Workshop on **B**eam-**I**nduced **Q**uenches

CERN

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Transient heat and mass transfer to superfluid helium

Application to superconducting magnet cooling

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Outline

- Introduction

- Experimental heat transfer
  - Surface heat transfer
  - Channel heat transfer
  - Confined geometry

- Modelling
  - Analytical and semi-analytical
  - Numerical models and applications

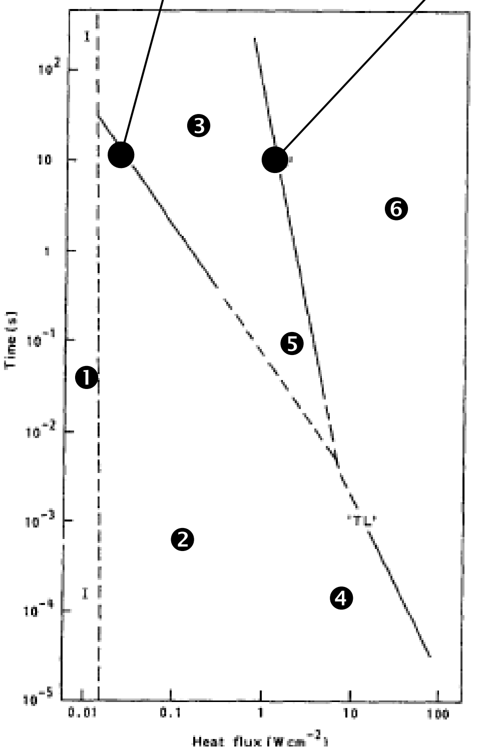
- Conclusions and proposal

Transient heat transfer regimes chart (1/2)

- Regime ❶ : $q<100$ W/m^2
  - – Landau regime
  - – Heat transferred by second sound
  - – Heat transferred by thermal diffusion
- Regimes ❷ and ❸: 100 W/m$^2<q<10$ kW/m^2
  - – Region II (developing vortex)

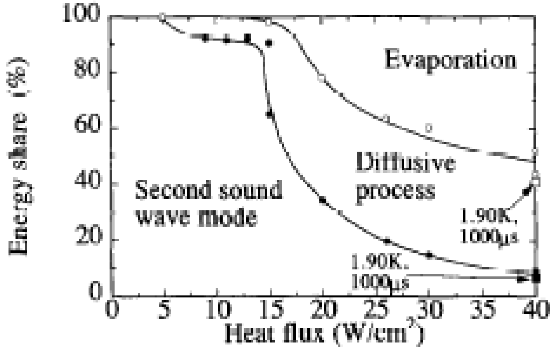
    This is the transition regime from laminar to turbulent
  - – Region III (quantized vortices)

    This is the turbulent regime (Gorter-Mellink regime)
- Regimes ❹ : Second sound waves first
  - – SS waves deformed by the interaction with quantized vortices (shock waves) with increasing q
  - – Heat pulse creates turbulence at the heated wall
  - – ↑ heat pulse ↑ % of energy transferred to create turbulence or boiling at the wall



Full turbulence boundary

Boiling boundary



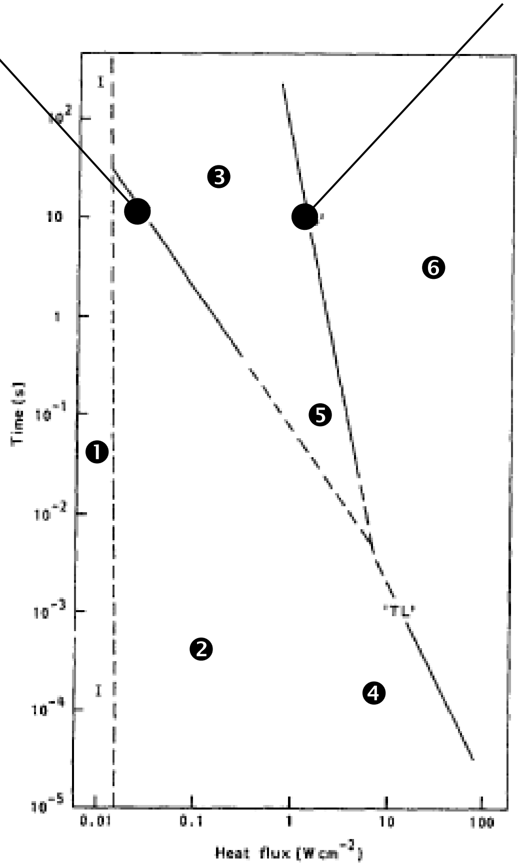
1.7 K and 1 ms

Nemirovskii, S. K. and A. N. Tsoi (1989). "Transient thermal and hydrodynamic processes in superfluid helium." Cryogenics **29**(October): 985-994

Shimazaki, T., M. Murakami, et al. (1995). "Second sound wave heat transfer, thermal boundary layer formation and boiling: Highly transient heat transport phenomena in He II." Cryogenics **35**(10): 645-651.

Transient heat transfer regimes chart (1/2)

- Regime ❺ less or not studied
  - SS, vortices development, diffusion and boiling
- Regime ❻ : Boiling
  - depends on the sub-cooling in saturated helium
- Limitations to use in modeling
  - Boundaries defined within one order of magnitude
  - Most of experiments performed in saturated He II
    - Transition to He II - He I – vapor less investigated
    - Triple phases study needed
  - Regimes boundary established for large dimension (tube or wire)
    - Confinement effect never really investigated
  - Effect of pressure evolution during transient less investigated



Full turbulence boundary

Boiling boundary

Surface heat transfer

- Wire heat transfer experiment
  - Extension of the pseudo-Kapitza regime above the critical heat flux in transient regime
    - Kapitza conductance unchanged during transient
    - Higher in sub-cooled then saturated

