Modeling of Heat Transfer from SC Coils to He II: Nb-Ti Vs. Nb$_3$Sn

M. La China

Acknowledgements

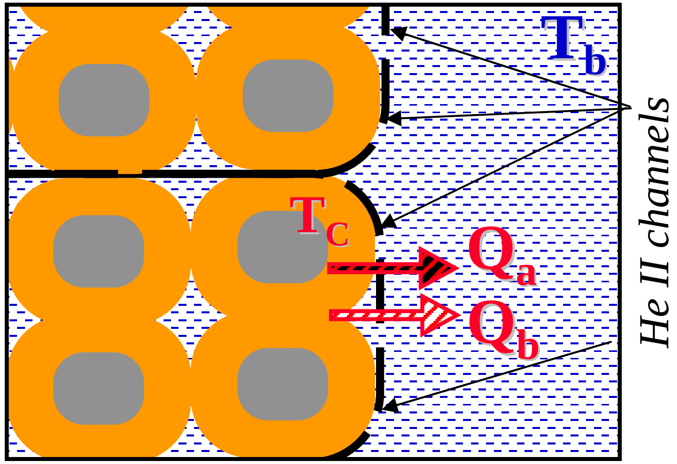
D. Tommasini, W. Scandale, E. Todesco

Introduction

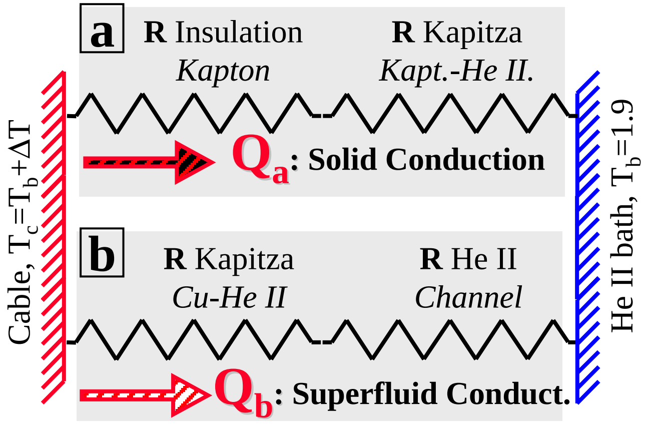
- We are modeling steady-state heat transfer from SC Rutherford cable to an isothermal He II bath (1.9 K).
- We consider different insulations from all polyimide to epoxy impregnated.
- We profit of previous measurements done at CEA-Saclay [1] on different insulation schemes.
- We consider electrical SC properties (Nb-Ti, Nb_3Sn) to evaluate the temperature margin ΔT to find the maximum heat drainable in different working conditions.

Heat Transfer Model (1/2)

Nb-Ti (porous insulation)



- He II is in direct contact with the strands
- Heat flux is shared by two parallel paths (**a** & **b**).



