The heat transfer characteristics of classical insulation system under saturated and supercritical

Nobuhiro KIMURA, Sławomir PIETROWICZ
High Energy Accelerator Research Organization (KEK)
/Cryogenic Science Center, Tsukuba, Japan

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- Calibration of temperature sensors
- Conduction heat through the insulation:
  - Experiment in vacuum
  - Mathematical model of process
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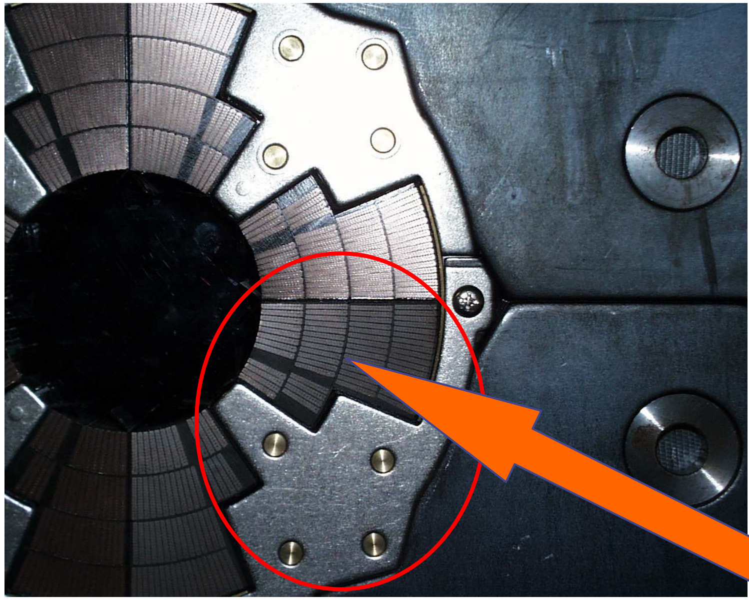
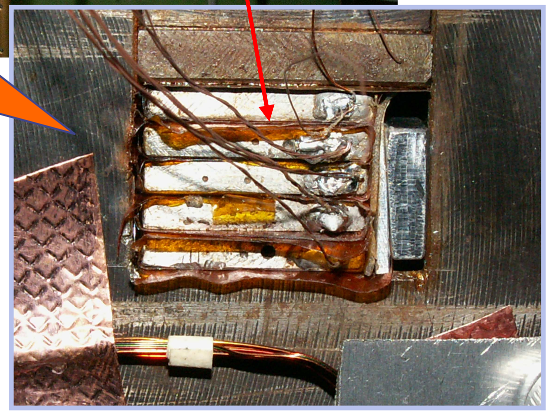
  - ✓ saturated helium (He I)
  - ✓ supercritical helium (SHe)
- Description of convection heat transfer at saturated and supercritical helium
- Summary and future plan

Experimetal set-up at KEK

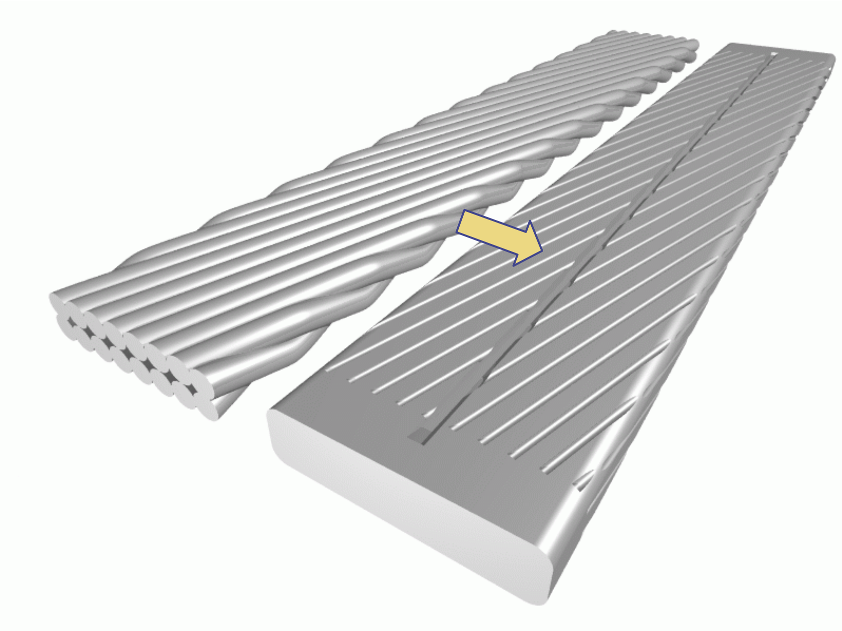


Cross section of LHC/IRQ magnet

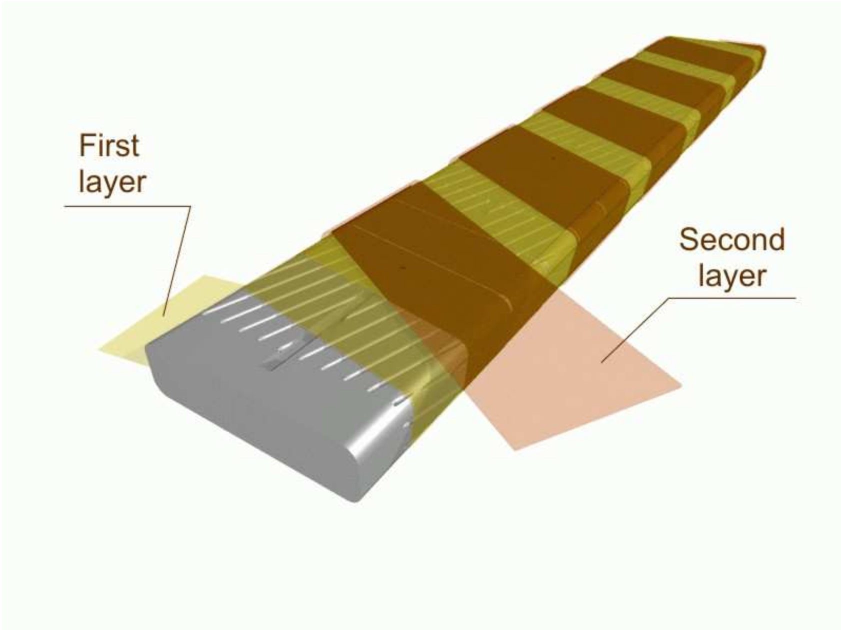


The holder

Cable structure



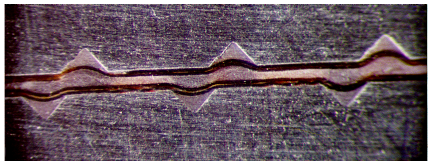
The real and tested mock-up



Description of the tested cable

Real cable

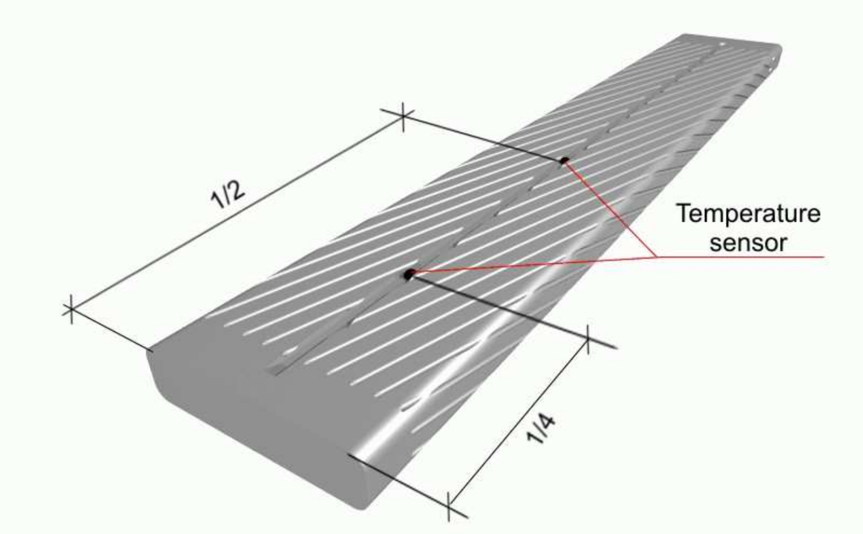
Tested cable



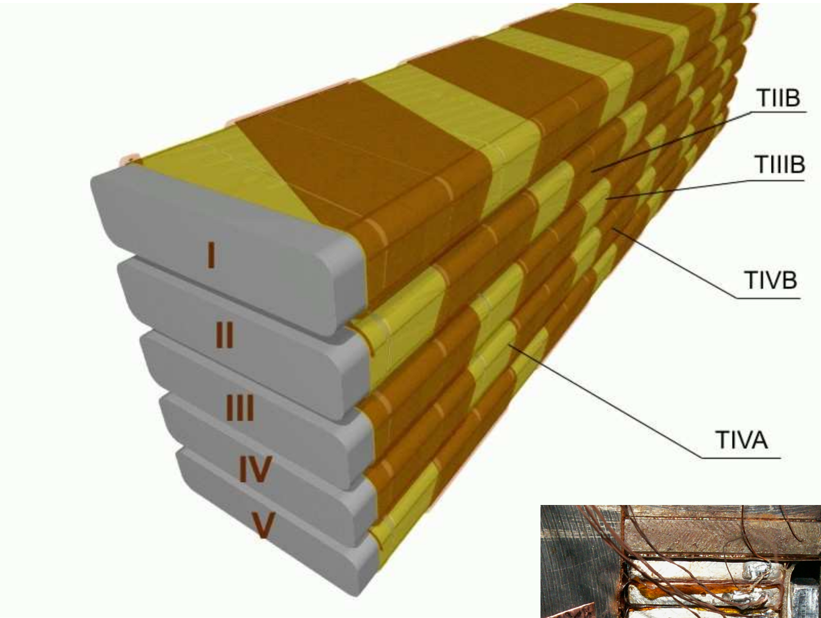
B. Baudouy

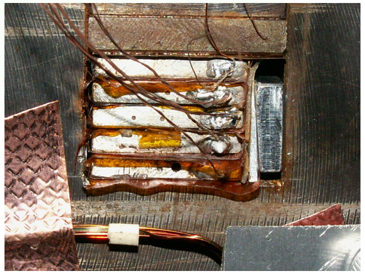
- *1st layer: Kapton 200 HN (50 µm x 11 mm) in 2 wrappings (no overlap)*
- *2nd layer: Kapton 270 LCI (71 µ m x 11 mm) with a 2 mm gap*
- *Thermal treatment at 170° C for polymerisation*

