dapnia

cea

saclay

Workshop on superconducting magnets and cryogenics for accelerator frontier

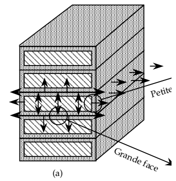
KEK, Feb. 15, 2007

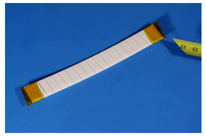
He II heat transfer in electrical insulation for accelerator magnet

Bertrand Baudouy
CEA Saclay
DSM/Dapnia/SACM/LCSE

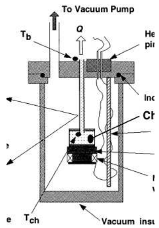
Outline

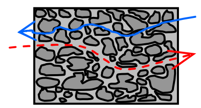
- He II heat transfer and electrical insulation
  - The *classical* insulation and heat transfer
  - The *ceramic* insulation and comparison





- He II Heat transfer in confined geometry
  - Heat transfer in small tubes
  - Heat transfer in porous media





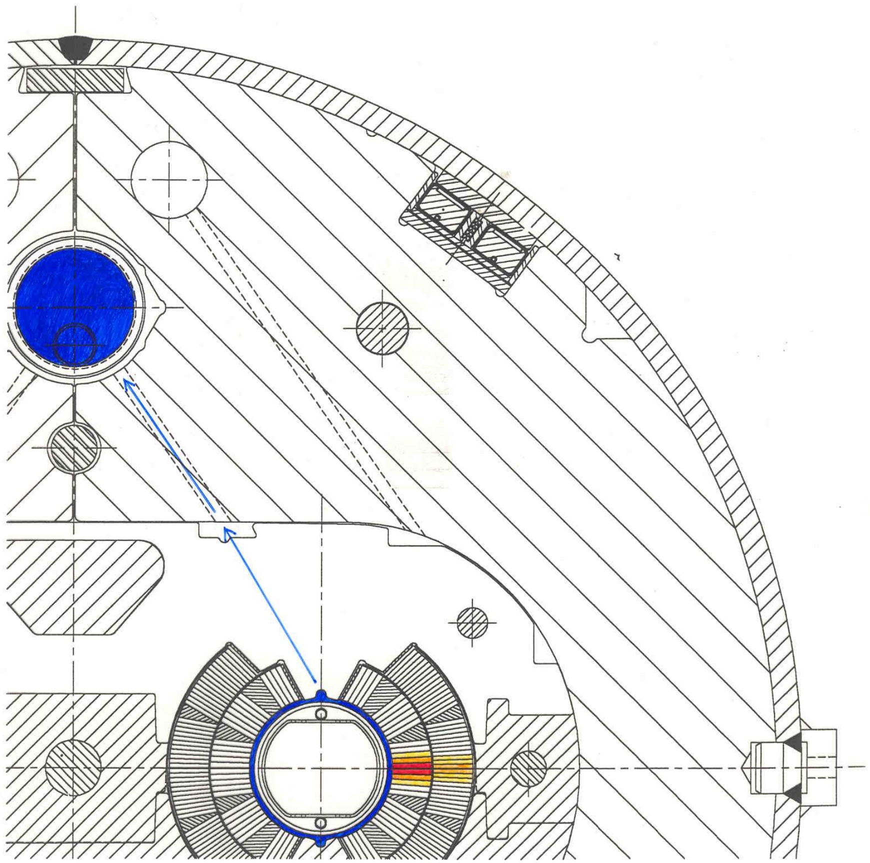
- Heat transfer in coil models
  - NED activities
  - Activities @CERN
- Propositions
- References

Reminder

dapnia

saclay

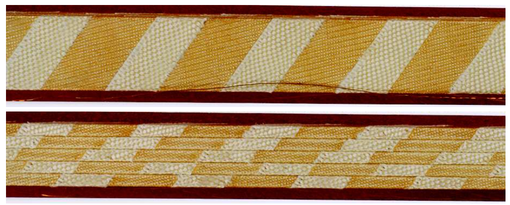
- Heat transfer from the conductor to the cold source define the temperature margin
- Electrical insulation is the largest thermal barrier against cooling
- Electrical insulation can be
  - Non-existent
  - Monolith
  - For LHC magnet
    - $T_{conductor}$=1.9 K or $T_{conductor}$~4 K [Burnod 1994]



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

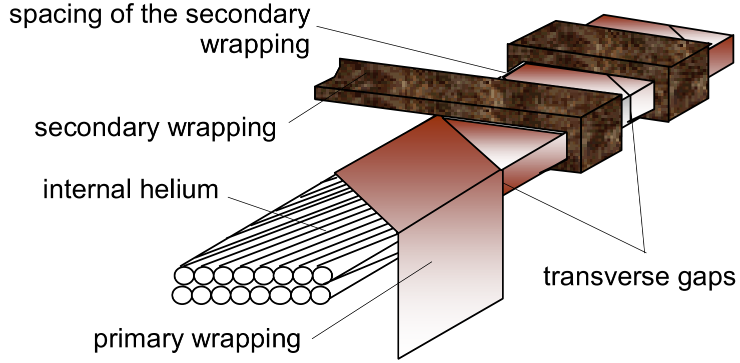
The *classical* insulation

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



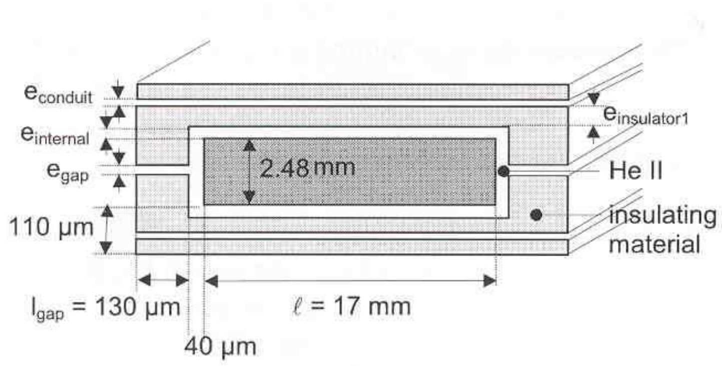
- The LHC insulation work : 2 wrappings
  - First wrapping in polyimide with 50% overlap
  - Second wrapping in polyimide with polyimide glue with gap

