SUMMARY

1. REVISION RECORD

DESCRIPTION	REVISION	DATE and AUTHOR
Creation for version V11-2	A	10/04/2012 – SA
Add comments related to ASME Section 8 Div I and II	B	26/04/2012 – FF
Update with simulation V11-3	C	04/05/2012 – SA
Updated with simulation 317111-JLAB-He-Vessel-19-02-14	D	21/02/2014 – SA – AP
Updated with comments from APAVE	E	17/03/2014 – AP
Update with comments from E.Sun and the new geometry of the suspension links and clevis	F	05/11/2014 – SA – AP
Correction of the CTE for Nitronic 50 and 304L	G	27/11/2014 – SA – AP
Updated with stresses in the coil support	H	23/12/2014 – SA – AP
Correction of the CTE for the equivalent material	I	23/02/2015 - SA - AP

This revision of the report is in accordance with the following drawing of the helium vessel:

317111-JLA-703-001-revN.PDF

2. ABSTRACT

ASME VIII Division 1 (version 2010) was used in APAVE calculation report for all the parts calculable following analytical rules (openings, cylindrical parts under internal and external pressure…). However all the equipment cannot be calculated according to division 1.
That's the reason why ASME VIII Division 2 (version 2010) was used by Sigmaphi (to take into account the other loads than pressure and geometries which cannot be calculated with division 1).
The helium vessel is built according to the ASME Section VIII Division 1.

This report presents the FEA analysis made by Sigmaphi. The shells thicknesses are optimized wherever it is possible to reduce the weight and ease the welding. This report concerns only the helium vessel: suspension links and chimneys for helium supply and return will be studied in other reports. The calculation considers two worst case scenarios:

- The first one includes:
  - Cool down from room temperature (293K) to liquid helium temperature
  - The dead weight
  - The gravity
  - The orientation of the He vessel
  - The horizontal acceleration provided by the magnet moving girder
  - The maximum unbalanced magnetic forces when the coil is off centered related to the iron yoke
  - The helium maximum pressure during a quench.
  - Preload applied by suspension links
- The second one concerns only the test pressure after welding.

The helium vessel mechanical design as proposed by this report complies with the ASME BPVC requirements for the two worst cases studied.

3. FEA Software

The FEA software used is ANSYS 15.04 Mechanical (ANSYS Professional NLS)

4. USER'S DESIGN SPECIFICATION

The user's specification is given below:

- Fluid: liquid and/or gaseous helium
- Operating temperature: -268°C (4K)
- Thermal stress : Cool down from 20°C to -268°C (4K)
- Design pressure: 6 atm inner, vacuum outer
- External forces:
  - Collared coil weight: 152 000 N (gravity = 9806.6mm/s²)
  - The dipole is inclined at 9.2°
  - Lateral acceleration: 152 000 N (1g)
  - Magnetic forces: Horizontal 69000 N, Vertical 77 000 N (coil off centered of 3 mm at 45° related to the yoke)
  - Preload in suspension links: 90500N
- 2 worst cases are studied:
  - All the external forces + design pressure
  - Test pressure only (7*1.43 = 10 bars)

5. FEA MODEL GEOMETRY AND MESHING

The following figure represents the helium vessel with chimneys and pipes for the helium supply and return:

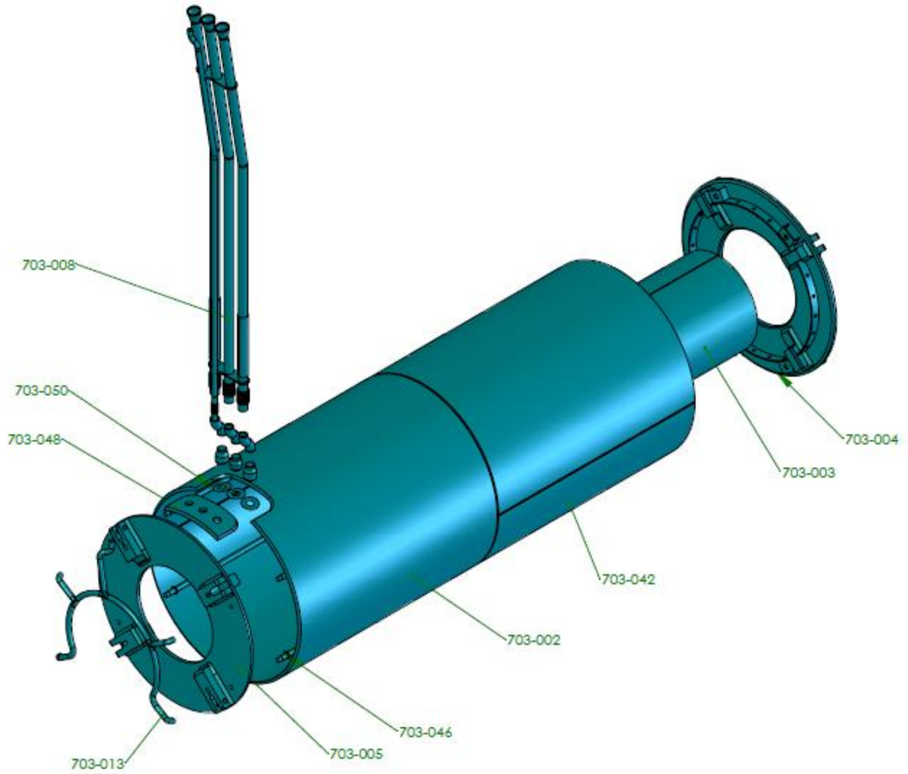


Figure 1: view of the helium vessel with pipes and chimney for the helium supply and return

Chimney, pipes and suspension links are not considered in this report. However suspension links are used in this FEA model because it implies stresses in the vessel. The following figure represents the parts which appear in the FEA model: Suspension links and Helium vessel without pipes and chimney.

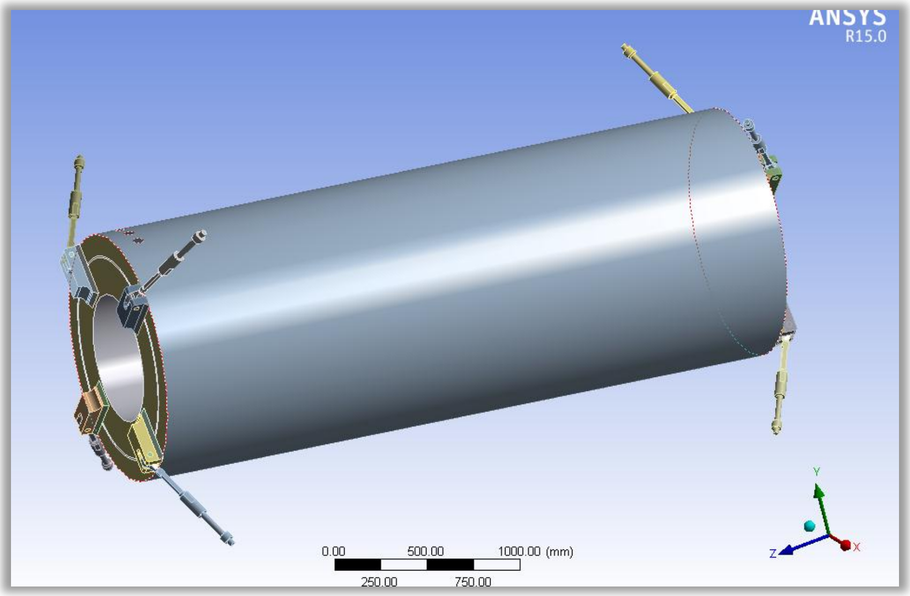


Figure 2: view of the helium vessel and suspension links

The following table summarizes materials, thickness and weight for each part of the helium vessel:

Part designation	Part number	Material	Thickness (mm)	Tol. (mm)	Thickness of the FEA model (mm)	Weight (kg)
Outer tube 1/2	317111-JLA-703-002-rev H	SA 240 grade 304 L, UNS No.S30403	20	+/-0.5	19.5	1185
Inner tube	317111-JLA-703-003-rev F		12	+/-0.5	11.5	748
Flange side end	317111-JLA-703-004-rev K		30	+/-0.5	29.5	374
Flange side arrival	317111-JLA-703-005-rev K		30	+/-0.5	29.5	366
Outer tube 2/2	317111-JLA-703-042-rev B		20	+/-0.5	19.5	1203
Rustine	317111-JLA-703-048-rev A		20	+/-0.5	19.5	16

The following figure summarizes the main dimensions of the helium vessel:

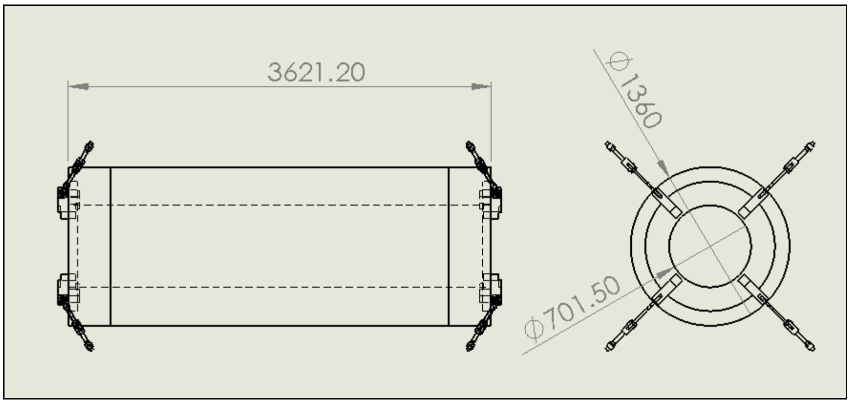


Figure 3: main dimensions of the helium vessel

The elements used for the meshing of the helium vessel are the following one:

- Shell elements for tubes and flanges of the helium vessel
- Volume elements for the other parts of the model (clevis, reinforcements and suspension links)

