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Heat transfer through Nb_3Sn electrical insulation

Jaroslaw Polinski, Bertrand Baudouy

CEA/DAPNIA/SACM

Contest

- Motivations of the investigations
- Ceramic (innovative) insulation – stack method
- RAL conventional insulation – drum method
- Technical solution study
- Conclusions

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Motivations of the investigations

- Operation of the SC accelerators is connected with energy deposition in SC cables due beam losses
  - Current (NbTi) LHC – e ≈ 0.4 – 0.6 W/m, 10 – 15mW/cm^3
  - Future (Nb_3Sn) LHC – e ≈ 2 – 3 W/m, 50 – 80mW/cm^3
  - Max temperature margin of the SC cable ≈ 1.4K

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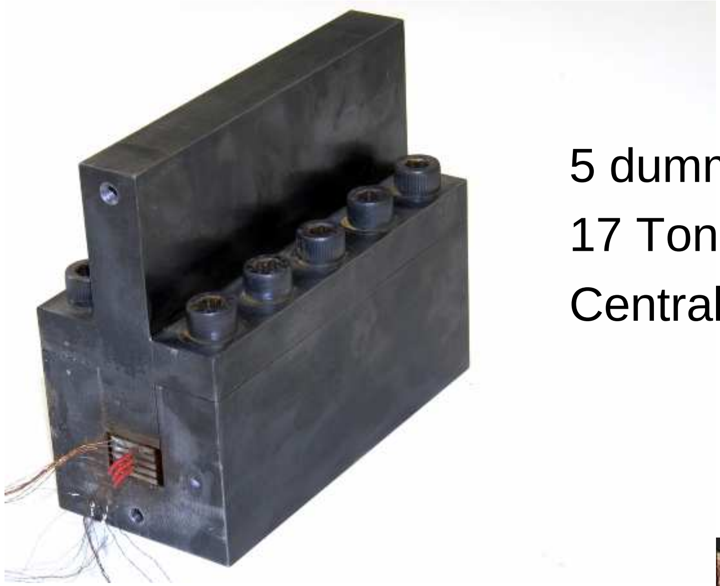
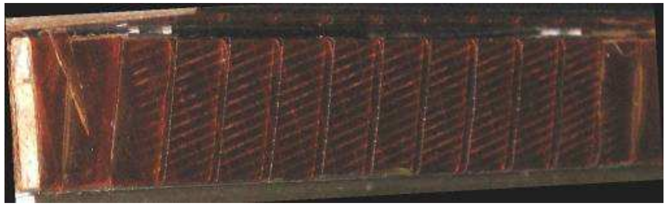
Motivations of the investigations

Kapton insulation sample



5 dummy stainless steal conductors stack
17 Tons on the samples as specified
Central conductor heated



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
Thermally treatment at 170°C for polymerisation

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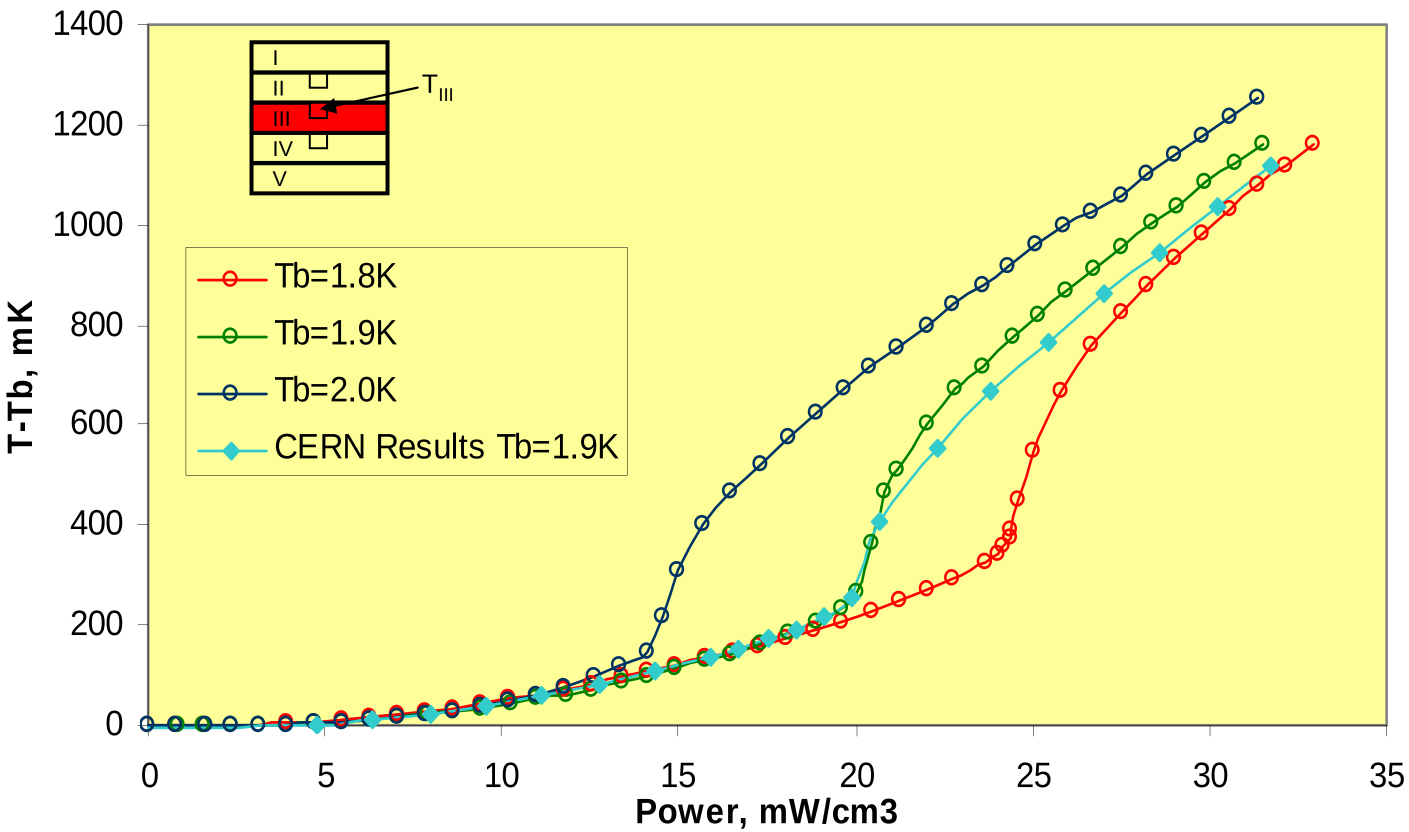
Motivations of the investigations

Kapton insulation results



For Q=10 mW/cm³ (NbTi) – ΔT≈50 mK

For Q=50 mW/cm³ (Nb_3Sn) – ΔT≈2.2K !!!

