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Review of heat transfer mechanisms in superconducting magnets

Bertrand Baudouy
CEA Saclay
DSM/Dapnia/SACM/LCSE

Outline

- Different heat transfer modes to cool magnets
  - Introduction
  - Pool boiling, Static He II, Forced flow single phase, Forced flow two-phase
  - Comparison
- Heat transfer in the electrical insulation and coil: Rutherford Cable type
  - Phenomenology
  - Past Results
  - Some ideas
- Current and Possible R&D programs (NED)
  - The method
  - The experimental apparatus
  - The Tests

Introduction – Temperature margin

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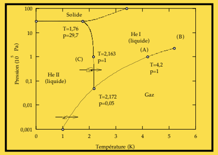
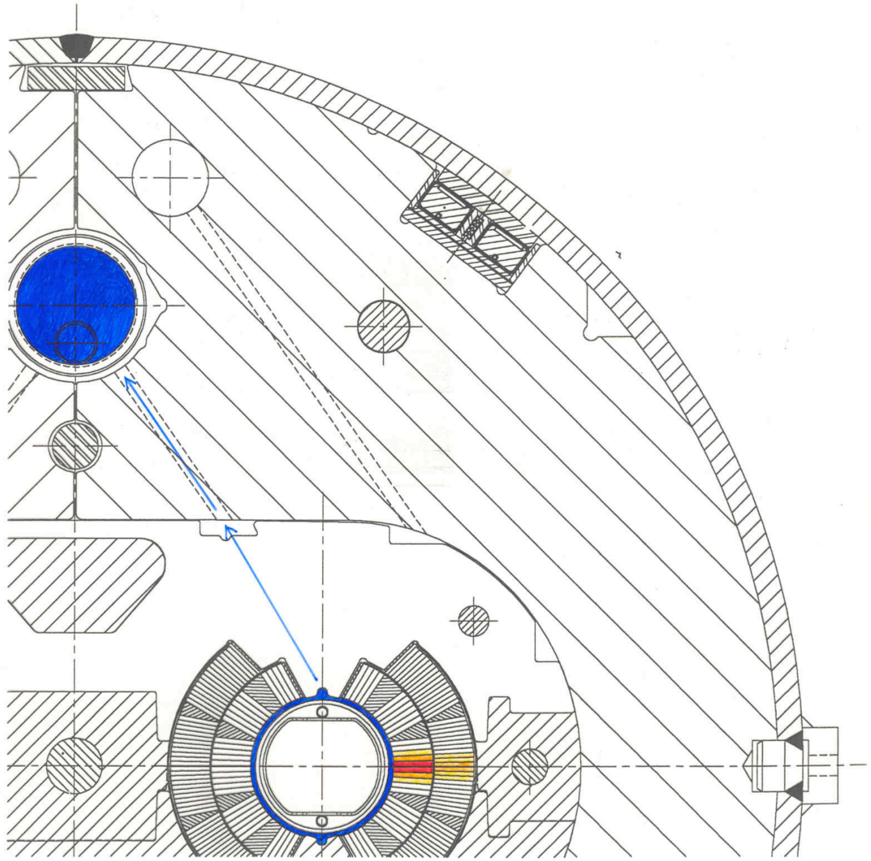


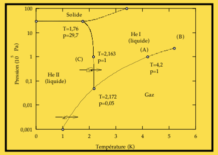
- Heat transfer from the conductor to the cold source define the temperature margin
- Electrical insulation is the largest thermal barrier against cooling
- Electrical insulation can be
  - Non-existent
  - Monolith
  - For LHC magnet
    - $T_{conductor}$=1.9 K or $T_{conductor}$~4 K [Burnod 1994]



- Previous works focused on the thermal paths (He II)
  - Creating paths between the conductors by wrapping configurations and minimizing the glue…
  - No complete work on the solid material (holes, conductive insert or porosity)
  - No complete work with He I or SHe

Introduction – Cooling modes

- Cooling mode and thermodynamical state
  - Working temperature and stability margin (superconducting properties), Refrigeration power, Mechanical constraint (space), Size and cost
- Immersion in a stagnant liquid
  - Saturated and sub-cooled He I, Saturated or pressurized He II
- Forced flow cooling (internal or external to the cable)
  - Sub-cooled Helium, Supercritical, Superfluid, two-phase
- Two types of magnet for heat transfer point of view
  - “Dry coil” magnet : Helium in contact with the insulation or structure only
    - Conduction (cable + insulation + structure) and surface heat transfer
  - “Wet coil” magnet : Helium in contact with the insulation and the cable
    - Helium Heat transfer and conduction (cables + insulation) and Surface heat transfer
- With heat exchanger or not
- Best solution for thermal stability : helium in contact with the cable?
    - Enthalpy reserve in the cable, better heat transfer coefficient
    - Quench issue : Δp within the insulation?



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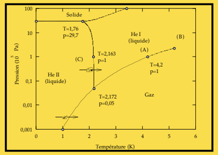
Pool boiling @ Atm pressure

- Characteristics
  - High heat transfer coefficient in nucleate boiling
  - easy design
  - Heat transfer by natural convection and eavily influenced by gas
  - Major (dis)advantage is T=4.2 K
  - Non uniform cooling due to vapor formation



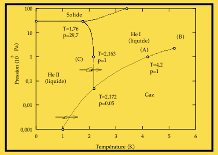
- Heat transfer
  - 3 Regimes : Natural convection, Nucleate boiling, Film boiling
  - Highest heat transfer in nucleate boiling, no film of gas on surface
  - $q_{max} \approx 10^4$ W/m^2 for $\Delta T \approx 1$ K

- Solutions to enhance heat transfer rates and thermal stability
  - Natural convection Channels or thermosiphon to eliminate stagnant vapor zone and enhancement of heat transfer [Jones 1978]
  - Increase surface rugosity [Butler 1970] et [Nishi 1981]
  - Increase of heat transfer coefficient by larger cross-section channel [Nishi 1983] et [Wilson 1983]
- Typical heat loads 1 W/m and magnet length of 20 m [Van Weelderen 2004]

Saturated He I forced flow

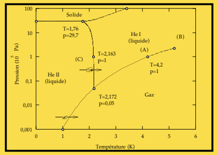
- Characteristics
  - Isothermal fluid over the cooling circuit (4.2 K)
  - High heat transfer coefficient
  - Save space and weight compared to pool boiling
  - Smaller helium content in the system
  - Two-phase flow but ($\rho_l/\rho_v \approx 7$ at 4,2 K)

- Heat transfer
  - Good heat transfer up to x=98 % [Mahé 1991] et [Neuvéglise 1995]
  - $q_{max} \approx 10^4$ Wm^{-2} for a SS tube of Ø10 mm $m=610^{-3}$ kg^{s-1} and $\Delta T \approx 1$ K [Mahé 1991] (titre initial de 0).



Static pressurized He II

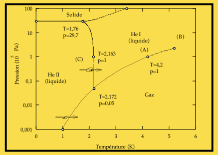
- Characteristics
  - Lower operating T (higher performance of superconductor)
  - Improved local heat transfer
  - High heat conductivity (reduced vapor generation)
  - Bath cooled magnet and also CICC (45T Magnet @ NHMFL)
  - Double bath technique or with HX



- Heat transfer
  - $k \approx 10^5$ W/m.K for $\Delta T \approx 0.3$ K, over it is He I ($k \approx 0.02$ W/m.K)
  - Dimension of cooling channel between cable and HX
  - $q_{max} \approx 10$ kW/m^2 for L=1 m and $\Delta T \approx 0.35$ K (15 kW/m^2 for He II sat)
  - Interface thermal resistance between solid and He II (Kapitza resistance)
    - Cu $R_k = 3\ 10^{-4}$ K.m^2/K and Kapton $R_k = 10^{-3}$ K.m^2/K
- Performances:
  - For LHC main magnets 1 W/m and for high heat loads (inner triplets 15 W/m)
  - If Requires attention to conduction paths then extendable to 50 W/m [Van Weelderen 2004]

