FJPPL workshop 2012 @ Université Blaise Pascal Clermont-Ferrand - 28-30 May 2012

LHC-3
Superconducting Magnets for the LHC Luminosity Upgrade

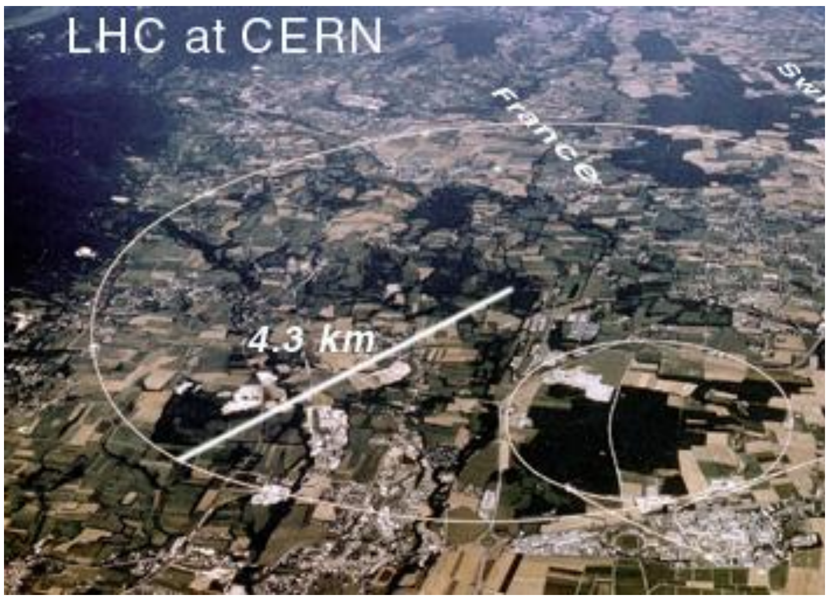
KEK : N. Kimura, T. Okamura, A. Yamamoto, T. Ogitsu, T. Nakamoto, Y. Makida, K. Sasaki, T. Okamura, S. Takada** ***U. of Tsukuba*

Irfu : B. Baudouy, S. Pietrowicz, A. Four, J. Rifflet, M. Durante, F. Rondeaux

KEK-CEA Superconducting Magnet Co-operation Program

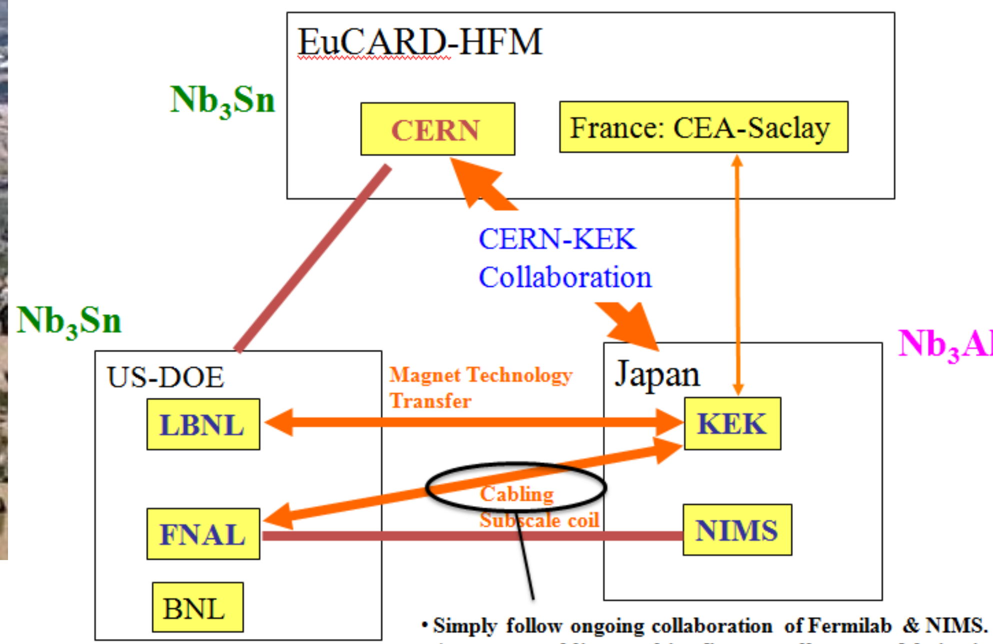
For the LHC luminosity upgrade: Replacing the final focus system of the interaction regions with higher performance magnets

Increasing the magnetic field from 9 T (NbTi) to beyond 12 T using Nb_3Sn or Nb_3Al



High Field Accelerator Magnet Development

A Global Cooperation Network



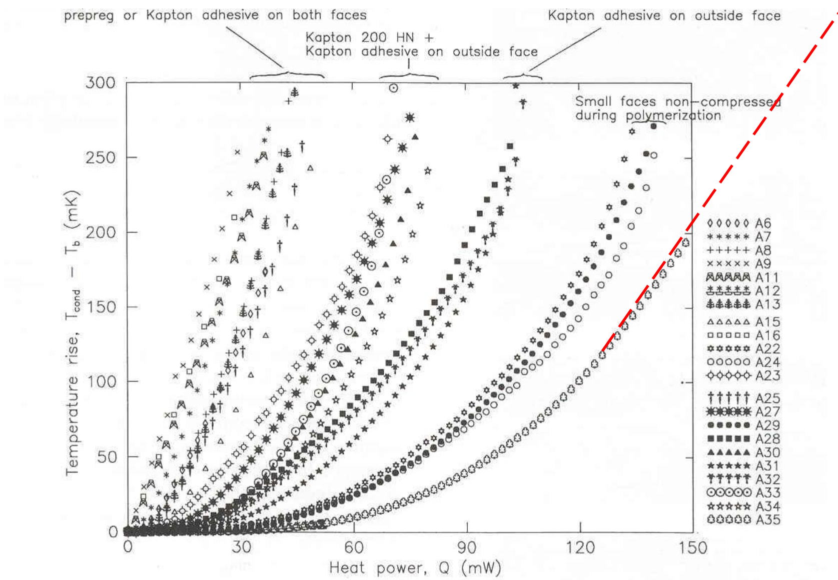
- Simply follow ongoing collaboration of Fermilab & NIMS.
- A compact cabling machine fits to small amount fabrication.

The goal is to construct a high field magnet with Nb_3Al or Nb_3Sn cable.

Background (2/3)

- Heat transfer viewpoint→ electrical insulation of the cable is the largest thermal barrier

- "Beam losses" for the LHC upgrade
  - 50 - 80 mW/cm^3 or 2 - 3 W/m (cable)→At least 5 times higher than for LHC
  - With NbTi LHC magnet polyimide insulation ΔT~ K (porous to helium)
  - New insulation developed at CERN ΔT~ 0,3 K



For Nb_3Sn Magnets

- Insulation=fiber glass tape impregnated with epoxy resin
- Dry insulation (no helium)
- ΔT?

