

HIE-ISOLDE Cryomodule *Thermal Analysis – 2nd part*

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7th October 2014

- 1 About the 1st part
- 2 Supporting frame
- 3 Omega plates
- 4 Vacuum vessel cleaning
- 5 RF cable
- 6 Solenoid splice
- 7 Conclusions and next steps

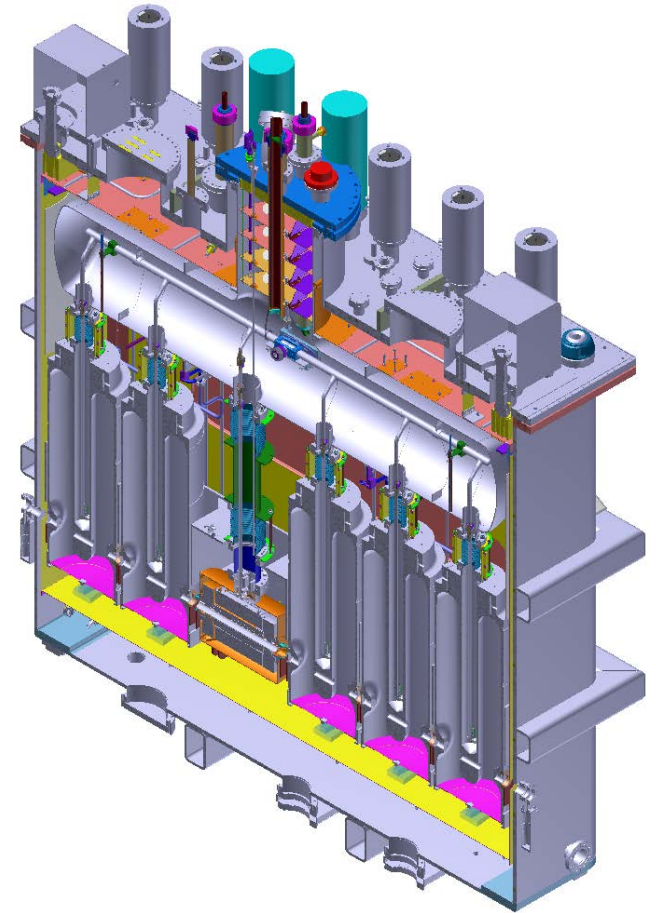
Targets:

1. Global temperature and heat flux mapping;
2. Design validation;
3. Validation of the experimental tests;
4. Simulation tool for future thermo-mechanical analysis;



« A model is a selective abstraction of the reality »

- Problem formulation
- Analytical estimations
- FEM model
- Analysis of the results



HIE-ISOLDE: Procedure



1. Initial status

- 300K structures

2. Thermal shield cool down

- 300K-75K
- 13 bar

3. Reservoir + frame cool down

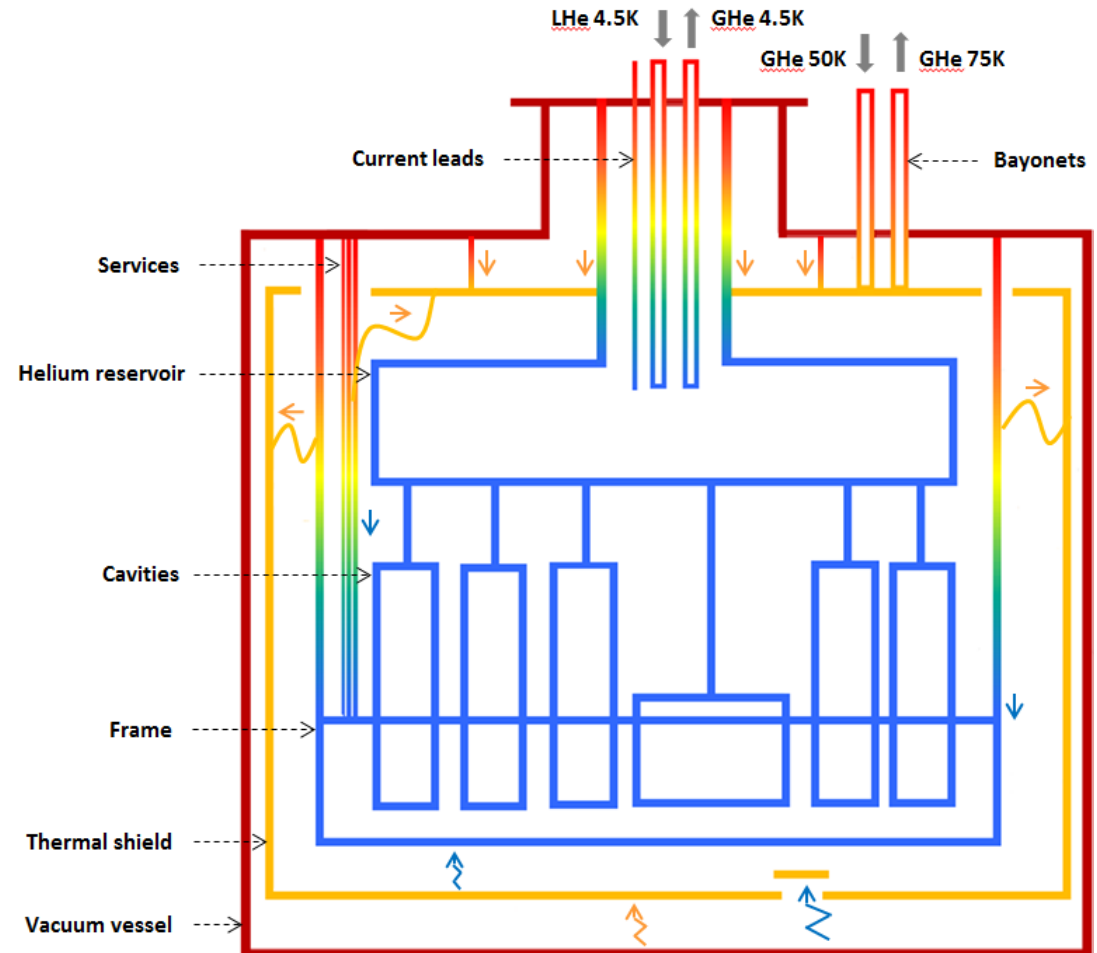
- 300K-75K
- 2.5 bar

4. Reservoir + frame cool down

- 75K-4.5K
- 2.5 bar

5. Global cool down

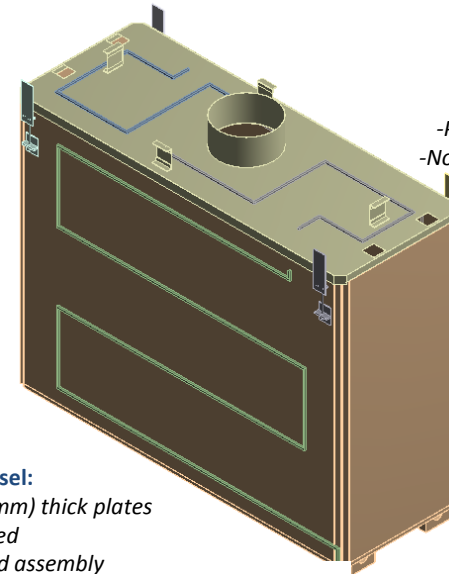
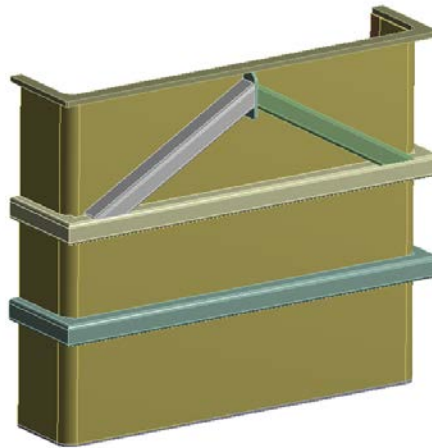
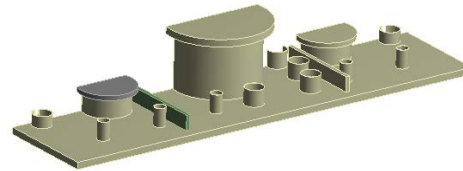
- Thermal shield circuit : 13barG, 55-75K
- Cold mass circuits: 1.3 barG, 4.5K



HIE-ISOLDE: Model

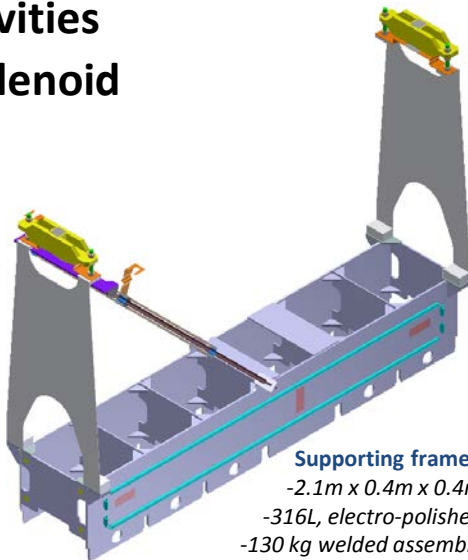


- ❑ Vacuum vessel
- ❑ Top plate
- ❑ Thermal shield
 - Cryogenics circuit
- ❑ Supporting frame assembly
 - Actively cooled frame
 - Suspension rods
- ❑ Helium reservoir
 - Cryogenics piping
- ❑ 5 cavities
- ❑ 1 solenoid

