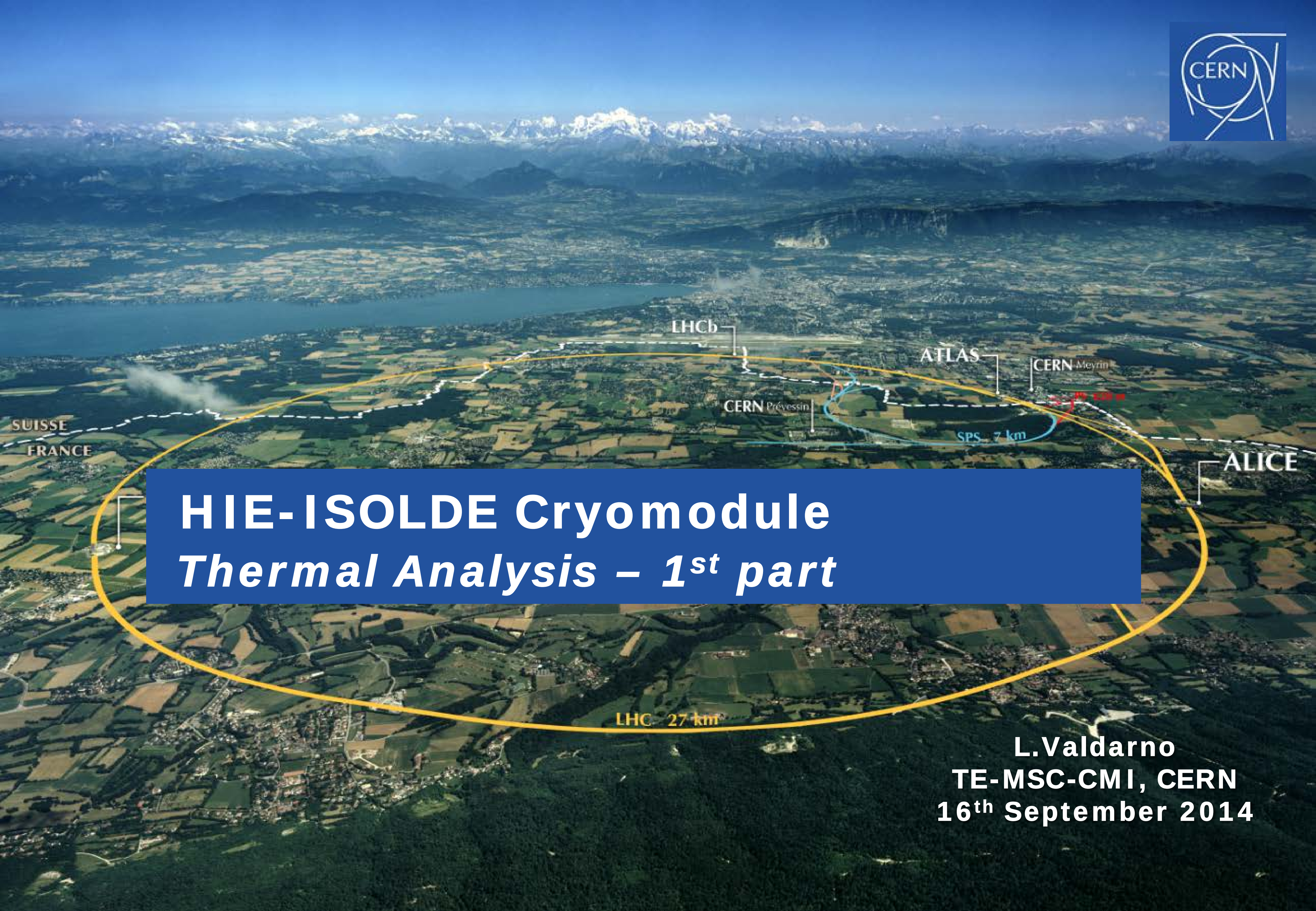


HIE-ISOLDE Cryomodule

Thermal Analysis – 1st part

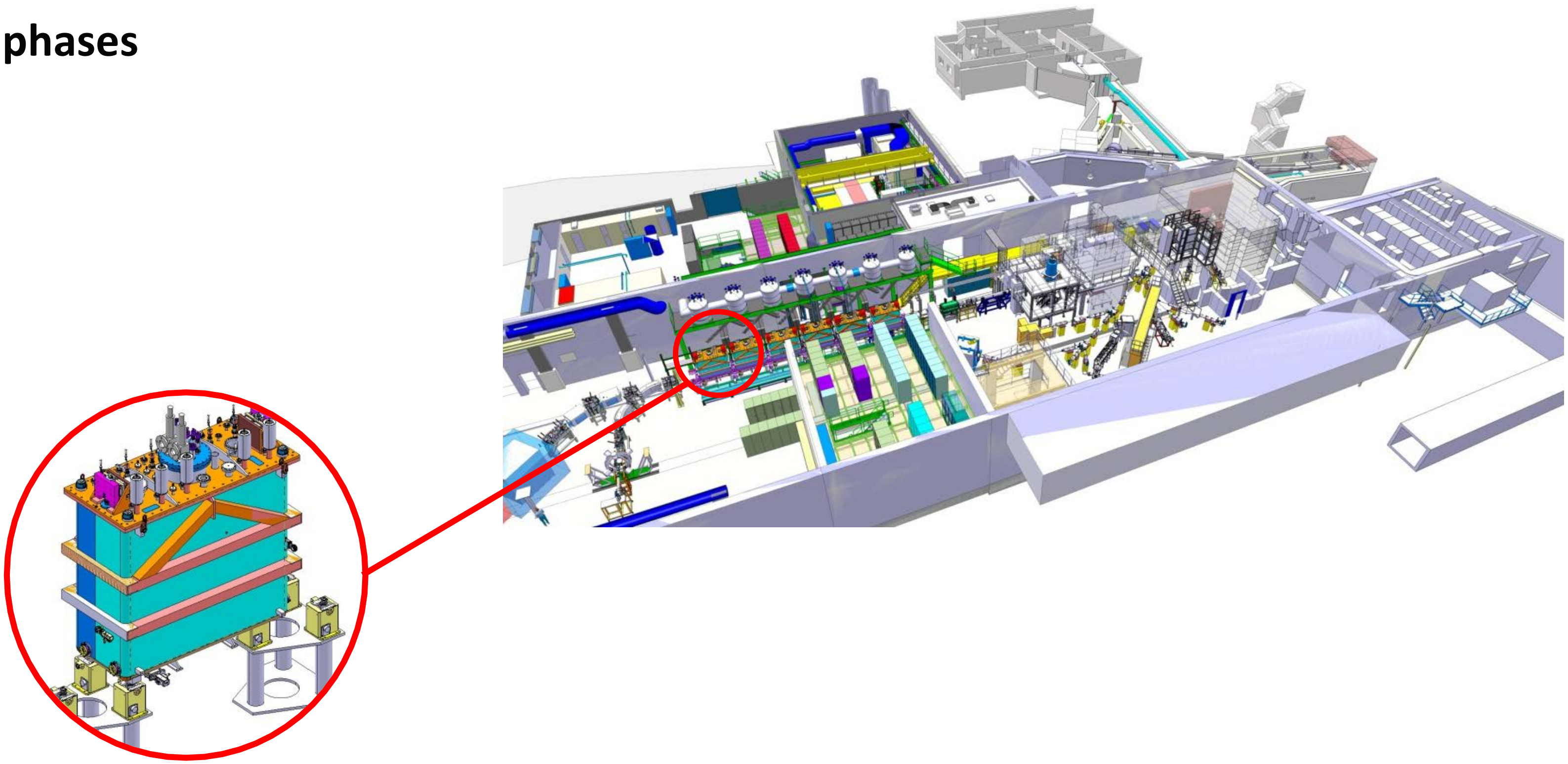
L.Valdarno
TE-MSC-CMI, CERN
16th September 2014

Agenda

1. Introduction
2. Objective
3. HIE-ISOLDE: FEM Model
4. HIE-ISOLDE: Model checks
5. Thermal steady-state analysis
6. Thermal transient analysis
7. Advanced thermal analysis
8. Conclusions and next steps

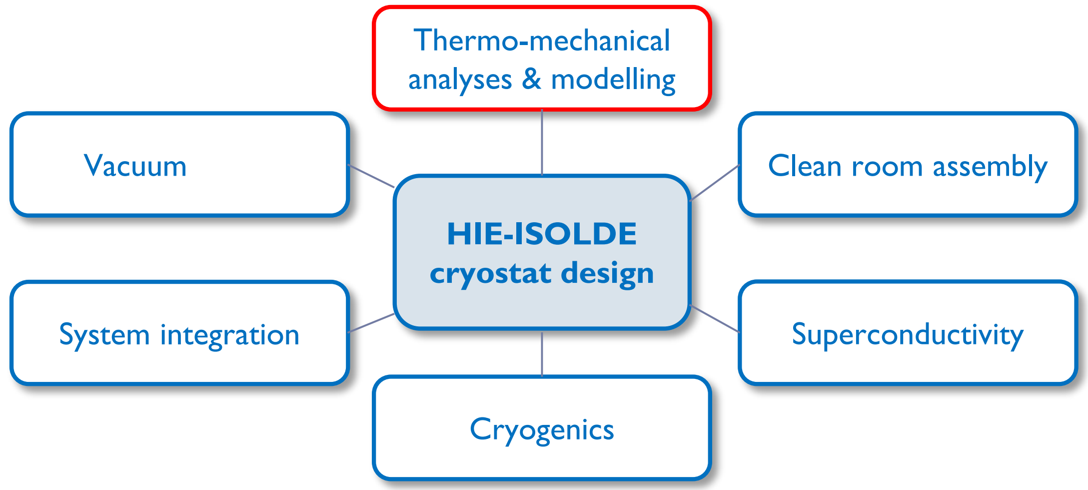
Introduction

- ❑ **High Intensity and Energy ISOLDE**
- ❑ **Current state**
- ❑ **Future phases**



Objective

- ❑ **Global temperature and heat flux mapping**
- ❑ **Design validation**
- ❑ **Advanced thermal analysis**



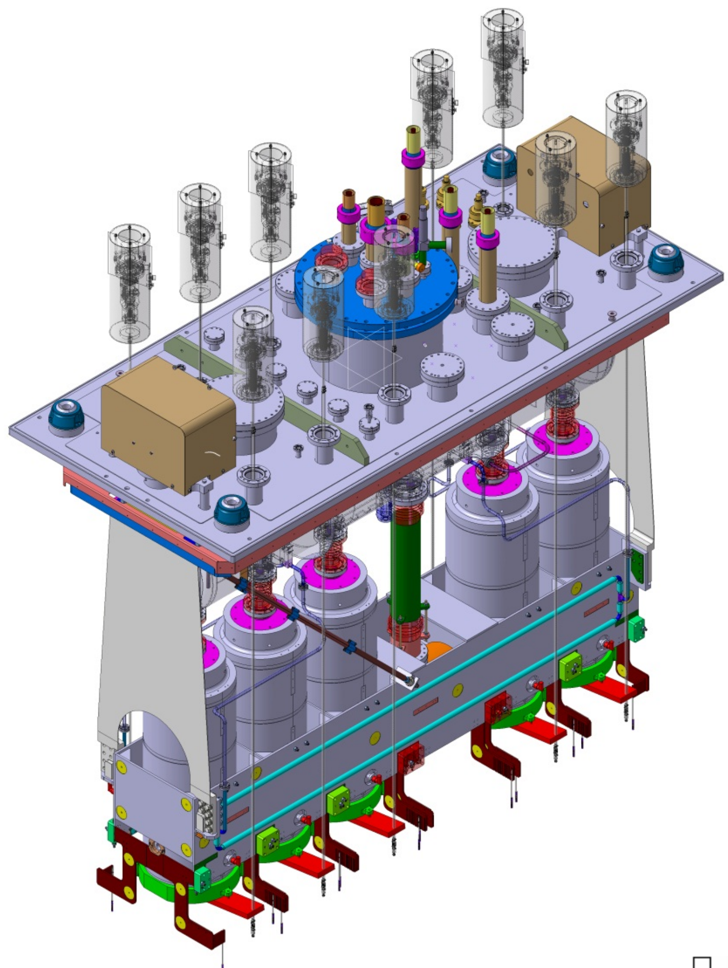
Targets:

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

Outline

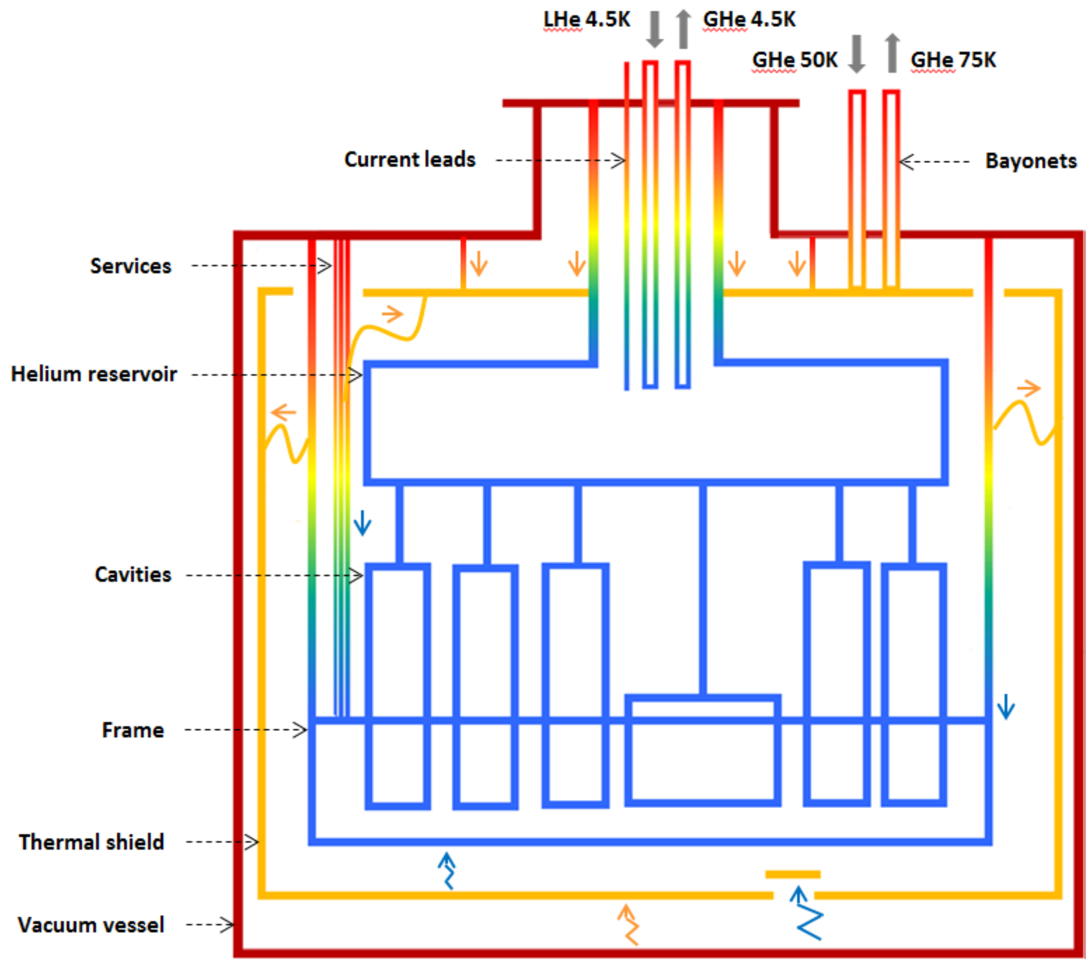
HIE-ISOLDE: Main components

- **Vacuum vessel**
  - Interfaces
- **Top plate**
  - Seal interface
- **Thermal shield**
  - Cryogenics circuit
- **Helium reservoir**
  - Cryogenics piping
  - Cryogenics supply
- **Supporting frame assembly**
  - Actively cooled frame
  - Suspension rods
  - Adjustment mechanisms
- **5 QWR cavities**
  - RF supply and pick-up
  - Tuner and coupler motors
- **1 solenoid**
  - Protection system
  - Current leads



HIE-ISOLDE: Procedure

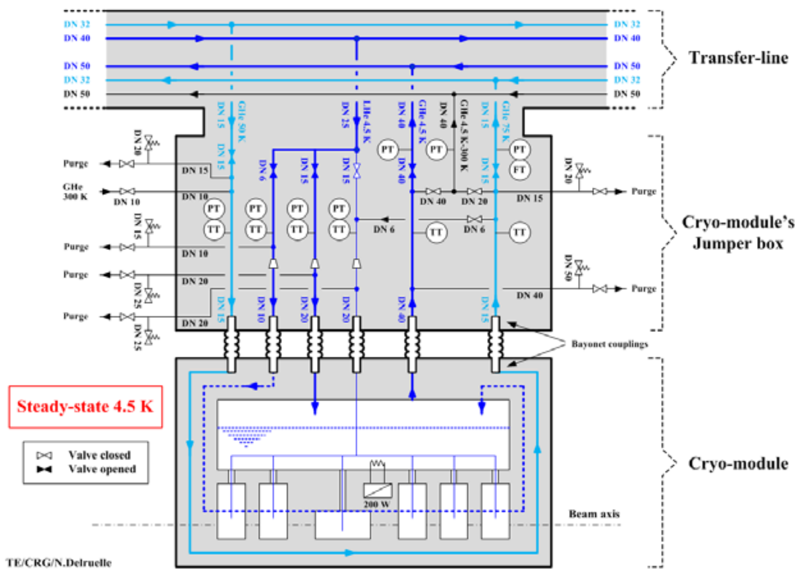
1. **Initial status**
   - 300K structures
2. **Thermal shield cool down**
   - 300K-75K
   - 13 bar
3. **Reservoir + frame cool down**
   - 300K-75K
   - 2.5 bar
4. **Reservoir + frame cool down**
   - 75K-4.5K
   - 2.5 bar
5. **Global cool down**
   - Thermal shield circuit : 13barG, 55-75K
   - Cold mass circuits: 1.3 barG, 4.5K

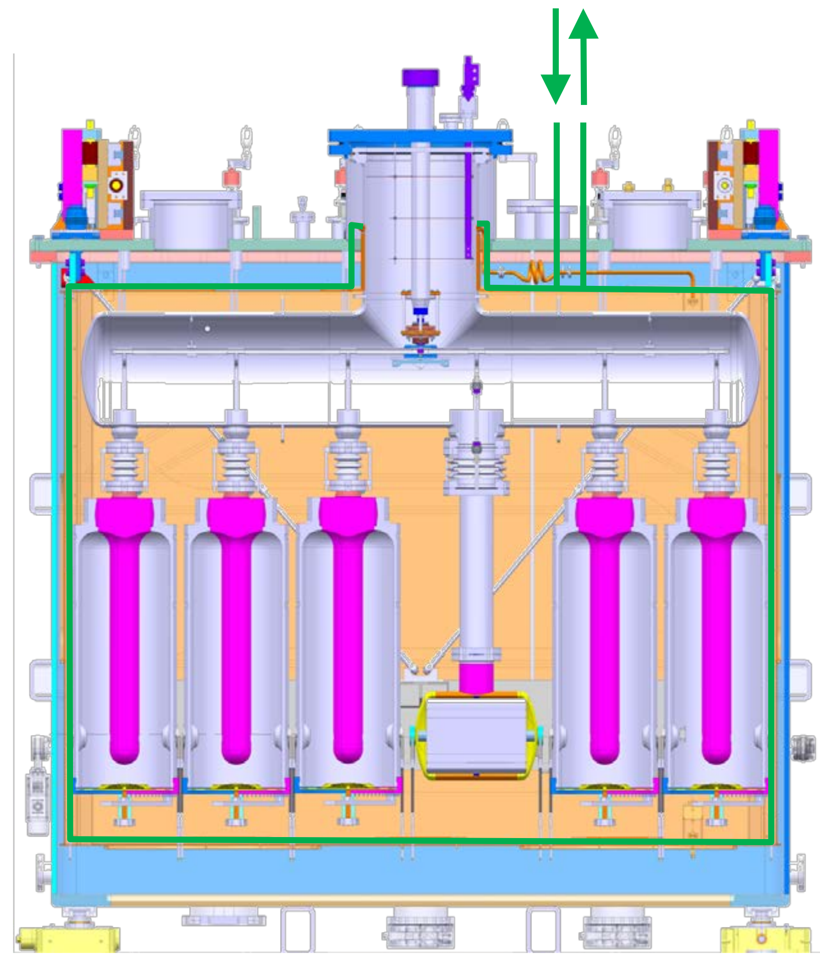


HIE-ISOLDE: 55K-70K GHe circuit

Characteristics:

- 55K-70K gaseous helium
- 13 bar nominal

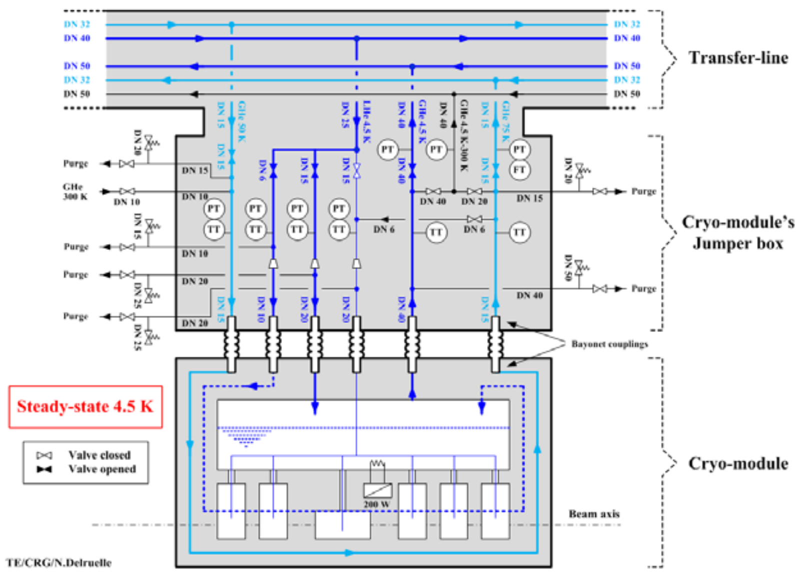


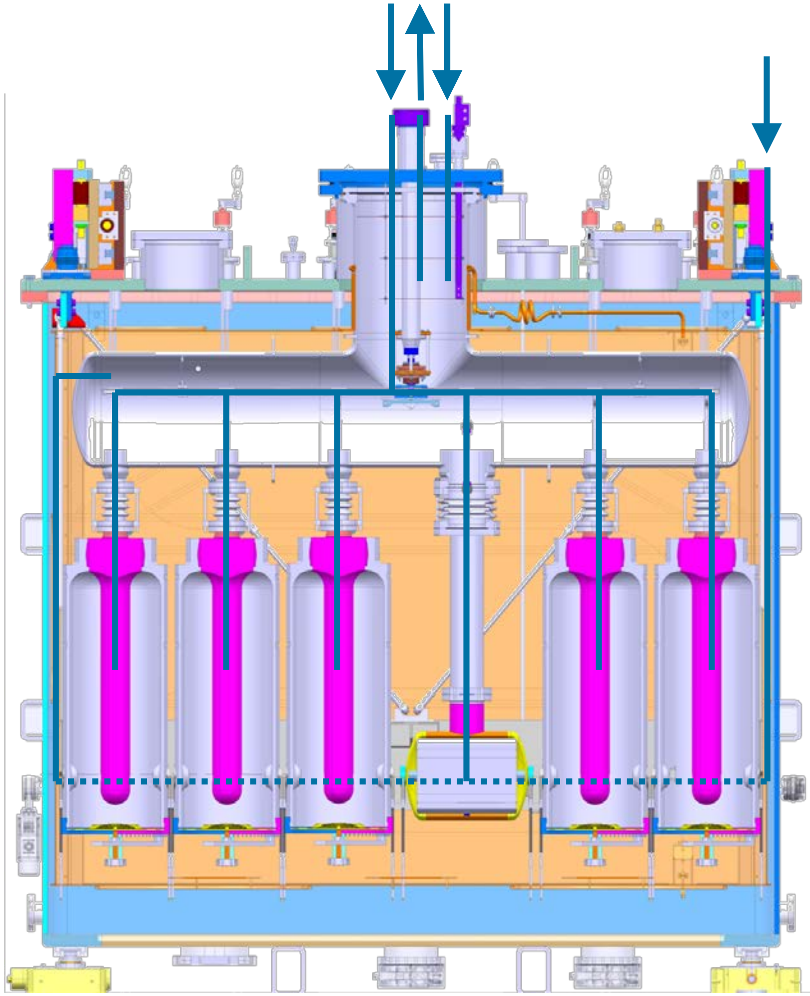


HIE-ISOLDE: 4.5K LHe-GHe circuit

Characteristics:

- 2.5 bar transient
- 1.3 bar nominal





Outline

Analytical heat loads estimation

- **conduction**

$$\dot{q} = -\frac{A}{L}\int_{Tcold}^{Twarm} k(T)dT$$

- **radiation**

$$q_{w-c} = \frac{\sigma\left(T_{warm}^4 - T_{cold}^4\right)}{\frac{1-\varepsilon_w}{\varepsilon_w A_w} + \frac{1}{A_w F} + \frac{1-\varepsilon_c}{\varepsilon_c A_c}}$$

- **convection**

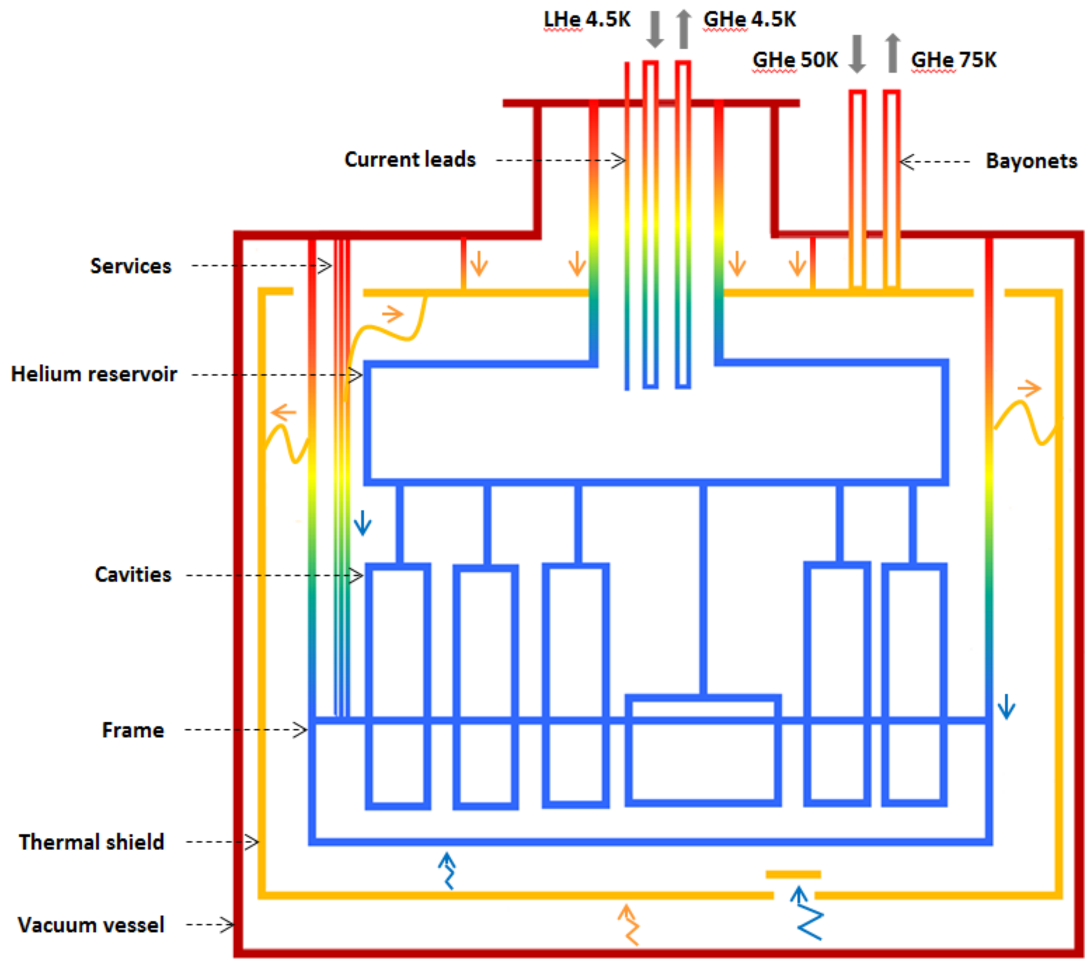
$$Q = hA_{tr}\Delta T$$

$$h = Nu.k/d$$

$$Nu = \alpha Re^{0.8} Pr^n$$

$$Re = \frac{4Q_m}{\pi d\mu}$$

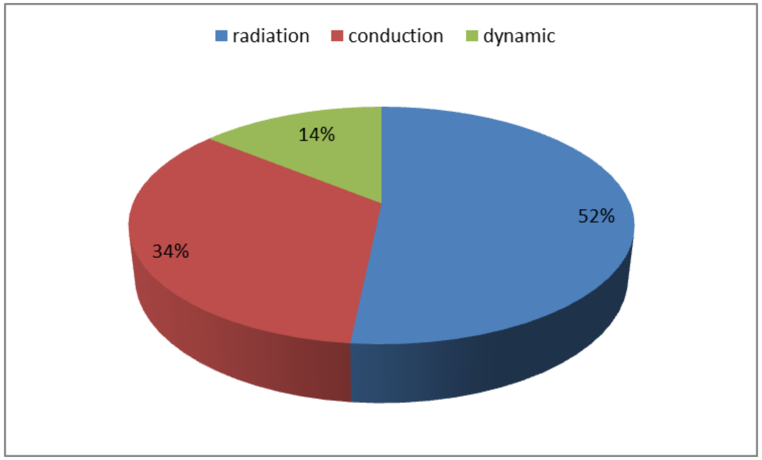
$$\Pr = \frac{Cp.\mu}{k}$$



HIE-ISOLDE: 55K-70K GHe circuit

Heat loads estimation of the 55K-70K GHe circuit

Heat	Source	Value [W]	With margin [W]
Radiation	Radiative heat exchange VV vs. TS	190	350
Conduction	Thermal shield supports	10	20
	Reservoir thermalization	58	58
	Tie-rods thermalization	9	9
	RF cables thermalization	15	25
	RF pick-up	15	15
	Tuner-coupler rods	4	4
	GHE Bayonets (CM side)	3	6
	Solenoid adjusting rods	1	1
	Instrumentation	7	10
Dynamic	RF cables thermalization	52	52
tot.		**364**	**550**

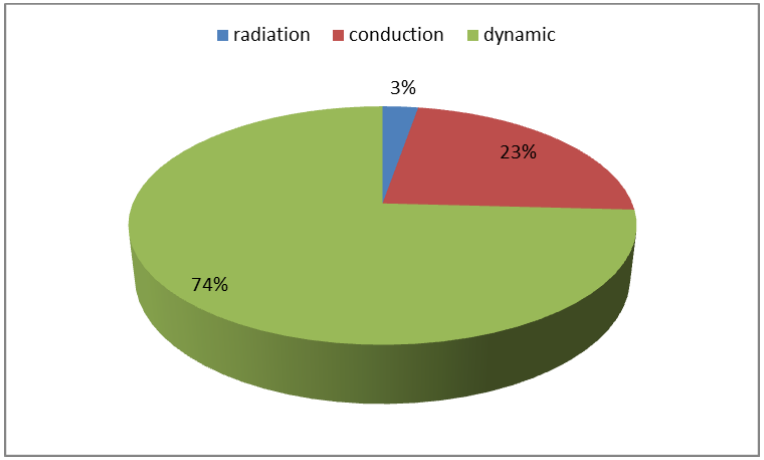


HIE-ISOLDE: 4.5K LHe-GHe circuit

Heat loads estimation of the 4.5K LHe-GHe circuit

Heat	Source	Value [W]	With margin [W]
Radiation	Radiative heat exchange TS vs. CM	0.57	0.81
	Beam port openings	0.83	0.83
	Viewports openings	0.2	0.3
	Gap around the TS lid	0.3	0.45
Conduction	Reservoir thermalization	6.1	6.1
	Tie-rods thermalization	0.2	0.2
	RF supply cables	1	2.5
	RF pick-up cables	1	2.5
	Tuner-coupler rods	0.1	0.1
	Bayonets (CM side)	6.1	12.2
	Solenoid adjusting rods	0.03	0.03
	Instrumentation low current	0.4	0.4
	Instrumentation heaters	1.3	1.3
Dynamic	Coupler	2	5
	Cavities	50	50
tot.		**70**	**82**

+ liquefaction load



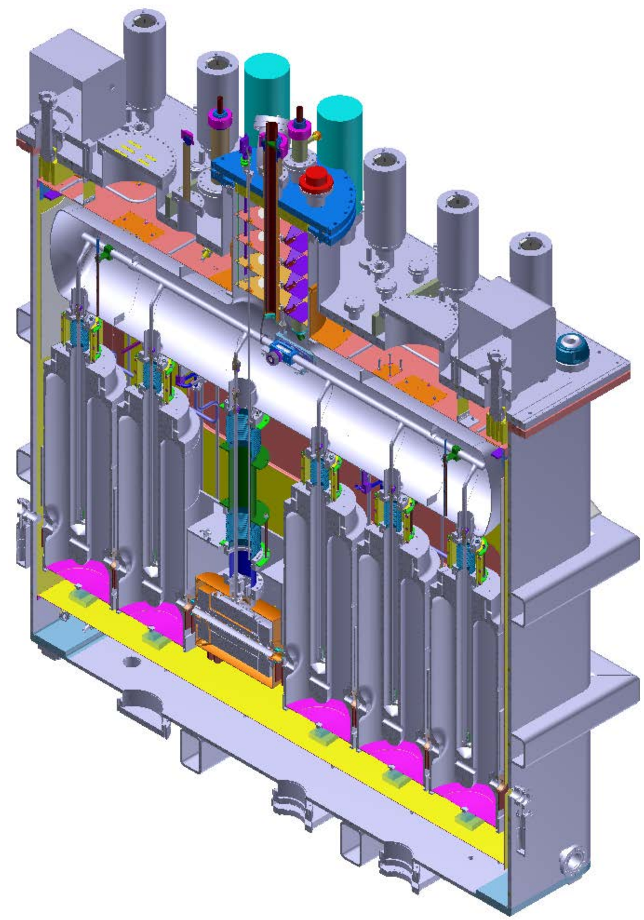
Outline

1. HIE-ISOLDE: cryomodule
2. Analytical heat loads estimation
3. **FEM model**
4. Model checks
5. Thermal steady-state analysis
6. Conclusions and next steps

FEM Model

- **Complexity of geometry**
  - Number of components
  - Connections

- **Complexity of thermal phenomena**
  - Wide temperature range (4.5K-300K)
  - Internal forced helium flow
  - Radiation