a **R** Insulation *Kapton* — **R** Kapitza *Kapt.-He II.*

Q_a: **Solid Conduction**

b **R** Kapitza *Cu-He II* — **R** He II *Channel*

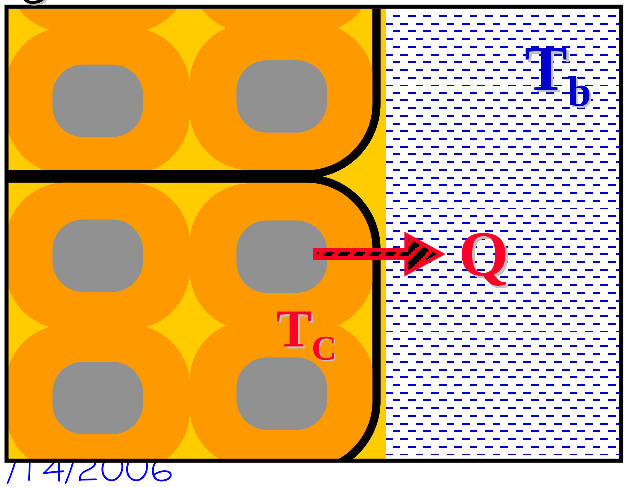
Q_b: **Superfluid Conduct.**

Cable, $T_c=T_b+\Delta T$

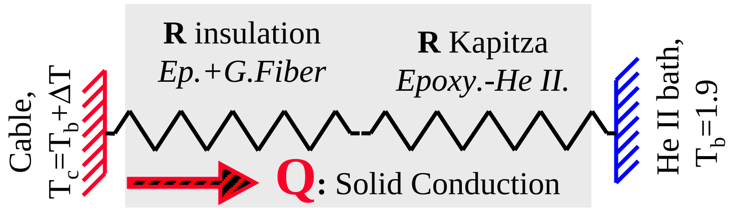
He II bath, $T_b=1.9$

1) Q_a Vs. Q_b depends on insulation porosity
2) Q_a & Q_b are non linear
3) Q_b has saturation level

Nb$_3$Sn (sealed insulation)



- No He II reaches the strands
- Heat goes through solid conduction first, then to He II



R insulation *Ep.+G.Fiber* — **R** Kapitza *Epoxy.-He II.*

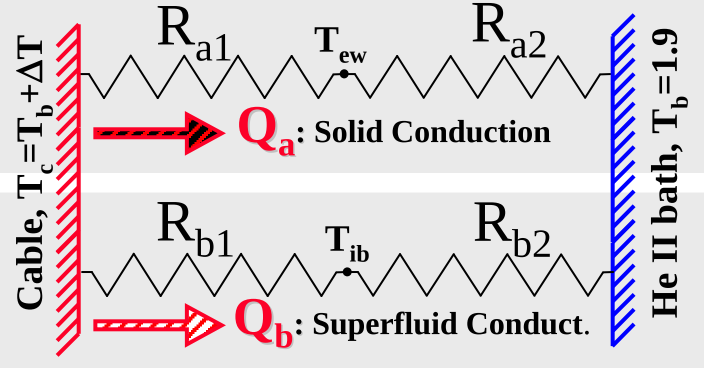
Q: Solid Conduction

Cable, $T_c=T_b+\Delta T$

He II bath, $T_b=1.9$

Heat Transfer Model (2/2)

- Porous insulation details:

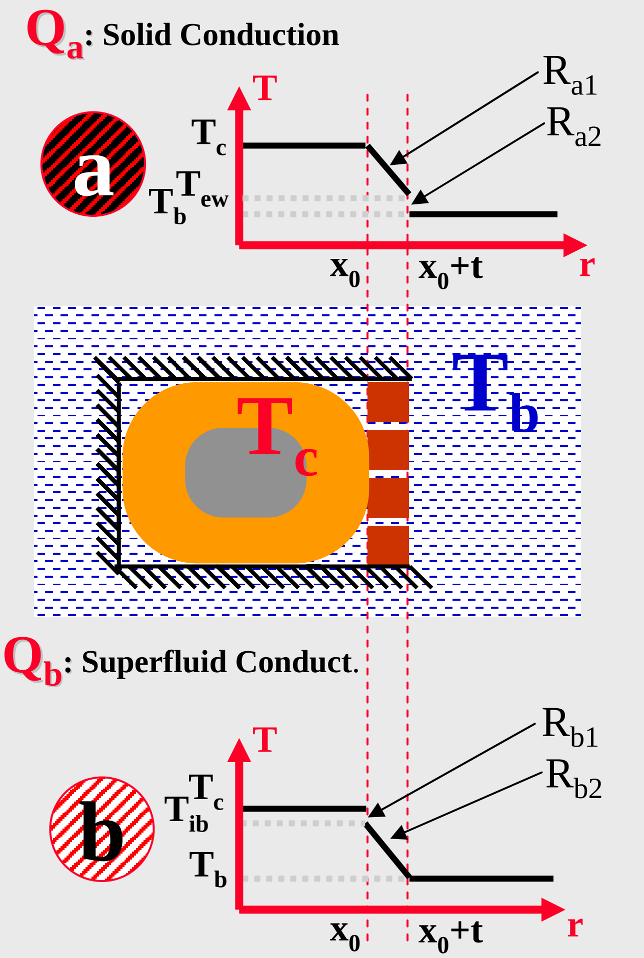


- R_{a1}: **Kapton conduction**
- R_{a2}: Kapitza Kapton-He II
- T_{ew}=T external wall

