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# Recent developments in heat transfer through electrical insulation for accelerator magnet coils

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# Outline

- Introduction on He II heat transfer in accelerator magnet coils

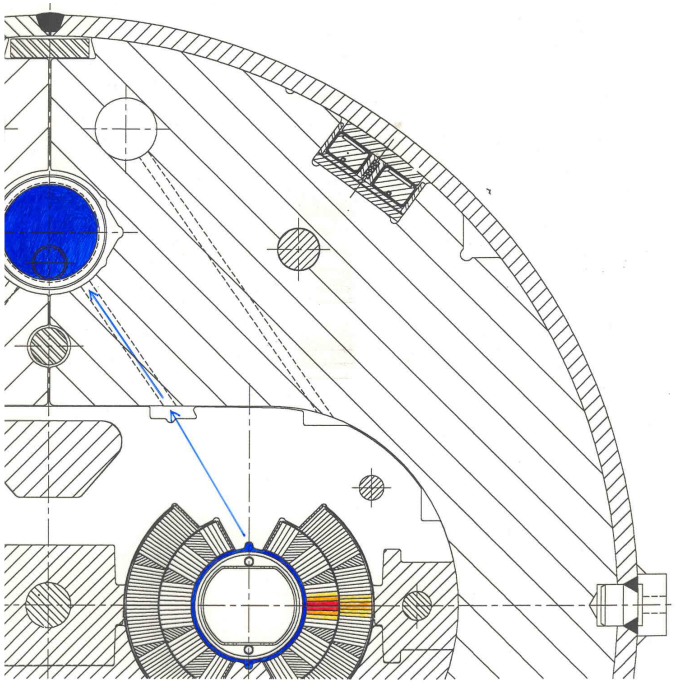
- Heat transfer in All-polyimide electrical insulation
- Heat transfer in ceramic porous insulation
- Heat transfer in All-impregnated insulation

- Comparison of insulation thermal characteristics

- Perspectives

# He II heat transfer in accelerator magnet coils

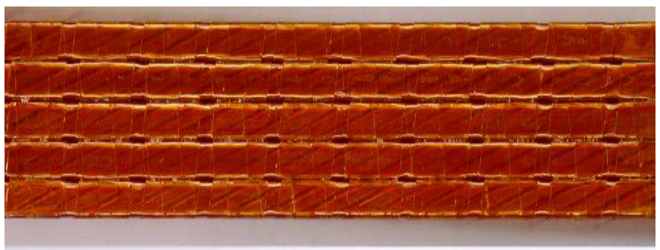
- "Wet" magnets with "heat exchanger"
  - Large internal losses and small stored energy
  - Single phase coolant in contact with conductor
  - Cooling Source: Internal heat exchanger

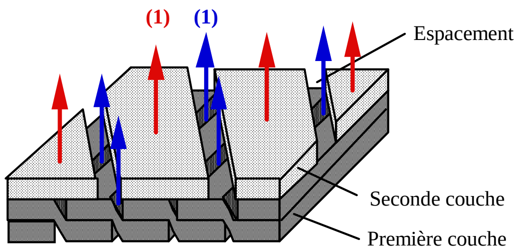


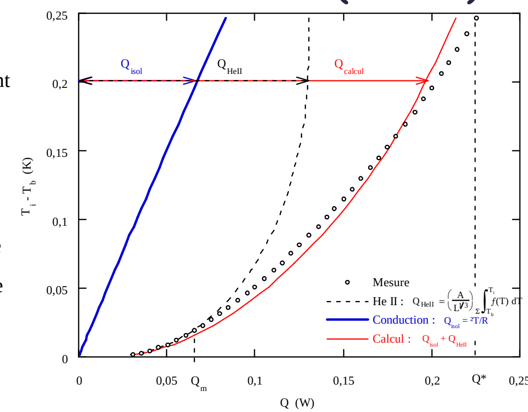
- Heat transfer between the conductor and the cooling source determines the temperature margin

- Electrical insulation constitutes the largest thermal barrier

- LHC Electrical Insulation : All-polyimide
  - 10 mW/cm$^3$ or 0.4 W/m (cable)
  - $\Delta T$<0.3 K with permeable insulation or $\Delta T$~4 K with monolithic insulation (He II)
  - He II + Conduction





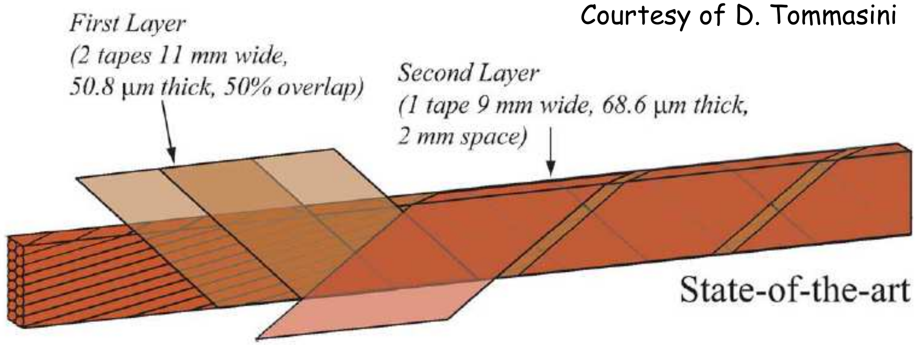
# He II heat transfer in accelerator magnet coils