Forced flow He II

- Characteristics
  - Same advantages of Static pressurized He II
  - Applied when He II static cooling is not sufficient
  - Internally cooled magnets
  - Needs specific pumps, HX, more complicated cooling scheme
- Heat transfer
  - Kapitza resistance not a function of velocity [Kamer 1988]
  - Classical Frictional Δp up to $Re \approx 10^7$ [Fuzier 2001]
  - Transition velocity for advection effect (1m/s for ΔT=0.1 K @ 1.8 K) [Van Sciver 1998]
  - Negative JT coefficient (0.2 m/s for 100 m)
    - CICC : Dh=0.5 mm Δp=75 kPa (150 mK)
    - Smooth tube : Dh=10 mm Δp=1 kPa (5 mK)
  - Pumps add heat loads on the system
  - Parallel hydraulic channel may help
- Not applied for accelerator magnets [Van Weelderen 2004]



Forced flow supercritical helium

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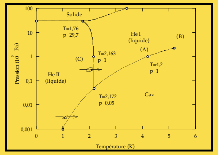
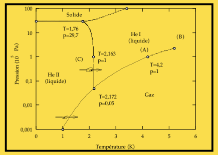
- Characteristics
  - Comparable heat transfer coefficient to pool boiling
  - Single phase flow (no vapor formation)
  - Adjustable heat transfer with mass flow (temperature optimization)
  - Can be « plugged » to refrigeration plant and use of cooling from 300 K
  - Internally cooled conductor, For CICC, better electrical insulation
- Heat transfer
  - Classical heat transfer Nu [Giarratono 1971], $q \approx 10^4$ W/m^2 for $\Delta T \approx 1$ K
  - JT coefficient positive or negative
  - Pressures are P≈3-8 bar, ΔP≈1-2 mbar per magnet
  - T≈4.4 K, ΔT≈50-150 mK per magnet
- Performances[Van Weelderen 2004]:
  - Typical heat loads are ≈2 W per magnet (RHIC)
  - 6 W per magnet (cross flow in SSC)



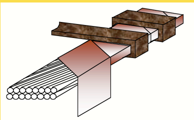
Comparison of cooling modes

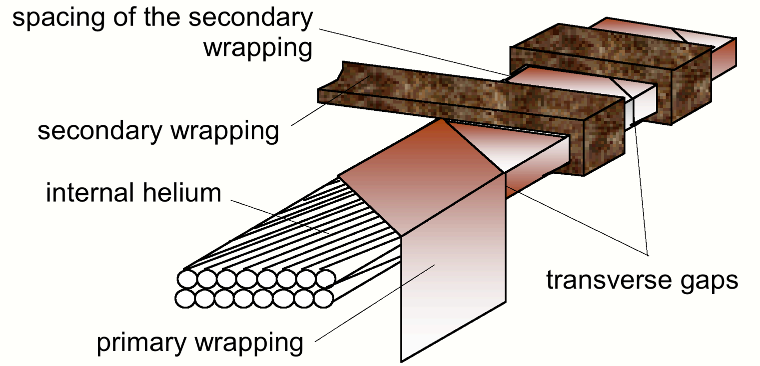


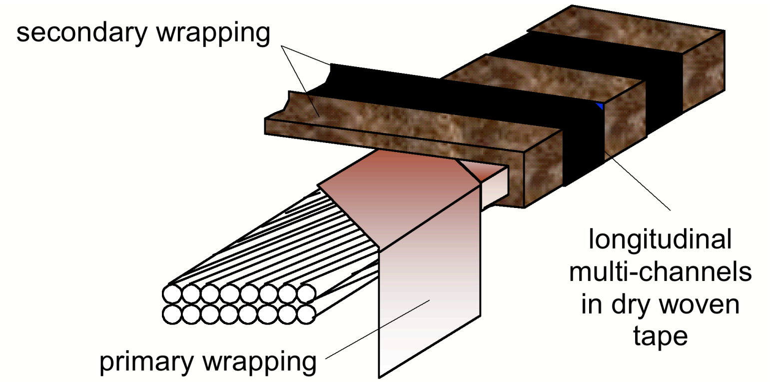
- Pool boiling (~1 W/m)
  - Liquid-vapour phases, vertical liquid heat conduction paths and ullage space necessary
- Forced convection of superfluid helium (~1 W/m)
  - Single phase, circulation pump needed, no accelerator implementation yet
- Forced convection of supercritical helium (~1-10 W/m)
  - Easy to implement for low heat loads, Single phase Mass flows of O(W/0.1 kg/s), High heat load possible at the expense of T-margin and high ΔP, Cross-flow construction needed for high heat loads
- Static pressurized He II (~1-10 W/m)
  - With a two-phase flow of saturated helium II (bayonet heat exchanger) heat loads of O(10W/m), High conductivity avoids “dead spots”, Concept certainly extendable to heat loads of about 50W/m

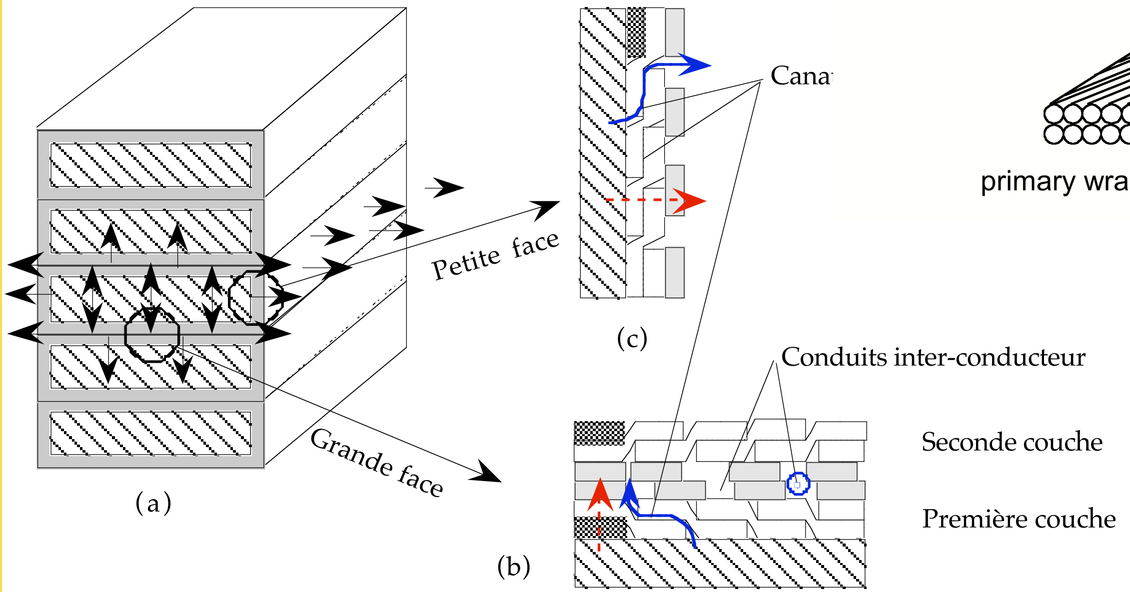
Heat transfer in superconducting coil

- Heat transfer in a coil
  - Insulations
  - Phenomenology
  - Past results
  - Insulation for GSI
  - “Comparison”
  - Some ideas









Evolution of insulation

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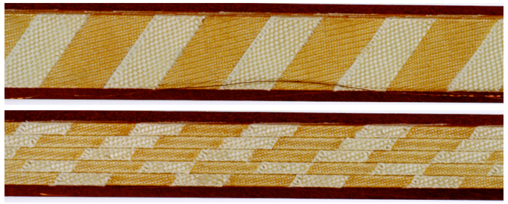

- Historical insulation : 2 wrappings
  - First wrapping in polyimide with 50% overlap
  - Second wrapping in epoxy resin-impregnated fiberglass with gap

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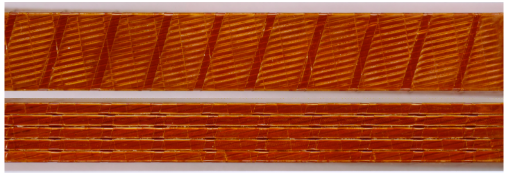
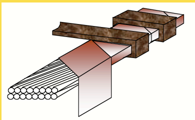
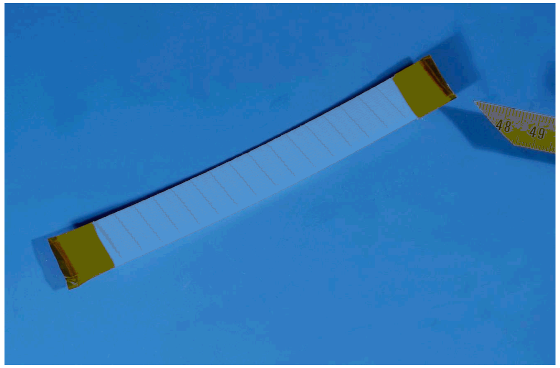


