MICE project
Thermal analysis

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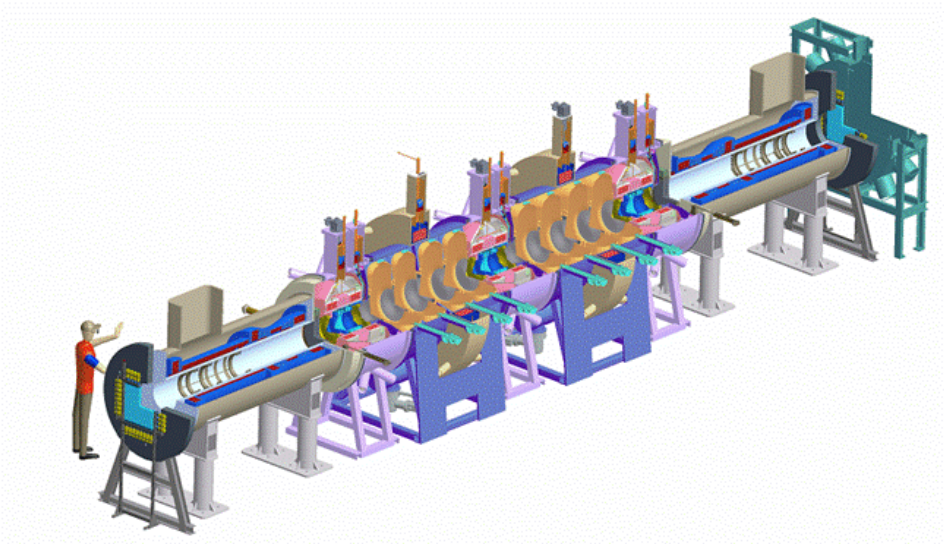
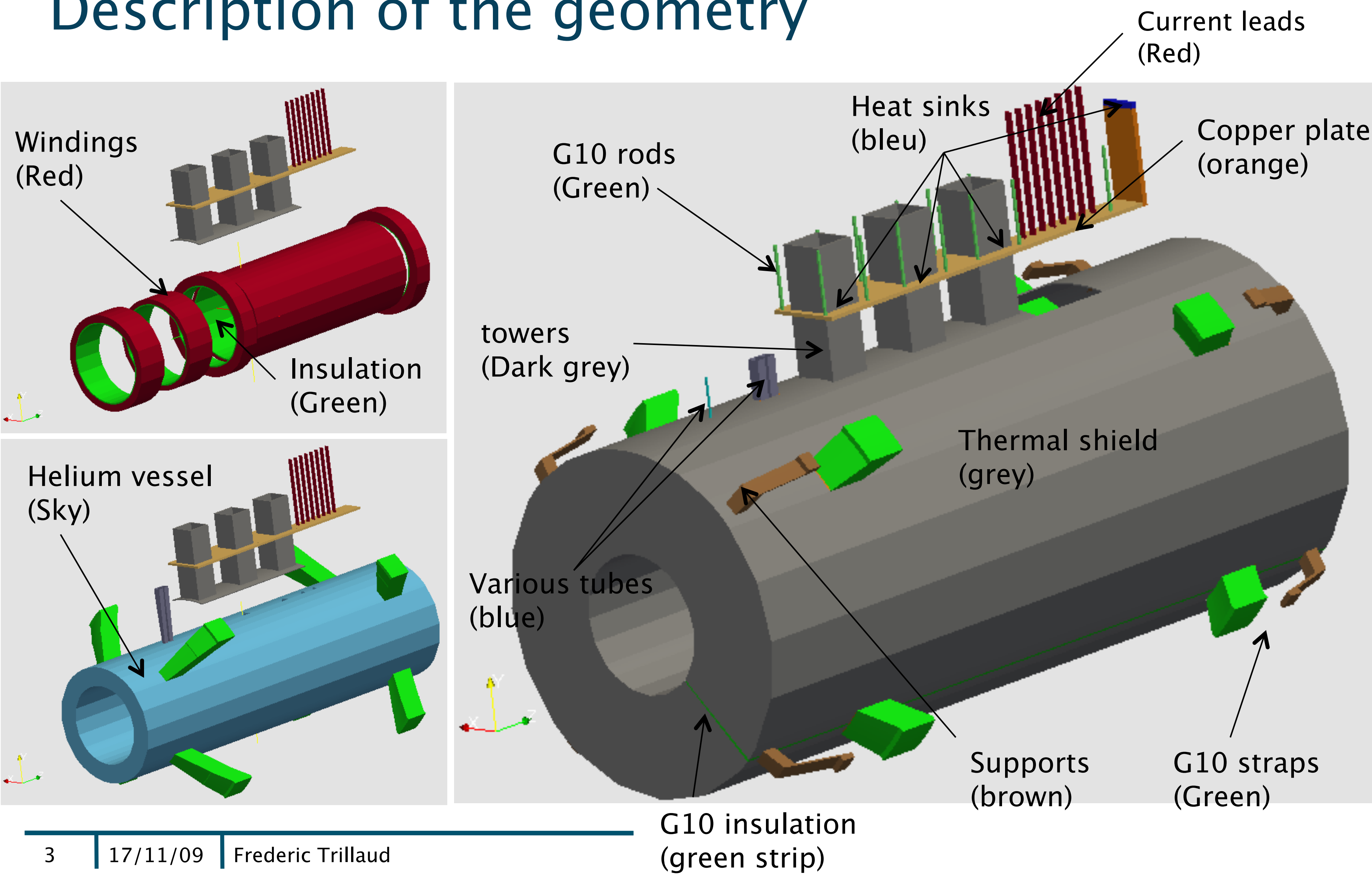


Fig. 1: Layout of MICE.

