Modeling of heat transfer in an accelerator superconducting coil with a ceramic insulation in supercritical helium

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Outline

- Motivation
- Description of ceramic insulation

Experiment

- Stack of conductors
- Set-up
- Experimental Results

Thermal Modeling

Full model

- Geometry and mesh
- Domains, boundary conditions
- Numerical Results

„Conduction” model

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Motivation

- Decreasing of temperature rise in superconducting cables;

- From our experimental results the heat transfer of the dissipated heat from the cables to the cold mass in pressurized superfluid helium improves about 30 times,

- Some magnets are operated in supercritical helium - J-PARC

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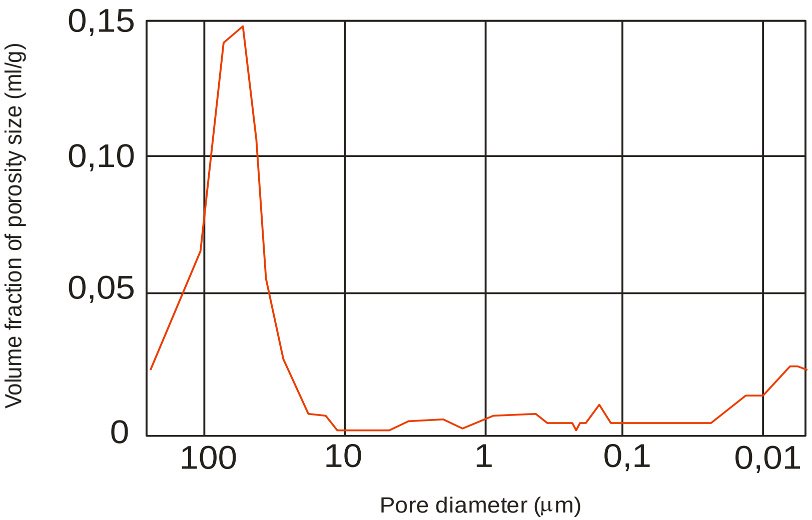
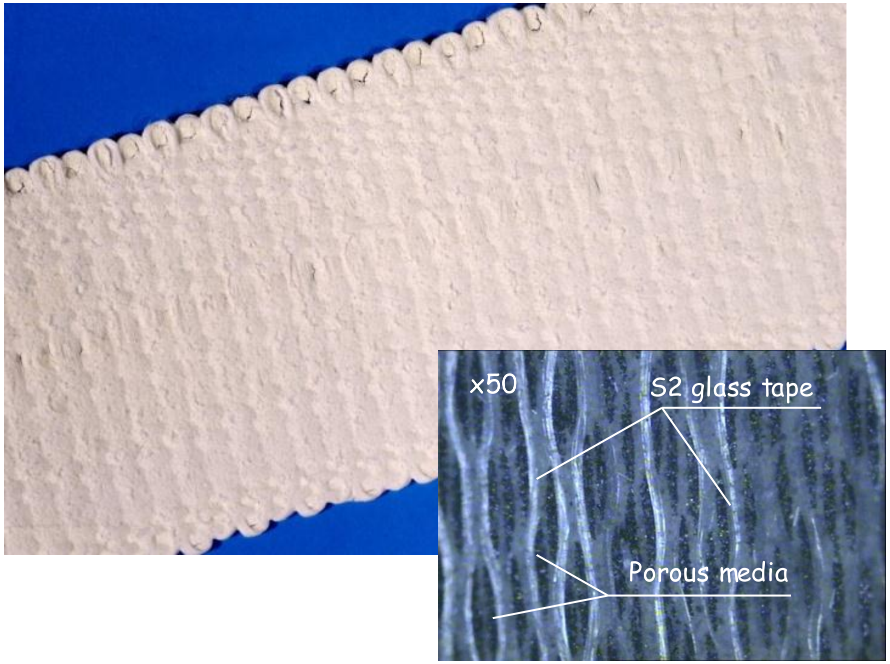
Description of ceramic insulation

The comparison of insulation materials

	Ceramic (S2 -glass)	Classic (Polyimide)	Full impregnation
Pore size	d~70 µm (peak)	10 to 100 µm	-
Porosity ε	4.5 to 29 % (~ 19%)	~1 %	-
Conductivity	k≈4 10^{-2} W/Km (??)	k_{kapton}≈10^{-2} W/Km @ 2 K	- k_{epoxy}≈10^{-2} W/Km



The pore diameter vs. volume fraction of porosity size, the data obtained using mercury injection technique



S2 glass tape + porous media

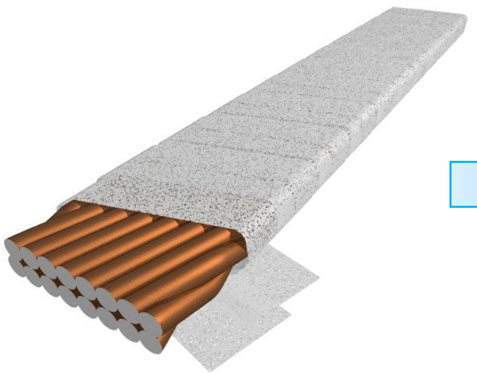
Stack of conductors

Ceramic insulation

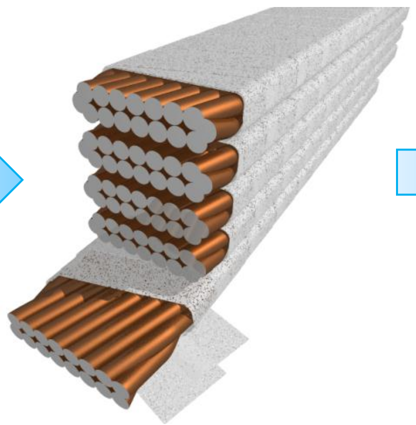
- Two wrapping layers, with an overlap of 50% each other
- S2 glass tape + porous media - 0.1 mm thick and 15 mm wide
- Heat treatment about 100 hours at 660 °C