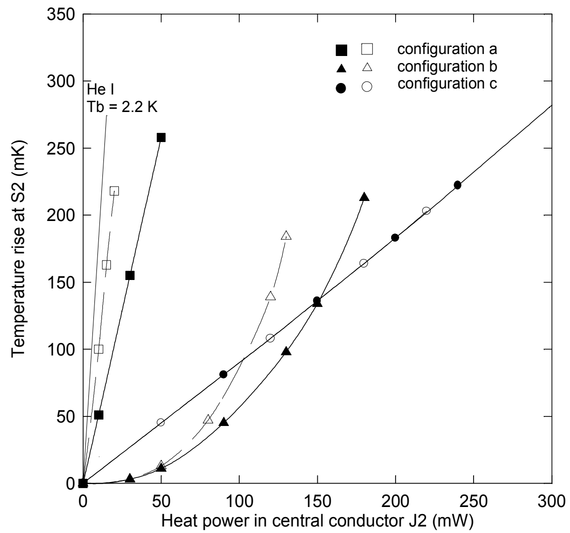
- Current LHC Insulation : 3 wrappings [Meuris 1999]
  - First 2 wrappings with no overlap
  - Last wrapping with a gap



Heat transfer in *classical* insulation (1/2)

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



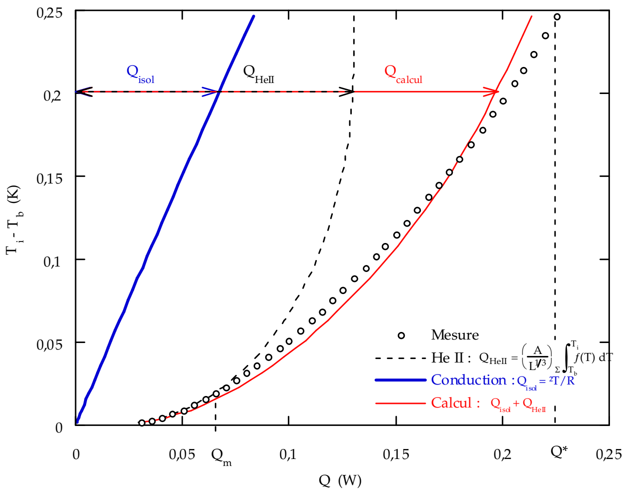


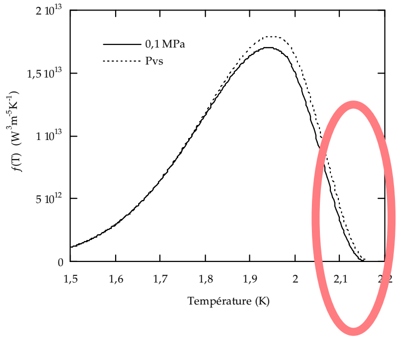
[Baudouy 1996] and [Meuris 1999]

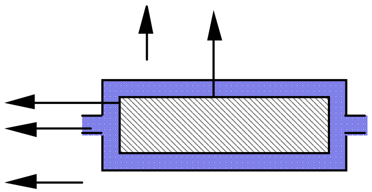
Heat transfer in *classical* insulation (2/2)

- Importance of conduction in the insulation
  - For Large ΔT, He II HT < Conduction HT

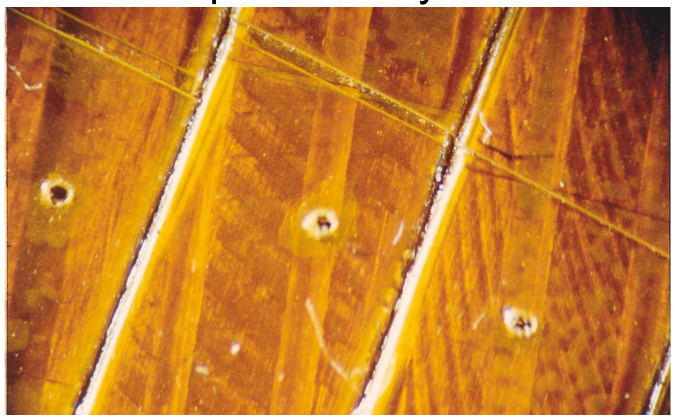
[Kimura 1999] and [Baudouy 2OO1]

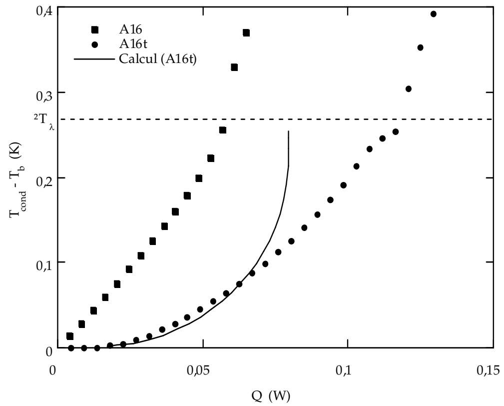




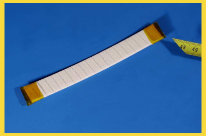


- Importance small face porosity [Baudouy 1996]
  - Artificial permeability with 6 holes of ϕ 200 µm