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Motivations of the investigations

- Operation of the SC accelerators is connected with energy deposition in SC cables due beam losses
  - Current (NbTi) LHC – e ≈ 0.4 – 0.6 W/m, 10 – 15mW/cm^3
  - Future (Nb_3Sn) LHC – e ≈ 2 – 3 W/m, 50 – 80mW/cm^3
  - Max temperature of the SC cable ≈ 1.4K

- Nb_3Sn technology need the thermal treatment over 600^{o}C
  - Polyimide (Kapton) insulation operation temperature > 400^{o}C

<u>NEW GENERATION MAGNETS CALL FOR NEW MATERIALS FOR SC CABLES ELECTRICAL INSULATIONS</u>

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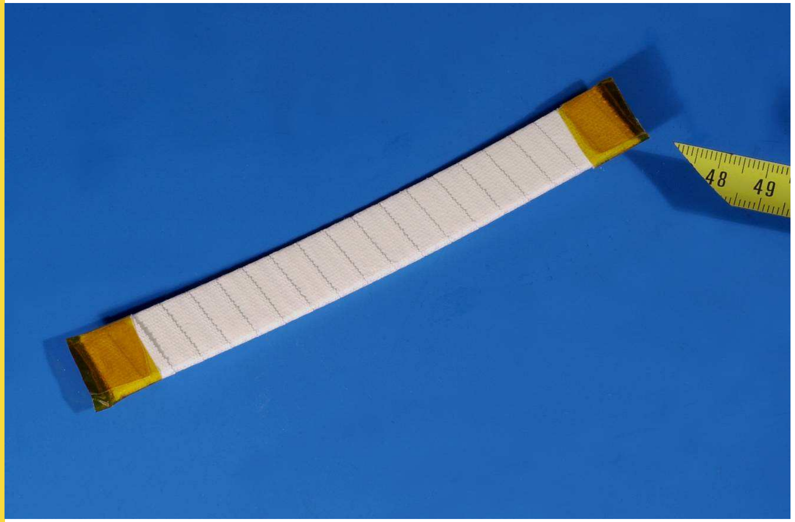
Ceramic (innovative) insulation

Insulation material

- Mineral fibre tape vacuum impregnated with epoxy resin
- Treated for 50 hours at 666ºC at 10 MPa

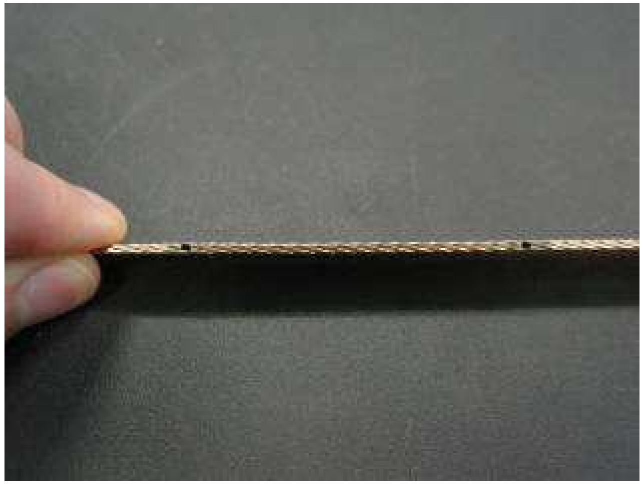


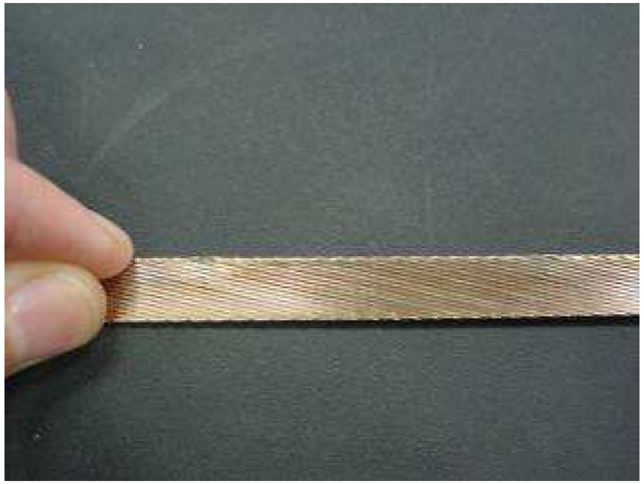
Single cable and sack of cables with ceramic insulation – photo F. Rondeaux

Ceramic (innovative) insulation

Dummy conductors (KEK)

- Material: CuNi
- Dimensions: 1.9mm x 11mm x 150mm (T x W x L)
- Conductor fabricated in real cable technology
- CERNOX temp. sensors placed in the quarter of the length and in axis of the conductor





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Ceramic (innovative) insulation

Test condition

- 10 MPa on the samples as specified
- Temperature of the bath Tb= 1.8K, 1.9K and 2.0K
- All conductors heated
- Supplied current range: 0 – 10 Amps
- Dissipated heat range: 0 – ≈42 mW/cm^3
- Temperature measured on the central conductor