- LHC upgrade
  - Use of $Nb_3Sn$ Magnets to reach 15 T to achieve the expected luminosity
  - "Beam losses" in the order of 50 to 80 $mW/cm^3$ or 2 to 3 W/m
  - What is the expected $\Delta T$ on the coil for such loads?
- Development of new insulation systems
  - Ceramic porous insulation to increase the permeability to helium
    - Developed and tested at CEA-Saclay
  - New wrapping scheme for all-polyimide insulation
    - Developed and tested at CERN for the LHC upgrade
  - All-impregnated electrical insulation
    - Developed at RAL and tested at CEA-Saclay for the NED project

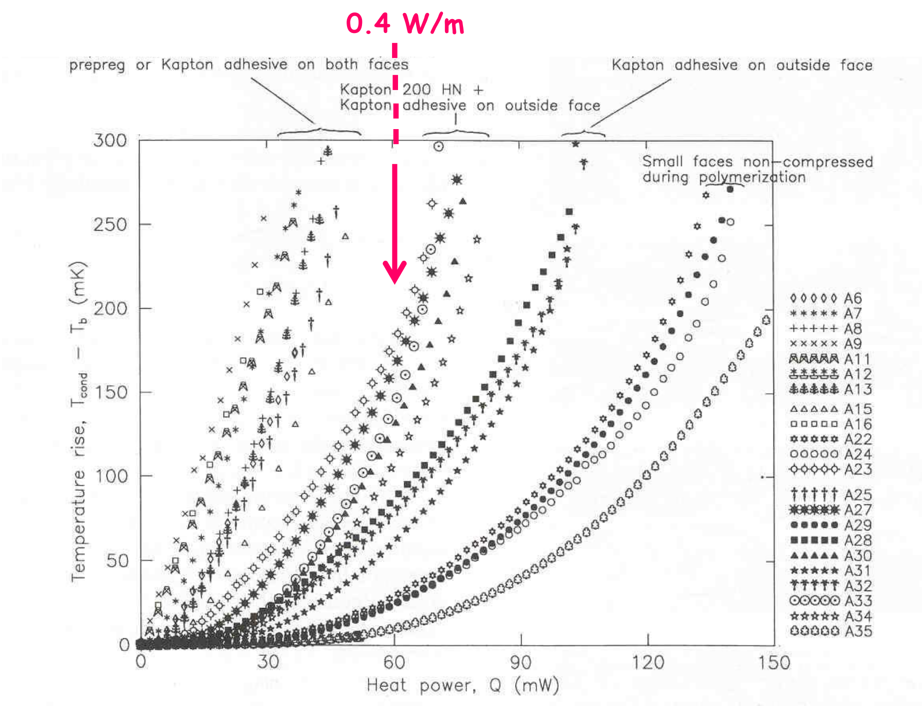
# Heat transfer in All-Polyimide Electrical Insulation (1/2)

- State-of-the-art All-Polyimide Electrical Insulation
  - Developed at Saclay and KEK with Kapton, Apical or Upilex
  - Two layers with polyimide glue for binding

Courtesy of D. Tommasini



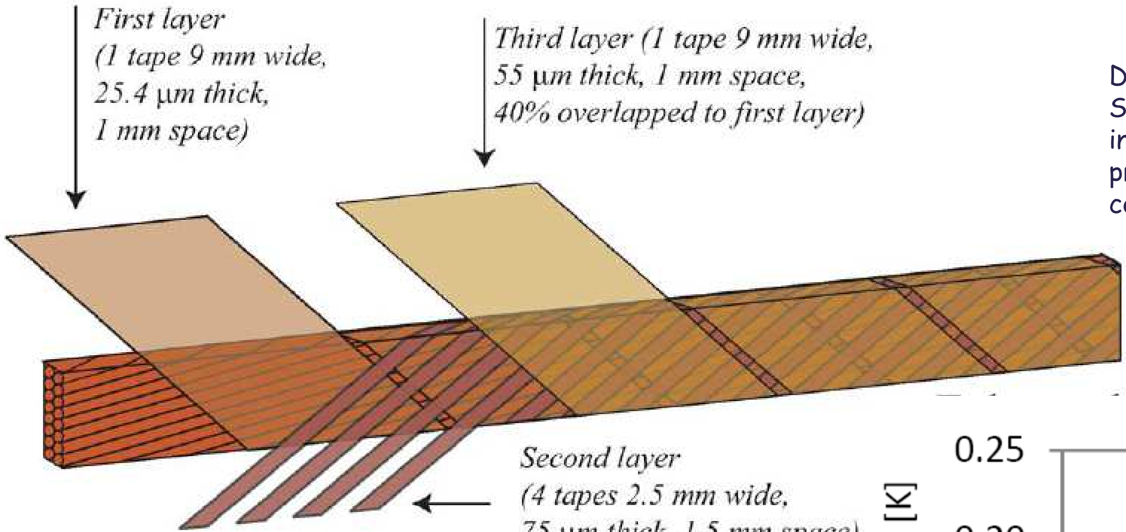

Measurement at 1.9 K




- Thermal performance
  - Current LHC Heat load —> $\Delta T \sim 0.3$ K
  - LHC Upgrade heat load —> $\Delta T > 1$ K