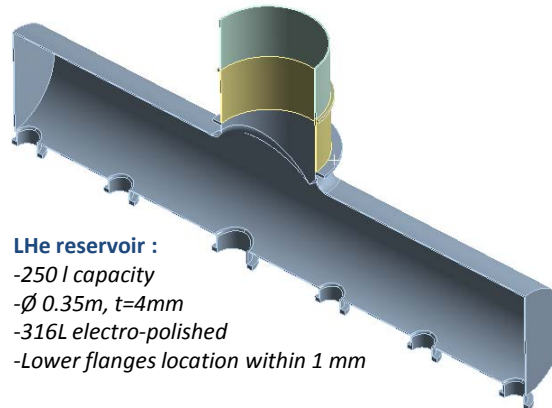


Vacuum vessel:
-15 mm (40mm) thick plates
-316L polished
-4.5 T welded assembly

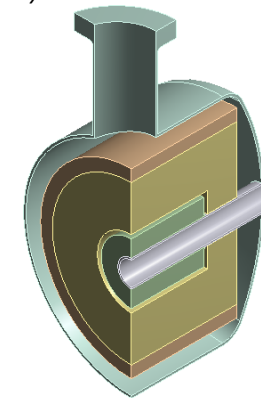
Thermal Shield :
-2.2m x 1.8m x 0.9m
-300 kg bolted assembly
-2 mm thick Cu Ni-plated
-Piping : GHe 70K, 13 bara
-No porosities after brazing



Supporting frame :
-2.1m x 0.4m x 0.4m
-316L, electro-polished
-130 kg welded assembly
-Piping : LHe 4.5K, 4.5 bara



LHe reservoir :
-250 l capacity
- \varnothing 0.35m, t=4mm
-316L electro-polished
-Lower flanges location within 1 mm

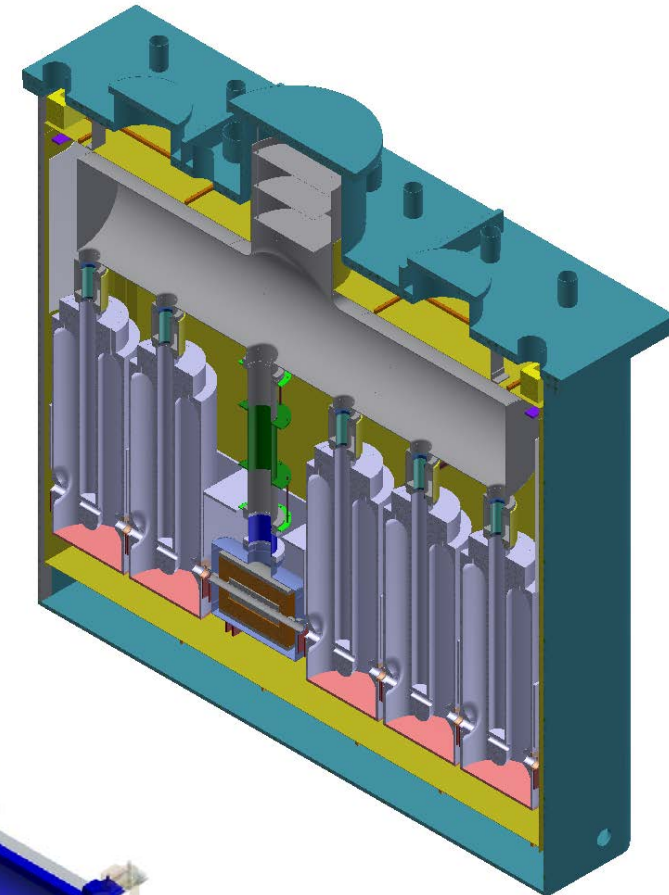
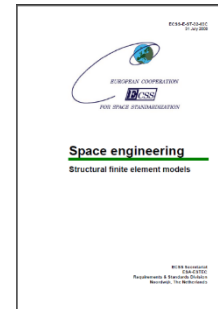


HIE-ISOLDE: Model checks

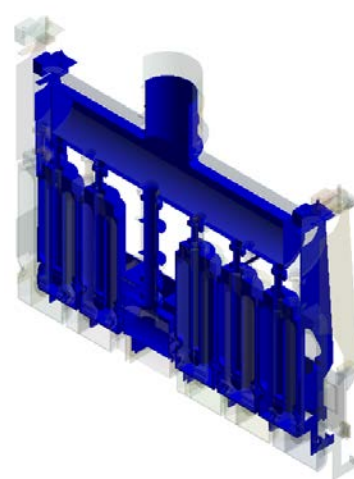
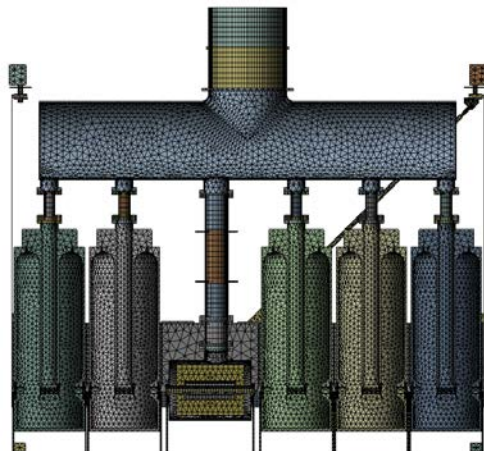
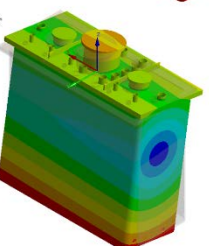
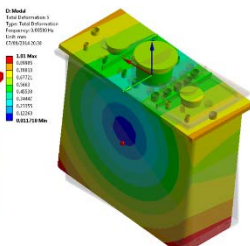
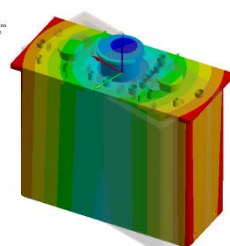


Finite Element Model (source ESA/ECSS standards):

- Geometry
- Mesh
- Loads
- Rigid body motion



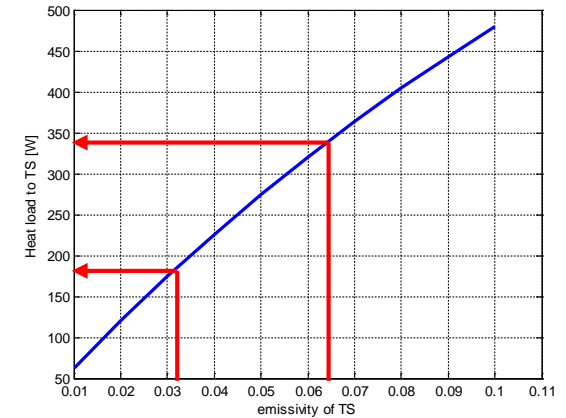
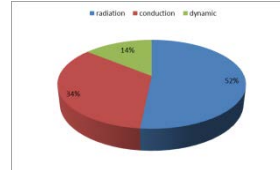
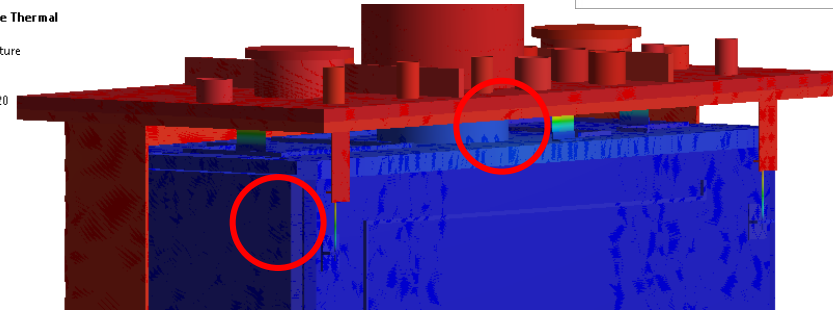
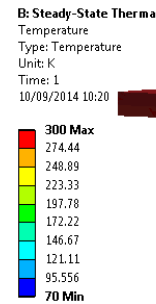
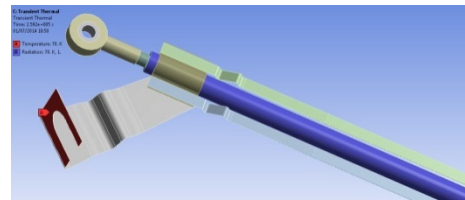
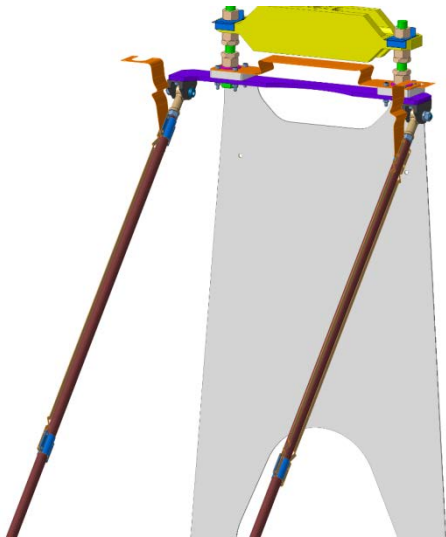
$$M_R = \begin{bmatrix} m & 0 & 0 & 0 & -mz_{cog} & my_{cog} \\ 0 & m & 0 & mz_{cog} & 0 & -mx_{cog} \\ 0 & 0 & m & -my_{cog} & mx_{cog} & 0 \\ 0 & mz_{cog} & -my_{cog} & I_{xx} & I_{xy} & I_{xz} \\ -mz_{cog} & 0 & mx_{cog} & I_{yx} & I_{yy} & I_{yz} \\ my_{cog} & -mx_{cog} & 0 & I_{zx} & I_{zy} & I_{zz} \end{bmatrix}$$



Thermal steady-state analysis

- ❑ OB: Radiative heat transfer between the Vacuum Vessel and the Thermal Shield
- ❑ Emissivity
 - Vacuum vessel: 0.2
 - Thermal shield: [0.033, 0.066]

$$\dot{q}_{1 \rightarrow 2} = \dot{q}_1 = -\dot{q}_2 = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1 - \varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1 - \varepsilon_2}{\varepsilon_2 A_2}}$$



	Two thermalisations	One thermalisation
Only conduction	50 h	65 h
Conduction + radiation	21 h	23 h

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Supporting frame



Ob: temperature mapping during the cooling down

Hp:

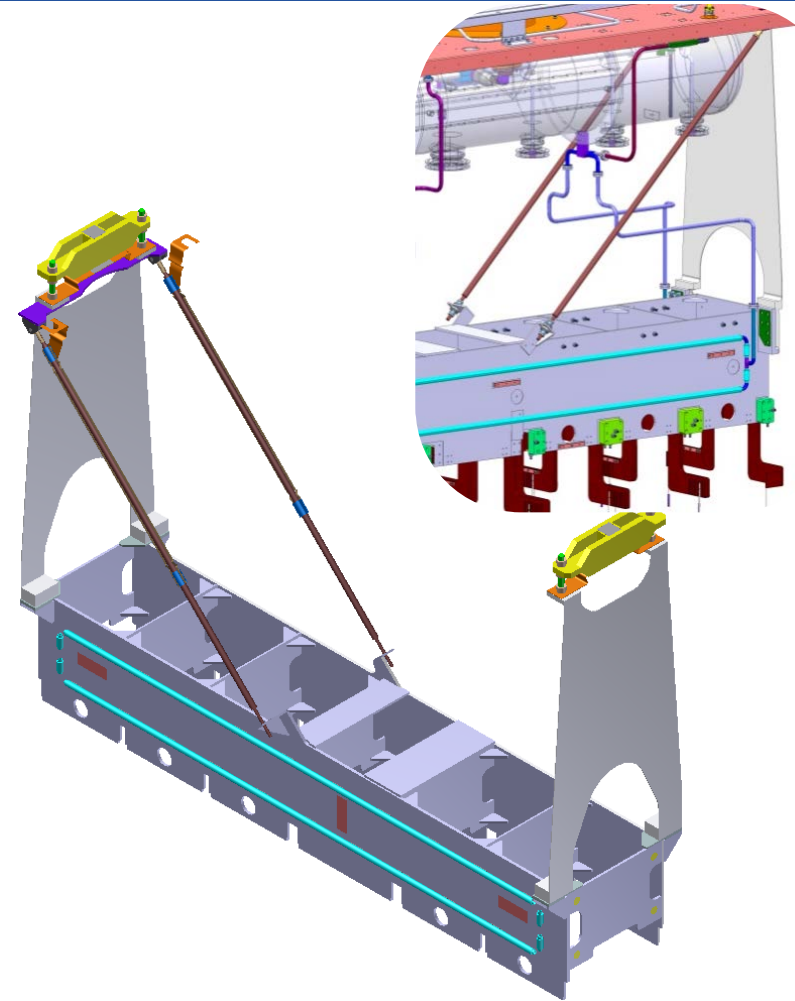
1. Isolated system;
2. Perfect contact between the parts;

Loads:

- Conduction;
- Forced convection in the cooling circuit @4.5K;
- Radiation to the TS@70K;

Materials:

- Frame: stainless steel 316L
- Thermalisations: copper

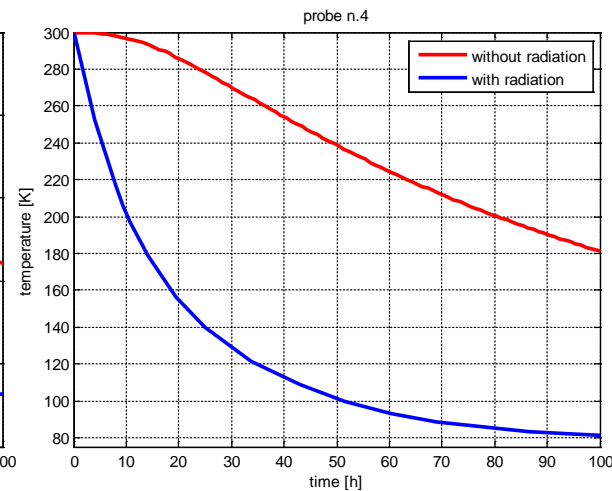
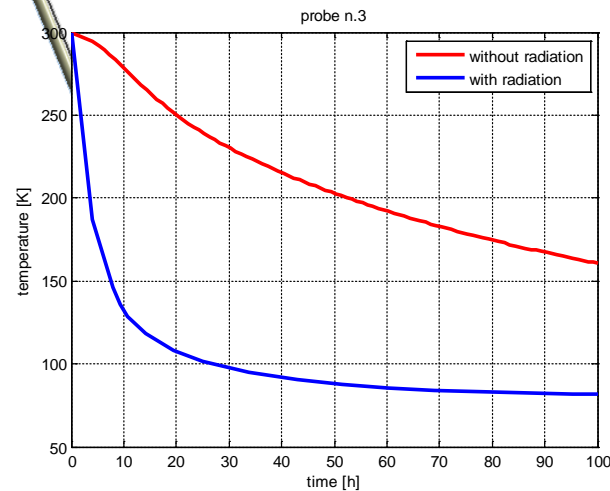
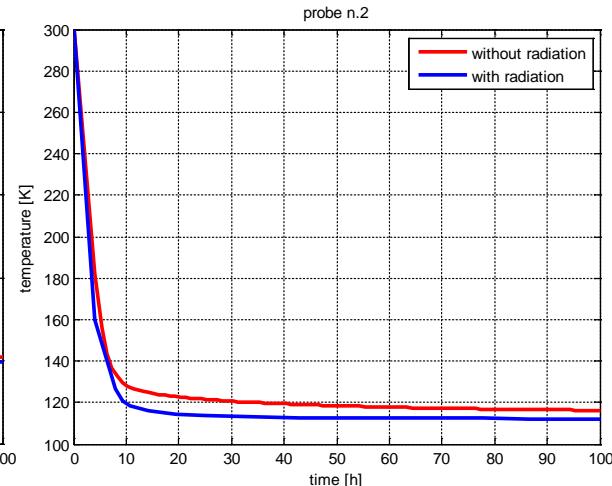
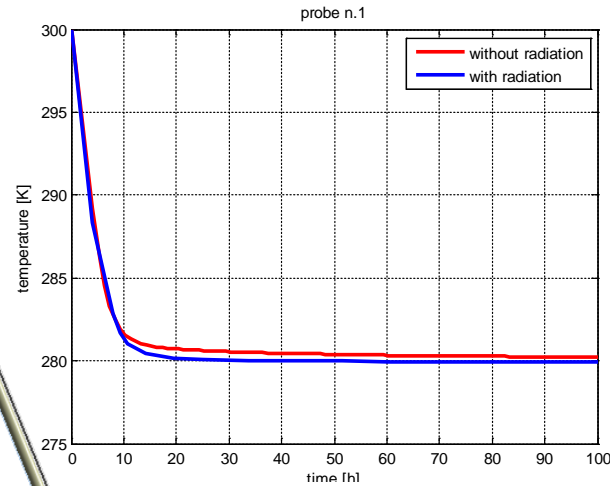


Supporting frame



Hp: isolated system

- ☐ Cooling phase 2:
 - TS@70K
 - CM warm
- ☐ Tin=300K
- ☐ Boundary conditions:
 - T(A)=300K
 - T(B)=T(C)=70K
 - Rad on the panel

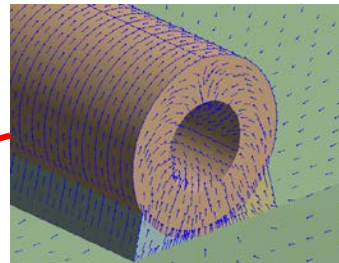
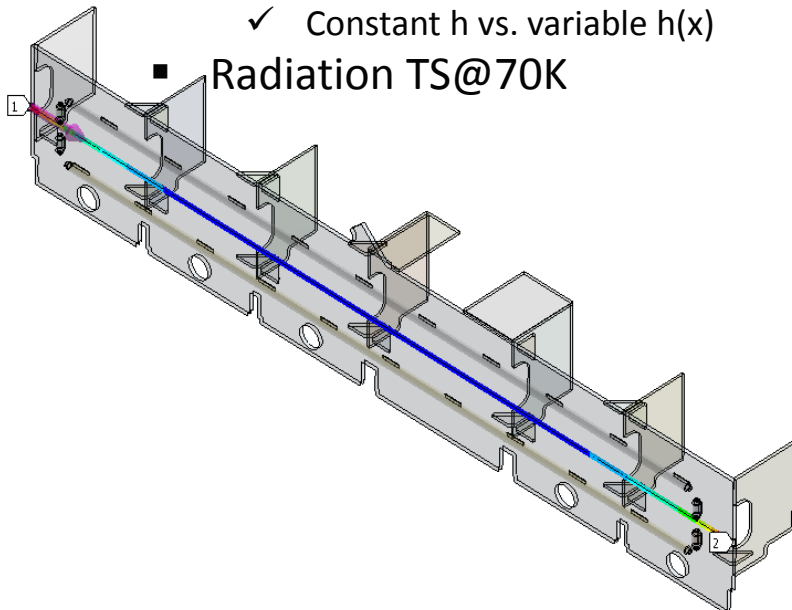


