Dipartimento
di Ingegneria Astronautica
Elettrica ed Energetica

Sapienza
Università di Roma

Thermal Field in a NMR Cryostat

Annunziata D'Orazio
Agostini Chiara
Simone Fiacco

COMSOL
CONFERENCE
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Overall Objective of Research Program

The main objective of the present work was to study the thermal field inside the cryostat:

1) developing three different models of cryostat with particular reference to the type of closures placed at the ends.

2) considering insulation and boundary conditions able to simulate the effect of a "cold head" placed in contact with a very limited portion of the cryo-shields.

3) considering tie - rods mounted in real cryostat to maintain the empty cavity and to center the magnetic field.

OUTLINE

- **Introduction**
- **Modelling Using Comsol Multiphysics**
- **Results**
- **Conclusions**

NMR Superconducting Magnet

- Advantages
  - Homogeneous, stable and high static field
  - Possibility to disable the power to the magnet
  - Excellent diagnostic image

- Disadvantages
  - Expensive
  - High residual external field (require shielding)
  - Maintaining cryogenic temperatures
  - Quench risk

Structure of cryostat

- Concentric structure coaxial with the superconducting windings to avoid helium evaporation

- Composed by:
  - Magnet immersed in liquid helium at 4 K
  - Radiative shields
  - Cold head