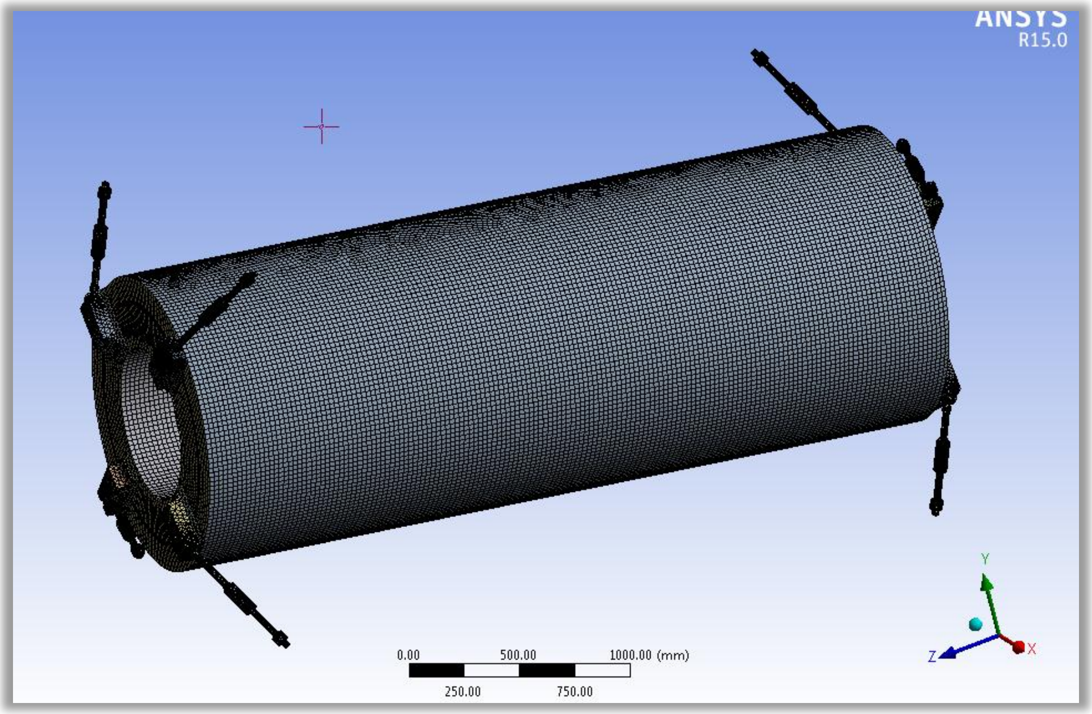


Figure 4: mesh of the helium vessel and suspension links

6. FEA MODEL CONTACT AND BOUNDARIES CONDITIONS

We apply SPHERICAL JOINT on the spherical part of the suspension links and a frictional contact between suspension links and clevis of the helium vessel (f=0.1).

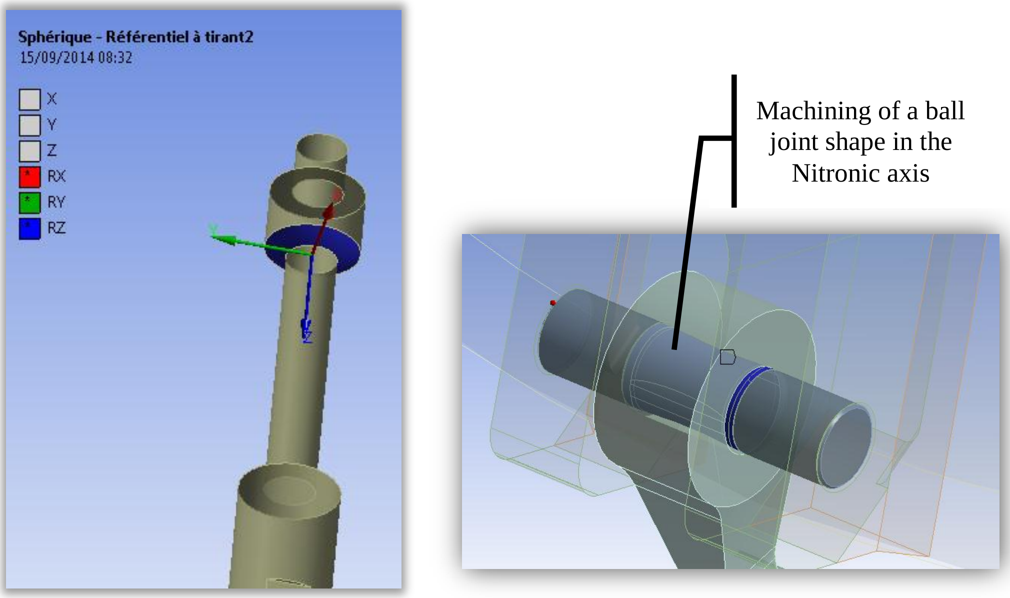


Figure 5: frictionless support on the blue area

Clevis and flanges of the helium vessel are bonded together thanks to the weld. All the forces between clevis and flanges are transmitted by the weld: there is no direct contact between clevis and flanges. All the parts of the helium vessel are considered bonded thanks to 100% penetration weld.

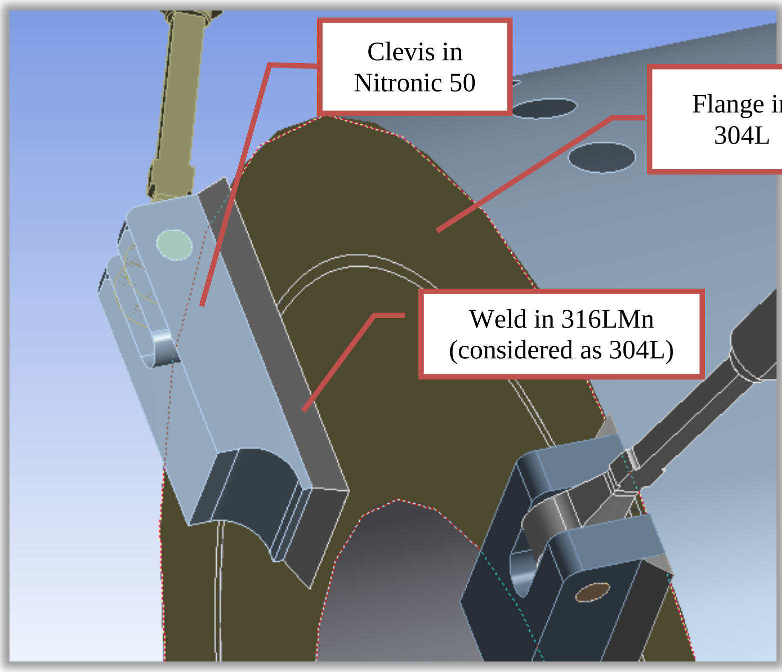


Figure 6: view of the weld between clevis and flanges

7. FEA MODEL MATERIALS

Material properties depend on the temperature which varies between 300 K and 4 K: these mechanical properties are based on published data. The maximum allowable stress S for the helium vessel is based on ASME Section VIII UG23, UHA 23 and Section II Part D for the parts in stainless steel in contact with the pressure.

Remember that suspension links are not considered in this report. An equivalent material (CTE and Young's modulus) has been created for the suspensions links in order to simplify the FEA model. This suspension link is considered at a uniform temperature of 150K and is equivalent in terms of stiffness and thermal contraction to the suspension link made of several materials with a temperature between 300K and 4K.

The following figure summarizes the materials used in this FEA model:

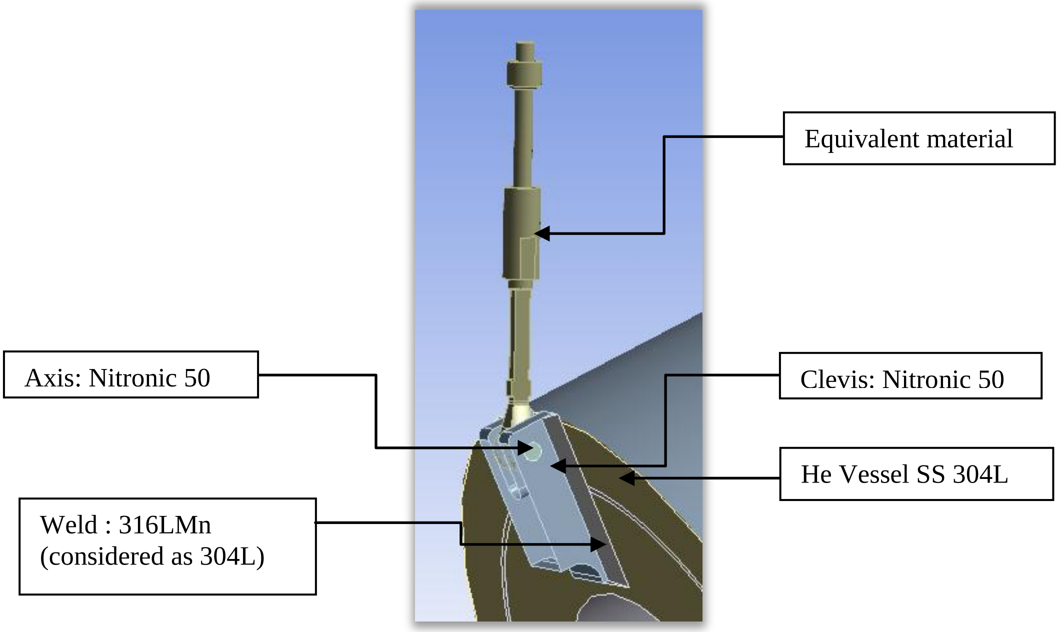


Figure 7: materials used in the FEA model

- *Equivalent material for suspension links (Nitronic 50 and Ti-6AL-4V)*

  See the document "Equivalent material for the suspension links rev B.doc"

- *Helium Vessel 304L*

  Material: 304L - UNS No. S30403 (SA 240 TP 304 L, 1.4307) - Nominal composition: 18Cr-8Ni
  According to ASME Section VIII Division I, UG23, High Alloy Steel UHA 23, Materials Section II Part D

  Allowable stress to use for ASME VIII Division 2 is Sm of ASME II Part D. Allowable stress used in Sigmaphi calculation report is S of ASME II Part D instead of Sm as the manufacturing is done following ASME III division 1. In our case Sm = S because material properties are considered at room temperature.