Content

- Introductory material:
  - Description of the geometry.
  - Cast3M (Finite Elements solver) and assumptions.
  - Material properties.
  - Cryocoolers characteristics.
  - Heat by radiation: super-insulation.
- Steady state Analysis.
- Recommendations
- References.

Description of the geometry



Code 3D Finite Elements: Cast3M

- Code CasT3M: non-linear steady state model. Solver based on Theta-method solving the transient heat balance equation with the heat capacity set to zero. Convergence in 10 steps with a criterion equal to 1e-6, 408237 nodes.

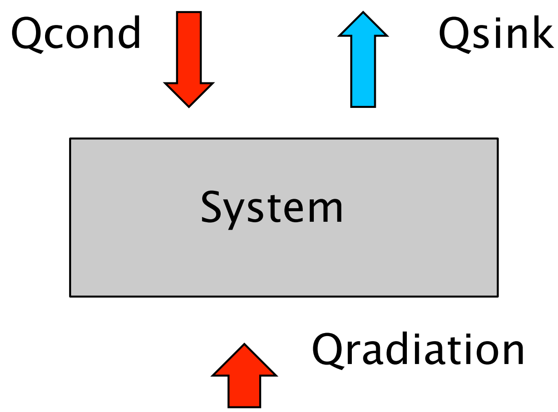
- Assumptions:
  - ✓ Perfect connections between pieces.
  - ✓ Steady state.
  - ✓ Fixed temperature at the boundaries (300 K and 4.2 K) and fixed heat flux (current leads).
  - ✓ Normalized thermal conductivities and specific heat capacities for some geometries.
  - ✓ Material properties as a function of temperature (4 K to 300 K).

- Normalized thermal conductivity and specific heat capacity taking into account the geometrical differences between the model and the actual geometry:
  - ✓ Thermal conductivity: $$a = \frac{V_{\text{real}}}{l_{\text{real}}^2} \times \frac{l_{\text{mod}}^2}{V_{\text{mod}}}$$
  - ✓ Specific heat capacity: $$\frac{V_{\text{real}}}{V_{\text{mod}}}$$

Boundary conditions and geometrical details

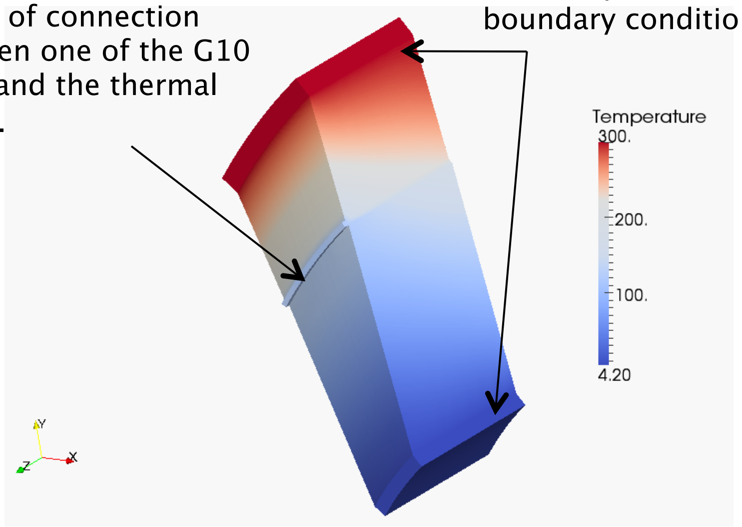
- Fixed temperatures at boundaries: tubes, G10 straps, supports, cryocoolers.

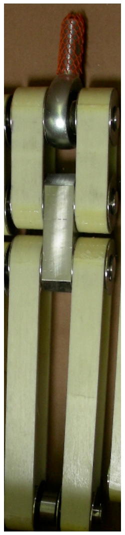
- Geometrical limitations due to the complexity of some of the parts. The first principle is respected ($Q_{sink} = Q_{radiation} + Q_{cond}$). However, the local thermal profile is expected to differ.



Model of connection between one of the G10 strap and the thermal shield.