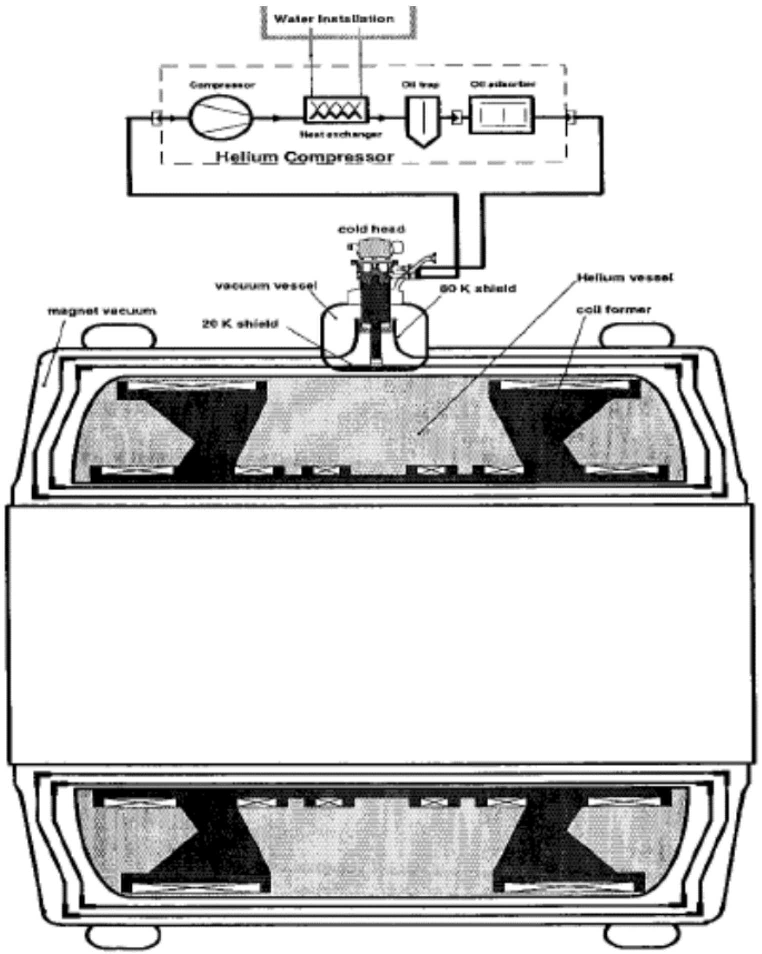


Figure 1: Cryostat's scheme with cryo-shields and cold head

Real Cryostat

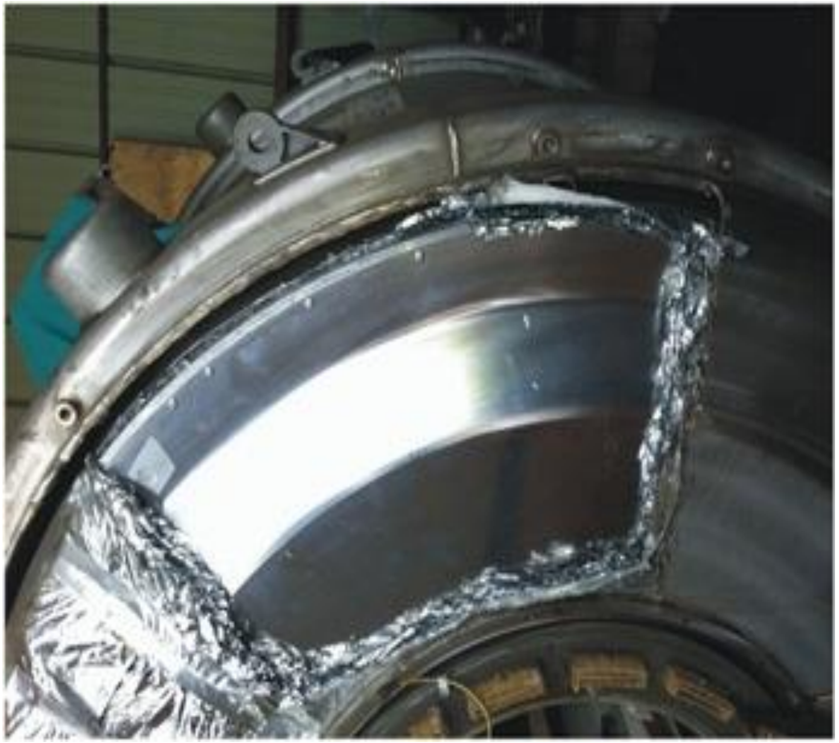


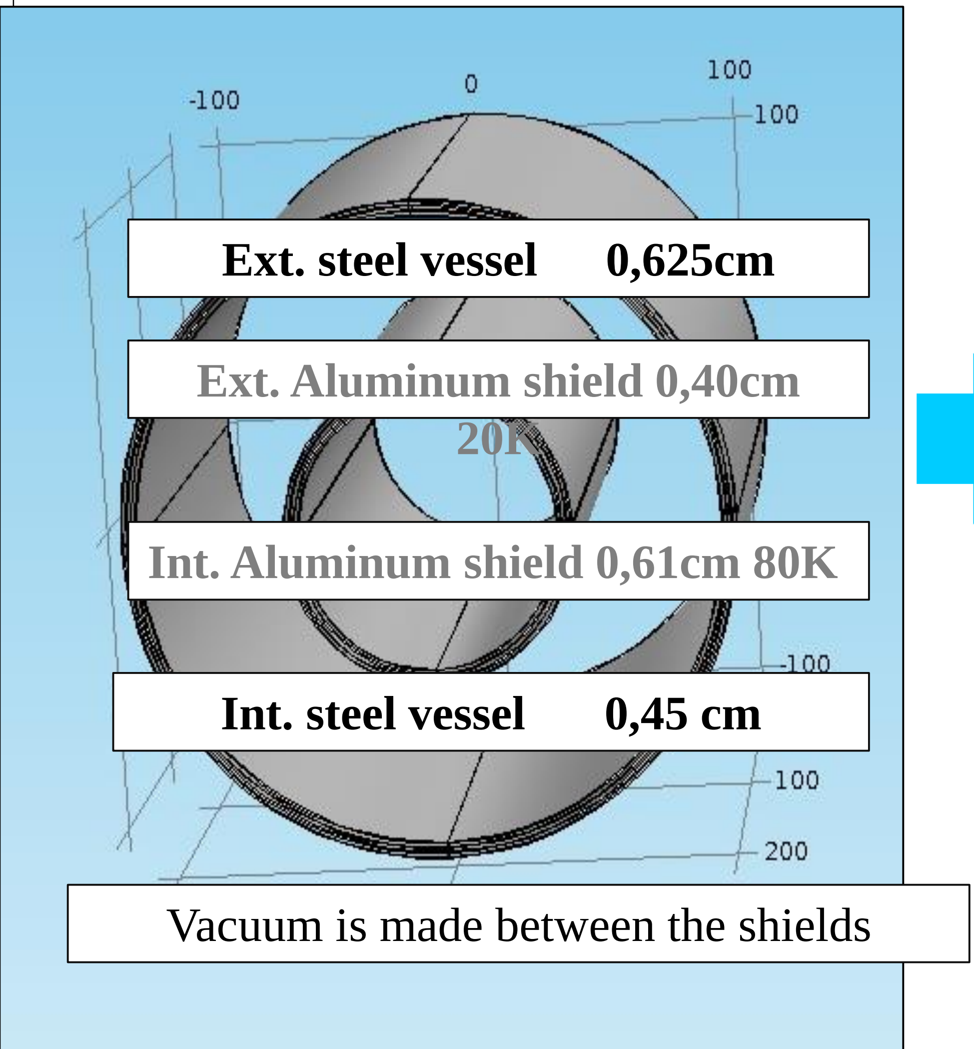
Figure 2: Front view of a real cryostat

Figure 3: Concetric vessels

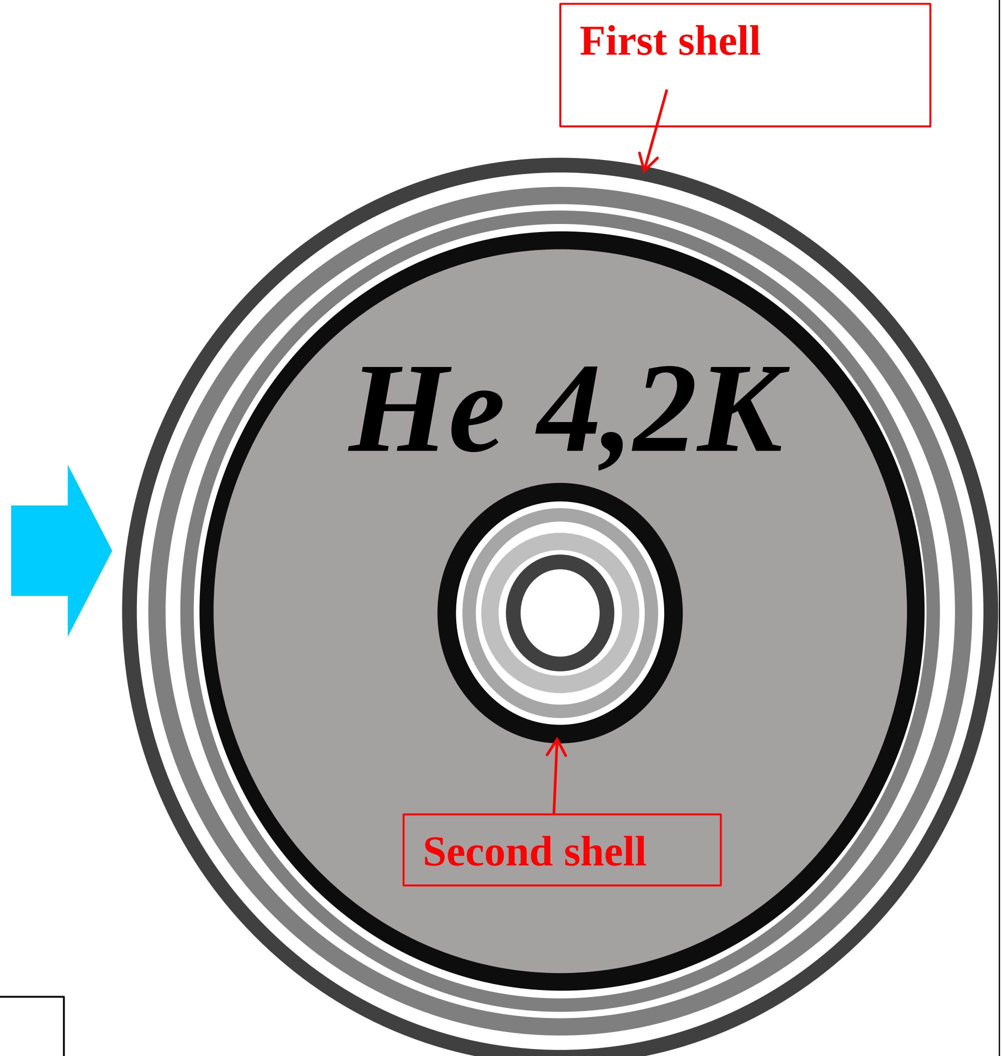
Simplified geometry of Cryostat

- At the beginning a very simplified model of cryostat constited of open concentric cylinders spaced from vacuum zones has been developed.

- This model no take into account the thermal field near the closures simulating only the heat exchange in the central part of the cryostat.



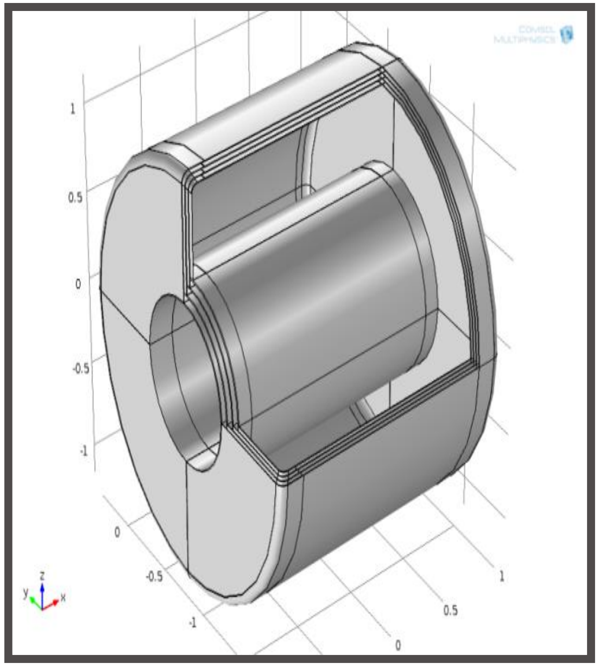
-100
0
100
100
Ext. steel vessel 0,625cm
Ext. Aluminum shield 0,40cm
20K
Int. Aluminum shield 0,61cm 80K
-100
Int. steel vessel 0,45 cm
100
200
Vacuum is made between the shields



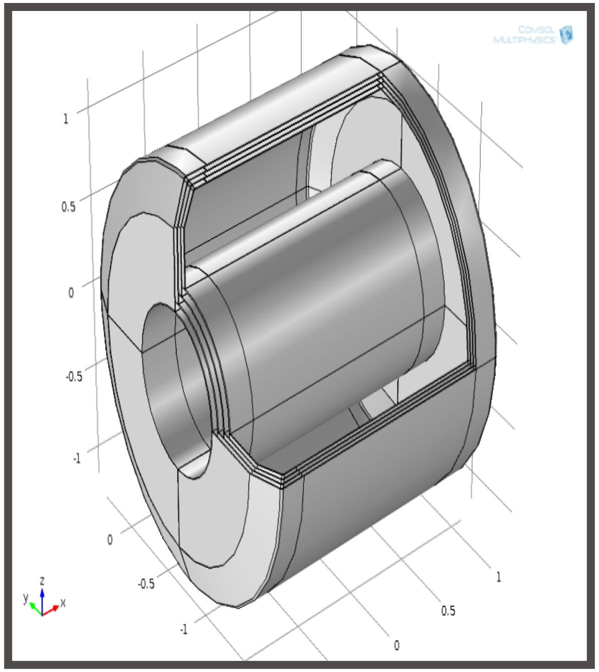
First shell
He 4,2K
Second shell

Model of Cryostat with closures

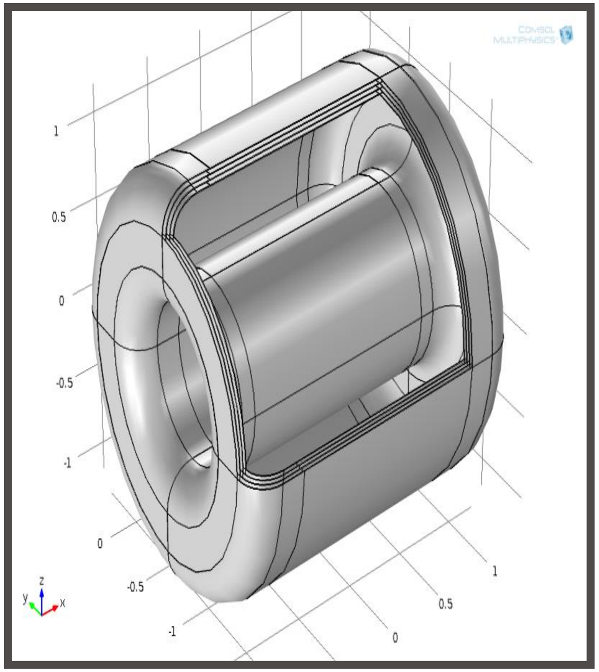
- A more realistic model has been developed to investigate the thermal field near the closures. More specifically, three different geometries with particular reference to the type of closures placed at the ends have been implemented.