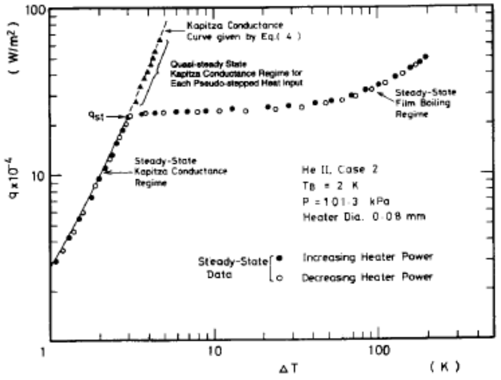


Figure 6 Steady-state heat transfer on the horizontal wire in a pool of subcooled He II at atmospheric pressure (Case 2)

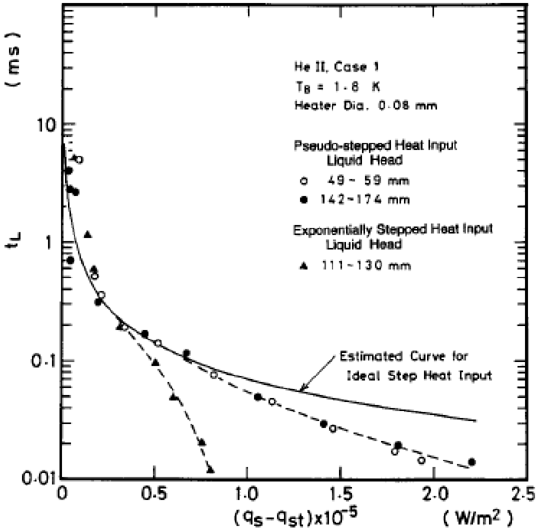


Figure 7 Lifetimes t_L of quasi-steady Kapitza conductance heat fluxes q_s for pseudo-stepped and exponentially stepped heat inputs for various liquid heads at T_B = 1.8 K (Case 1) plotted against the increments $(q_s - q_{st})$

$$q_{st} = \left(\frac{1}{L} \int_{T_{bath}}^{T_\lambda} f(T)\,dT \right)^{1/3}$$

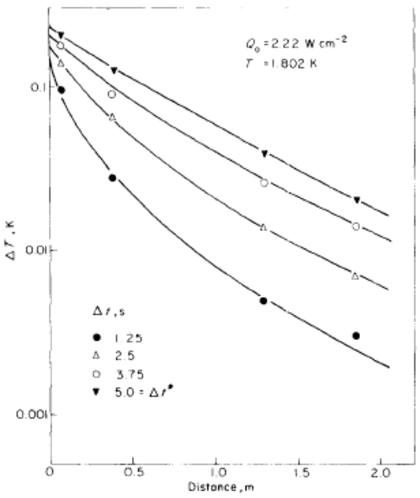
  - Time of the pseudo-Kapitza regime limited

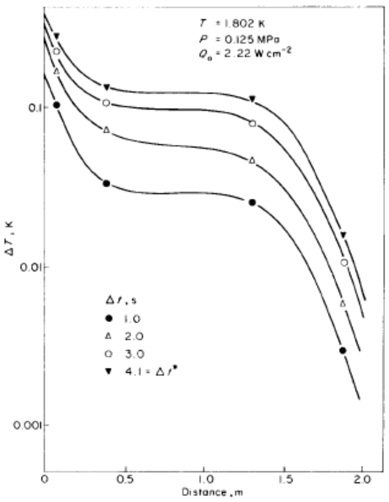
  - Heat transfer coefficient for higher heat flux rarely analyzed (after phase change)
    - Heat transfer coefficient data are taken from steady-state studies

Shiotsu, M. et al. (1996). "Estimation of Kapitza conductance effect on steady and transient boiling heat transfer in He I based on Kapitza conductance results in He II." Cryogenics 36(3): 197-202.

Channel heat transfer (1/2)

- Long tube experiment (~ 10 m)
  - Test in an open (saturated helium) and closed (pressurized) configurations





  - Time to reached boiling is higher in the open system
    - Very short He I regime due to bad heat transfer in the closed system
  - Peak heat flux $q_{T\rightarrow T\lambda}$ is controlled by the properties of He not by the boundary conditions

Van Sciver, S. W. (1979). "Transient heat transport in He II." Cryogenics **19**(7): 385-392.

Channel heat transfer (2/2)

- Short tube experiment (few cm)
  - Short tube = smaller enthalpy reserve before reaching T_λ

$$\frac{\Delta E}{\Delta E_0} = \frac{q.t}{\Delta h_\lambda}$$

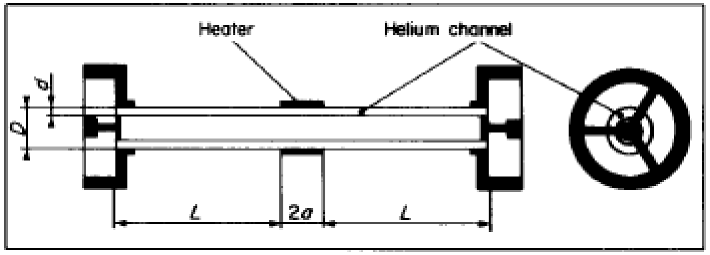
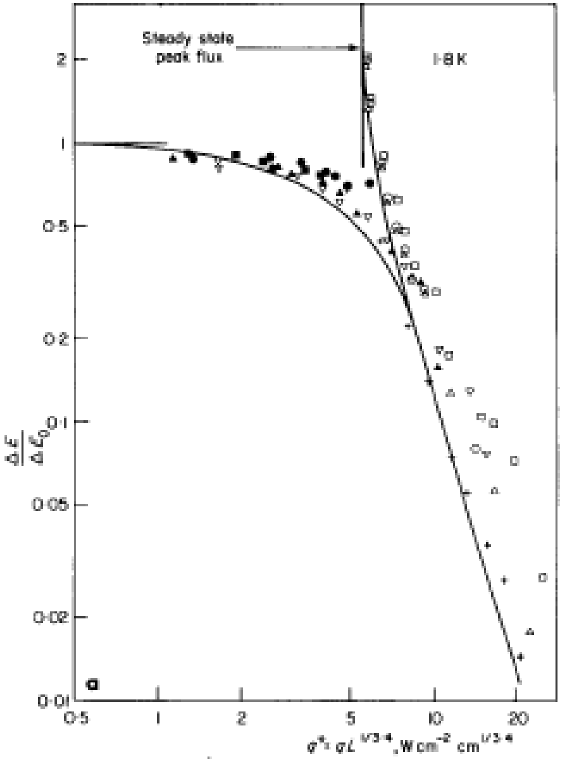
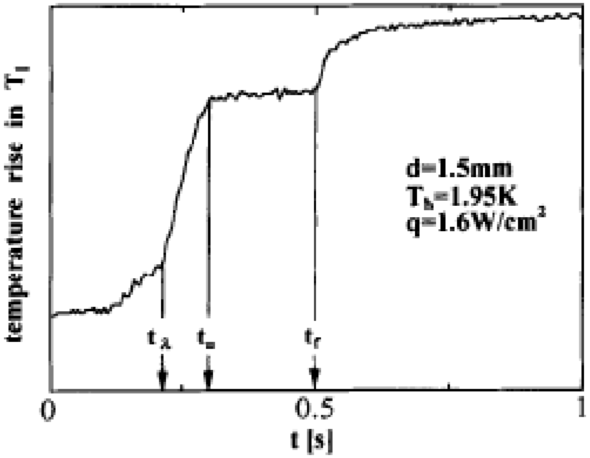