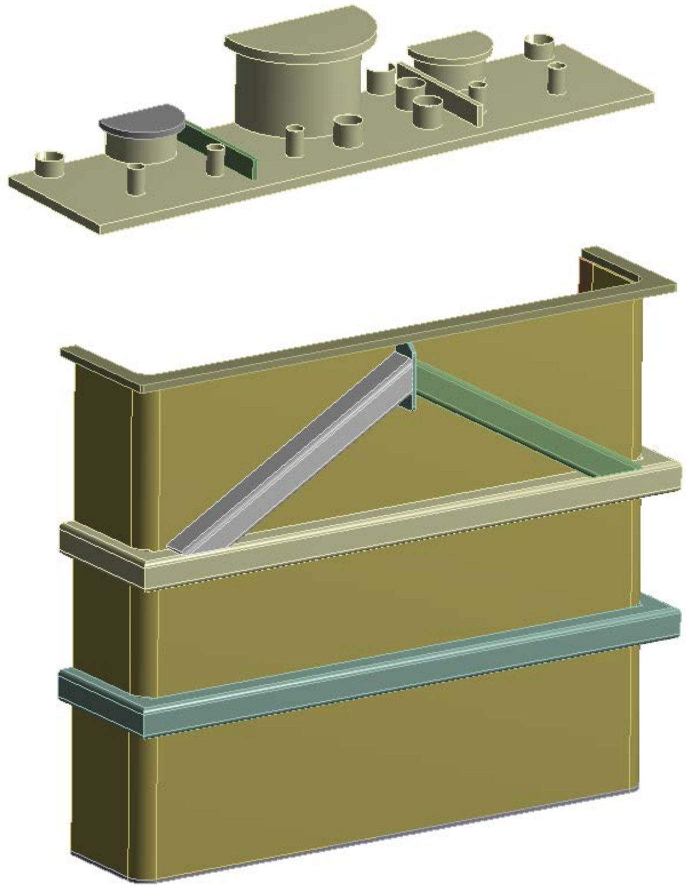


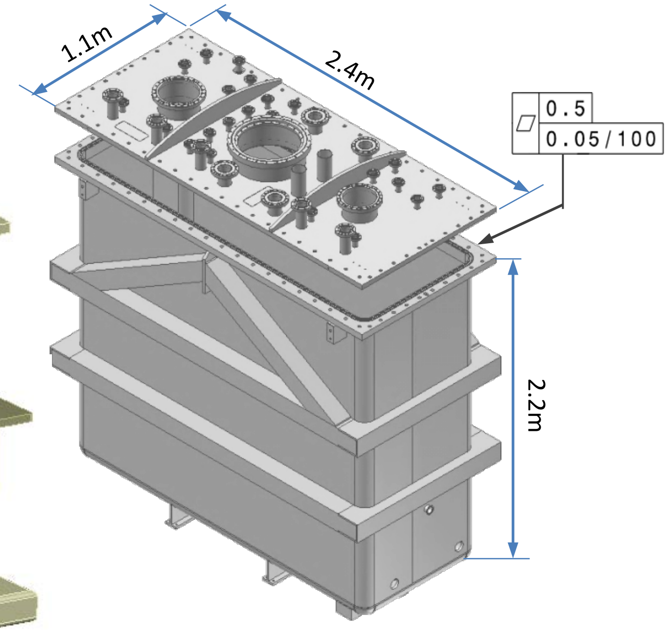
Targets of FEM analysis:

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

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

HIE-ISOLDE: Model

- ❑ **Vacuum vessel**
- ❑ **Top plate**
- ❑ **Thermal shield**
  - Cryogenics circuit
- ❑ **Supporting frame assembly**
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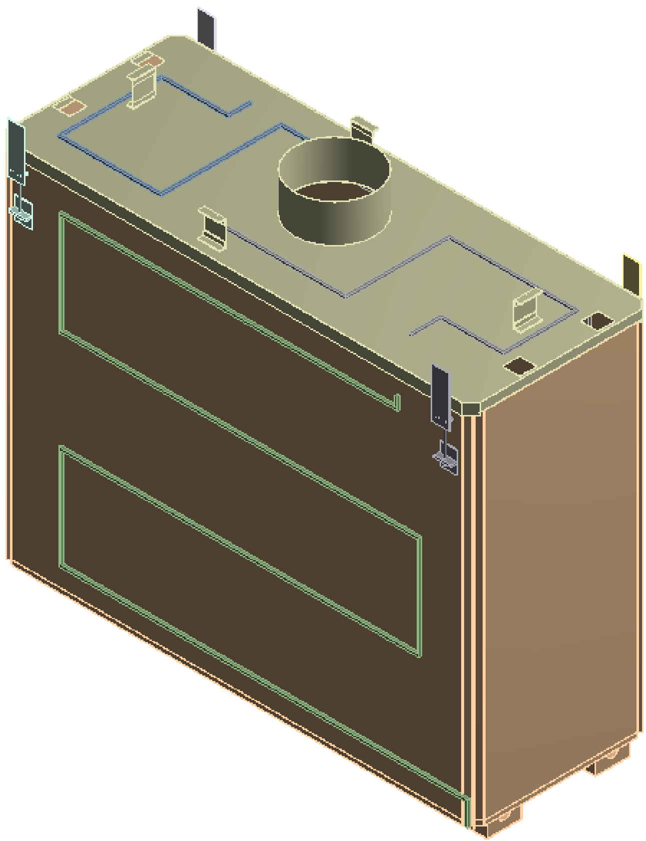
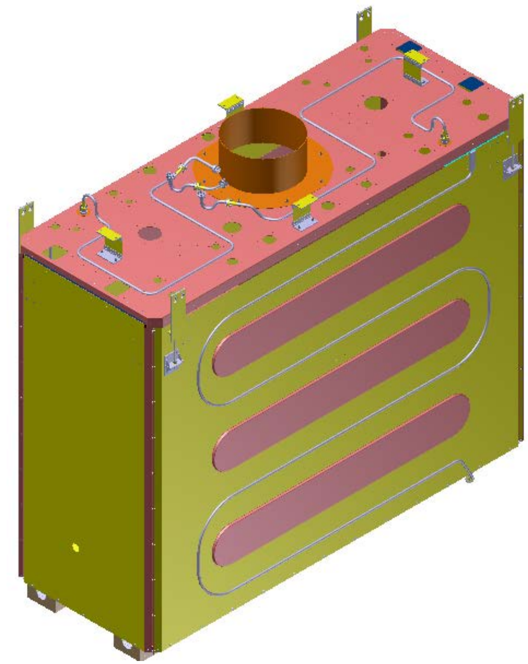




Thermal Shield :

-2.2m x 1.8m x 0.9m

-300 kg bolted assembly

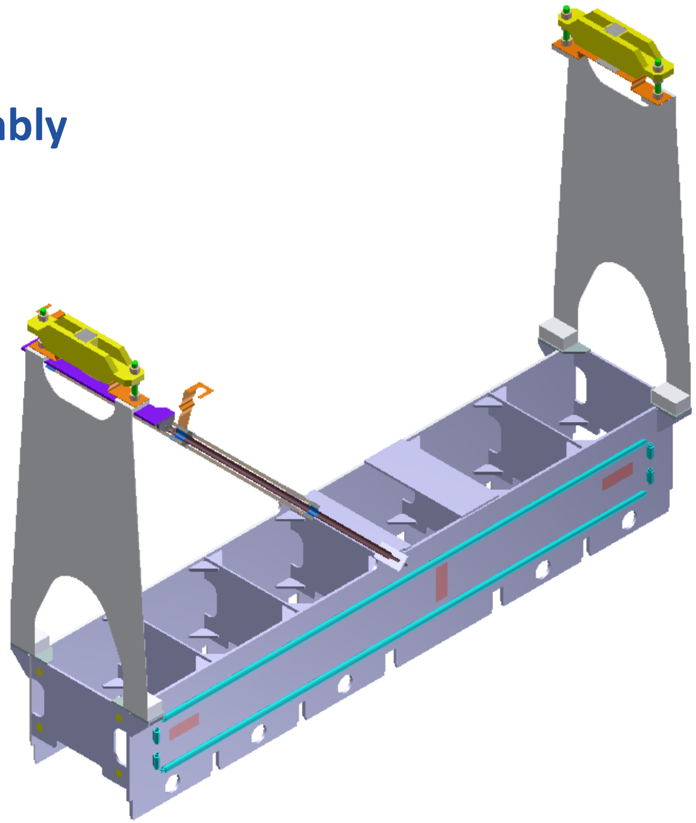
-2 mm thick Cu Ni-plated

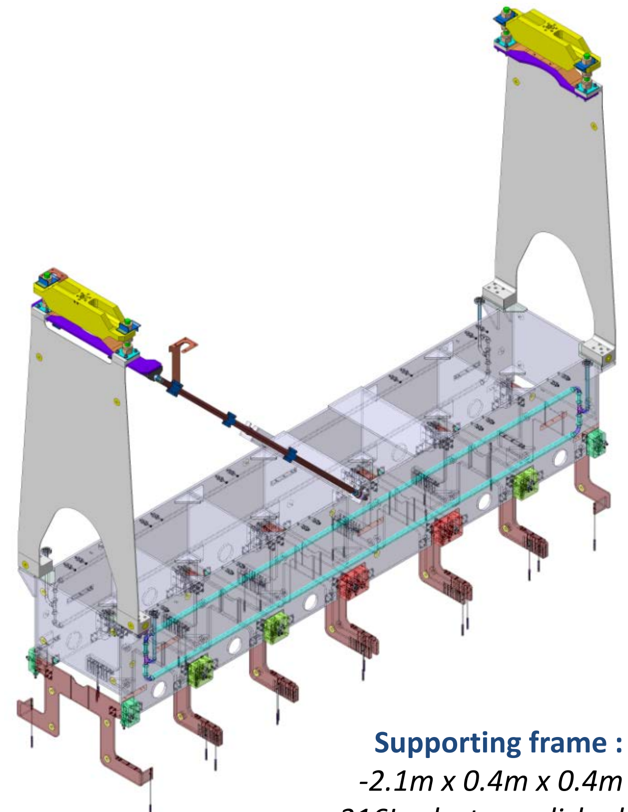
-Piping : GHe 70K, 13 bara

-No porosities after brazing

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





Supporting frame :

-2.1m x 0.4m x 0.4m

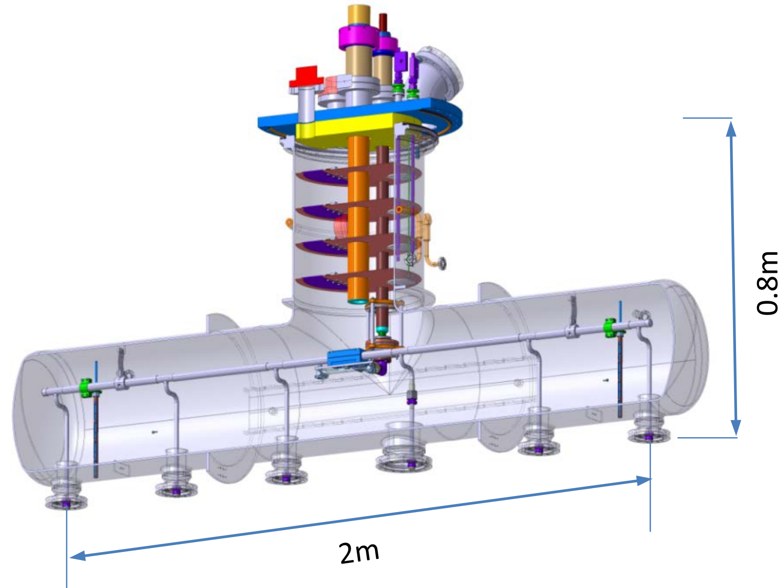
-316L, electro-polished

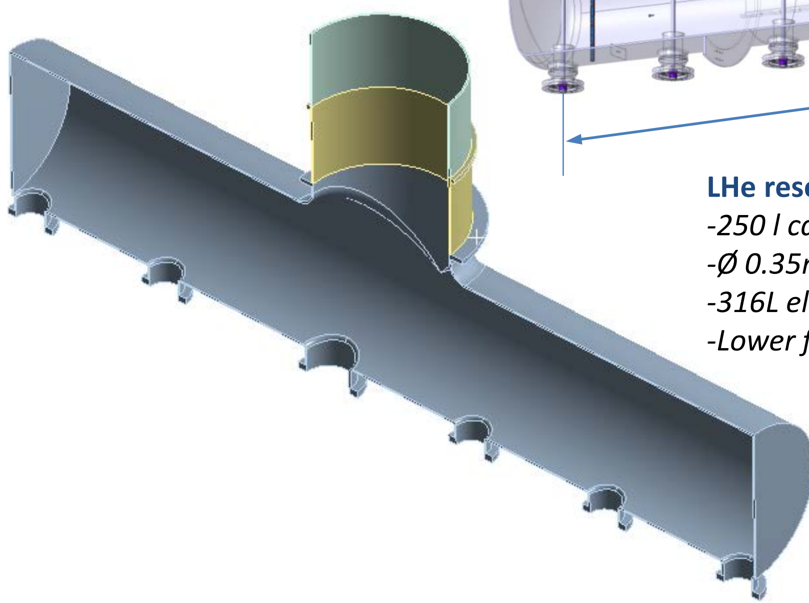
-130 kg welded assembly

-Piping : LHe 4.5K, 4.5 bara

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





LHe reservoir :