Background (3/3)

- Heat transfer study and material characterization are necessary
  - Thermal properties of Nb_3Sn magnets insulations
  - Effect of radiation has to be considered also for the lifetime of the magnet
  - Heat transfer in an insulation magnet coil
- Development of "innovative" ceramic insulation
  - Thermal treatment (insulation+Nb_3Sn, easier and less costly construction)
  - Fiberglass + ceramic precursor (CEA patent)
  - Higher heat transfer rate, larger He volume in the insulation (Cp) and heat exchange surface increase (matrix participation)
- Development of heat transfer codes
  - Thermal design and optimization of the cooling paths

Objectives

For the LHC luminosity upgrade, Cryogenic Science Center of KEK and SACM of Irfu have started a collaboration mainly on :

- Heat transfer through electrical insulation
  - Heat transfer in coil mock-up
  - Measurement of the thermal properties @ He II temperature
  - Development of He II heat transfer code
  - Thermal conductivity measurement @ low temperature

KEK-SACM/Irfu Exchanges

- Nobuhiro Kimura @ Saclay
  - Oct. 10-Nov. 5; Porous insulation tests in pressurized He II

- Takahiro Okamura
  - Oct. 31st- Nov. 5; He II heat transfer code

- S. Pietrowicz, A. Four and B. Baudouy @ KEK
  - 10-18 of March; Porous insulation tests in supercritical He and He I

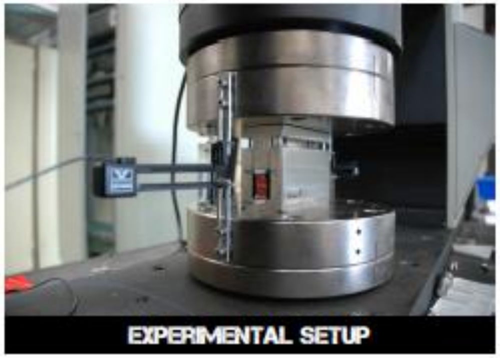
- Funding FJPPL: 4 k€ per team

The porous ceramic insulation

	Ceramic	Classic	Full Impregnation
Pore size (µm)	100	10 to 100	0
Porosity (%)	4.5 to 29	1	0
Conductivity (W/m.K)	$4\ 10^{-2}$	10^{-2}	10^{-2}

- Mechanical characterization on mini Race track magnet up to 60 MPa (Irfu/Sacm)

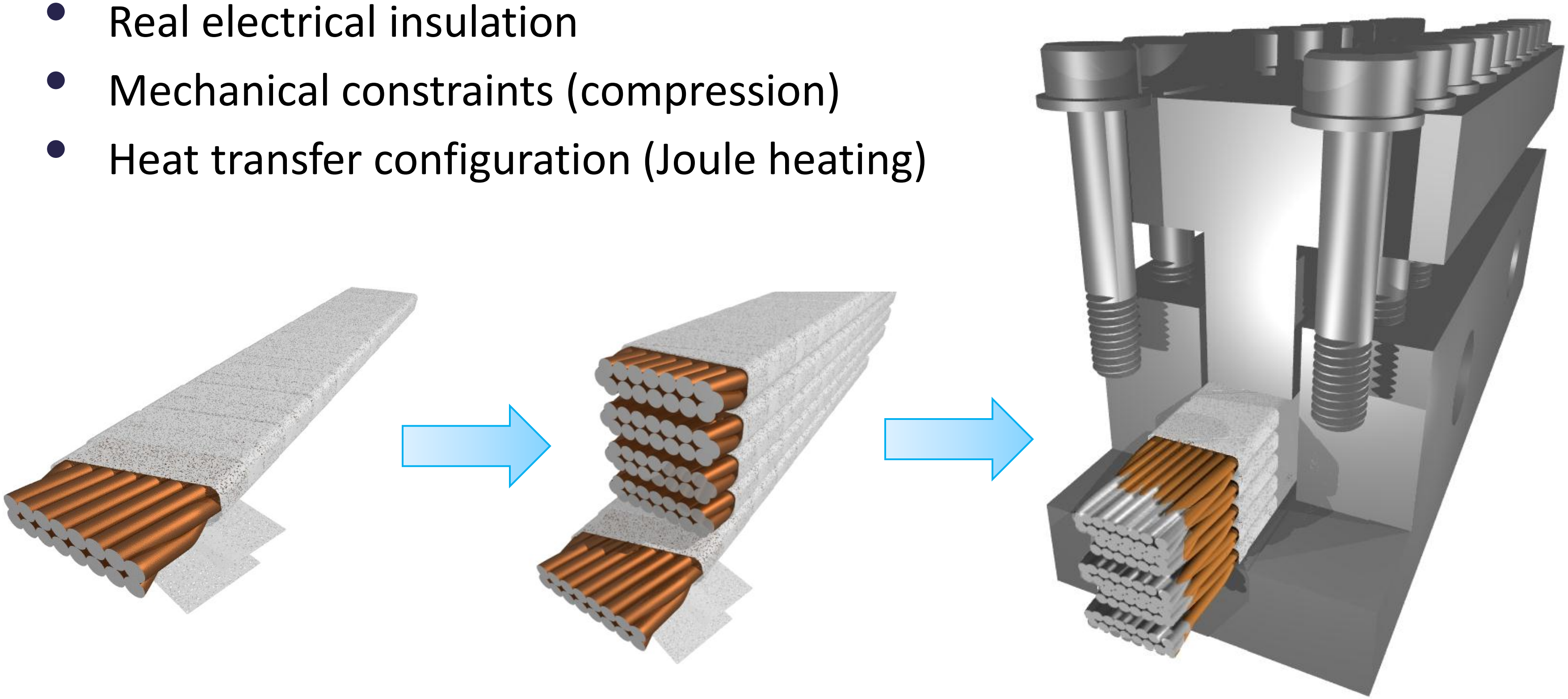
Courtesy of P. Manil (CEA)



- Race track magnet with the porous insulation under construction (SMC program in collaboration with CERN and RAL)

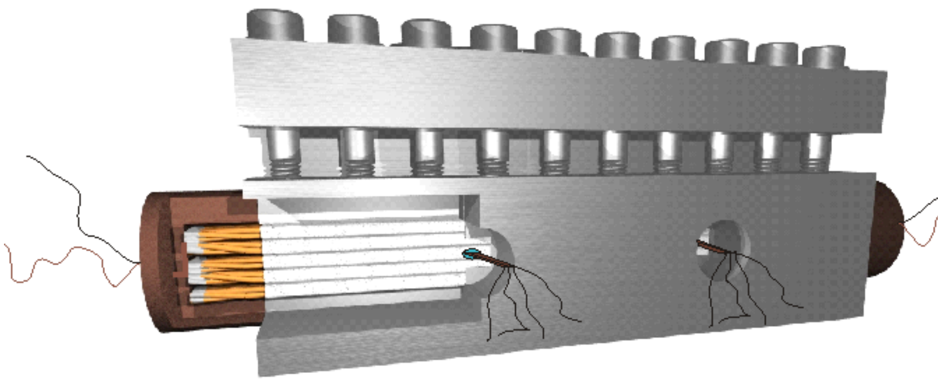
The Stack Experiment : Heat transfer in a coil