Compressive load

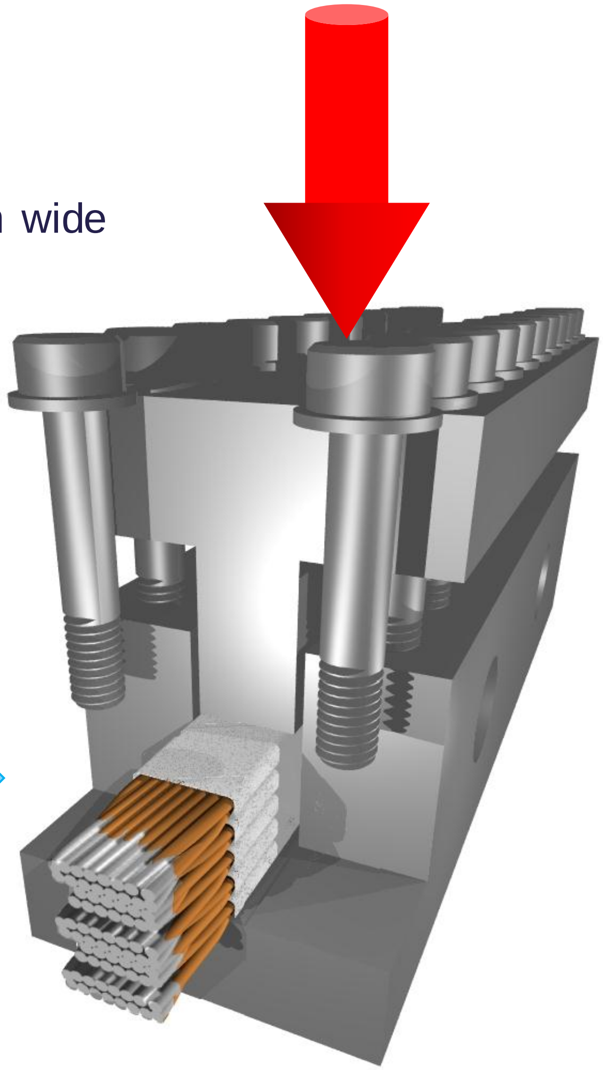
- **10 MPa** and **20 MPa**



NiCu Cable with insulation



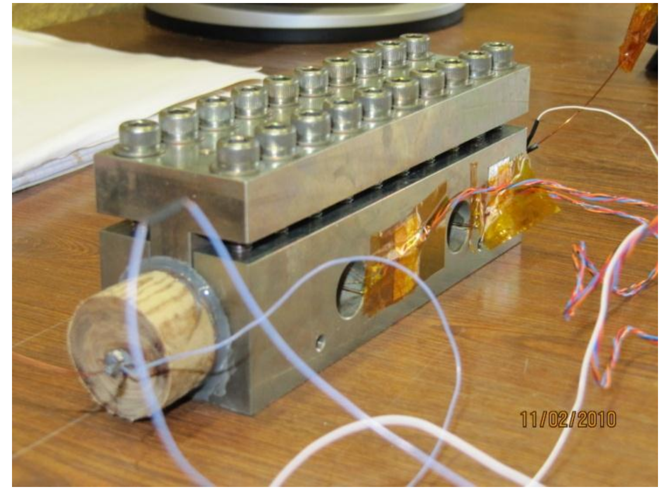
Stack of conductors

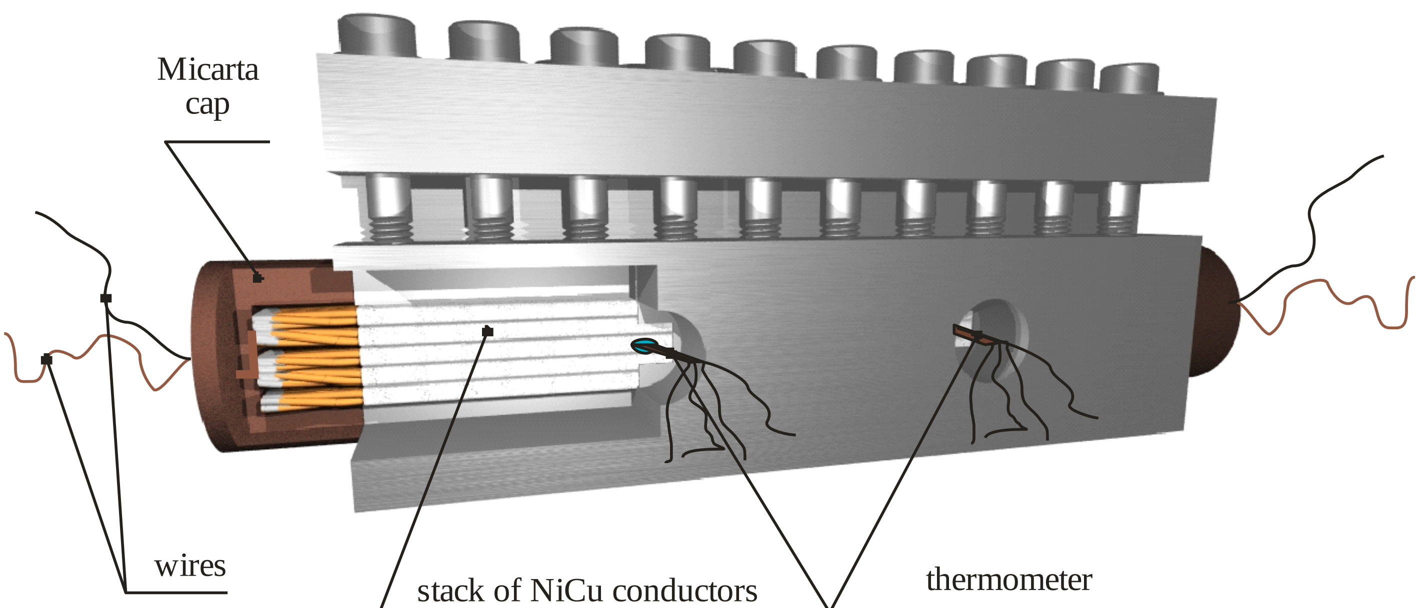


Stack in the mold

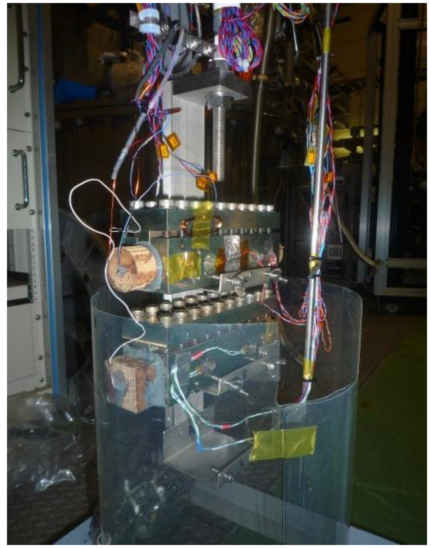
Stack of conductors

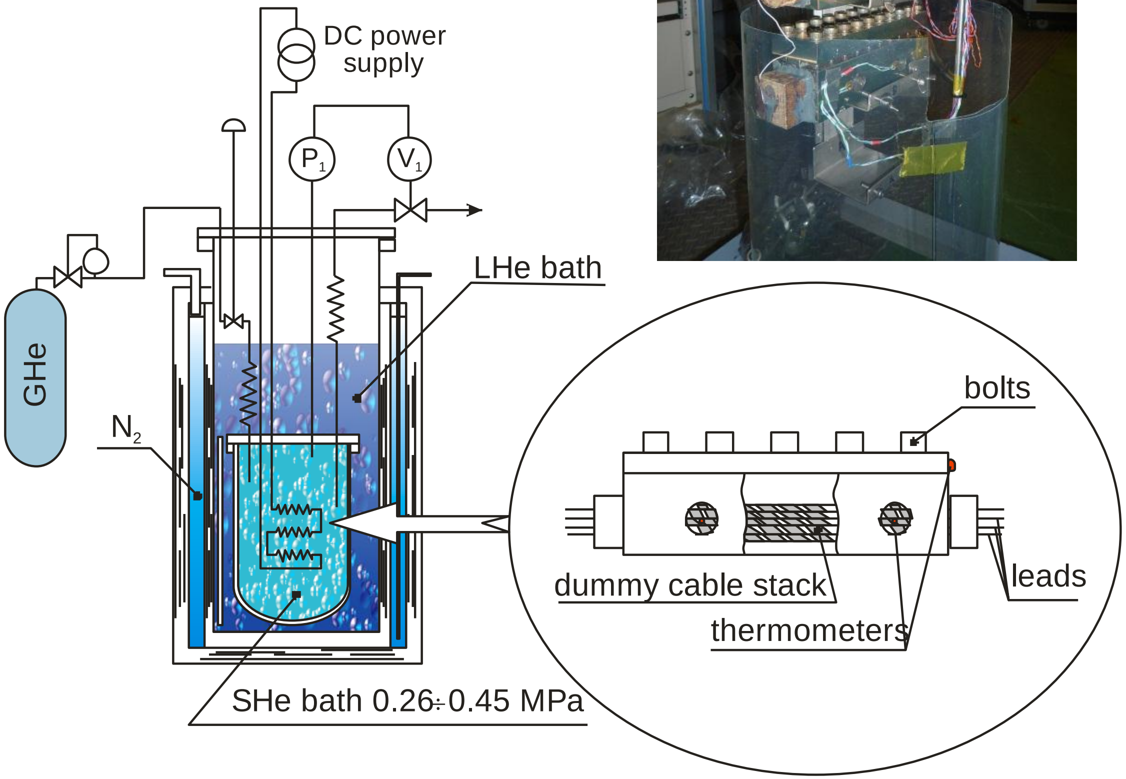
- 5 pseudo-conductors stack (made of CuNi)