-250 l capacity

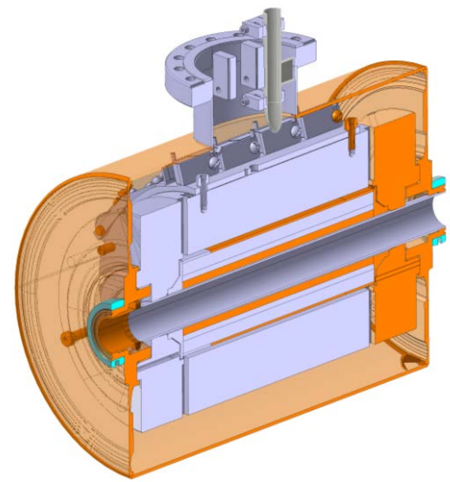
-Ø 0.35m, t=4mm

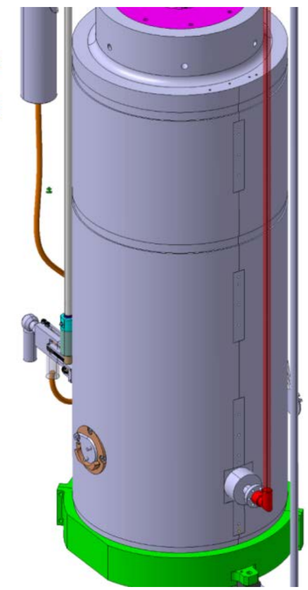
-316L electro-polished

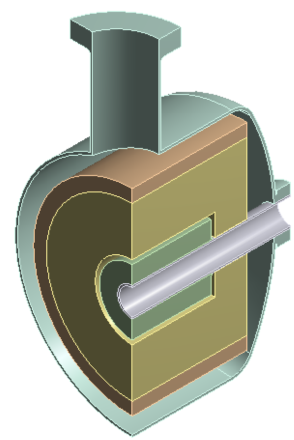
-Lower flanges location within 1 mm

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**







HIE-ISOLDE: Model

- Vacuum vessel
- Top plate
- Thermal shield
  - Cryogenics circuit
- Supporting frame assembly
  - Actively cooled frame
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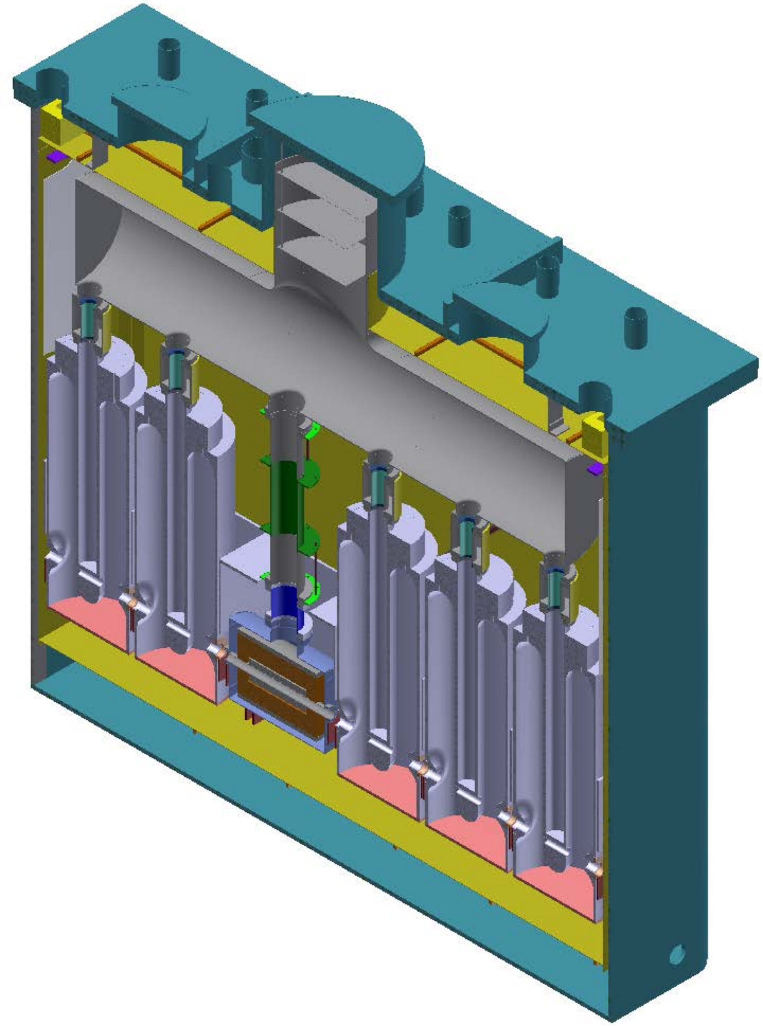
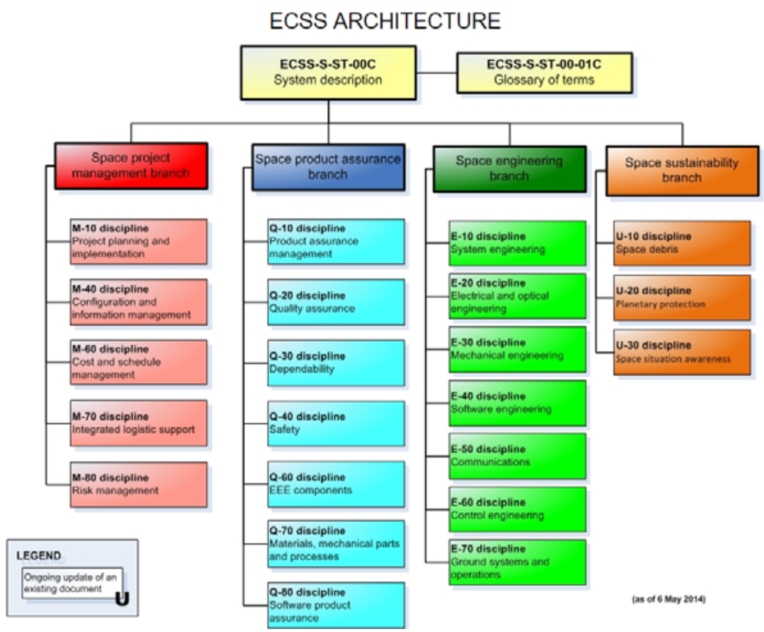


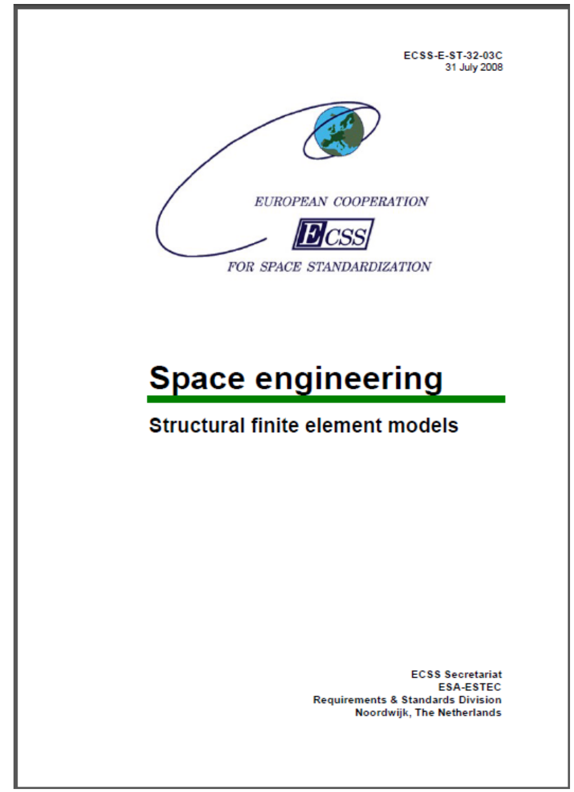
Outline

HIE-ISOLDE: Model checks

Finite Element Model (source ESA/ECSS standards):

- ❑ Geometry
- ❑ Mesh
- ❑ Loads
- ❑ Rigid body motion




ECSS-E-ST-32-03C
31 July 2008

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space engineering

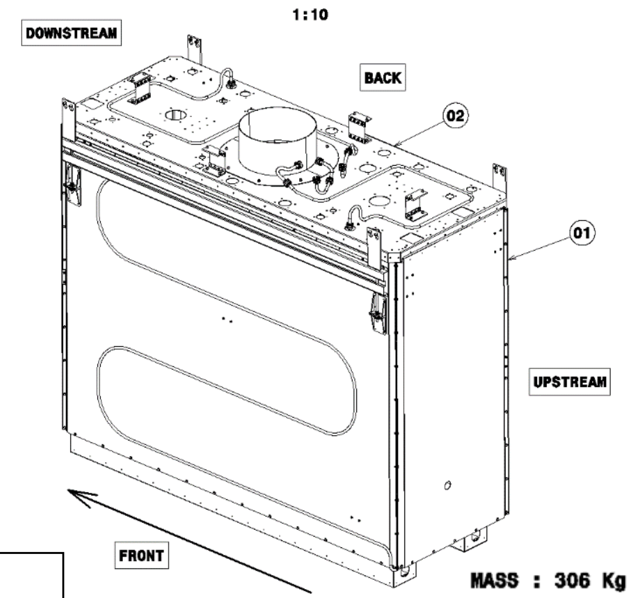
Structural finite element models

ECSS Secretariat
ESA-ESTEC
Requirements & Standards Division
Noordwijk, The Netherlands

HIE-ISOLDE: Model checks

Finite Element Model (source ESA/ECSS standards):

- ❑ **Model geometry**
  - ✓ Mass (components, total)
  - ✓ Centre of gravity (with common SoR)
  - ✓ Moments of inertia
  - ✓ Contacts (around n. 300)