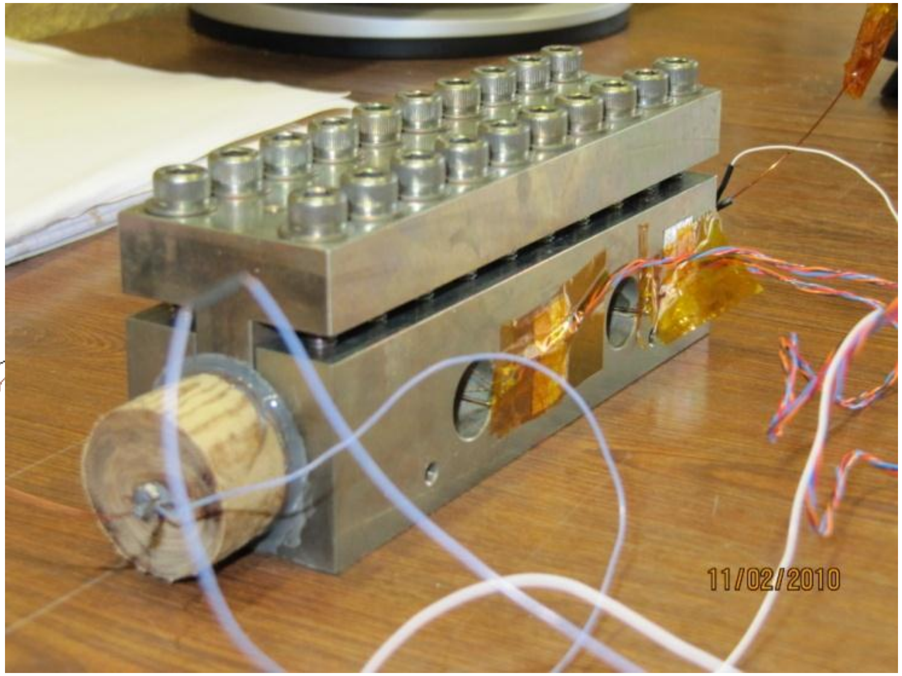
- Characterization of the thermal performance of the insulation
  - “real cable” geometry (CuNi cable)
  - Real electrical insulation
  - Mechanical constraints (compression)
  - Heat transfer configuration (Joule heating)



The Stack Experiment : Mock-up

- Characterization of the thermal performance of the insulation
  - Central cable instrumented with bare ship sensors

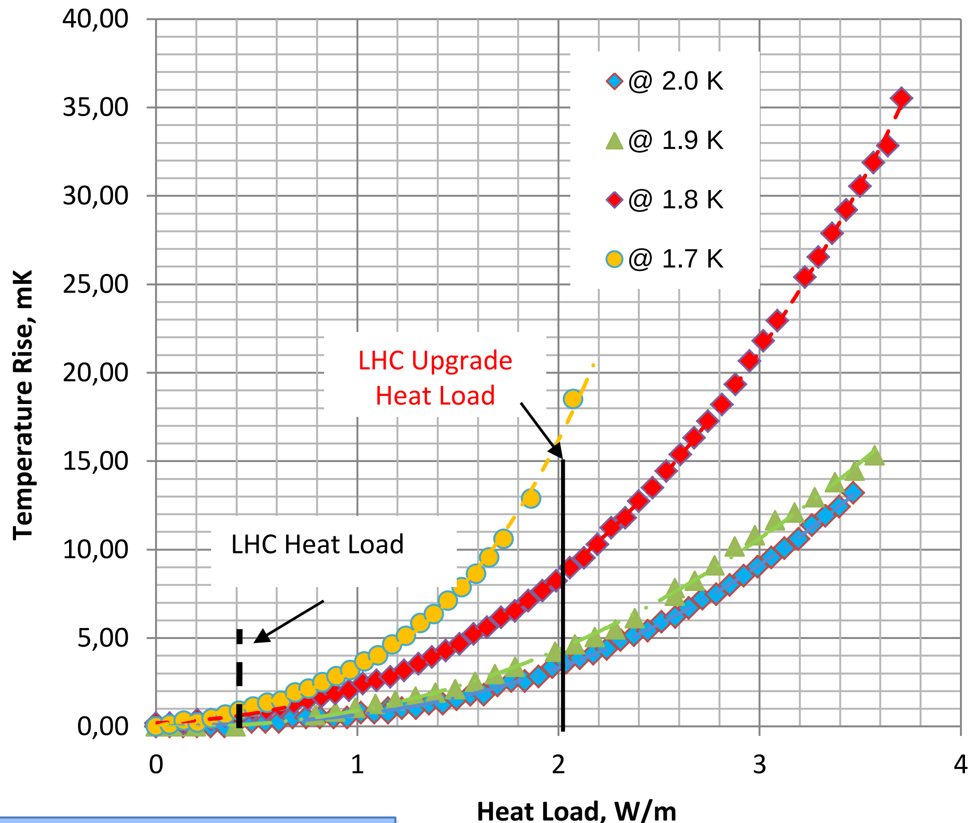




The Stack Experiment : Results (1/3)

- Samples tested in pressurized He II from 1.7 to 2.1 K @ Saclay
- Samples tested in He I at atmospheric pressure and in supercritical helium @ KEK

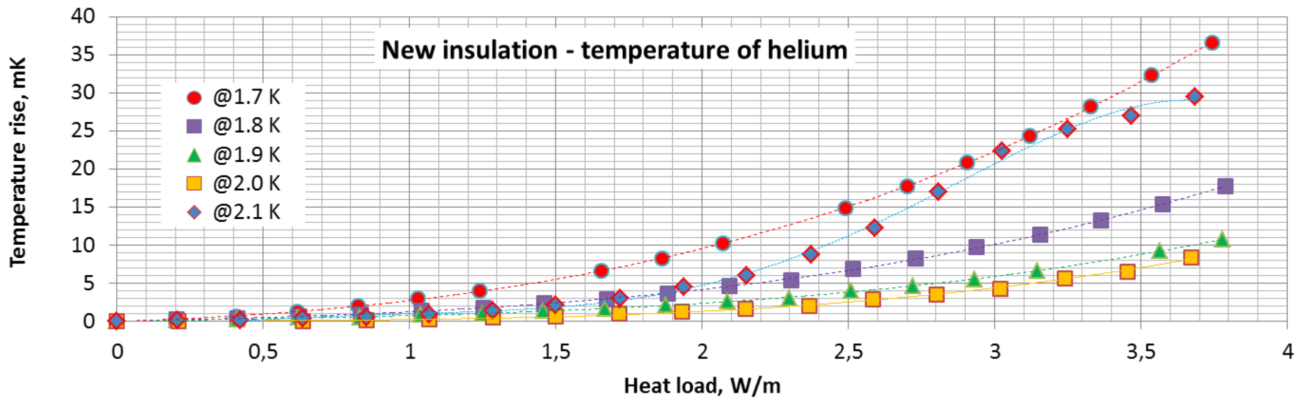
- ΔT <20 mK for the LHC upgrade heat load
- Δ T <5 mK for the current LHC heat load
- 100 times more efficient than the current LHC insulation!