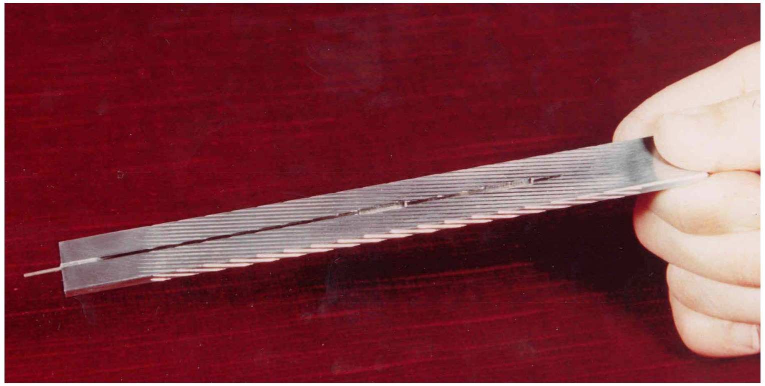
The stack of tested cables and temperature sensors



The installation places of Allan Bradley temperature sensors





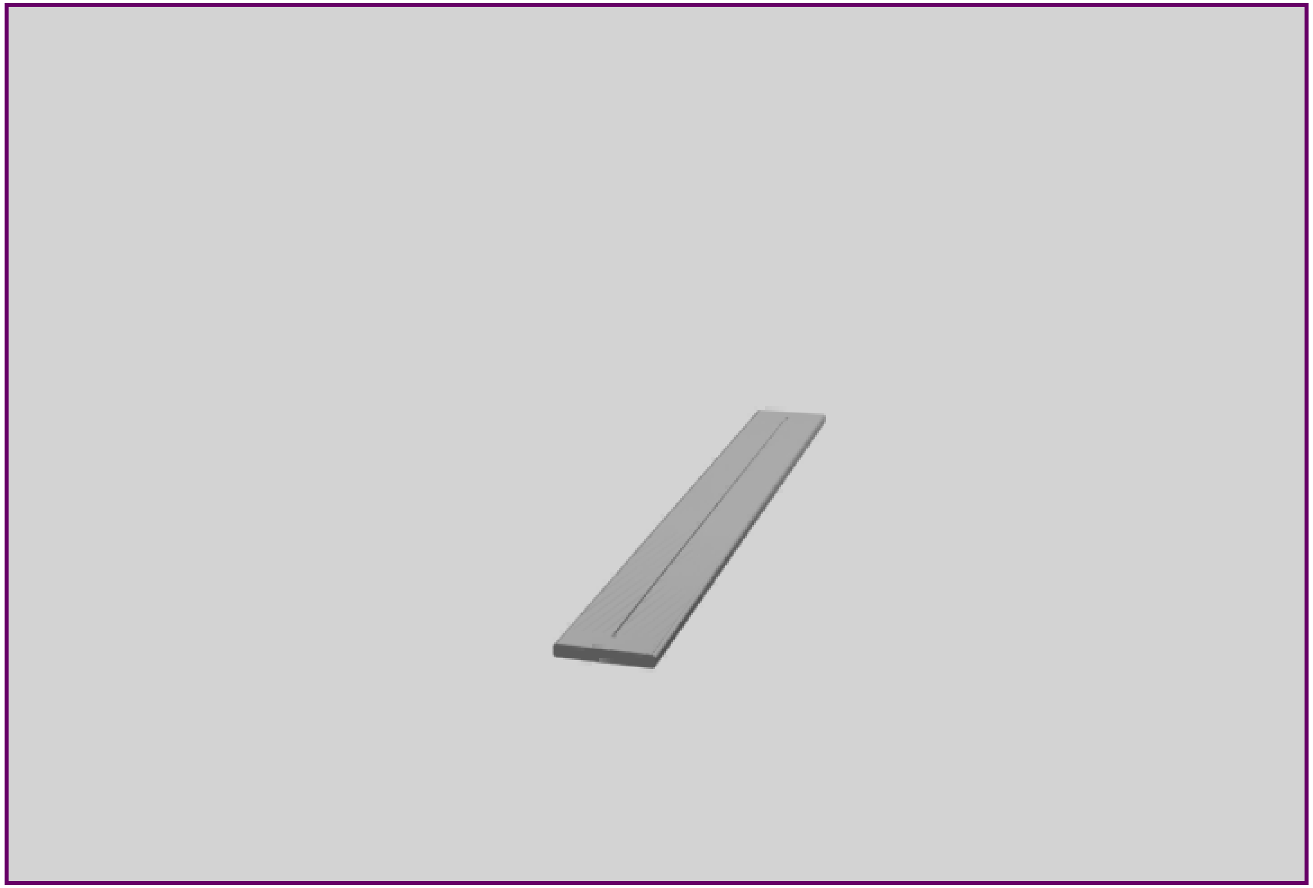


B. Baudouy

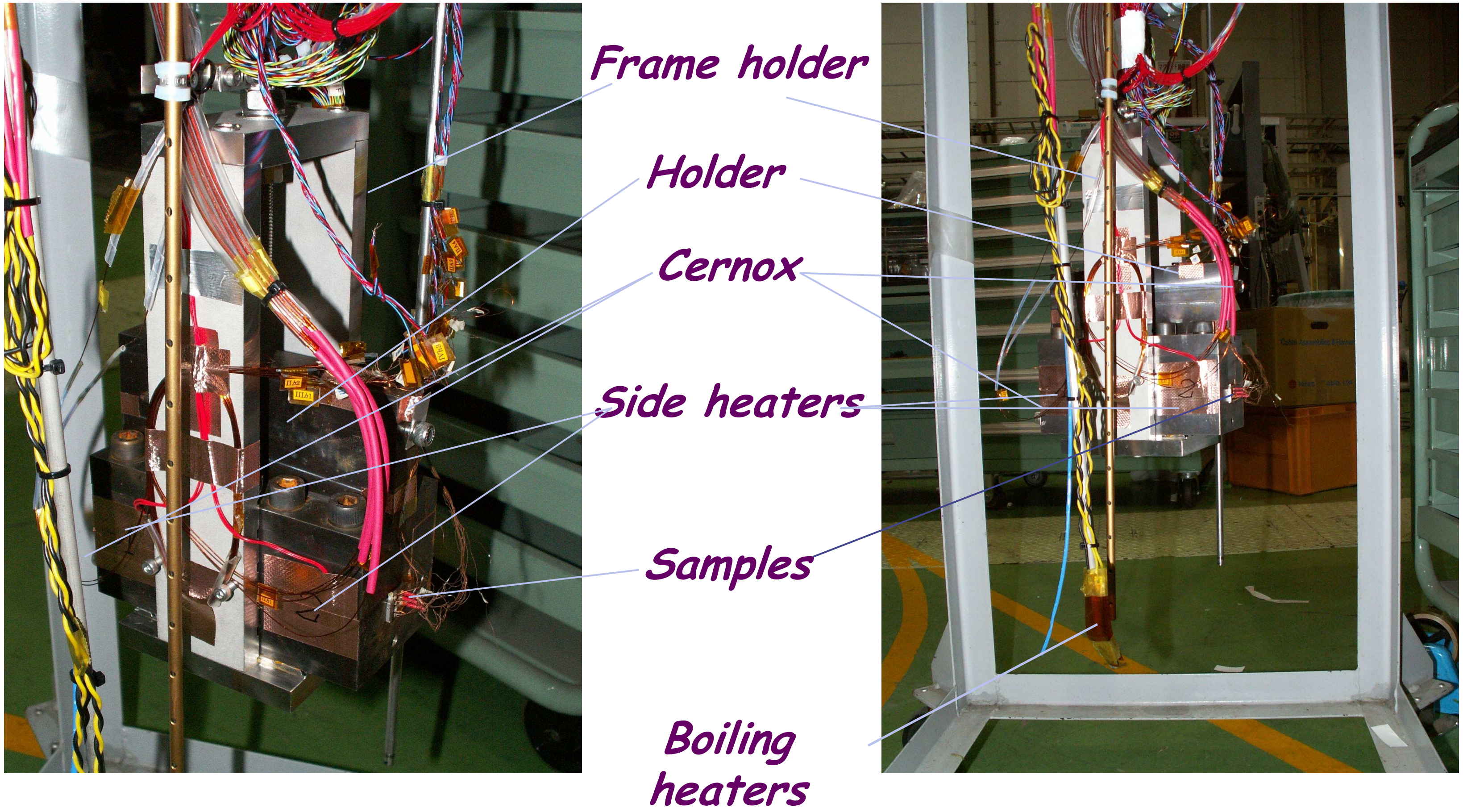
Geometrical and material description of tested stack

Material	Stainless Steel
Cable cross section	2.56 mm X 17 mm
Length	150 mm
Insulation Material	Polyimide

Holder (made at Saclay)