Fig. 1 Test sections used in study. Cross-sectional view. Experiments have been performed on two specimens with d = 0.2 cm and on one specimen with d = 0.1 cm. L = 4.0 cm, a = 0.5 cm and D = 1.0 cm for all test sections



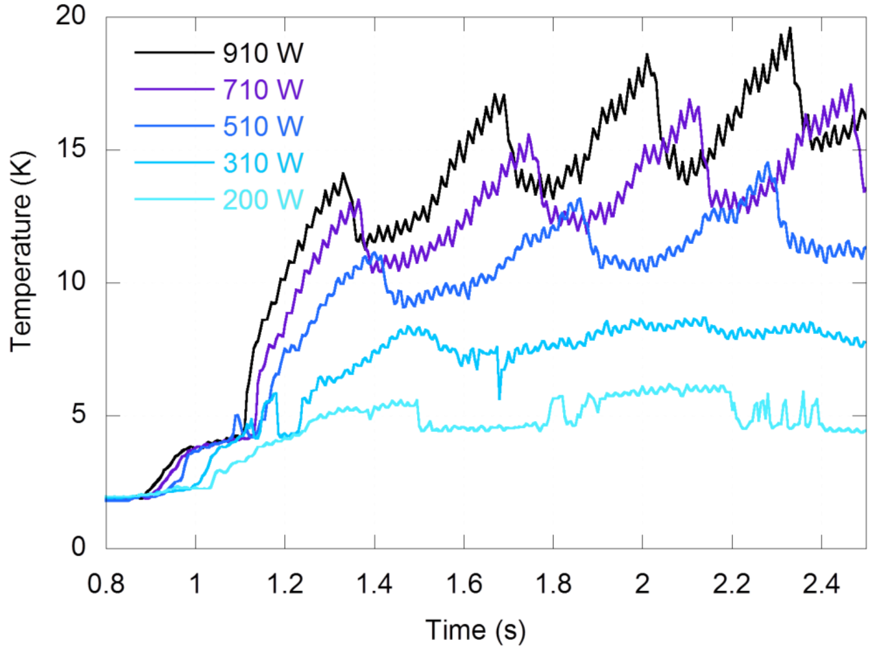


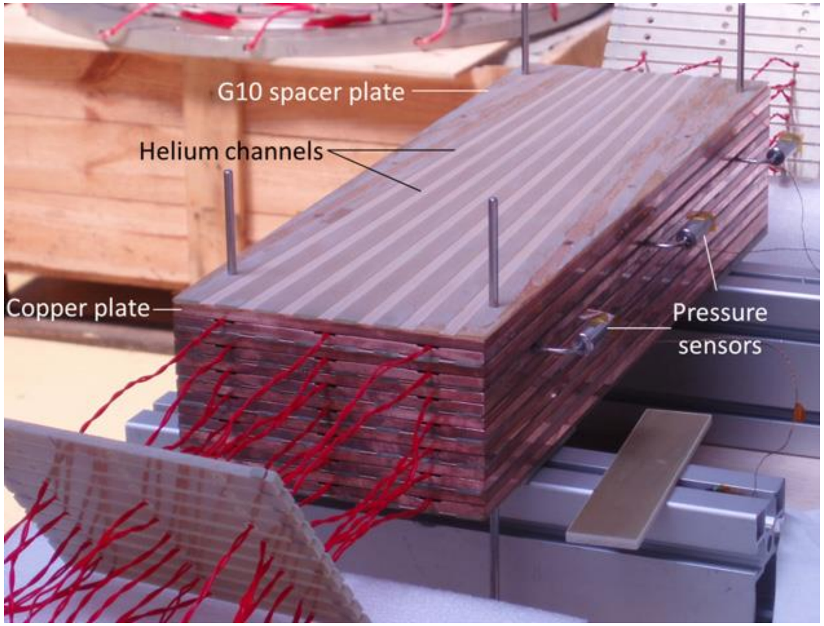
- $t_\lambda \rightarrow Ts = T_\lambda$
- $t_m \rightarrow$ nucleate boiling
- $t_f \rightarrow$ film boiling

Seyfert, P., et al. (1982). "Time dependent heat transport in subcooled superfluid helium." Cryogenics August: 401-408.
Kobayashi,et al. (1997). "Heat transfer through subcooled He I layer from distributed heat source in a pressurized He II channel." Cryogenics **37**(12): 851-855.