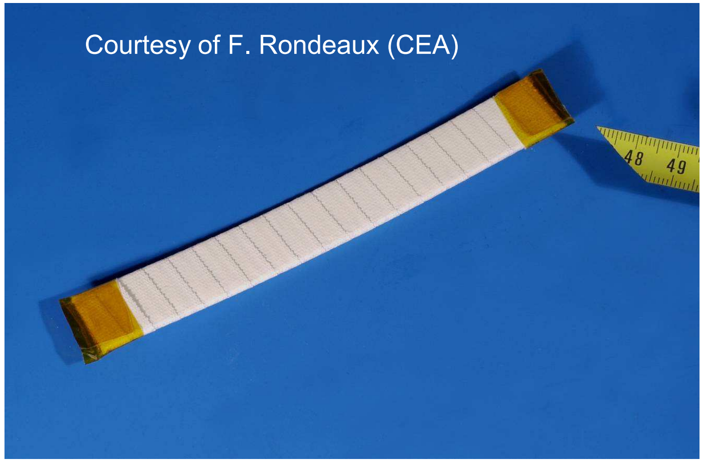




The *ceramic* insulation

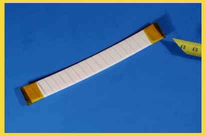


- For the next generation of high field magnets, Nb_3Sn is considered
- Higher heat deposition than in current magnets is expected
  - Beam losses : 10 mW/cm^3 (LHC) and 50 to 80 mW/cm^3 (LHC upgrade)
- Since 1997, development by J.M. Rey and F. Rondeaux
  - Ceramic materials are investigated in replacement for the classical insulation (Fiberglass + epoxy resin impregnated after heat treatment)
  - One step process
    - Obtain a coil after heat treatment (Same than Nb_3Sn) with no impregnation
    - Good wrapping and resistance to heat, reduce fabrication complexity and costs
  - Increase the volume of He in the insulation and the thermal path
    - Higher enthalpy reserve and overall thermal conductivity
- Innovative insulation for Nb_3Sn magnet
  - Fiberglass tape + Ceramic precursor
  - (80%SiO_2 + argil) [Puissegur 2004]



Courtesy of F. Rondeaux (CEA)

Heat transfer considerations

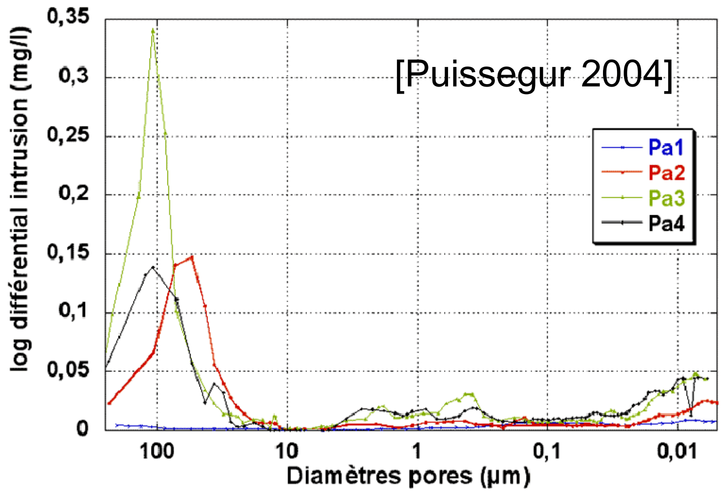


	Ceramic	*Classical* (Polyimid)
• Geometry	Porous	Channels (slits)
• Pore size, d	~100 µm	10 µm at Saclay (determined) 100 µm at KEK (determined)
• Porosity,ε	4.5 to 29 %	~1 % (ratio of A_{HeII}/A_{total})
• Conductivity, k	≈4 10^{-2} W/Km	k_{kapton}≈10^{-2} W/Km @ 2 K
• Kapitza conductance	h_k=3200 W/m²K	h_k=4000 W/m²K @ 1.5 K

– Thickness < 10 µm for a Kapitza resistance influence…

→ What is the influence of the geometry on the total HT?

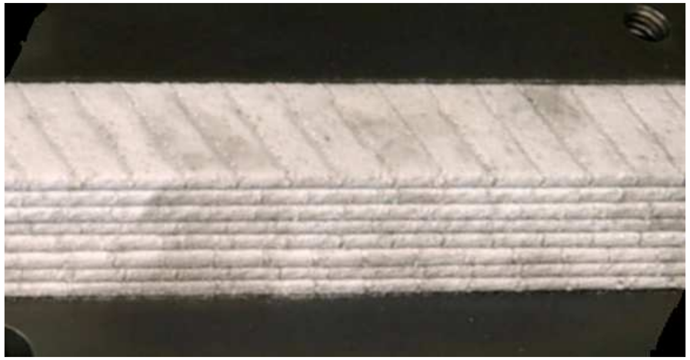
→ Helium + conduction = Insulation?

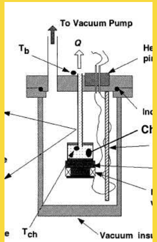


He II Heat transfer in confined geometry

- Physical law in He II modified by the geometry?
  - Properties modified?
  - A(T), ρ_s, …
  - HT regimes modified?
  - Landau regime
  - Superfluid turbulence (fully developed?)

- Modeling sufficient?
  - Coupling between solid and He II
  - Porous media model?