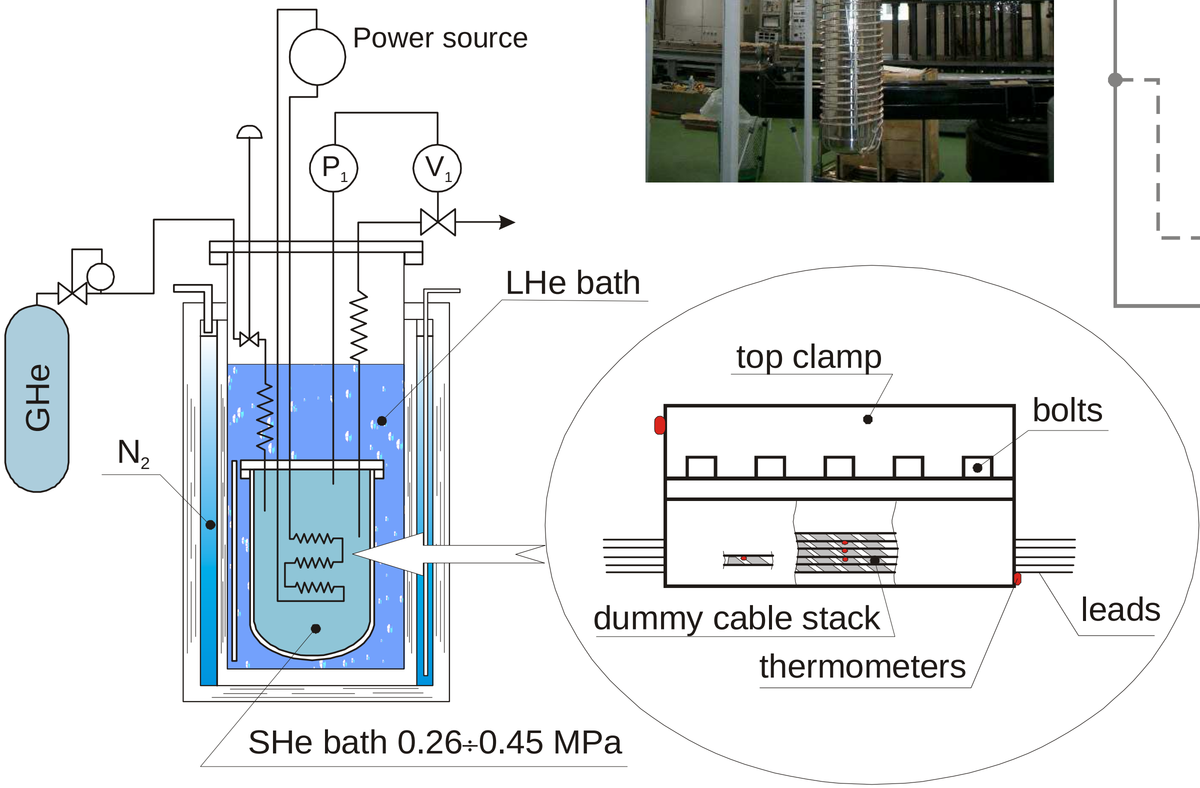
Experimetal set-up at KEK



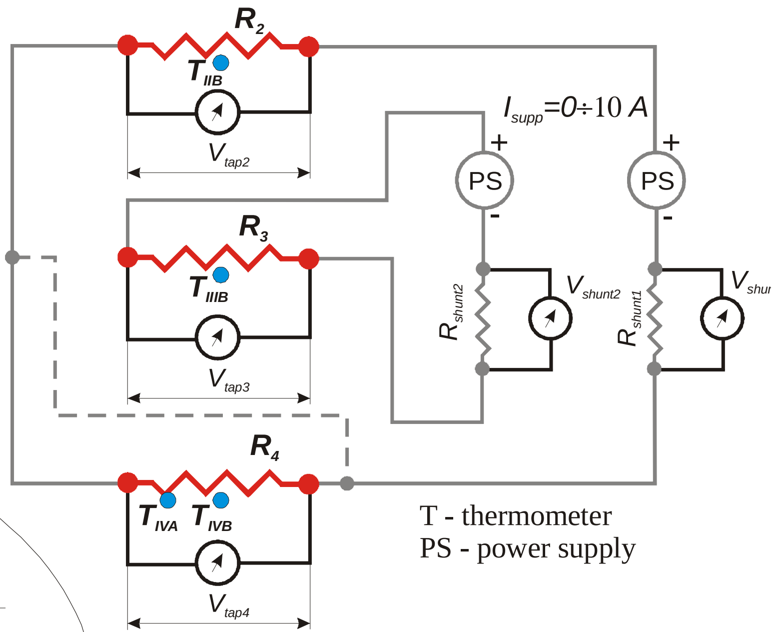
Cryostat and electrical circuit

P_1 – pressure transducer

V_1 – pressure control valve

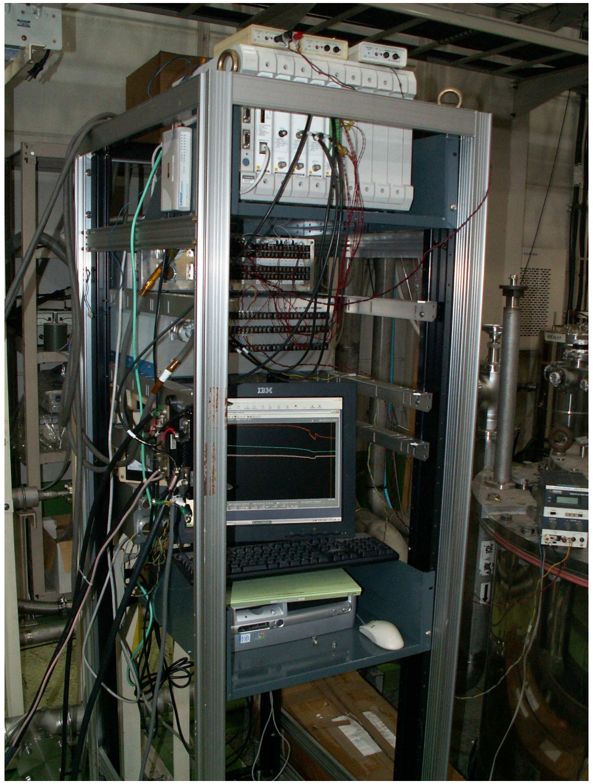


Electrical circuit for Joule Heating



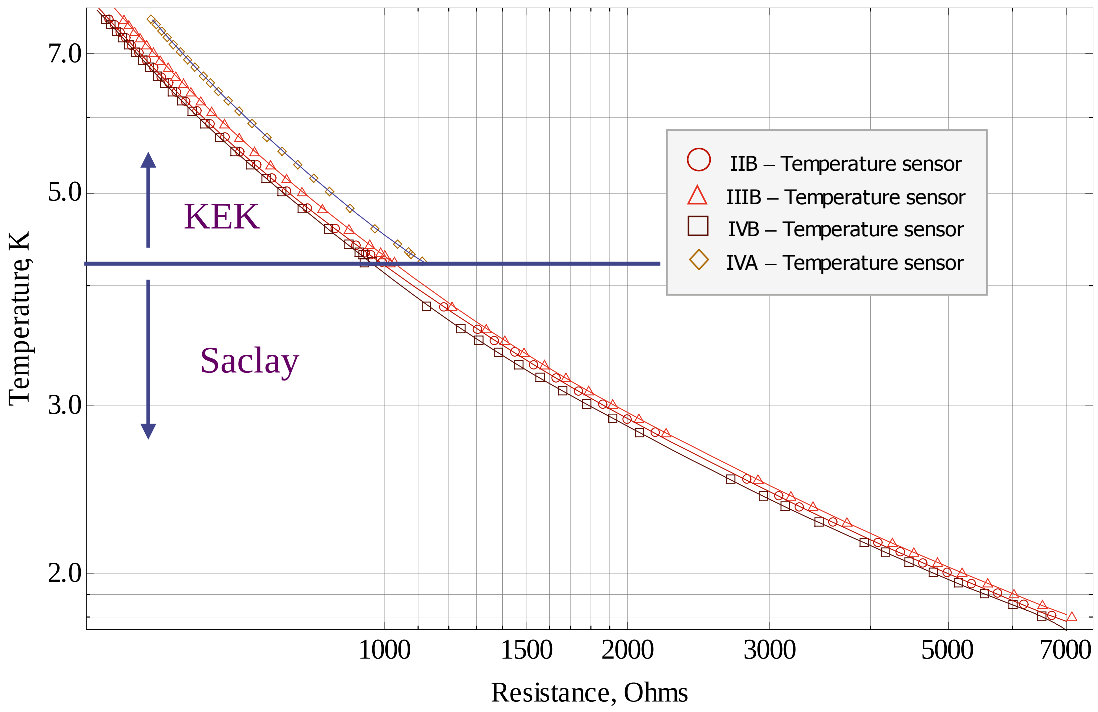
During the tests four temperature sensors, two Cernox sensors, current and voltage were acquired on the three samples

Experimetal set-up at KEK

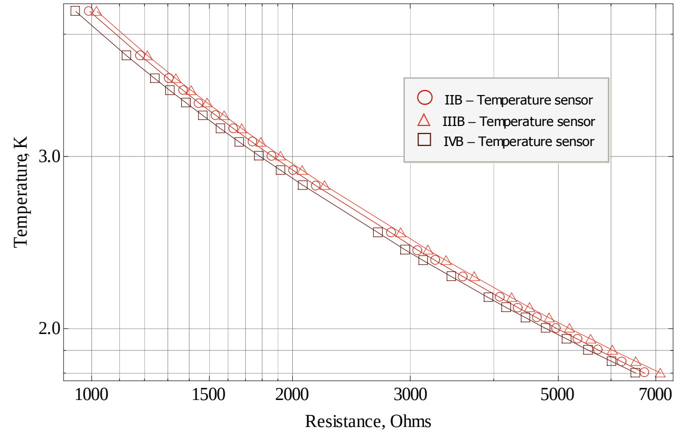


The details of measurement system

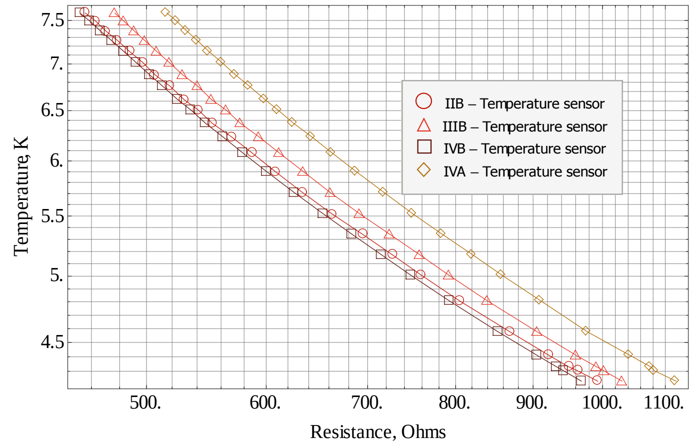
Calibrations of temperature sensors



The relation between resistance and temperature with the approximated functions



The calibration data obtained at Saclay (1.8 K – 4.2 K)



The calibration data obtained at KEK (4.2 K – 7.6 K)