Confined geometry heat transfer - channel

- Heat and mass transfer study in the frame work of the design of the Iseult/Inumac whole body 11.7 T MRI magnet under construction in Saclay
- Experimental model vertically oriented in a pressurized bath
  - Channel dimension: 5,46×0,8 mm²
  - Number of channels : 2×7
  - Power : Q applied for 1.5 s (from 0.83 to 2.33 s)
  - Pressurized helium at 1 bar and 1.8 K



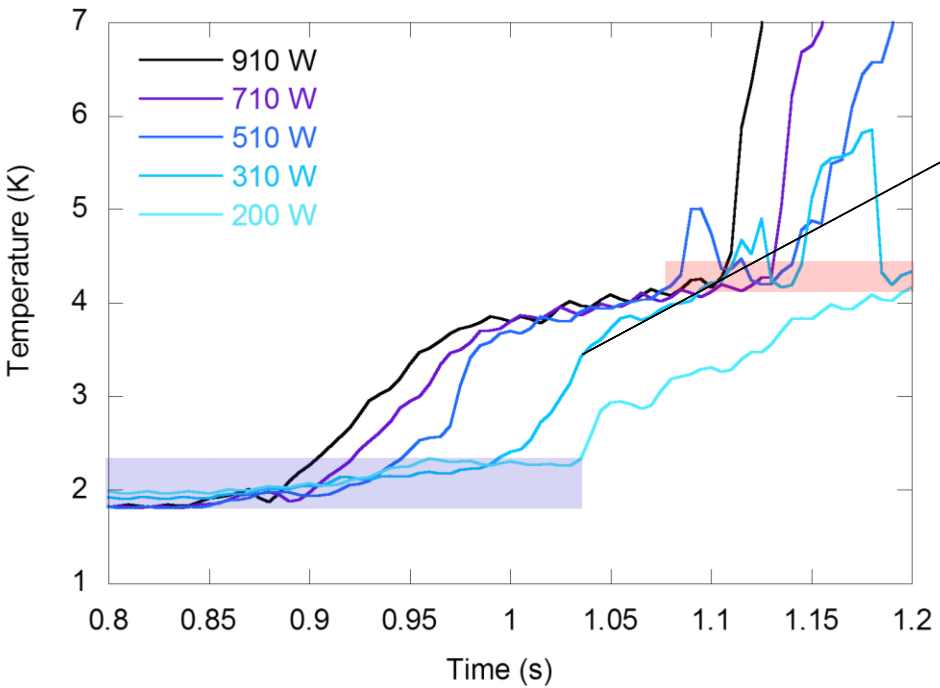


Meuris C, "Experimental simulation of helium pressure rise during a quench of a superconducting coil cooled by a superfluid helium bath." Cryogenics 53 (2013) 17–24

Confined geometry heat transfer - channel

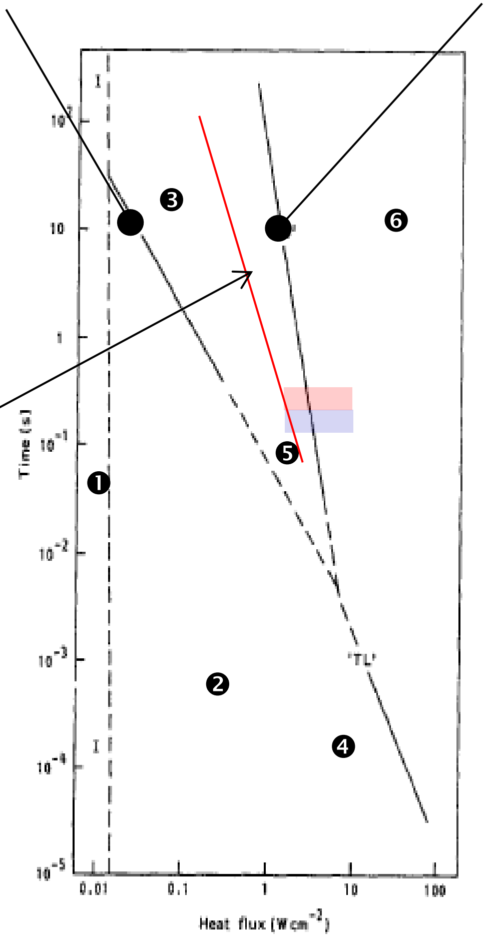
- Heat dissipated on the entire channels
- Three transient regimes
  - – Gorger-Mellink, He I, boiling and film boiling

- In such geometry the behavior of the helium is strongly connected to the evolution of the pressure
- He I region is missing