  The proof test pressure chosen is 10 bars: this pressure covers a manufacturing following division 1 and 2 (Division 2: 1.43 time the operating pressure, Division 1: 1.3 time the operating pressure).

  Yield strength at 20°C = 172 MPa (25 ksi)
  Max Allowable Stress S at 20°C for parts under pressure in normal operating: **S=115 MPa** (16.7 ksi)
  Max allowable stress for test under pressure at 10 bars: **S=155 MPa** (22 ksi)
  Note: We disregard the yield stress enhancement at low temperature and consider only the S value given at 20°C for design contingency and material certification easiness.

  The following tables and graphs give the coefficient of thermal expansion and the young's modulus as a function of the temperature for stainless steel 304L:

Stainless steel 304 L

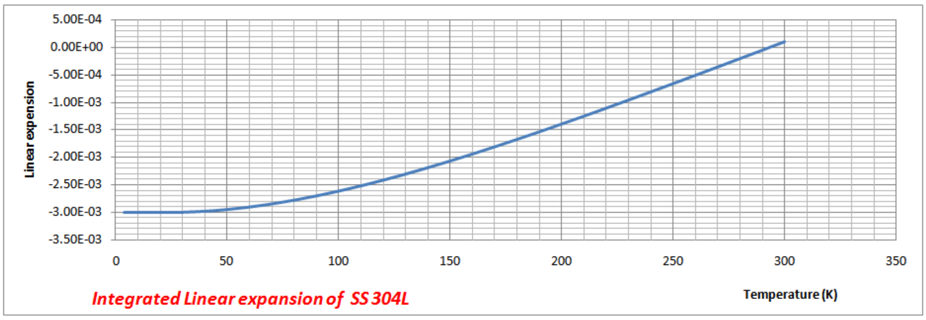
		SS 304	SS 304
	DL/L*10^5	units: GPa	units: GPa
a	-2.96E+02	2.10E+02	2.10E+02
b	-3.98E-01	1.22E-01	1.53E-01
c	9.27E-03	-1.15E-02	-1.62E-03
d	-2.03E-05	3.61E-04	5.12E-06
e	1.71E-08	-3.02E-06	-6.15E-09
T	23	5-57	57-300

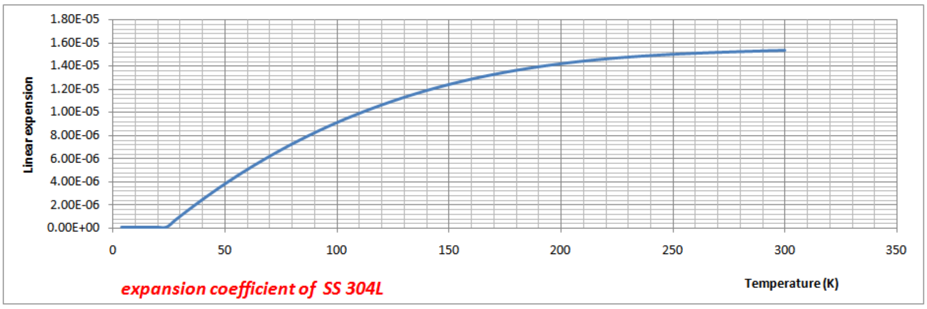
Density	7900 Kg/m3

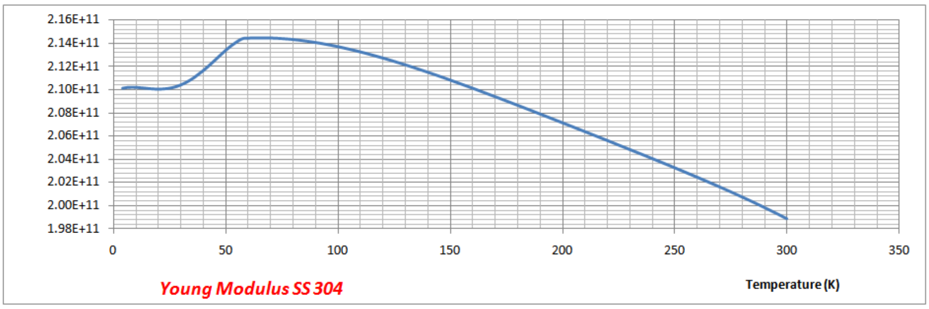
Equation of the form	
$y = a + bT + cT^2 + dT^3 + eT^4$	T≥Tlow(23°K)
y=f	T<Tlow(23°K)

*Refrences for this material : http:// Cryogenics.nist.gov

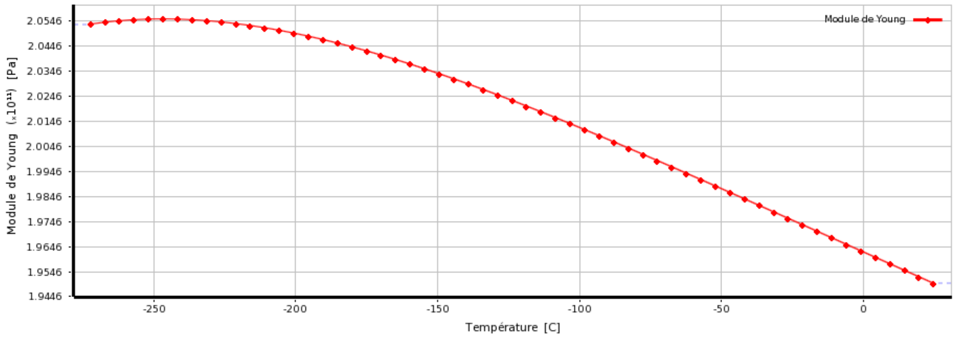
Equation of the form - Integrated coefficient	
$dy/dT = b + 2.cT + 3.dT^2 + 4.eT^3$	T≥Tlow(23°K)
dy/dT=0	T<Tlow(23°K)





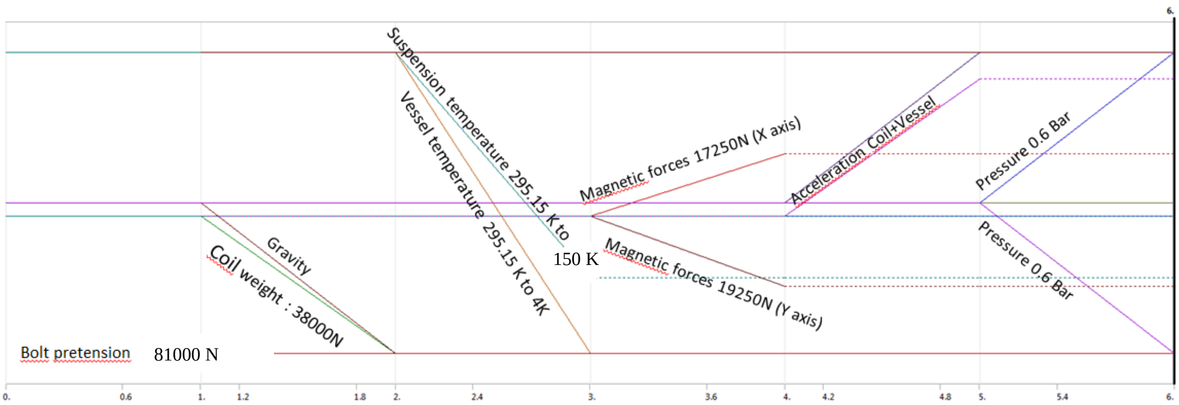


- *Nitronic 50 (clevis)*
  The material used for the clevis on the helium vessel is Nitronic 50 (UNS N°S20910). We consider a maximum allowable stress equal to **252 MPa** (=2/3 of the min. yield strength = 2/3 * 55ksi) because this part is not under pressure.



**DBPM software*

8. FEA MODEL LOADING



1. Preload applied on suspension links

We apply a preload on suspension links in order to keep it under tension even when all the external forces are applied. These parts are designed to support the mechanical stress induced by the worst case scenario. The preload applied on each suspension link is equal to 81000 N

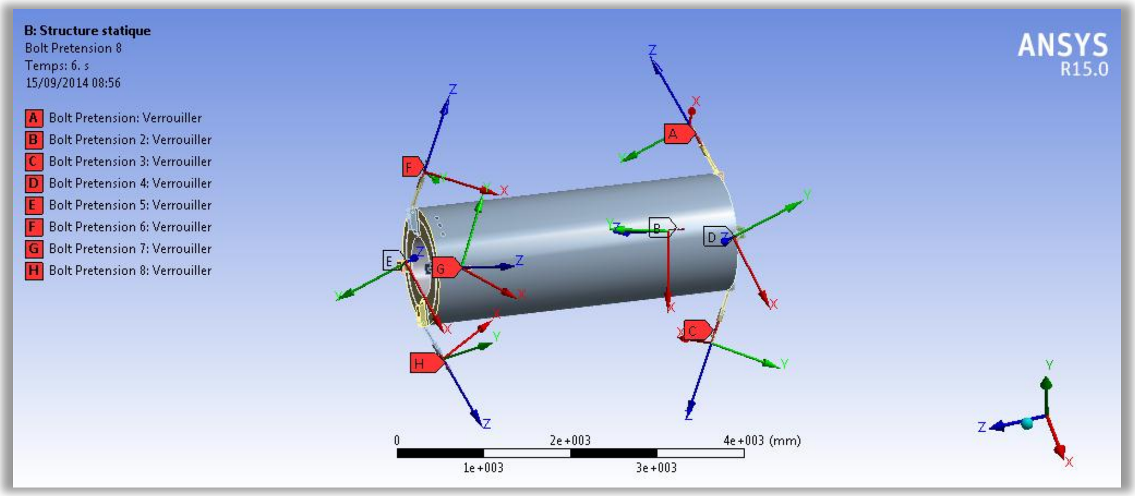


Figure8: application of the preload on suspension links

2. Gravity 9808.6mm/s²+ Weight collar + coil :

We apply the weight of the coil and collars to the superior coil supports of the He Vessel (4 Times). The total force is 152000 N (15500 Kg), we apply 38000 N per contact on the –Y axis

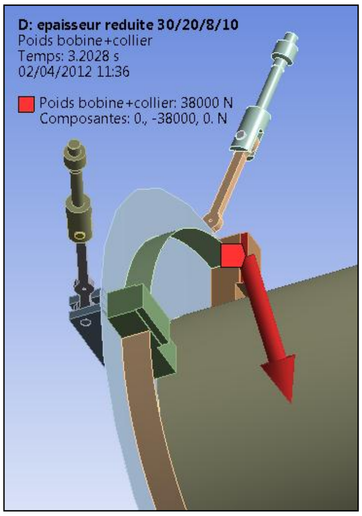


Figure 9: application of the weight on coil supports

3. Magnetic forces on two direction –X axis and Y axis:

We simulate a magnetic force (the imbalanced magnetic forces extracted from OPERA simulation-file 317111-Vers20 Rev D + displace yoke 3mm X and Y.OP3) to the He Vessel. This force is applied on 4 lateral coil supports for X forces and 4 superior coil supports for the Y axis. The total force is 69000N for X direction. So we apply 17250N per contact in this direction. The total force is 77000N for Y direction. So we apply 19250N per contact in this direction.