Calibrations of temperature sensors

The Chebychev polynomial type was used for approximation of the data. The value of temperature was calculated using the formula:

$$Temp(K) = \sum_{n=1}^{i} A_n \cos(n \arccos(X))$$

where the parameter X was obtained from equation

$$X = \frac{(Z - Z_L) - (Z_u - Z)}{Z_u - Z_L}$$

and

$$Z = Log(\text{resistance})$$

Z_L - Lower limit of Log(resistance) used in computing Chebychev coefficients
Z_U - Upper limit of Log(resistance) used in computing Chebychev coefficients

IIB - Temperature sensor								
Useful range of fit		Temperature		1.8 K		7.58 K		
		Resistance		6736.4 Ohms		455.83 Ohms		
Lower and upper limits of Log(resistance) used in computing Chebychev coefficients:				Z_L		2.65881		
				Z_U		3.82843		
The Chebychev coefficients								
A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
3.82684	- 2.64141	0.796178	-0.234149	0.0697256	-0.0219728	0.00726667	- 0.00092183	-0.00341534

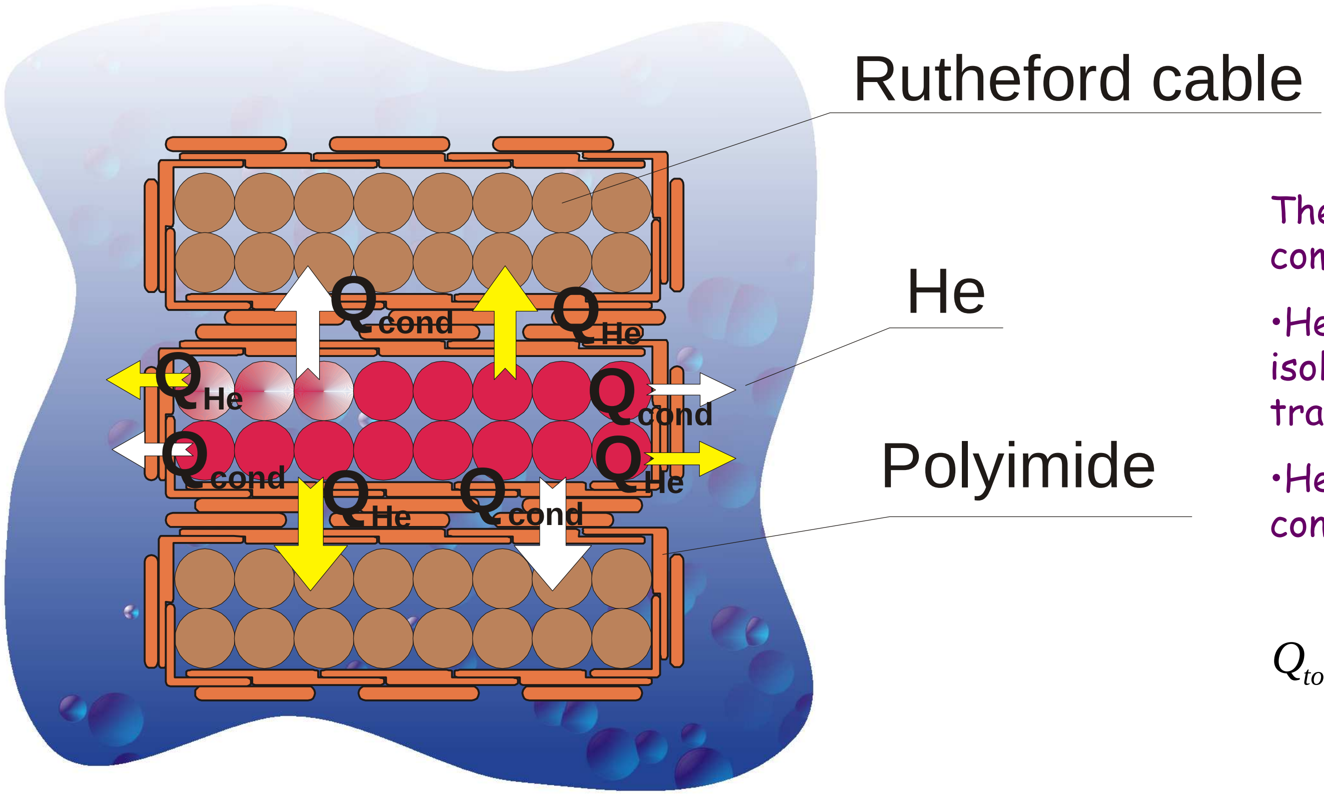
IIIB - Temperature sensor								
Useful range of fit		Temperature		1.8 K		7.58 K		
		Resistance		7124.484 Ohms		476.532 Ohms		
Lower and upper limits of Log(resistance) used in computing Chebychev coefficients:				Z_L		2.67809		
				Z_U		3.85275		
The Chebychev coefficients								
A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
3.81057	- 2.63415	0.808093	-0.237077	0.0666404	-0.0190007	0.00978455	- 0.00599556	- 0.000868823

IVB Temperature sensor								
Useful range of fit		Temperature		1.8 K		7.58 K		
		Resistance		6538.206Ohms		452.08 Ohms		
Lower and upper limits of Log(resistance) used in computing Chebychev coefficients:				Z_L		2.65522		
				Z_U		3.81546		
The Chebychev coefficients								
A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
3.81111	- 2.63848	0.815768	-0.240083	0.0647994	-0.016981	0.00942031	- 0.00686603	-0.00225587

IVA Temperature sensor								
Useful range of fit		Temperature		4.23 K		7.58 K		
		Resistance		1118.28Ohms		515.8786 Ohms		
Lower and upper limits of Log(resistance) used in computing Chebychev coefficients:				Z_L		2.71255		
				Z_U		3.04855		
The Chebychev coefficients								
A_0	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8
5.68348	-1.6542	0.221315	- 0.0253967	0.0077495	- 0.0000635265	0	0	0

The limits of temperature and coefficients used during calculations of temperature values

The identification of heat flux in Rutherford cables



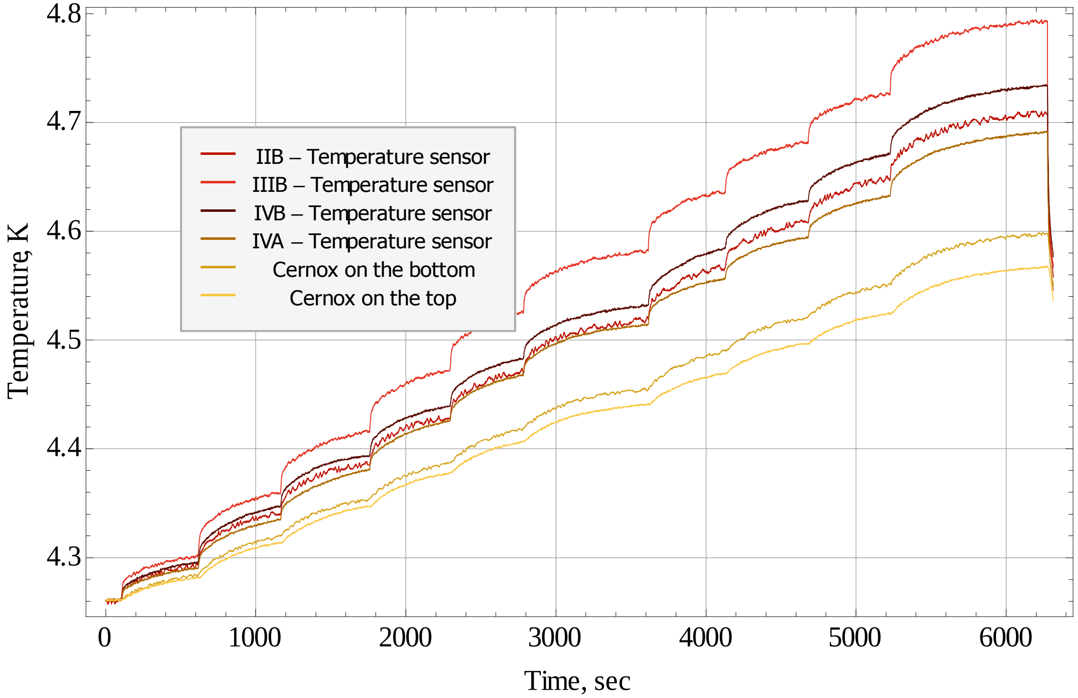
The total heat is sum of two components:

•Heat flux through the isolations – conduction heat transfer

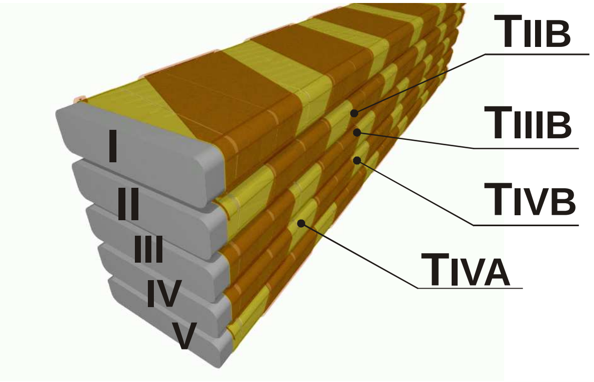
•Heat flux in helium – convection heat transfer

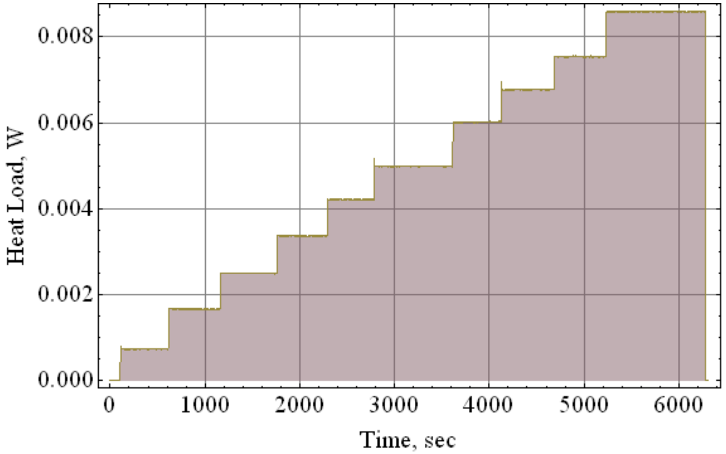
$$Q_{total} = Q_{conduction} + Q_{convection}$$