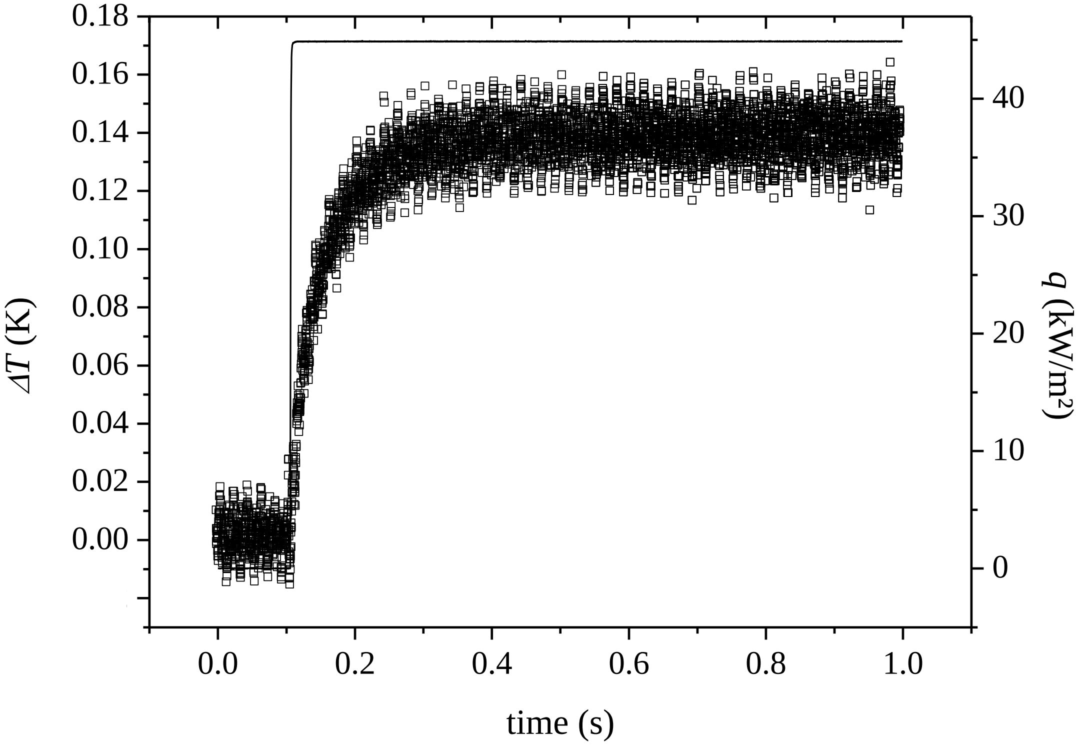
Full turbulence boundary

Boiling boundary



Confined geometry heat transfer - porous media

- Porous Media tested
  - Silicone carbide
  - 10.8 μm of average pore diameter
  - 62 % of porosity
  - 1.5 mm of thickness

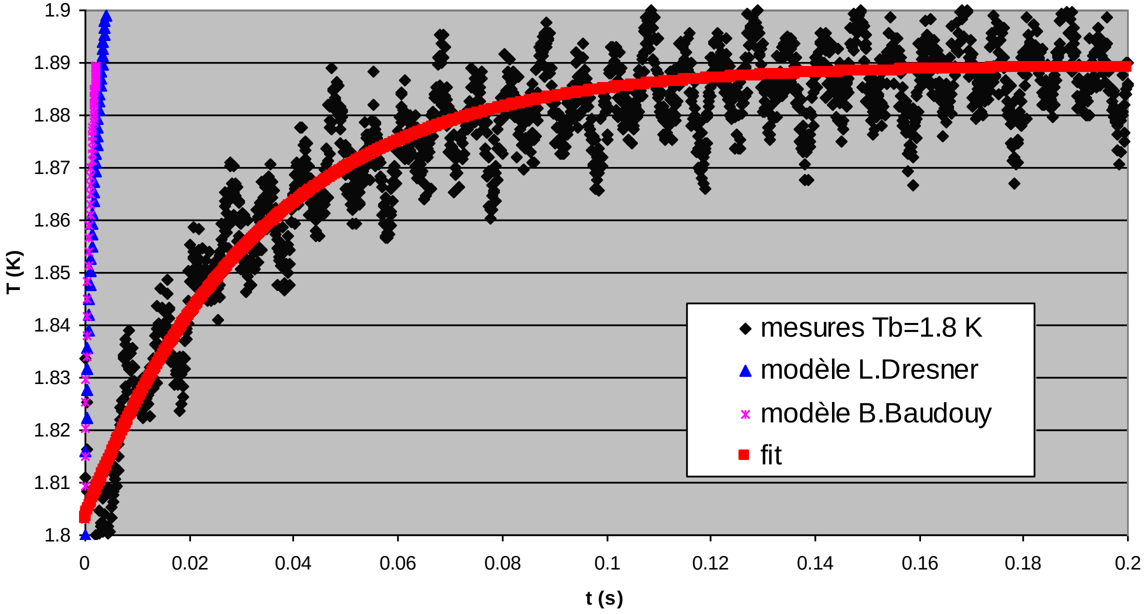


Allain, H. and B. Baudouy (2008). Investigation of transient heat transfer in porous media in He II. Advances in Cryogenic Engineering 53. J. G. Weisend. Chatanooga; TN, AIP Conference Proceedings 823. 53: 207-214

Confined geometry heat transfer - porous media

- Comparison against analytical diffusion model with tortuosity
  - Time constant given by models in the order of the ms
  - Time constant of the physical phenomena 100 higher

$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{\omega^{4/3}} \frac{\partial}{\partial x}\left(f \frac{\partial T}{\partial x} \right)^{\frac{1}{3}}$$



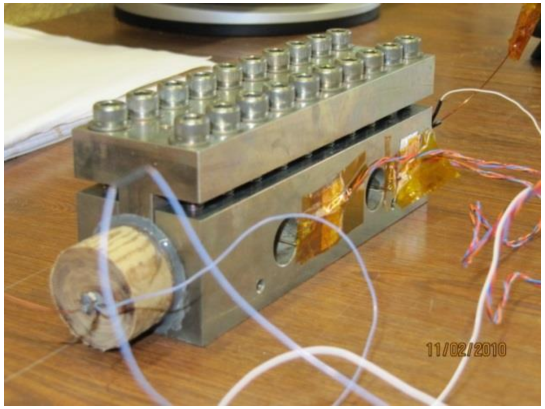
q=48.6 kW/m²

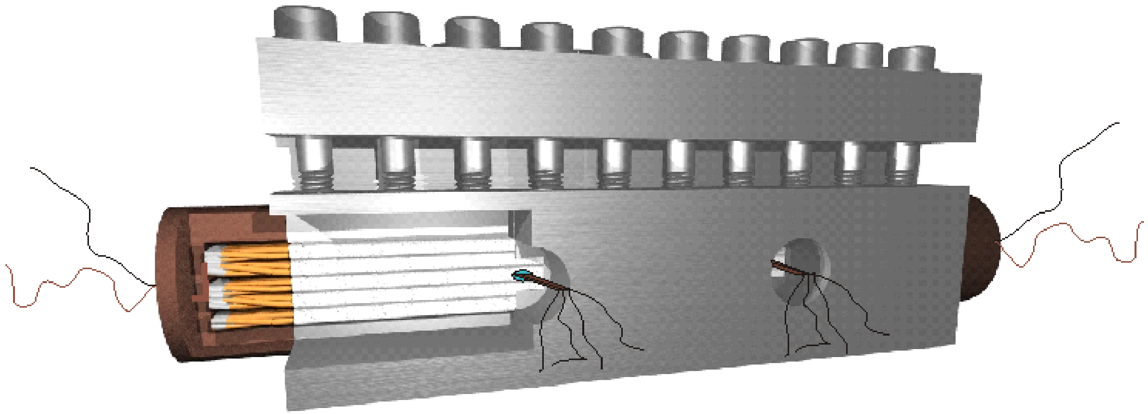
- Need to consider the two-fluid model to understand the fluid movement in the porous media and to find a model at the porous media scale

