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Cryogenics, a science for magnets

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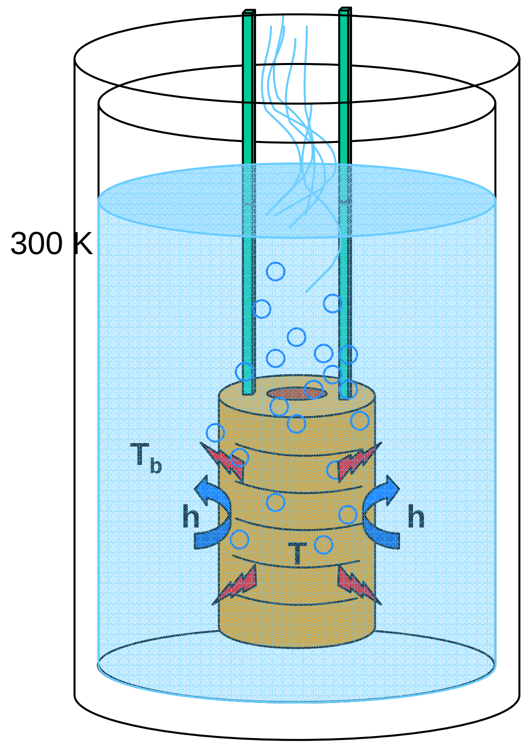
Superconducting Magnet thematic day, CEA Dapnia, July 3rd 2006

Outline

- Superconducting magnet cooling
  - Heat transfer in superconducting magnet
  - Magnet types and Cooling methods
- State of the art
  - Accelerator magnets
  - Detector magnets
  - Magnets for the other scientific communities
- Propositions
  - Design limits and future needs
  - Cryogenics R&D at Dapnia
  - Propositions of R&D actions

Heat transfer in SC magnets (1/2)

- To insure stability ($T_{magnet}<T_{critical}$) and protection (T_{max}) of the magnet
  - Against permanent thermal losses (Q_p)
    - Thermal radiation (300 K to T_{magnet})
    - Conduction through current leads, structural elements and support
    - Internal volume dissipation such as "Beam losses" and "AC losses"
  - Against transient perturbations (Q_t)
    - Local Super/Norm transition
    - Magnet Quench
  - With cooling power (Q_R)
    - Q_R=h.(T-Tb).p/A with cryogenic fluids
    - Q_R=Cryocooler power
  - Thermodynamic properties of magnet components
    - Heat capacity C, Thermal conductivity k
  - Cooling power (Q_R)
    - Thermodynamic properties of cryogen
    - Cryocooler performance



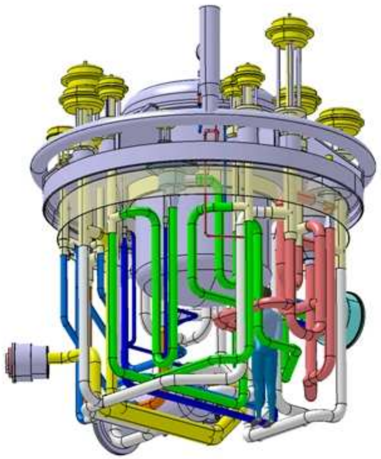
$$C\frac{\partial T}{\partial t}=\nabla.\left(k\vec{\nabla}T\right)+Q_p+Q_t-Q_R$$

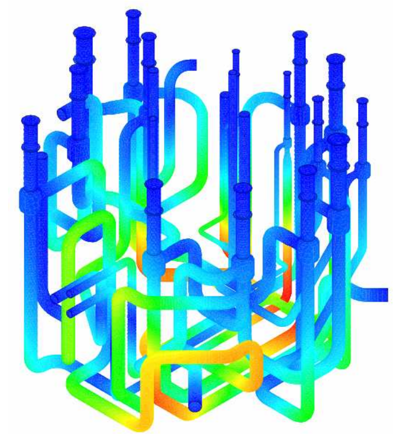
Heat transfer in SC magnets (2/2)

- In operation with fixed H(T) and J(A/m²)
  - Superconductor used impose T_b, C et k
  - Thermal losses : Q_p et Q_t (W)
  - Design impose geometry : A (m²), wetted perimeter, p (m)
  - **Only one free parameter for cryogenics engineer : h** pour $T<T_c$

- h, surface heat transfer coefficient depend on
  - Cryogen, Cooling methods (flow, static, boiling), magnet geometry (confinement), material components of the magnet