Conduction heat through the insulation



The temperature changes during the experiment (the middle sample heated)





The heat dissipated during the experiment

Conduction heat through the insulation

The conduction heat flux can be described by the equation:

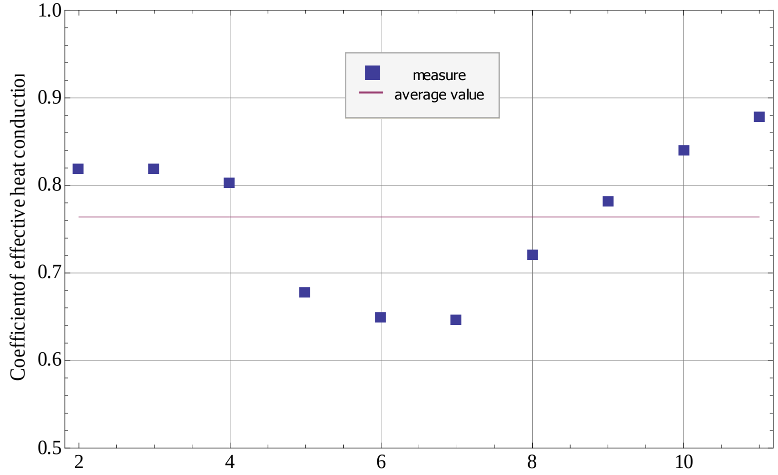
$$Q_{conduction} = A\varepsilon \int_{T_1}^{T_2} \frac{k(T)}{\delta} dT$$

where: *A* – total area of heat transfer;
ε – coefficient of effective area of heat conduction,
δ – thickness of insulation,
k(T) – conductivity of solid material as a function of temperature.

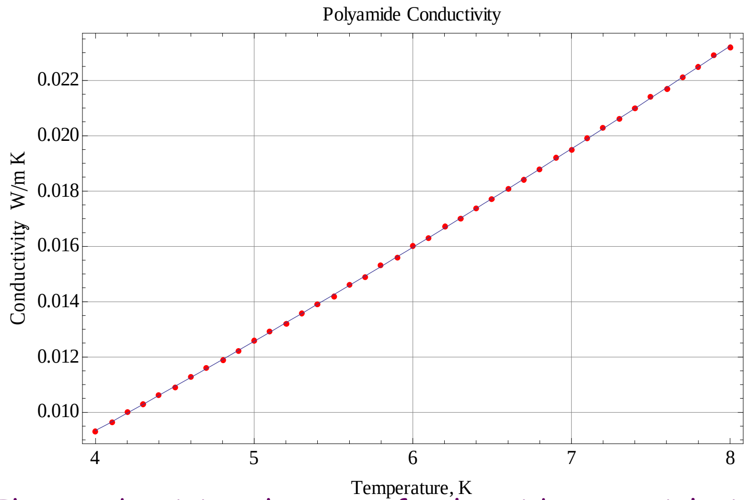
The ε coefficient is a consequence of gaps existing in the second layer of insulation and can be calculated from the expression

$$\varepsilon = \frac{1}{n-1} \sum_{i=2}^{n} \frac{Q_i}{\frac{A\,k(T)\left(T_{IIIB_i} - T_{IVB_i}\right)}{\delta}}$$

The average value of coefficient calculated from equation above equals **0.764048**

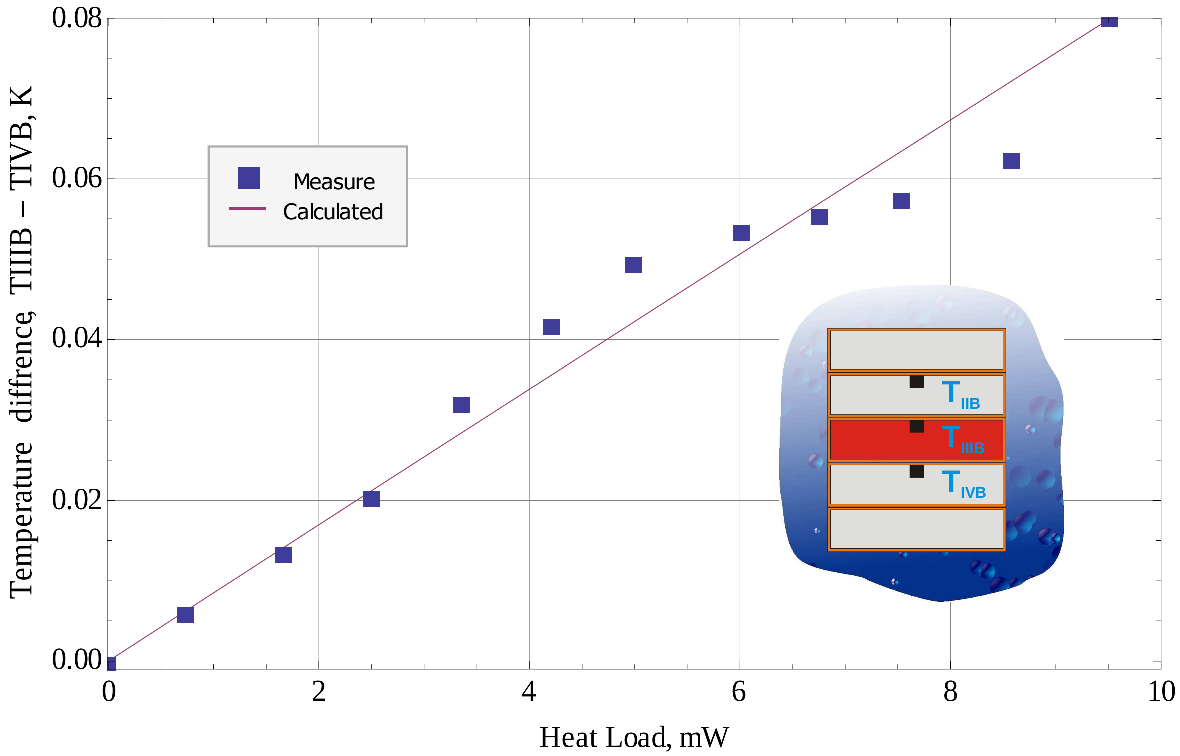


The coefficient of effective heat conduction area and average value



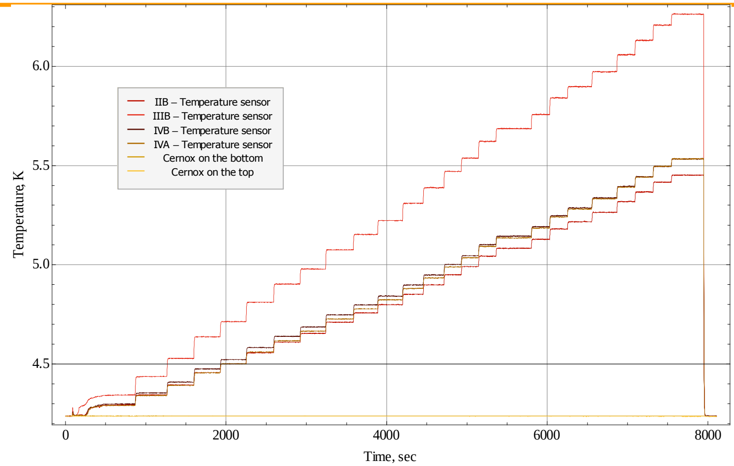
The conductivity changes of polyamide material with temperature

The identification of conduction heat

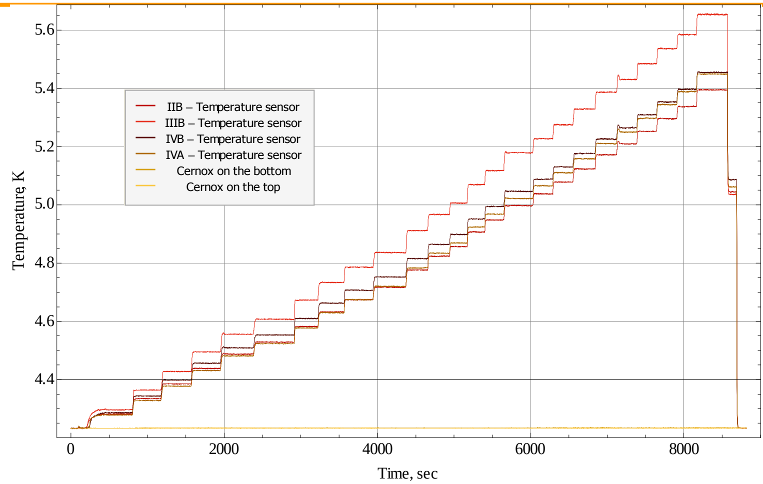


The calculated and measured differences of temperature between T_{IIIB} and T_{IVB} as the function of heat loaded to the sample III.

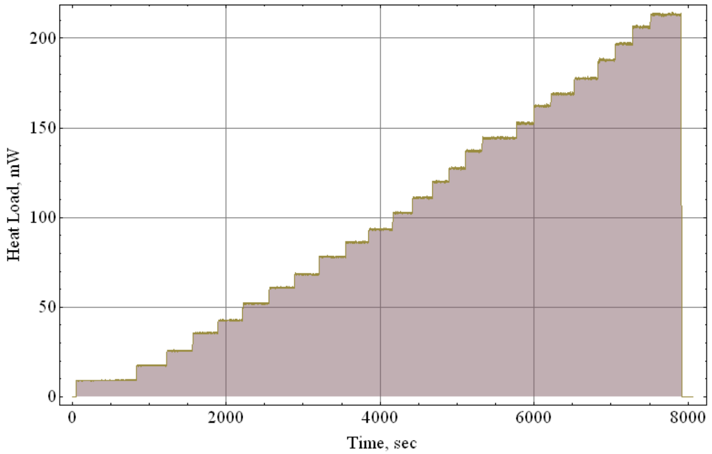
The experimental results at saturated helium