Geometry with flat closures



Geometry with inclined closures



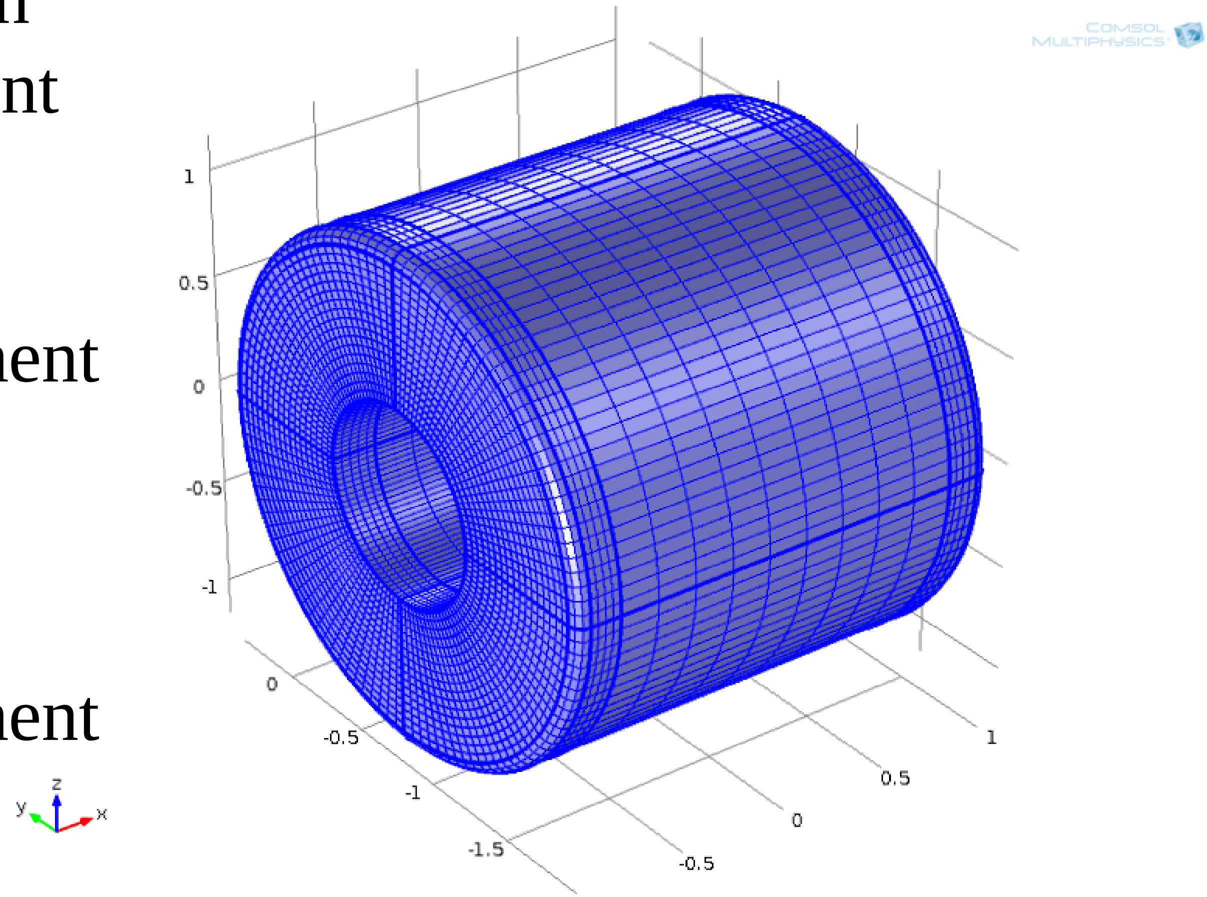
Geometry with rounded closures

Mesh

❑ Swept mesh with elements of different sizes :

❖Closures: Maximum element size 0.1 m

❖Cylinders: Maximum element size: 0.2 m



Materials

	Type of material	ρ (kg/m3)	Thermal conductivity [W/m K]	Specific Heat [J/K. kg]
Outer vessel	304 Stainless Steel	7999.5	Variable with Temperature	Variable with Temperature
Radiative Shields	6063 – T5 Aluminum	2712.6	Variable with Temperature	Variable with Temperature
Inner vessel	304 Stainless Steel	7999.5	Variable with Temperature	Variable with Temperature
Cold head	OFHC Copper	8940	Variable with Temperature	Variable with Temperature

Numerical study of the thermal field

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

- $\rho C_p \frac{\partial T}{\partial t}$ → **Change in internal energy in the domain**
- $\rho C_p \mathbf{u} \cdot \nabla T$ → **Convective term**
- $\nabla \cdot (k \nabla T)$ → **Conductive term**
- Q → **Heat Source**

ρ	density(SI unit: kg/m3)
Cp	specific heat capacity at constant pressure (SI unit: J/(kg·K))
T	absolute temperature (SI unit: K)
u	velocity vector (SI unit: m/s)

Boundary condition

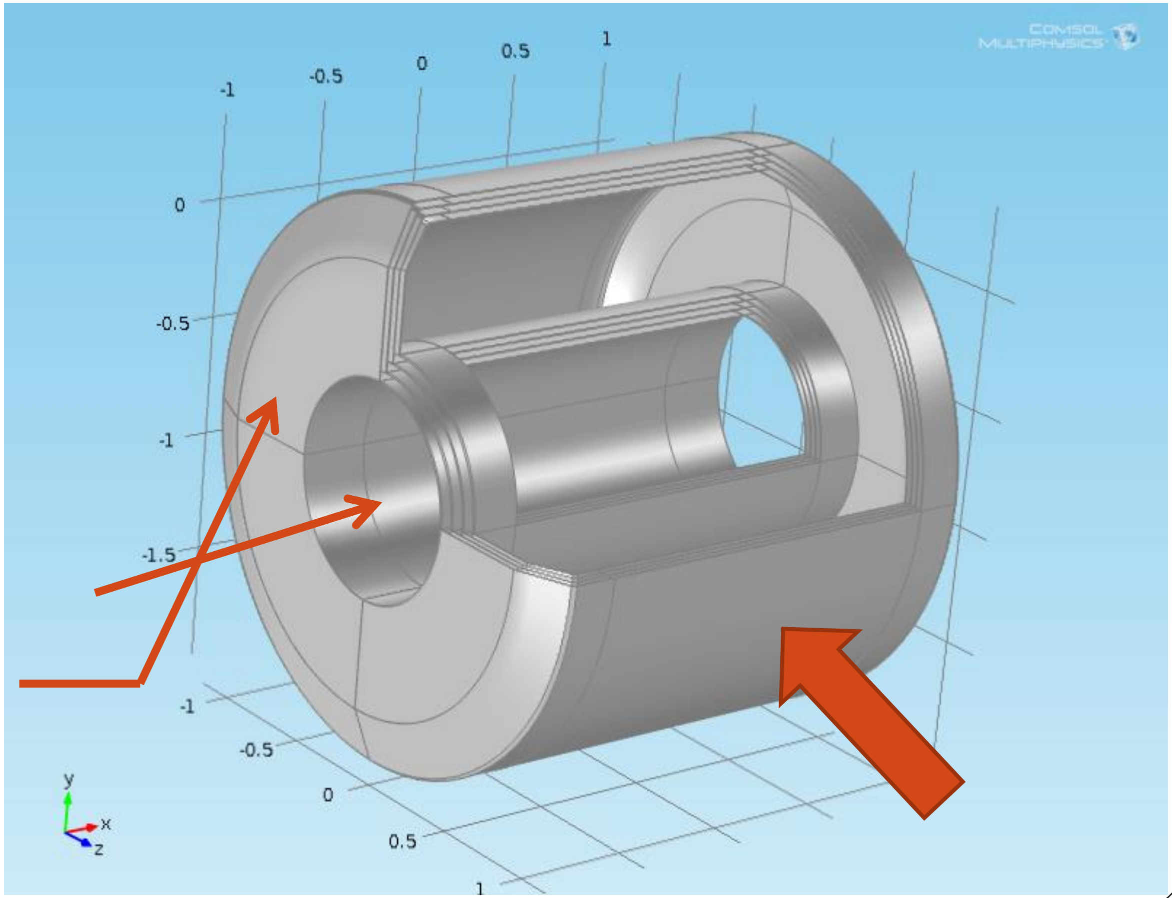
- ❑Heat flux
- ❑Radiation Surface to ambient;
- ❑Radiation Surface to Surface
- ❑Specified temperature
- ❑Specified inward heat flux