- The LHC insulation work : 2 wrappings
  - First wrapping in polyimide with 50% overlap
  - Second wrapping in polyimide with polyimide glue with gap



- Current LHC Insulation : 3 wrappings [Meuris 1999] [Kimura 1998]
  - First 2 wrappings with no overlap
  - Last wrapping with a gap
  - Apical R_{th} Kapitza and k @ 2 K
    Just tested at Saclay



Courtesy of F. Rondeaux (CEA)

[Puissegur 2004]

- Innovative insulation for Nb_3Sn magnet
  - Fiberglass tape + Ceramic precursor
  - Smaller Porosity (d~0.1 µm, ε?, th=400 µm)
  - k≈4 10^{-2} W/K.m (k_{kapton}≈10^{-2} W/K.m) @ 2 K

Heat Transfer : Phenomenology

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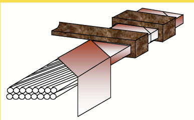
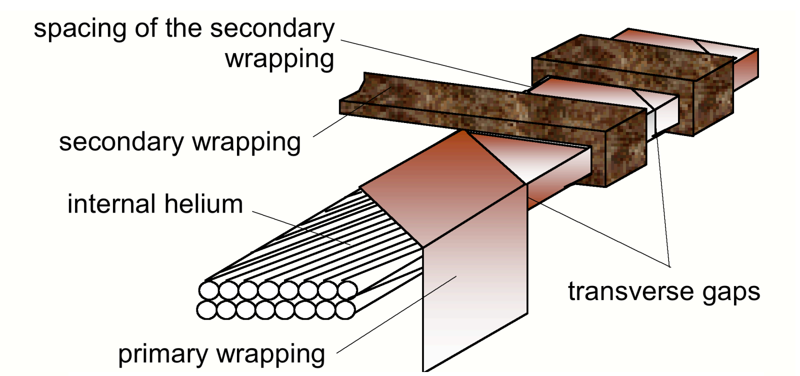
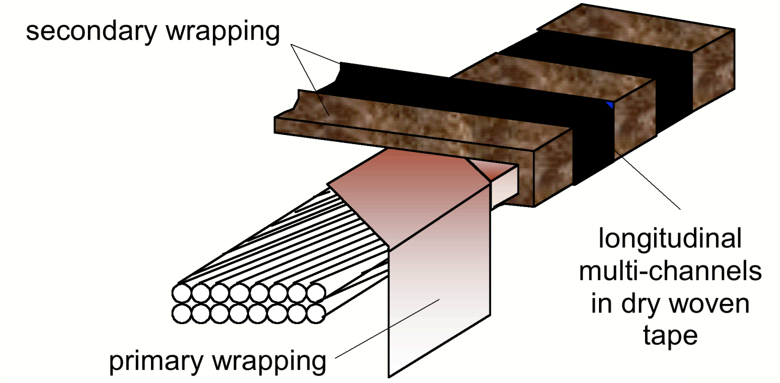
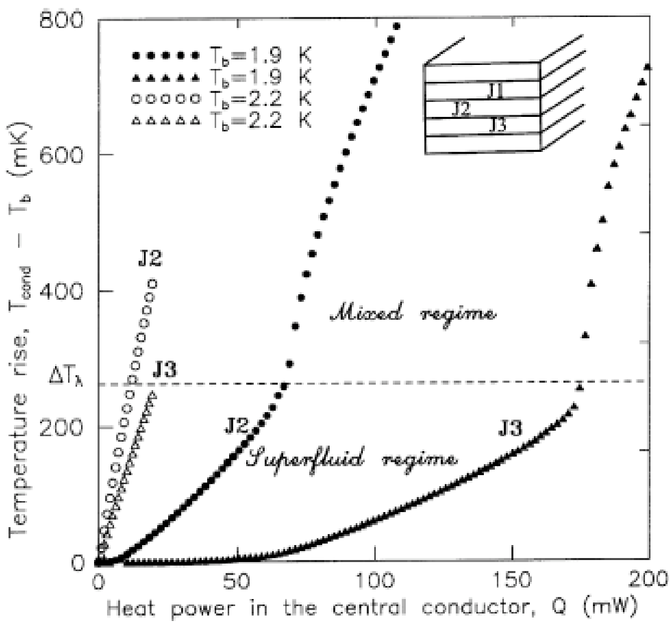
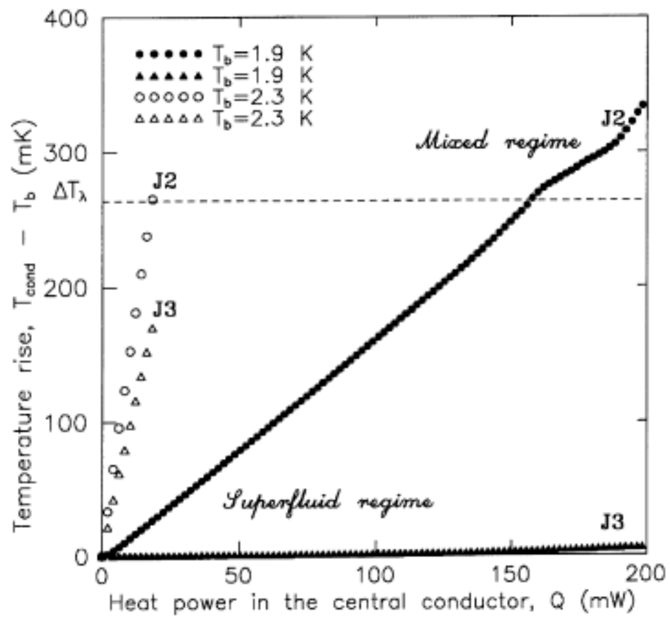
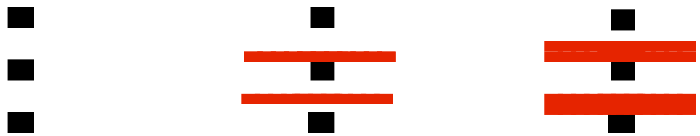