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

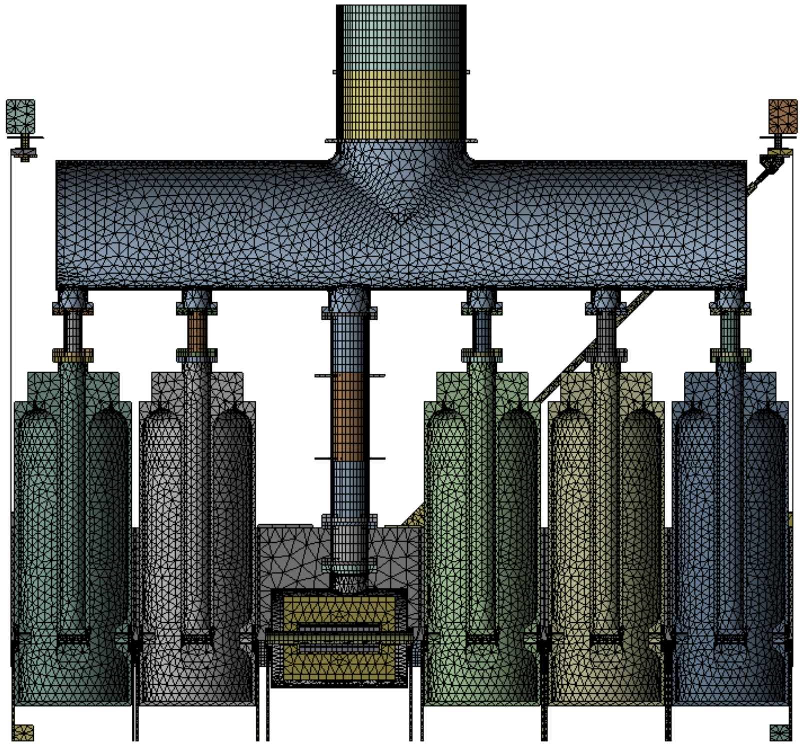
```
                    ***********  PRECISE MASS SUMMARY  ***********

TOTAL RIGID BODY MASS MATRIX ABOUT ORIGIN
             Translational mass                |  Coupled translational/rotational mass
     0.29976       0.0000        0.0000        |    0.0000        -300.12         13.345
     0.0000        0.29976       0.0000        |    300.12         0.0000         0.55811
     0.0000        0.0000        0.29976       |   -13.345        -0.55811        0.0000
  ---------------------------------------------|------------------------------------------
                                               |        Rotational mass (inertia)
                                               |   0.46185E+06    176.57          1278.1
                                               |    176.57        0.58399E+06    -12322.
                                               |    1278.1       -12322.          0.19057E+06

TOTAL MASS = 0.29976
  The mass principal axes coincide with the global Cartesian axes

CENTER OF MASS (X,Y,Z)=     1.8619       -44.520       -1001.2

TOTAL INERTIA ABOUT CENTER OF MASS
     0.16078E+06    151.72         719.29
      151.72       0.28351E+06    1039.4
      719.29        1039.4        0.18998E+06

PRINCIPAL INERTIAS =    0.16076E+06   0.28353E+06   0.18998E+06
ORIENTATION VECTORS OF THE INERTIA PRINCIPAL AXES IN GLOBAL CARTESIAN
  ( 1.000,-0.001,-0.025)  ( 0.001, 1.000, 0.011)  ( 0.025,-0.011, 1.000)
```

Bounding Box	
Length X	2188.4 mm
Length Y	886. mm
Length Z	1991. mm
Properties	
Volume	3.6088e+007 mm³
Mass	299.53 kg

HIE-ISOLDE: Model checks

Finite Element Model (source ESA/ECSS standards):

- **Element topology**
  - ✓ Aspect ratio: max. edge length /min edge length;
  - ✓ Jacobian ratio: measure of the deviation of a given element from an ideally shaped element;
  - ✓ Warping factor: warp angle is the out of plane angle;
  - ✓ Skewness: minimum angle between two lines joining opposite midsides of the element;
  - ✓ Convergence of mesh refinement;



Nodes: 283,005
Elements: 113,146

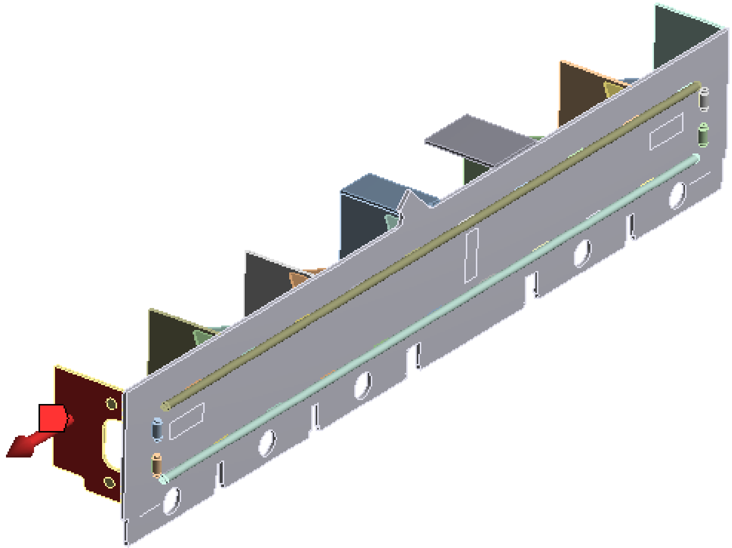
	min	max	average	st.dev.	ideal
Aspect ratio	1.03	25.97	1.45	0.6	1
Jacobian ratio	0.45	49.81	1.08	0.4	1
Warping factor	0	1.44E-14	3.43E-15	0	0
Skewness	3.91E-03	0.99	0.21	0.1	0

HIE-ISOLDE: Model checks

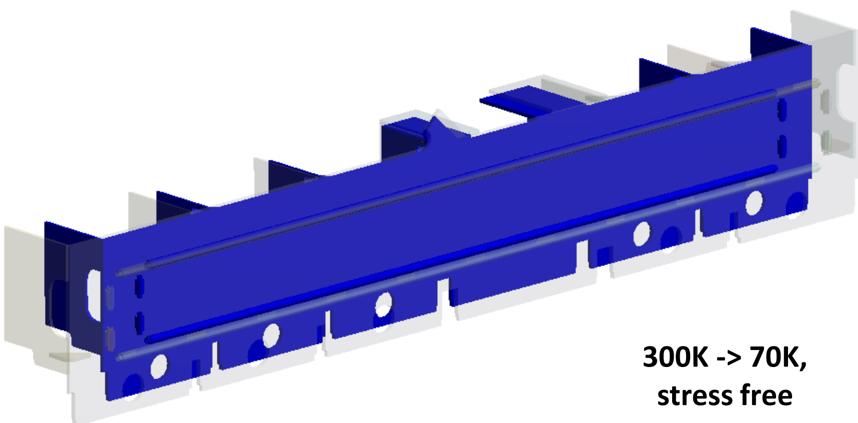
Finite Element Model (source ESA/ECSS standards)

- **Static analysis**
  - ✓ Unit load check
  - ✓ Load resultants
  - ✓ Residual load vector
  - ✓ No internal mechanism

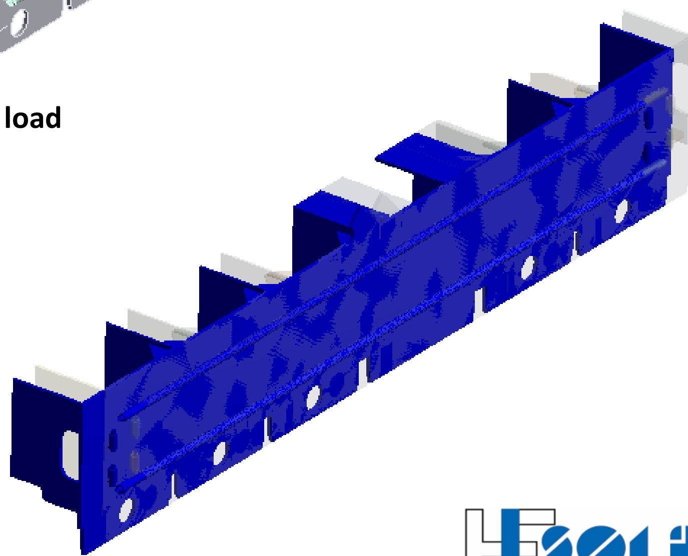
- **Stress free thermo-elastic deformation**
  - ✓ Uniform temperature decrease



1N force load



300K -> 70K, stress free structure



HIE-ISOLDE: Model checks

Finite Element Model (source ESA/ECSS standards):

- ❑ **Static analysis**
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  - ✓ Load resultants
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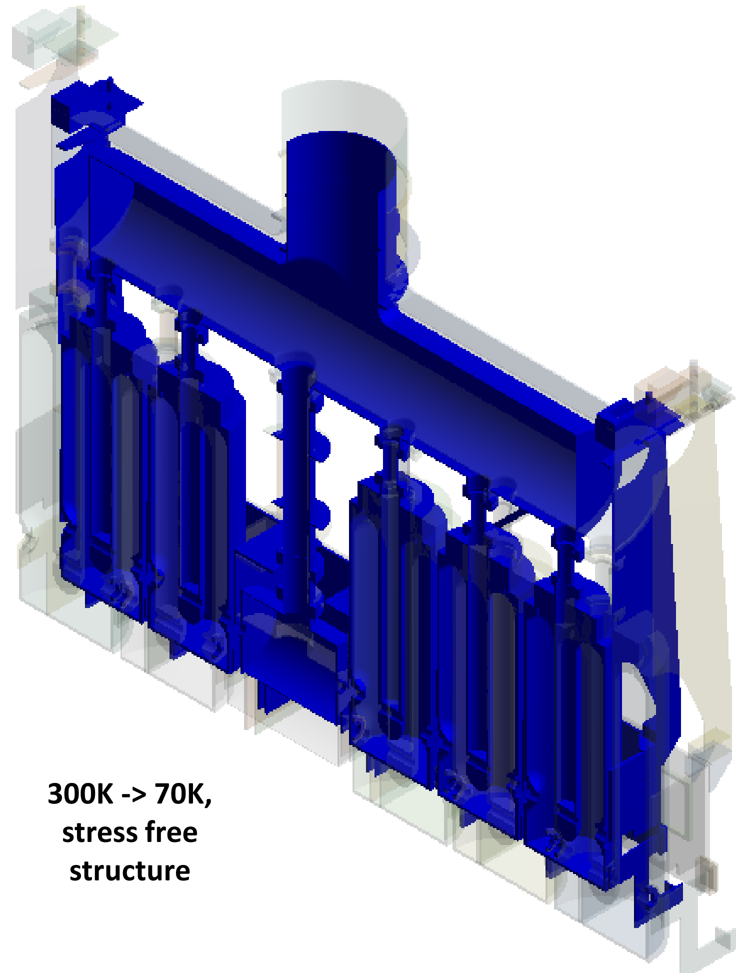
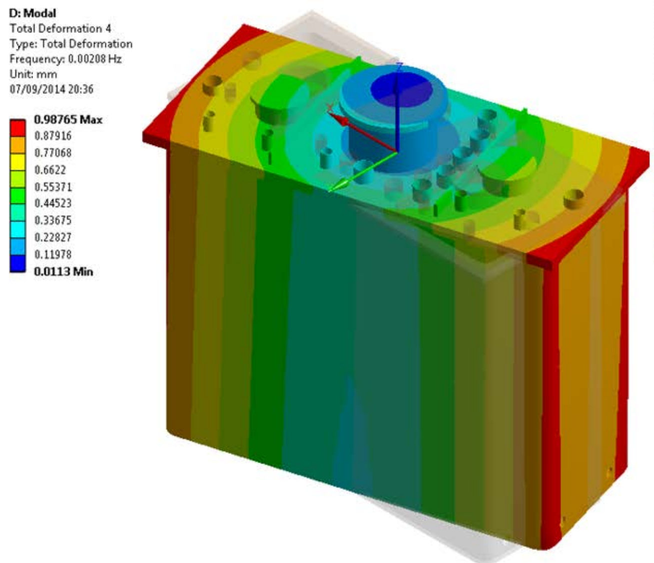
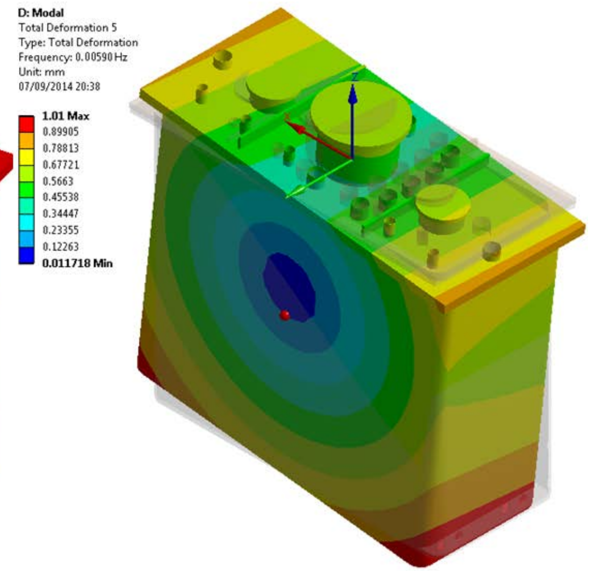