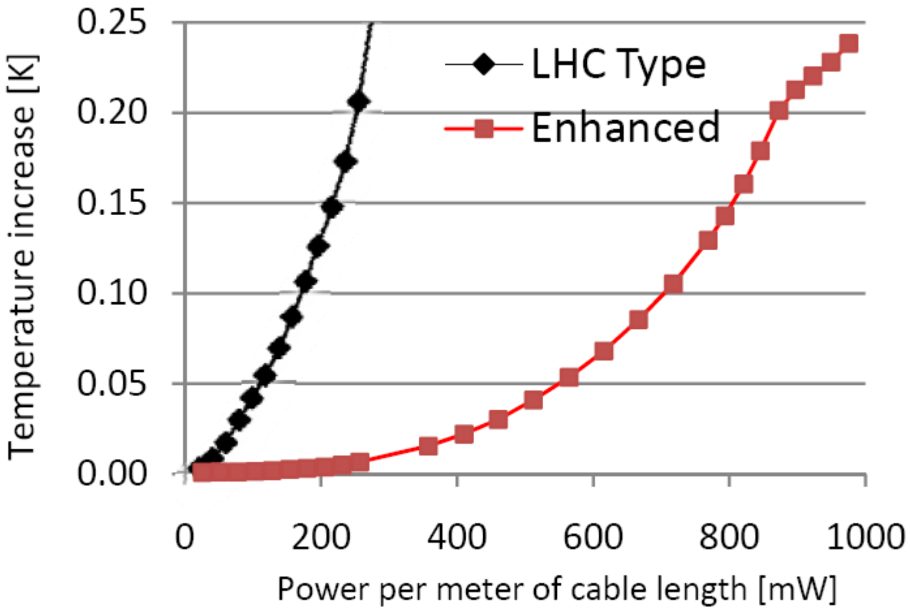
# Heat transfer in All-Polyimide Electrical Insulation (1/2)

- New All-Polyimide Electrical Insulation scheme developed at CERN




D. Tommasini and D. Richter, "A new cable insulation Scheme improving heat transfer to superfluid helium in Nb-ti superconducting accelerator magnets" presented at the 11th European particle accelerator conference (EPAC'08)

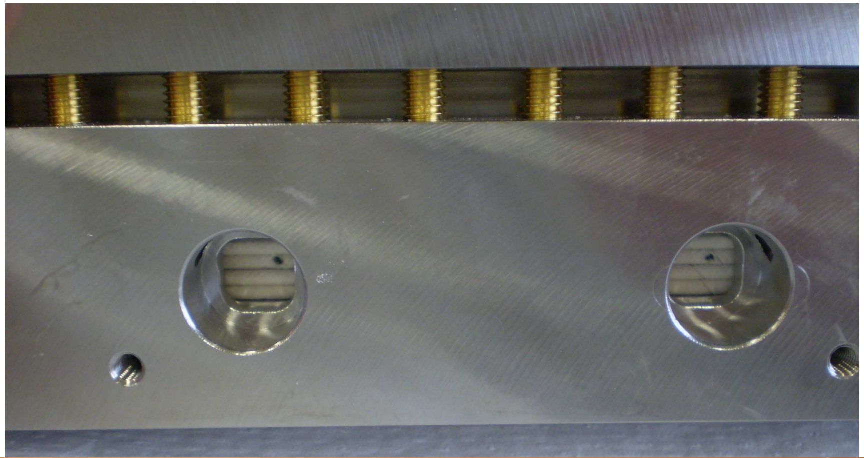
Measurement at 1.9 K

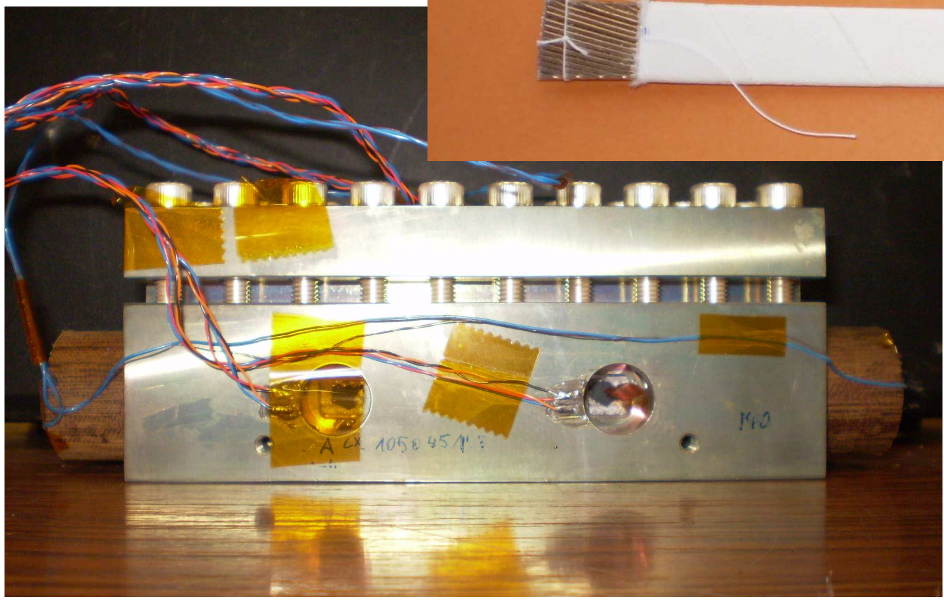



- Avoids direct overlap wrapping by separating the first and last tapes by a series of polyimide strips wound counter-wise
-Three distinct layers are wound with spacing, with the first and third layer providing at the same time cooling channels and dielectric insulation

