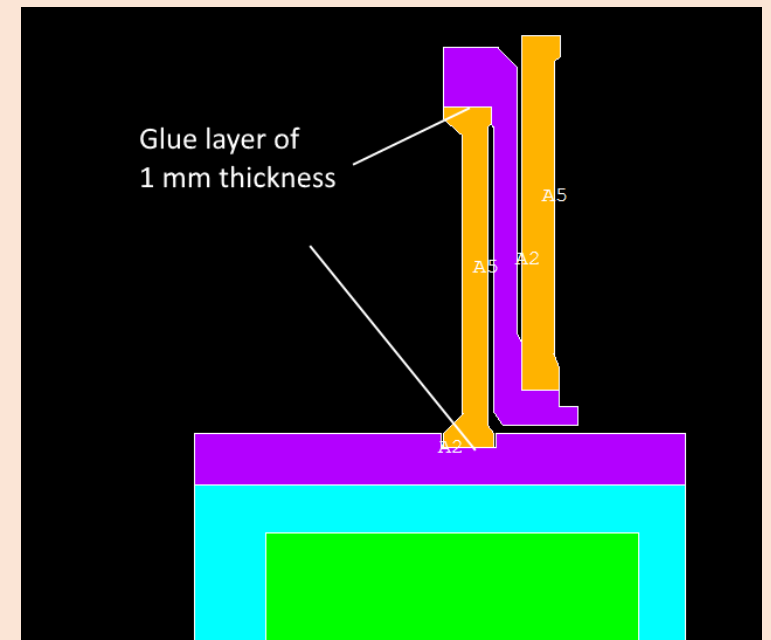


Total heat load on 4.5 K is $0.57 \cdot 8 = 4.6 \text{ W}$
 Total heat load on 60 K is $6.17 \cdot 8 = 49.4 \text{ W}$