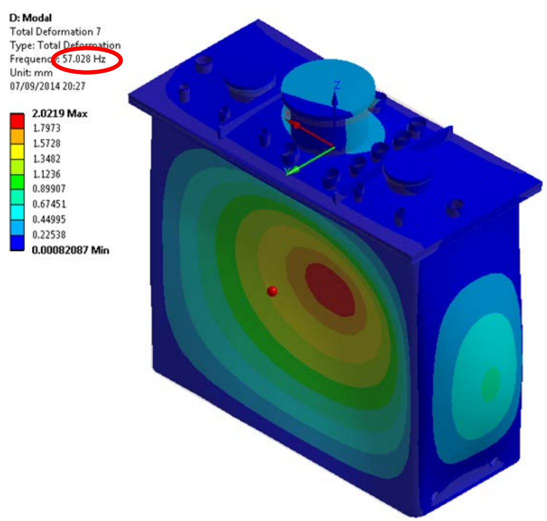
300K -> 70K, stress free structure

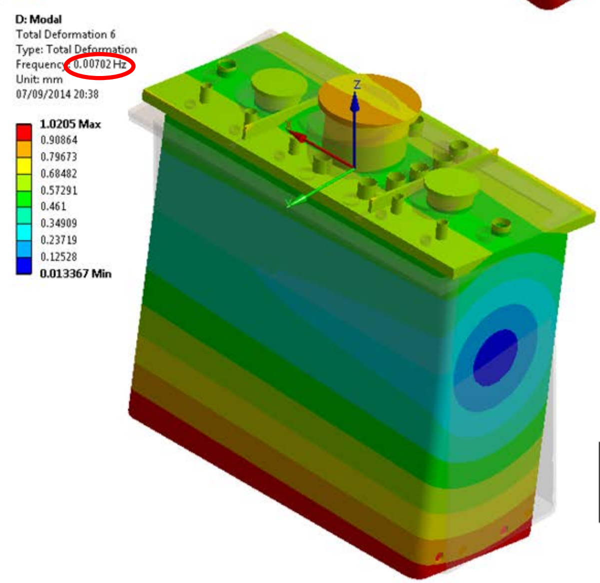
HIE-ISOLDE: Model checks

- **Modal analysis**
  - ✓ Six rigid body motions ≈ 0.005 Hz
  - ✓ Highest rigid body freq./lowest elastic mode freq. ratio < 10e-4







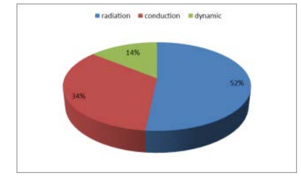


Outline

1. HIE-ISOLDE: cryomodule
2. Analytical heat loads estimation
3. FEM model
4. Model checks
5. **Thermal steady-state analysis**
6. Conclusions and next steps

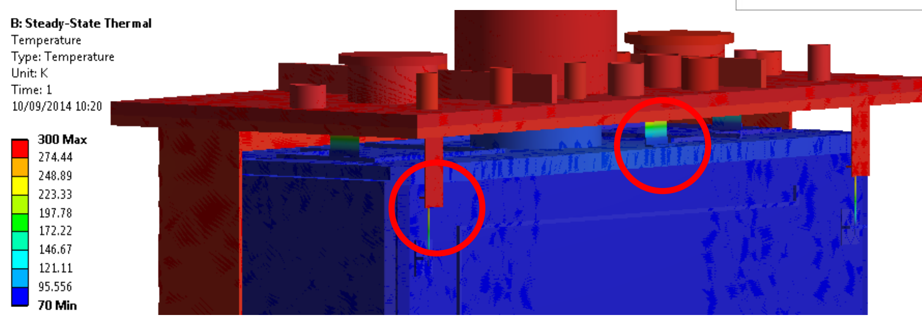
Thermal steady-state analysis (1/2)

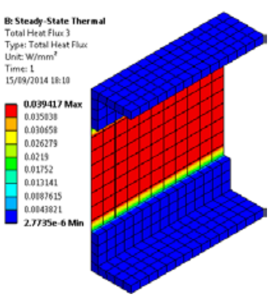
- OB: Radiative heat transfer between the Vacuum Vessel and the Thermal Shield

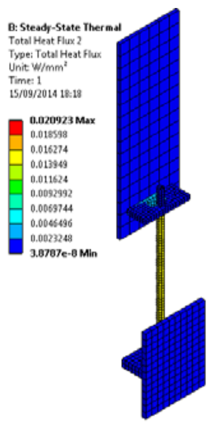


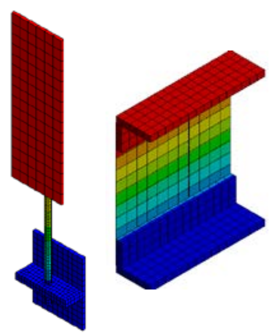
- Emissivity
  - Vacuum vessel: 0.2
  - Thermal shield: [0.033,0.066]

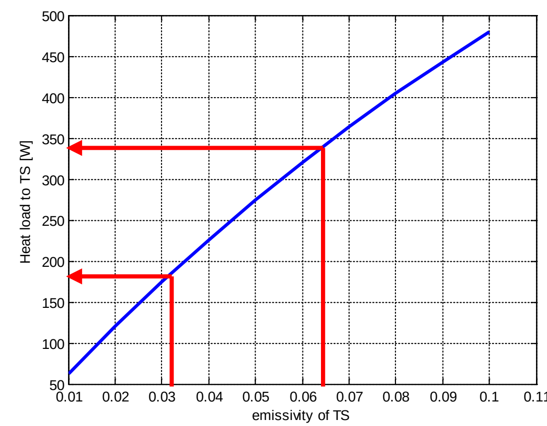
$$\dot{q}_{1\to 2} = \dot{q}_1 = -\dot{q}_2 = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1-\varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1 F_{12}} + \frac{1-\varepsilon_2}{\varepsilon_2 A_2}}$$





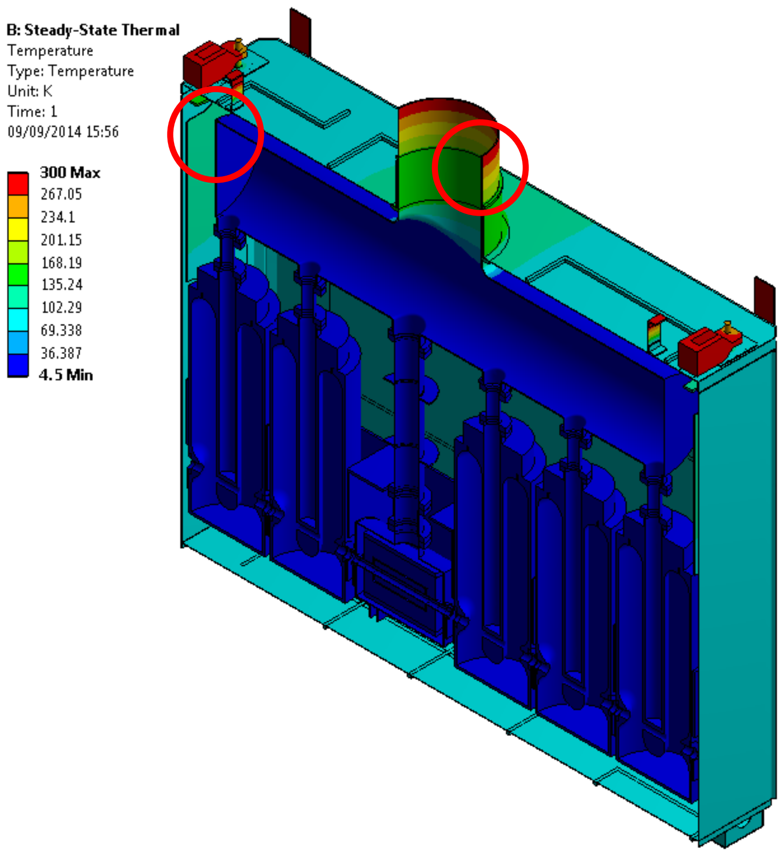


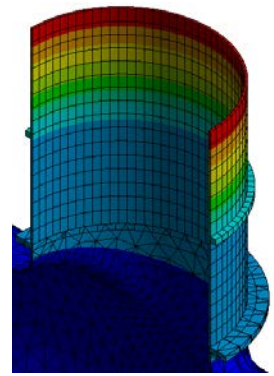


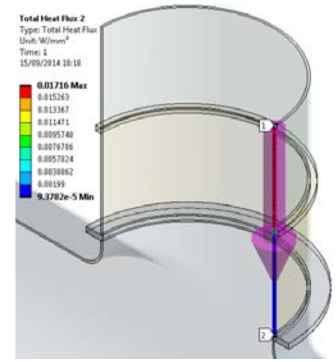


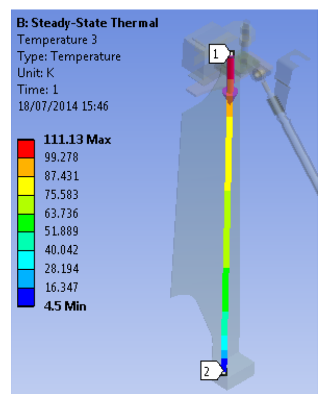
Thermal steady-state analysis (2/2)

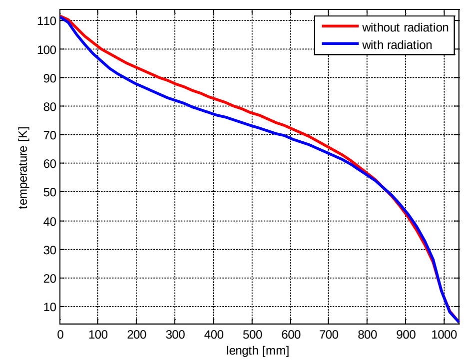
- OB: Temperature mapping inside the CM







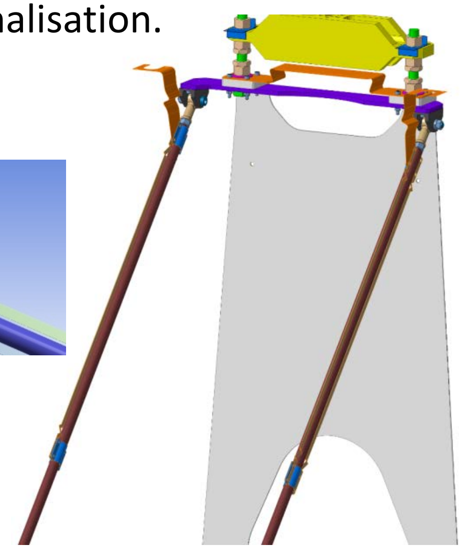




Thermalisation (1 / 2)

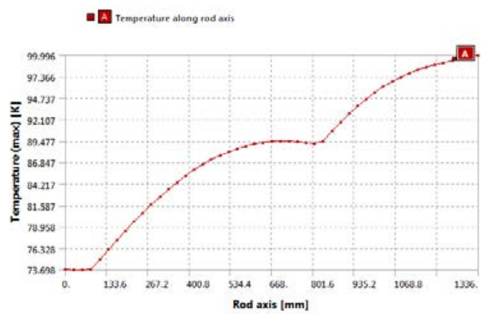
OB: determine the efficiency of the two copper stripes on cooling down of the oblique rod supporting the frame. The results are compared to an alternative option with just a single thermalisation.