Frame

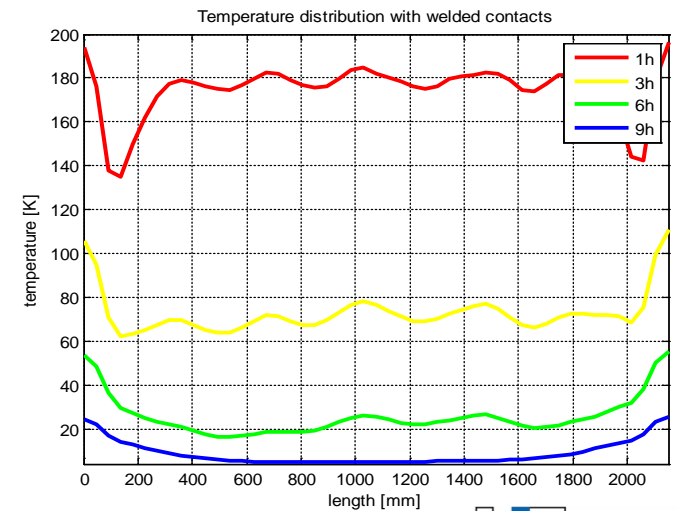
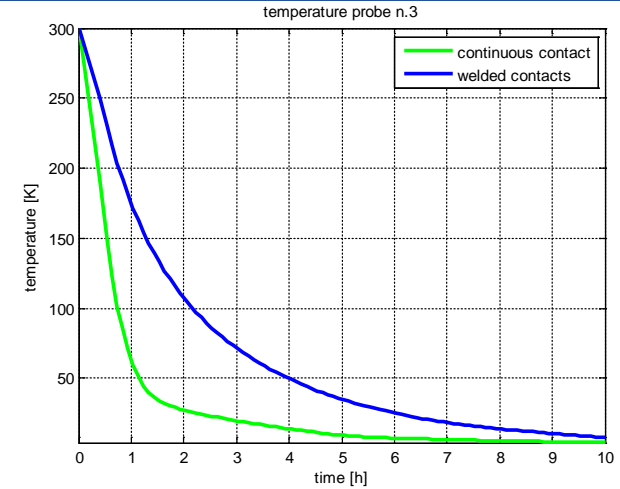
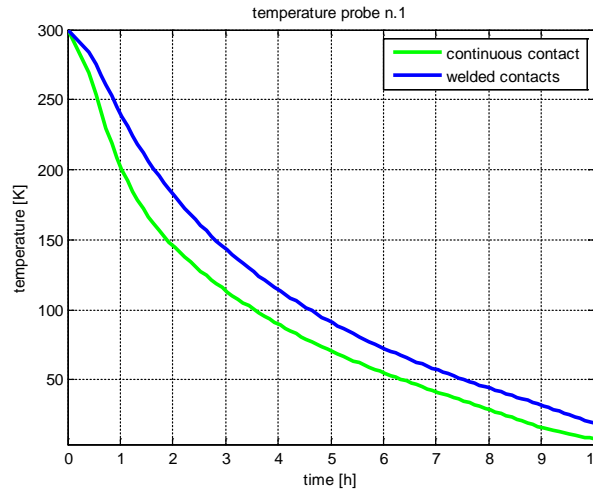
Hp: isolated system

- ❑ Cooling phase 3-4:
 - TS@70K
 - Frame 300K to 4.5K

- ❑ Boundary conditions:
 - Forced convection:
 - ✓ continuous contact vs. welded contact
 - ✓ Constant h vs. variable h(x)
 - Radiation TS@70K



Heat flux in the stainless steel tube



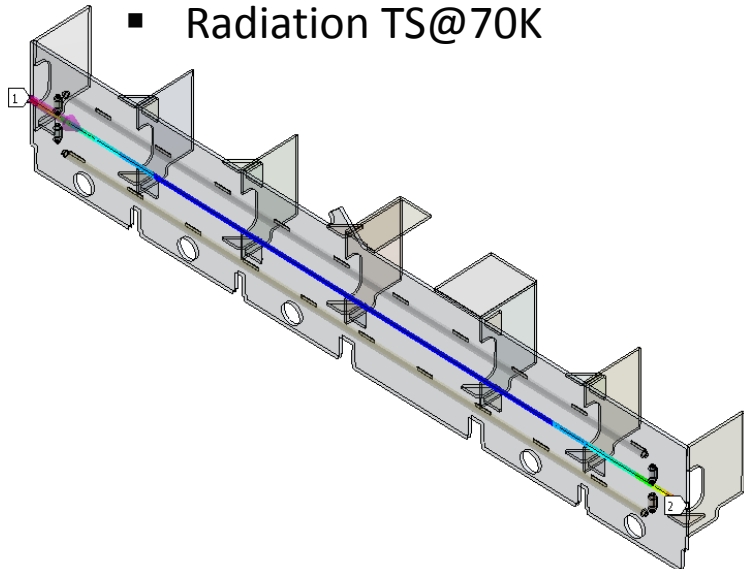
Frame



Hp: isolated system

- ❑ Cooling phase 3-4:
 - TS@70K
 - Frame 300K to 4.5K

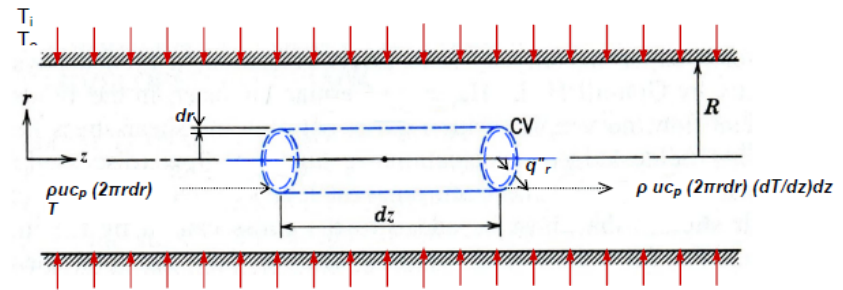
- ❑ Boundary conditions:
 - Forced convection:
 - ✓ continuous contact vs. welded contact
 - ✓ Constant heat flux vs. variable
 - Radiation TS@70K



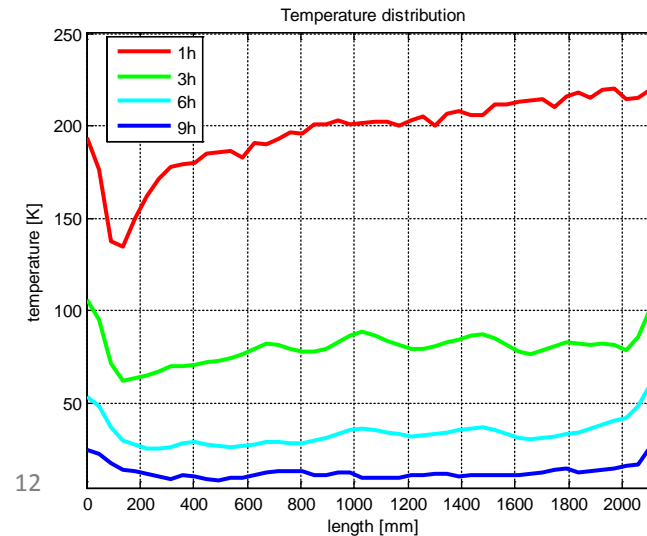
Fully developed turbulent flow

For turbulent flow ($Re_D > 2000$)

$$Nu_D = f(Re_D, Pr) = C Re_D^n Pr^m \quad \text{and} \quad Pr \equiv \frac{\mu_f C_p}{k_f}$$



$$T - T_c = \frac{\rho c_p}{k_f} \frac{\partial T}{\partial z} \frac{u_c R^2}{4} \left[\left(\frac{r}{R} \right)^2 - \frac{1}{4} \left(\frac{r}{R} \right)^4 \right]$$

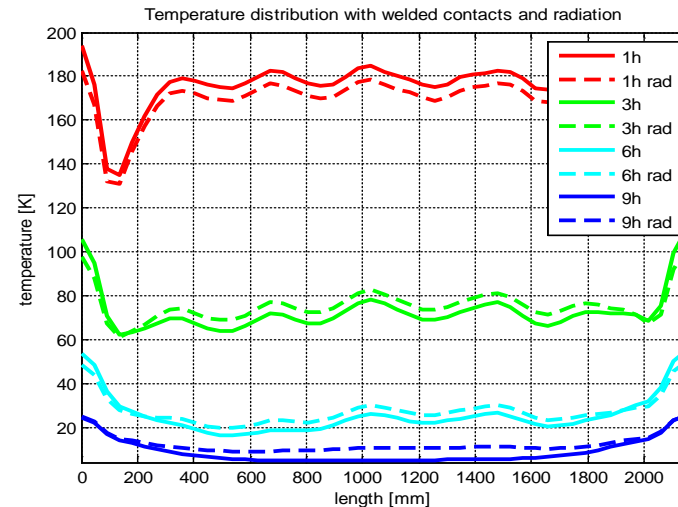
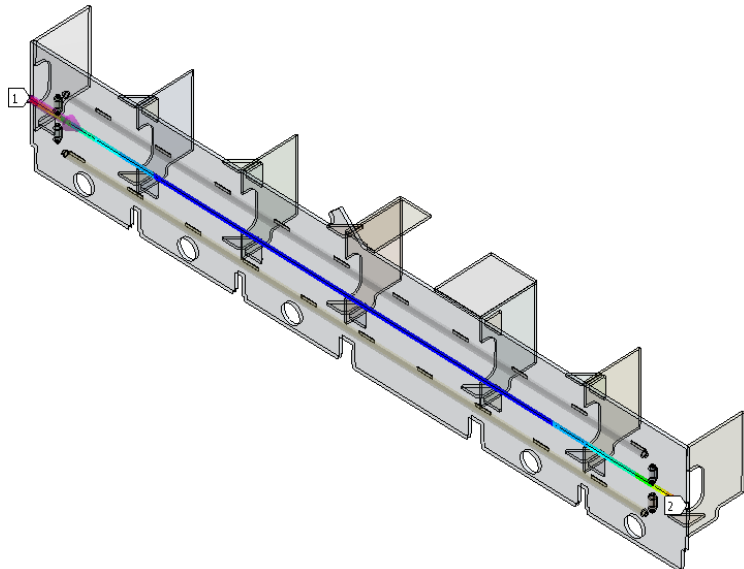
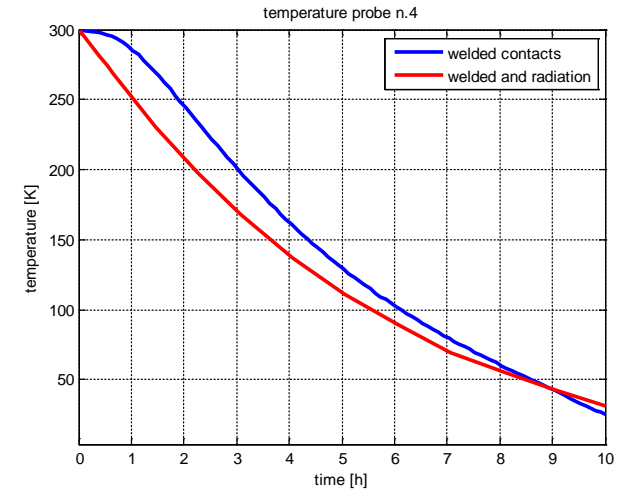
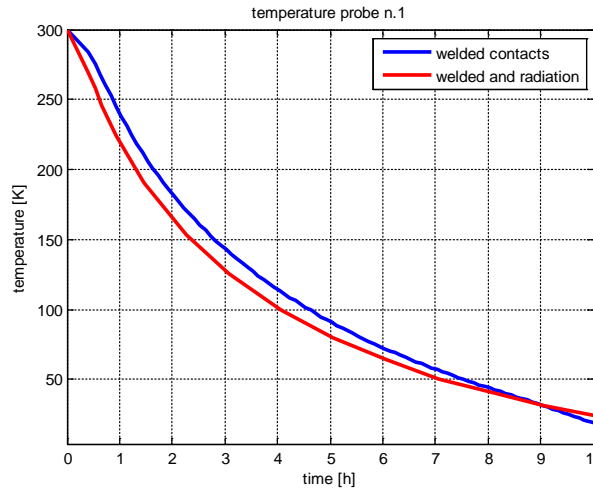