# Heat transfer in ceramic porous insulation (1/2)

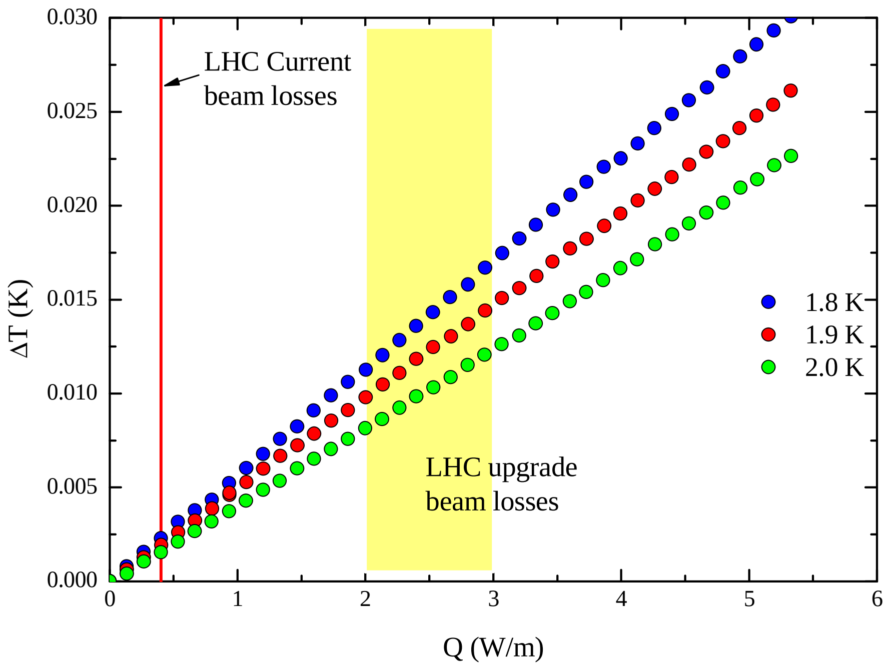
- Ceramic “porous” electrical insulation
  - One wrapping with 50% overlap
  - Heat treatment of 100 h at 660°C
  - 5 conductors heated
  - 10 MPa compression only!

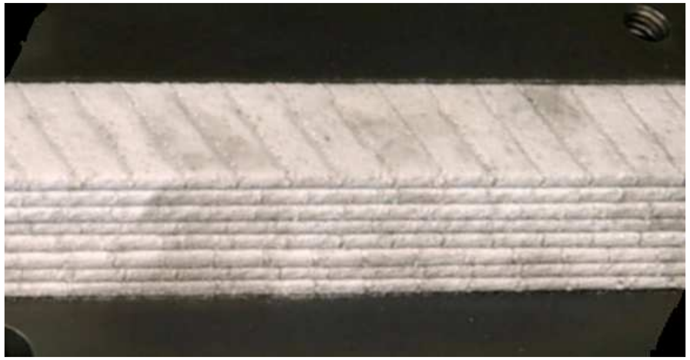




- 100% pure collaboration KEK-Saclay
  - KEK Sample holder
  - KEK temperature measurement technique
  - Saclay insulation

# Heat transfer in ceramic porous insulation (2/2)



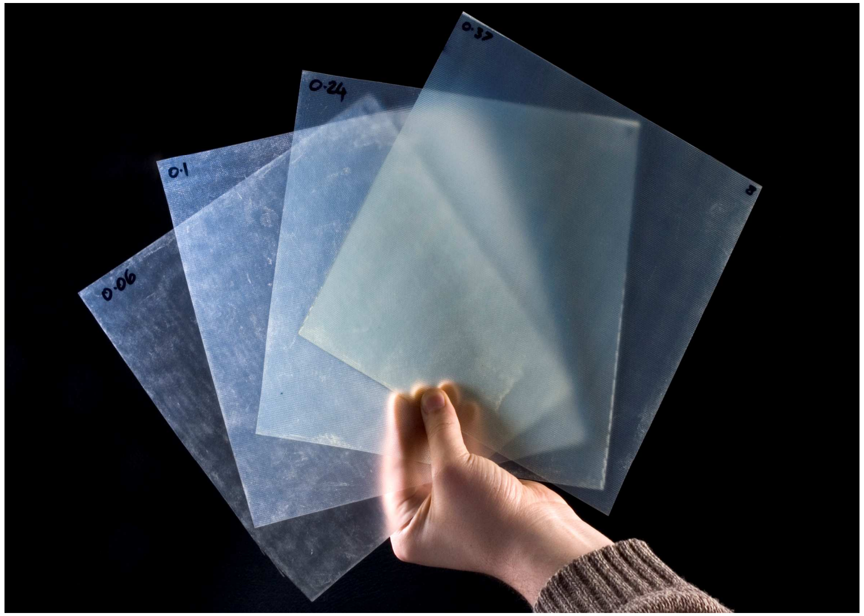



# Heat transfer in All-impregnated insulation (1/3)

- Two electrical insulation scheme developed during the NED project
  - Ceramic porous media
  - All-impregnated electrical insulation