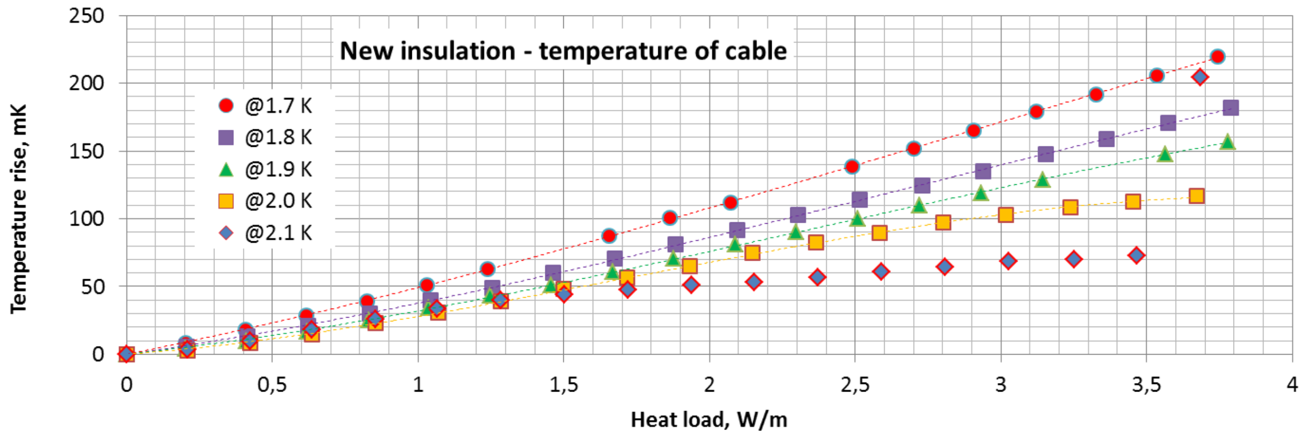


$$\Delta T_{\text{fully impregnated insulation}} > \Delta T_{\text{current insulation}} \gg \Delta T_{\text{porous insulation}}$$

The Stack Experiment : Results (2/3)

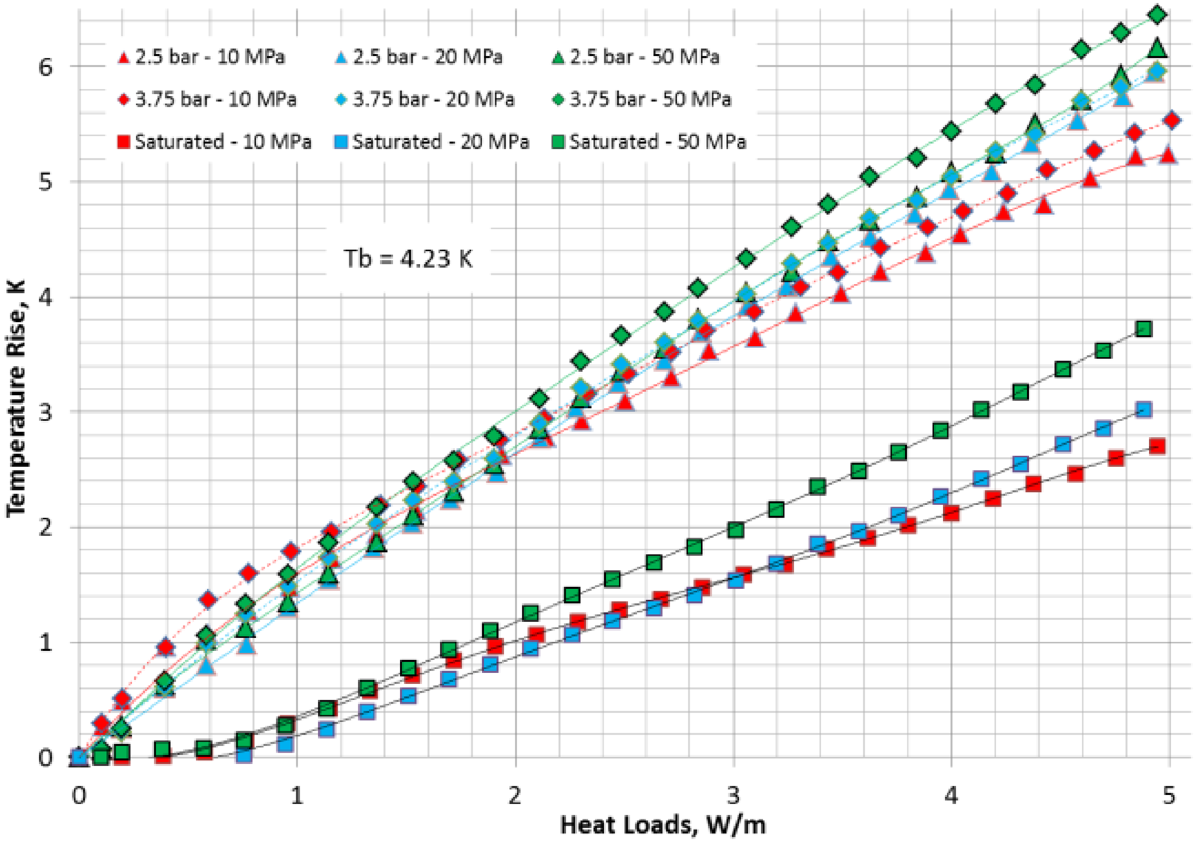
- Construction of a stack with a porous insulation under a 50 Mpa compression
- Test in He II @ Saclay in Nov. 2011
  - Two sensors: one in the fluid one on the conductor





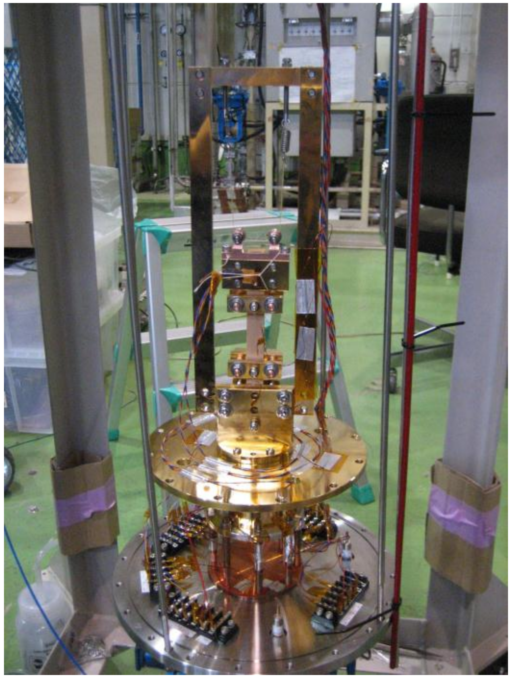
The Stack Experiment : Results (3/3)