- All conductors connected in series: 9 mΩ
- Supplied current range: 0 – 25 A
- Dissipated heat load: 0 – 5 W/m
- Installed two temperature sensors at conductor III (at the center)





Experimental set-up

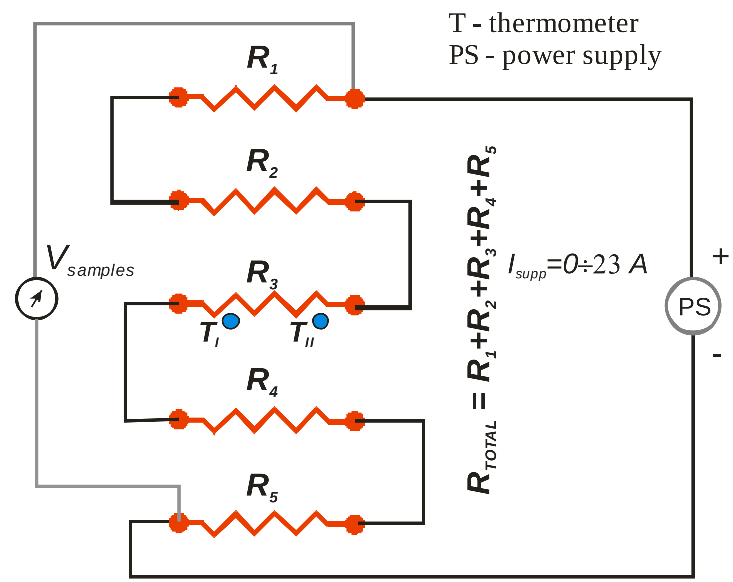




P – pressure transducer

V – pressure control valve

Electrical circuit for Joule Heating



Measured parameters:

1. Current on power supply;
2. Voltage on stack of conductors;
3. Voltage on temperature sensors (CERNOX™);

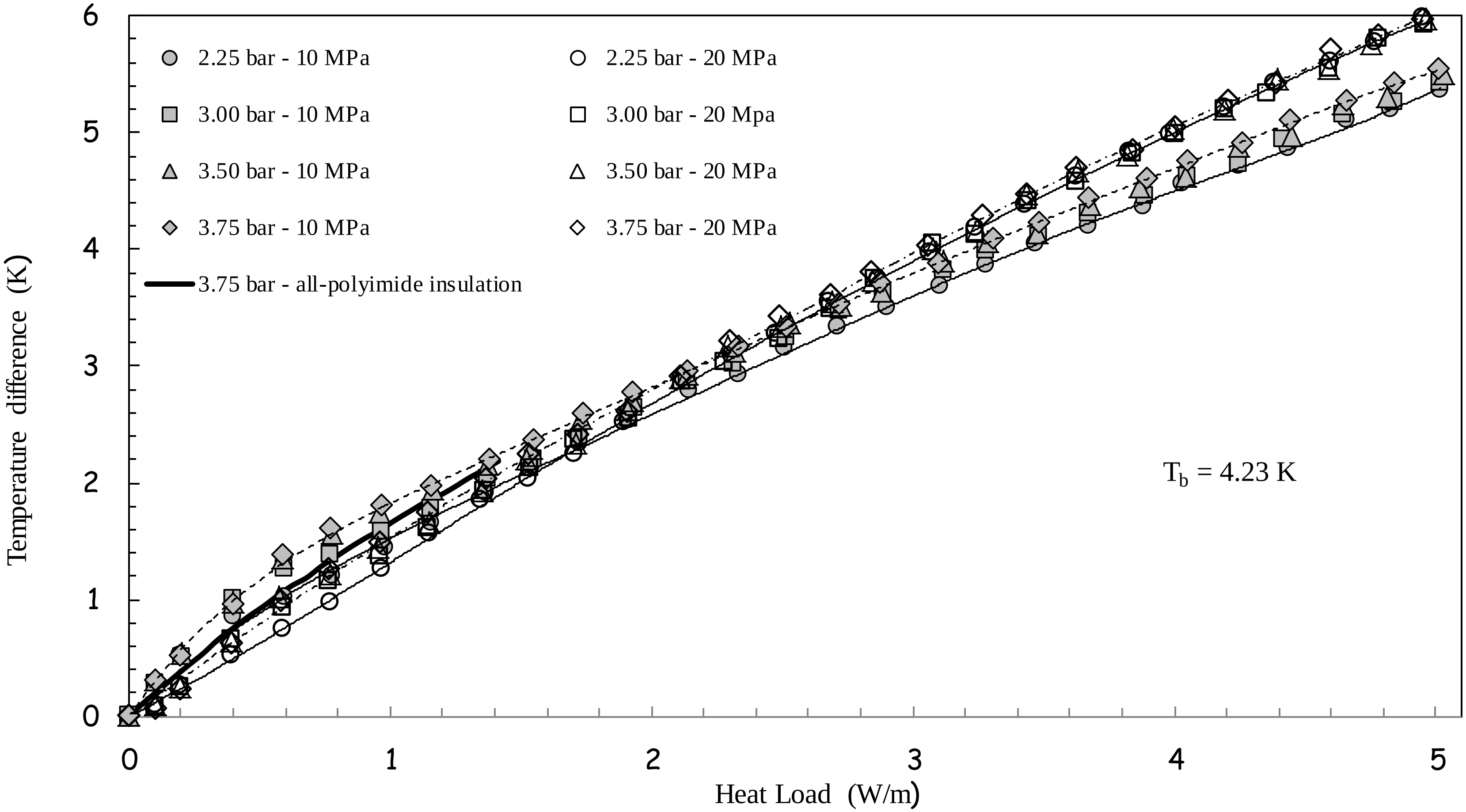
Experiment at supercritical helium

- Two stacks of samples were tested in supercritical helium (T=4,23K and p varying from 2,25 to 3,75 bar with a 0,25 bars step);

- Heat was dissipated in 27 steps in range from 0 to 5 W/m;

- The steady state condition was obtained after 240 sec.

Experimental results in supercritical helium



Evolution of temperature difference for the 10 MPa and 20 MPa experimental molds with ceramic insulation in saturated and supercritical helium (dotted lines show the results obtained for the highest value of 3.75 bar absolute pressure, solid lines concern the lowest value of 2.25 bar absolute pressure, bold solid line depicts the results obtained for all-polyimide insulation at supercritical helium of 3.75 bar)

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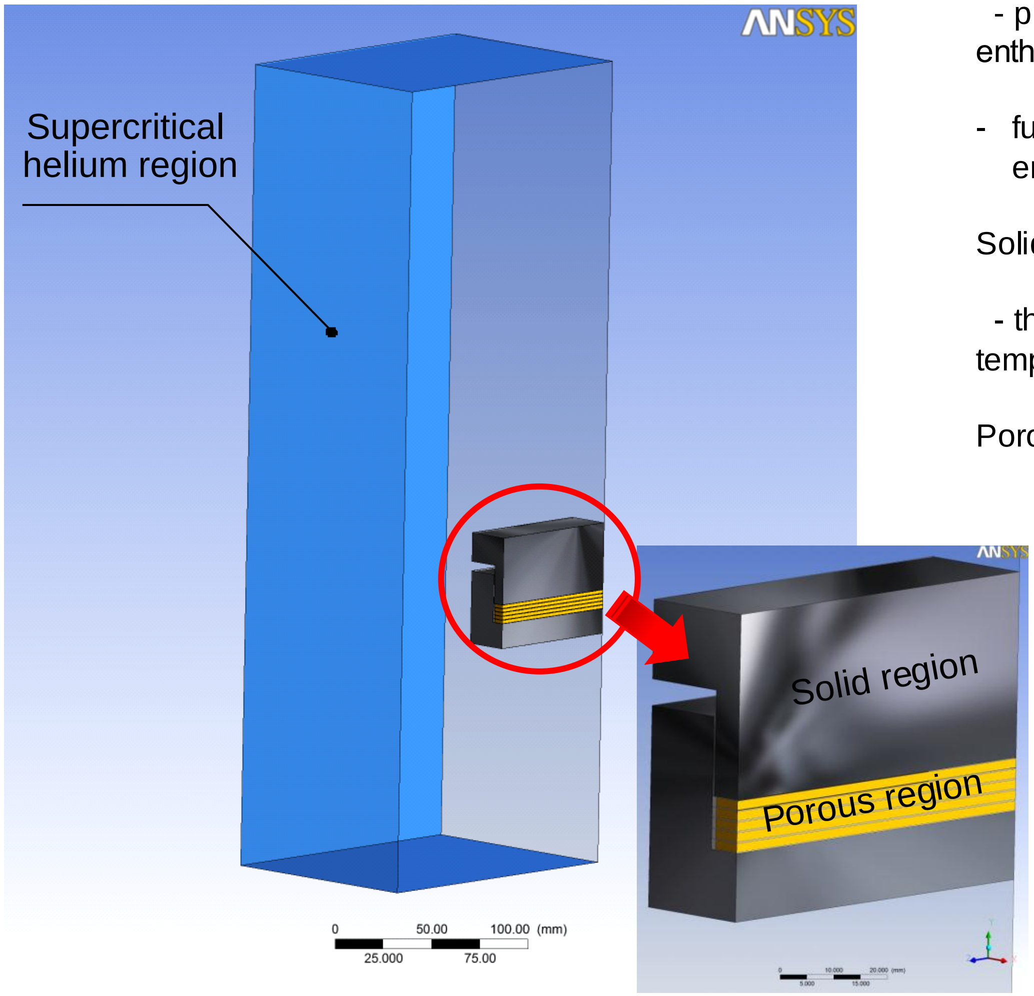
Numerical modeling – full model

□ Geometry and boundary conditions



Appiled geometry with the details of mock-up

Supercritical helium region:
- properties of the fluid (k, c_p, viscosity, entropy, enthalpy, etc…) are taken from Hepack (*.rgp file)