- The fiberglass epoxy insulation
  - Plain weave E glass fiber sheets
  - Mixture of DGEBF epoxy resin, typified by Dow DER354 and DETDA hardener, typified by Albemarle Ethacure 100

- Impregnation
  - Produced using a vacuum impregnation technique in a similar way to magnet impregnation
  - Curation under 1 MPa pressure at a temperature of 90°C
  - When the epoxy was gelled the temperature was raised to 130°C for 16 hours

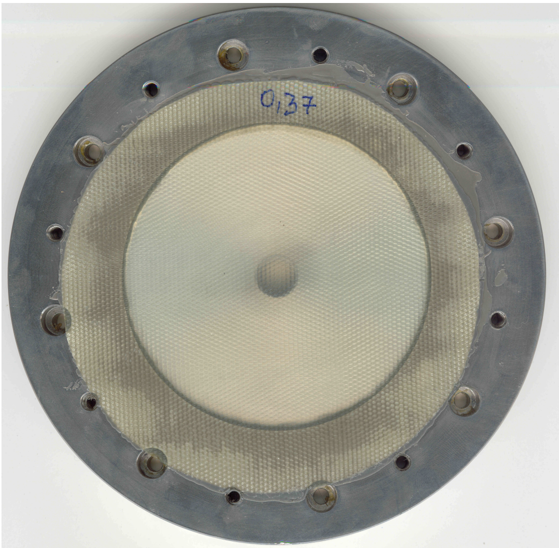


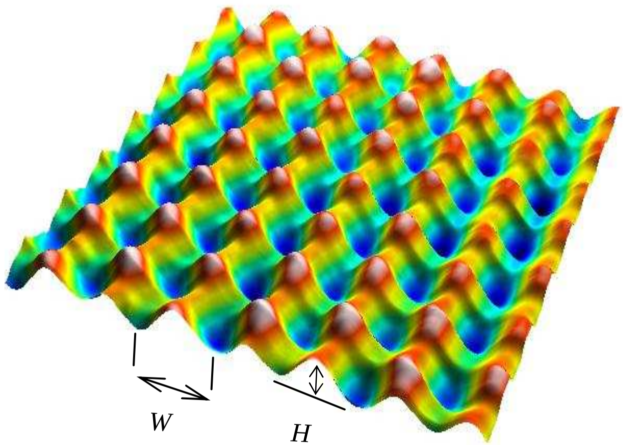

S. Canfer et. al, "Insulation Development for the Next European Dipole", IEEE Trans. on Applied Superconductivity, 18 issue 2, 2008, pp. 1387-1390

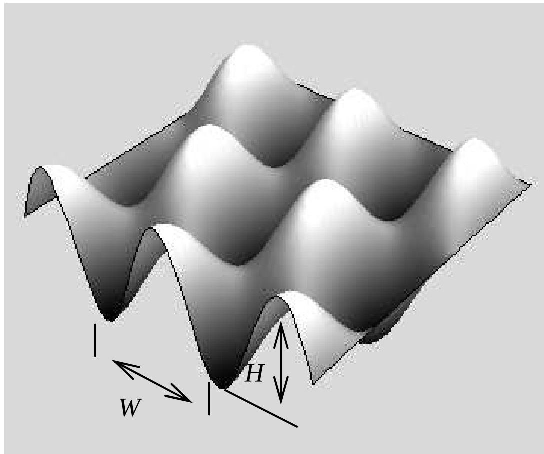
# Heat transfer in All-impregnated insulation (2/3)

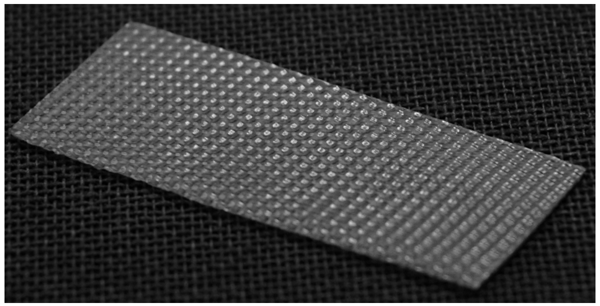
- Kapitza resistance and thermal conductivity in He II determination
  - 4 thicknesses (39, 106, 144 and 293 µm)
  - Profile measurement for real thickness and surface

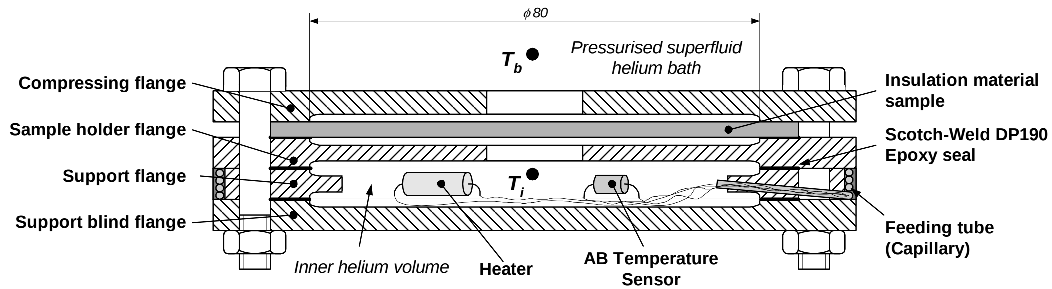
$$R_s = \frac{A\,\Delta T}{Q_s} \approx \frac{2}{n \cdot T_b^{n-1} h_K} + \frac{l}{k}$$