G10 strap, boundary conditions





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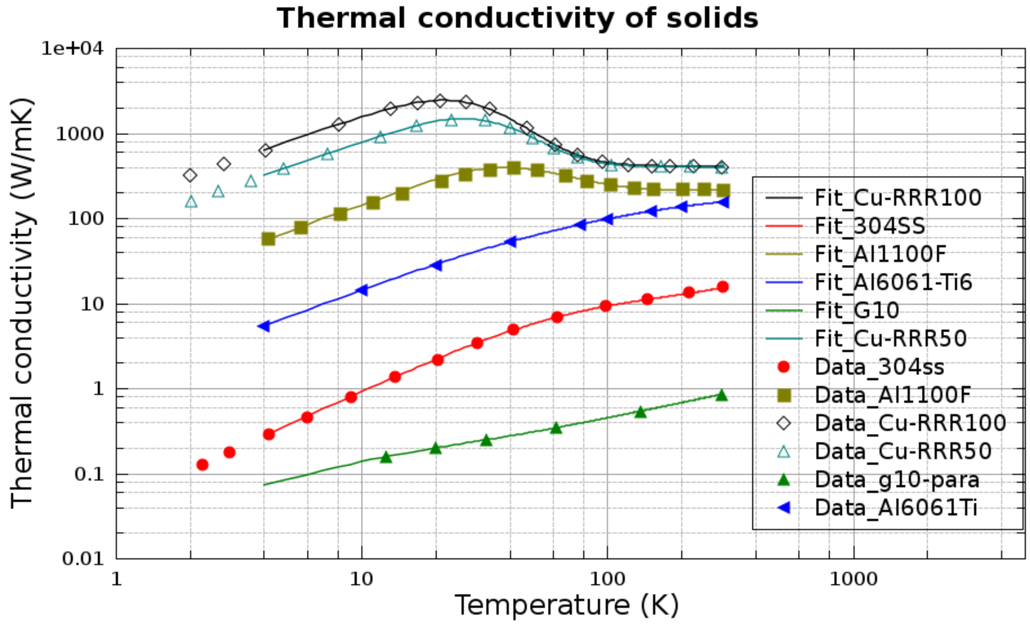
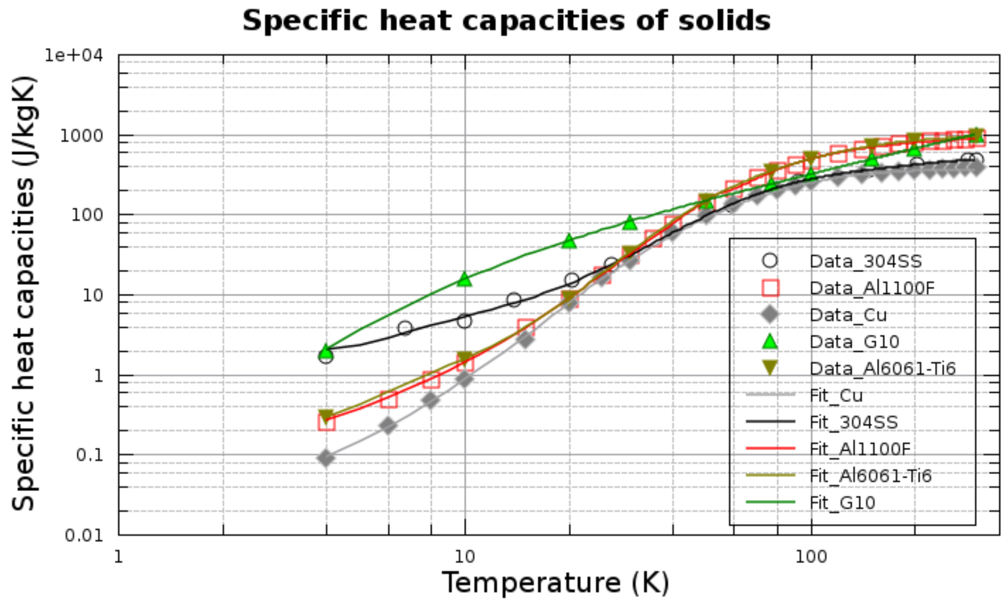
Material properties

- Fit equations are compared to data found in the litterature showing a good overall agreement within 15 %.

- Data sources: see the last slide (References).





Implementation of super-insulation

- ✓ The radiation heat load through super-insulation layers was simulated as a heat exchange coefficient (equivalent thermal conductivity: 5e-5 W/m-K [See J.W. Ekin]):

$$k_{\mathrm{mli}} = \frac{5 \times 10^{-5}}{e_{\mathrm{mli}}}, \mathrm{W/m^2K}$$

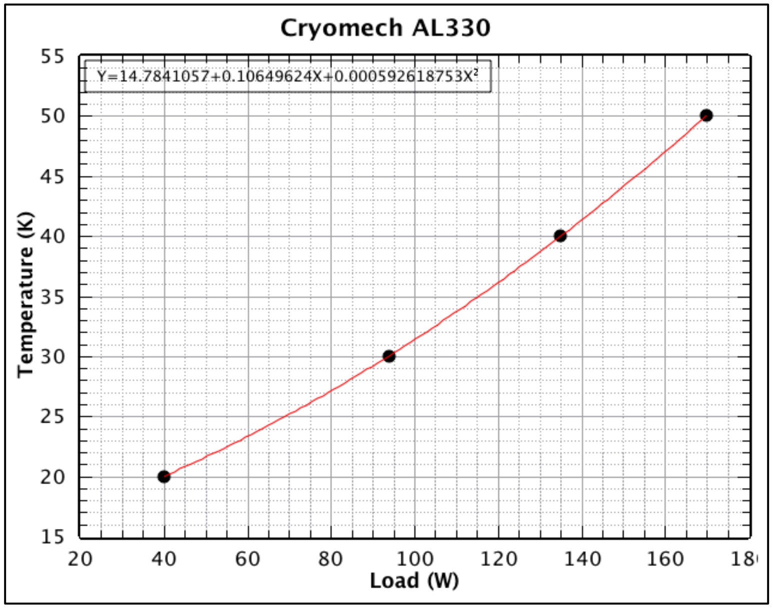
- ✓ The total thickness of the super-insulation, e_{mli}, is given by:

$$e_{\mathrm{mli}} = \frac{n_{\mathrm{layers}}}{npct}.$$

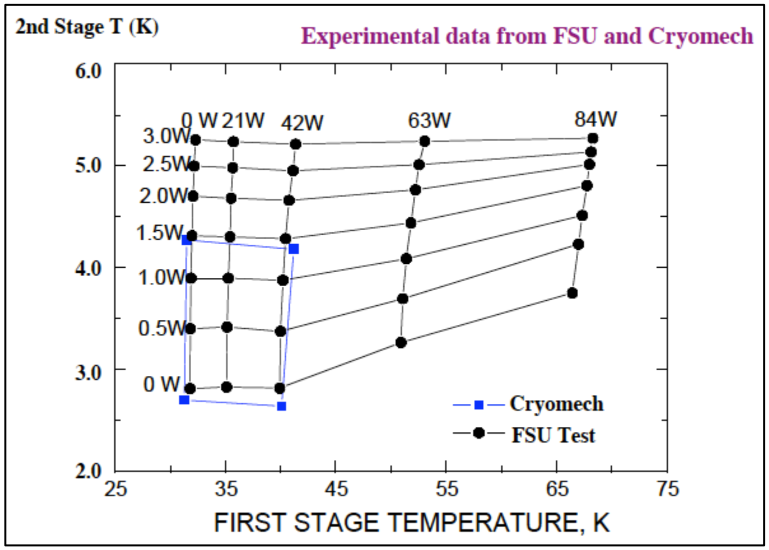
  - ✓ Where the number of layers, n_{layers}, is equal to 50.
  - ✓ The optimum thickness per number of layers given by J.W. Ekin (p. 38), *npct*, is equal to 30 layers per centimeter.

Cryocoolers: operating points

AL330	Single stage
Flux (W)	170
Temperature (K)	50



PT415	First stage	Second stage
Flux (W)	1.5	70
Temperature (K)	4.5	60



Current lead: copper and HTS (1/3)

- Two questions are addressed:
  - Expected temperature profile in operation and fault mode.
  - Minimum heat flux to extract at the connection between the copper and HTS lead.

- The second question deals with the necessity to keep the HTS lead below a certain temperature which depends on current and magnetic field.

- In the subsequent analysis, the critical surface of the HTS lead is not taken into account.

Copper and HTS leads (2/3)

- Heat balance equation: $\frac{d^2T}{dz^2} + \frac{\rho}{k} l J^2 = 0.$
- Analytical solution: $T\left(z\right) = -\frac{\rho}{k} J^2 z^2 + \frac{dT}{dz}|_0 z + T_0$
- Flux conservation:

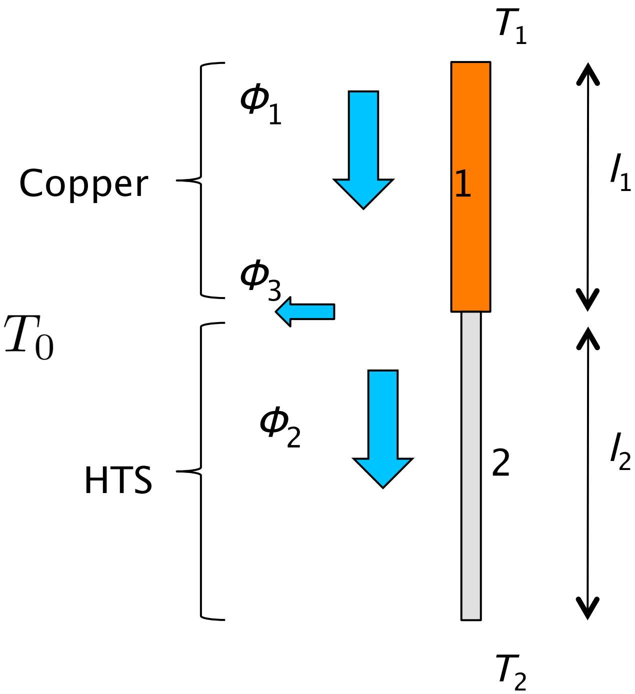
$$-A_1 k_1 \frac{T}{dz}|_{z=l-} = -A_2 k_2 \frac{dT}{dz}|_{z=l+} + \phi_3$$

- Maximum temperature (HTS):

$$\frac{z}{l}|_{\max} = \frac{1}{2} + \frac{k}{\rho} \frac{\left(T_{\text{in}} - T_{\text{out}}\right)}{J^2 l^2}.$$

- ✓ Ratio length to cross-section area, l/A:

$$\frac{l}{A} = \frac{1}{I} \sqrt{\frac{2k}{\rho} \left(T_{\text{in}} - T_{\text{out}}\right)}.$$