- R_{b1}: Kapitza Cu-He II
- R_{b2}: **He II conduction**
- T_{ib}=T internal bath (He channel inlet)

Assumptions:

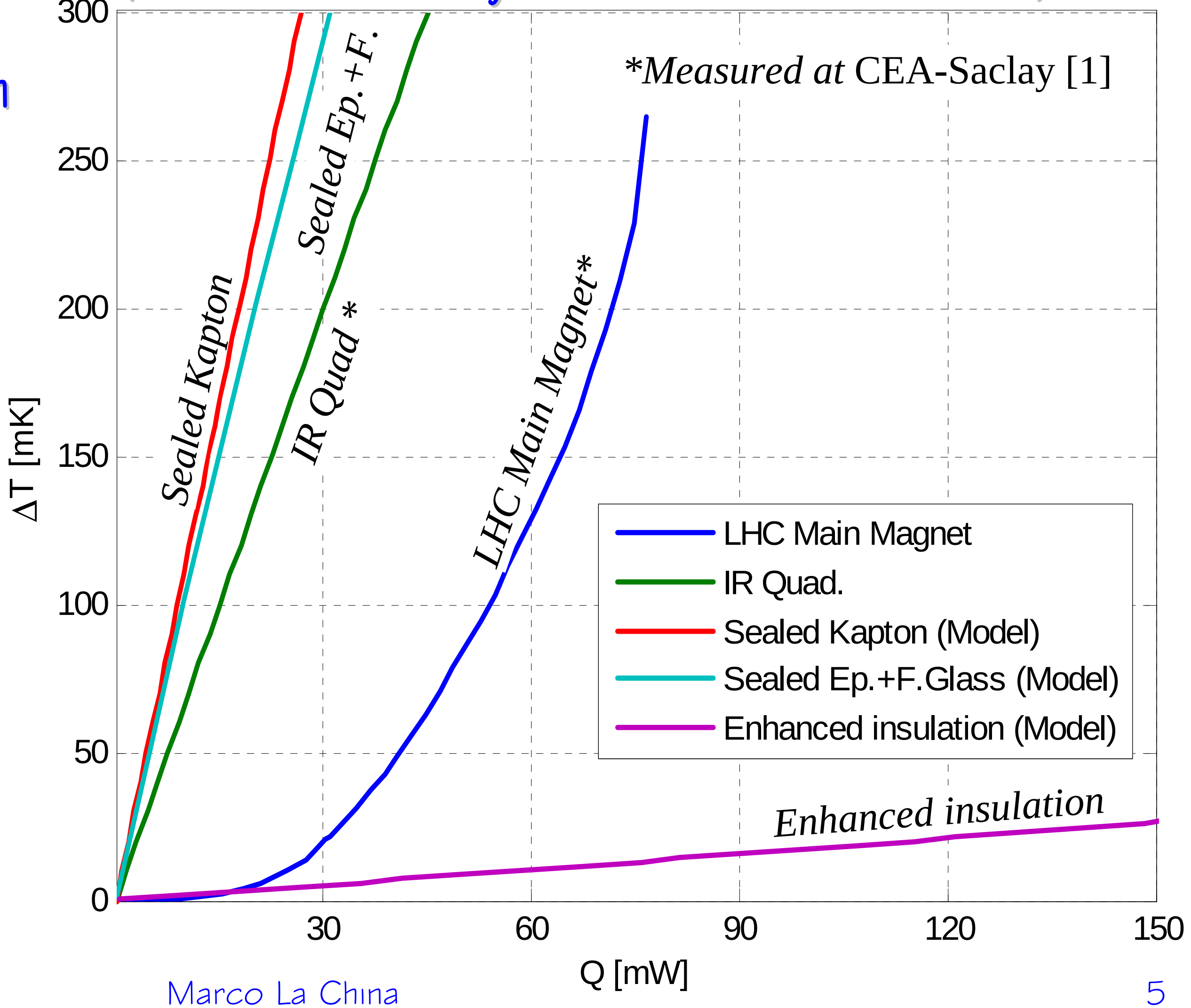
- Negligible thermal boundary resistance at the strand-insulation interface [2,3]
- Parallel paths are decoupled
- Conductor and He II bath are isothermal
- He II heat transfer regime is Gorter-Mellink [4] (may lead to under-estimate).