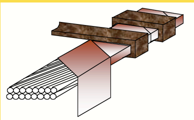


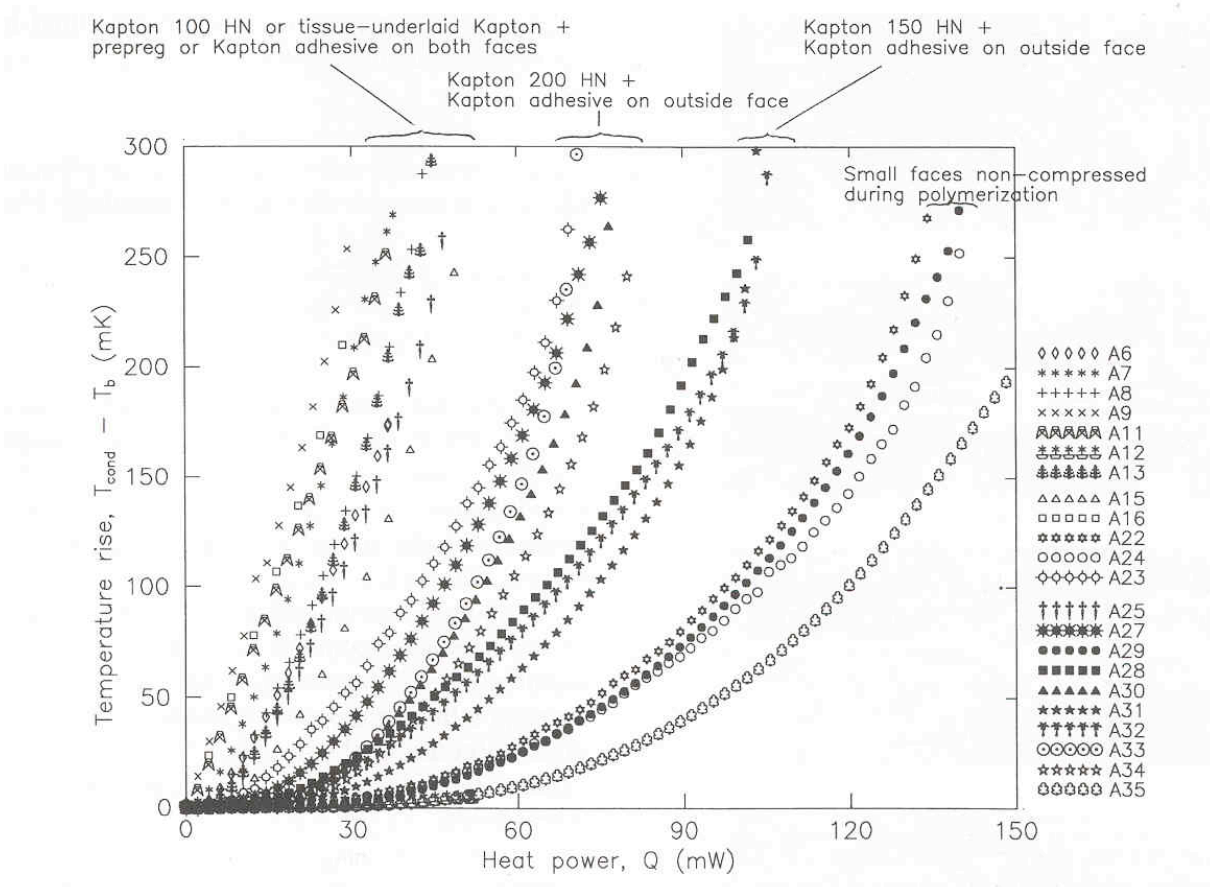


[Meuris 1999]

Results : The different configurations

- Epoxy Resin or glue on both side of the layer fills up the helium path
- Dry fiber thermally decouples the conductors
- Very small paths for He for polyimide insulations with gaps due to overlapping





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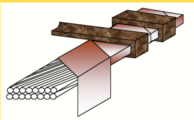
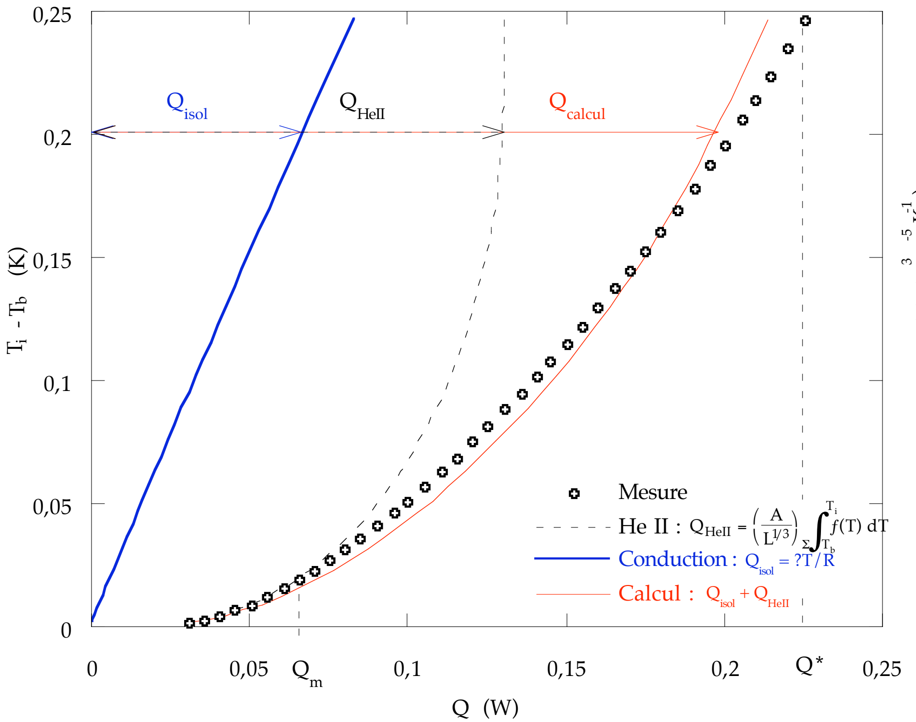
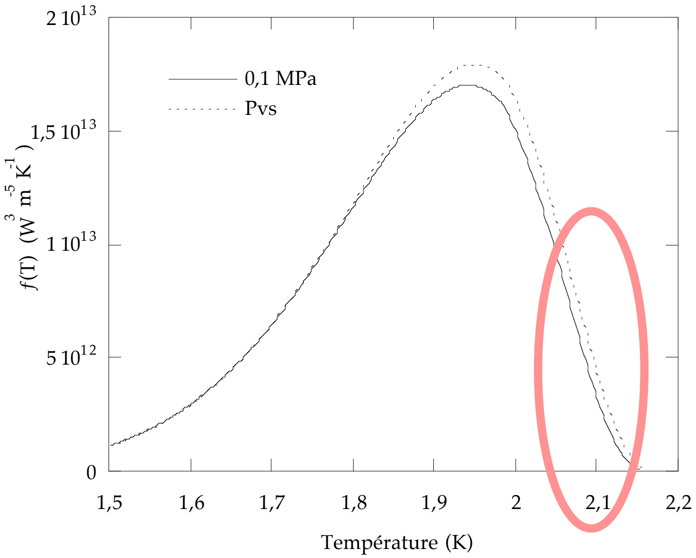
Results : The insulation is participating

- Study on conventional insulations
  - d~10 μm, channel length ~ mm
  - He II in // conduction + Kapitza





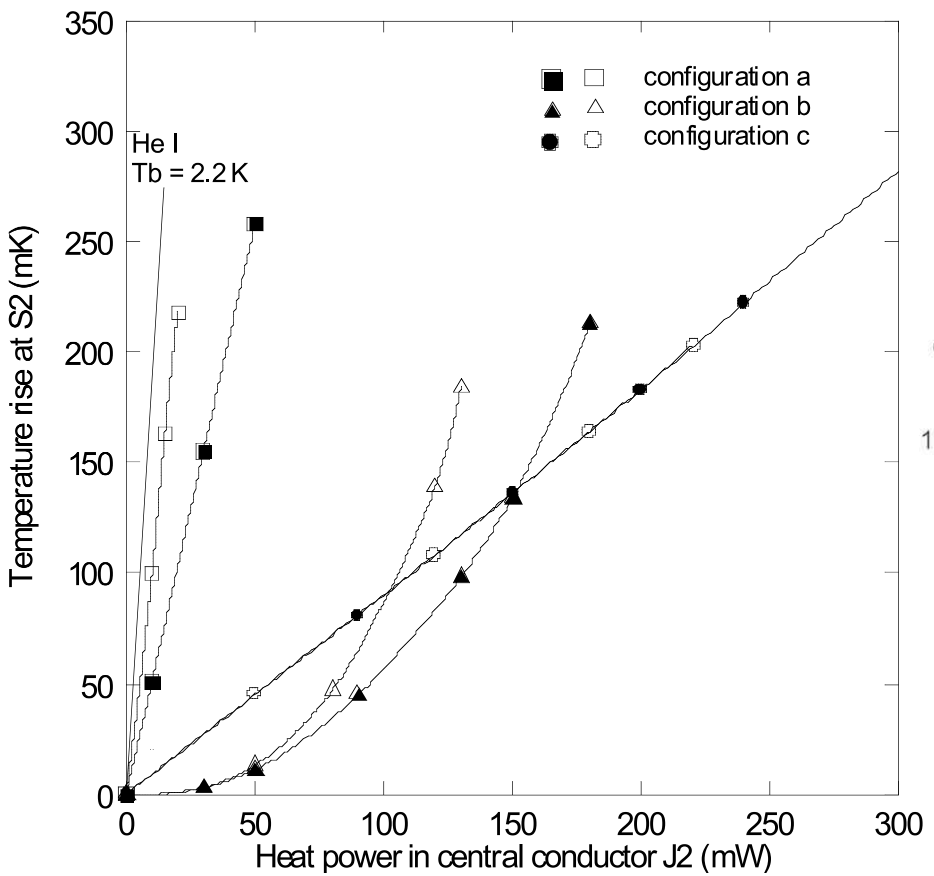


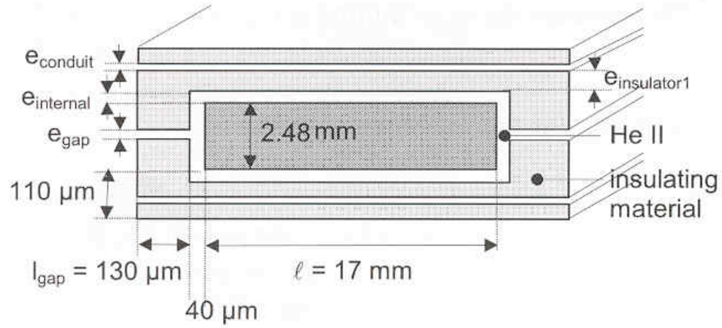
[Baudouy 2OO1] and [Kimura 1999]