Frame



Hp: isolated system

- ❑ Cooling phase 3:
 - TS@70K
 - Frame 300K to 4.5K
- ❑ Boundary conditions:
 - Forced convection
 - Radiation TS@70K



Supporting frame

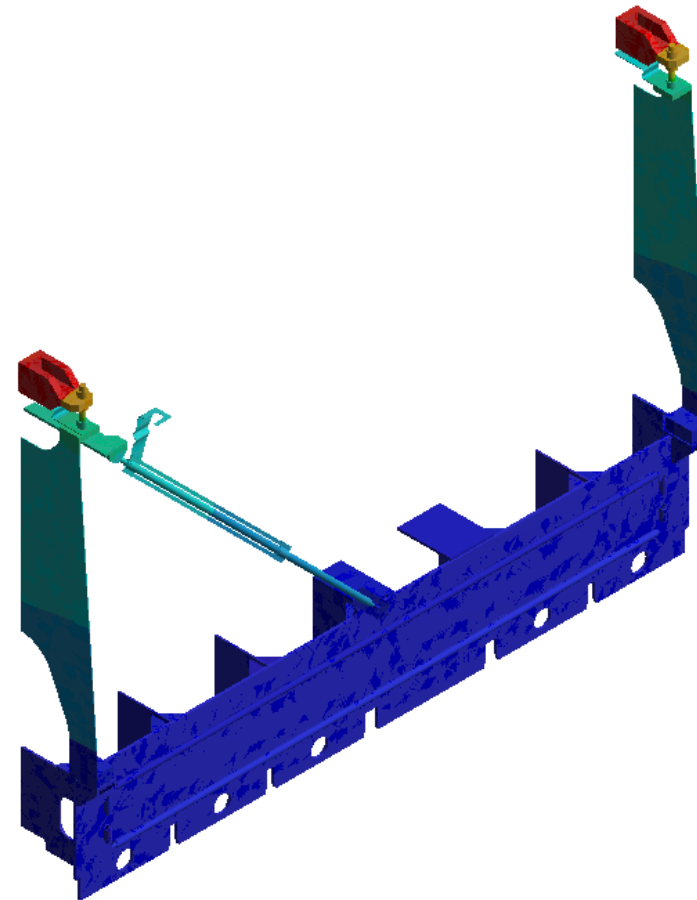
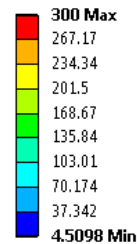


Hp: isolated system

- ❑ Cooling phase 3-4:
 - TS@70K
 - Frame 300K to 4.5K

- ❑ Boundary conditions:
 - Forced convection
 - Radiation TS@70K

Temperature
Type: Temperature
Unit: K
Time: 1
28/09/2014 22:49



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Omega Plate



Ob: determination of the displacement of the targets

Hp:

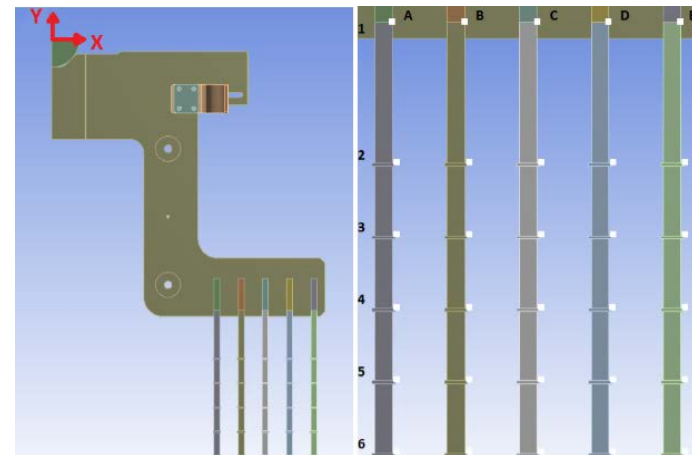
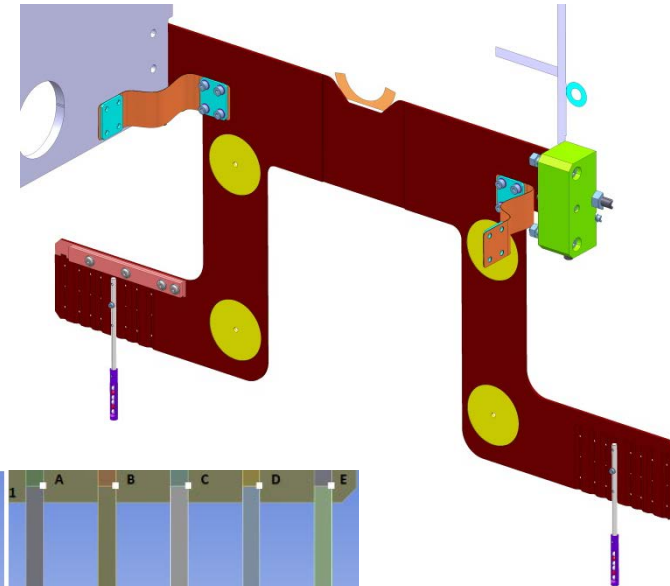
1. Isolated system;
2. Perfect contact between the parts;

Loads:

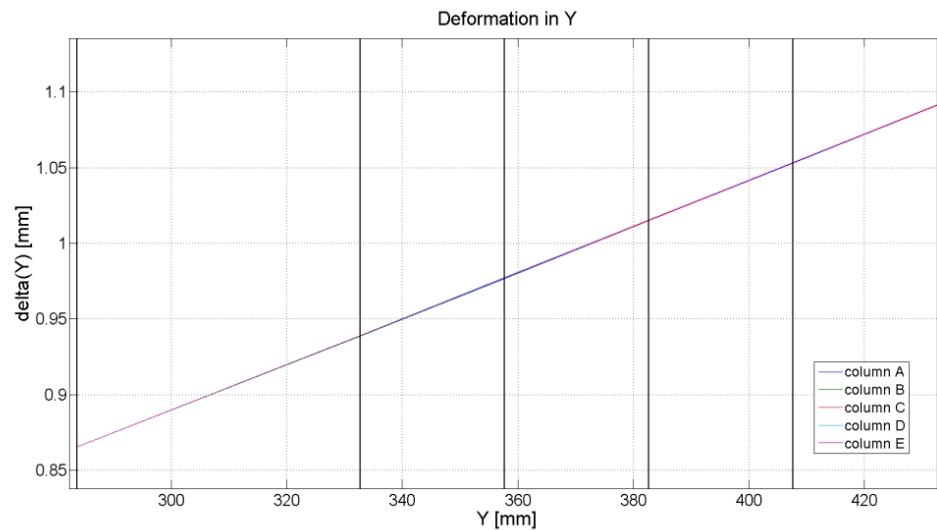
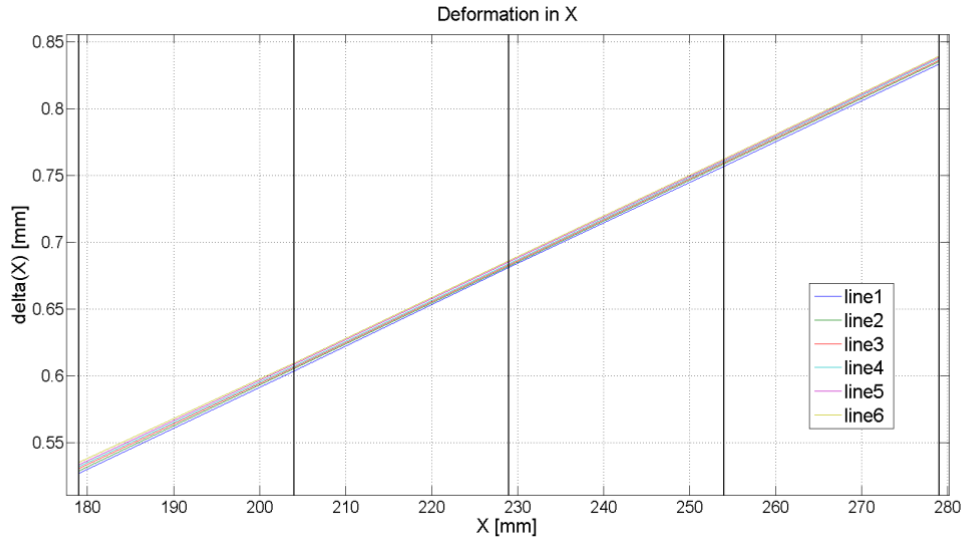
- Conduction 4.5K on thermalisation;

Materials:

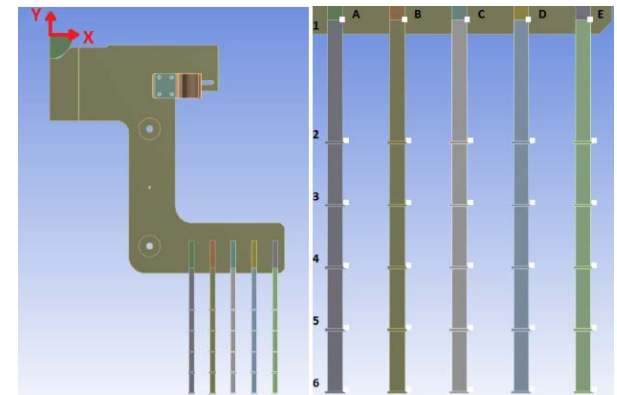
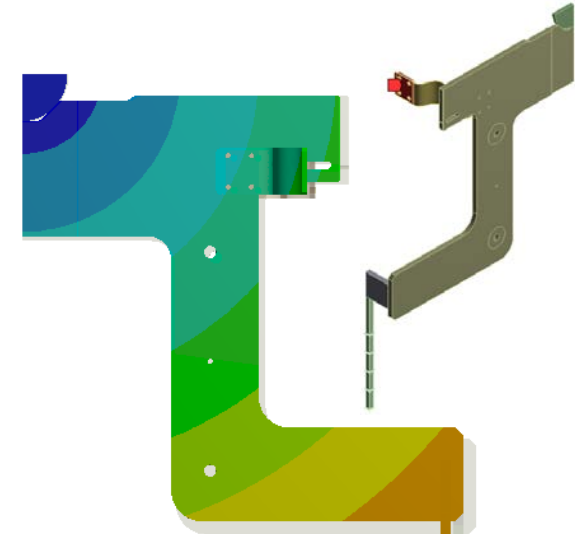
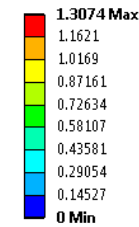
- Frame: stainless steel 316L
- Thermalisation: copper
- Targets: titanium



Omega Plates



Total Deformation
 Type: Total Deformation
 Unit: mm
 Time: 1
 01/10/2014 15:23



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Vacuum vessel cleaning (1/2)



Ob: Stress analysis/buckling verification of the bottom beams of the vacuum vessel for cleaning;

Hp:

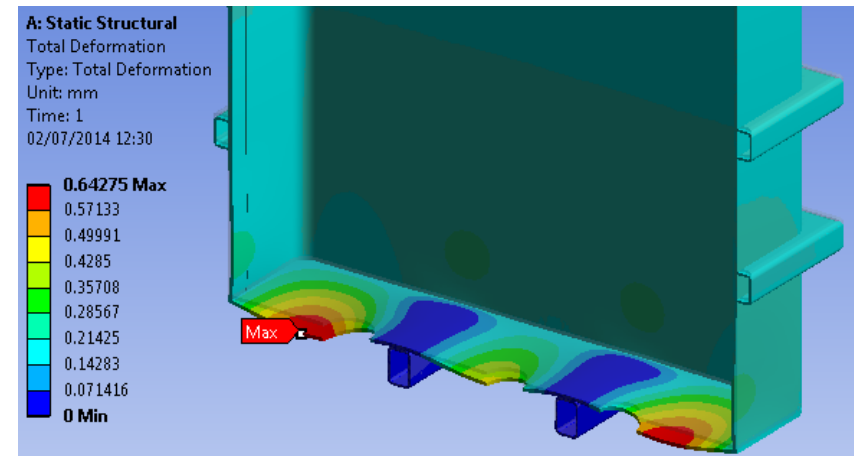
1. Isolated system;
2. Perfect contact between the parts;

Loads:

- Gravity;
- Fluid:
 - $density \rho = 2\rho_{H_2O} = 2000 \text{ kg/m}^3$;
 - $volume V = 4 \text{ m}^3$;

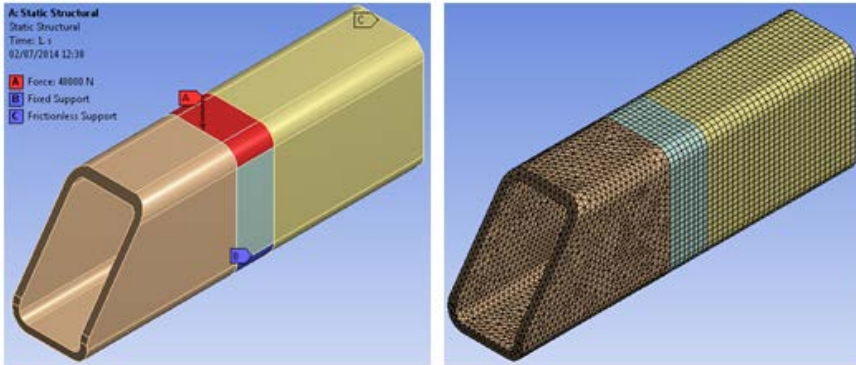
Materials:

- Stainless steel 316L

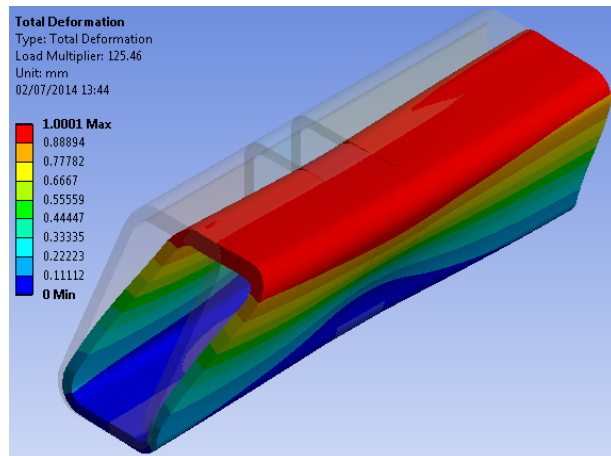


The bottom plate of the vacuum vessel is affected by a max total deformation of 0.64 mm under the mentioned load condition. The maximum von Mises stress on the bottom plate is 60MPa, 2.8 times below the yield strength.

Vacuum vessel cleaning (2/2)

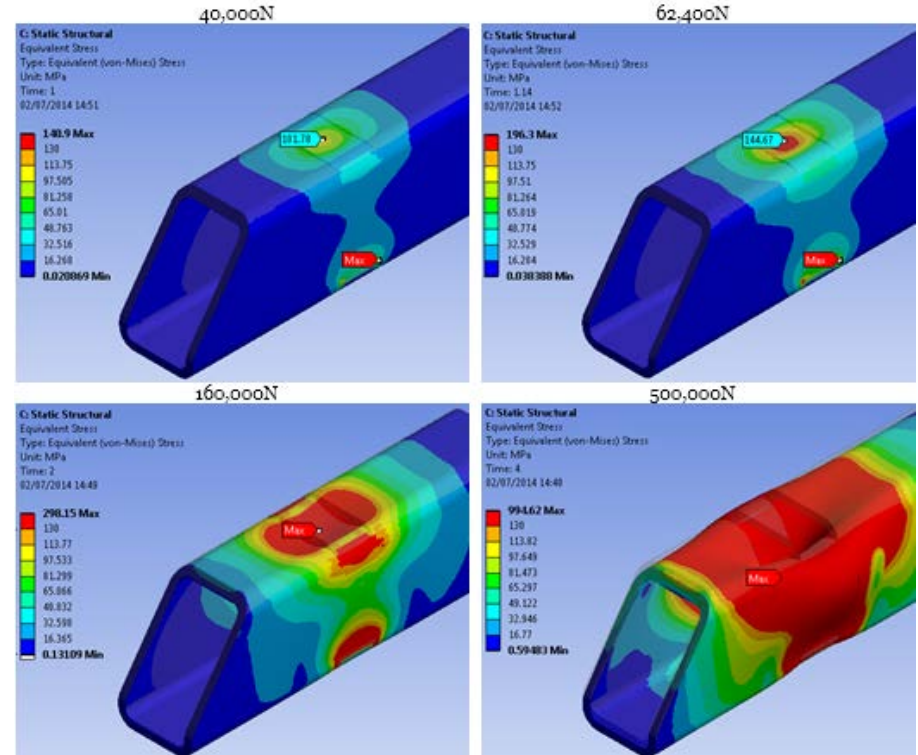


The linear buckling analysis shows a load multiplier (buckling factor of safety for the applied load) of 125.46 on the first mode



In the large deformation analysis, a total load of 500,000N (conservative assumption) is applied in 4 steps together with an additional lateral force of 500N in order to create instability.

The section shows stress over 130MPa around 60,000N (in line with the results from the elastic analysis). After this limit the plastic region starts to spread all around the beam even if any buckling phenomenon is still not involved.



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RF cable



Ob: temperature mapping of the RF cable

Hp:

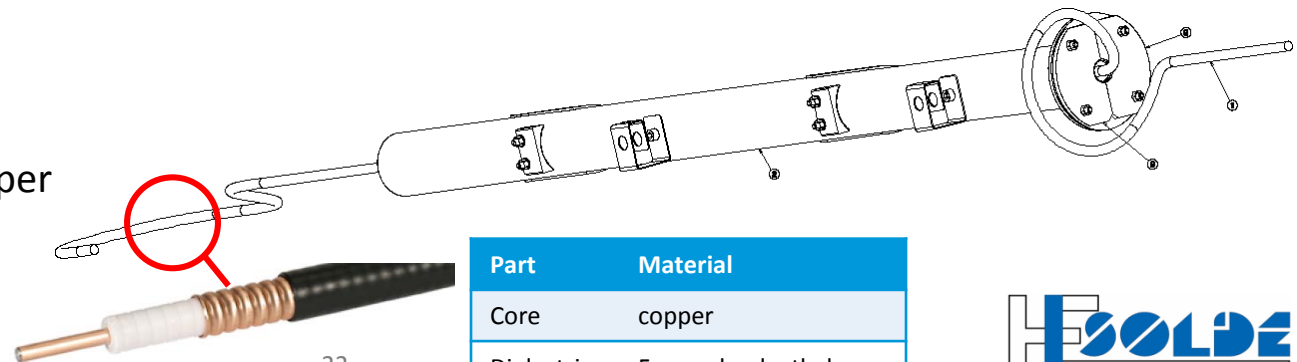
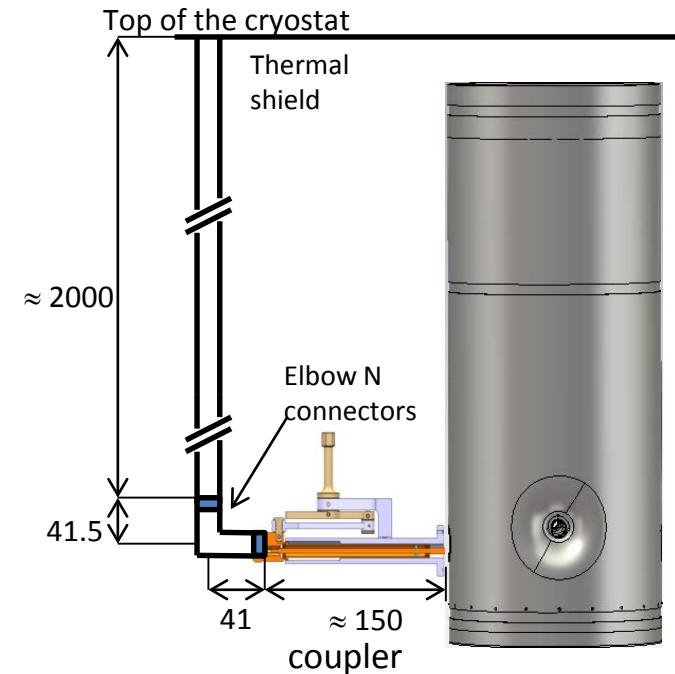
1. Isolated system
2. Perfect contact between the parts;