Allain, H. and B. Baudouy (2008). Investigation of transient heat transfer in porous media in He II. Advances in Cryogenic Engineering 53. J. G. Weisend. Chatanooga; TN, AIP Conference Proceedings 823. 53: 207-214

Confined geometry heat transfer– Stack

- 5 conductors stack, all conductors heated
  - – Dissipated heat range: 0 – ≈ 5.6 W/m
  - – Installed two temperature sensors in the central conductor
- Test in pressurized helium 1 bar

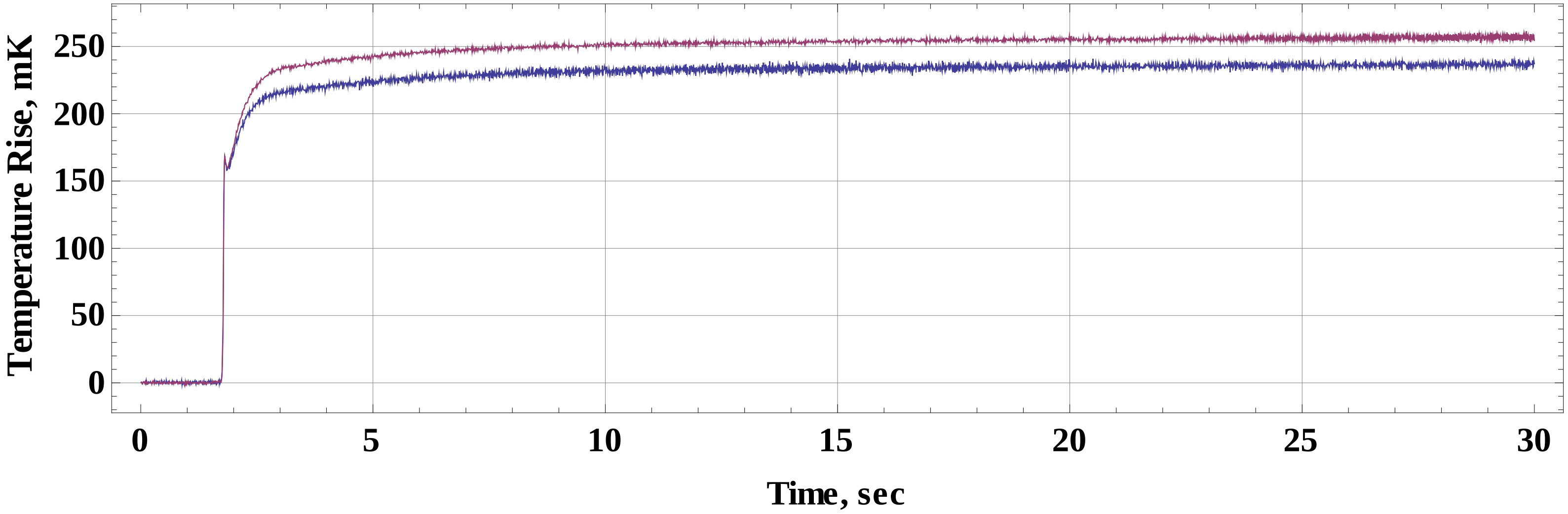




	Ceramic	Classic (Polyimid)	Full impregnation
Pore size	d~70 µm (peak)	10 to 100 µm	-
Porosity ε	4.5 to 29 %	~1 %	-
Conductivity	k≈4 10^{-2} W/Km	k_{kapton}≈10^{-2} W/Km @ 2 K	- k_{epoxy}≈10^{-2} W/Km

Confined geometry heat transfer– Stack

- Pressurized helium at 1.9 K
- Large heat dissipation of 9.22 W/m of conductor
- Temperature difference under ΔT_{λ}
- Long thermal characteristics time due enthalpy rise of the internal helium and the porous thermal barriers



Analytical Modeling

- Model
  - 1D diffusion equation in the turbulent regime (Gorter-Mellink)

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(f(T) \frac{\partial T}{\partial x} \right)^{1/3} \text{ in } 0 \le x \le \infty \text{ and for } t > 0$$

$$T = T_0 \text{ at } x = 0 \text{ and for } t > 0$$

$$-\left(f \frac{\partial T}{\partial x} \right)^{1/3} = q_0 \text{ at } x = 0 \text{ and for } t > 0$$

- Similarity solutions
  - Constant properties and semi-infinite domain
  - Mean property to be defined
  - Works for large dimensions only and no phase change

- Integral method
  - Temperature dependent properties and finite geometry modeling
  - direct result without the need of the evaluation of an average temperature
  - Phase change implementable

L. Dresner, Transient Heat Transfer in Superfluid Helium, Advances in Cryogenic Engineering, Plenum Press,(1981) 411-419
Baudouy, B. (2009). "Heat balance integral method for heat transfer in superfluid helium." Thermal Science **13**(2): 121-132

Numerical Modelling

- Linearization of the diffusion equation done since the 80's with "in-house" code [Seyfert1982]

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial q}{\partial x} \quad \textit{with} \quad q = -\left(f(T) \frac{\partial T}{\partial x} \right)^{1/3}$$

  - Implementation in commercial codes Castem or Comsol [Baudouy1996 and 2008]

- Full two-fluid or simplified model developed since the 90's
  - Numerical difficulties due to the fact that the thermo-mechanical and the Gorter-Mellink mutual friction terms are several orders of magnitude larger than the other terms
  - Simplified superfluid equation (Kitamura)
  - Numerical segregated solution for full model (Tatsumoto)
  - Full model implemented in Comsol (Allain)

- Theoretical and numerical modeling in porous media
  - Method of volume averaging used and theoretical proof that the Landau regime leads to a Darcy problem at the macroscopic level (Allain)

Kitamura T et al. A numerical model on transient, two-dimensional flow and heat transfer in He II. Cryogenics 1997;37:1–9..
Tatsumoto H et al. Numerical analysis for steady-state two-dimensional heat transfer from a flat at one side of a duct containing pressurized He II. Cryogenics 2002;42:9–17.
Roa YF et al. A two-fluid-model analysis on transient, internal-convection heat transfer of He II in a vertical Gorter-Mellink duct heated at the bottom surface. Cryogenics 1996;36:457–64
Allain, H., et al. (2010). "Upscaling of superfluid helium flow in porous media." Int. J. Heat Mass Trans **53**(21-22): 4852-4864.
Allain, H., et al. (2013). "Investigation of suitability of the method of volume averaging for the study of heat transfer in superconducting accelerator magnet cooled by superfluid helium." Cryogenics 53(0): 128-134.