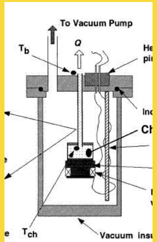


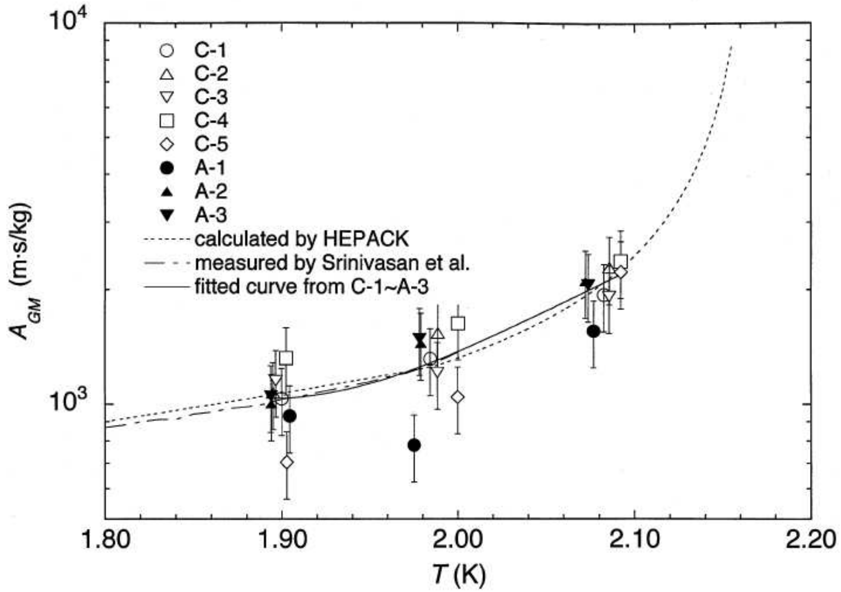
He II Heat transfer in small tubes/slits

dapnia
cea
saclay

- Heat transfer in small channels [Kimura 1999]
  - $d_{eq} \in [56; 4800]$ µm
  - $L \in [30; 40]$ mm
- Heat transfer in small slits? [Kimura 2005]
  - 53 µm x 16 mm
  - A_{GM} not modified
  - vortex spacing 1 µm
  - fully developed turbulence

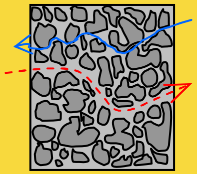
$$q_e^{\,3} e = \int \frac{s^4 (\rho_s T)^3}{A_{GM} \rho_n} dT$$



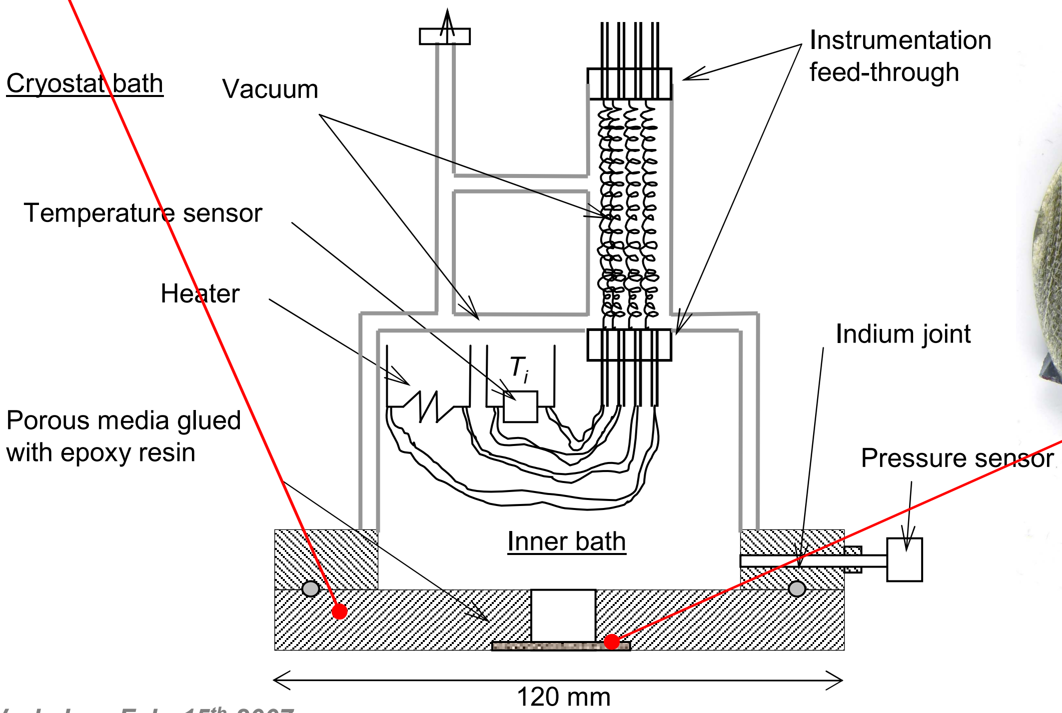


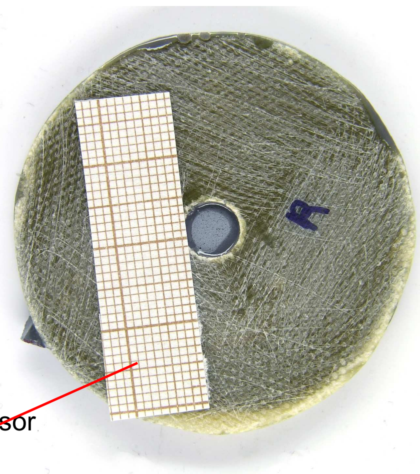
- Heat transfer in d_{eq} of 1 µm range?
  - Modification of the Physical law?
  - Bulk properties?