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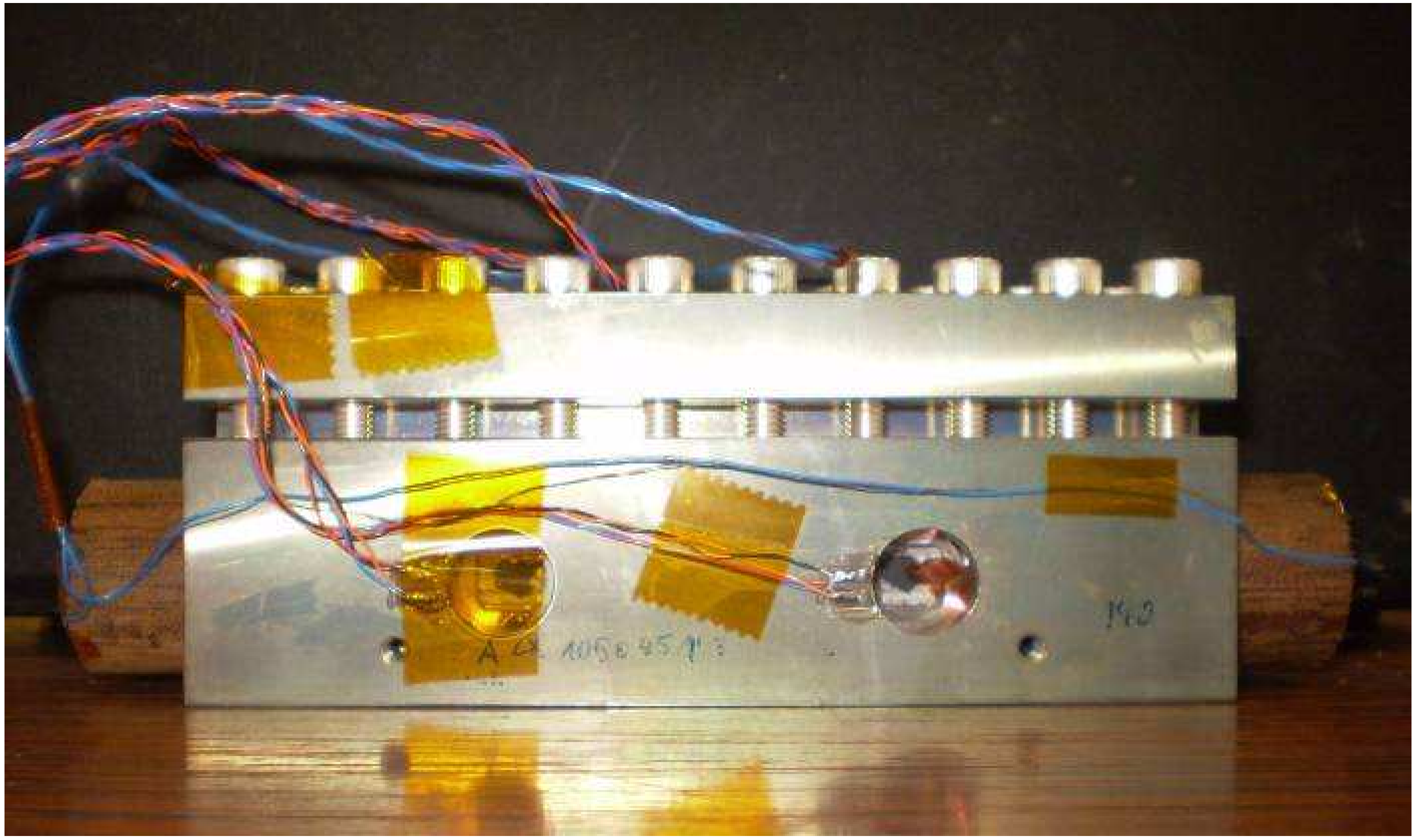
Ceramic (innovative) insulation

KEK sample



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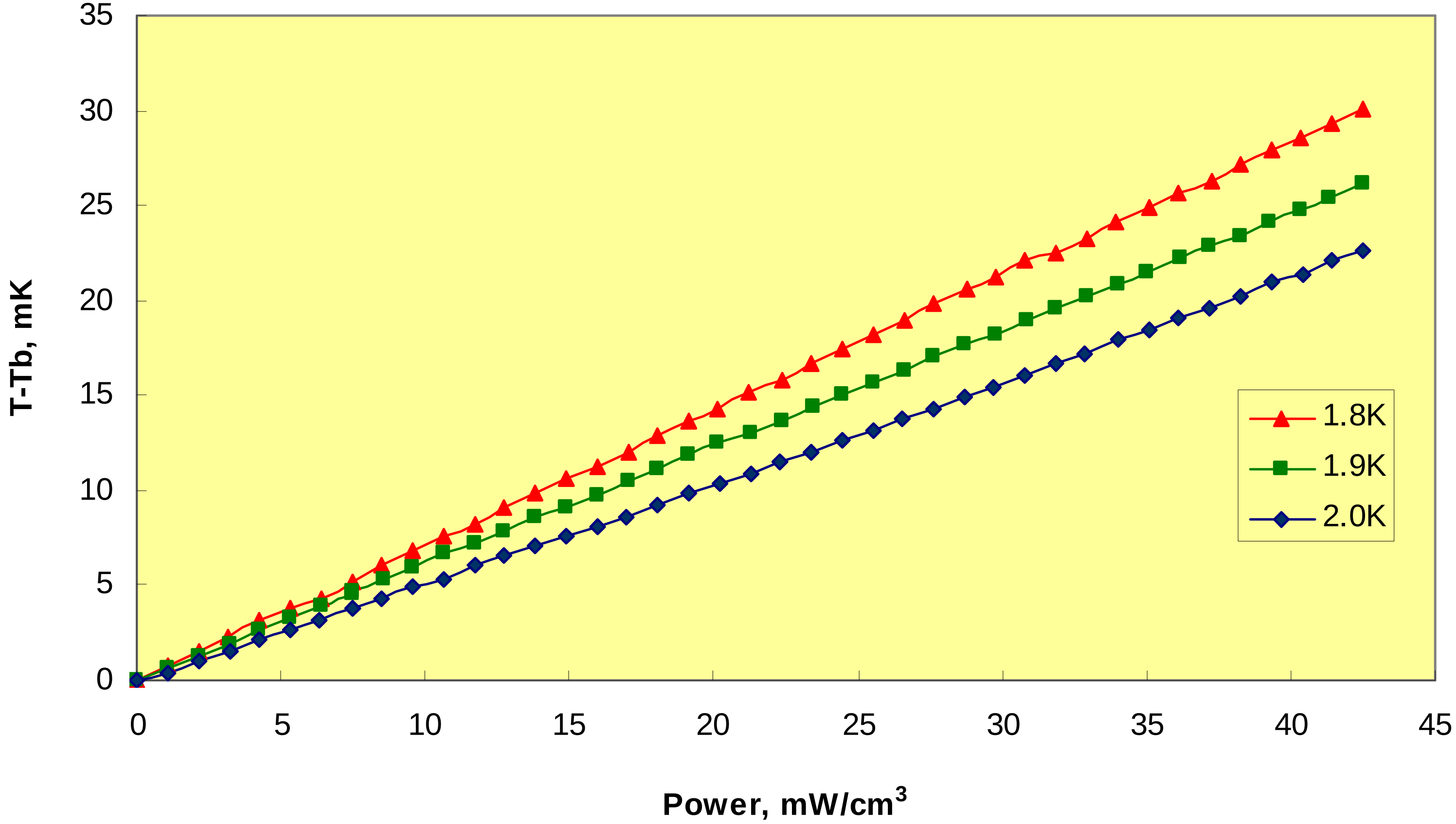
Ceramic (innovative) insulation