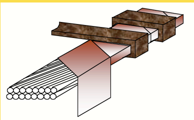
$$\vec{\nabla} T \approx -\frac{A\rho_n}{\rho_s^3 s^4 T^3} \left|\vec{q}\right|^2 \vec{q}$$

For Large ΔT, He II HT < Conduction HT

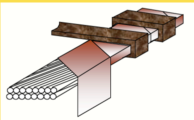
Results : Conclusions







The insulation for GSI magnet



- GSI001 : a conductive insulation
  - Inner layer : Polyimide 25 µm thick with adhesive on one side (50 % overlap)
  - Outer layer : Polyimide 24 µm thick with adhesive on both side (50 % overlap)

- UNK magnets PF insulation : A classic
  - Inner layer : Polyimide 20 µm thick with twist pitch of 5 mm
  - Outer layer : Prepreg fiber glass 100 µm thick with 1mm gap

- UNK magnets PP insulation : An all Polyimide Insulation
  - Inner layer : Polyimide 20 µm thick with twist pitch of 5 mm
  - Outer layer : Polyimide 40 µm thick with adhesive on both side, 1 mm gap

- UNK magnets PFM insulation : A classic improved for He II
  - Inner layer : Polyimide 20 µm thick with twist pitch of 5 mm
  - Outer layer : Prepreg fiber glass 100 µm thick with 5 mm gap

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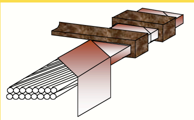
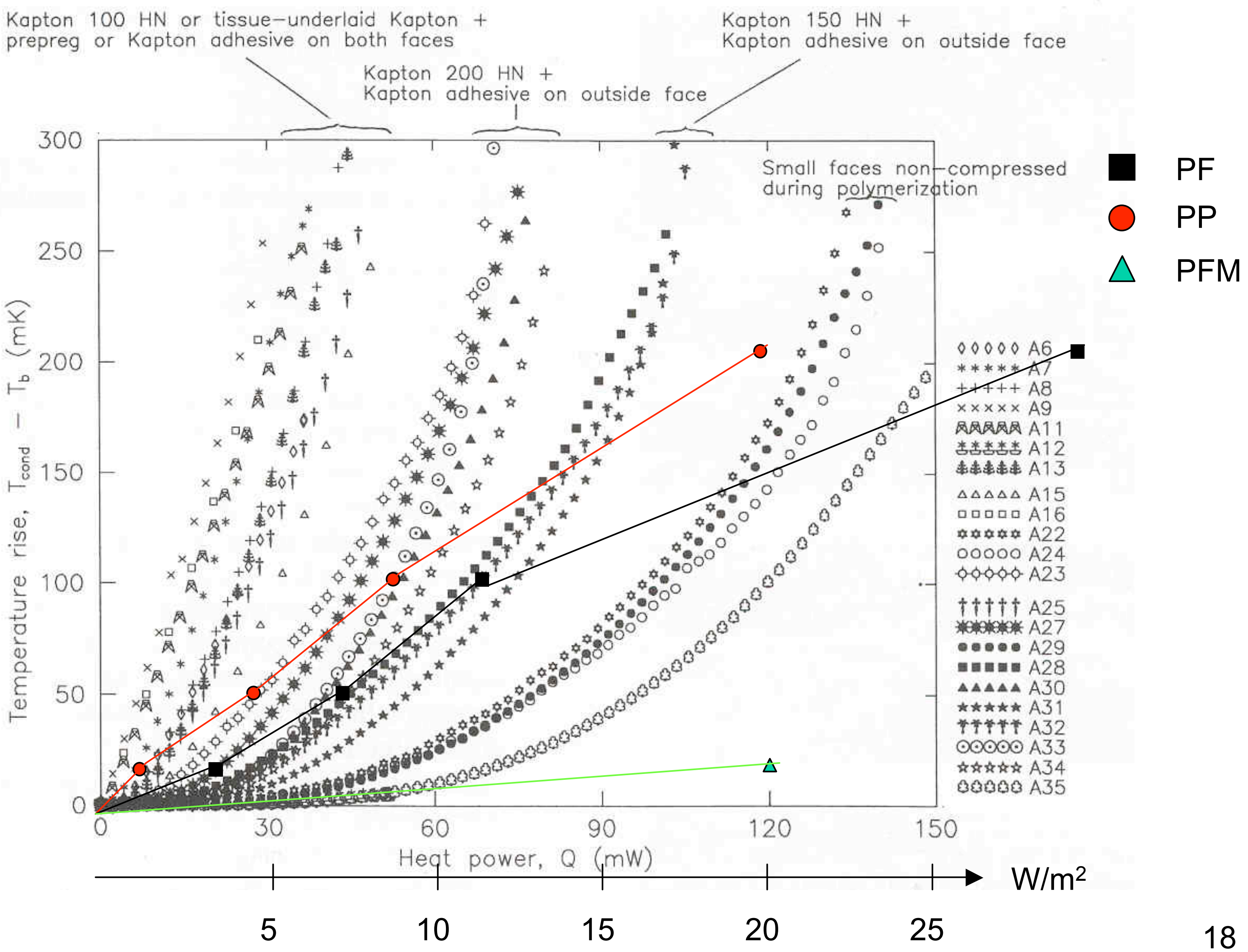
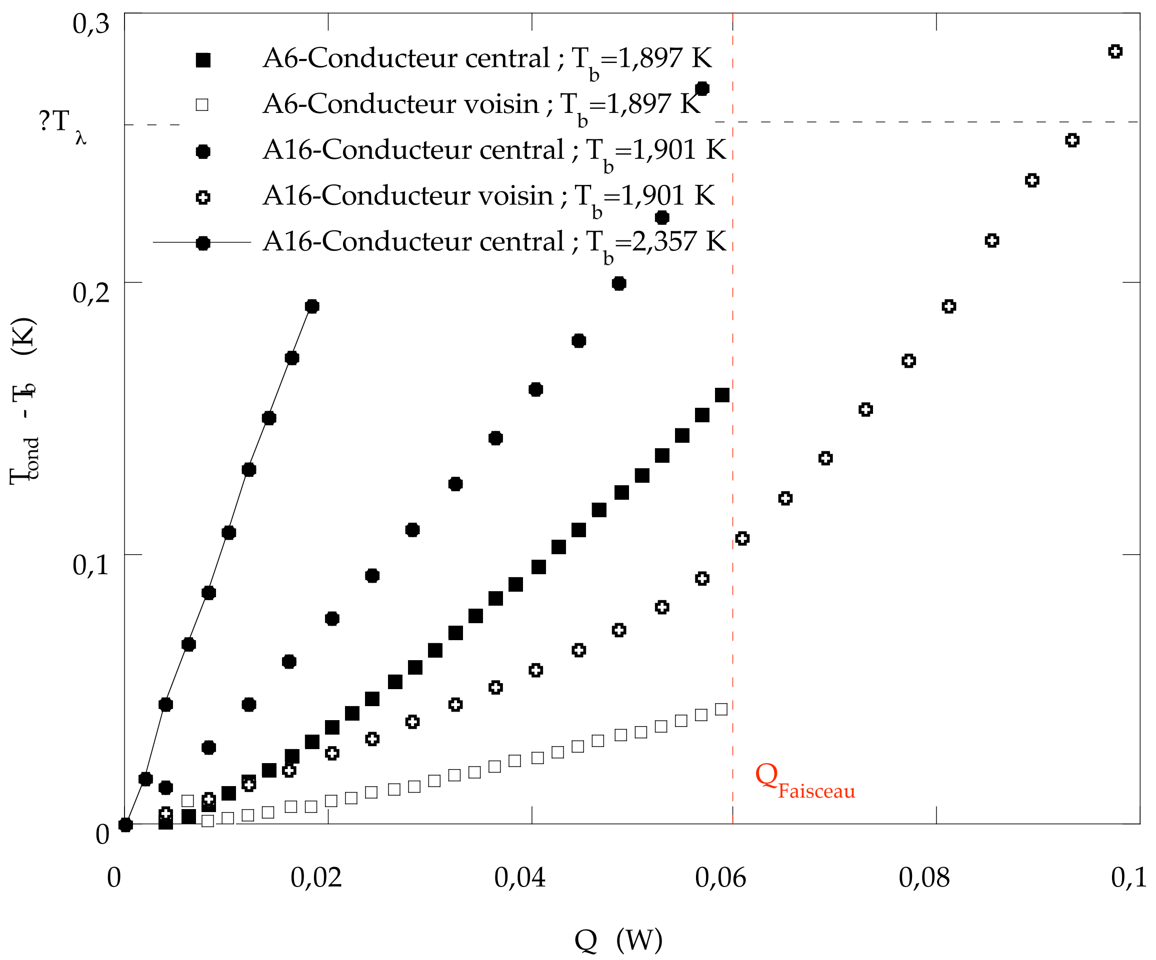
Comparison