Initial conditions:

- ➢External Temperature=293.15 K
- ➢Internal temeperature: 4.2 K

Heat convective transfer coefficients (1)

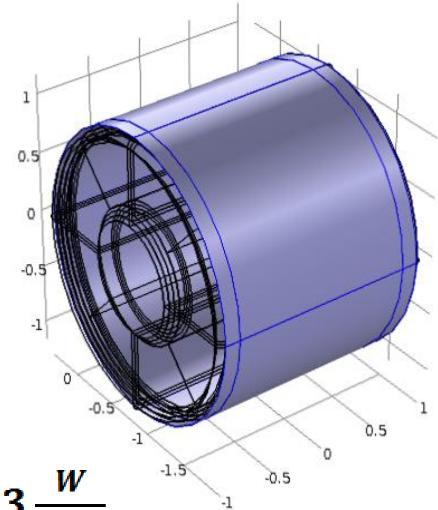
- Helium
  - *Liquid*
  - *Vapor*
- Air
  - *External cylinder*
  - *Internal cylinder*
  - *Vertical wall*



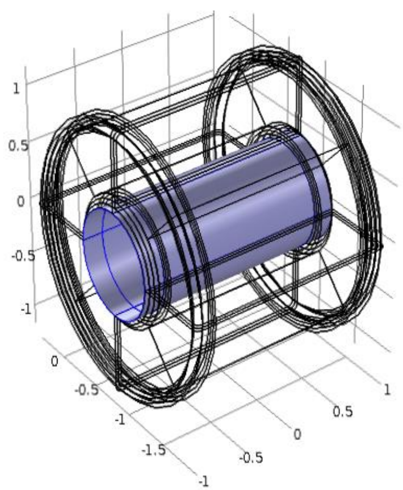
Heat convective transfer coefficients (2)

External steel vessel

$$h_{ext} = 2.13\,\frac{W}{m^2K}$$



$$h_{int} = 2.23\,\frac{W}{m^2K}$$



- **Heat flux**

$$-n \cdot (k\nabla T) = h_{ext}(T_{ext} - T)$$

$q = k \cdot \nabla T$ **conductive heat flux vector** $\left[\frac{W}{m^2}\right]$

n **normal vector of the boundary**

h_{ext} **heat transfer coefficient**

- **Heat flux**

$$-n \cdot (k\nabla T) = h_{int}(T_{ext} - T)$$

$q = k \cdot \nabla T$ **conductive heat flux vector** $\left[\frac{W}{m^2}\right]$

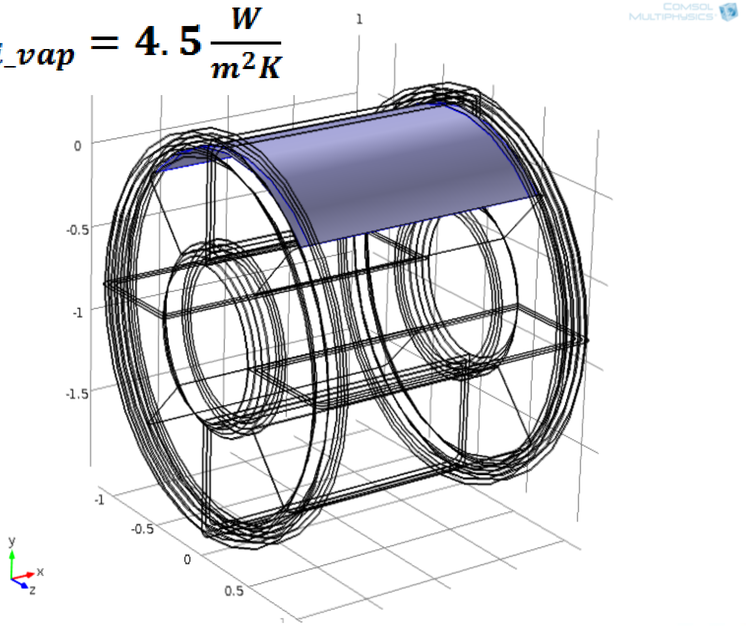
n **normal vector of the boundary**

h_{int} **heat transfer coefficient**

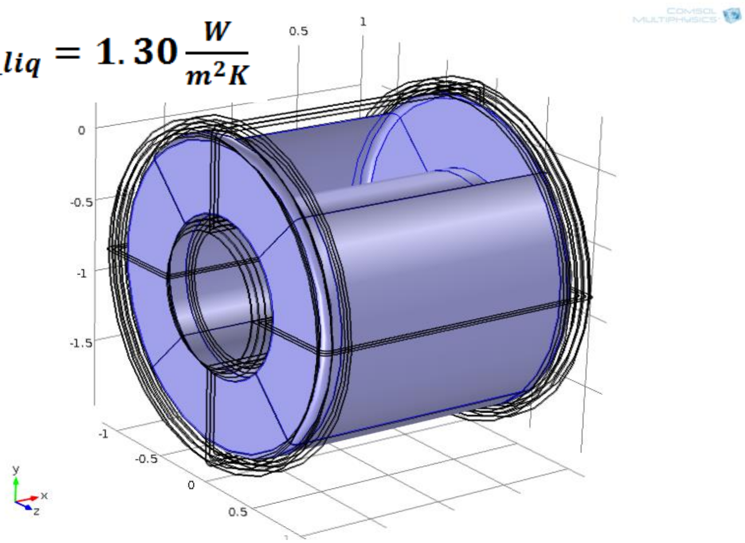
Heat convective transfer coefficients (3)

Internal steel vessel

$$h_{i\_vap} = 4.5 \frac{W}{m^2K}$$



$$h_{i\_liq} = 1.30 \frac{W}{m^2K}$$



- **Heat flux**

$$-n \cdot (k\nabla T) = h_{i\_vap}(T_{ext} - T)$$

$q = k \cdot \nabla T$ **conductive heat flux vector** $\left[\frac{W}{m^2}\right]$

n **normal vector of the boundary**

h_{i_vap} **heat transfer coefficient with helium vapor**

- **Heat flux**

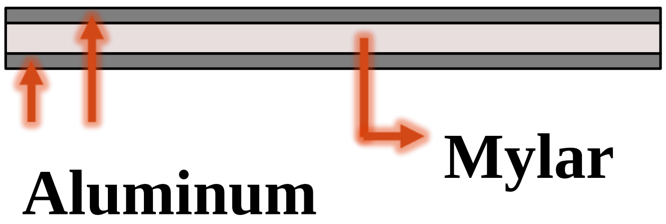
$$-n \cdot (k\nabla T) = h_{i\_liq}(T_{ext} - T)$$