Test results



For Q=10 mW/cm³ (NbTi) – ΔTmax<10 mK

For Q=50 mW/cm³ (Nb_3Sn) – ΔT<35 mK !!! *(2.2K for Kapton insulation)*

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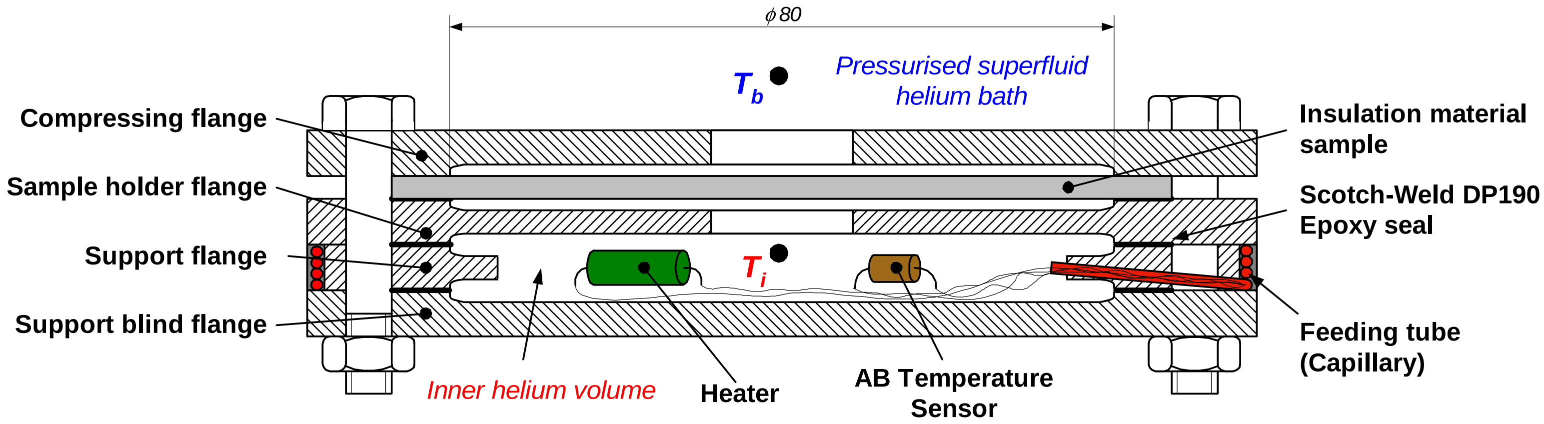
RAL insulation

Construction of the drum test support



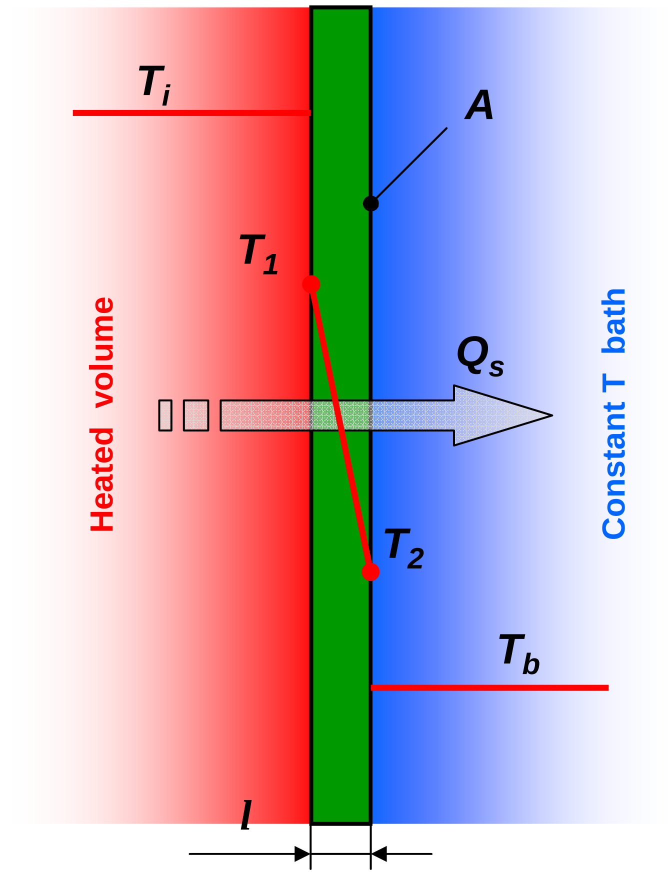
Sample holder flange

Support flange

RAL insulation

Drum setup

– Theoretical Background of the Method (1/2)



$$\frac{Q_S}{A} = \begin{cases} h_K\left(T_i^n - T_1^n\right) \\ \frac{\lambda}{l}\left(T_1 - T_2\right) \\ h_k\left(T_2^n - T_b^n\right) \end{cases} = \frac{1}{R_s}\left(T_i - T_b\right) = \frac{1}{R_s} T\Delta$$

A – Active area of the heat transfer
h_k – Kapitza heat transfer coefficient
λ – Thermal conductivity of the material
l – material thickness
R_S – overall thermal resistance of the sample
T_i – temperature of the heated volume
T_1 – temperature of the sample surfaces from the heated volume side
T_2 – temperature of the sample surfaces from the constant T bath
T_b – temperature of the constant T bath

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RAL insulation

Drum setup

– Theoretical Background of the Method (2/2)

Since $\Delta T >> T_b$ it can be assumed that:

$$h_K\left(T_i^n - T_1^n\right) \approx n \cdot h_K \cdot T_i^{n-1}\left(T_i - T_1\right)$$

$$h_K\left(T_2^n - T_b^n\right) \approx n \cdot h_K \cdot T_b^{n-1}\left(T_2 - T_b\right)$$

And finally overall thermal resistance of the sample:

$$R_s = \frac{A\Delta T}{Q_s} = \frac{1}{n \cdot h_K \cdot T_i^{n-1}} + \frac{l}{\lambda} + \frac{1}{n \cdot h_K \cdot T_b^{n-1}} \approx \frac{2}{n \cdot h_K \cdot T_b^{n-1}} + \frac{l}{\lambda} \approx \frac{2}{R_K} + \frac{l}{\lambda}$$

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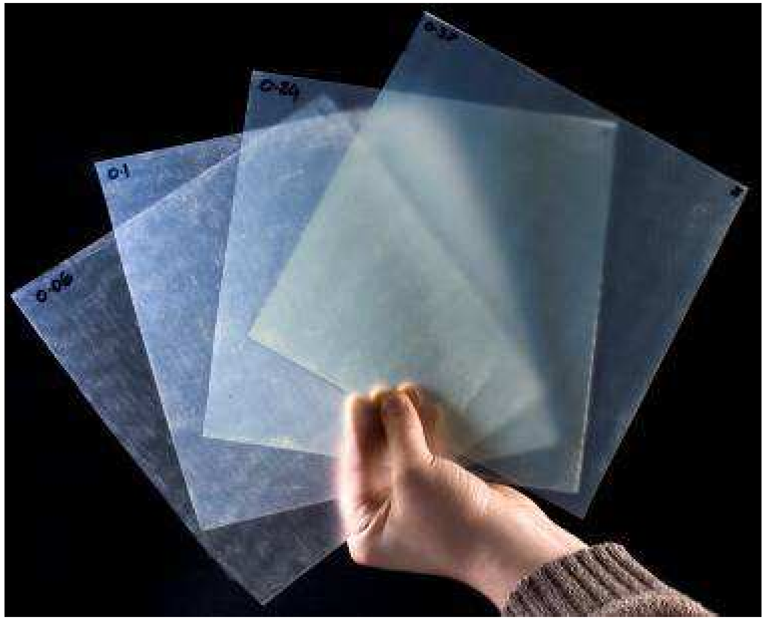
RAL insulation