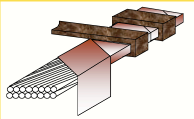
- Test in boiling He I





Heat transfer in He I and He II





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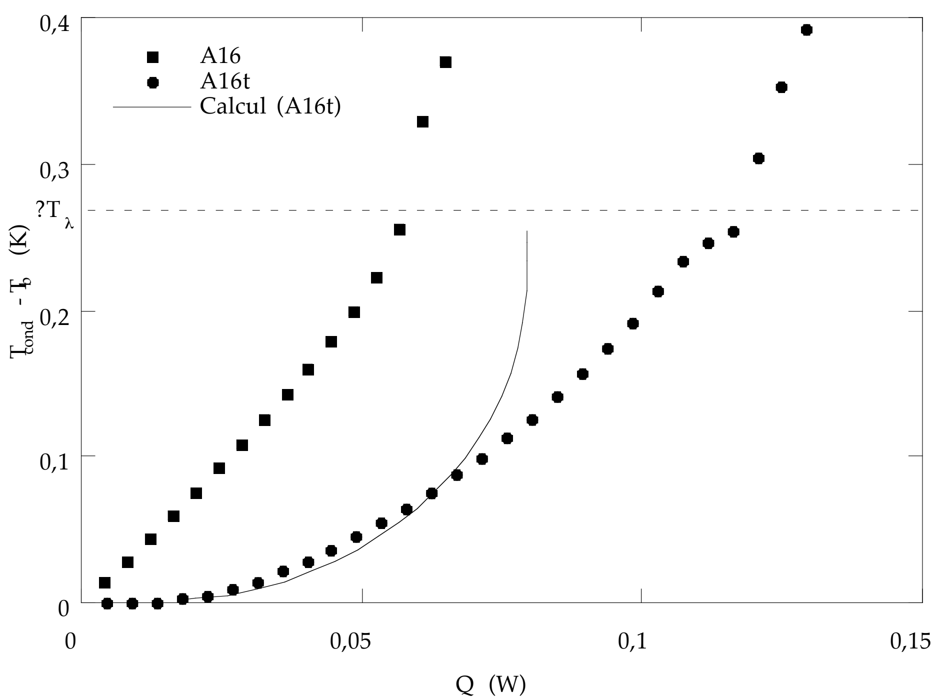
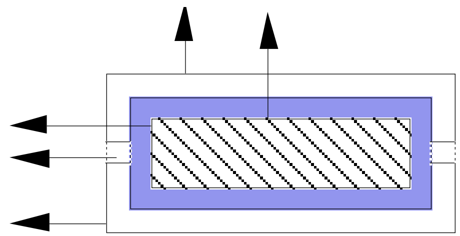
Small face with holes

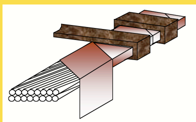
- Artificial permeability with 6 holes of Φ 200 μ [Baudouy 1996]
- Holes reduce permeability and R_{th} of small face and of the insulation






[Wilson 2002]

- Small ΔT, heat transfer through the holes
- High ΔT, heat transfer through holes and conduction



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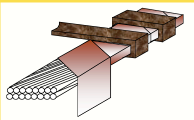
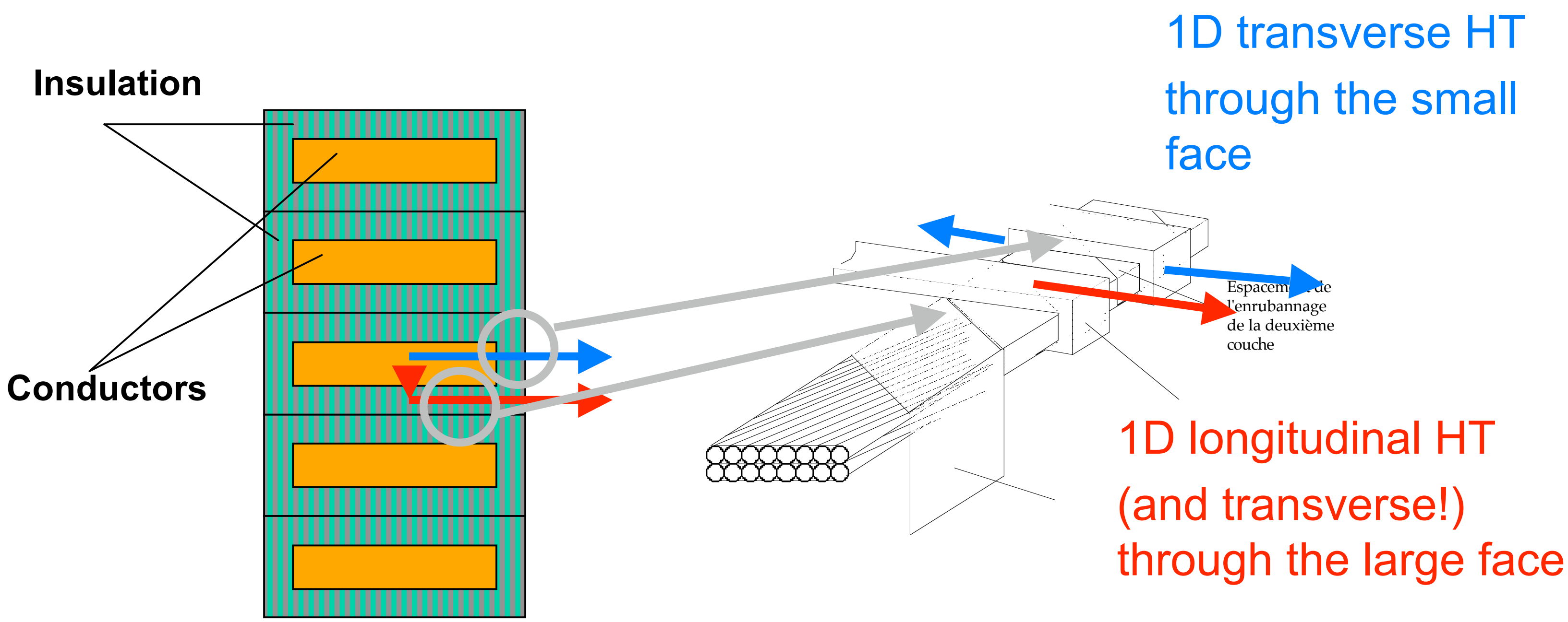
Ideas for insulation in non He II

- Work needed on the material itself
  - Thermal conductivity of Kapton, Apical, Peek?
  - Can it be enhanced?
  - Other insulation system?
- Increase heat transfer between the cable layer
  - Porous second layer like for NED or dry fiber glass
  - Has to be tested in He I or She
- Increase the Heat transfer through the small face
  - No epoxy resin and minimum amount of polyimide glue
  - Large overlap gap for second layer
  - Optimized overlap for the second layer

  - Direct contact between helium and the conductor is good
  - has to be tested in He I or SHe
- Increase the helium in the cable
  - Central core in porous material?