Heat flux through He II limited by saturation: λ transition at channel inlet ($T_{ib}=T_\lambda$)

Porous Vs. Sealed Insulations

- Porous insulations: -Large heat flux for small ΔT but limited by He II channel saturations (determined by channel dimensions)
  -Limited heat flux for large ΔT (bad Kapton conduction)
- Sealed insulations:
  -Small heat flux for small ΔT.
  -Large heat flux for large ΔT (no channel saturations)
- Model:
  Isothermal bath & conductor
  (may result in an overestimation of heat flux respect to non isothermal model)



Comparison for Operating Conditions: *Same* or *Specific*

1. We consider two coils in a He II bath (T_b=1.9) :
   1. Nb_3Sn with *sealed* insulation
   2. Nb-Ti with *porous* insulation

2. We impose the *same* engineering current density J_{eng} and operative peak field B
   ...not a realistic case...

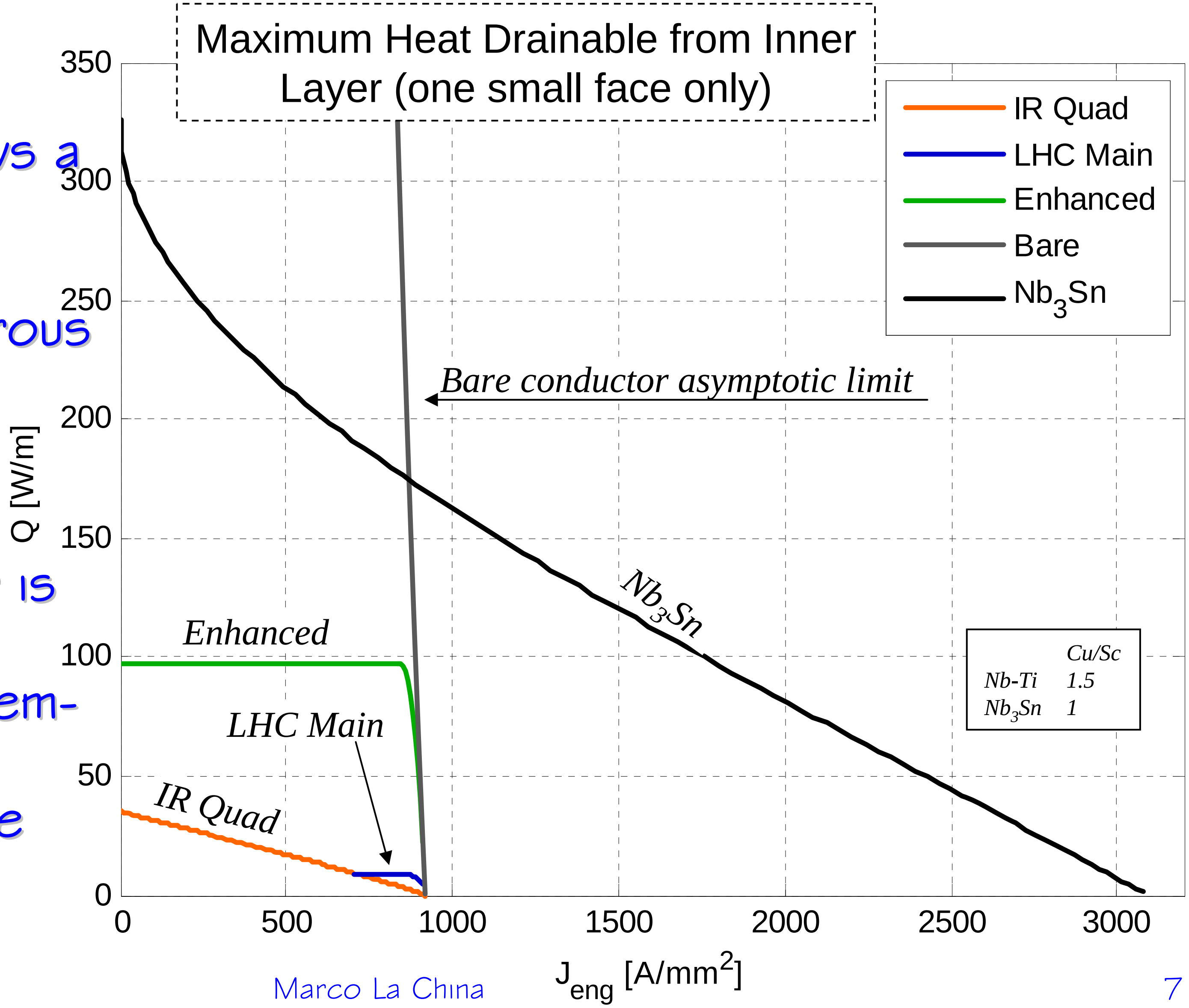
2. We impose J and B_{ult} *specific* of two alternative designs for triplet upgrade (E. Todesco)
   ...a realistic case...