- **RAL insulation material** - fiberglass tape and epoxy resin

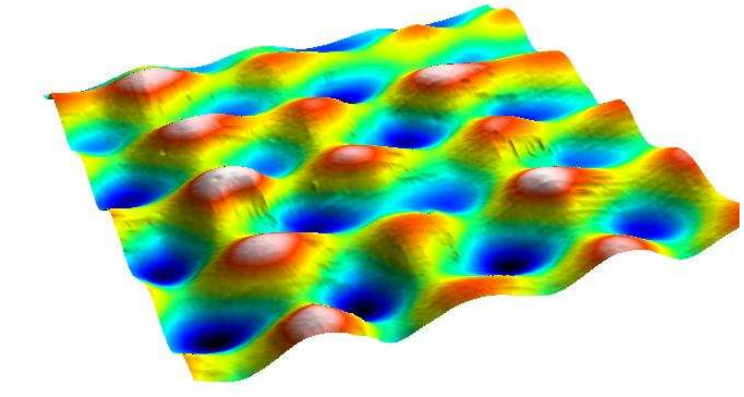


Tested sheets

RAL insulation

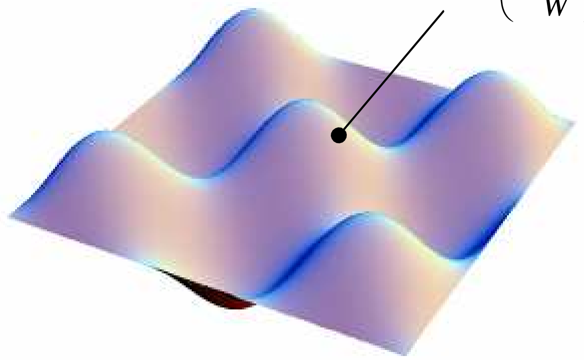
Study of sheets surface area and thickness

Sheet surface photo

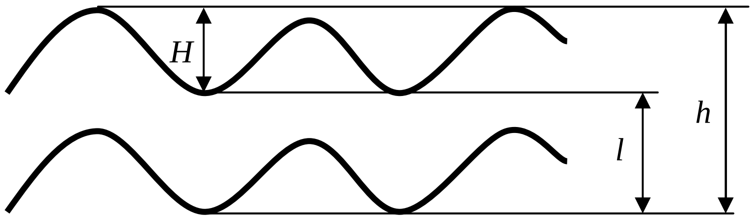


3D profilometer results example

$$f(x,y) = H/2 \cdot \sin\left(x\frac{2\pi}{W}\right) \cdot \sin\left(y\frac{2\pi}{W}\right)$$



Surface mathematical description



Thickness determination

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RAL insulation

Tests conditions

- 4 sheets with different thicknesses
- 7 different temperatures of the bath from range: 1.55 K – 2.05 K
- Temperature of the inner volume: Tb – $T\lambda$
- Heat dissipated in inner volume: 0 – 0.8 W
- Range of ΔT accounted in computation process: 10 – 30 mK

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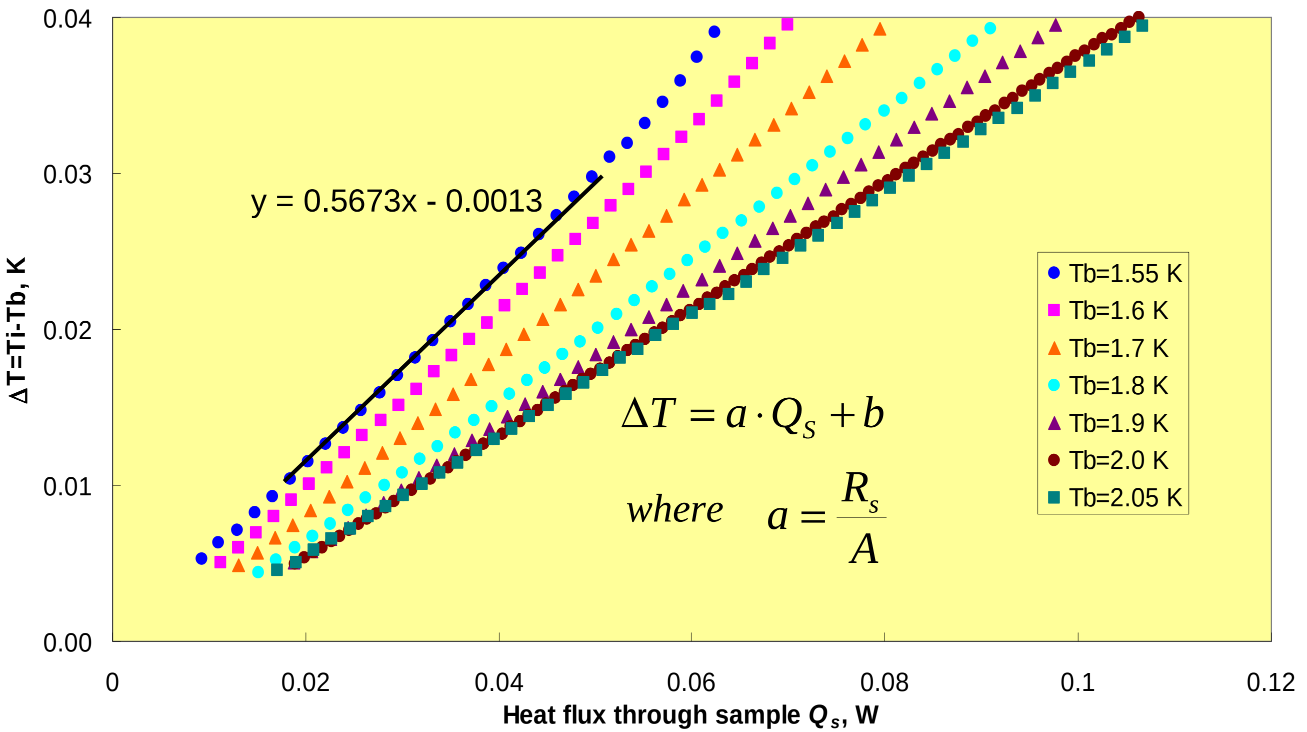
Test results and computation process, example for l=0.039 mm



Evolution of the temperature difference across the sample with heat flux as a function of the bath temperature.