- Cryogenics for magnet design is also
  - Vacuum technology, Fluids Cryo-distribution and cryoplant
  - **Team work** with magnet designers, mechanical engineer, vacuum engineer…

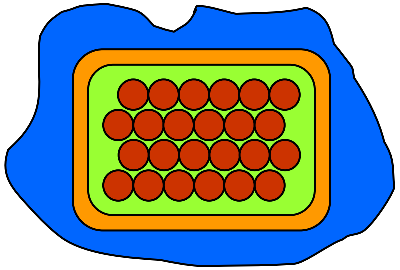


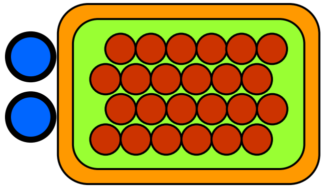


Maximum horizontal displacements (red parts):5.7 mm
SIS for ITER

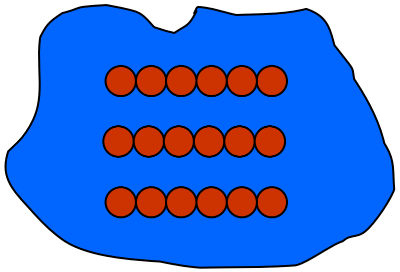
Magnet Types / Cooling method

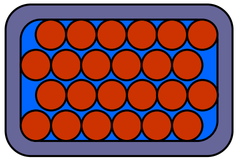
- "Dry magnet" : No contact between the cryogen and the conductor
  - Conduction in the magnet : bath or Cryocooler
  - External flow of cryogen to the coil (CMS, ATLAS, …)

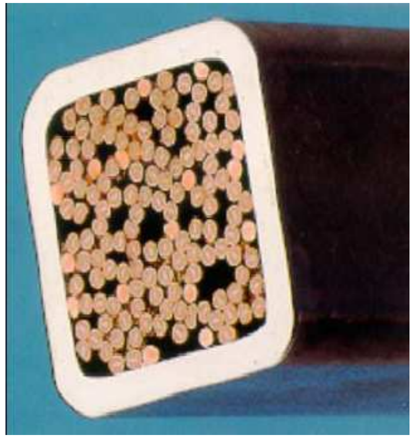




- "Wet magnet" : Contact between the cryogen and the conductor
  - Bath : single phase stagnant He II (Tore Supra, ISEULT, LHC, 45 T NHMFL,…)
  - Flow : single phase in CICC (W7X, ITER, …)







- "Cryostable" or "adiabatic" magnets
  - "Cryostable" $Q_R > Q_p + Q_t$ (Iseult, Tore Supra, …)
  - "Adiabatic" (CMS, …)

Cooling method : The Baths

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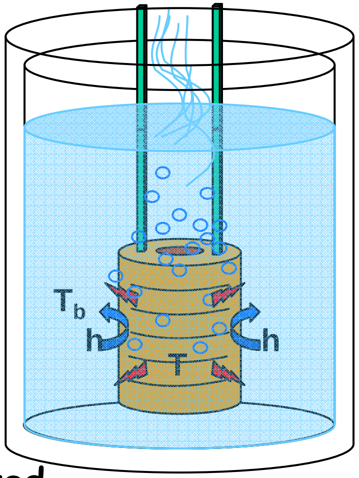
- Saturated bath (P=1 Atm et Tsat)
  - Implementation
    - **Simple design and operation** for cryogenics
    - Latent heat cooling (phase change); (He 4.2 K, N_2 77.3 K et H_2 20.4 K)
    - Non uniform cooling due to **vapor formation**, dry out
  - Heat transfer in nucleate boiling : $q_{max} \approx 10^4$ W/m² for $\Delta T \approx 1$ K
  - Large scale magnet or compact system (He ~1 W/m)



- Pressurized He II (1.9 K at P=1 Atm)
  - Implementation
    - Design and operation of cryogenics **costly and more complicated**
    - Heat exchanger He II sat / He II p
    - Design for the heat paths between cable and the HX
  - Large Heat transfer : **$k \approx 10^5$ W/m.K** for $\Delta T \approx 0.3$ K and $\mu \approx 3\ 10^{-6}$ Pa.s)
    - Thermal (Kapitza) resistance between solid and He II
      - R_k=3 10^{-4} K.m²/W for Cu and R_k= 10^{-3} K.m²/W for Kapton
  - LHC ~1 W/m, Concept extendable to 50 W/m with proper heat path (channels and insulation)