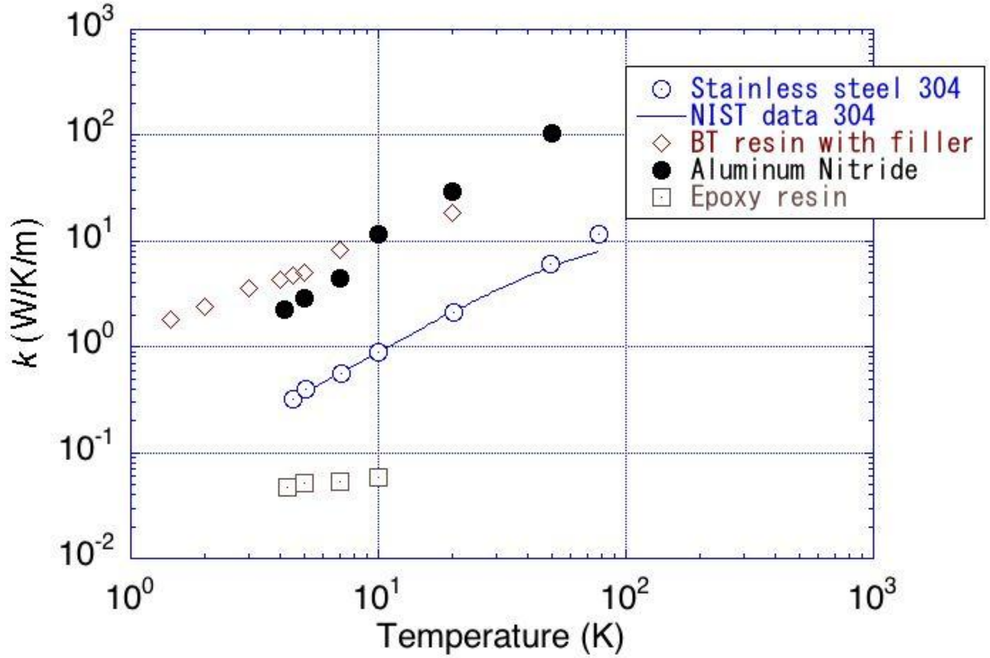
- Construction of a stack with a porous insulation under a 50 MPa compression
- Test in supercritical and normal helium @ KEK in March 2012

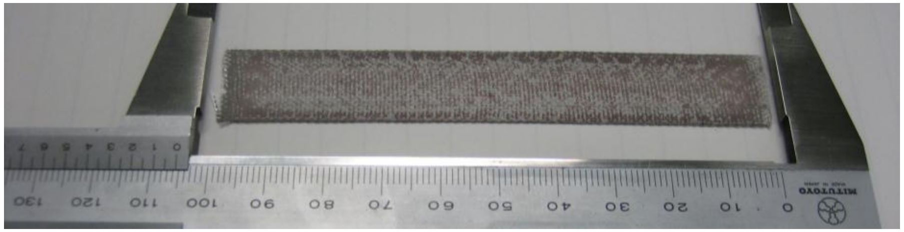


Thermal conductivity measurement @ KEK

- Measurement of radiation resistant materials (2 K – 77 K)
  - BT resin*, Aluminum Nitride and Epoxy resin
  - To be measured
    - porous insulation from Saclay
    - Cyanate Esther







* Bismaleimide-Triazine Resin

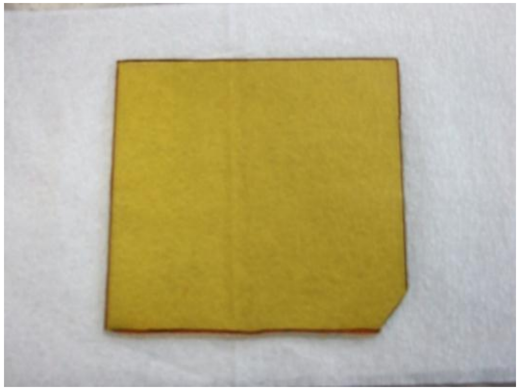
Thermal conductivity measurement @ KEK

- High radiation resistant materials such as Cyanate Ester resin are being developed for the Nb_3Al coil impregnation in KEK, and preparing sample for the thermal conductivity measurement
  - Candidate materials were already delivered to KEK
  - Preparing radiation resistant test under high radiation environment using gamma source in JAEA Takasaki is going on now.

Spec.