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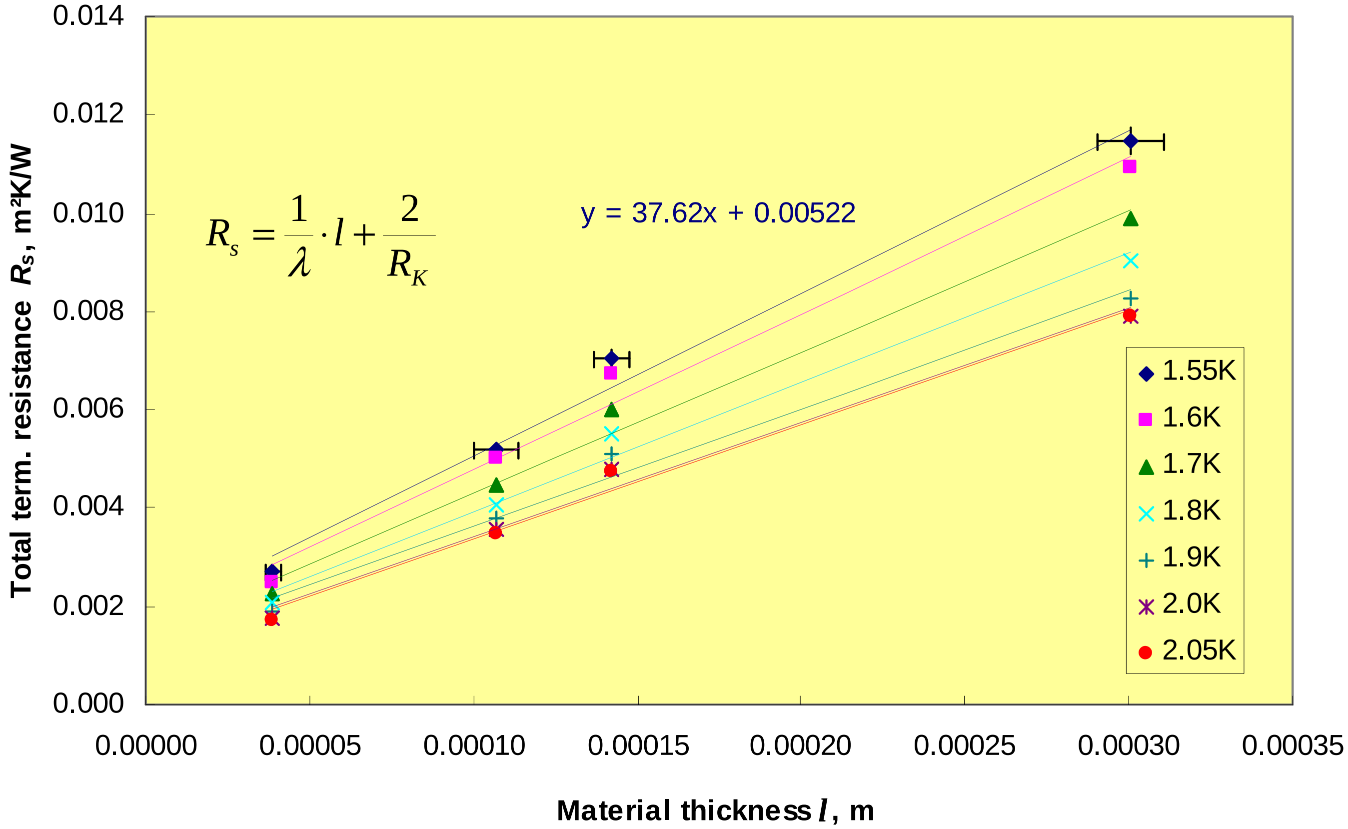
Computation process



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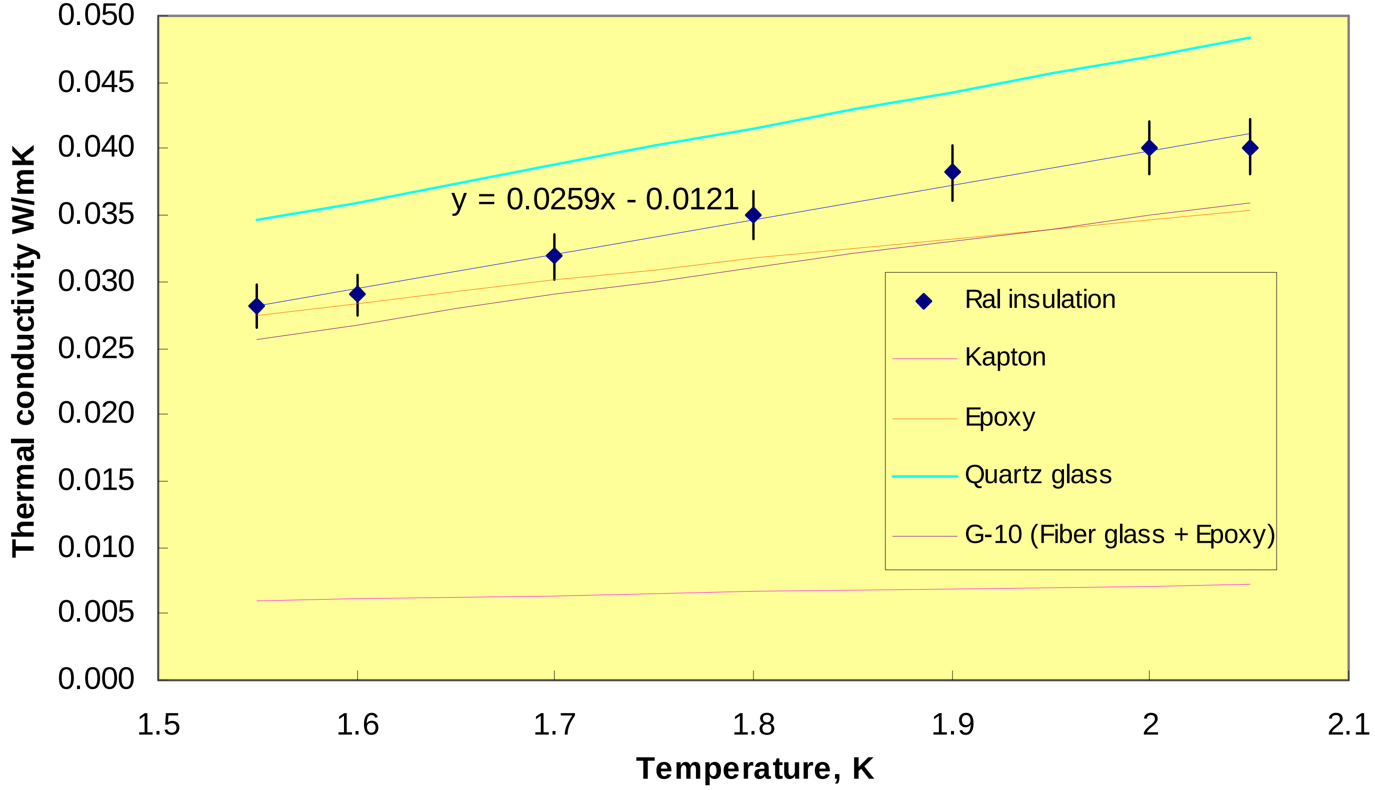
RAL insulation