He II Heat transfer in porous media



- Experimental work
  - CEA Saclay
  - NIFS
- Numerical work
  - NIFS
  - CEA Saclay in development





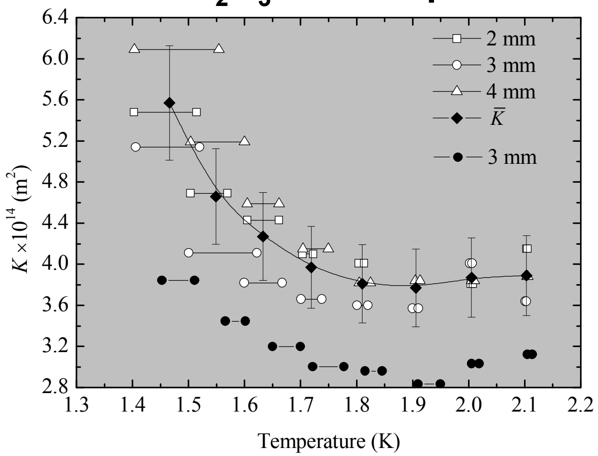
Flow properties

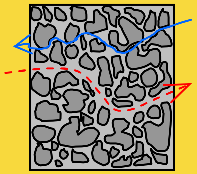
- Permeability in pure Landau regime

$$\vec{\nabla} p_e = \omega \mu_n \frac{\vec{v}_n}{K_e} \qquad q_e = K \frac{1}{e} \int \frac{(\rho s)^2 T}{\mu_n} dT$$

  – Evidence that K is temperature dependent
  – Analysis is based on the assumption that the Darcy law is valid

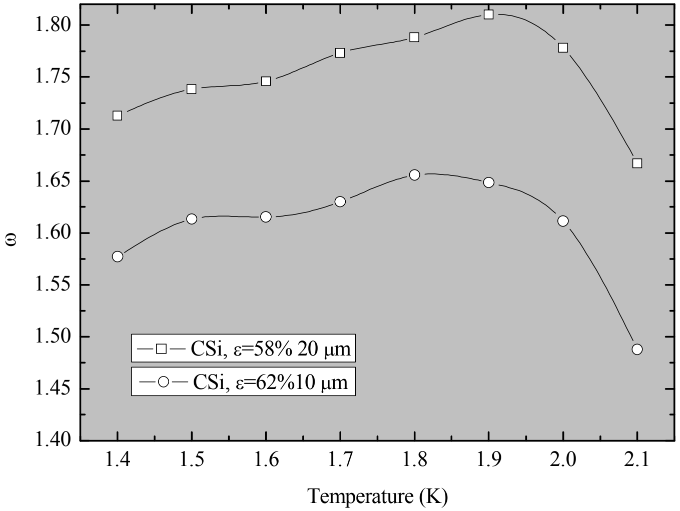
Al_2O_3 ε=32% 2μm



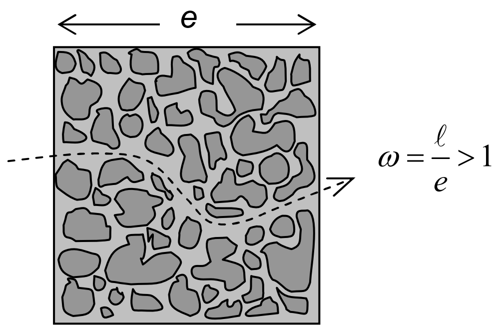


- Tortuosity in Gorter-Mellink regime

$$q_e{}^3 e = \frac{1}{\omega^{4/3}} \int \frac{s^4 (\rho_s T)^3}{A \rho_n} dT$$



  – Tortuosity constant within 10% for both samples
  – Concept of 1D tortuosity is valid in ZNMF



[Baudouy 2005]

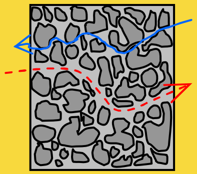
Intermediate regime – Saclay model

$$\left|\vec{\nabla} T_e\right| = \frac{1}{K}\frac{\mu_n}{(\rho s)^2 T} q_e + \omega^4 \frac{A\rho_n}{s^4(\rho_s T)^3} q_e^{\ 3}$$

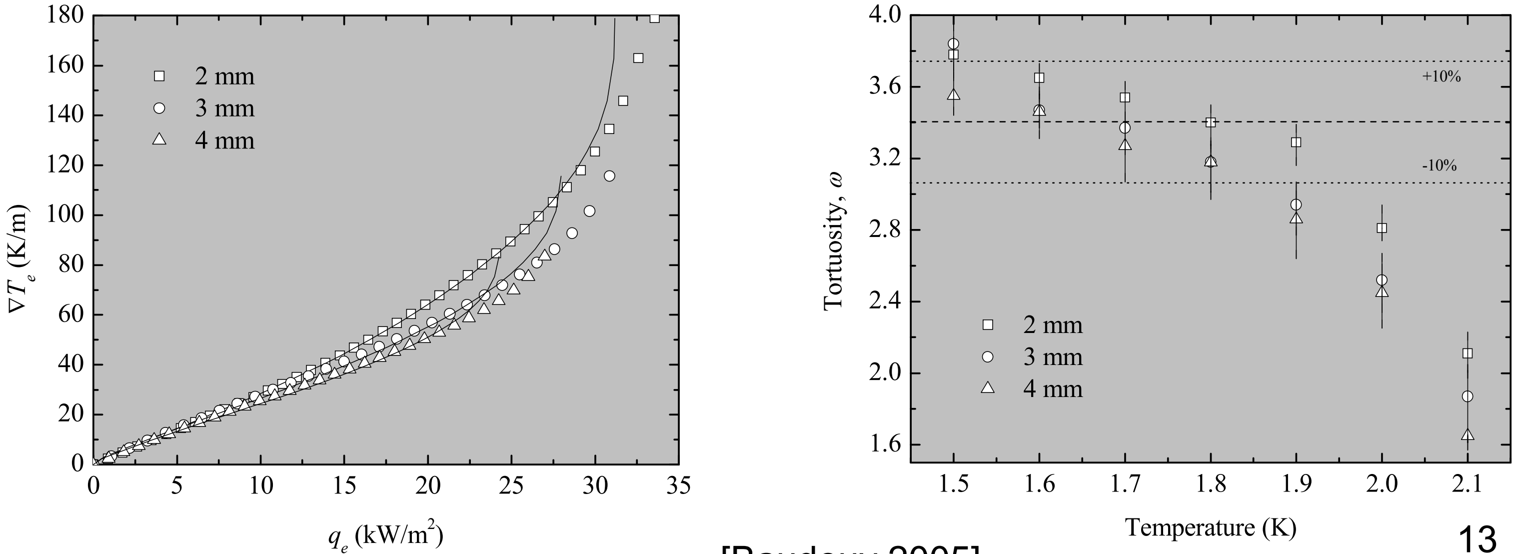
- Fair agreement between model and data
  - Extracted ω decreases with T
  - 10% permeability K variation induces 5% tortuosity ω variation