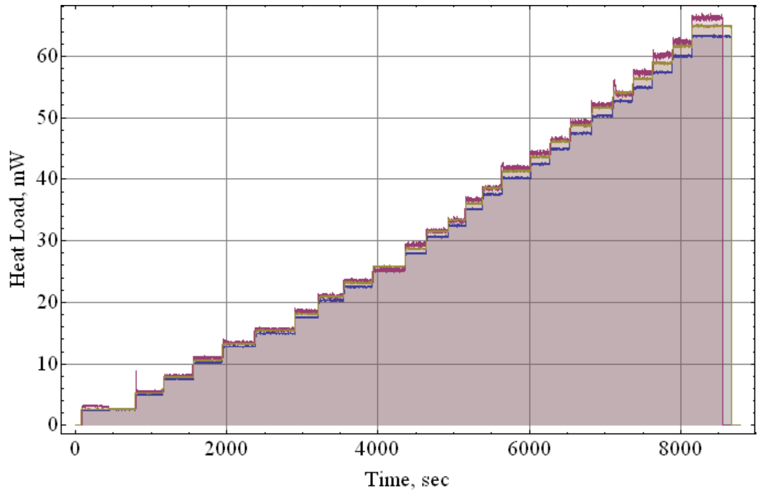
The change of temperature during the experiment in all monitoring sensors for the heated sample III



The rise of temperature for the three heated samples



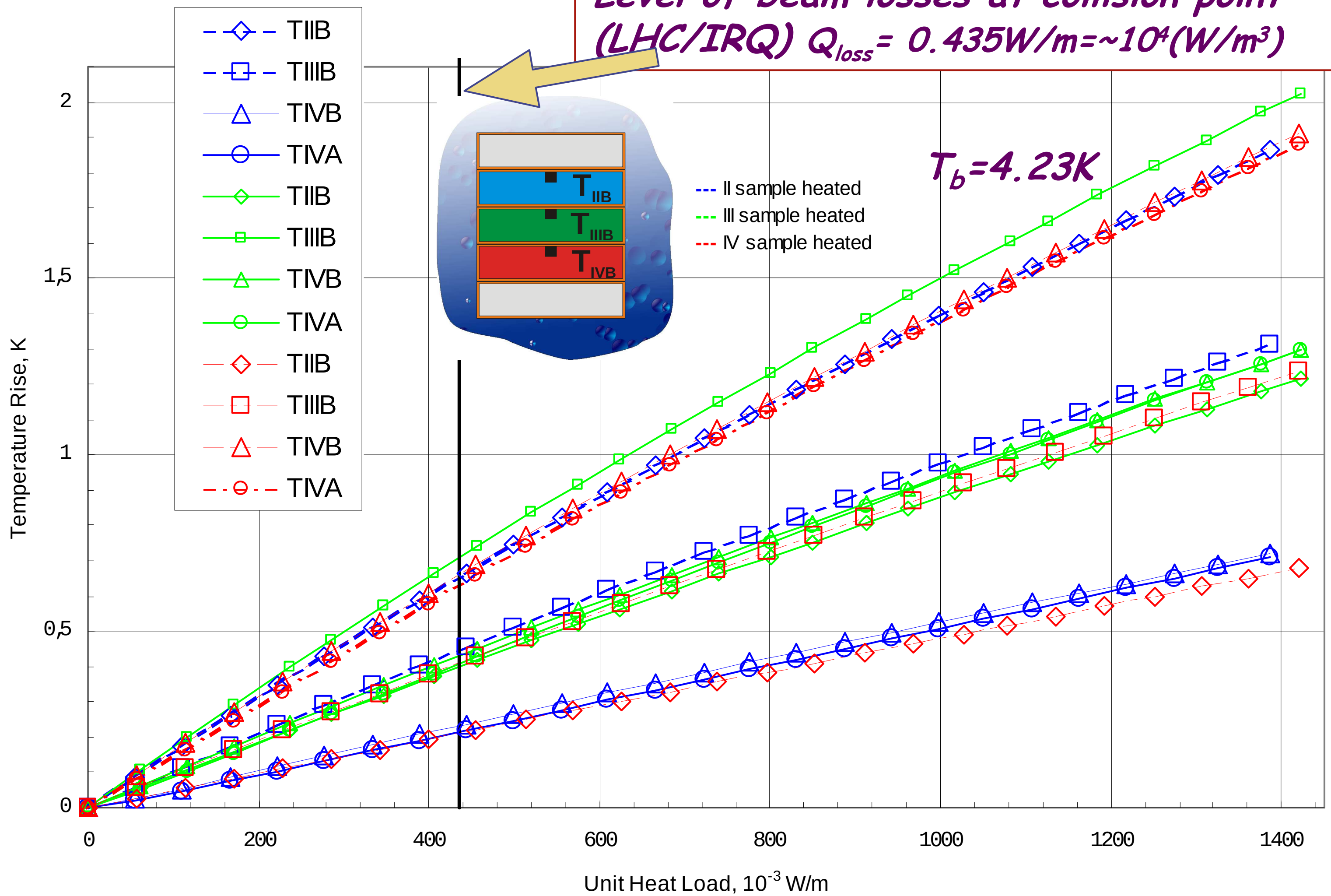
The change of dissipated energy for the heated middle sample



The change of dissipated energy for the three heated samples

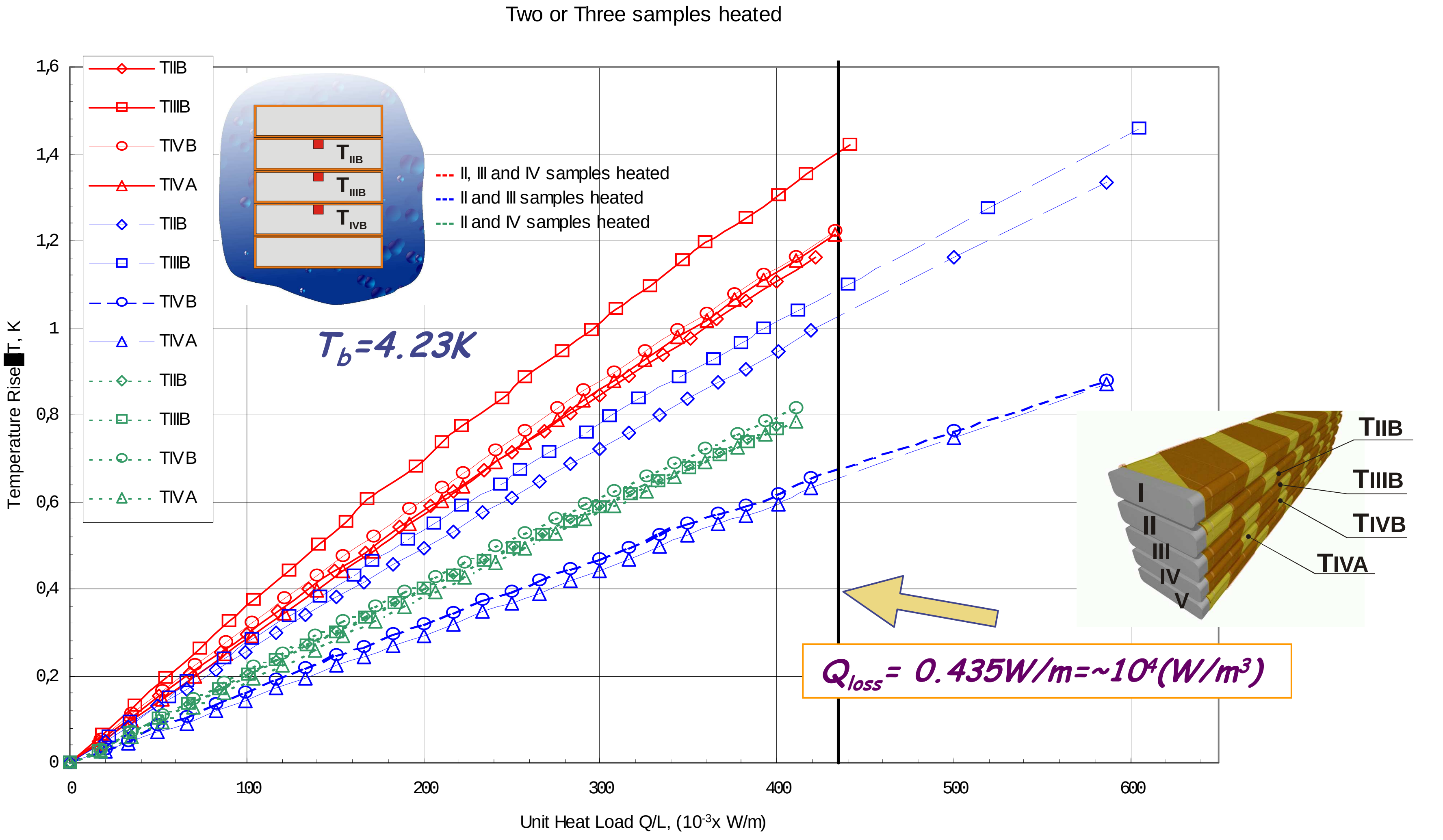
The experimental results at saturated helium

Level of beam losses at collision point (LHC/IRQ) Q_{loss}= 0.435W/m=~10^4(W/m^3)



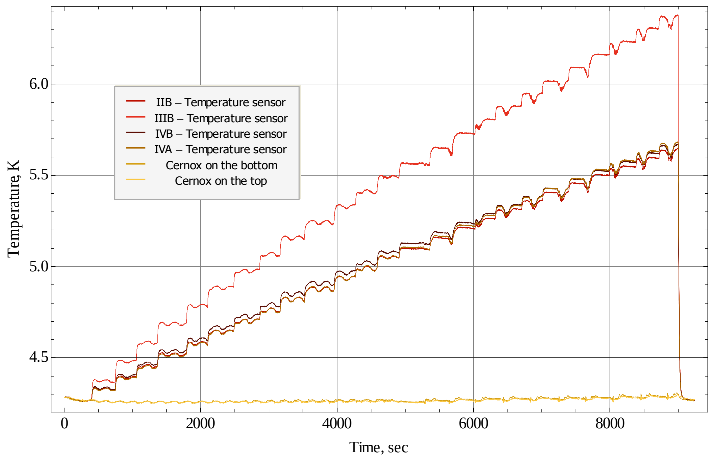
The temperature rise in the samples vs. unit heat load for the one heated sample