- full model of the flow (continuity, momentum and energy equations),

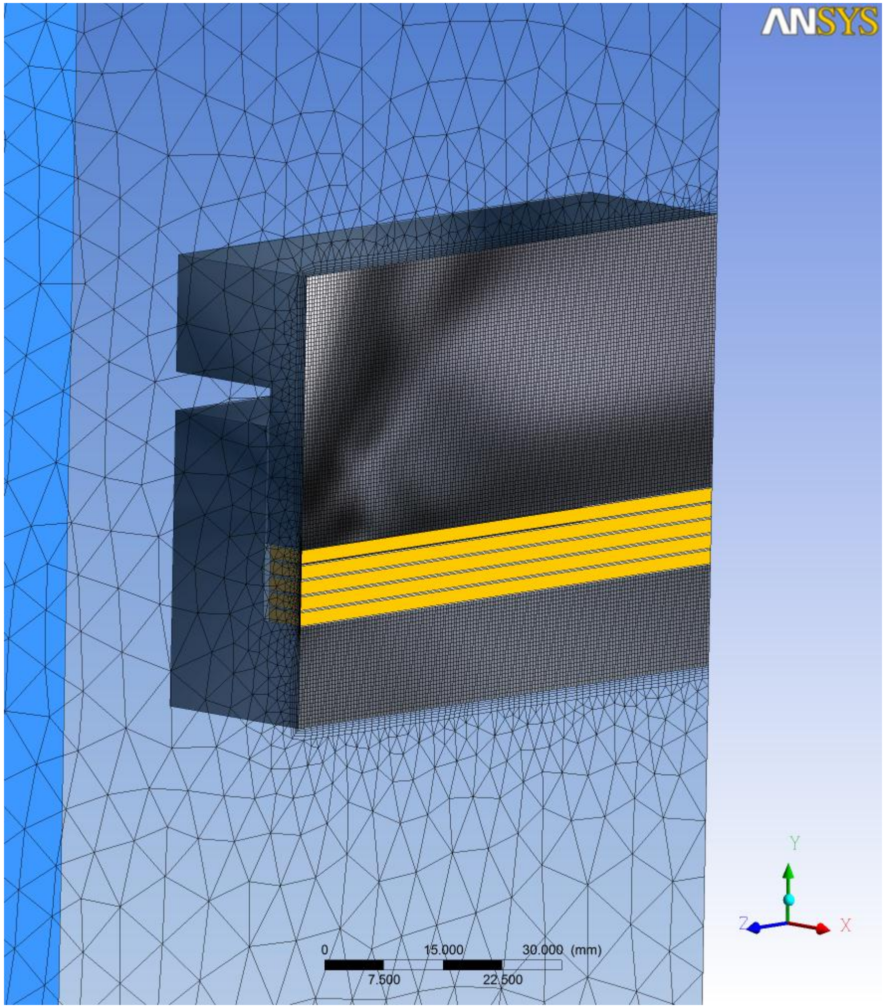
Solid region:

- thermal properties (k) are a function of the temperature.

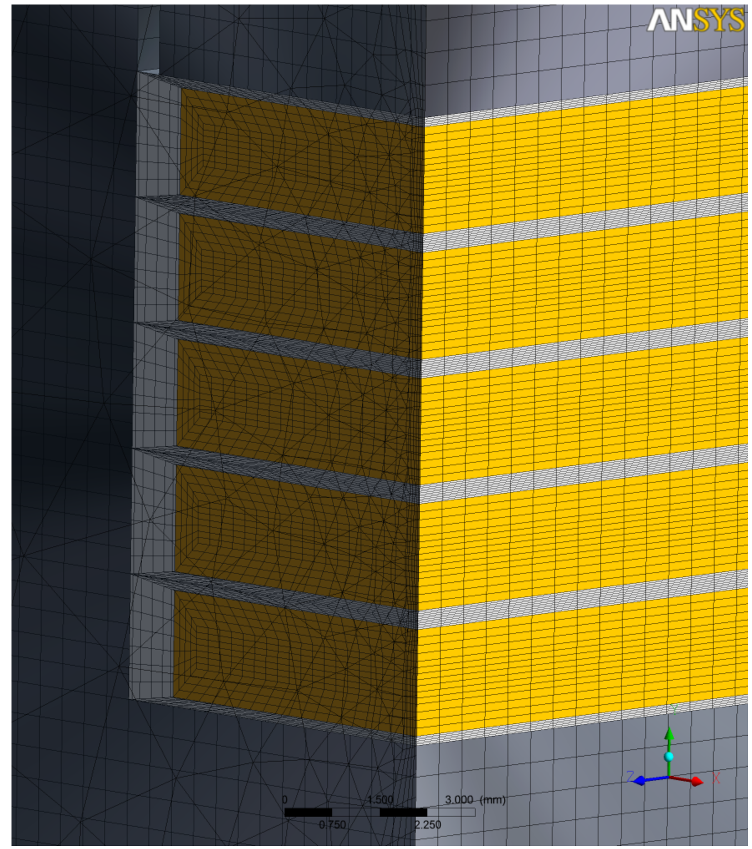
Porous region:

- the porosity of the cable – 0,08
- the porosity of the insulation – 0,12 for 10 MPa and 0,10 for 20 MPa of compressive load;
- the heat transfer coefficient between solid and fluid in the insulation region – 250 W/m^2 K in cable – 200 W/ m^2 K;