Loads:

- Conduction;
- Power generation: Joule effect;
- Radiation to ambient;

Materials:

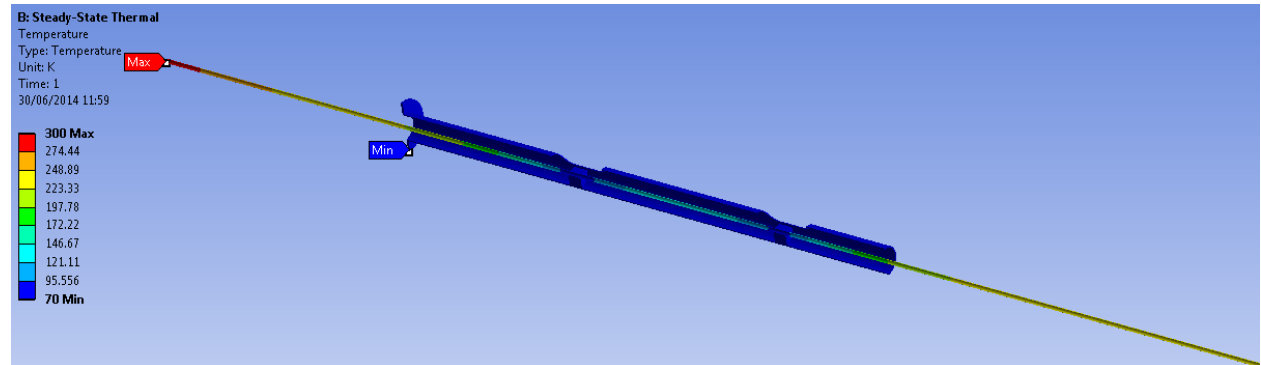
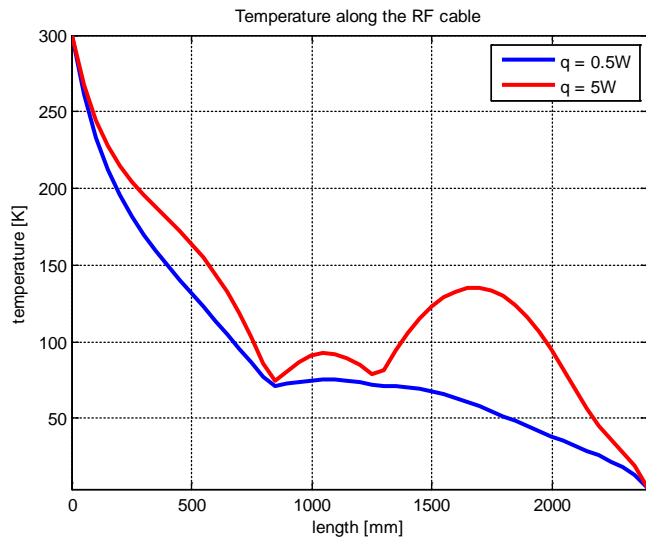
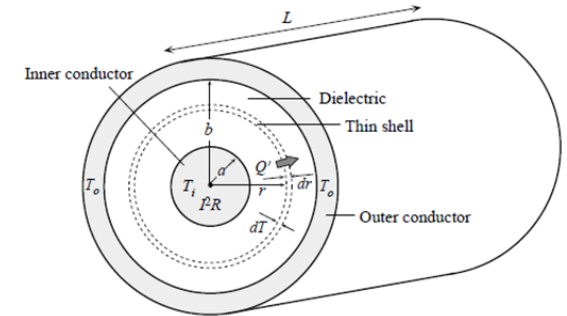
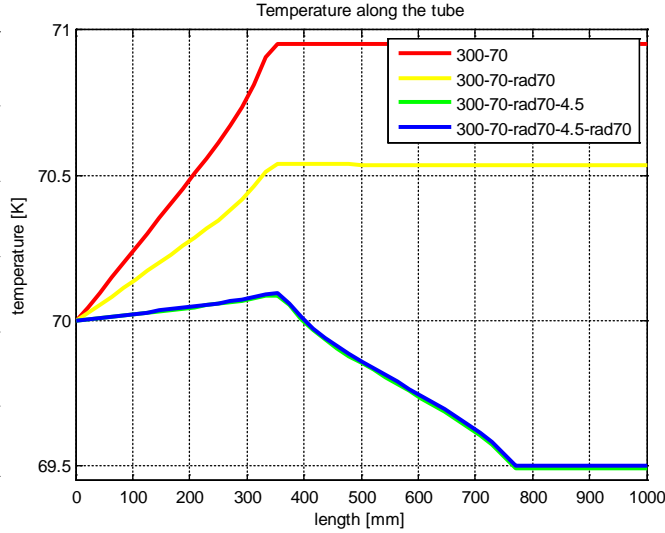
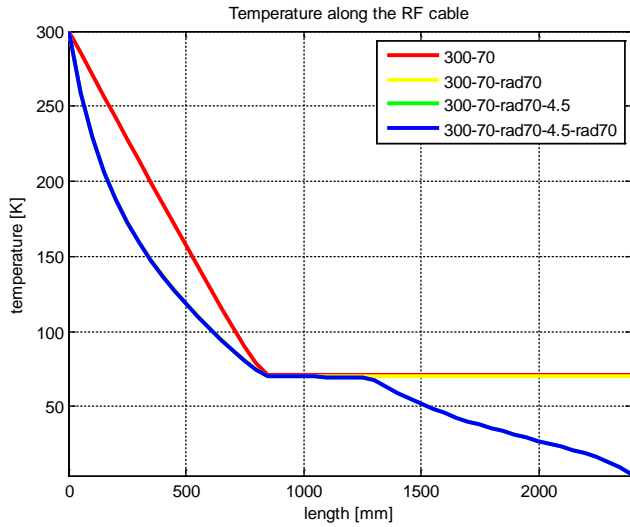
- stainless steel 316L
- Thermalisations: copper



Part	Material
Core	copper
Dielectric	Foamed polyethylene



RF cable



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Solenoid Splice



Ob: determination of the thermal transient behaviour of the TS

Hp:

1. Isolated system;
2. Perfect contact between the parts;

Loads:

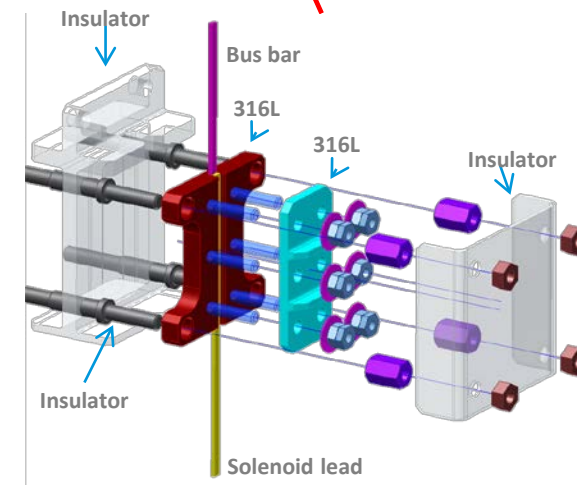
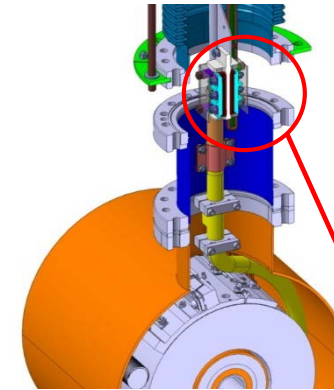
- Heat generation for joule effect;
- Forced convection @4.5K;

Materials:

- Stainless steel 316L
- Copper RRR100

Parameters :

- $R < 10 \text{ n}\Omega$
- Dynamic heat dissipation $< 1\text{mW}$
- 120A nominal
- Self protected

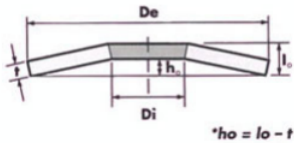


Solenoid Splice



DR-D5

Rondelle élastique standard



En ce qui concerne leurs caractéristiques dimensionnelles et de charge, notre gamme de rondelles élastiques est conforme au standard **DIN 2093**. En revanche, pour la matière, elles sont produites selon la norme de matière **BS1449 Pt 1 équivalente CS70** et la **DIN 17222 50CrV4**. Elles sont entièrement ébavurées avec les angles arrondis. Elles offrent une alternative économique aux rondelles de la norme **DIN 2093** avec des performances acceptables dans des conditions sévères.