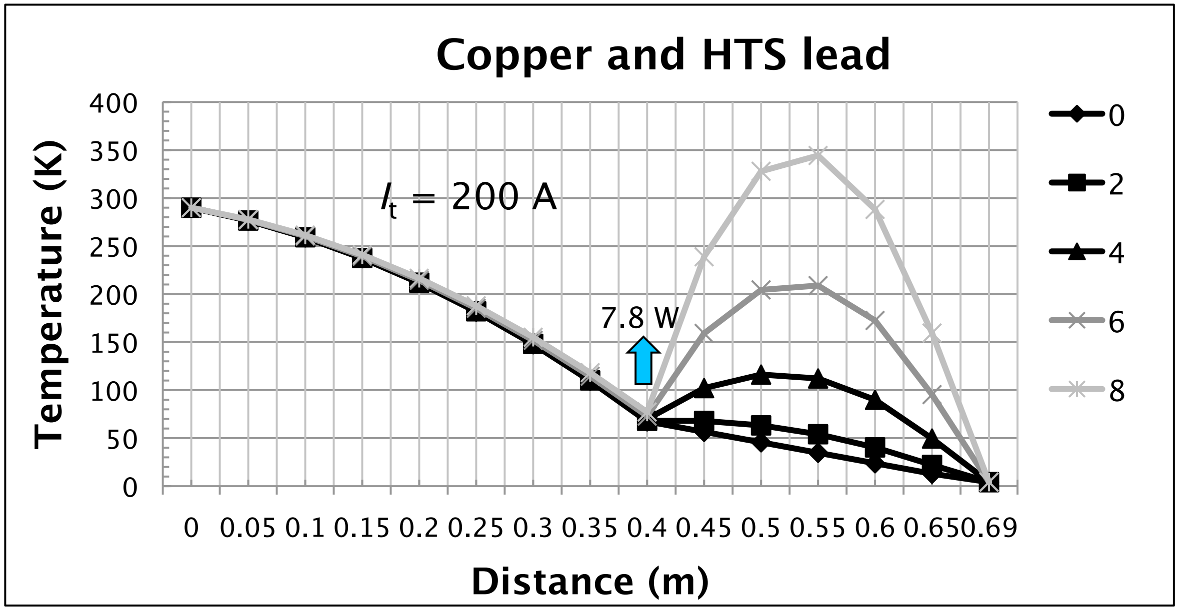


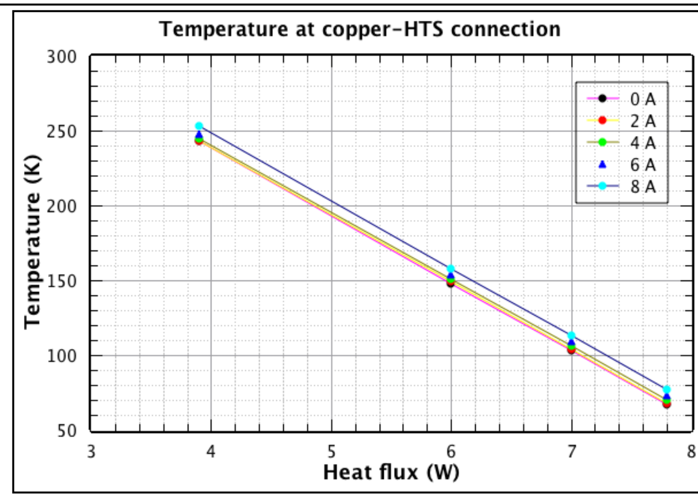
Assumptions:

✓Adiabatic conditions.
✓Steady state.
✓Uniform cross-section area per section.
✓Clamped temperatures at boundaries.
✓Average thermal conductivity and resisitivity.
✓*Quasi-static quench over the entire length of the HTS lead.*

Copper and HTS leads (3/3)

- Minimum flux to keep the connection below 70 K is equal to 7.8 W.
- "Sensitivity" of the connection temperature during fault: 1.25 K/A
- No matter how good is the connection: necessity of having voltage taps across the HTS leads