3. We get the temperature margin $\Delta T=T_c-T_b$ we combine it with the heat transfer correlations and we obtain the corresponding heat flux

Maximum Heat Flux for Same B (9T) and J_{eng}

- The asymptotic limit of a bare conductor shows a great margin of improvement available for porous insulation

- Bare conductor is not Rutherford cable …measurements of a bare Rutherford cable are desirable…



Maximum Heat Flux for Specific Conditions (Large Ap. High G Quads [11])

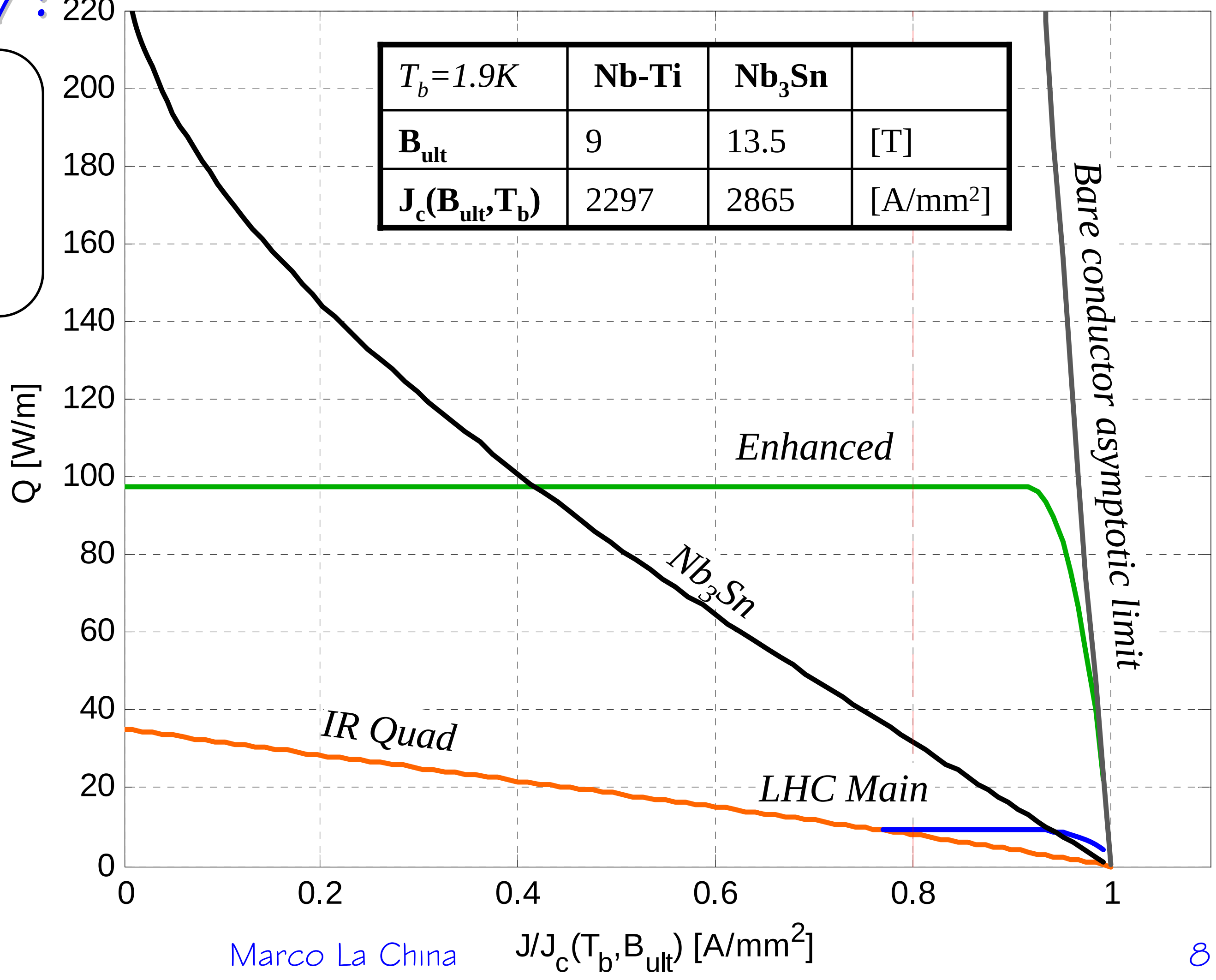
- Comparative study :