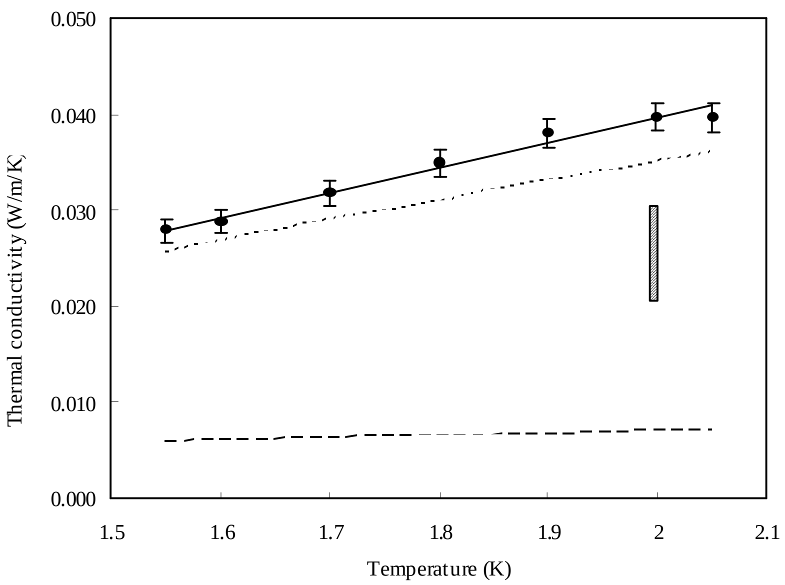



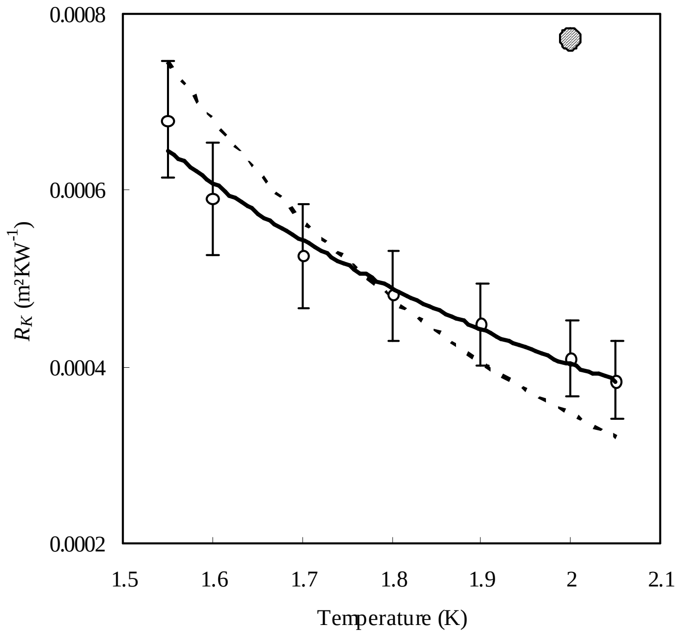





# Heat transfer in All-impregnated insulation (3/3)

- Kapitza resistance and thermal conductivity in He II

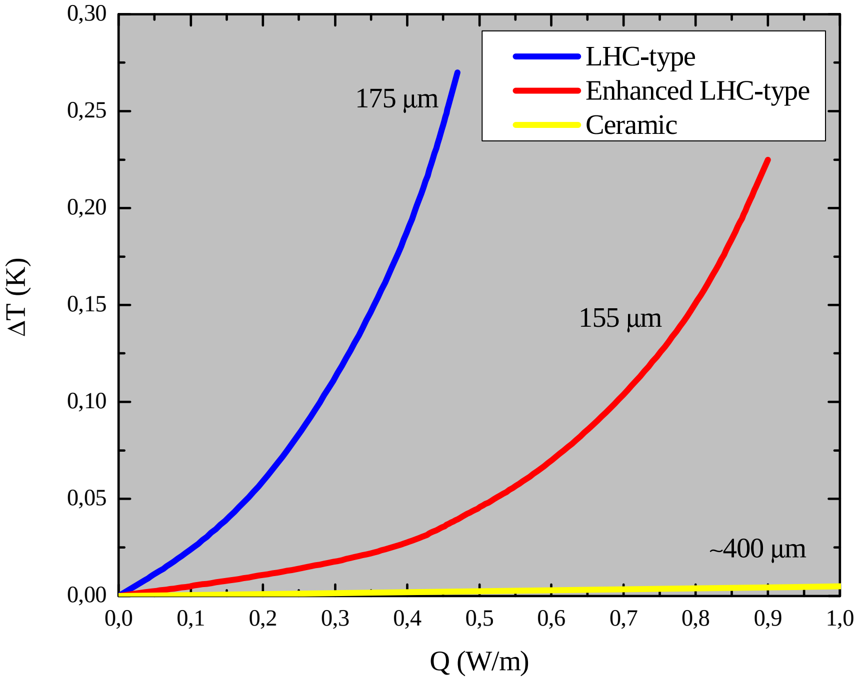


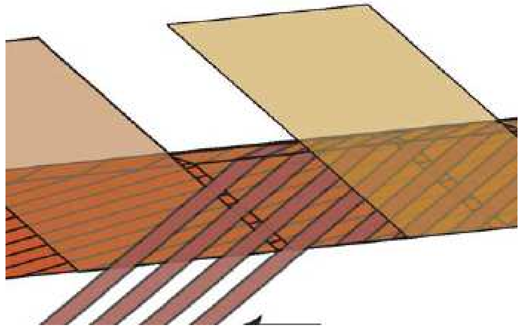



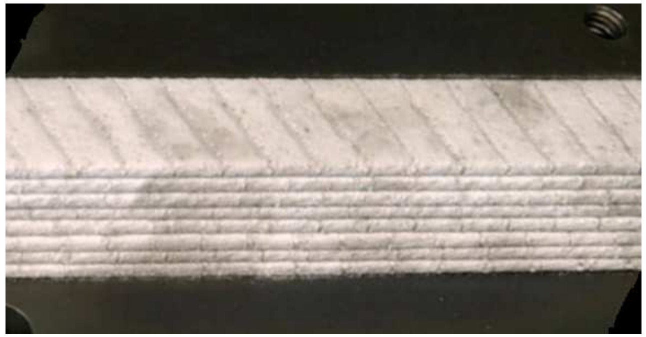

- Thermal conductivity is roughly 5 times larger than the Kapton's one
- Kapitza resistance is two times lower than one data found in the literature


B. Baudouy and J. Polinski, "Thermal conductivity and Kapitza resistance of epoxy resin fiberglass tape at superfluid helium temperature", Cryogenics 49, Issue"3-4, March-April 2009, Pages 138-143