Numerical Modelling | One fluid model (1/3)

- Simplified model considering one fluid in simplifying the superfluid velocity equation

$$s\nabla T = -A\rho_n|u_n - u_s|^2(u_n - u_s)$$

- Continuity equation $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho\, u) = 0$

- Momentum equation $\rho\frac{\partial u}{\partial \tau} = -\rho(u\cdot\nabla)u - \nabla p - \nabla\cdot\left[\frac{\rho_n\,\rho_s}{\rho}\left(\frac{s}{A\rho_n|\nabla T|^2}\right)^{2/3}\nabla T\nabla T\right] +$

$$\eta\left[\nabla^2 u + \frac{1}{3}\nabla(\nabla\cdot u) - \left(\frac{\rho_s^3 s}{A\rho^3\rho_n|\nabla T|^2}\right)^{1/3}\left\{\nabla^2(\nabla T) + \frac{1}{3}\nabla(\nabla\cdot\nabla)T\right\}\right]$$

- Energy equation $\rho c_p\frac{\partial T}{\partial \tau} = -\rho c_p(u\cdot\nabla)T - \nabla\cdot\left\{\left(\frac{1}{f(T)|\nabla T|^2}\right)^{1/3}\nabla T\right\}$

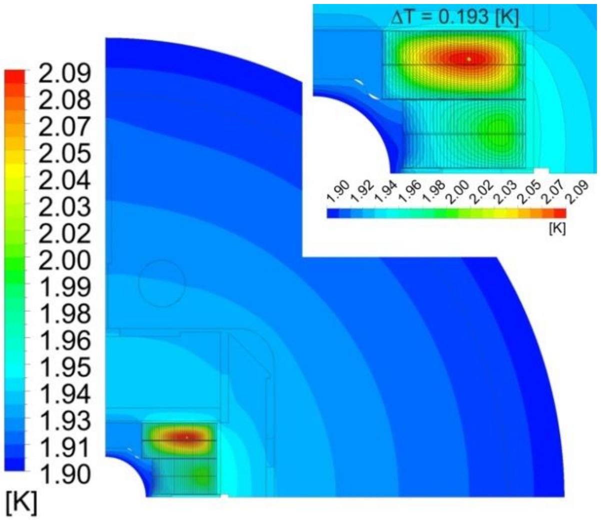
- No second-sound modeling - Not valid for very small heat pulse
- No phase change implemented

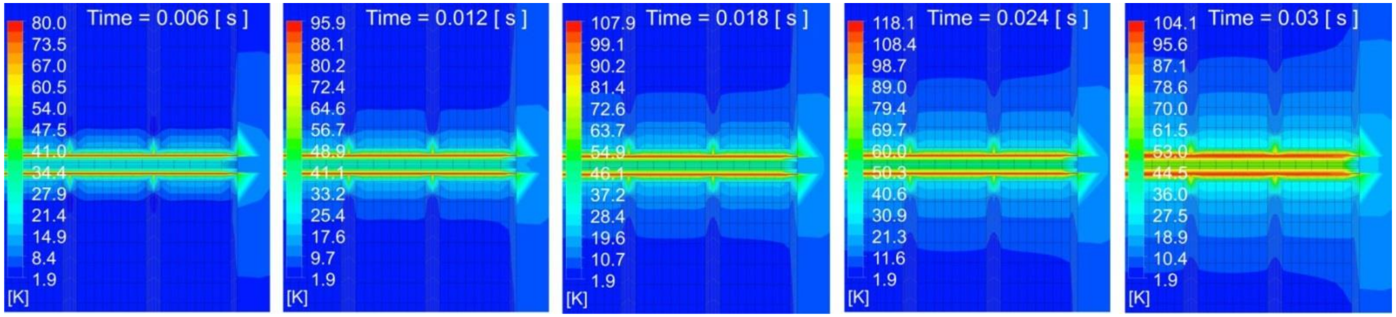
Kitamura T et al. A numerical model on transient, two-dimensional flow and heat transfer in He II. Cryogenics 1997;37:1–9

Numerical Modelling | One fluid model (2/3)

- Calculations performed with ANSYS-CFX® (finite volume method with SST (Shear-Stress-Transport) turbulence model is used

- Used to compute the steady-state and transient temperature evolution in the *Fresca 2* coil model
  - Steady-state: 0.2 W in each conductor
  - Quench heating simulation: 4 heaters delivering 50 W/cm² triggered after 25 ms (quench detection). Current sharing temperature reached in 4-5 ms
  - No joule heating in the conductor and no phase change in the helium