$q = k \cdot \nabla T$ **conductive heat flux vector** $\left[\frac{W}{m^2}\right]$

n **normal vector of the boundary**

h_{i_liq} **heat transfer coefficient with liquid helium**

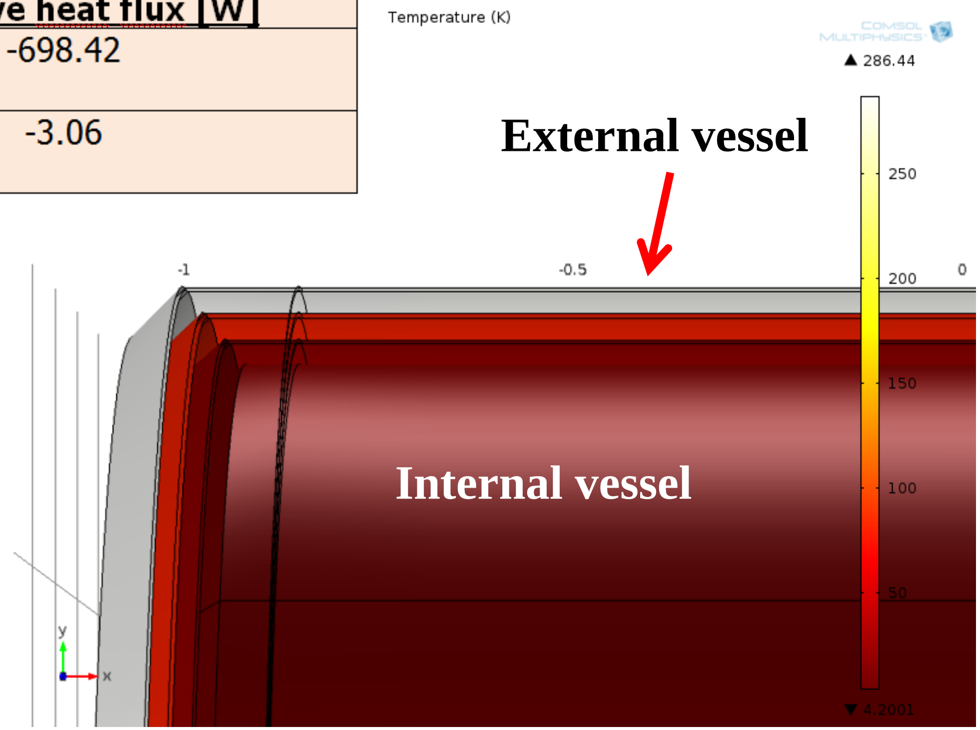
DAM (Double Aluminized Mylar)



Higher temperature gradient region

Simulation without DAM

Geometry with flat closures	
Surfaces	**Radiative heat flux [W]**
External surface external steel vessel	-698.42
External surface internal steel vessel	-3.06



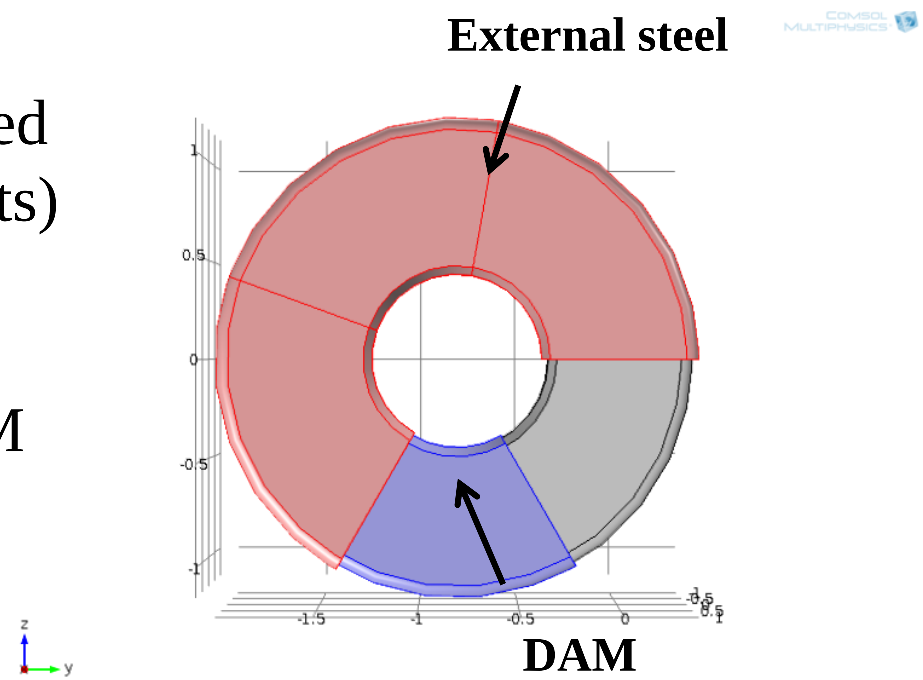
Thermal Boundary conditions:

- Specified temperature on raditive cryo-shields maintained at 80 K and 20 K respectively.

The radiative net heat flux received by the shield maintained at 80K is very high and not sustainable by any commercial cold head

Simulation with DAM (1)

- Ideal case:
  - ❖separated DAM sheets: no contact points are considerated (only radiation between sheets)
  - ❖a single sheet with an effective emissivity taking in account the effect of 60 DAM sheets
  - ❖Perfect insulation



The heat flux entering the external aluminum vessel, from 698.42 to 2.985 W.

Simulation with DAM (2)

- A more realistic model was analyzed in Matlab

- In addition to the radiative contribution, a further conductive term was considered throught the spacer (k=0.0012)

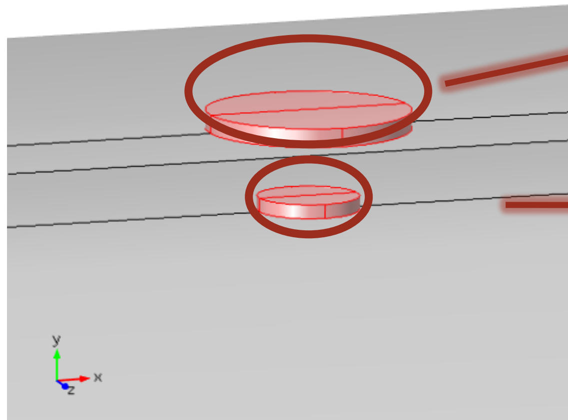
Cold Head

- In combination with an effective insulation system, radiative shields are maintained at a specified temperature by a “cold head”.

- In this work the Pulse Tube Refrigerator with two refrigerating stages is used in order to reduce the temperature gradient in the cryostat.

Model of Cold head in Comsol

- ❑Two copper plates (4.12 cm diameter and 2.06 cm diameter), simulating two refrigerant stages of a pulse tube, put in contact with two cryo-shields

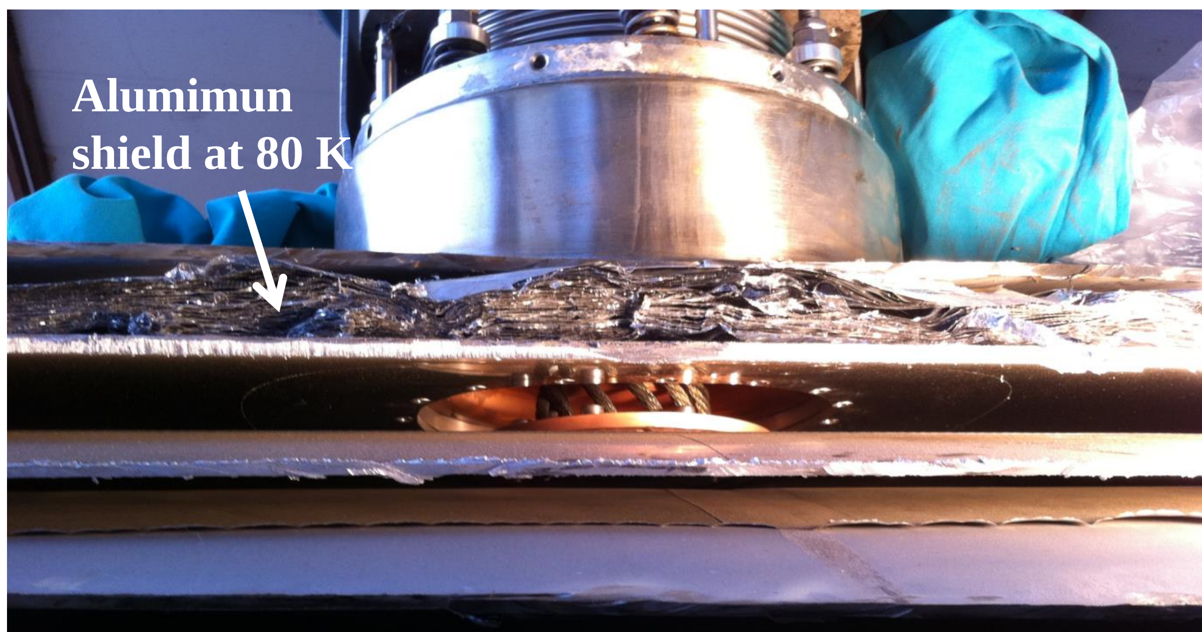


TF80

- r_{TF80}=20.6 mm
- s_{TF80}=5 mm

TF20

- r_{TF20}=10.3 mm
- s_{TF20}=4 mm



- ❑Thermal boundary conditions :
  - ❖ Specified temperature
  - ❖ Specified inward heat flux