2D calculations

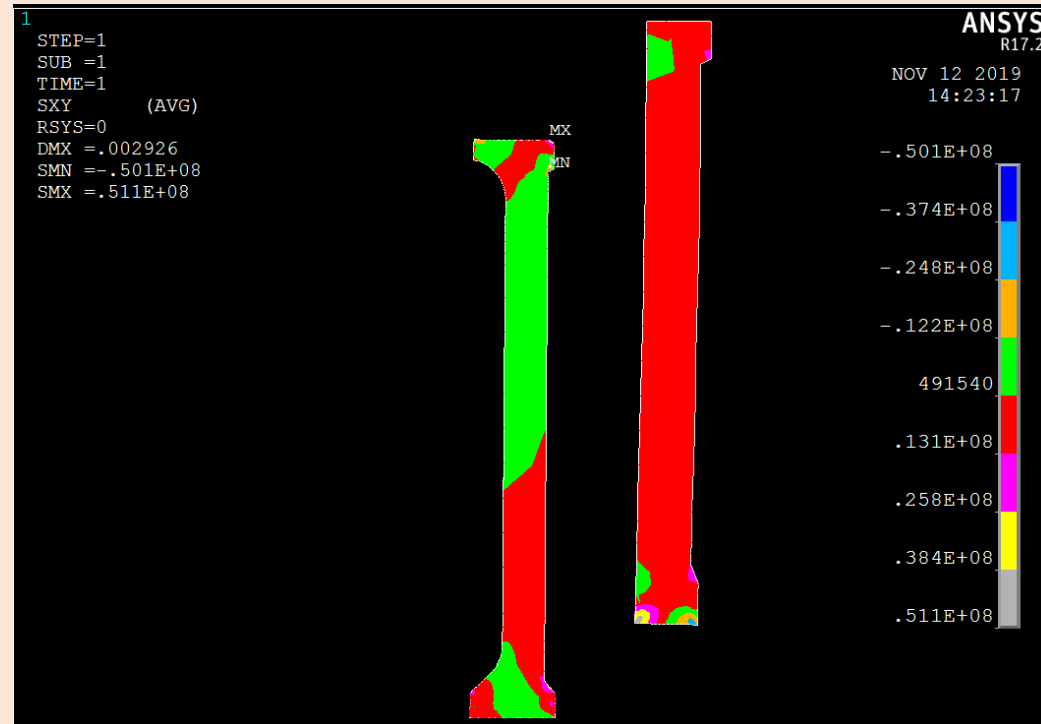
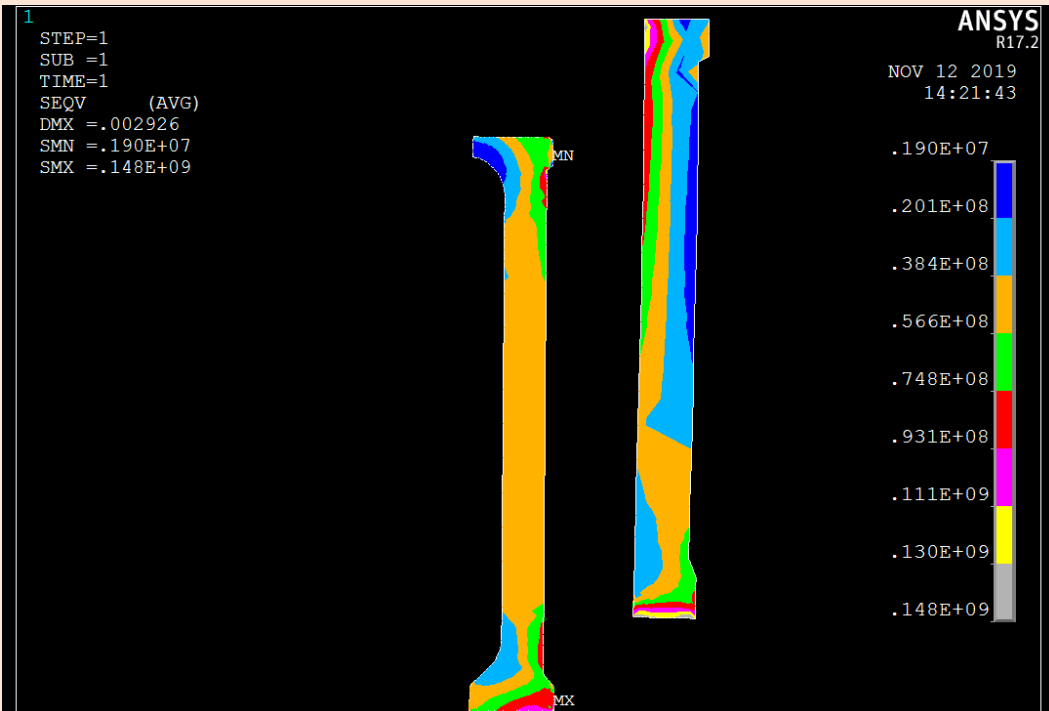
The ANSYS 2D calculations were made to compare with 3D model, presented above.

The G-10 cylinder was rigidly fixed by Epoxy glue.



Von-Mises stress on G-10. Max. 148 MPa on the edge

Shear stress on G-10. Max. ~ 51 MPa.



Comparison of two designs

Parameters	The design with 8 struts (safety factor)	The design with the single strut (safety factor)
Maximal stress in the SC winding, MPa	62 (1.62)	34 (2.94)
Maximal stress in the St. steel plate of the coil, MPa	150 (4)	< 88 (6.8)
Maximal deformation in Z direction, mm	3.6 (the less the better)	1.7 (the less the better)
Maximal shear stress in the SC winding (G-10 reference), MPa	23 (3.2)	20 (3.65)
Maximal von Mises stress in the cold G-10 of the strut, MPa	53 (11.3)	86 (6.95)
Maximal von Mises stress in the warm G-10 of the strut, MPa	50 (5.66)	67 (4.22)
Maximal shear stress in the G-10 of the cold strut, MPa	59 (1.1)	44 (1.48)
Heat load to 4.2 K surfaces for one coil, W	~ 4.1	~ 4.7

The safety factor for G-10 is for M.B. Kasen et al., next slide

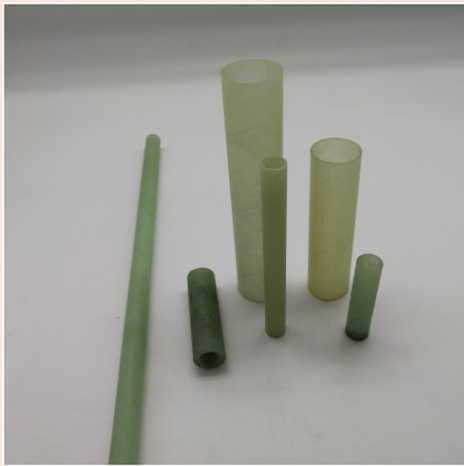
G-10 properties and the G-10 cylinder procurement issue