- Model fails to predict a constant ω over the entire range of temperature

- For T≤1.9 K ω=3.40.4, which corresponds to 10% variation



Al2O3 ε=32% 2μm



[Baudouy 2005]

Numerical simulation

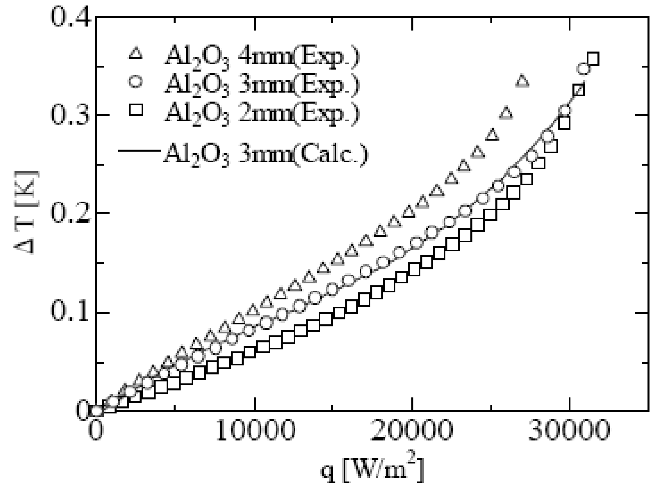
dapnia

cea

saclay

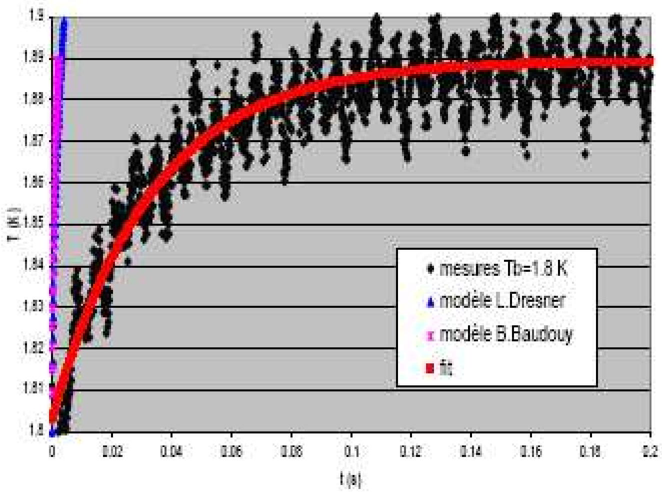
- Steady State and transient He II heat transfer model in porous media
  - Network of 1 D tubes
  - Vn neglected in small tubes
  - Friction term model with friction factor f
  - Adjusting tortuosity to match the experimental results

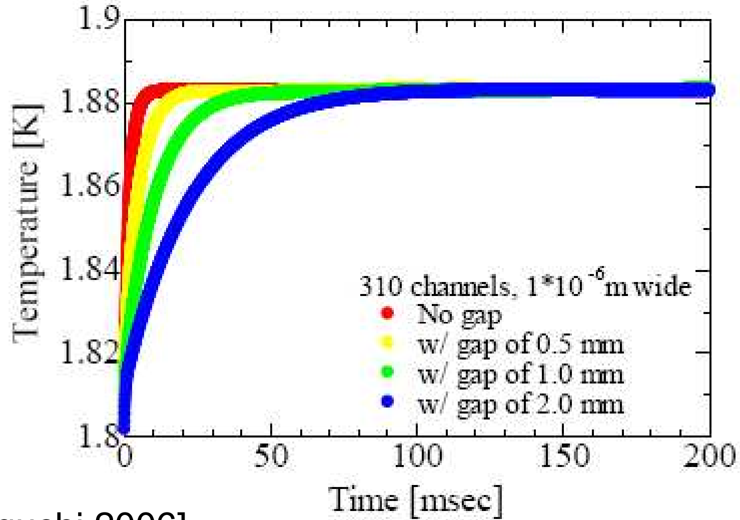
[Hamaguchi 2005]



ω=4.6 (ω =3.4 at Saclay)

$$L_i^{1/m} = \frac{1}{2}\gamma|u_s - u_n|\left(1+\sqrt{1-\frac{4\alpha}{\gamma d|u_s-u_n|}}\right)$$





[Hamaguchi 2006]

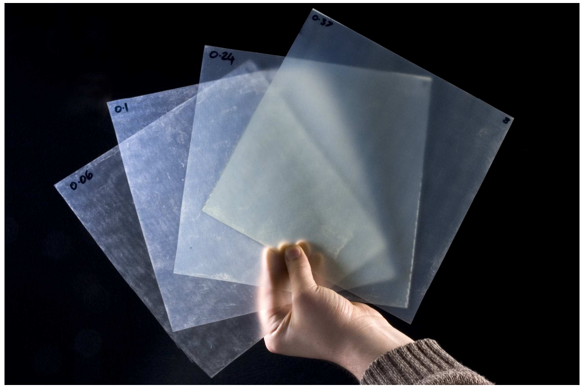
NED Program (1/3)