Mesh



General view of fluid and experimental mold

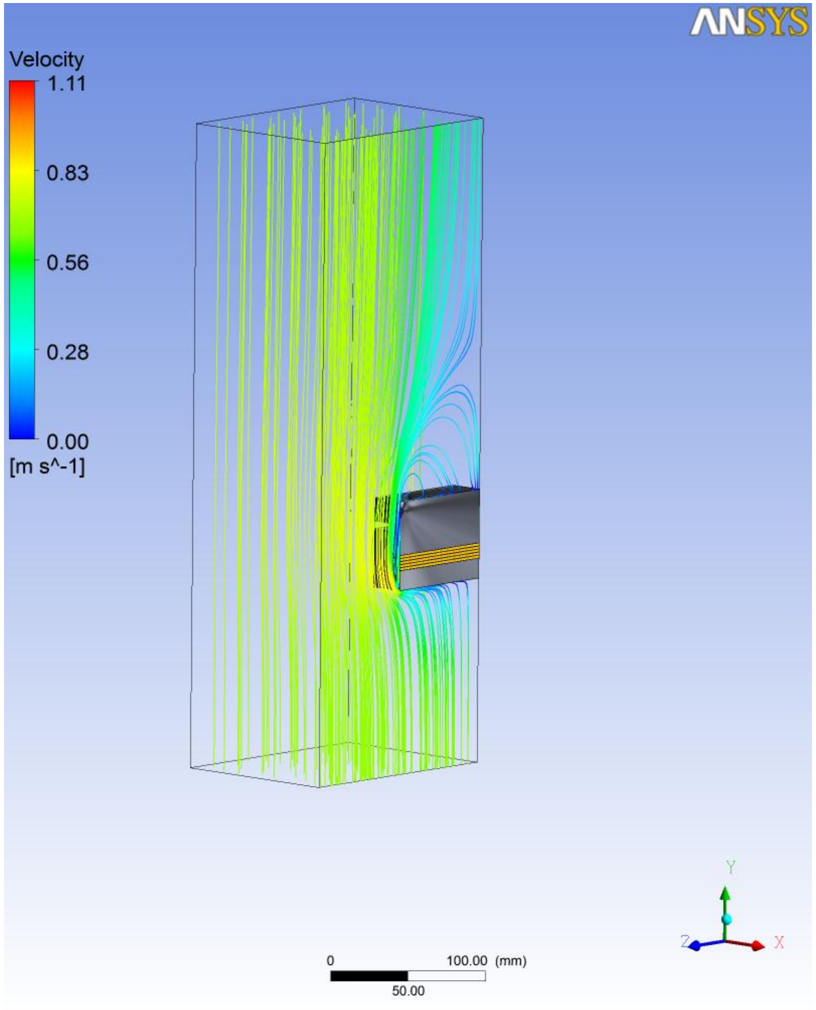


The details of applied mesh

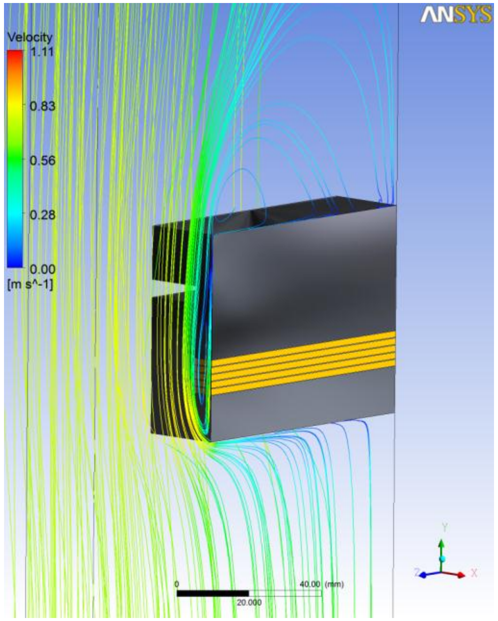
1,5 mln of nodes
1,8 mln of elements

The combination of structural (solid elements) and unstructural (fluids) meshes

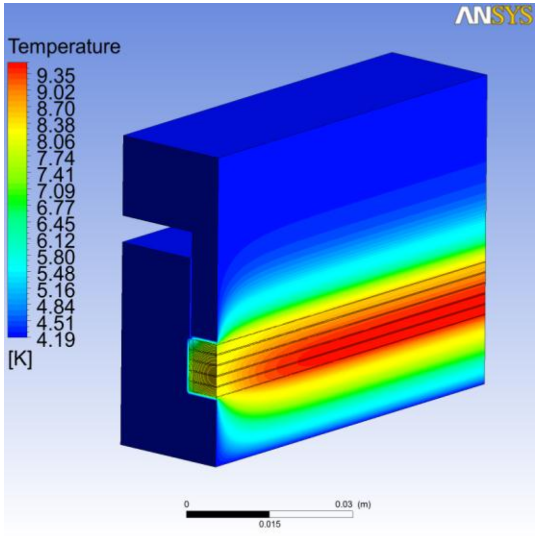
Numerical results for full model



The streamlines of supercritical helium at 3.0 bars and 4.955 W/m heat load



Detail of the streamlines around experimental mock-up



Temperature distribution on the walls and symmetry sides

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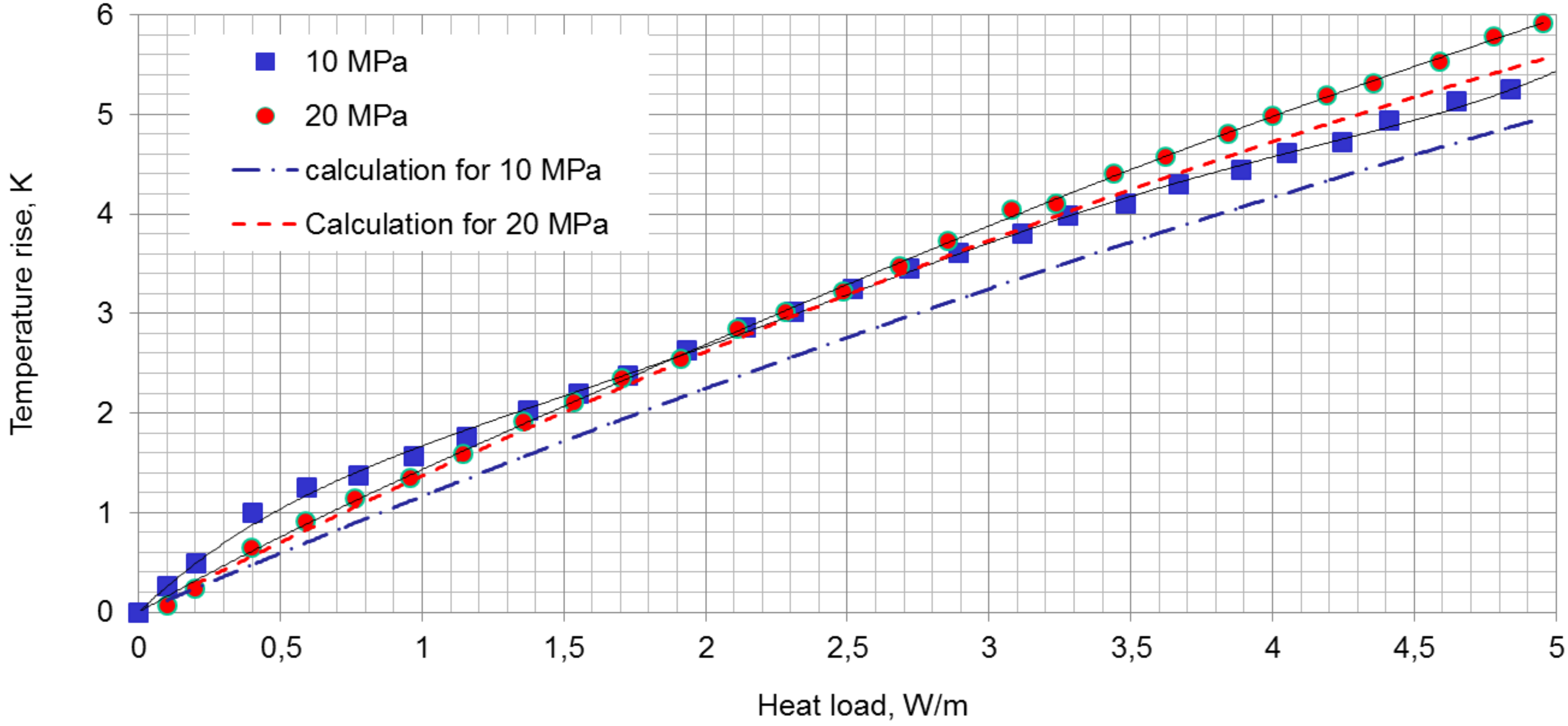
Full Model – numerical results at 3.0 bar