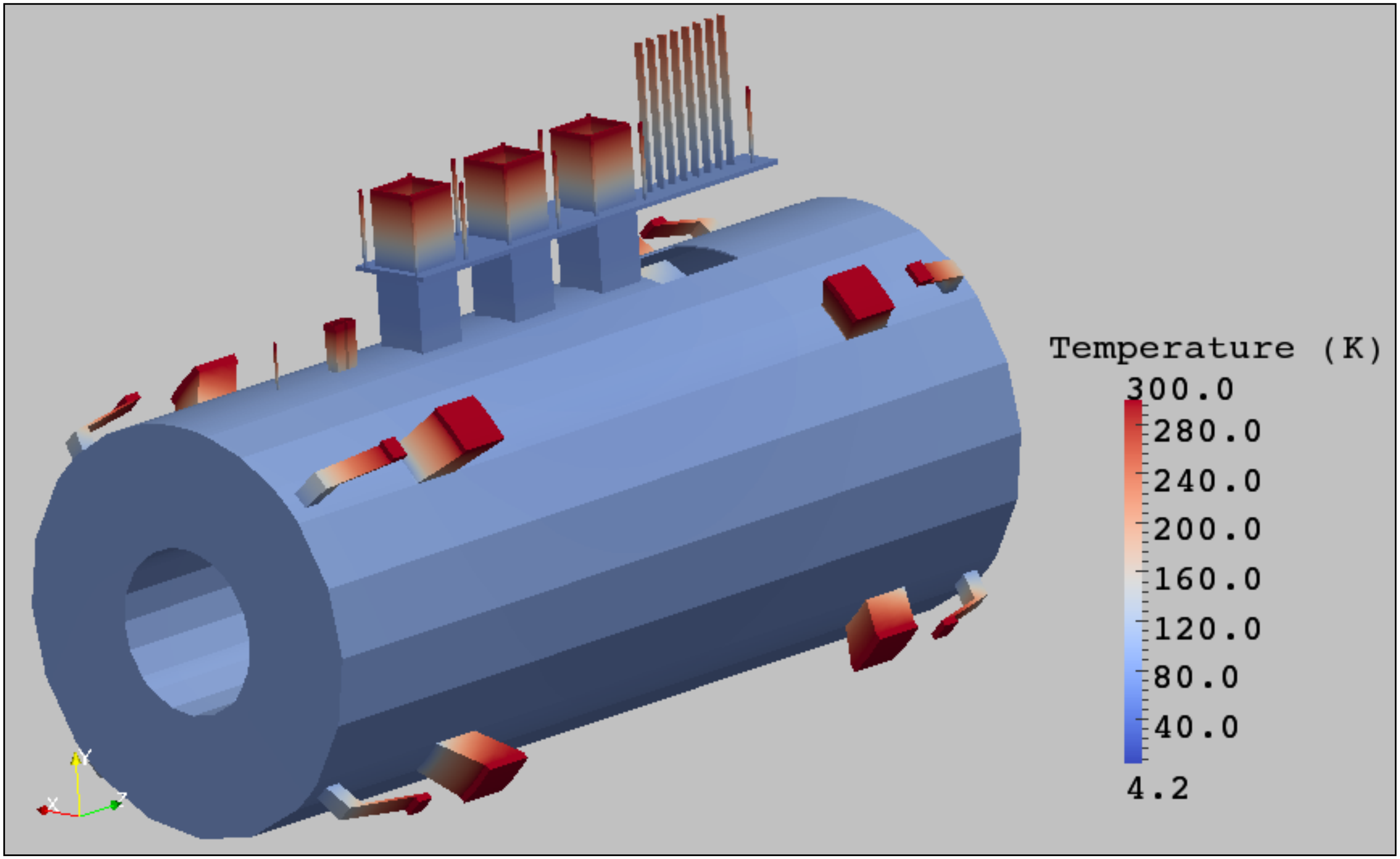


HTS matrix current (A)	0	2	4	6	8
Temperature at connection (K)	67	68	70	73	77
Max T (K)	290	290	290	290	344
z/l @ max T (%)	0	0	0	0	80

Heat loads and heat sinks

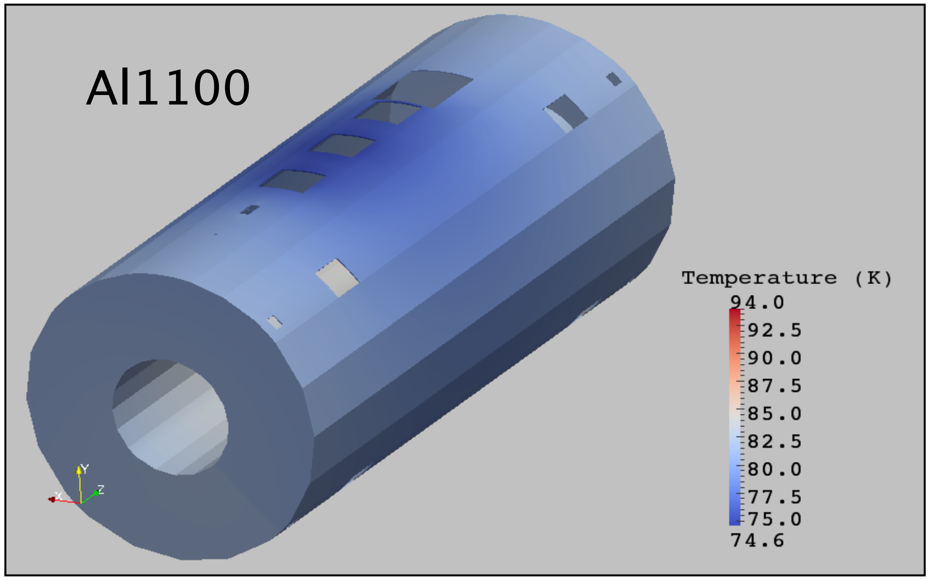
- Heat sinks:
  - 3 pulsed tubes:
    - #1: 65 K
    - #2: 65 K
    - #3: 70 K
  - 1 Single stage cryocooler (not yet in use): 60 K
- Here are the heat loads for the following simulations:
  - Conduction:
    - G10 straps: 300 K/4.2 K
    - End supports (Stainless steel and G10): 300 K
    - Current leads (I_t = 0 A): 4 W.
  - Radiation through super-insulation:
    - Source: enclosing vessel at 300 K.

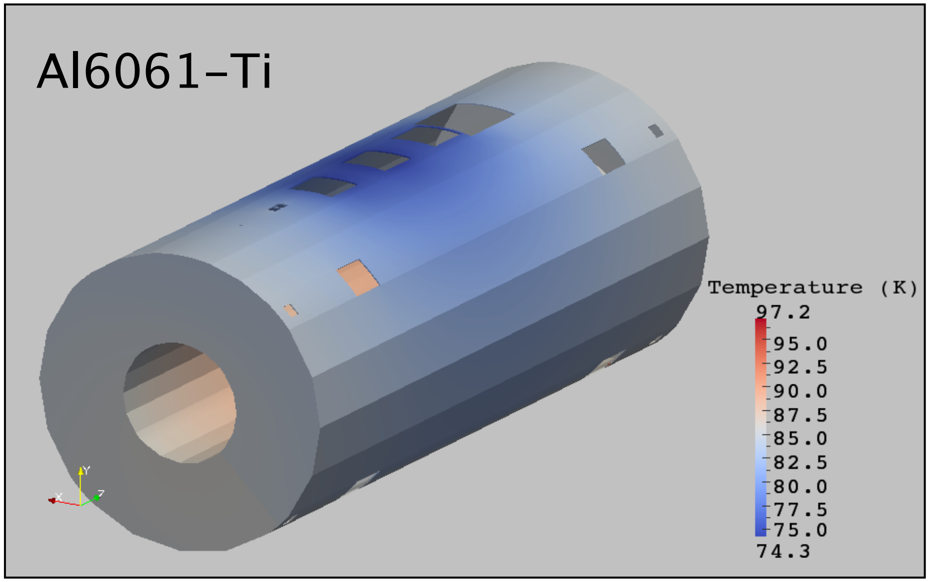
Results: full solution on existing setup