Thermal conductivity, comparison with other materials



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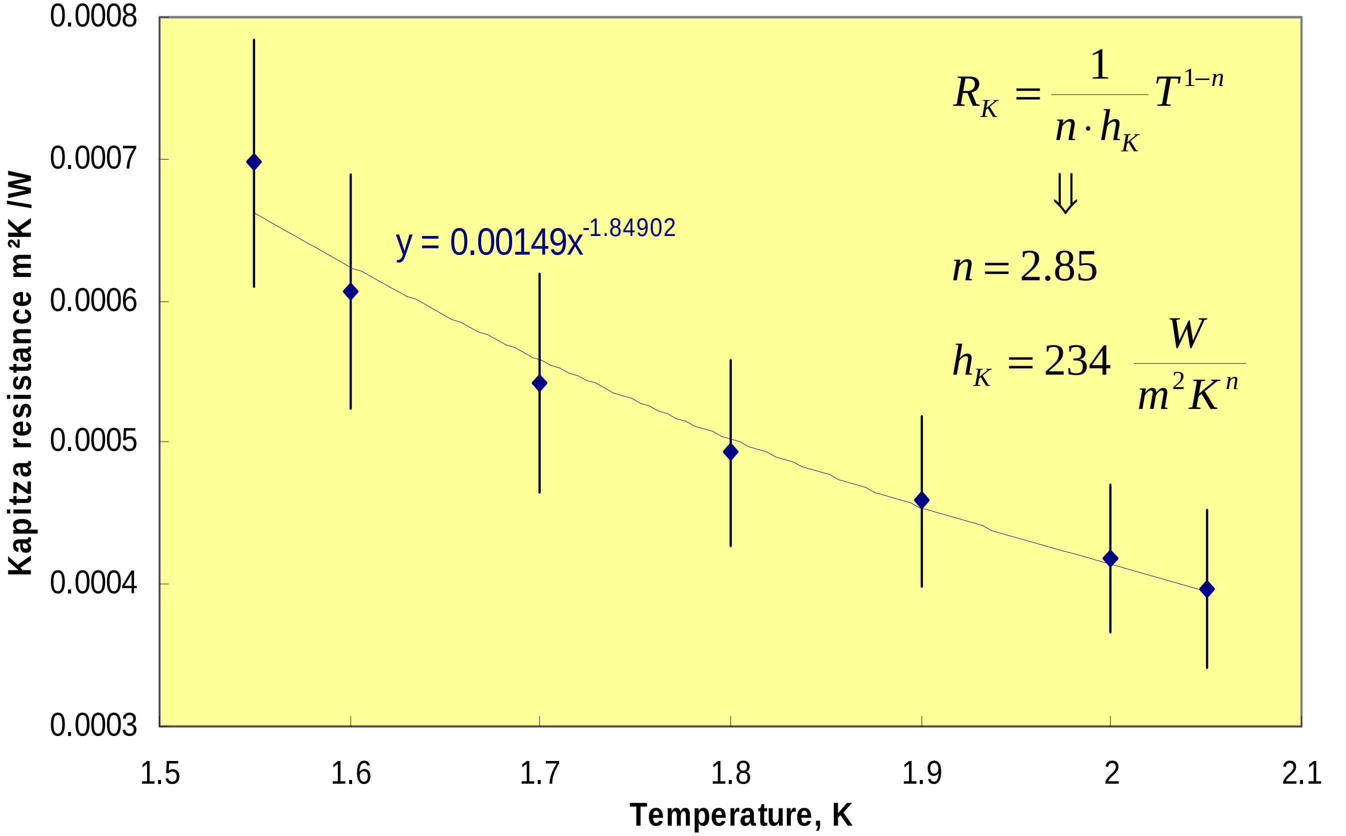
RAL insulation