# Insulation Thermal Characteristics

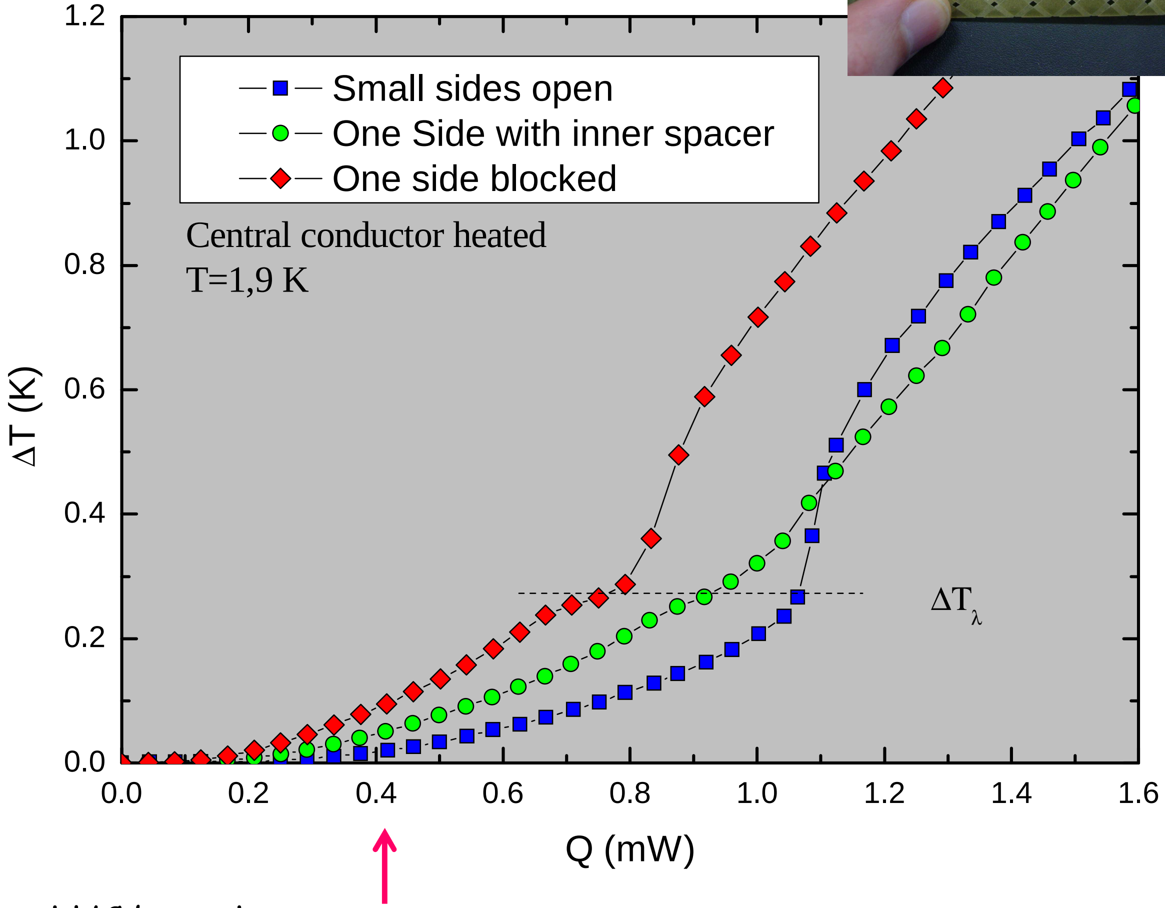


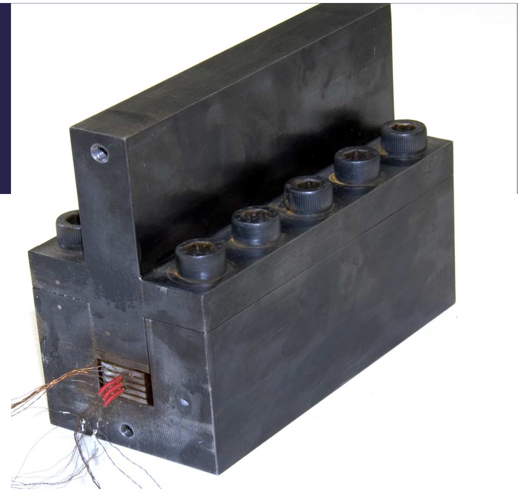



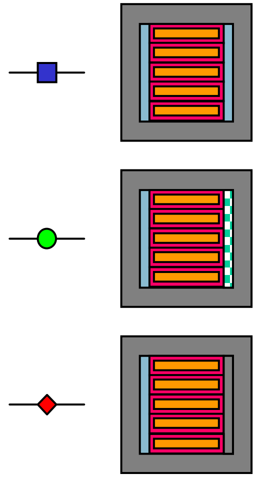


# Boundary conditions effects

- Small face effects



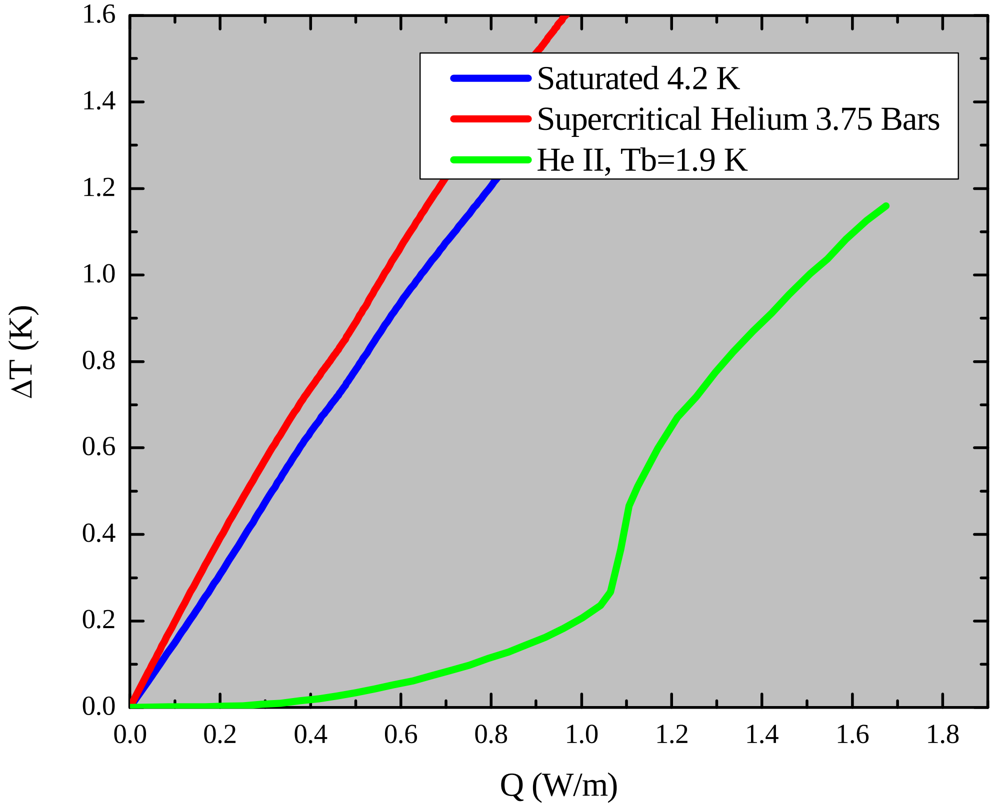


LHC beam Losses

- Q=0.4 W/m
  - ΔT=0.02 K
  - ΔT=0.03 K
  - ΔT=0.06 K

# Helium Thermodynamics effect

- Measurements in Saturated He I, Supercritical He I and He II
- Measurements done with the inner spacer located on one “small face”




- Q=0.4 W/m
  - ΔT=0.02 K
  - ΔT=0.65 K
  - ΔT=0.75 K

- Equivalent measurements should be performed on the porous insulation
  - He I and She at KEK and He II at Saclay

S Pietrowicz, N Kimura, BBaudouy, J. Polinski, A Yamamoto, “Thermal behaviors of Rutherford type stack of cables with polyimide isolation in normal and supercritical helium ”, ICEC Seoul 2008

# Perspectives

- 2 electrical insulation candidates for 15 T Nb3Sn magnets
  - Ceramic insulation (permeable insulation ?)
  - All impregnated insulation (dry insulation)

- Ceramic insulation (permeable state) within FJPPL
  - Thermal conductivity measurement (KEK within CERN-KEK Collabaration)
  - He II Stack experiment
    - Continuation of He II exp at Saclay and sHe and bHe at KEK (FJPPL)
  - He II Insulation only experiment

- Ceramic insulation (impregnated state) to be discussed
  - Thermal conductivity measurement at KEK
  - He II Stack experiment at KEK and Saclay
  - Kapitza experiment at Saclay

- All impregnated insulation to be discussed
  - Stack experiment at KEK and Sacla

- Development of ceramic insulation