NED R&D program : Method

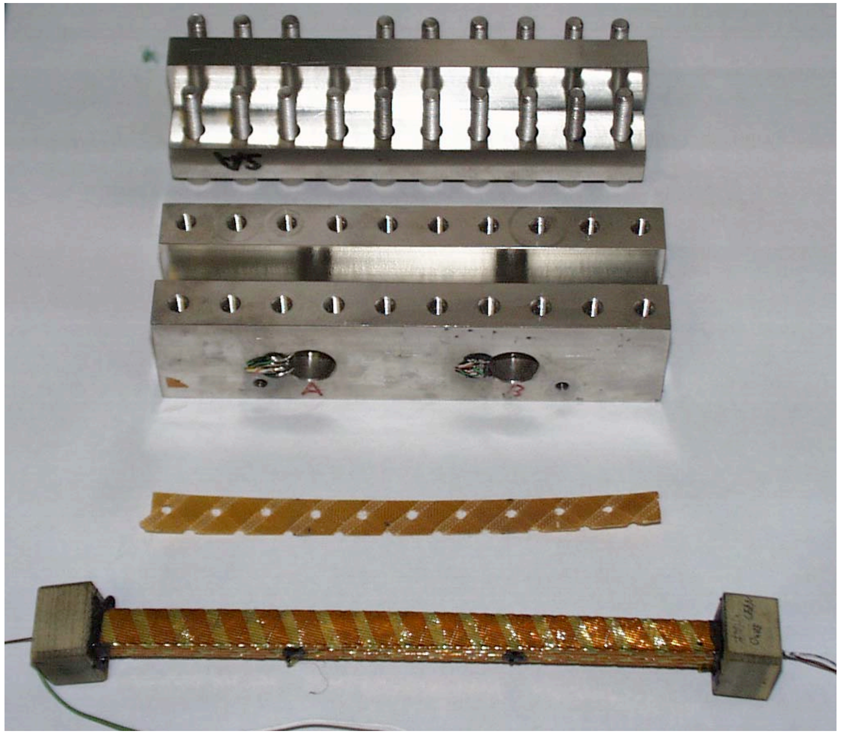


- Stack experiment
- 1D transverse HT (Drum set-up)
- 1D longitudinal HT (Conduit experiment)

} Stack = Drum + Conduit

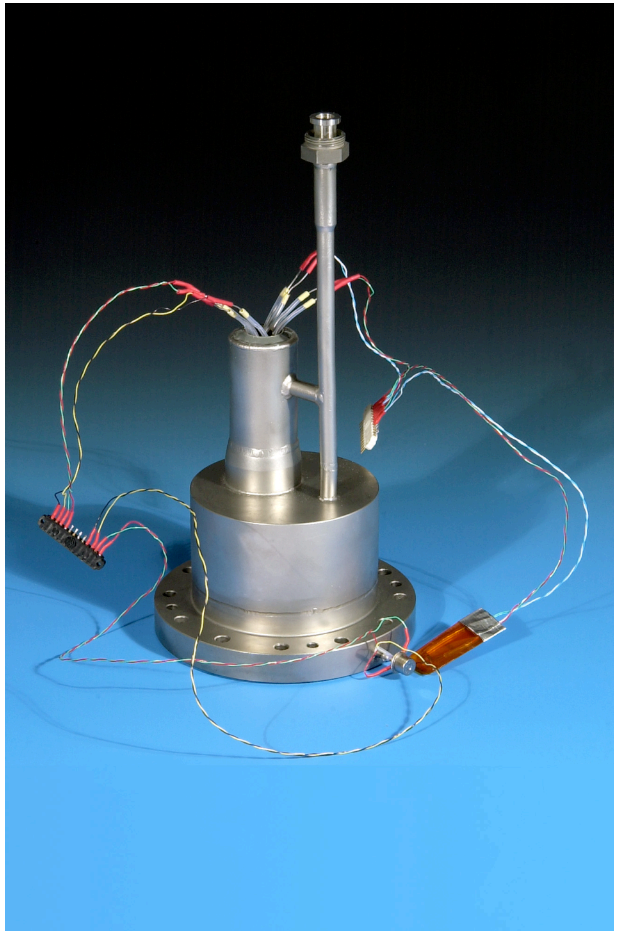
NED R&D program : Experimental apparatus

- Stack of five insulated conductors under mechanical constraint
- Conductor = CuNi Strands Ø 0.8 mm (w=11 mm x t=1.5 mm)



Courtesy of N. Kimura (KEK)

- Drum experiment for 1D steady-state measurement



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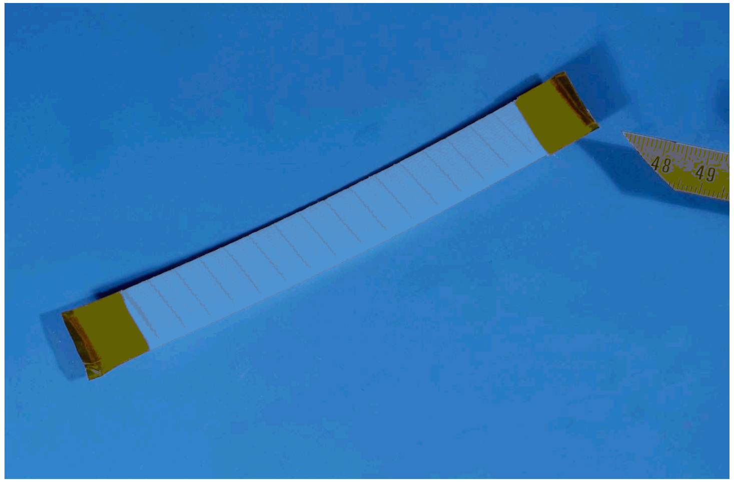
NED R&D program : The tests

- Two types of insulation are considered
  - glass fiber tape, vacuum-impregnated with epoxy resin
  - “innovative” insulation (glass fiber tape + ceramic)



Courtesy of F. Rondeaux (CEA)

- At least four cooling schemes can be envisioned
  - pool boiling He I at 4.2 K and 1 atm
  - superfluid helium at 1 atm
  - He I at 4.35 to 4.5 K and 1.2 to 1.7 atm
  - Static supercritical helium?

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References

- R. Van Weelderen, NED presentation, CERN, 08/07/2004
- M. C. Jones and V. Arp, "Review of hydrodynamics and heat transfer for large helium cooling systems", *Cryogenics* Aug. (1978), p. 483
- A. P. Butler et al. "Improved pool boiling heat transfer to helium from treated surfaces and its application to superconducting magnets", *Int. J. of H. Trans.* Vol. 13 (1970), p. 105
- M. T. Nishi et al. "Roughened surface study on Japanese test coil for Large Coil Task", *IEEE Trans. on Mag.* Vol. 17 n°1 (1981), p. 904
- M. T. Nishi et al., "Boiling heat transfer characteristics in a narrow cooling channel", *IEEE Trans. on Mag.* Vol. 19 n°3 (1983), p. 390
- M. N. Wilson, **Superconducting Magnets**, Clarendon Press, 1986
- H. Kamer, Proceedings of ICEC 12, p. 299-304, 1988
- Fuzier, Cryogenics 41, p. 453-458, 2001
- Van Sciver, Cryogenics, 38, p. 503-512, 1998
- [Giarratono 1971]
- Burnod L, Leroy D, Szeless B, Baudouy B, and Meuris C.Thermal modelling of the L.H.C. dipoles functioning in superfluid helium. Proceedings of 4th EPAC 1994.p. 2295-2297.
- Meuris C, Baudouy B, Leroy D, and Szeless B. Heat transfer in electrical insulation of LHC cables cooled with superfluid helium. Cryogenics 1999; 39: 921-93
- Kimura N, Kovachev Y, Yamamoto A, Shintomi T, Nakamoto T, Terashima A, Tanaka K, and Haruyama T. Improved heat transfer for Rutherford-type insulated cables in pressurized He II. Proceedings of Maget technology 1998.p. 1238-1241.
- Baudouy B, François MX, Juster F-P, and Meuris C. He II heat transfer through superconducting cables electrical insulation. Cryogenics 2000; 40: 127-136.
- Kimura N, Yamamoto A, Shintomi T, Terashima A, Kovachev V, and Murakami M. Heat transfer characteristics of Rutherford-type superconducting cables in pressurized He II. Ieee Transactions on Applied Superconductivity 1999; 9: 1097-1100