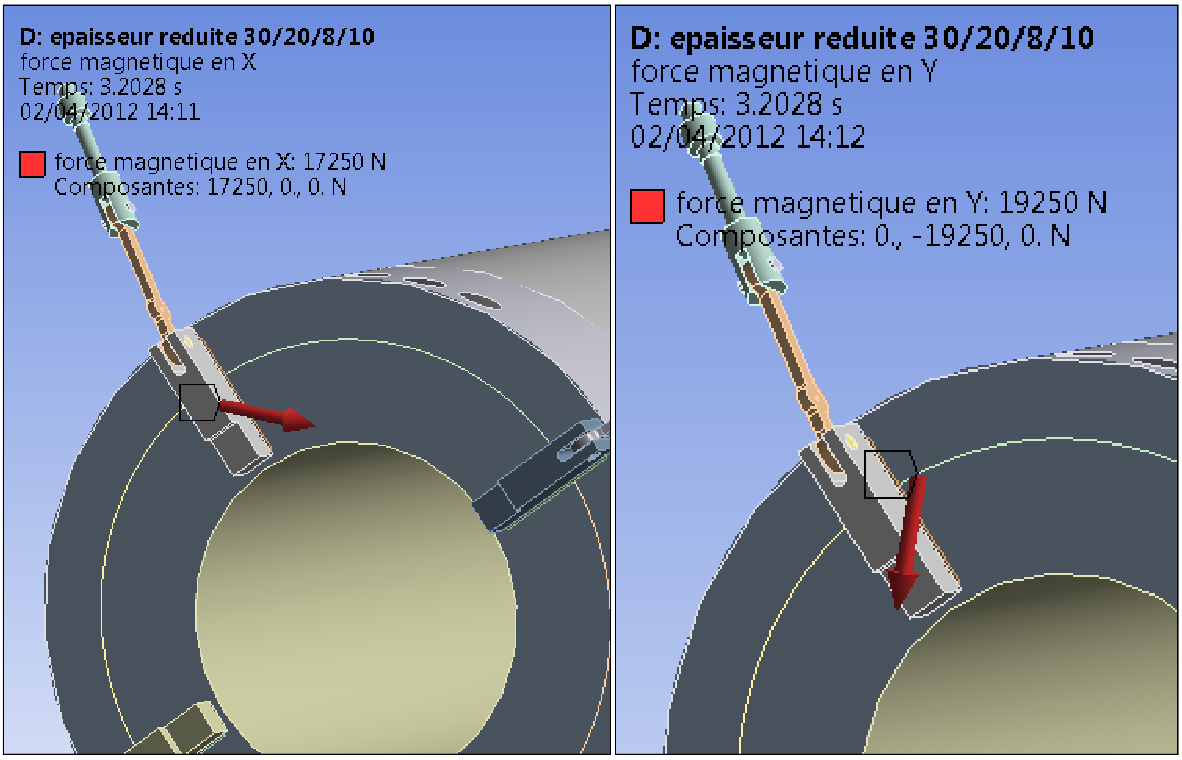


Figure 10: application of the magnetic forces in X & Y-direction

4. <u>Acceleration 1G on the Y axis:</u>

We simulate the acceleration (1G) of the He Vessel, this forces is applied on 4 lateral coil supports. The total force is 152000 N (coil + helium vessel weights). So we apply 38000 N per contact on the X axis.

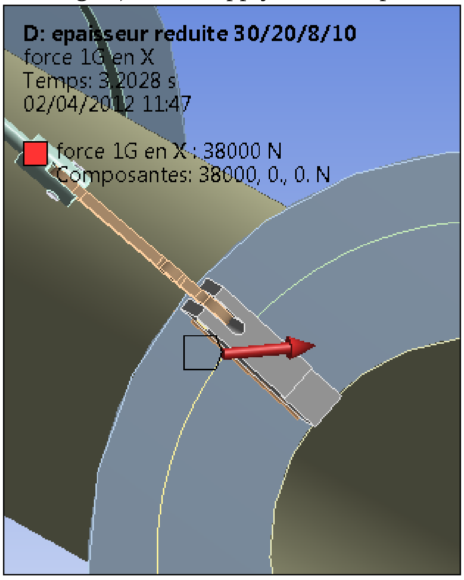


Figure 8: application of the lateral acceleration in X-direction

5. <u>Thermal contraction:</u>

We apply a thermal condition from 295.15K to 4K to the helium Vessel. Suspension links are considered at a uniform temperature of 150K with an equivalent material in order to simplify the FEA model.

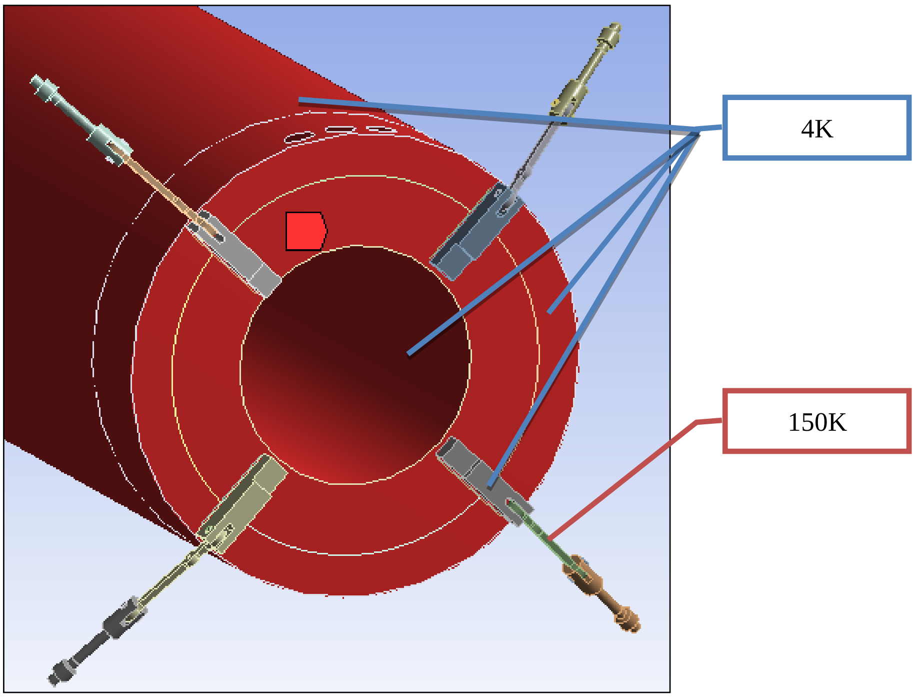


Figure 9: application of the thermal contraction

6. <u>Pressure 0.6 MPa in the HeVessel (simulation of quench)</u>

An internal pressure of 0.6 MPa (6 atm) is applied into the Helium Vessel. Helium is gaseous in this case. 0 atm is applied outside the helium vessel.

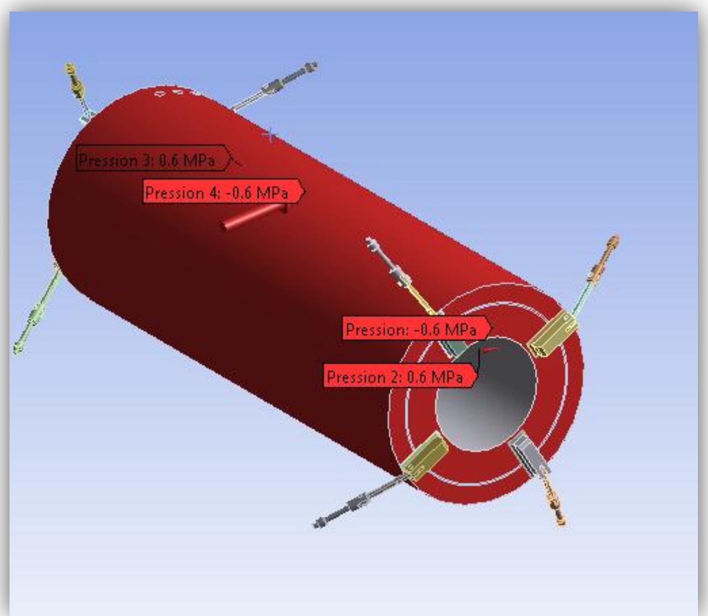


Figure 10: application of the internal pressure

9. FEA MODEL SOLVING

The model is solved by successive steps as defined in the following table. Each step corresponds to the application of one loading (see the last item):