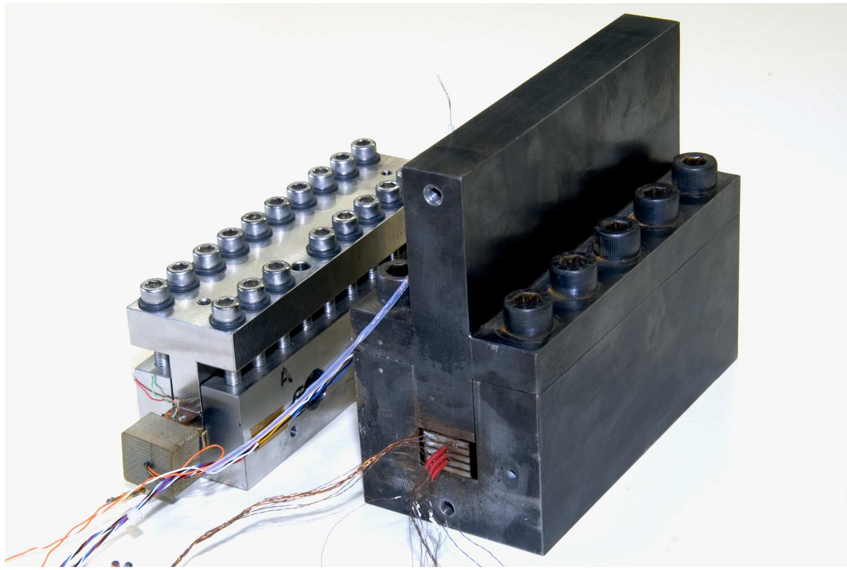
- Collaboration between CEA-Saclay, KEK, CERN and RAL
  - Tests in He II at CERN and Saclay
  - Tests in SHe at KEK
- Construction of a Double bath Cryostat (WUT and CEA-Saclay)
- Construction of molds by KEK (N. Kimura)
- Construction of 1D HT drum

[Chorowski 2006]

NED Program (2/3)

- Tests of Saclay stack sample
- RAL (S. Canfer) *classical* Nb_3Sn insulation to be tested
- Ceramic insulation stack samples to be constructed
  - KEK method
  - Help of N. Kimura at Saclay in March 2007

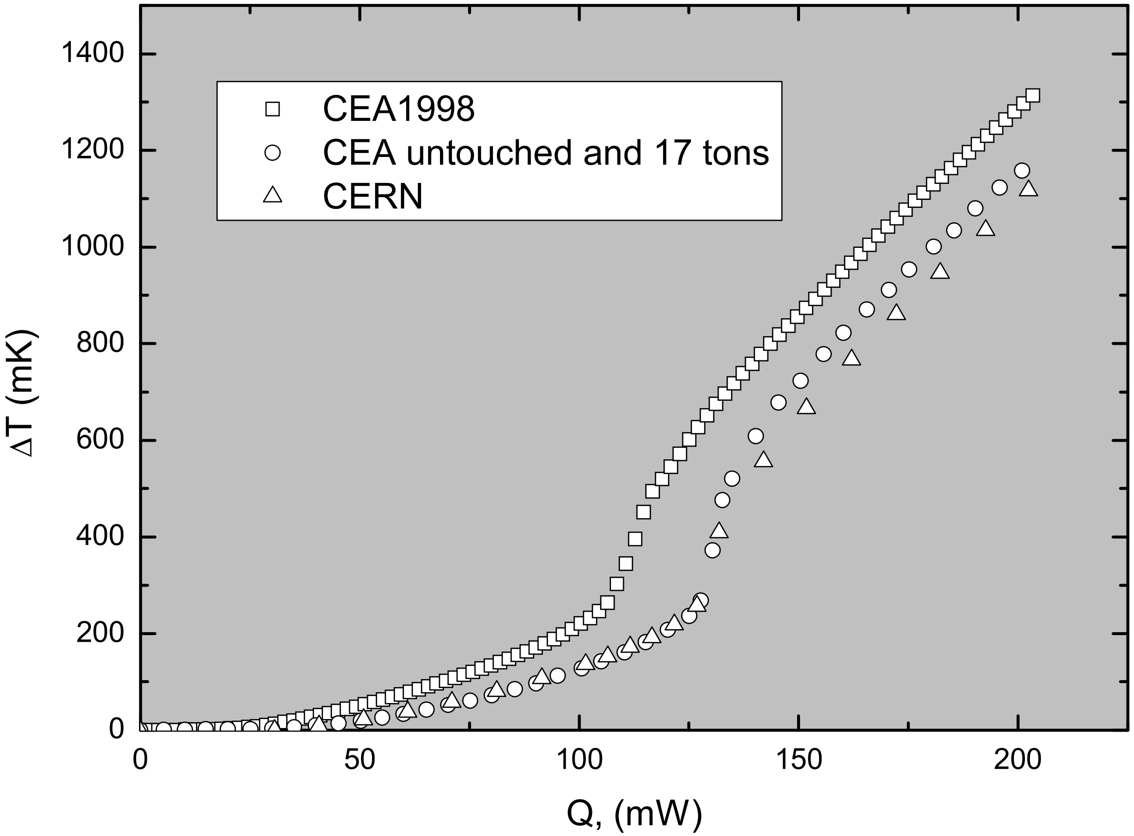




NED Program (3/3)

- Test of 10 years old sample made @ Saclay
  - Untouched
  - 17 tones on the samples as specified
  - Comparison with CERN results (untouched)