Référence	De	Di	t	lo	Force en Newtons @ 75% de ho*
DR-D5 015P DH	8.0	3.20	0.20	0.40	26
DR-D5 017P DH	8.0	3.20	0.30	0.55	104
DR-D5 019P DH	8.0	3.20	0.40	0.60	185
DR-D5 021P DH	8.0	3.20	0.50	0.70	358
DR-D5 023P DH	8.0	4.20	0.20	0.45	39
DR-D5 025P DH	8.0	4.20	0.30	0.55	118
DR-D5 027P DH	8.0	4.20	0.40	0.60	210
DR-D5 045P DH	10.0	3.20	0.30	0.65	98
DR-D5 049P DH	10.0	3.20	0.50	0.75	278
DR-D5 051P DH	10.0	4.20	0.40	0.70	189
DR-D5 053P DH	10.0	4.20	0.50	0.75	295
DR-D5 055P DH	10.0	4.20	0.60	0.85	504
DR-D5 057P DH	10.0	5.20	0.25	0.55	58
DR-D5 059P DH	10.0	5.20	0.40	0.70	210
DR-D5 061P DH	10.0	5.20	0.50	0.75	326
DR-D5 067P DH	12.0	4.20	0.40	0.80	179
DR-D5 069P DH	12.0	4.20	0.50	0.85	284
DR-D5 071P DH	12.0	5.20	0.40	0.80	188
DR-D5 073P DH	12.0	5.20	0.50	0.90	350
DR-D5 075P DH	12.0	5.20	0.60	0.95	506
DR-D5 077P DH	12.0	5.20	0.80	1.10	998
DR-D5 079P DH	12.0	6.20	0.50	0.85	326
DR-D5 081P DH	12.0	6.20	0.60	0.95	551
DR-D5 083P DH	12.0	6.20	0.80	1.10	1090
DR-D5 087P DH	12.5	6.20	0.35	0.80	151
DR-D5 089P DH	12.5	6.20	0.50	0.85	293
DR-D5 097P DH	12.5	6.20	0.70	1.00	660
DR-D5 119P DH	14.0	6.20	0.90	1.25	1228
DR-D5 121P DH	14.0	7.20	0.35	0.80	123
DR-D5 123P DH	14.0	7.20	0.50	0.90	280
DR-D5 125P DH	14.0	7.20	0.80	1.10	796
DR-D5 129P DH	15.0	5.20	0.40	0.95	176
DR-D5 135P DH	15.0	5.20	0.70	1.10	555

Référence	De	Di	t	lo	Force en Newtons @ 75% de ho*
DR-D5 137P DH	15.0	6.20	0.50	1.00	290
DR-D5 139P DH	15.0	6.20	0.60	1.05	423
DR-D5 141P DH	15.0	6.20	0.70	1.10	578
DR-D5 145P DH	15.0	8.20	0.70	1.10	666
DR-D5 147P DH	15.0	8.20	0.80	1.20	983
DR-D5 157P DH	16.0	8.20	0.40	0.90	154
DR-D5 159P DH	16.0	8.20	0.60	1.05	410
DR-D5 161P DH	16.0	8.20	0.90	1.25	1013
DR-D5 167P DH	18.0	6.20	0.40	1.00	140
DR-D5 169P DH	18.0	6.20	0.50	1.10	245
DR-D5 171P DH	18.0	6.20	0.60	1.20	401
DR-D5 173P DH	18.0	6.20	0.70	1.25	553
DR-D5 175P DH	18.0	6.20	0.80	1.30	726
DR-D5 179P DH	18.0	8.20	0.70	1.25	596
DR-D5 181P DH	18.0	8.20	0.80	1.30	932
DR-D5 183P DH	18.0	8.20	1.00	1.50	1501
DR-D5 185P DH	18.0	9.20	0.45	1.05	213
DR-D5 187P DH	18.0	9.20	0.70	1.20	566
DR-D5 189P DH	18.0	9.20	1.00	1.40	1253
DR-D5 213P DH	20.0	8.20	0.60	1.30	412
DR-D5 215P DH	20.0	8.20	0.70	1.35	569
DR-D5 217P DH	20.0	8.20	0.80	1.40	750
DR-D5 219P DH	20.0	8.20	0.90	1.45	959
DR-D5 225P DH	20.0	10.20	0.50	1.15	254
DR-D5 227P DH	20.0	10.20	0.80	1.35	749
DR-D5 229P DH	20.0	10.20	0.90	1.45	1049
DR-D5 231P DH	20.0	10.20	1.00	1.55	1424
DR-D5 233P DH	20.0	10.20	1.10	1.55	1520
DR-D5 235P DH	20.0	10.20	1.25	1.75	2476
DR-D5 239P DH	22.0	10.20	1.22	1.82	2197
DR-D5 244P DH	22.5	11.20	0.60	1.40	425
DR-D5 245P DH	22.5	11.20	0.80	1.45	707
DR-D5 249P DH	22.5	11.20	1.25	1.75	1930

A: Static Structural
Total Deformation
Type: Total Deformation
Unit: mm
Time: 1
11/10/2014 17:49

0.0060624 Max
0.0053888
0.0047152
0.0040416
0.003368
0.0026944
0.0020208
0.0013472
0.0006736
0 Min

A: Static Structural
Equivalent Stress 3
Type: Equivalent (von-Mises) Stress
Unit: MPa
Time: 1
11/10/2014 17:50

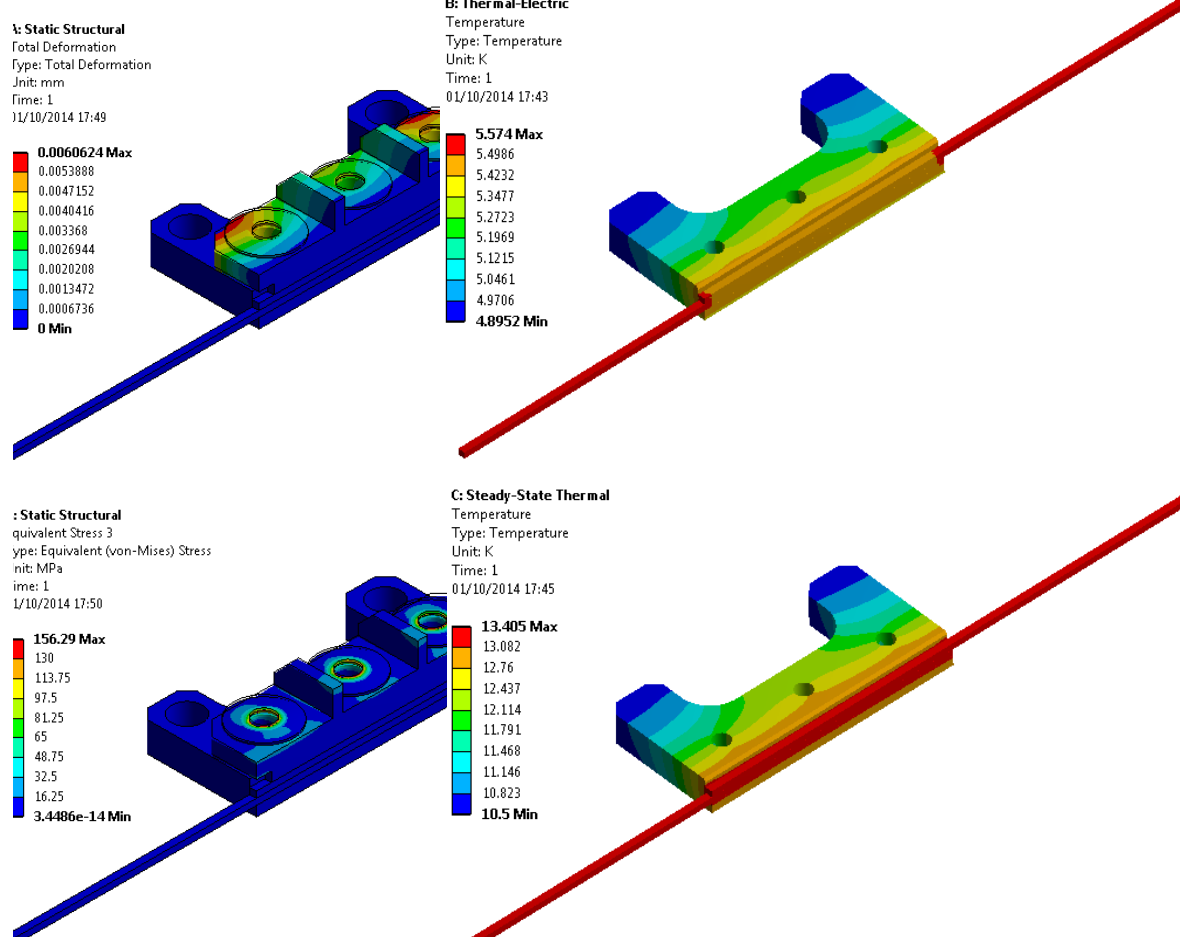
156.29 Max
130
113.75
97.5
81.25
65
48.75
32.5
16.25
3.4406e-14 Min

B: Thermal-Electric
Temperature
Type: Temperature
Unit: K
Time: 1
01/10/2014 17:43

5.574 Max
5.4986
5.4232
5.3477
5.2723
5.1969
5.1215
5.0461
4.9706
4.8952 Min

C: Steady-State Thermal
Temperature
Type: Temperature
Unit: K
Time: 1
01/10/2014 17:45

13.405 Max
13.082
12.76
12.437
12.114
11.791
11.468
11.146
10.823
10.5 Min



- 1 About 1st part
- 2 Supporting frame
- 3 Omega plates
- 4 Vacuum vessel cleaning
- 5 RF cable
- 6 Solenoid splice
- 7 **Conclusions and next steps**

- Thermal network;
- General analytical estimation of heat loads inside the cryomodule – updated version;
- FEM model – validated with the ECSS standards;
- Global thermal steady state analysis;
- Transient steady state analysis;
- Advanced analysis on some cases;

Next steps:

- Limits for cryogenic mass flow
- Alignment
- Current leads
- Instrumentation

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