Alternative designs for LHC IR triplet upgrade:

T_b=1.9K	**Nb-Ti**	**Nb3Sn**	
G	154	258	[T/m]
Bore	94	81	[mm]

- For J=0.8 Jc Nb_3Sn coil can evacuate ~3 times the heat of LHC Nb-Ti coils

Maximum Heat Drainable from Inner Layer (one small face only)



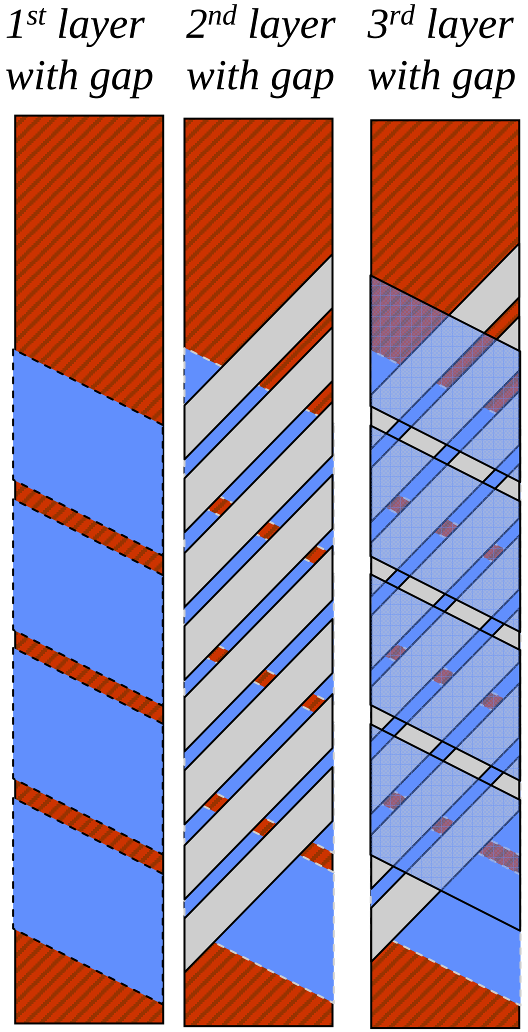
T_b=1.9K	**Nb-Ti**	**Nb_3Sn**	
B_{ult}	9	13.5	[T]
$J_c(B_{ult},T_b)$	2297	2865	[A/mm²]

Enhanced Insulation Details

Dedicated He II channels of finite size

- 3 layers with gaps
- Overlap between 1st and 3rd
- All polyimide insulation
- No special manufacturing or additional cost