J. Polinski (Saclay) and Courtesy of D. Richter (KEK)



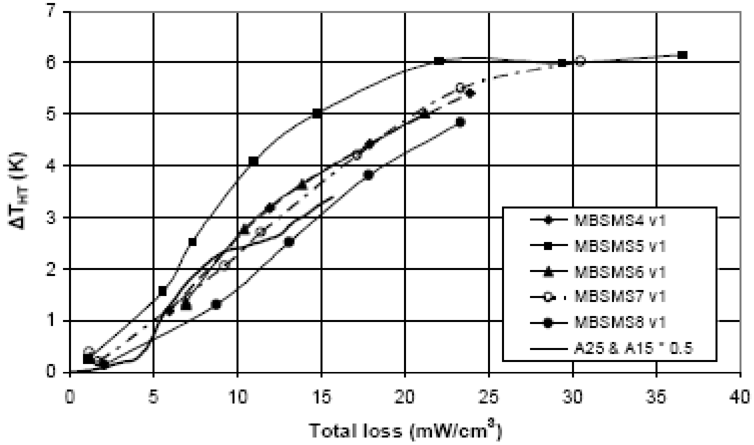
Program @ CERN

dapnia

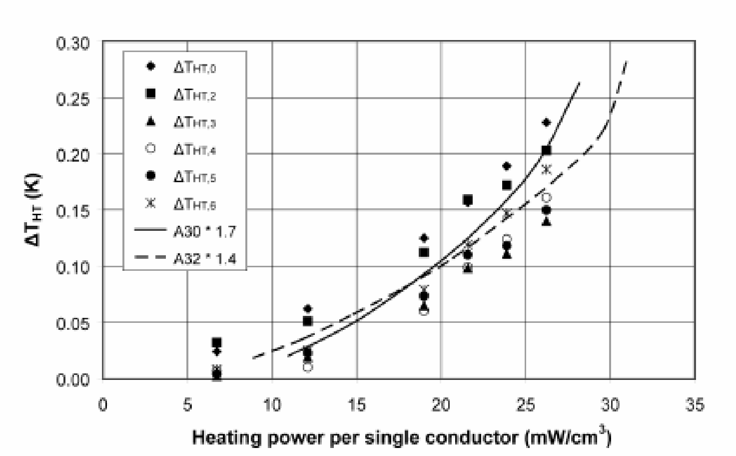
cea

saclay

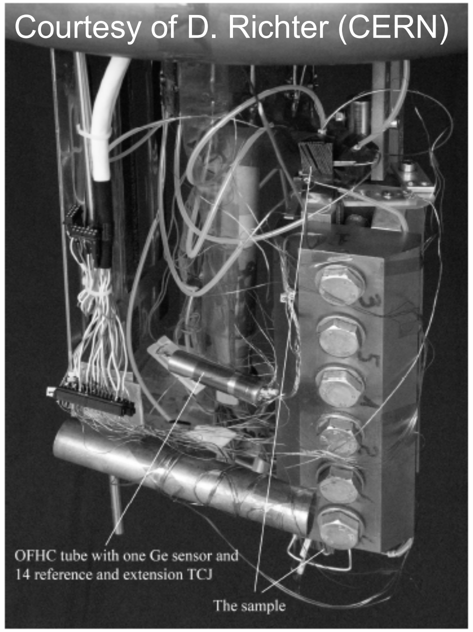
- Comparison between High Ramp Rate Quench measurement at CERN and Saclay stacks results
  - For $T>T_\lambda$, $Magnet_{CERN}$=0.5 Stack
  - Outer layer blocked



- Measurement of HT on a segment of an LHC dipole coil
  - For $T<T_\lambda$, $Coil_{CERN}$=1.5 Stack



[Richter 2005]



Propositions

- Fundamental HT understanding
  - Experimental work at characteristic dimension lower than 1 µm in porous media, slit and tube.
  - Numerical model more predictive (no entry parameters coming from exp.)
- Modeling heat transfer in the insulation
  - Study of HT coupling between conduction and He II
- Developing the insulation
  - Increasing the thermal conductivity of the solid matrix
- HT in coil model or magnet
  - Analysis of HRRQ to be continued at CERN
  - Experiment on coil segment at CERN is the missing link and has to be supported

dapnia

cea

saclay

References

- 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
- B. Baudouy, PhD Thesis, Université Paris VI, 1996
- 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
- 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 Magnet technology 1998.p. 1238-1241.
- A. Puigsegur, *Isolation céramique pour câbles supraconducteurs en Nb3Sn, PhD thesis,* Université de Montpellier II, 2005.
- *N. Kimura, A. terashima, A. Yamamoto, and T. Shintomi, "Heat transfer through narrow cooling channels in pressurized helium II", presented at CEC 1999, Montréal, Canada*
- N. Kimura, H. Nakai, M. Murakami, A. Yamamoto, and T. Shintomi, *"A study on the heat transfer properties Of pressurized helium II Through fine channels",* Adv. Cryo. Eng. 41A, 2005
- *B. Baudouy, Juster, F.-P., Allain, H, Prouzet, E., Larbot, A., Maekawa, R., "Heat transfer through porous media in static superfluid helium",* Adv. Cryo. Eng. 51, 2005
- *S. Hamaguchi, R. Maekawa, T. Okamura, and B. Baudouy, Experimental and numerical studies on thermal hydraulic characteristics of He II through porous media,* Adv. Cryo. Eng. 51, 2005
- *S. Hamaguchi, H. Allain and B. Baudouy, T. Okamura, and B. Baudouy, "Numerical study on transient heat and mass flow of he II through porous media",* ICEC 21, 2006
- *Chorowski, M, Polinski, J, Baudouy, B., Michel, F., Van Weelderen, R., "Optimization of the NED cryostat thermal shielding with entropy minimization method",* ICEC 21, 2006
- David Richter, Jerôme Fleiter, Bertrand Baudouy, Arnaud Devred, "*Evaluation of the Transfer of Heat from the Coil of the LHC Dipole Magnet to Helium II*" ASC 2006