Boundary Condition

- The imposed heat flux, to be removed by the refrigerating stage through each contact surface, was set as equal to the overall difference between the incoming and outgoing flux from the shield

Geometry with flat closures	
Surfaces	**Radiative heat flux [W]**
External surface external steel vessel	-8.12
Internal surface external steel vessel	3.06
External surface internal alu vessel	-3.06
Internal surface internal alu vessel	0.011

Q_{TF80} (external steel vessel surfaces)

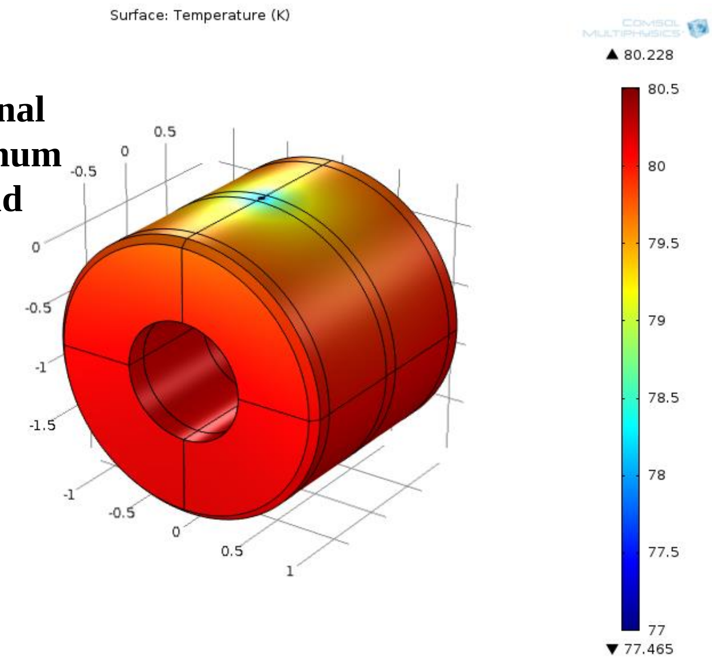
Q_{TF20} (internal alu vessel surfaces)

Thermal performance (1)

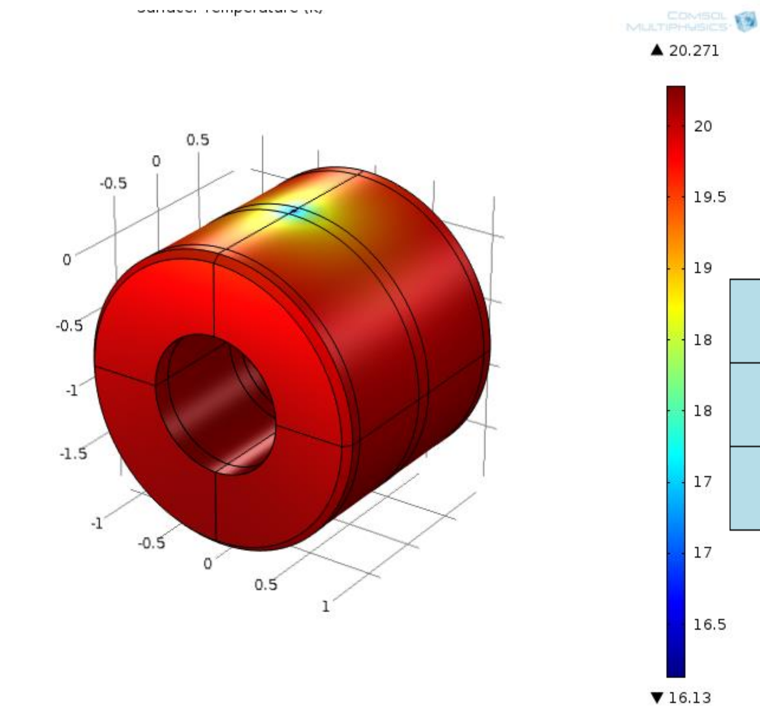
- **Geometry with flat closures**

Maximum Temperature	80.23 K
Minimum Temperature	77.46 K
Average Temperature	80 K

External Aluminum shield



Internal Aluminum shield

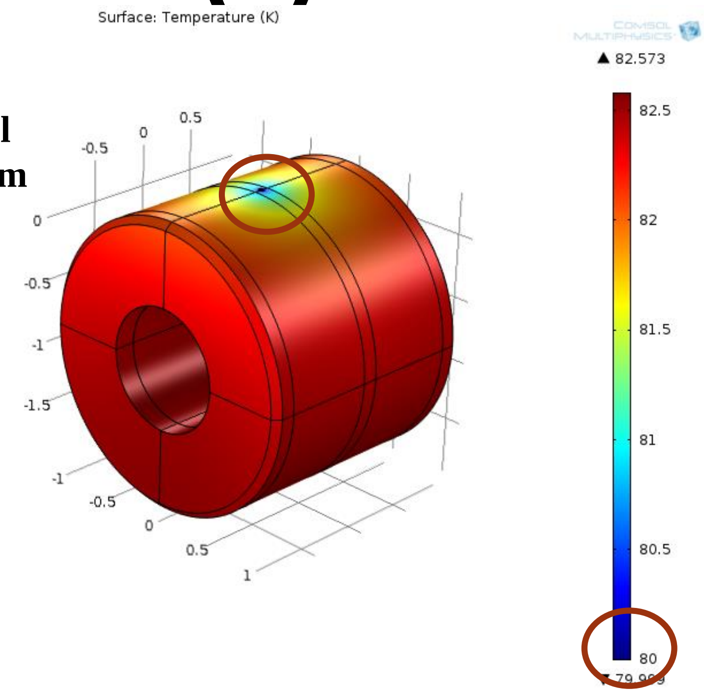


Maximum Temperature	20.27 K
Minimum Temperature	16.13 K
Average Temperature	19.99 K

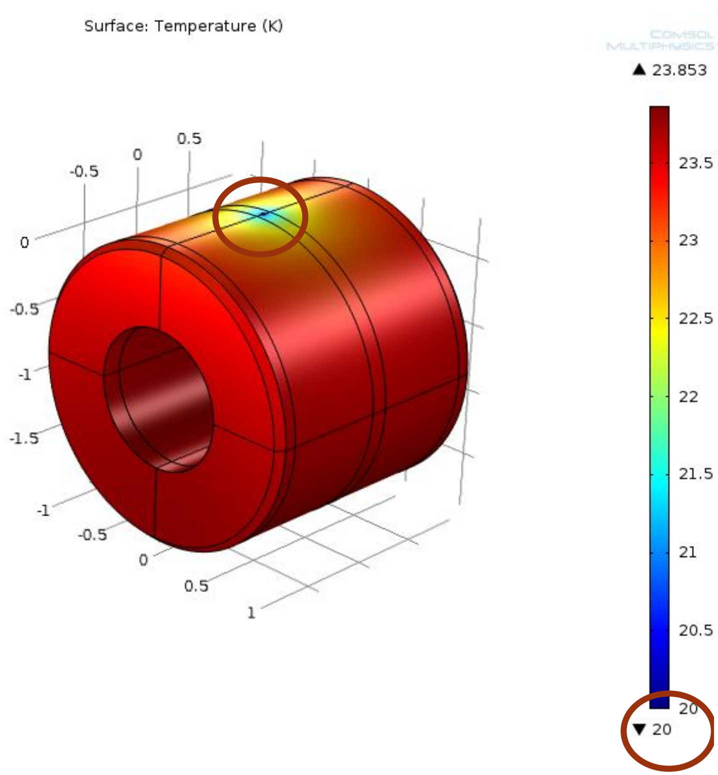
Thermal performance (2)