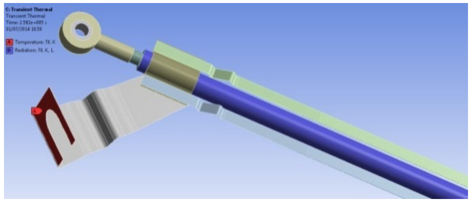
- ❑ Hp1: Isotropic coefficient of thermal expansion function of temperature

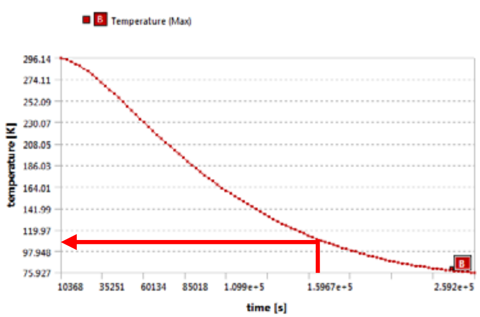


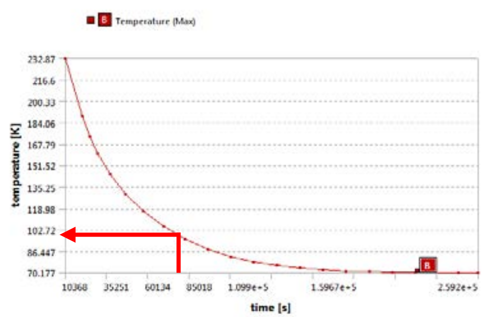
Only conduction

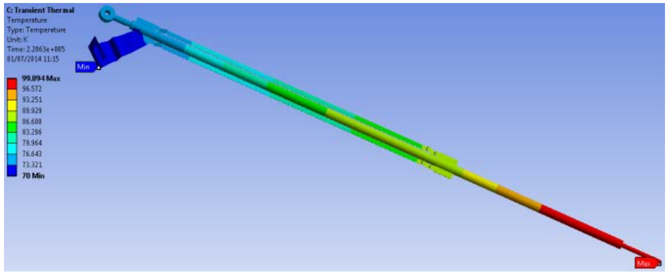
With radiation







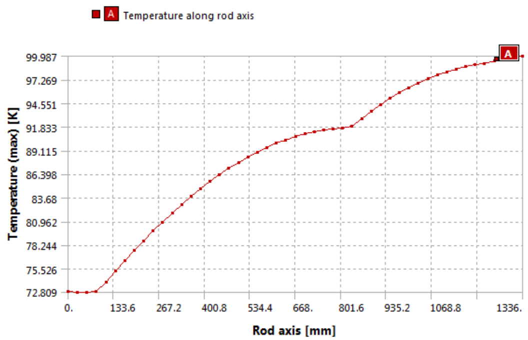


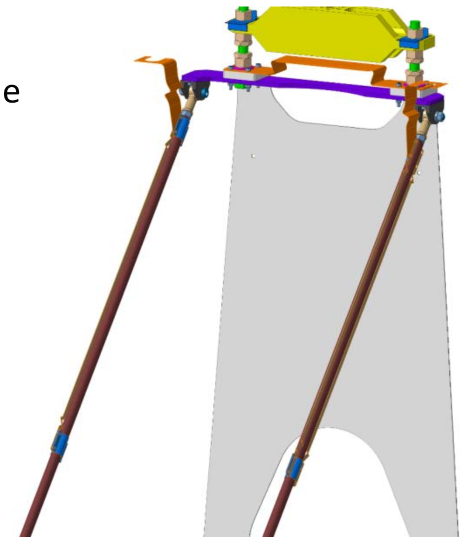


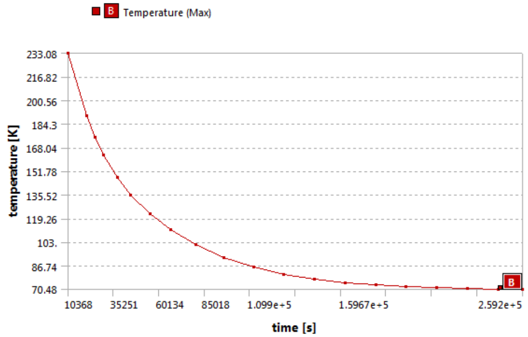
Thermalisation (2/2)

- Single thermalisation has an important effect only in case of pure conduction heat transfer increasing the time to reach T(max)<100K from 50 to 65 hours;
- In the conduction + radiation model (realistic case) this effect is less important due to the influence of the radiation;

With radiation







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

Outline

Conclusions

- ❑ 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;

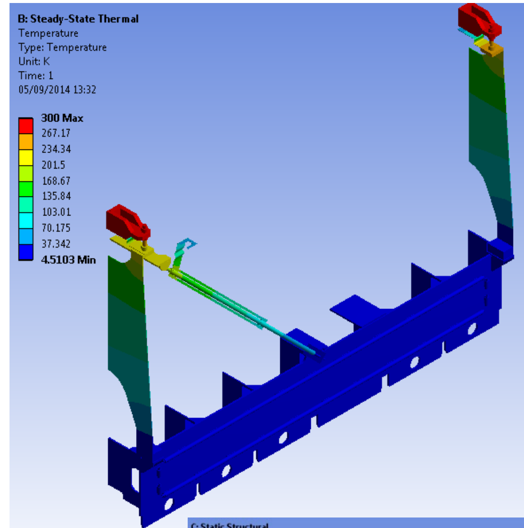
Next:

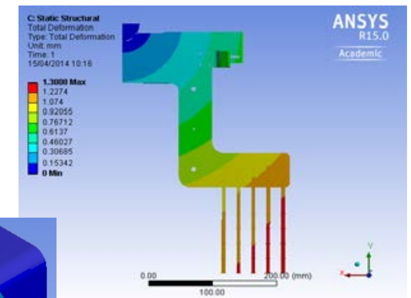
- ❑ Global radiation analysis – need for emissivity values in cryogenic conditions;
- ❑ Increase complexity of geometry;

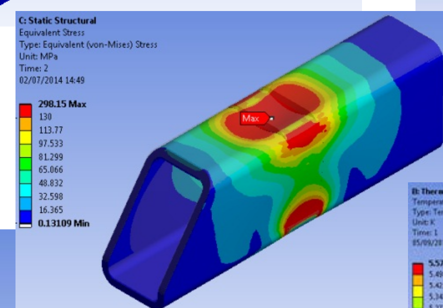
… in the next episode

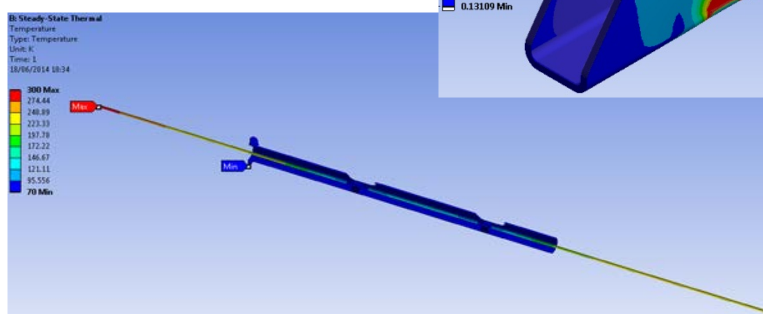
1. **Thermal transient analysis**

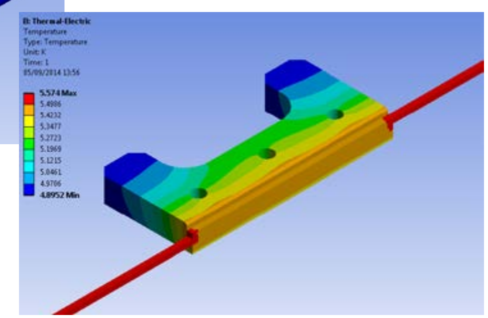
2. **Advanced thermal analysis:**
   - Frame support and cryogenic circuit;
   - Omega plates ;
   - Vacuum Vessel cleaning;
   - RF cable;
   - Solenoid splices.











References

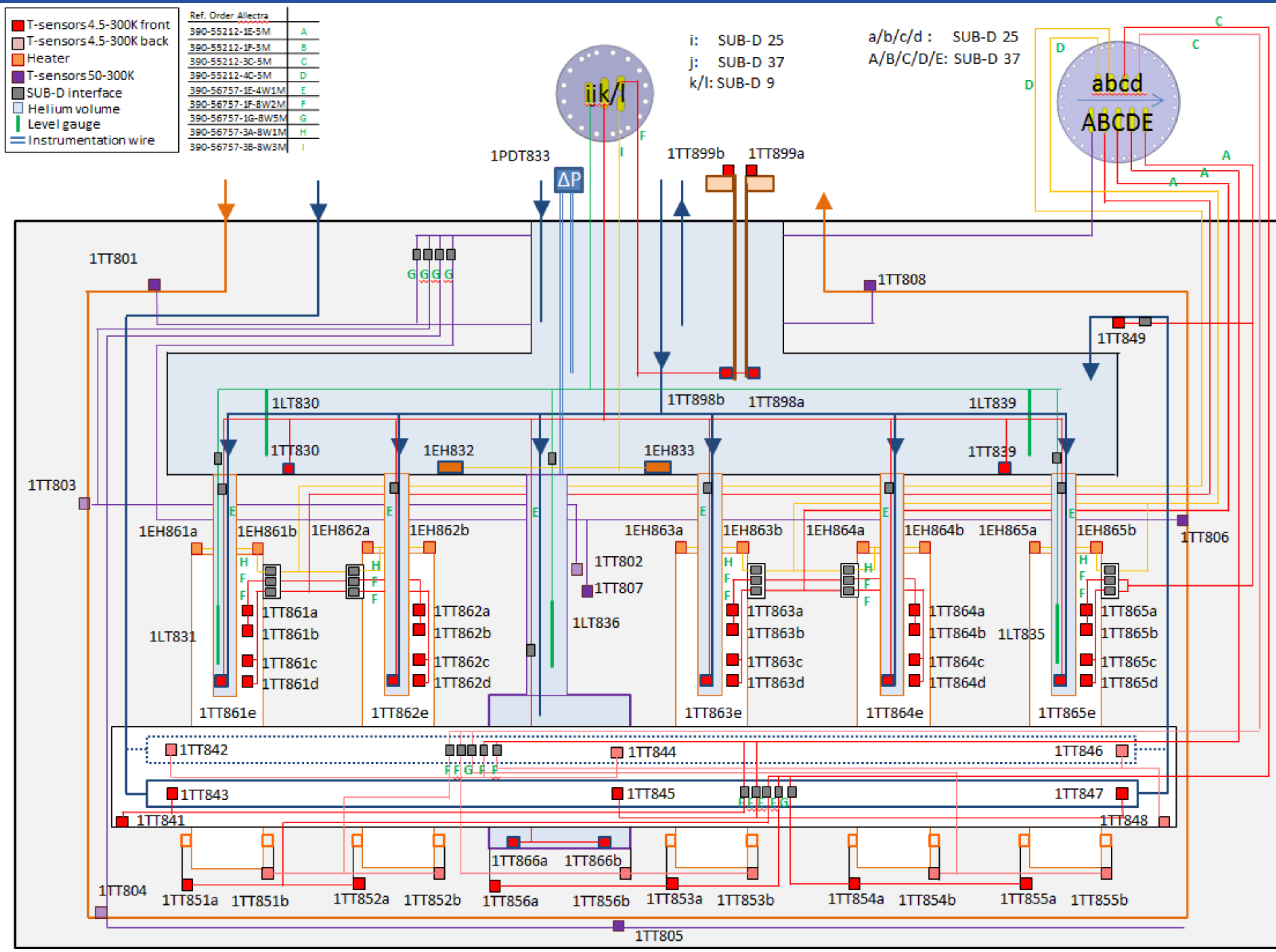
[1] Y. Leclercq, “Heat load estimation for the HIE-ISOLDE cryomodule,” CERN, 2013-03-12.

[2] N. Delruelle and Y. Leclercq, “Cryogenic procedures, layout and operation of the HIE-ISOLDE cryomodule,” CERN, 2013-07-01.

[3] D. Ramos, “Radiation heat exchange in the HIE-ISOLDE cryomodule,” CERN, 2013-08-01.

[4] L. Williams, “Cryostat for HIE-ISOLDE high energy cryomodule,” CERN, 2010-06-17.

Instrumentation



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390-55212-1F-3M	B
390-55212-3C-5M	C
390-55212-4C-5M	D
390-56757-1E-4W1M	E
390-56757-1F-8W2M	F
390-56757-1G-8W5M	G
390-56757-3A-8W1M	H
390-56757-3B-8W3M	I