The experimental results at saturated helium

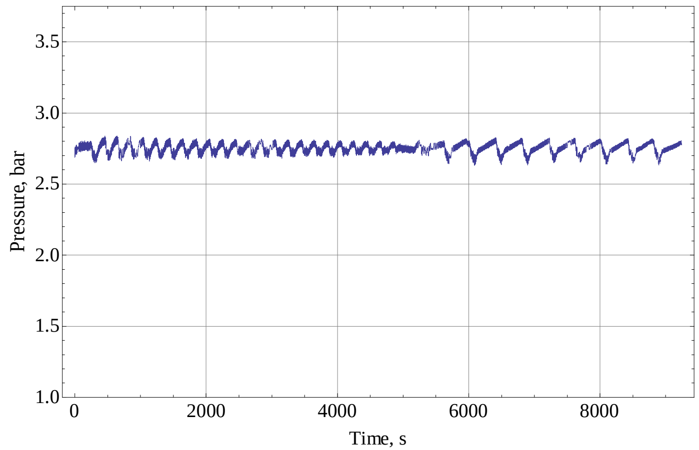


The temperature rise in the samples vs. unit heat load for the two or three heated samples

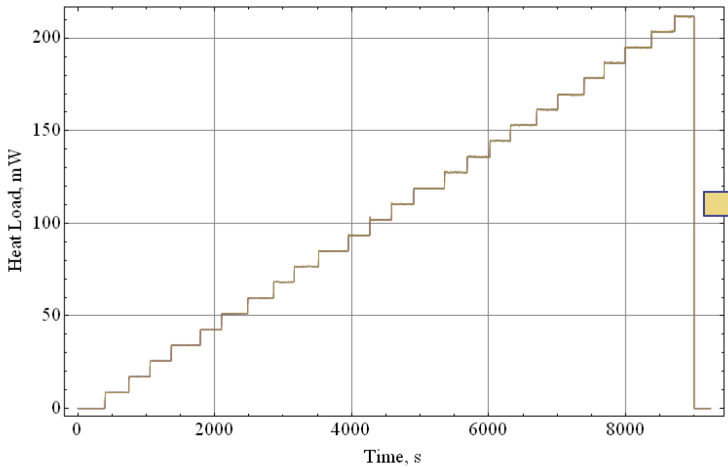
The experimental results at supercritical helium



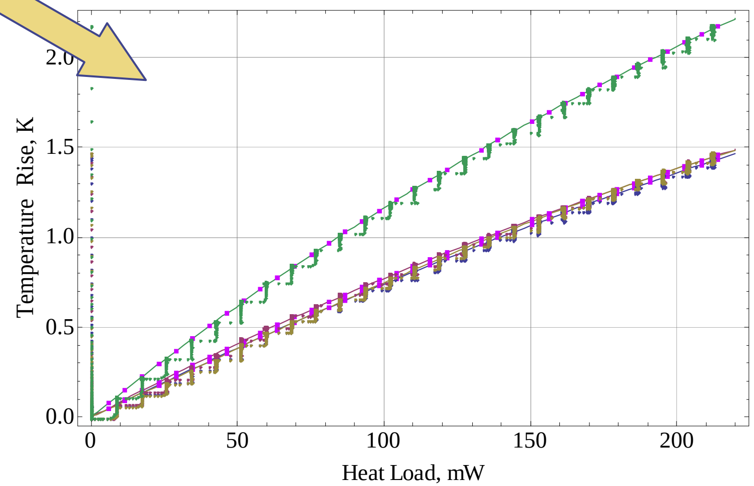
The changes of temperature during the experiment (2.75 bar)



The fluctuation of pressure in cryostat during the experiment (2.75 bar)

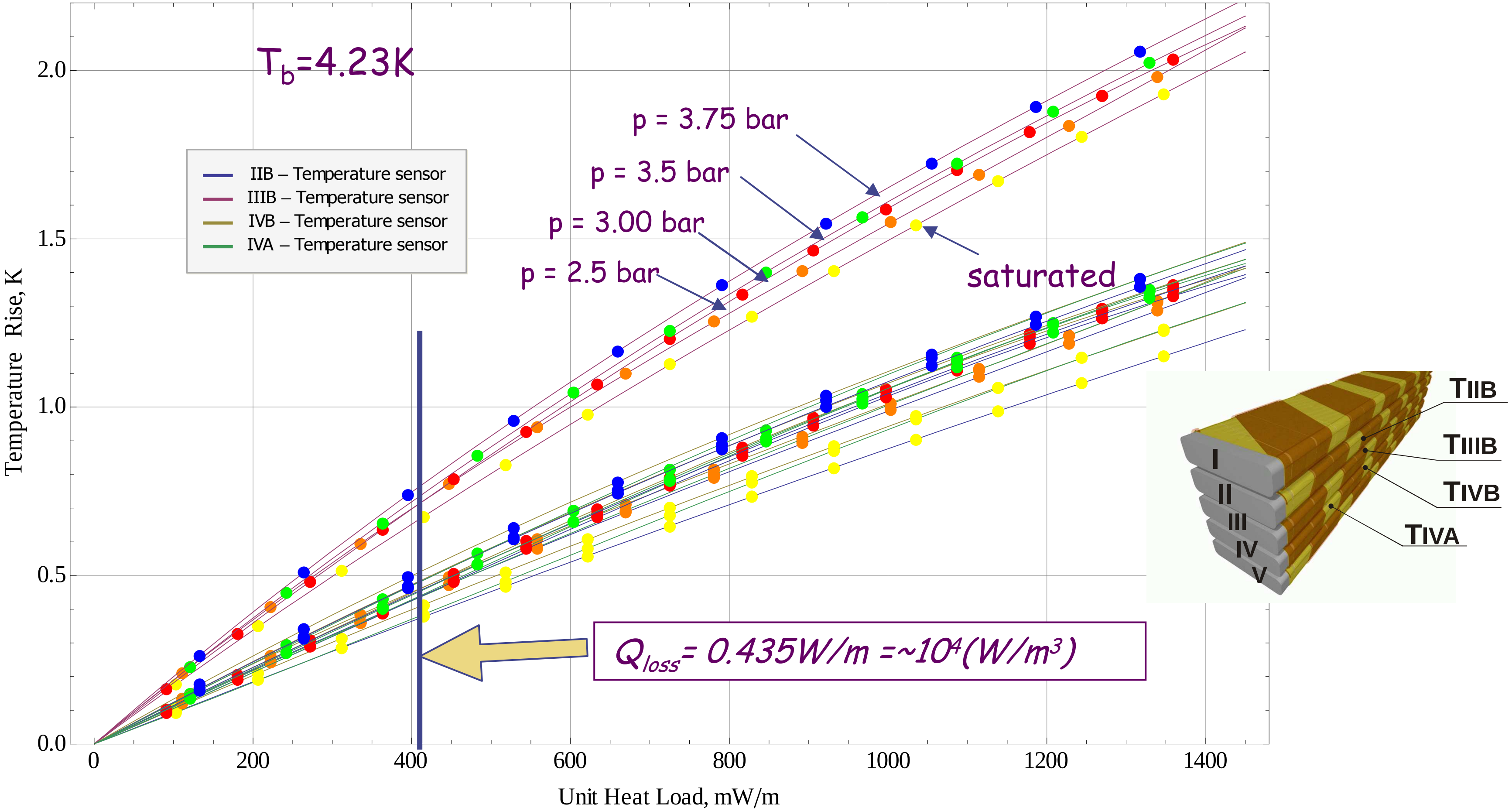


The changes of dissipated energy during the experiment (2.75 bar)



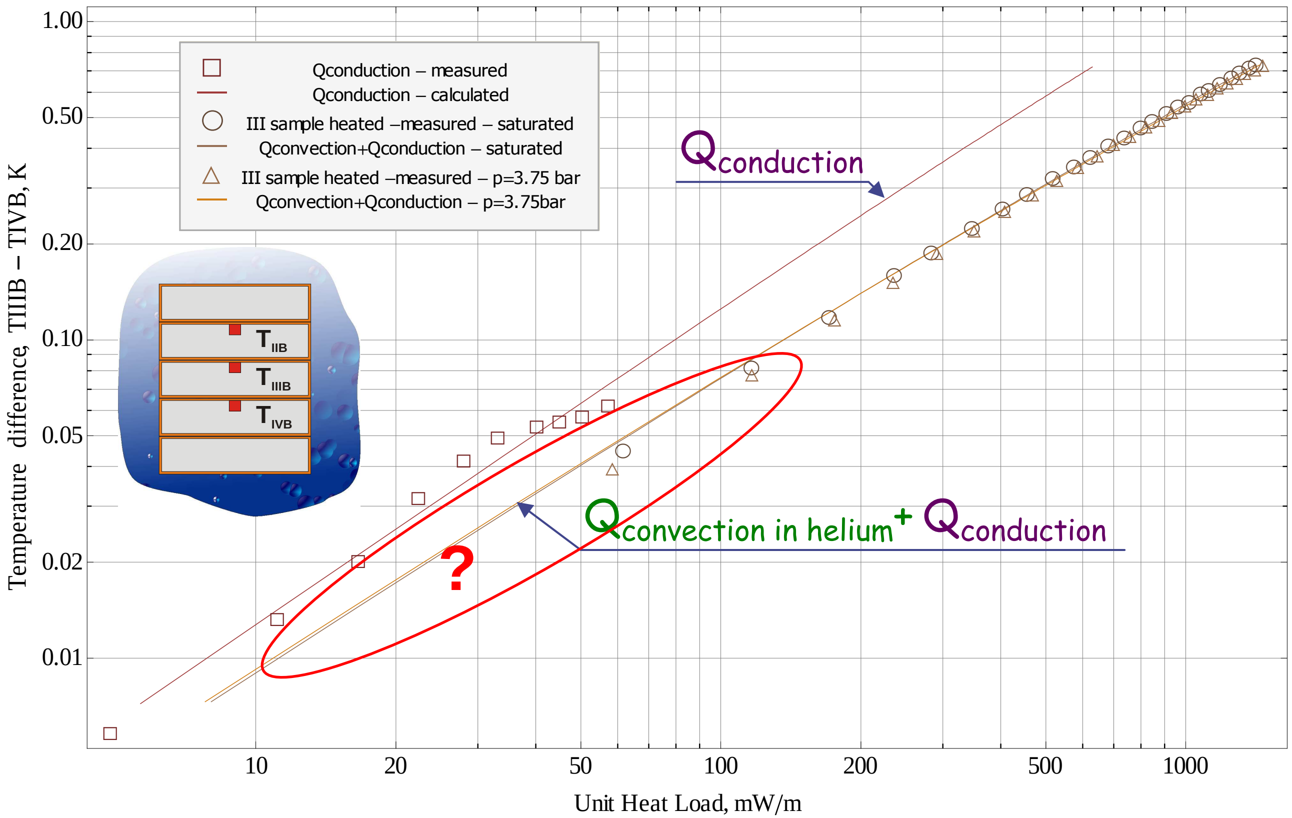
The temperature rise vs. heat load

The experimental results at supercritical helium



The temperature rise in the samples vs. heat load for the different values of absolute pressure (3.75 bar – blue points, 3.5 bar – green points, red points 3.0 bar, 2.5 bar– orange points, saturated bar – yellow point)

Description of convection heat transfer at saturated and supercritical helium



The comparison of measured and calculated heat transfer in saturated and supercritical helium

The convection heat transfer in considered case can be characterized by the dimensionless number called Nusselt number:

$$Nu = C\ Ra^n$$

where: C - empirically determined parameter,
n – coefficient,
Ra – Rayleigh number.