Thermal shield

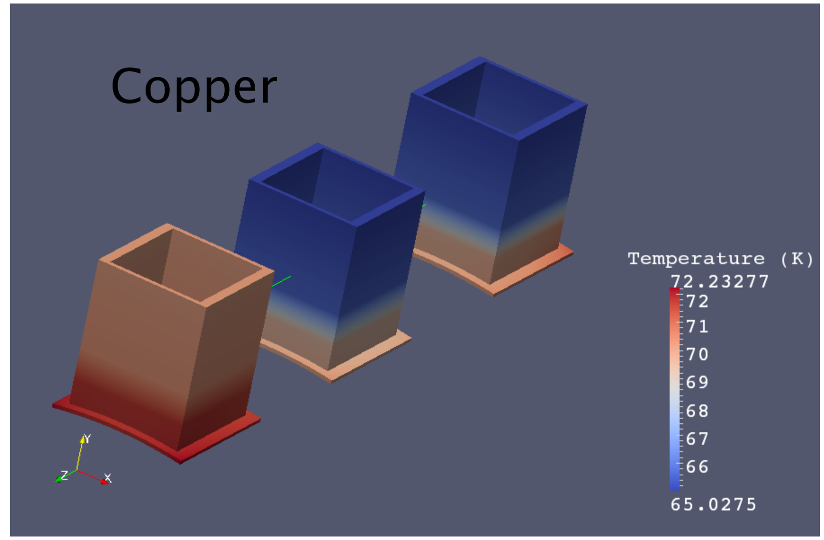
- The question being addressed:
  - Do we need to replace the actual shield with a shield having a better thermal condutivity.
- Fixed temperature at the cryocoolers: 65 K and 70 K (see next slide).
- Despite a large difference in the thermal conductivity (factor equal to 4 at 100 K), the temperature diferent is less than 4 K.
- The actual thermal shield in the assumptions of the model should be adequate.

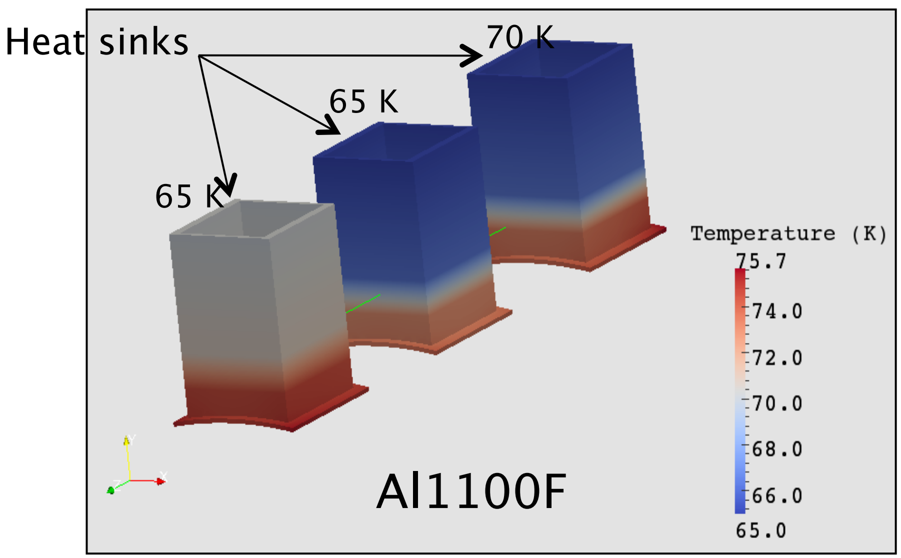


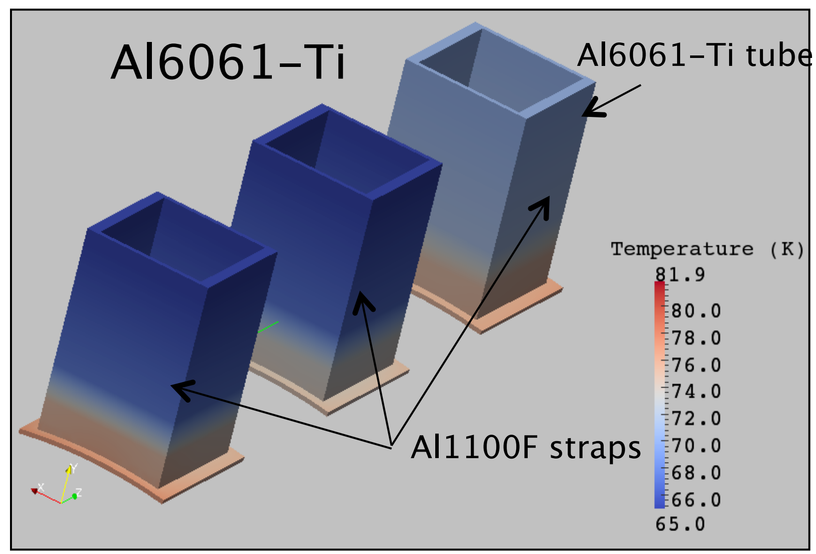


Cryocooler towers

- The question being addressed:
  - Influence of the choice of material on the temperature drop across the towers
- Fixed temperature at cryocoolers.
- A material with good thermal conductivity is beneficial.