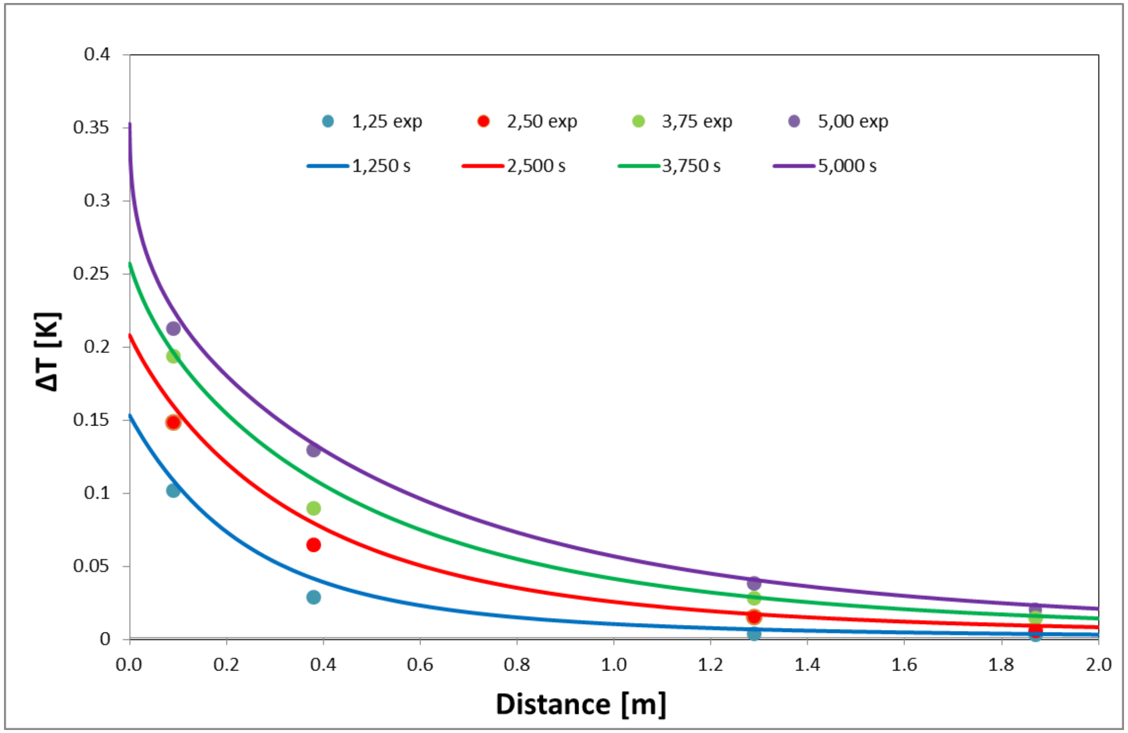




S. Pietrowicz, B. Baudouy, Numerical study of the thermal behavior of an Nb3Sn high field magnet in He II, Cryogenics 2013 53 72–77

Numerical Modelling | One fluid model (3/3)

- Implementation of the “one fluid” model into Fluent ® in 3D
- Comparison with the Van Sciver’s experiment



- Future work : short length comparison and implementation of phase change (He II- He I)

S. Pascali and R. Bruce @ CEA Saclay

Numerical Modelling | Full two-fluid model

- Code developed at Fluid Mechanics Institute of Toulouse (IMFT)
- Code based on the OpenFOAM® technology development of a new PISO algorithm including the terms of Gorter-MellinK

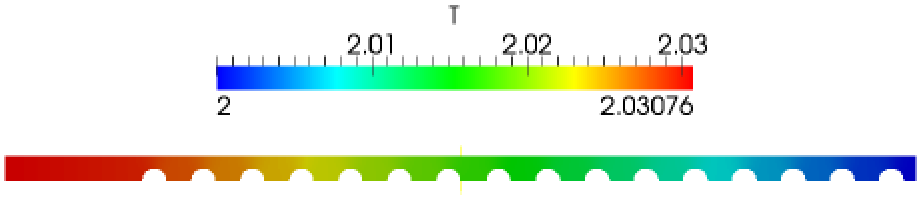


Figure 13: Plot of the temperature profile at steady state in a capillary tube filled by 16 beads. The presence of solid materials inside the capillary leads to an increase of the ΔT.

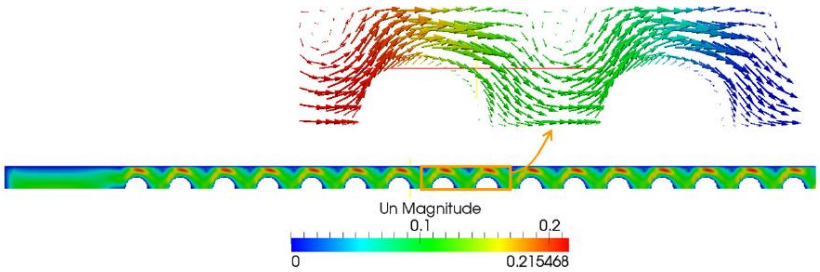


Figure 14: Plot of the normal velocity magnitude and of the normal velocity vectors in two adjacent REV. We clearly notice cyclic flow patterns.

- Modeling of second-sound but phase change is not implemented
- Modelling the physics at µs is a challenge (creation and interaction of vortex)

Soulaine, C. et al. A PISO-like algorithm to simulate superfluid helium flow with the two-fluid model; submitted to CPC, 2014
Soulaine, 2014. Numerical investigation of heat transfer in a forced flow of He II. In: Proceedings of the 15th International Heat Transfer Conference, IHTC-15 August 10-15, 2014, Kyoto, Japan

Conclusions

- He II Heat and mass transfer involved in magnet transient events
  - Knowledge in the fundamental law of transport at different space and time scales
  - Knowledge of **singular** data such as Kapitza resistance, pressure drop, thermal resistance through restriction and “closed” volume
  - Knowledge on the effect of phase change and pressure evolution on surface heat transfer and in the bulk helium

- Experimental data
  - Missing data on small/limited volume in pressurized helium below the ms time scale or heat input scale
  - Missing data through geometrical singularities and on non monotonous time heat input
    - Surface heat transfer
    - “Bulk” behavior

- Modeling
  - Implementation of phase changes in 3D code (He I and He II)

Experimental model proposal

- Heat transfer in the helium and the solid
- Chanel experiment
  - Different thicknesses and variable thickness
  - Channel heated from the bottom and the side
  - Open and closed configuration
- Measurement
  - Fast thermal and pressure sensors
  - Temperature and pressure at the wall and in the fluid
  - Total ΔP and local P
- What to model
  - Heat transfer in helium
    - Through the insulation (10 µm), between the collars (100 µm), elsewhere (1000 µm)
    - Combination in series and in parallel
  - Heat transfer at the heating surface
    - Kapitza, boiling, film boiling