The G-10 properties in the calculations were taken from:

M. B. Kasen, G. R. MacDonald, D. H. Beekman, Jr., and R. E. Schramm

MECHANICAL CHARACTERIZATION OF GIO-CR AND G11-CR MANUFACTURER A-PILOT PLANT (AVERAGE OF AT LEAST THREE SPECIMENS) Note 2

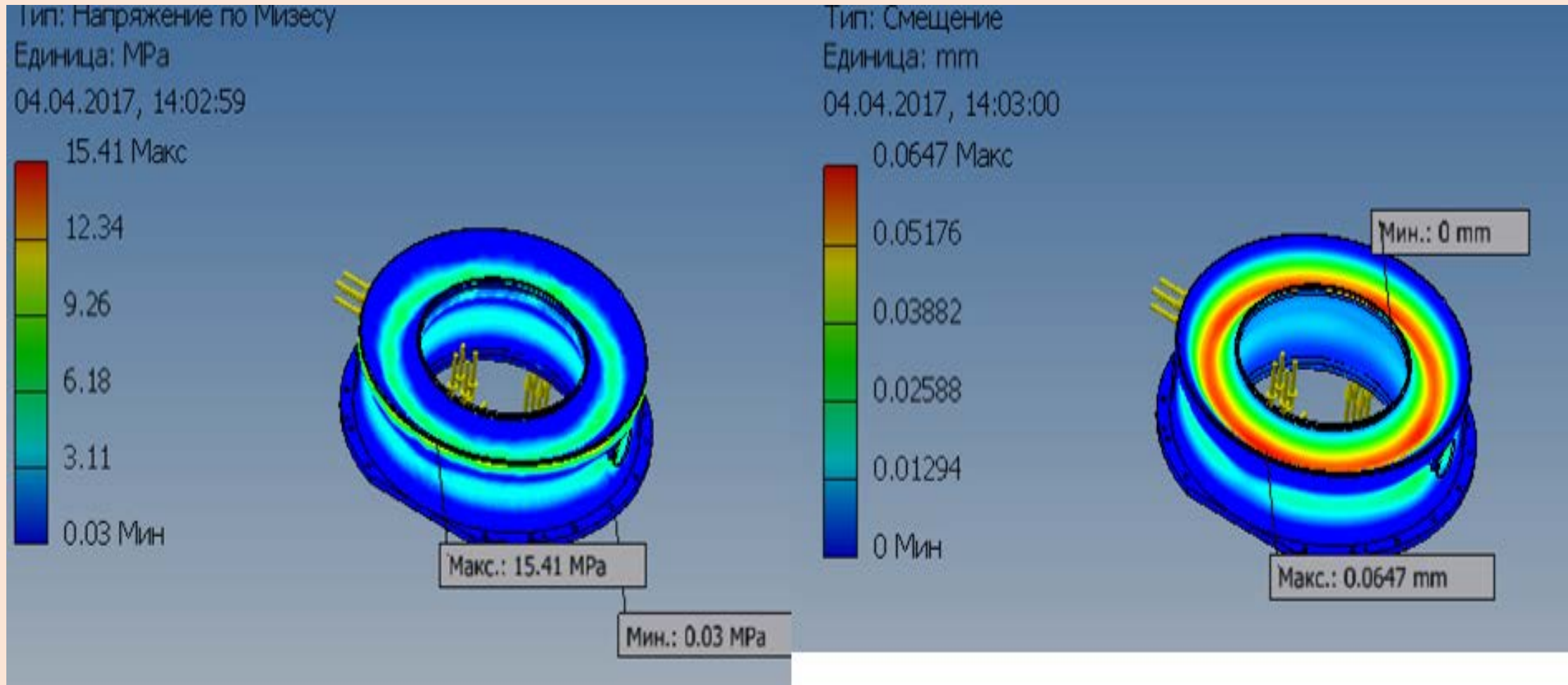
G10-CR	Young's Modulus (E)		Poisson's ratio, ν		Tensile strength		Compressive strength			Tensile failure strain		Shear strength (short beam)		Shear strength (Guillotine)		
	Temp. (K)	Warp (Gpa)	Fill (Gpa)	Warp	Fill	Warp (MPa)	Fill (MPa)	Warp (MPa)	Fill (MPa)	Normal (MPa)	Warp (%)	Fill (%)	Warp (MPa)	Fill (MPa)	Warp (MPa)	Fill (MPa)
	295	28	22.4	0.15	0.144	415	257	375	283	420	1.75	1.55	60	45	42	
	76	33.7	27	0.19	0.183	825	459	334	557	693	3.43	2.53	131	93	61	73
	4	35.9	29.1	0.211	0.21	862	496	862	598	749	3.67	2.7		105	73	79
G11-CR																
	295	32	25.5	0.157	0.146	469	329	396	315	461	1.82	1.73	72	45	41	
	76	37.3	31.1	0.223	0.214	827	580	804	594	799	3.21	2.85	120	92	57	57
	4	139.4	32.9	0.212	0.215	872	553	730	632	776	3.47	2.67		89	56	57