dapnia SACM

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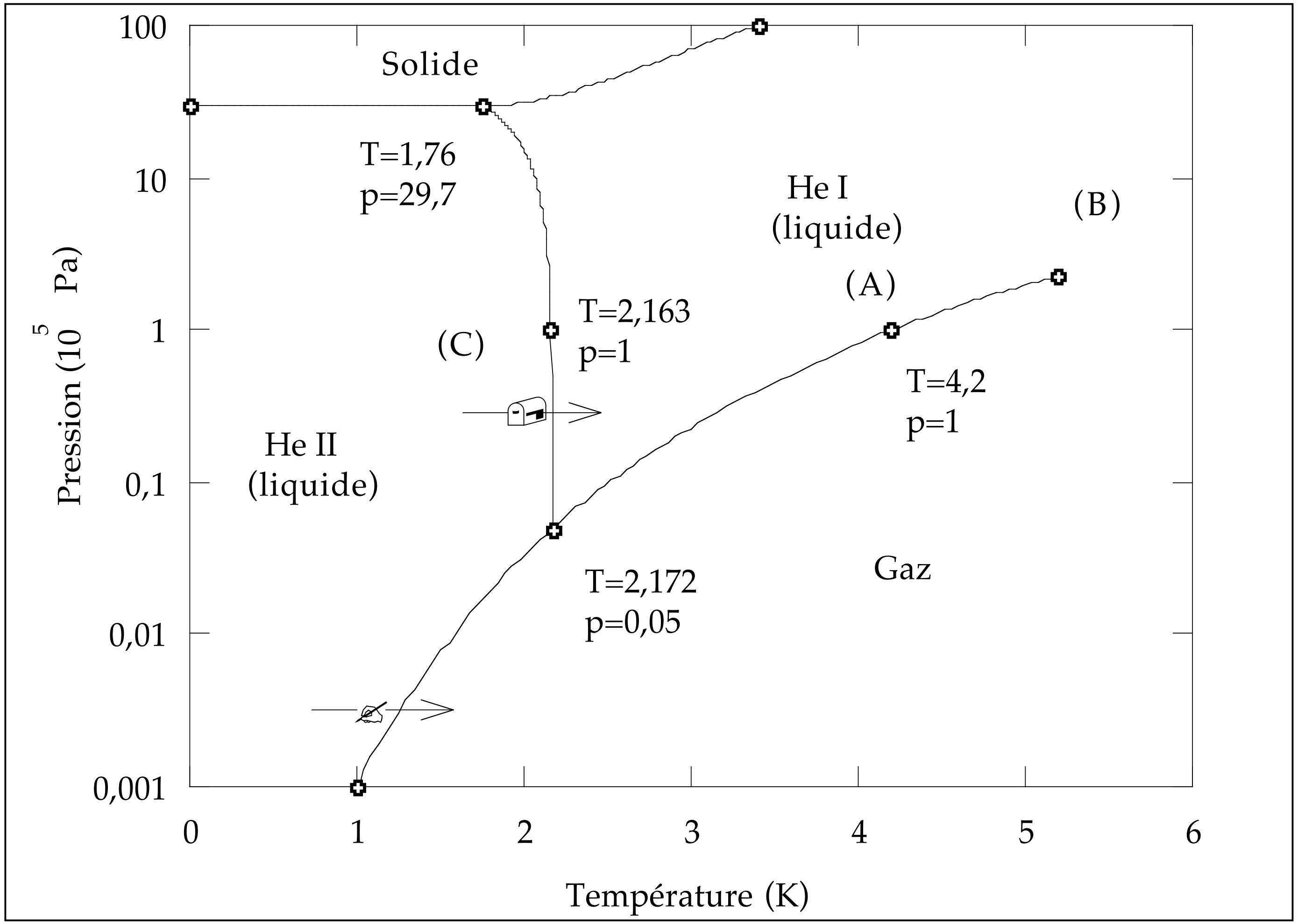
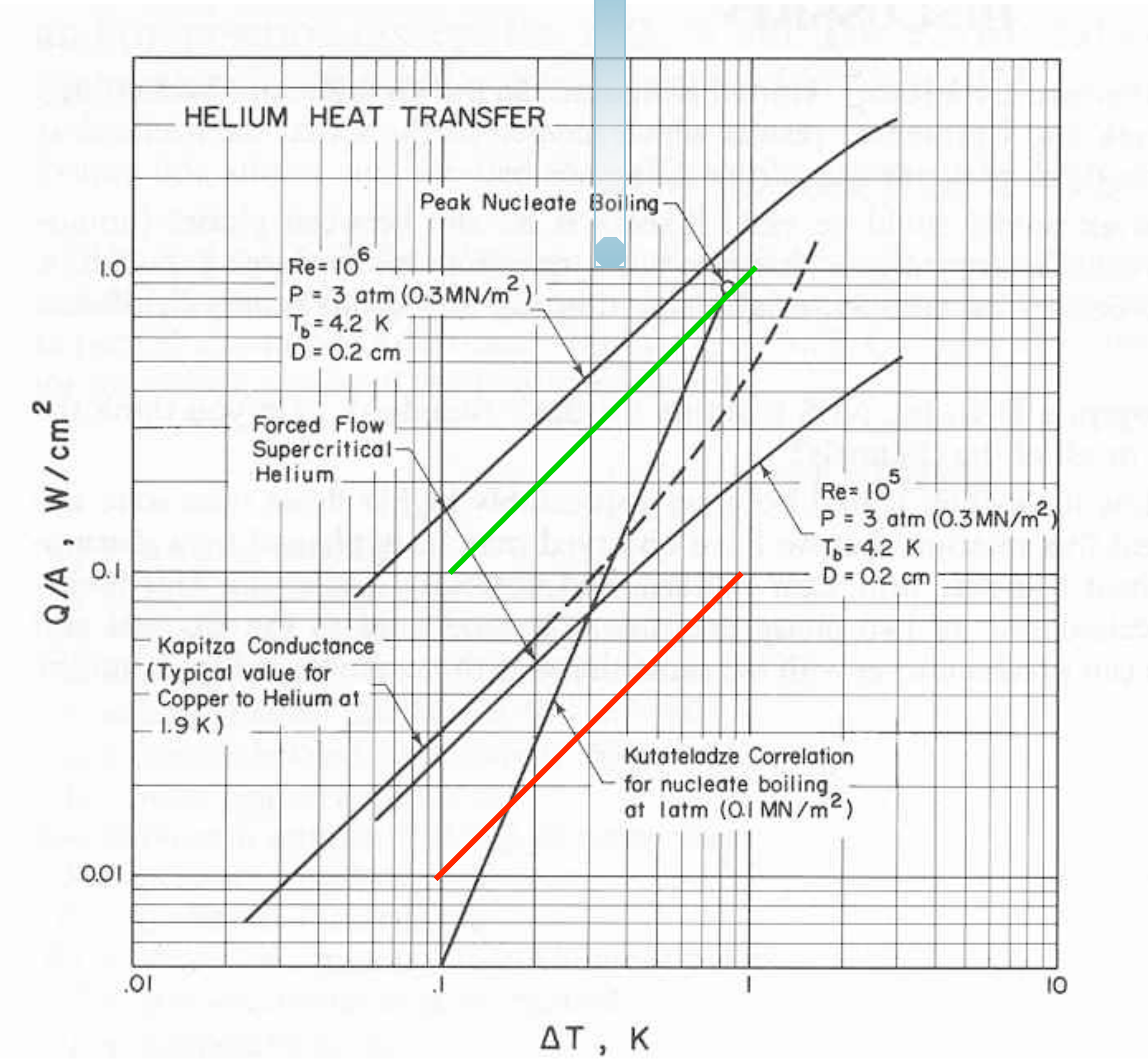
Phase diagram of helium



Heat transfer curves



R_k Kapton

He II, 1 m

Forced He II

He I,
Ø10 mm
m=610^{-3} kgs^{-1}