Example			
	Thickness [µm]	Width [mm]	Gap [mm]
1st	37.5	11	2
2nd	67	2	2.5
3rd	37.5	11	2



Summary

- For same B and J_{eng}, Nb_3Sn coils made by Rutherford cables can draw one order of magnitude more heat than Nb-Ti coils thanks to :
  - Greater temperature margin
  - Thermal conductivity of epoxy+fiberglass higher than Kapton

- For the same margin to critical surface (specific operating conditions), Nb_3Sn coils made by Rutherford cables can draw three times more heat than Nb-Ti coils

…however…

…there is still a large potential to increase the dimension of the cooling channels thus moving their saturation at higher heat fluxes: this makes Nb-Ti solution still interesting.

Desirable Initiatives

- The heat transfer experimental data supporting this study have been collected from literature.
- There is a lack of experimental data on heat transfer to Helium II from complex structures as Rutherford cables and Nb_3Sn coils.
- Experimental activities to fill this void, validate more complex predictive models (FEM 2D,3D) and alternative insulation schemes are needed.

References

1. C. Meuris, B. Baudouy, D. Leroy, B. Slezess, Heat transfer in electrical insulation of LHC cables cooled with superfluid Helium, *Cryogenics* ***39***, 921 (1999)
2. D.S. Matsumoto, C.L. Reynolds Jr., A.C. Anderson, Thermal Boundary Resistance at Metal Epoxy Interfaces, Phys. Rev. B, Vol. 16 n.8, 15 Oct. 1977.
3. F. Rondeaux, P. Bredy, J.M. Rey, Thermal Conductivity Measurements of Epoxy Systems at Low Temperatures, *Adv. Cryo. Eng.* ***48A*** *(Materials)*, 197 (2002)
4. J. Gorter, J. H. Mellink, On the irreversible processes in liquid Helium II, *Physica* ***15***, 285 (1949)
5. V. Arp, Heat transport through Helium II, *Cryogenics* ***10***, 96 (1970)
6. A. Kashani, S.W. Van Sciver, Kapitza Conductance of Technical Copper with Several Different Surface Preparations, *Cryogenics* ***25***, 238 (1985)
7. B. Baudouy, Kapitza Resistance and Thermal Conductivity of Kapton in Superfluid Helium, *Cryogenics* ***43***, 667 (2003)
8. J. Lawrence, A.B. Paterl, J.G. Brisson, The thermal conductivity of Kapton HN between 0.5 and 5 K, *Cryogenics* ***40***, 203 (2000)
9. Cryocomp v.3.06, distributed by Cryodata Inc., Copyright by Eckels Engineering, Florence SC, US 29501
10. A.V. Zlobin, Thermal Analysis and its Experimental Verification for the Present and Future IR Triplets, *Workshop on beam generated heat deposition and quench levels for LHC magnets*, 3-4 March 2005, CERN, Switzerland.
11. E. Todesco, J.P. Koutchouk, Scaling laws for β* in the LHC interaction regions, *CARE Workshop LUMI-06*, 17th October 2006, Valencia, Spain.

Thermal Resistances Review

- Thermal boundary resistance at interfaces between different materials (Kapitza):