Kapitza Resistance



For Kapton insulation:
@2.05K R_K*=0.00134 m²K/W*
@1.55K R_K*=0.00277 m²K/W*

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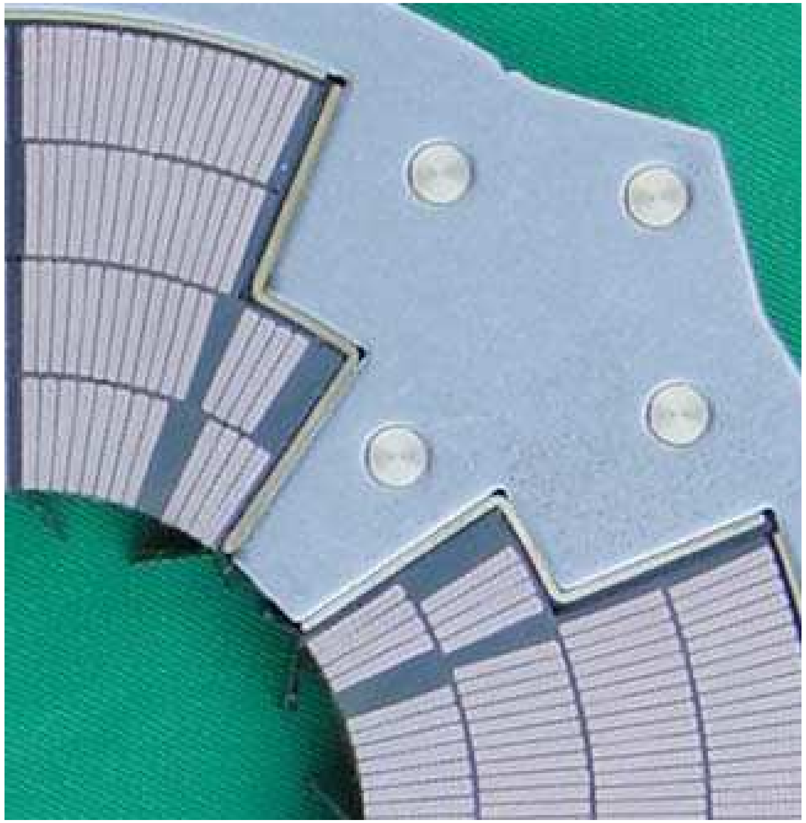
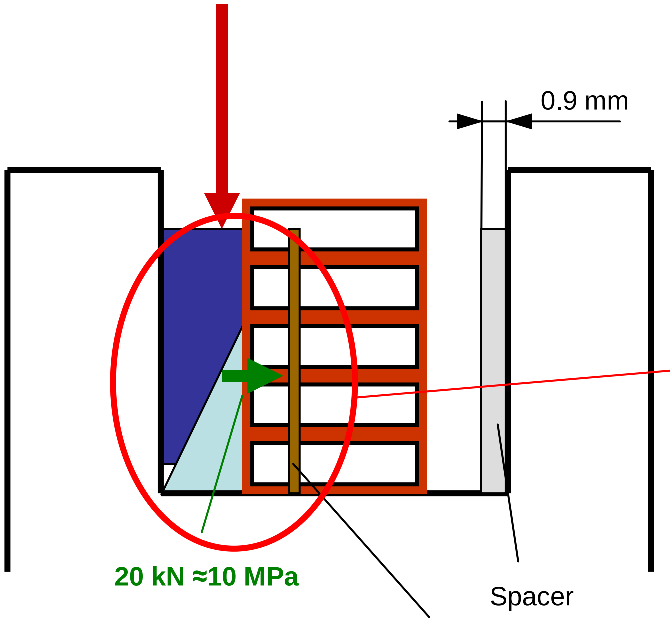
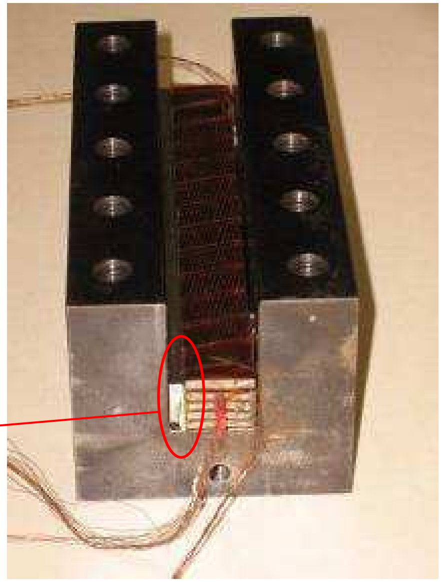
Technical solutions investigation



Technical solution investigation

Thermal blockades of the one side of the conductors stack





G10 interlayer spacer

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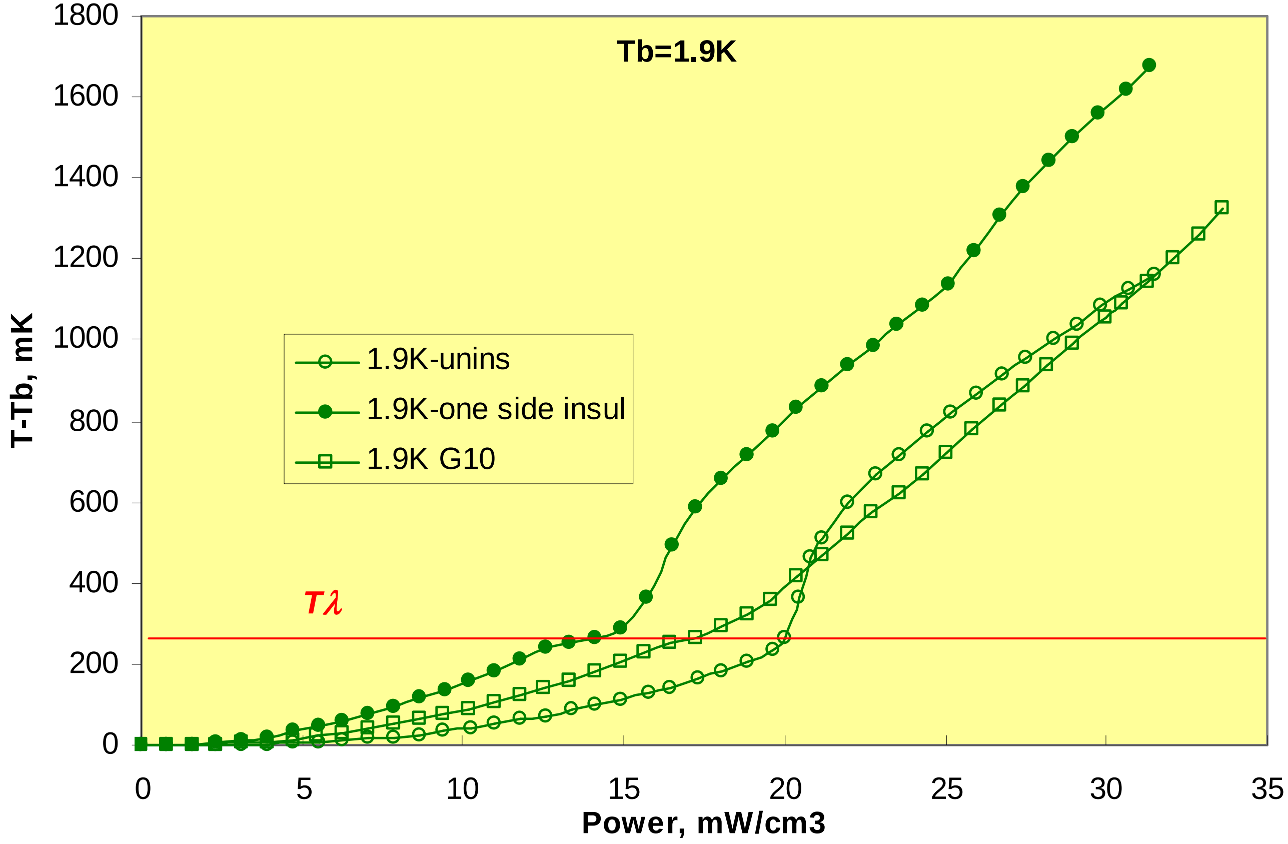
Technical solution investigation

Test results



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Conclusion

- For Nb_3Sn technology magnets beam losses heat generation in cables would be about 5 times higher then for NbTi technology
- Temperature margin as 2.2 K is expected when the LHC convectional electrical insulation is used to Nb_3Sn cables
- Innovative ceramic insulation seems to be very good solution for future Nb_3Sn magnets
- Thermal conductivity of the RAL insulation material is 5 times lower and Kapitza resistance is 4 times lower then for Kapton – RAL material can be considered as new conventional insulation
- Yoke of magnet can strongly restrict heat transport from cables. Application of the G10 interlayer spacers improve heat transfer process.

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Thank you for your attention