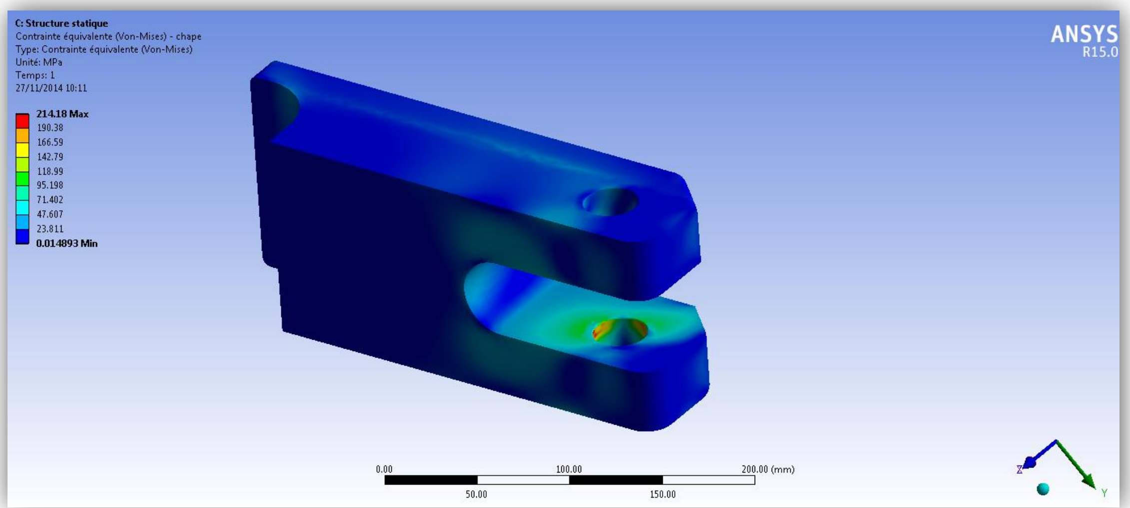
Propriétés	Etape 1	Etape 2	Etape 3	Etape 4	Etape 5	Etape 6
Contrôles d'incrément						
Temps final pour cet incrément	1.	2.	3.	4.	5.	6.
Incrément de temps automatique	Activé	Activé	Activé	Activé	Activé	Activé
Défini par	Sous-incréments	Sous-incréments	Temps	Sous-incréments	Sous-incréments	Sous-incréments
Reporter l'incrément de temps	N/A	Désactivé	Désactivé	Désactivé	Désactivé	Désactivé
Sous-incréments initiaux	10	10	N/A	10	10	10
Sous-incréments minimaux	10	10	N/A	10	10	10
Sous-incréments maximaux	100	1000	N/A	100	100	100

10. WORST CASE N°1: OPERATING CONDITIONS

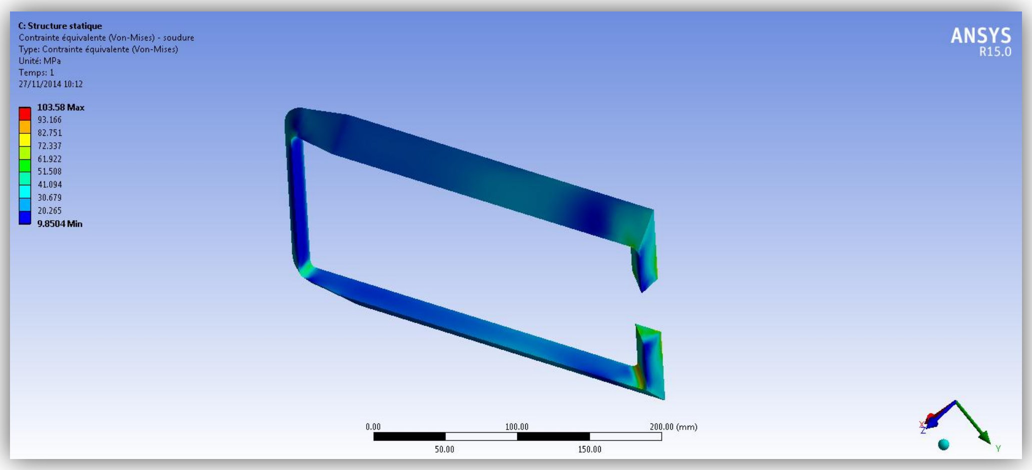
Considering the design contingency the peak stresses are below the maximum allowable stress at 20°C (S).
We consider all stresses as primary and general stress which disregards the need to classify and linearize the stresses. The stress analysis is based on the Von Mises criteria and considers S as the maximum allowable stress for all locations.

The following table gives the peak stress in superior, mid and inferior skin for each part of the helium vessel. The Von Mises stresses are below the allowable stress S for all these parts.

Part designation	Von Mises stress in superior skin	Von Mises stress in mid skin	Von Mises stress in inferior skin	S
Outer tube	61 MPa	33.8 MPa	66.9 MPa	115 MPa
Inner tube	65.5 MPa	38.2 MPa	45.6 MPa	115 MPa
Flange side end	50.8 MPa	34.5 MPa	53.3 MPa	115 MPa
Flange side arrival	48.1 MPa	31.5 MPa	44.5 MPa	115 MPa
Coil support	95.8 MPa and 102.6 MPa			115 MPa
Weld between clevis and flange	103.6 MPa			115 MPa
Clevis (Nitronic 50)	214.5 MPa			252 MPa



View of the clevis



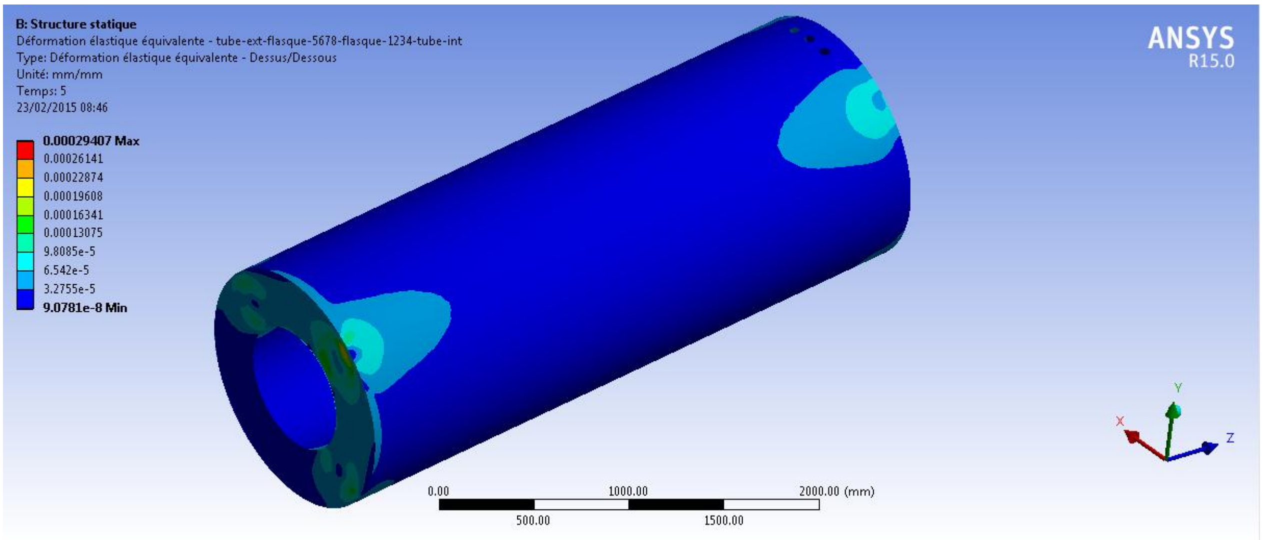
View of the welds

- **<u>Array of efforts in the tie rods</u>**

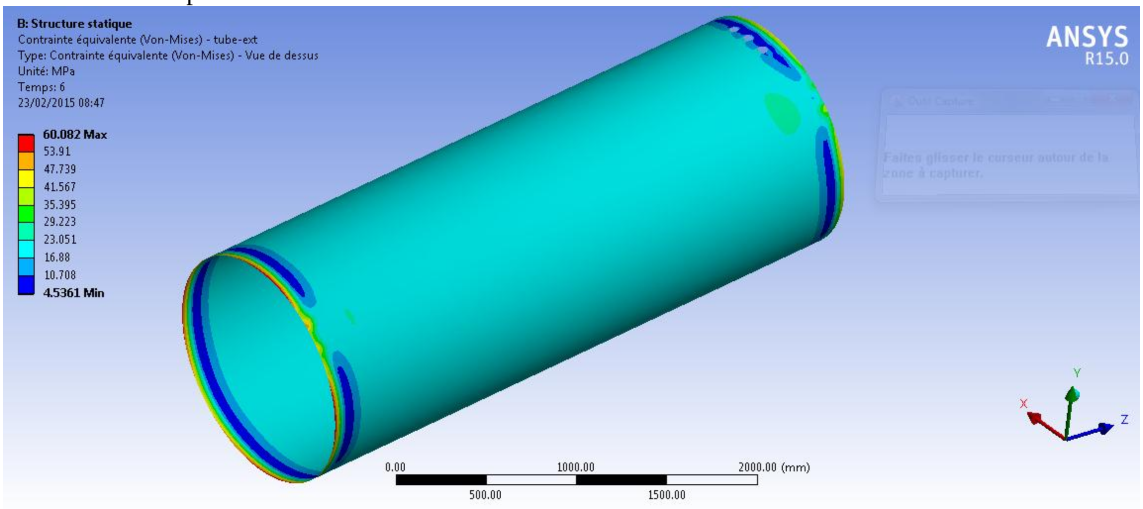
81000	81000	81000	81000	81000	81000	81000	81000	Pretension
55206	87055	96780	55053	109600	64064	63849	109570	coil weight+gravity -Y
52908	64520	94438	52782	107360	62071	61874	107330	Cold
48450	120990	91623	24125	113360	38538	64109	141790	Magnetique force
69663	147640	68638	6819	91578	21025	86321	167320	Acceleration X
66152	147870	68118	4035	89988	19330	84360	166110	pression 0.6 Mpa

The following screenshots give more details on the area of maximum stresses:

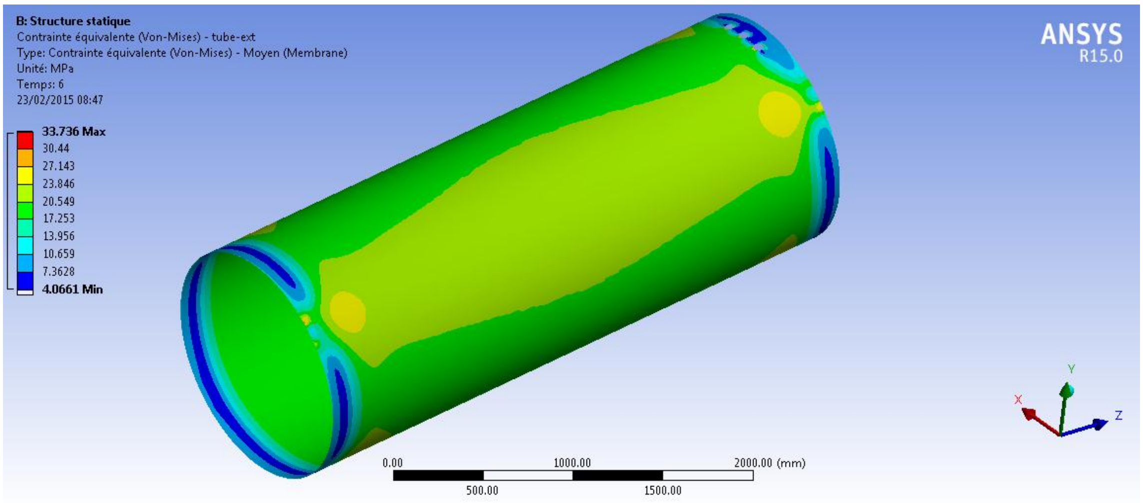
- **<u>Deformation of the Helium vessel:</u>**



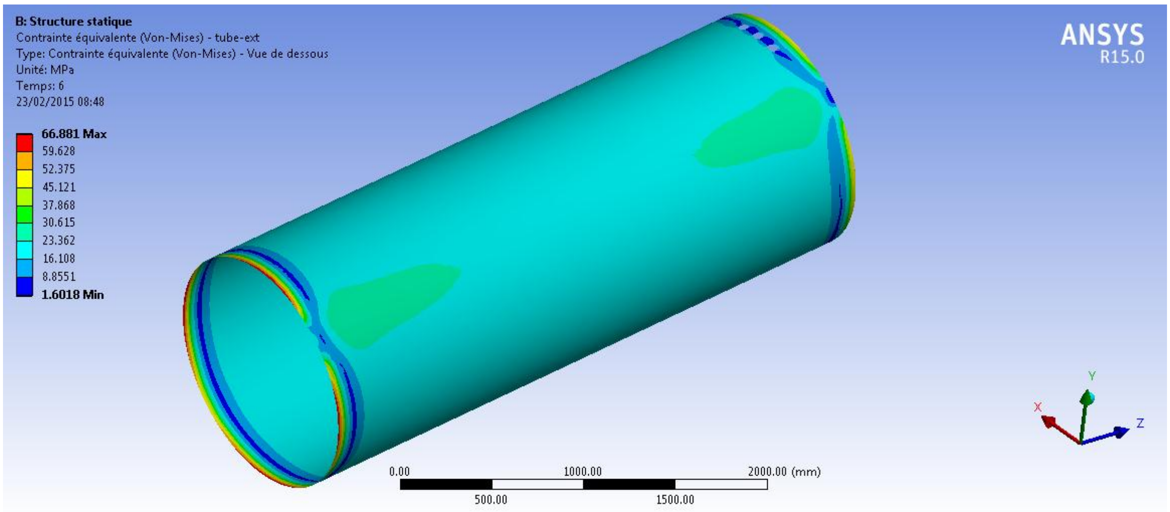
- **<u>Outer tube:</u>**
  - Superior skin:



  - Mid skin:

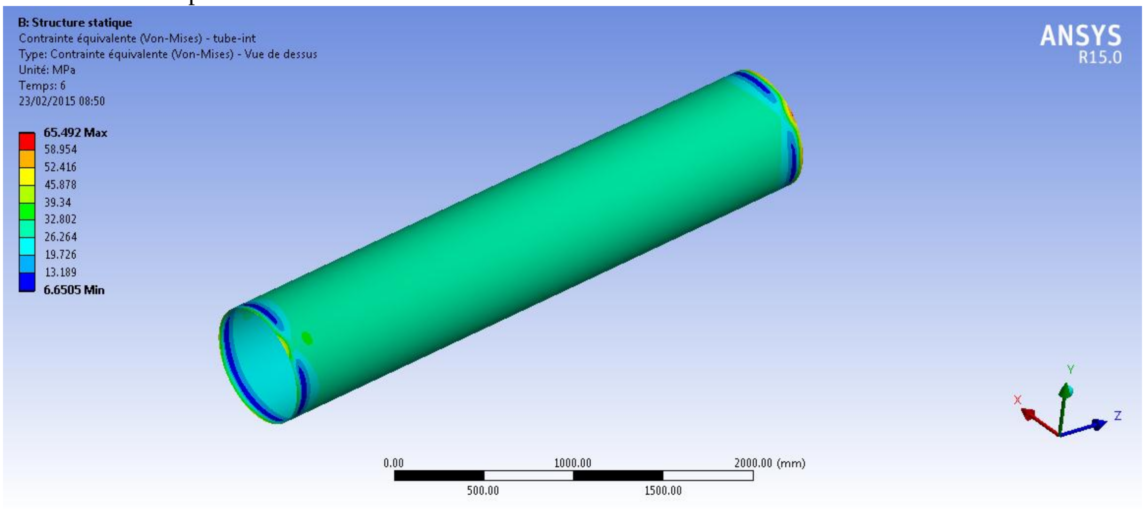


  - Inferior skin:

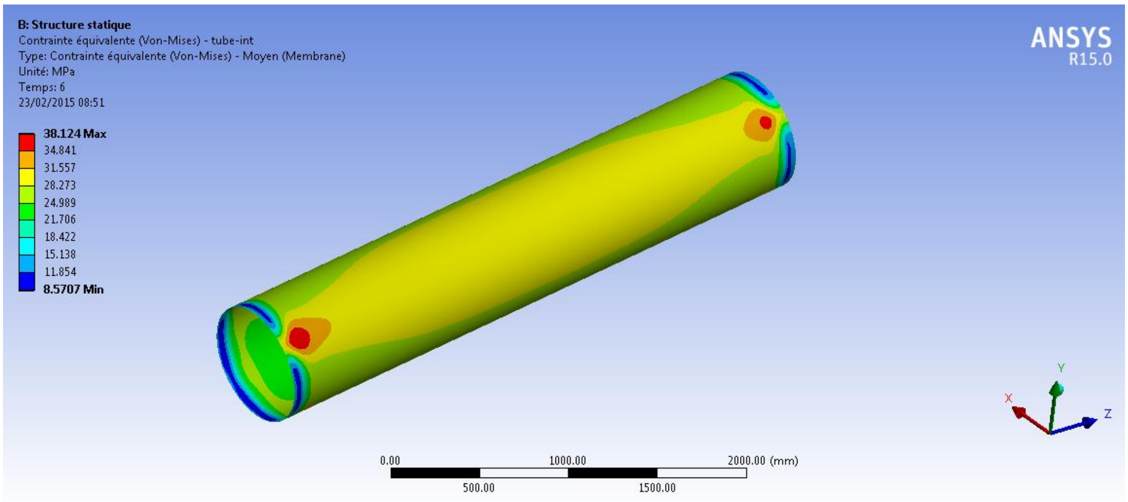


- **<u>Inner tube:</u>**

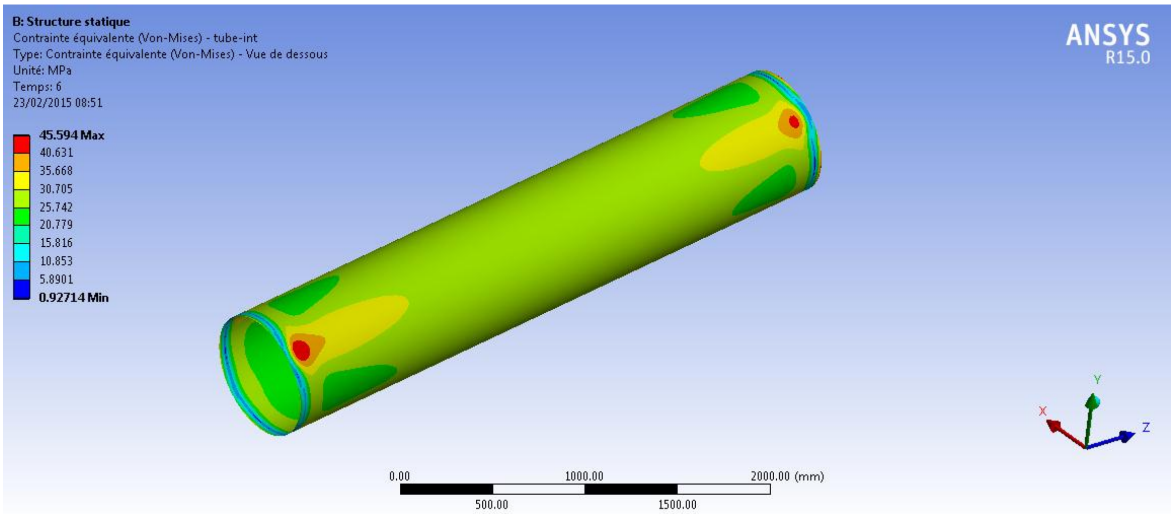
  - Superior skin:



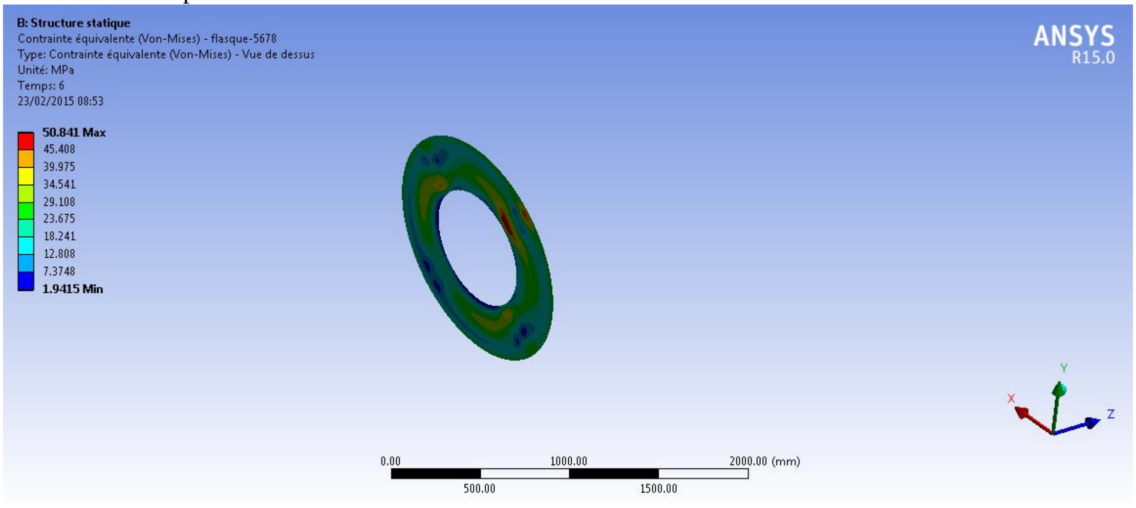
  - Mid skin:



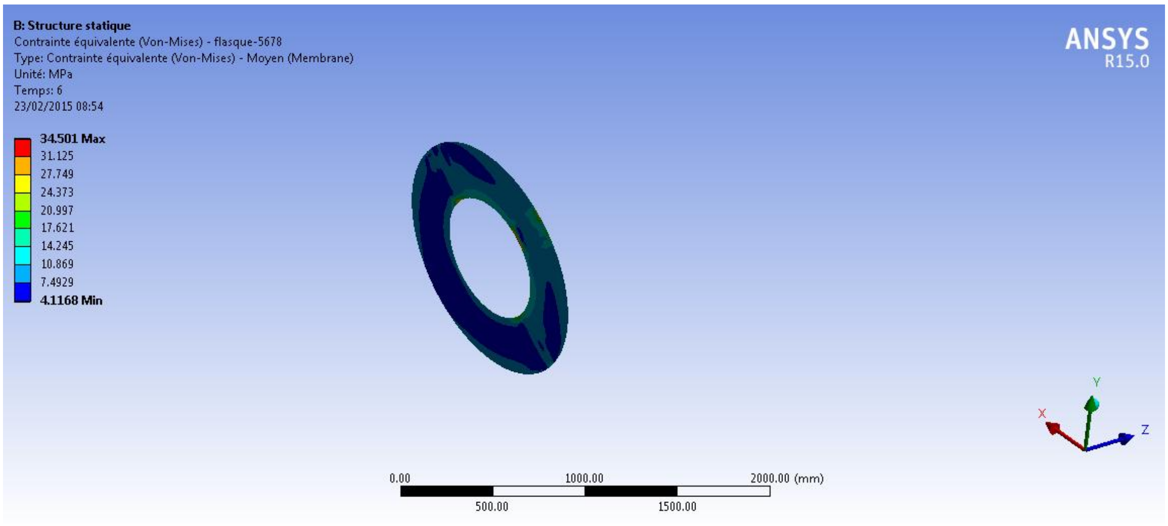
  - Inferior skin:



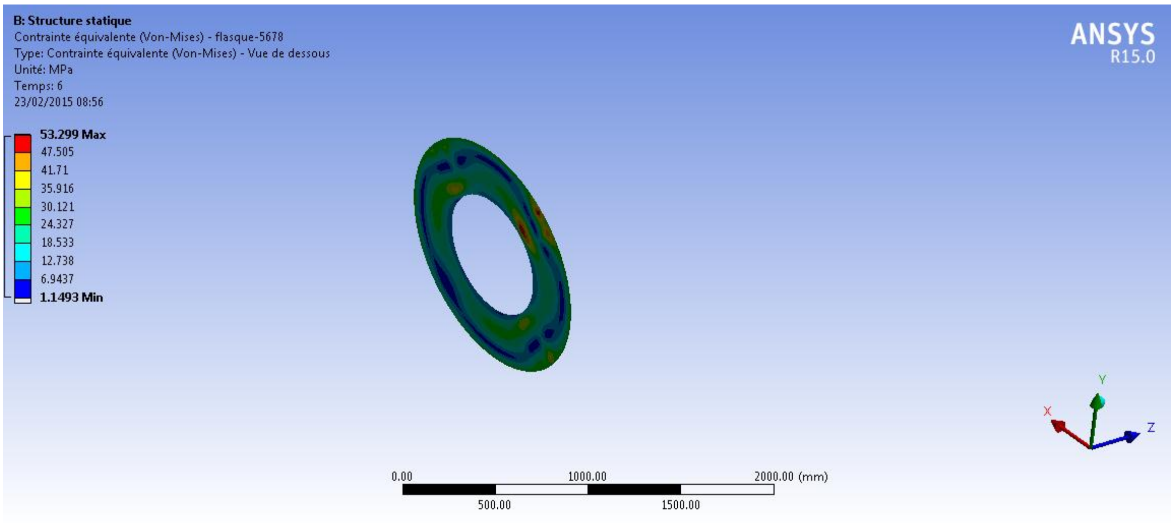
- **Flanges side end:**
  - Superior skin:



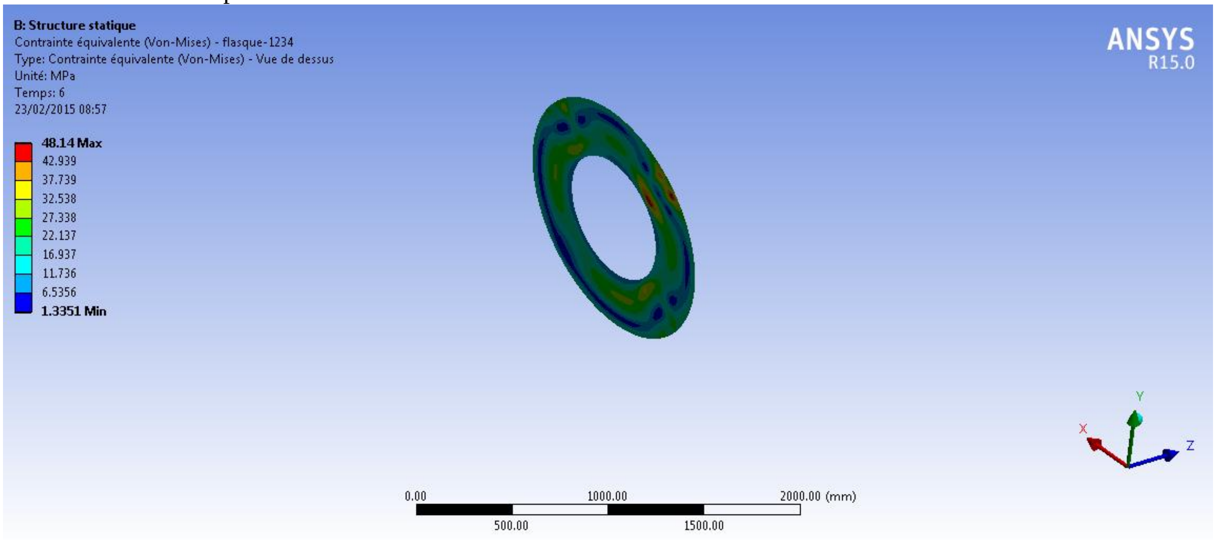
  - Mid skin:



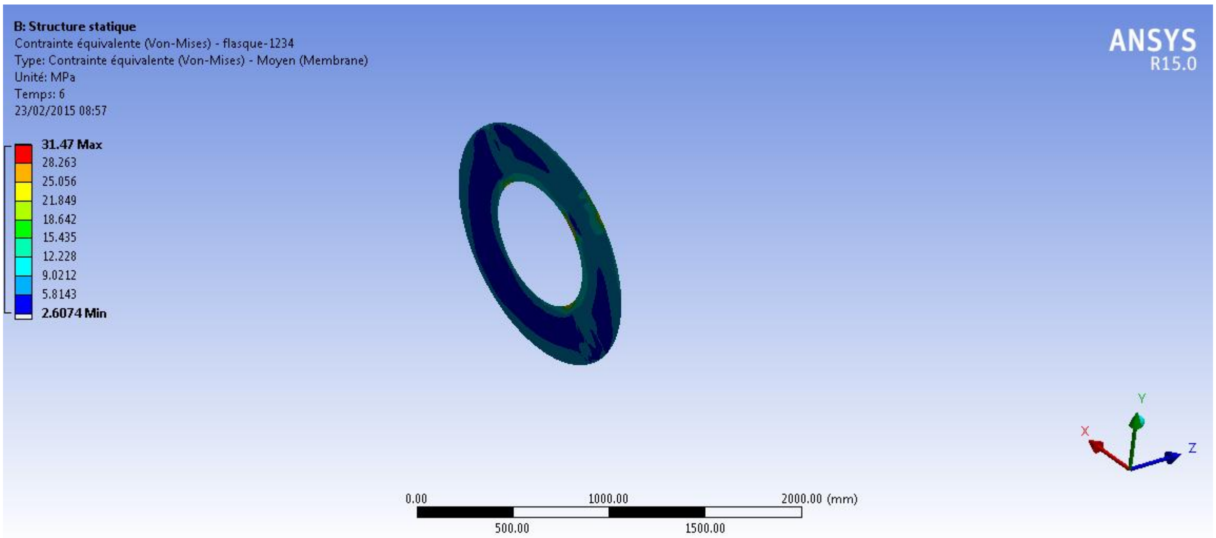
  - Inferior skin:



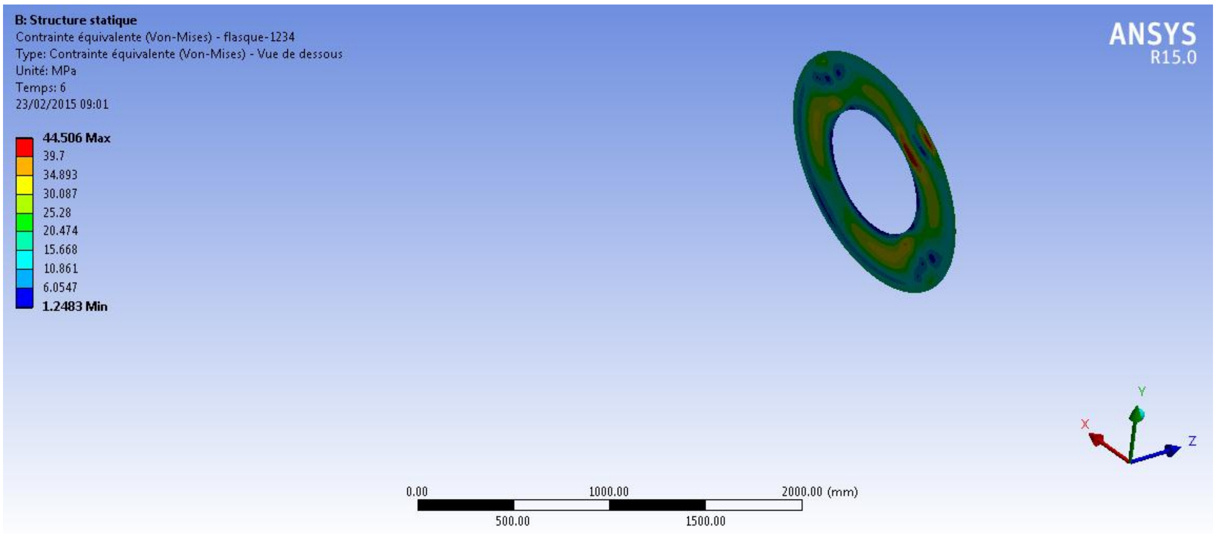
- **Flanges side arrival:**
  - Superior skin:



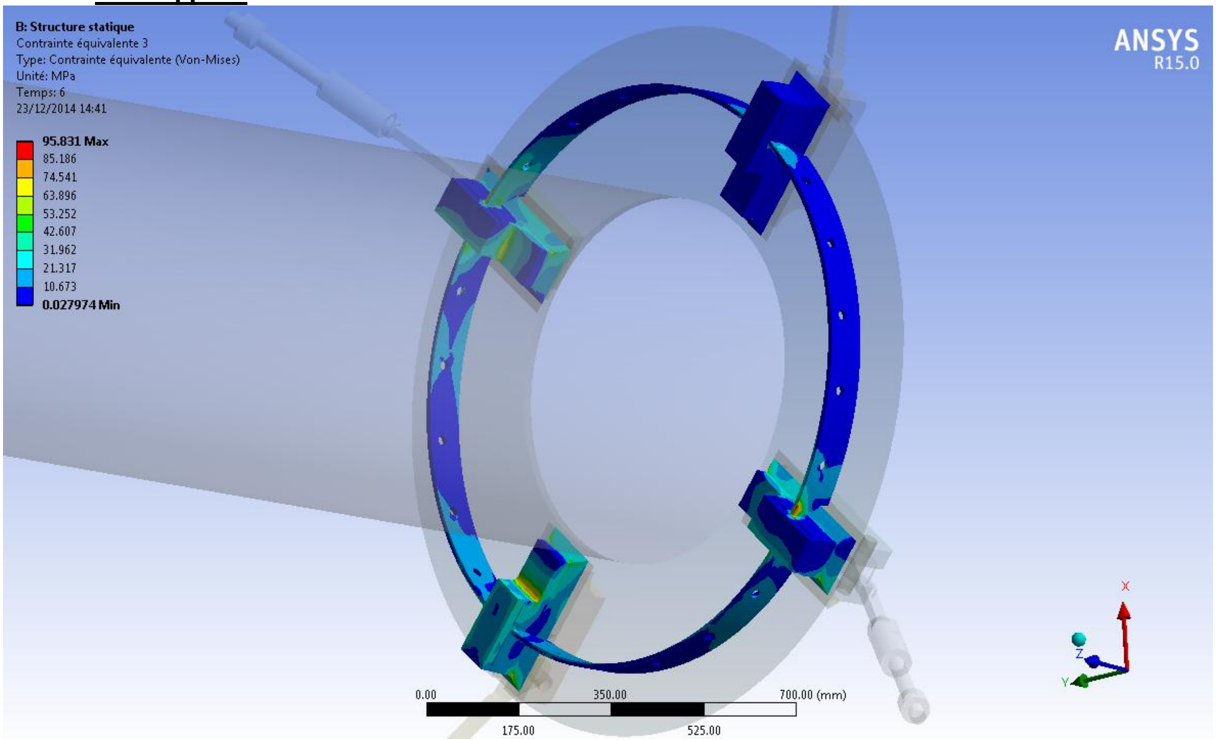
  - Mid skin:

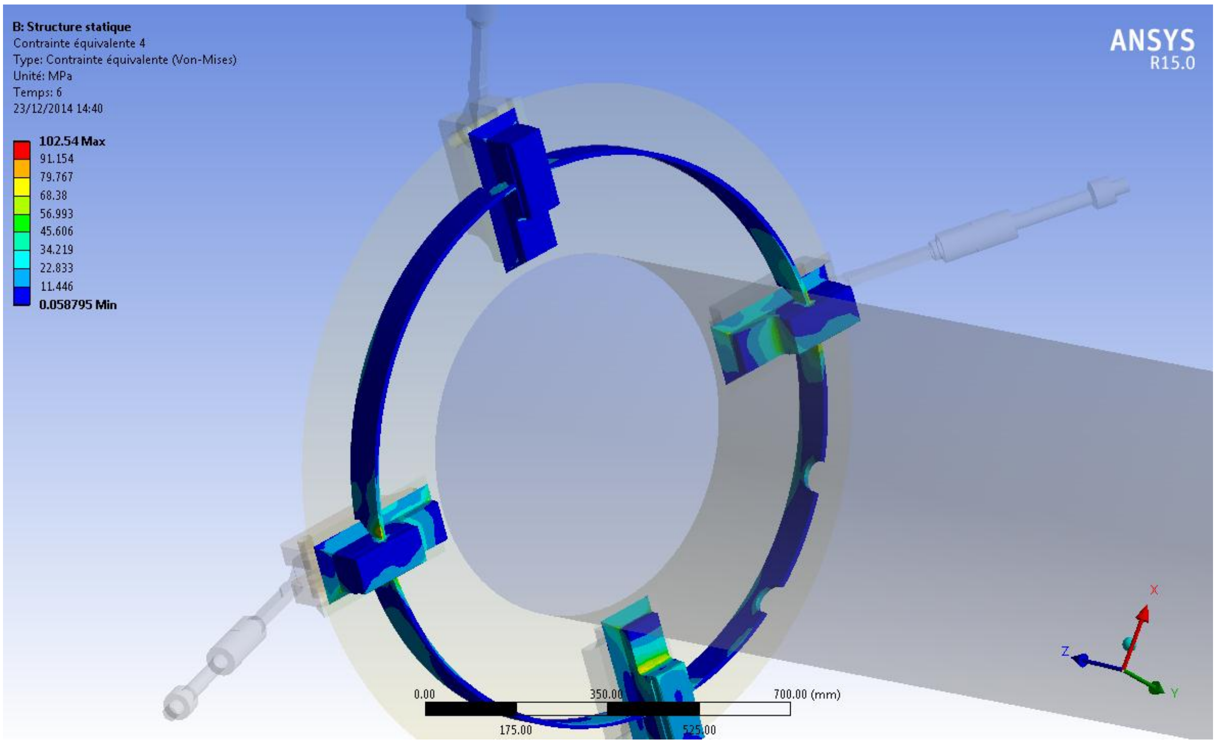


  - Inferior skin:



- **Coil support:**





11. WORST CASE N°2: TEST PRESSURE

The second worst case concerns the pressure test at 10 bars after welding of the helium vessel. The maximum peak stress is equal to 117 MPa which is inferior to 155 MPa (90% of the yield strength). This test implies we can manufacture the vessel according to both division 1 and division 2 because it's the worst case scenario.

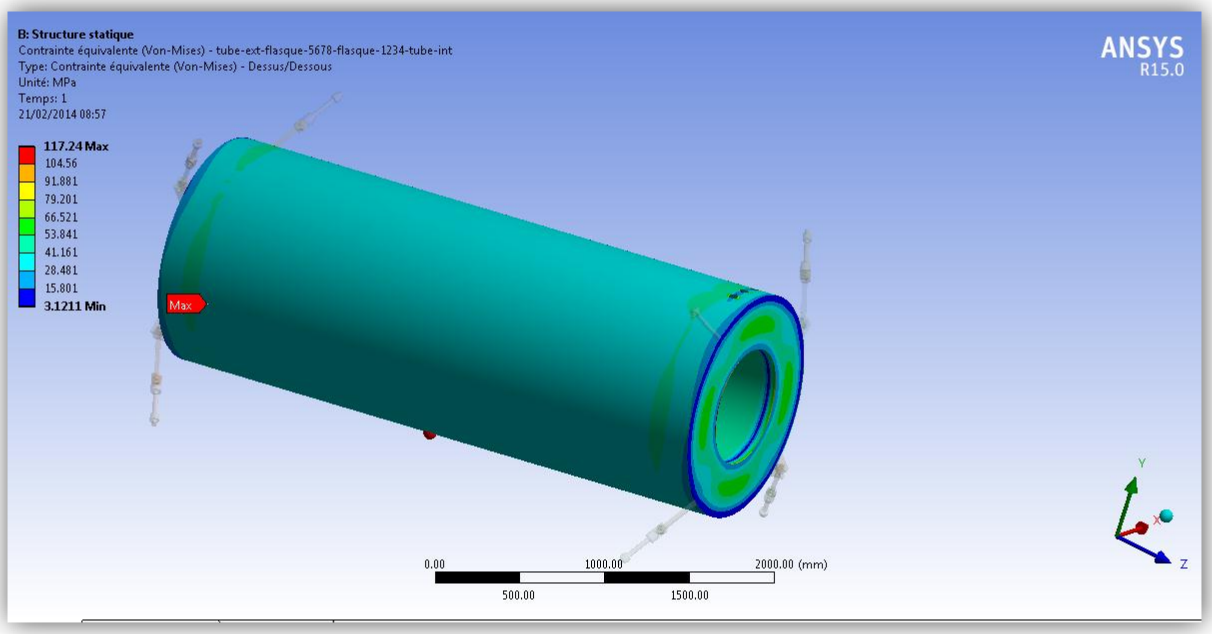


Figure 11: Von Mises peak stress (inferior & superior skin) during pressure test at 10 bars