Imposed temperature at the cold head surfaces

External Aluminum shield



Internal Aluminum shield

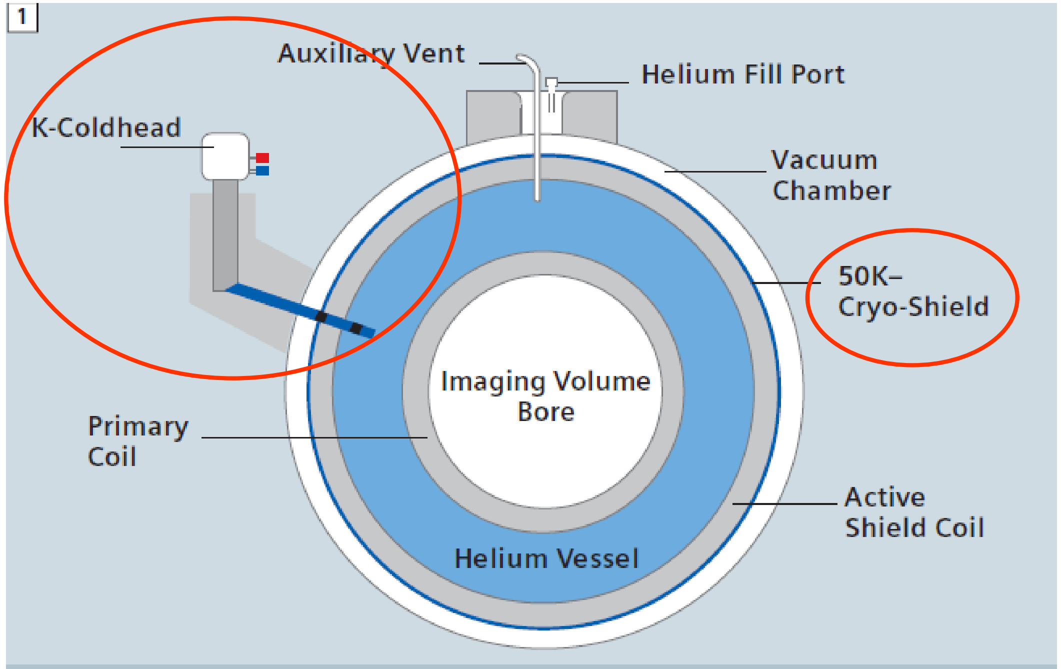


Maximum Temperature	82.57 K
Minimum Temperature	80 K
Average Temperature	82.36 K

Maximum Temperature	23.85 K
Minimum Temperature	20 K
Average Temperature	23.59 K

Zero-Boil Off System

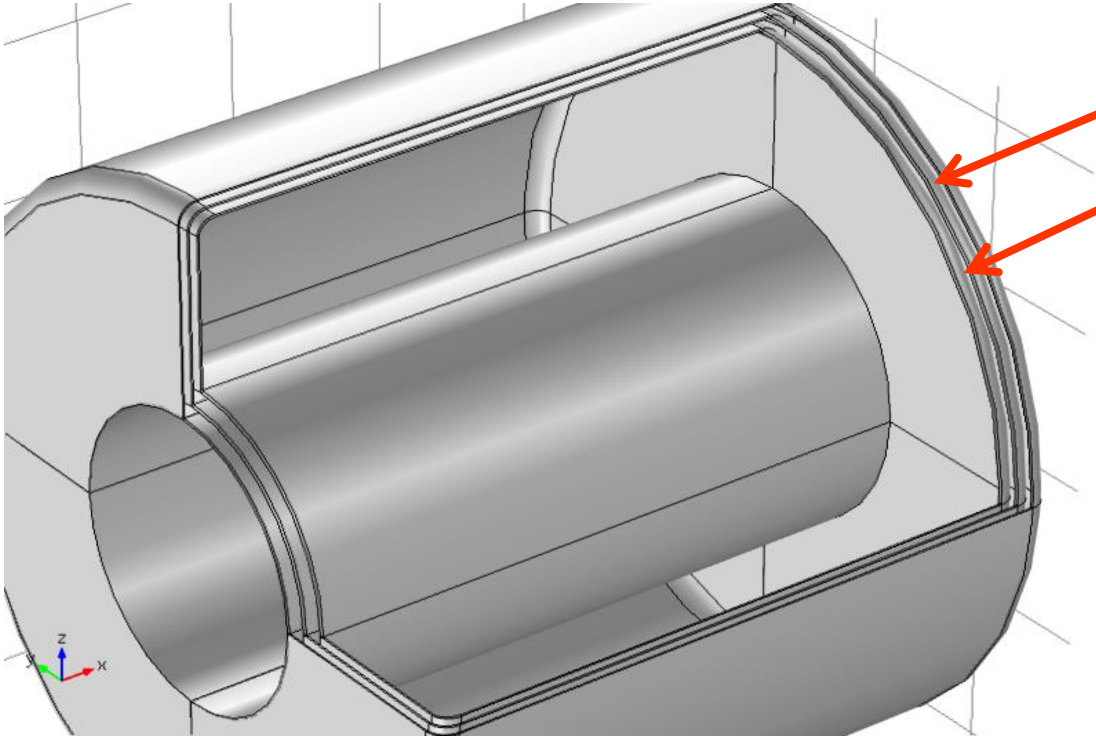
- Condensation inside the vessel of helium that could be evaporated, eliminating helium consumption.
- Single shield
- Two refrigerate stages (50 e 4,2 K)



1 MR system.

Model of Cryostat

- **Geometry with three vessels**



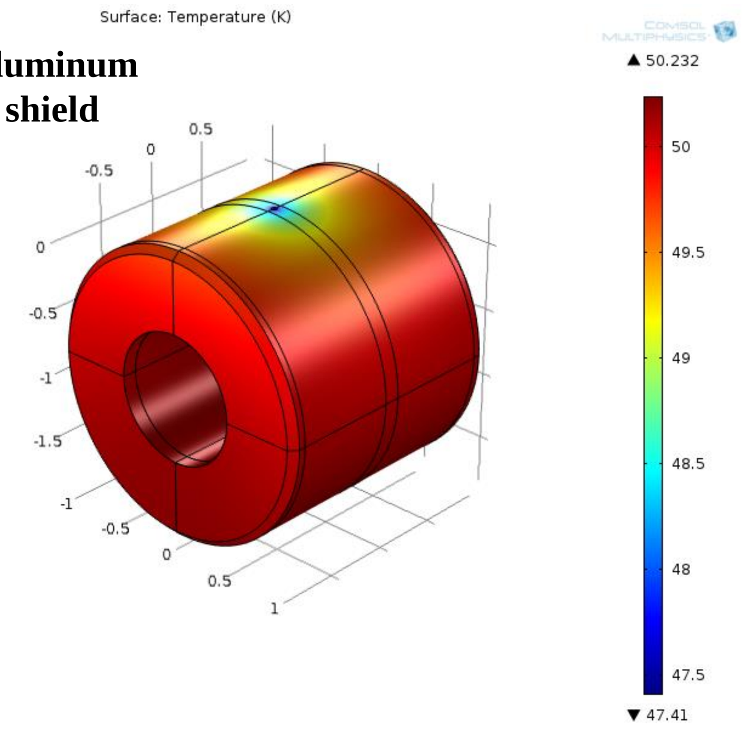
Thermal Problem Statement:

- T50
- T4.2
- E_dam=0.00133

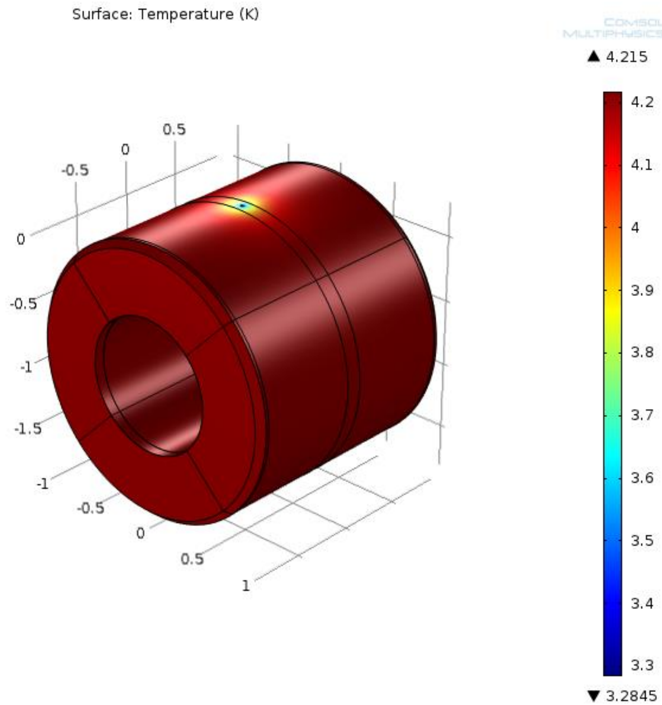
Results with cold head

Heat flux TF50	-6.36 [W]
Heat flux TF4.2	-0.44 [W]