Not all manufacturers of glass-epoxy plastics are able to produce G-10 cylinders.

We have confirmation from “JY Machinery” to produce large G-10 cylinders. Its G-10 material has the shear strength ~ 172 MPa!

Vacuum vessel calculations



The external pressure of 1 bar is applied.
The von Mises stress is 15.4 MPa.
Maximal deformation is 0.065 mm

Stick slip behavior

How this effect could be realized in the current design with huge mass – that is unclear. However, estimations are possible.

The radial expansion after powering is ~ 0.1 mm.

May it be reason of stick-slip behavior?

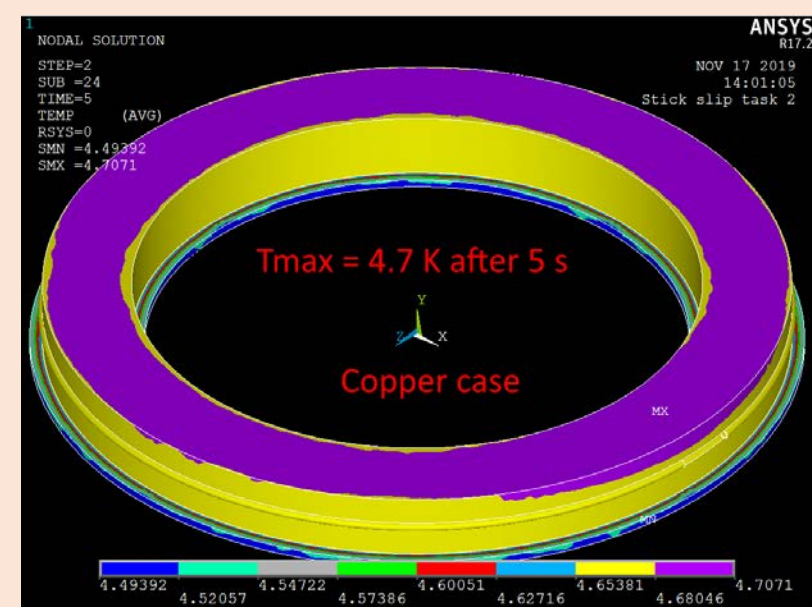
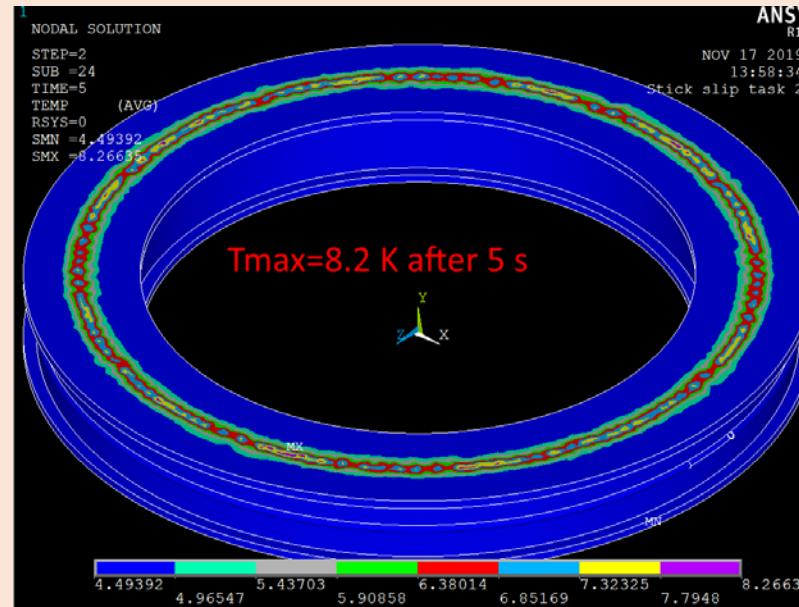
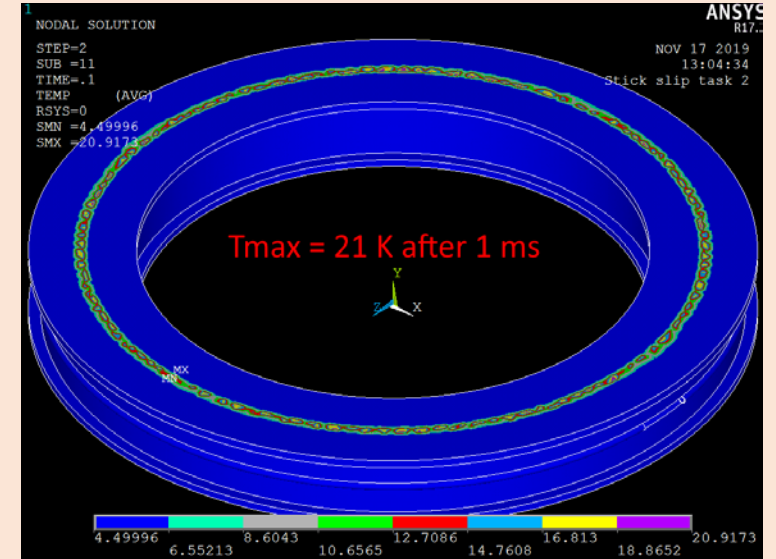
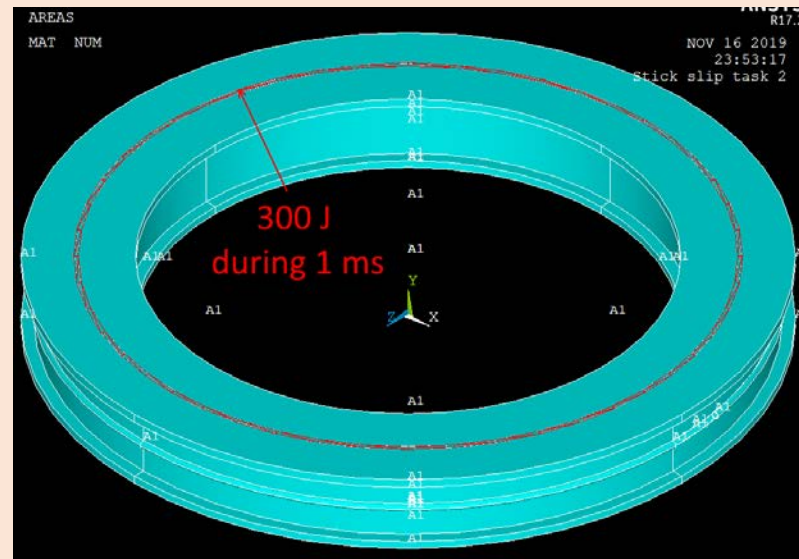
Energy release in friction movement is
 $E = [\text{force}] * [\text{length}] * [\text{friction c.}] =$
 $3 \text{ MN} * 0.1 \text{ mm} * 1 = 300 \text{ J}.$

Transient task was calculated.

The maximal temperature on the copper case is < 5 K.

Conclusion:
friction movements inside the coil structure will give not significant temperature rise;

and will be detectable by the sensors.



Heat capacity of stainless steel is 10 times less than for copper in 5-10 K range!

Conclusions

- Many 3D models of the coil designs were calculated in ANSYS. The main stresses in the coil appears from different CTE (coefficient of thermal expansion) 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 epoxy with filling powders are important.
- Two different designs of the support struts were calculated. The single support gives less stress in the coil and less Z deformation – two the most important parameters. The heat loads are the same.
- Only one manufacturer was found to produce G-10 cylinders (not simple glass-epoxy).
- Stick-slip task was calculated. No problems are expected from this effect. The coil structure should be “strong and stout” according common recommendations.