- low viscosity
- control of solidification
- mechanical strength

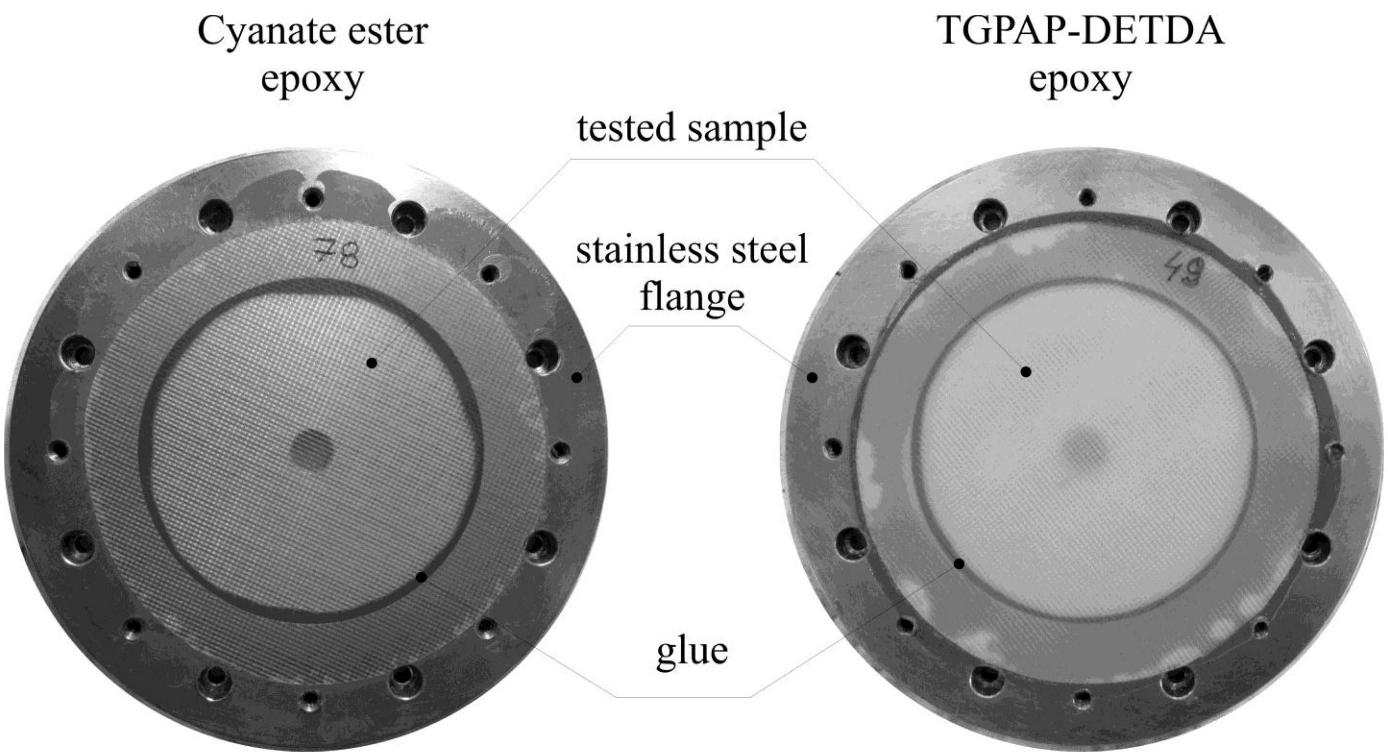
Cyanate Ester resin



Newly developed CE resins for HF accelerator magnets

Kapitza resistance and thermal conductivity @ Saclay

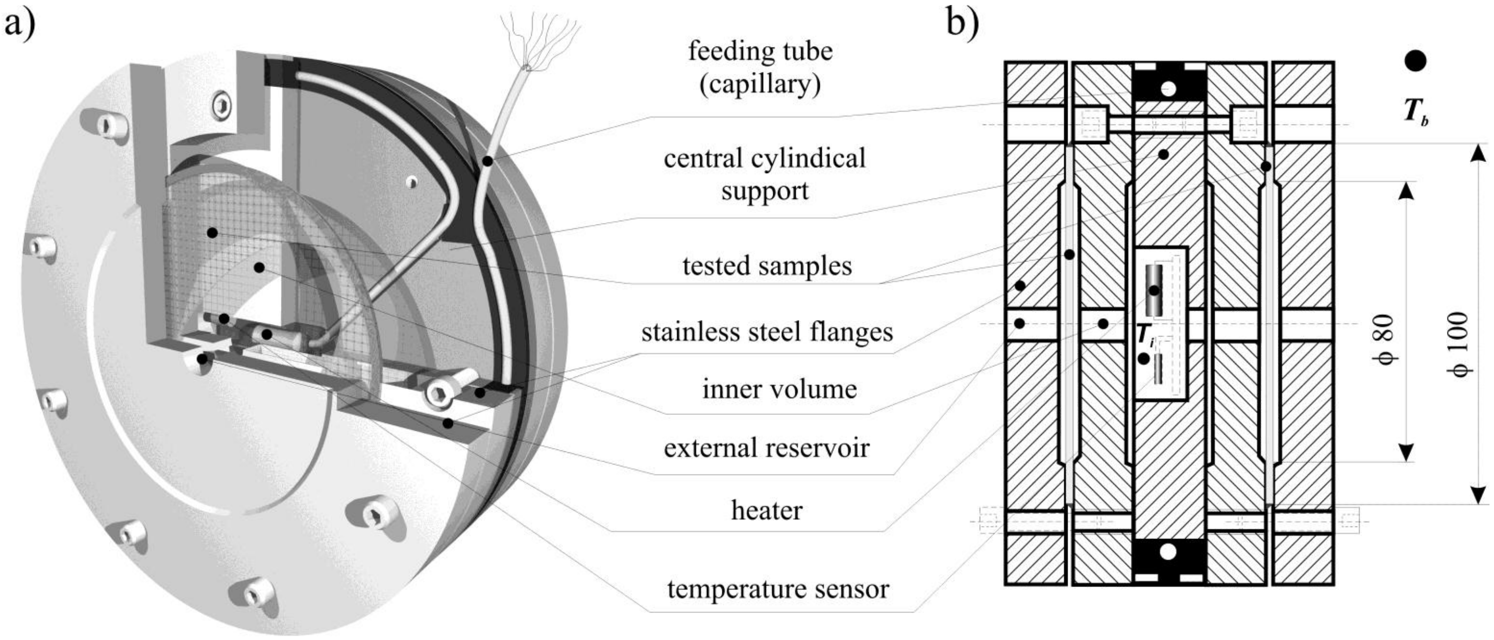
- Determination of the Kapitza resistance and thermal conductivity of radiation resistant material in He II:
  - Cyanate Esther
  - Tri-functional epoxy resin



Kapitza resistance and thermal conductivity @ Saclay

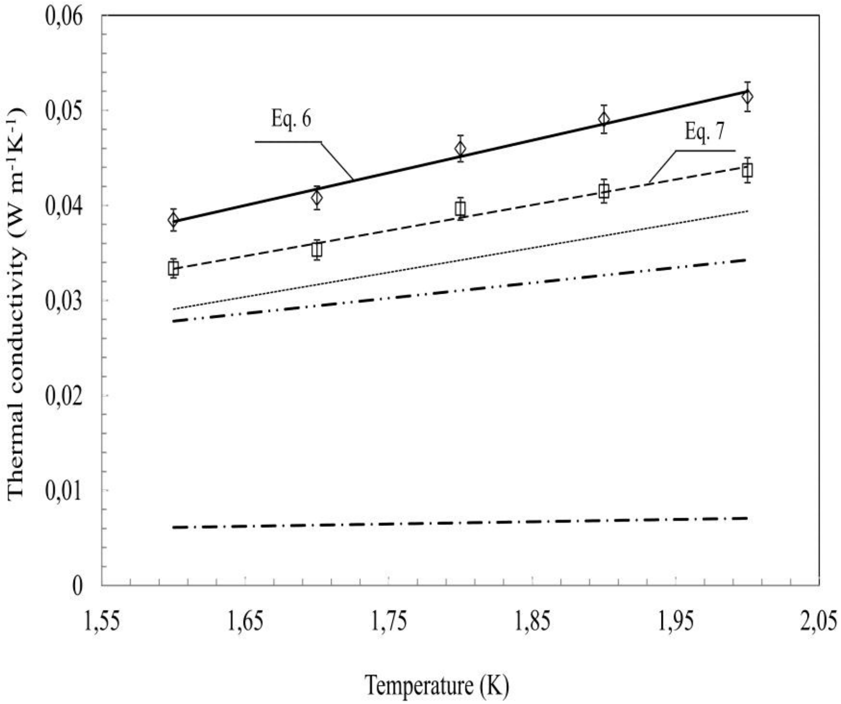
- Measurement of the total thermal resistance and extraction of the two component : Kapitza resistance and the thermal conduction resistance