Aluminum shield



Helium vessel

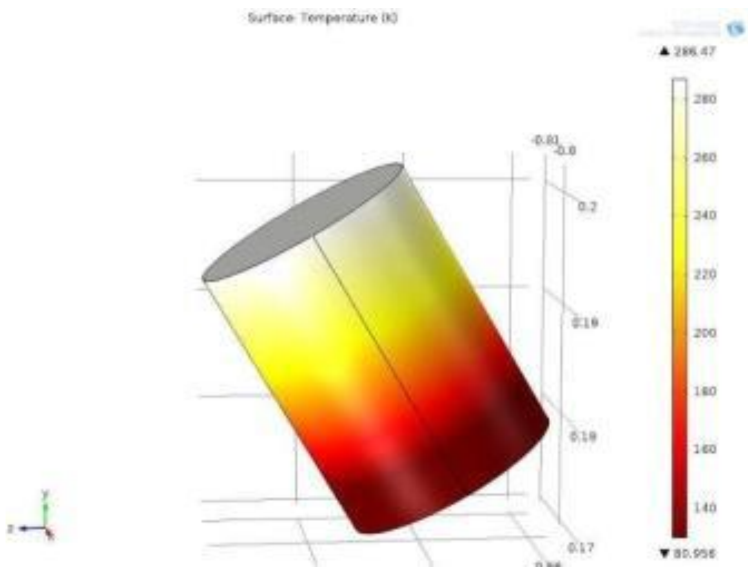


The temperature below 4.2K allows the helium vapor recondensation

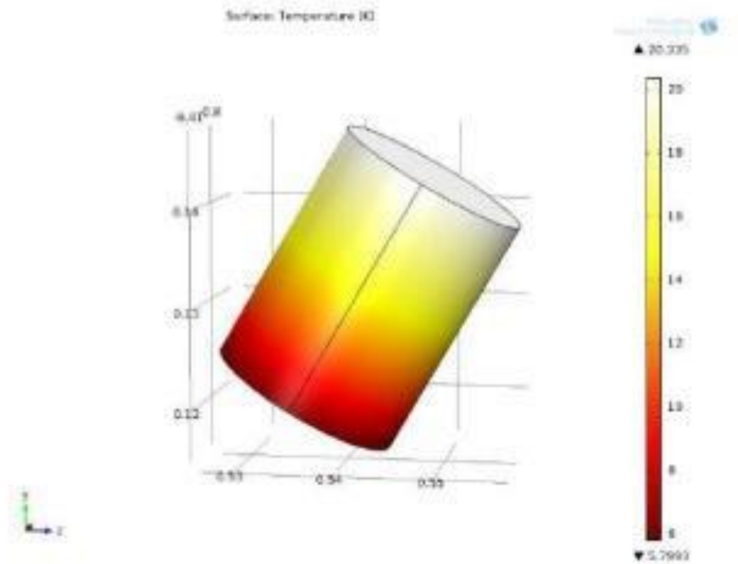
Simulation with tie rods

- For MRI machines, tie-rods are made of fiber glass because this material achieves a mechanical resistance near to theoretical resistance of the covalent bond.
- Each vessel contains 4 tie-rods which fix it on the opposite one.
- Provide a conductive way for heat among the vessels.

Temperature fields along tie rods for imposed heat flux (1)

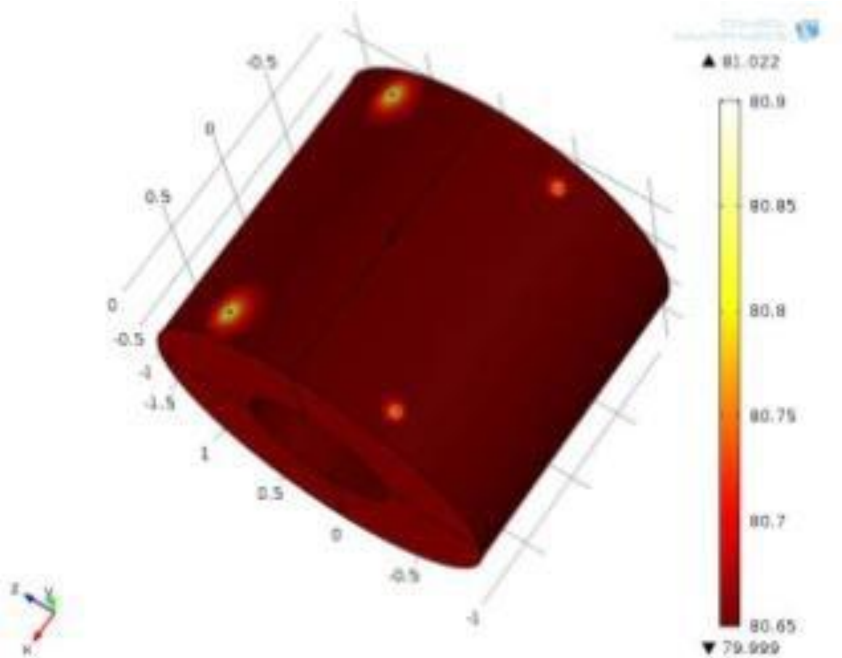


Thermal field along fiber glass tie-rod inserted between esxternal and internal aluminum vessel

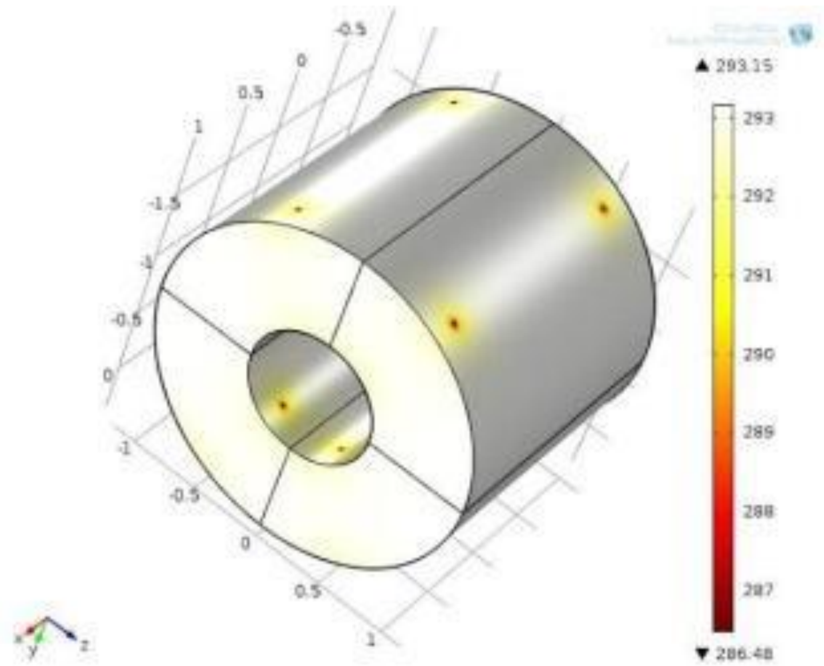


Temperature field along fiber glass tie-rod in contact with internal steel vessel containing liquid helium

Temperature fields along tie rods for imposed heat flux (2)



Thermal field on External Aluminum Vessel



Thermal field on External Steel Vessel

Discussion

- Temperature value at the end of the tie-rod, in contact with the external steel, is lower than the average temperature of the vessel (equal to 293.1 K).

- For internal steel vessel this effect is not negligible since the temperature value at the contact points with tie-rods reaches a value of 5.79 K so the liquid helium evaporates very quickly

Conclusions (1)

- Preliminary results related to the description of thermal field in a cryostat for nuclear magnetic resonance imaging have been presented.

- Resulting heat flux entering in 80K cryo-shield without DAM’s sheet is too high and not sustainable by any commercial cold head.

- Two boundary conditions have been analyzed to simulate the effect of the cold head.

Conclusions (2)

- Zero-boil off system have been simulated with helium vessel maintained at 4K; resulting heat flux entering in cryo-shield and vessel wall is sustainable by cold head.

- With regard to tie rods, the choice of material is crucial to maintain the empty cavity and avoid the quench of magnet.

FUTURE DEVELOPMENTS

Next simulations will concern more realistic geometrical and mechanical configurations.

Acknowledgments

- The authors thank Prof. Francesco Paolo Branca for constructive comments and helpful suggestions and for making available the NMR tomography.