Conclusion:

1. Good agreement between experimental and numerical results (especially for 20 MPa);
2. Long computational time – about 1 day for one point,

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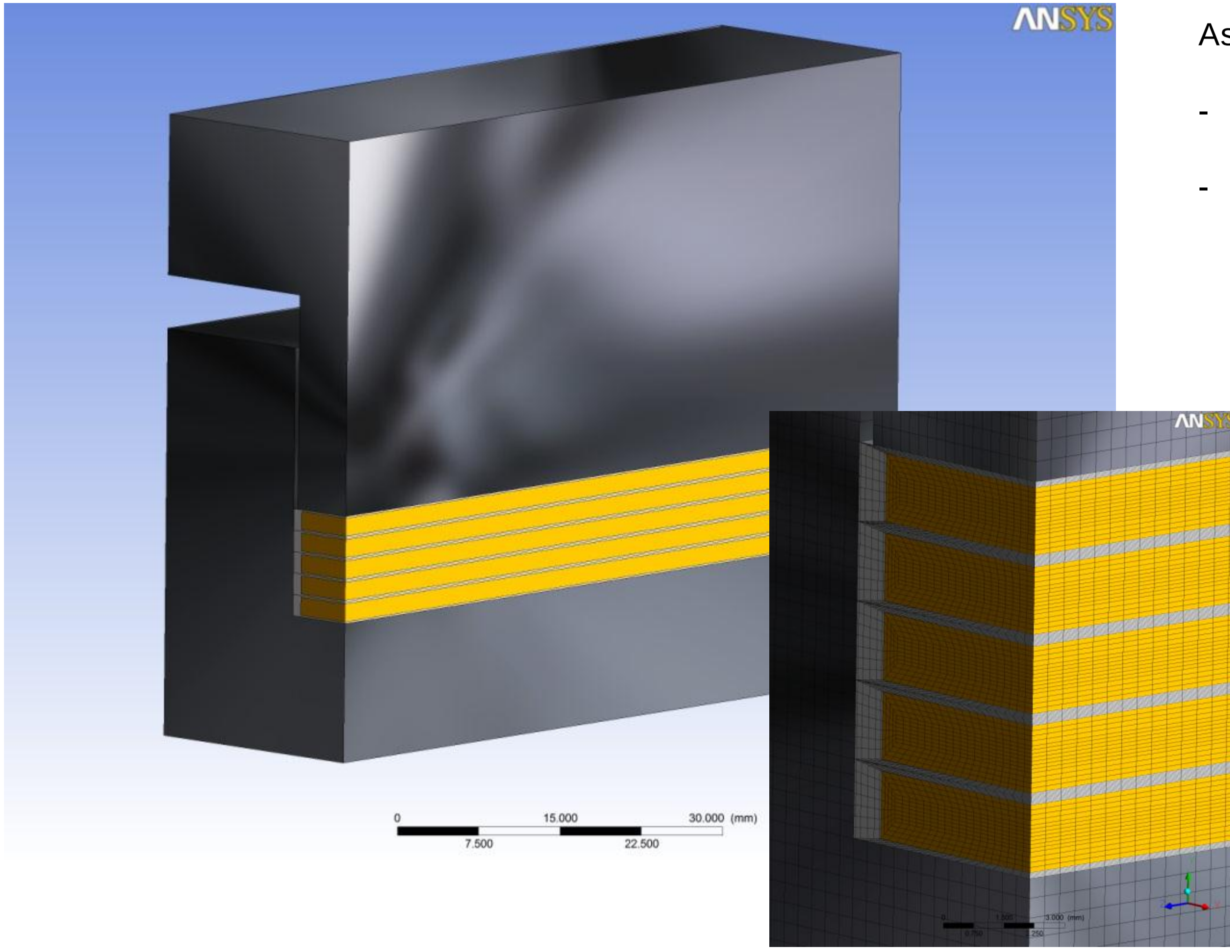
Simplified model – „conduction” model



The „conduction” model used during calculation and detail of the mesh

Assumptions:

- all elements are treated as the solid domain;
- thermal conductivity of the insulation and conductor are calculated according formula:

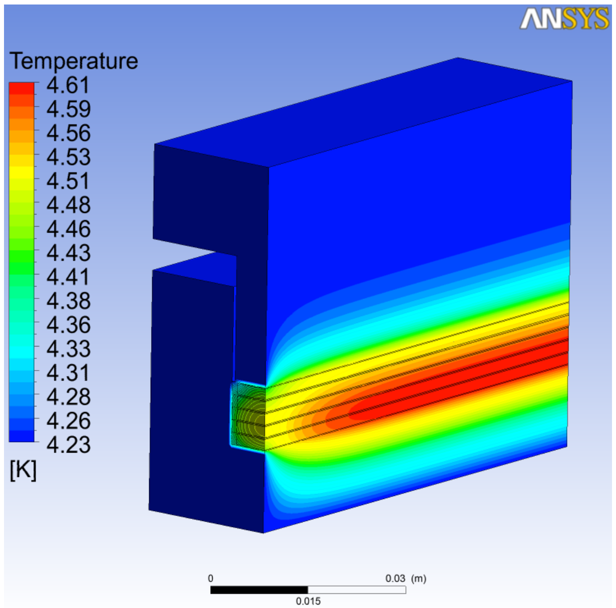
$$k_{total} = k_{solid}\,(1-\varepsilon) + k_{SHe}\,\varepsilon$$

Where:

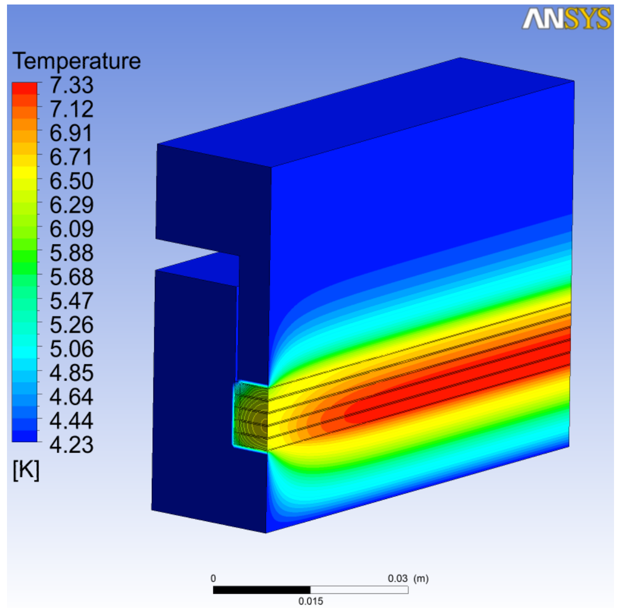
k_{solid} – thermal conductivity of solid
k_{SHe} – thermal conductivity of supercritical helium
ε – porosity.