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

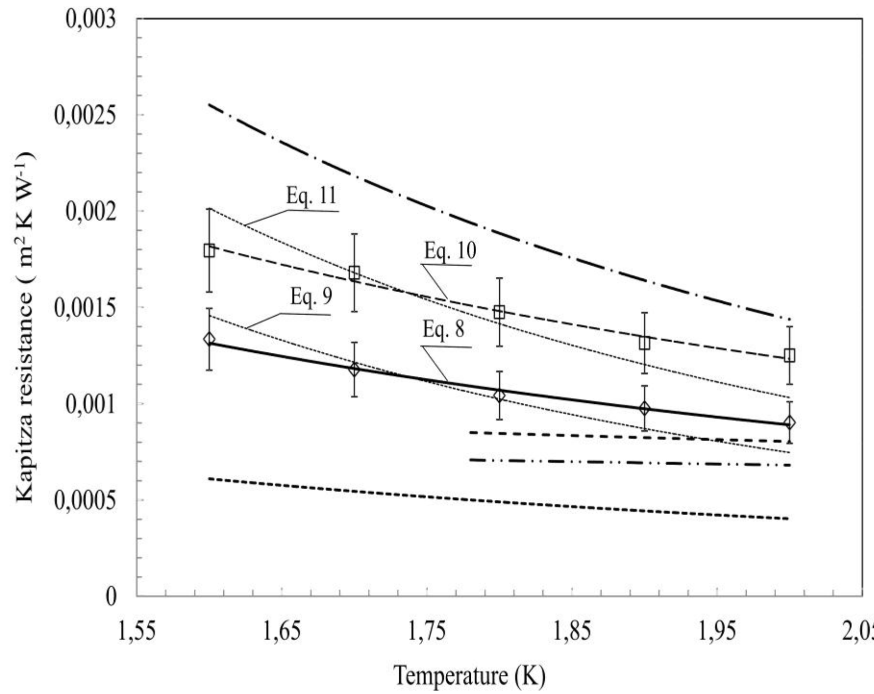


Kapitza resistance and thermal conductivity @ Saclay

Thermal Conductivity



Kapitza resistance



TGPAP-DETDA ◇, Cyanate ester mix ☐,
Kapton —·—·—, epoxy resin fiberglass tape ··· and epoxy —··—··—

Kapton —·—·—, epoxy resin fiberglass tape ---, Stay cast coating on polished surface —··—··—, - - -

Development of He II heat transfer code

- Development of "heat transfer" code in He II for :
  - Calculation of the maximum temperature rise in the magnet during steady-state heat load due to beam losses or AC losses for slow ramp field
  - Calculation of magnet's thermal – flow behavior during the quench detection event

- Two approaches
  - Direct DNS of the full system of equations
  - Implementation of a *simplified* model in commercial software - ANSYS CFX

Development of He II heat transfer code

- The system: NVS equations + superfluide turbulence term

Definition of superfluid and normal fluid component

$$\rho = \rho_s + \rho_n$$

$$\rho \mathbf{u} = \rho_n \mathbf{u}_n + \rho_s \mathbf{u}_s$$

Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Momentum Equation for the total fluid

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho_n \mathbf{u}_n \mathbf{u}_n + \rho_s \mathbf{u}_s \mathbf{u}_s) = -\nabla P + \mu \left(\nabla^2 \mathbf{u}_n + \frac{1}{3} \nabla (\nabla \cdot \mathbf{u}_n) \right)$$

Momentum Equation for the superfluid component

$$\frac{\partial \mathbf{u}_s}{\partial t} + (\mathbf{u}_s \cdot \nabla) \mathbf{u} = -\frac{1}{\rho} \nabla P + s \nabla T + \frac{\rho_n}{2\rho} \nabla \left| \mathbf{u}_n - \mathbf{u}_s \right|^2 + \underline{\underline{A \rho_n \left| \mathbf{u}_n - \mathbf{u}_s \right|^2 (\mathbf{u}_n - \mathbf{u}_s)^2}}$$

Energy Equation

Turbulent model of ST

$$\frac{\partial (\rho s)}{\partial t} + \nabla \cdot (\rho s \mathbf{u}_n) = \frac{A \rho_n \rho_s \left| \mathbf{u}_n - \mathbf{u}_s \right|^2}{T}$$

Development of He II heat transfer code

- Direct DNS of the full system of equations approach
  - To perform this, treatment of total fluid momentum equation especially pressure term is important
  - Momentum equation for total fluid component = Kim Moin Method

Momentum equation for total fluid	
Convection term	2nd order Adams-Bashforce Method
Viscosity term	Crank-Nicolson Scheme
Pressure term	1st order implicit scheme

  - Reduction of numerical viscosity (artificial viscosity) to obtain precise flow field
    - Compact Difference Scheme base on Pade expansion is employed

  - Under development (more details @ takahiro.okamura@kek.jp)

Development of He II heat transfer code

- Implementation of a *simplified* model in ANSYS CFX
    - The momentum equations for the superfluid component are simplified to the form

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

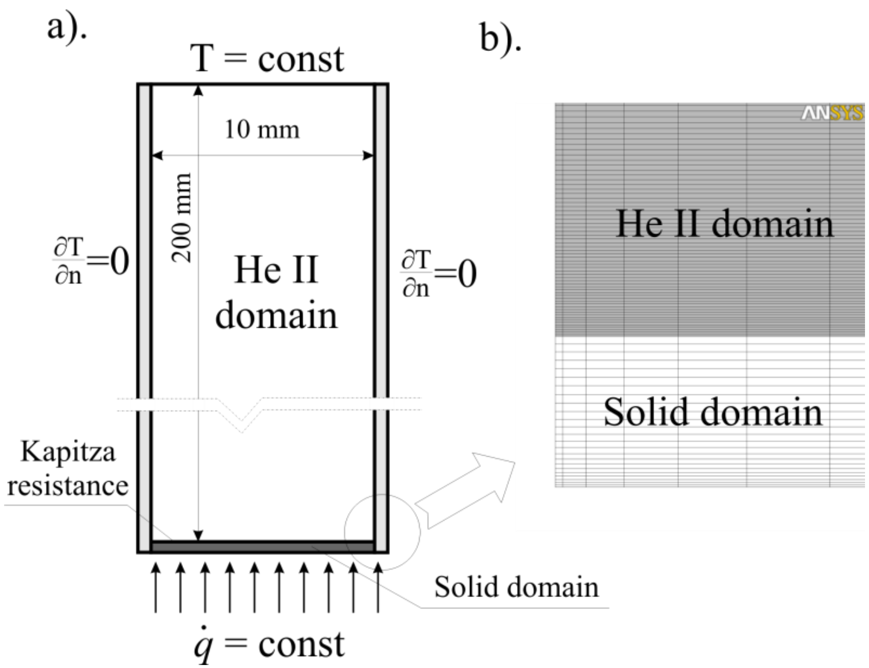
The thermo-mechanical effect term and the Gorter-Mellink mutual friction term are larger than the other