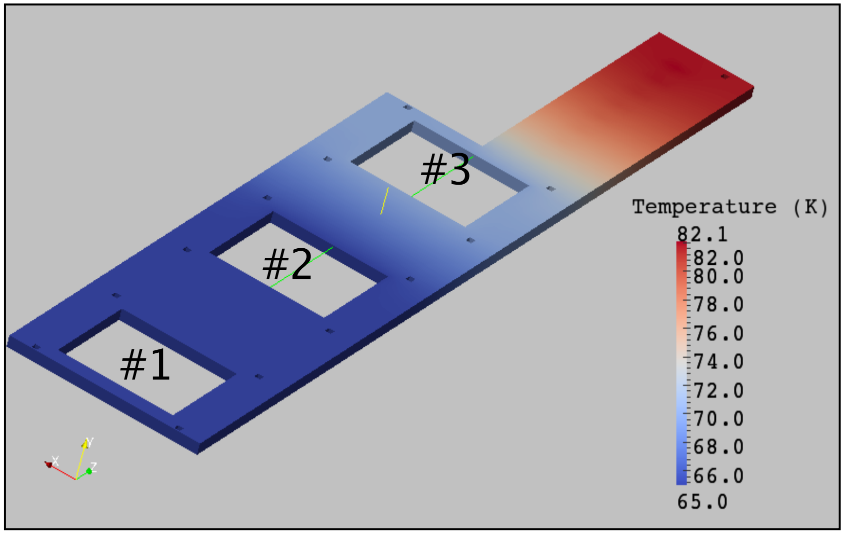




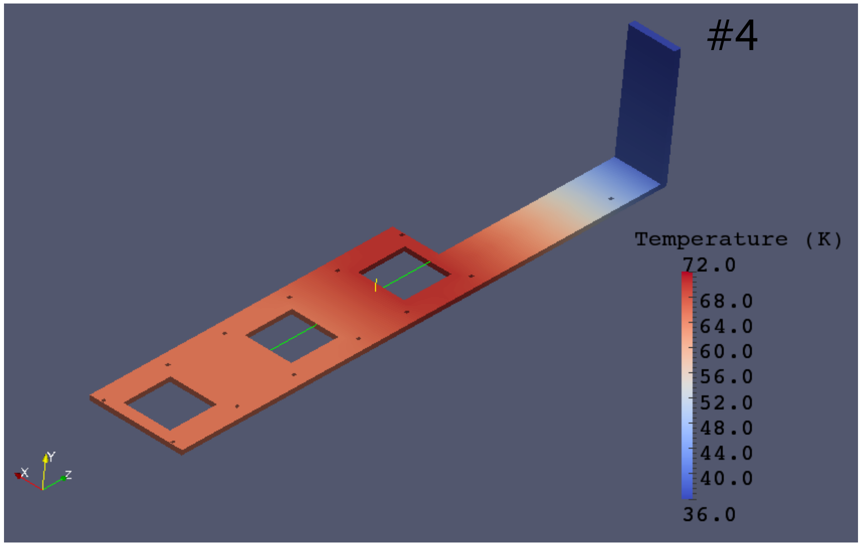


Copper plate and fourth cryocooler (2/2)

- The questions being addressed:
  - Can we explain the temperature at the lead connection?
  - an a fourth cryocooler help improving the temperature profile at the lead connections?
- The fourth cryocooler will help sinking a part of the power coming from the leads freeing the third one.



3 cryocoolers



4 cryocoolers

Fourth cryocooler copper connection

- Temperature drop at the copper connection, due to heat load.
- Pure conduction:

$$\phi = -Ak\frac{dT}{dz}$$

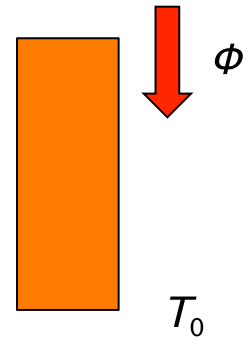
- Solution:

$$T(z) = \frac{|\phi|}{Ak}z + T_0(|\phi|)$$

- Fourth cryocooler characterisitic:

$$T_0(\phi) = a\phi^2 + b|\phi| + c$$

Assumptions:
-Steady state
-The cryocooler takes full load assuming no other coolers.



Heat flux, Φ (W)	100
a (K/W²)	5.93e-4
b (K/W)	0.106
c (K)	14.8
Section (m²)	0.0038
Length (m)	0.2
Sink temperature, T_0 (K)	31.4
ΔT (z=0.2 m) (K)	13.2
T @ Cu plate (K)	44.5

Recommendations

- “Letting cost and time frame aside”.

- Based on the previous analysis, the following items may be addressed:

  - ✓ Improvement of the connection between the copper plate and the thermal shield: material of better thermal conductivity, minimizing the distance, thicker walls.

  - ✓ A quality control may be imlemented to ensure proper welds between the various components critical to transfer heat from the shield to the cryocoolers: maximum contact areas, full solder penetration)

  - ✓ The current leads location may be better optimized to share the load over all the cryocoolers.

  - ✓ Appropriate location and number of thermal sensors and voltage taps must be further estimated: calibration of thermometry, defining salient parameters, ensuring that critical joints and components are covered.

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