  We use empirical fits q [W/m^2] ,T [K],

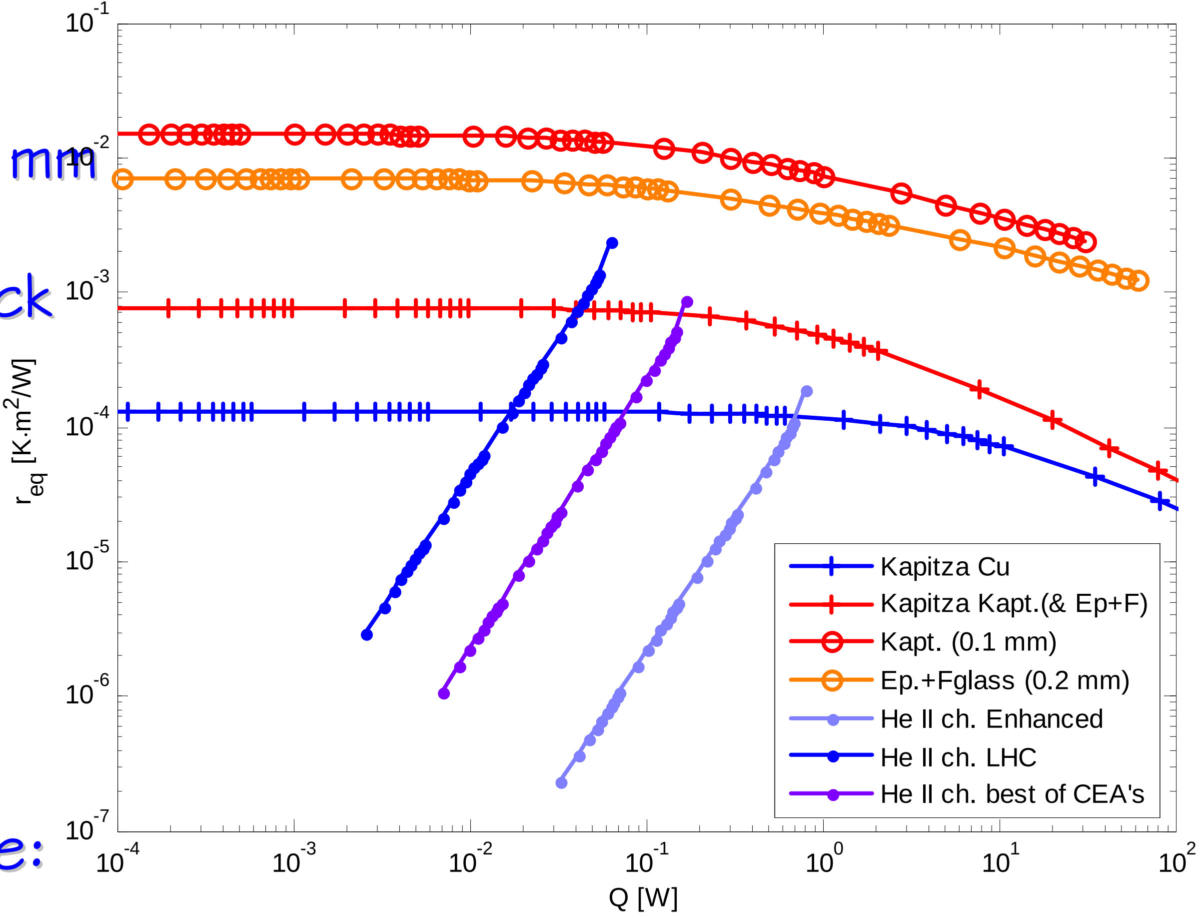
  - Cu-He II: $q = 460(T_{Cu}^{3.46} - T_{He}^{3.46})$, [7]
  - Kapton-He II: $q = 47.43(T_{Kap}^{4} - T_{He}^{4})$, [8] verified for small ΔT, we use it also for epoxy
  - Cu-epoxy: $q = 1300_{2K} \div 3600_{6K}(T_{Cu} - T_{Ep})$, [2] consistent with [3]

- Conduction in solids:
  - Kapton: K=4.638e-3*T.^0.5678 [8] verified for 0.5<T<5K
  - Epoxy+fiberglass: $K = 0.6*K_{Ep}+0.4*K_{G10}$, ($K_{Ep}$ & K_{G10} from [9] consistent with [3] and [10])

- He II thermal conductivity

  We consider a fully developed Gorter-Mellink regime [4] (conservative hypotheses [5])

Comparison of Equivalent Thermal Resistances in an Insulated Cable



- Bulk resistance of 0.1 mm thick Kapton ~2 times larger than 0.2 mm thick epoxy+fiberglass
- Boundary resistance (Kapitza):
  Kapton (& Ep.+F.) ~6 times larger than Cu
- HE II channel resistance:
  -depends on insulation porosity (channel lengths and cross-areas)
  -is always smaller than Kapton and epoxy+fiberglass but is limited by saturation