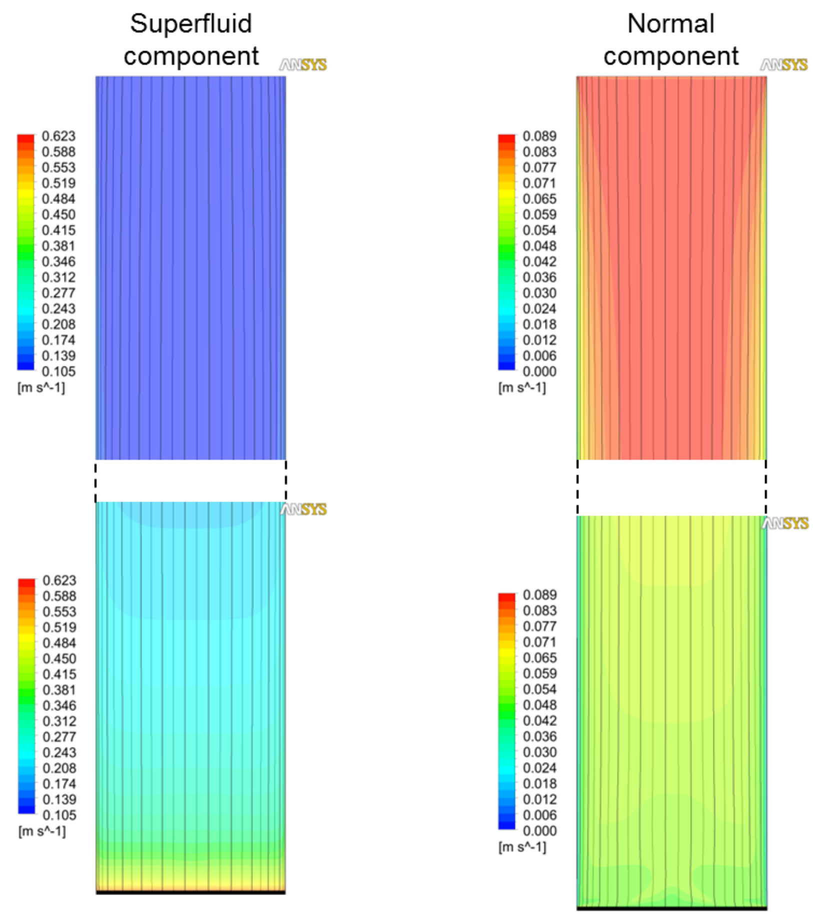
- Superfluid component: $u_s = u - \frac{\rho_n}{\rho}(u_n - u_s) = u + \left(\frac{\rho_n^3 s}{A\,\rho^3 \rho_n |\nabla T|^2}\right)^{1/3} \nabla T$
- Normal component: $u_n = u + \frac{\rho_s}{\rho}(u_n - u_s) = u - \left(\frac{\rho_s^3 s}{A\,\rho^3 \rho_n |\nabla T|^2}\right)^{1/3} \nabla T$

- Two-fluid model reduce into one fluid model

Development of He II heat transfer code

- Implementation of a *simplified* model in ANSYS CFX
  - Validation of the model

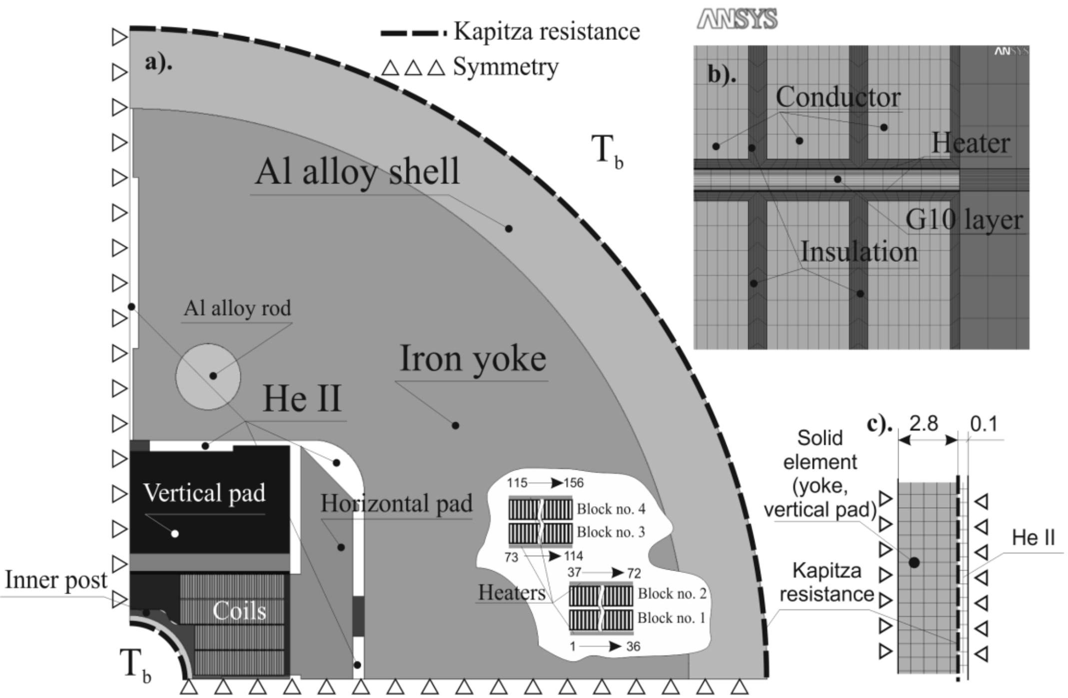


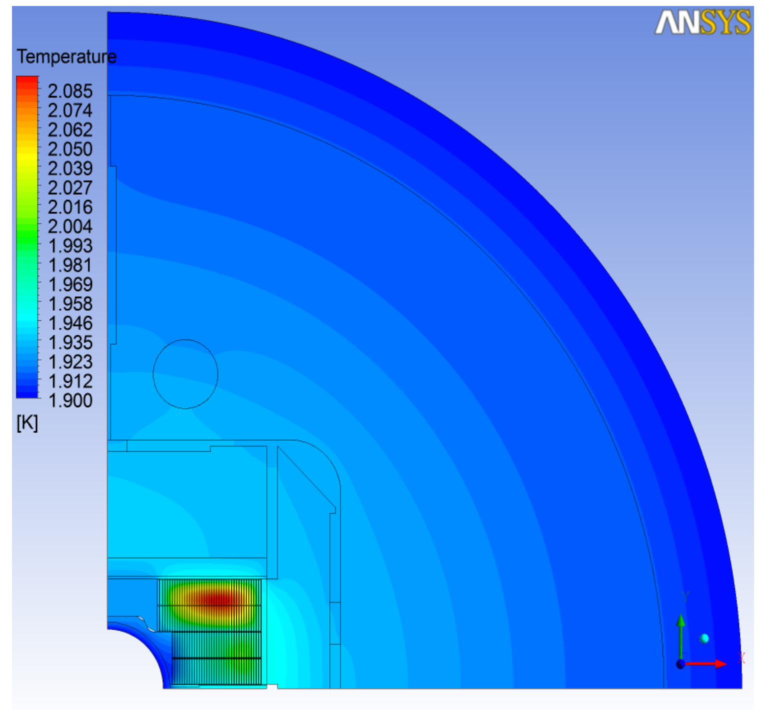


Applied heat flux	Maximum temperature		Error
	Analytical	Numerical	
W/m²	K	K	%
20877	2,1500	2,1371	0,602
13918	1,9823	1,9823	0,002
6959	1,9540	1,9540	0,000

Development of He II heat transfer code

- Implementation of a *simplified* model in ANSYS CFX
  - Calculation for the Fresca 2 magnet (Eucard HFM)





Future work

- Construction and tests of a stack experiment with Cyanate Ester insulation in He II (Saclay) and He I and HeS (KEK)
  - Irradiation using JAEA/Takasaki facility

- Measurement of the thermal conductivity (2 K – 77 K) (KEK)
  - Ceramic insulation
  - Cyanate Ester resin

- Measurement of the thermal conductivity and Kapitza resistance (2 K) (Saclay)
  - Cyanate Ester resin irradiated (50 MGy)

- Development of the DNS code