The Rayleigh number is a product of the Grashof and Prandtl numbers:

$$Ra \equiv Gr\ \Pr = \frac{g\ \beta\,(T_s - T_b)}{\delta\ \nu}$$

Convection heat transfer in tested cables equaled

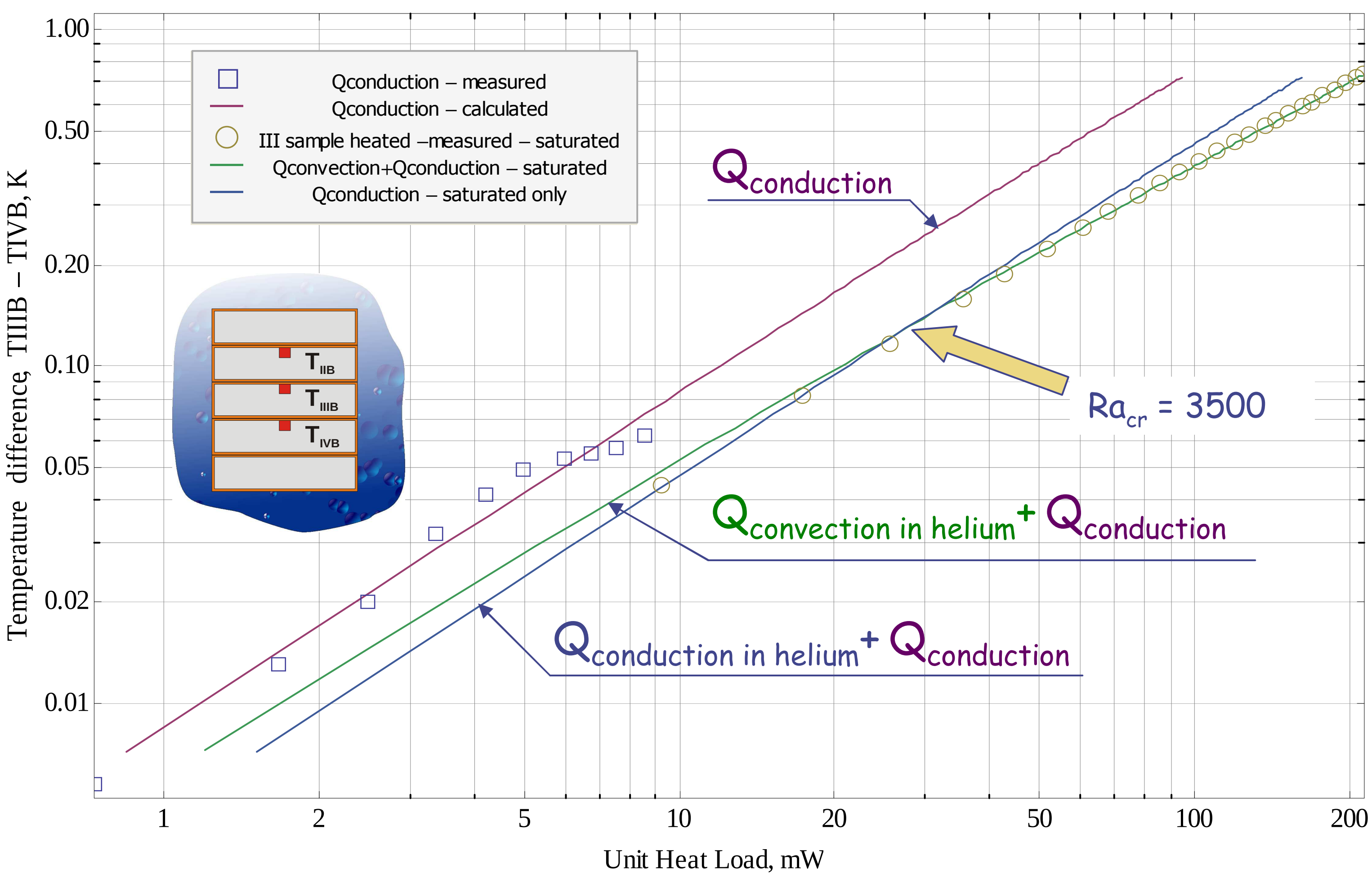
$$Q_{convection} = A\,(1-\varepsilon)\,\frac{Nu\ k}{\delta}\,(T_s - T_b) =$$

$$= A\,(1-\varepsilon)\,\frac{C\ Ra^n\ k}{\delta}\,(T_s - T_b)$$

The Nusselt number can be expressed as

$$Nu = 0.0143\ Ra^{\frac{1}{2.5}}$$

Description of convection heat transfer at saturated and supercritical helium



The comparison of measured and calculated heat transfer in saturated helium

Summary

1. *The cables have been tested at saturated and supercritical helium. The measurements at supercritical helium were performed for the following absolute pressure values: 2.0, 2.5, 2.75, 3.0, 3.25, 3.5, 3.75 bar;*
2. *The temperature sensors were calibrated in the temperature range from 4.2 to 7.6 K in modified set-up. The special function -* The Chebychev polynomial type- was used for approximation of obtained data in the range of temperature between 1.8 K to 7.6 K;
3. *During the experiments many scenarios of energy dissipation were carried out. The maximum dissipated energy obtained during the experiment (for the middle sample heated) was 1.440 W/m which caused the maximum temperature rise - about 2.0 K at saturated helium and 2.2 at supercritical helium (3.75 bar and 4.23 K);*
4. *The mechanism of conduction heat through Kapton was proposed and compared with experimental results. The average value of effective area coefficient of heat conduction is equal **0.764048**;*

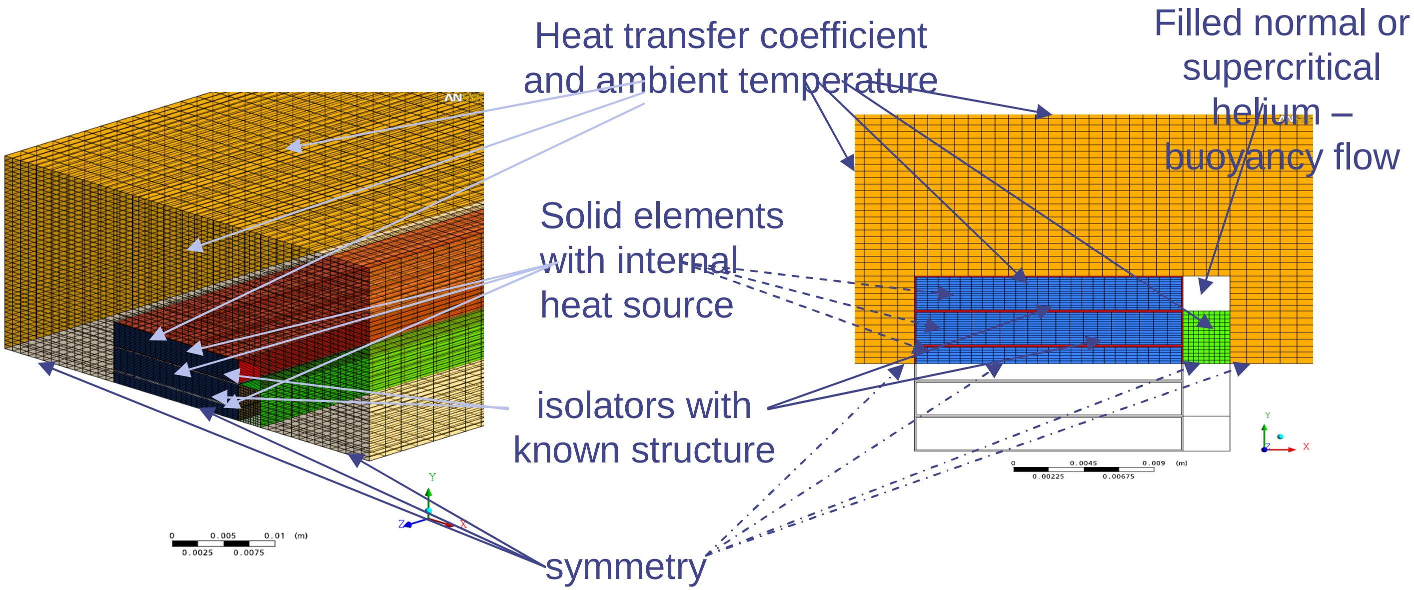
Summary

5. *In case of heating the three samples in the stack, for expecting value of beam losses equaled 0.435 W/m, the maximum temperature rise in the middle cable reached about 1.4 K, and 0.7 K for the one sample heated;*
6. *For the tested configuration of samples stack the critical Rayleigh number equals about 3200. When the Rayleigh number is changing in the range of 0 to 3200 the best model describing the total heat transfer from the sample to helium is heat conduction through the helium and insulation, after 3200 Rayleigh number the Benarda cells are created and convection mechanism of heat transfer begins.*
7. *The Nusselt number for tested configuration of stack can be expressed:*

$$Nu = 0.0143\, Ra^{\frac{1}{2.5}}$$

Future plan

1. *finishing the report describing the thermal- flow phenomena during the experiment at unsteady state, related to pulsed high beam loss at saturated and supercritical helium conditions;*
2. *validating the numerical calculations performed for the mentioned conditions.*



Applied boundary conditions