The time of calculation about 15 min.

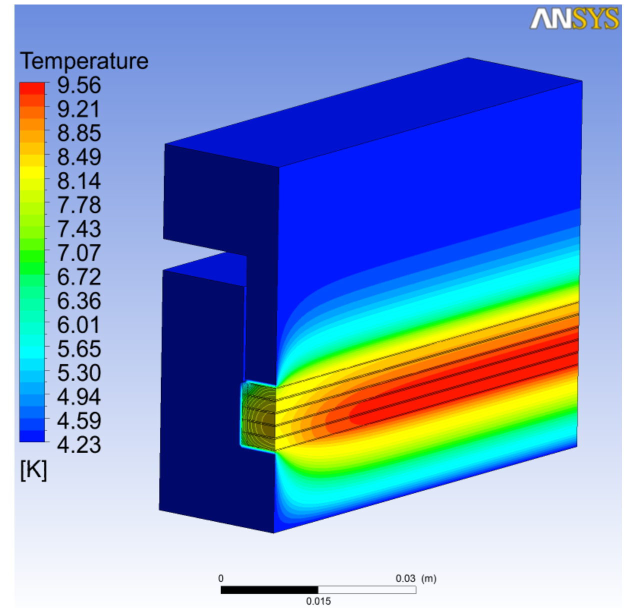
Numerical results – „conduction” model



q = 0.198803 W/m

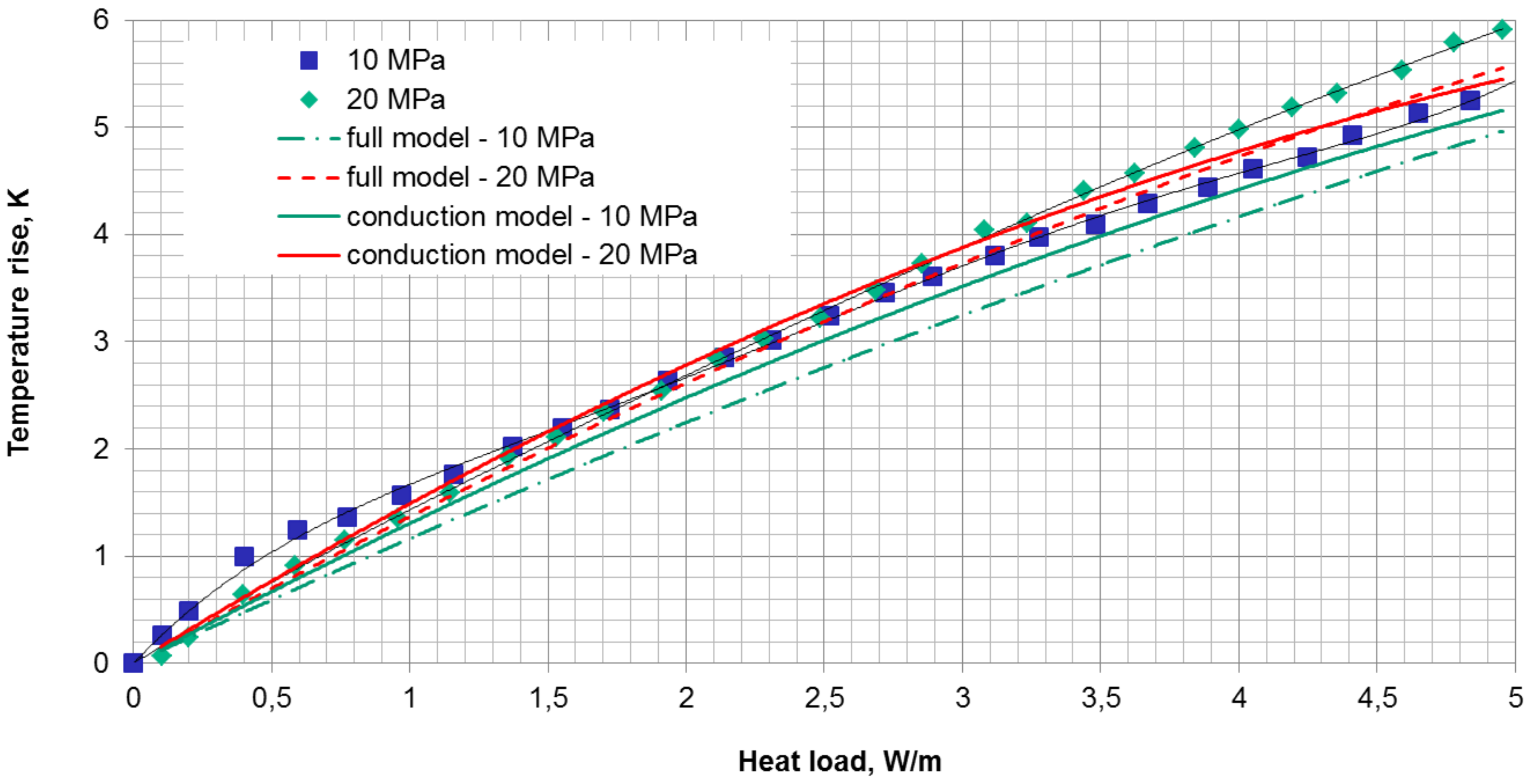


q = 2.4865 W/m



q = 4.9559 W/m

The distribution of the temperature for the heat load - a) 0.198803 W/m b) 2.4865 W/m and c) 4.9559 W/m
(the thermal conductivity of the SHe is taken for 3.0 bar of absolute pressure)



The comparison between full model, conduction model and experimental data for 3.0 bar of absolute pressure

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Conclusions

- The measurements of the temperature rise in the cable with ceramics insulation have been performed in the range up to 5 W/m of heat load.
- The full model (with flow in the porous media) gives very good agreement with experimental data but consumes a lot of calculating times.
- The good approximation of the thermal – flow process in the porous insulation is model based on the assumption that dominated mechanism of the heat transfers is conduction. The thermal conductivity of insulation materials can be changed by the simple formula

$$k_{total} = k_{solid}\,(1-\varepsilon) + k_{SHe}\,\varepsilon$$