Cooling method : Convection flow

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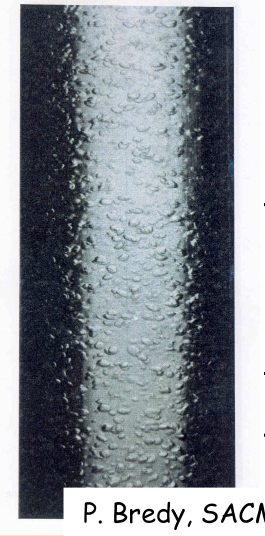
- Single phase forced convection
  - Implementation
    - **Pressurization system** and **periodic recooling** for operation (series of large magnets)
    - **Simple design** with traditional heat transfer and pressure drop correlations
  - Heat transfer (sensible heat with temperature increase)
    - Supercritical He (~0.1 kg/s and ~1-10 W/m) P≈3-8 bar, T≈4.4 K, ΔT≈50-150 mK per magnet
    - He II (~1 W/m) Advection effect for 1m/s for ΔT=0.1 K @ 1.8 K, Negative JT coefficient

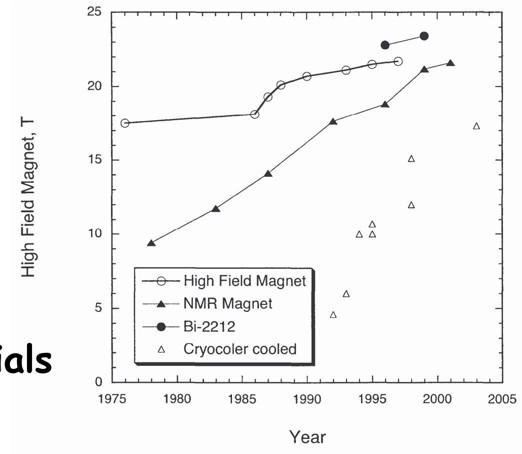
- Two-phase forced or natural convection
  - Implementation
    - Same advantages and inconvenient than bath cooling but **lower quantity of cryogen**
    - Operation needs pressurization system in forced flow and none in natural convection
  - Heat transfer due to nucleate boiling but degradation at high mass flow
    - Two-phase forced He flow $q_{max} \approx 10^4$ Wm^{-2} for Ø10 mm m=6 gs^{-1} and $\Delta T \approx 1$ K
    - Two-phase natural helium flow $q_{max} \approx 10^3$ Wm^{-2} for Ø10 mm m=20 gs^{-1} and $\Delta T \approx 0.3$ K
  - Forced convection : ATLAS (helium)
  - Natural convection : CMS (helium), HTS Synchronous Machine (Nitrogen)



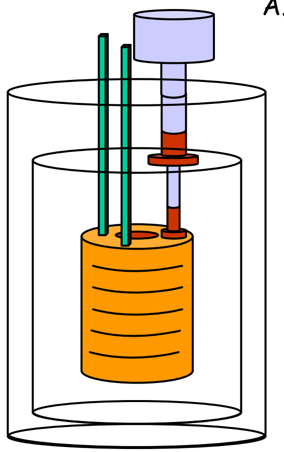
P. Bredy, SACM

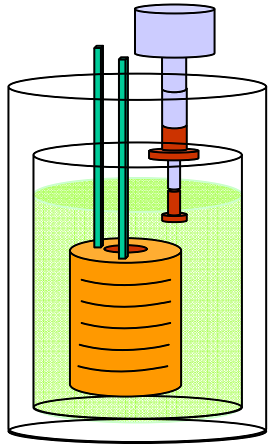
Cooling method : Conduction

- Cryocooler
  - Implementation
    - **Simple** design and operation
    - Small LTS magnet or HTS magnet
    - **Low thermal conductivity and diffusivity of materials**
  - Performance
    - Commercial : 1.5 W at 4 K but **fast improvements**
    - R&D : 1 W at 1.8 K
  - Heat Transfer
    - Conduction through magnet or cryogen
  - Examples
    - 10T magnet class commercialized since 1990
    - 18T NbTi and Nb_3Sn magnet (MIMS, Toshiba et TIT)
      - Cooled by CR de 1 W at 1.8 K
    - Magnet cooled with solid cryogen
      - HTS…

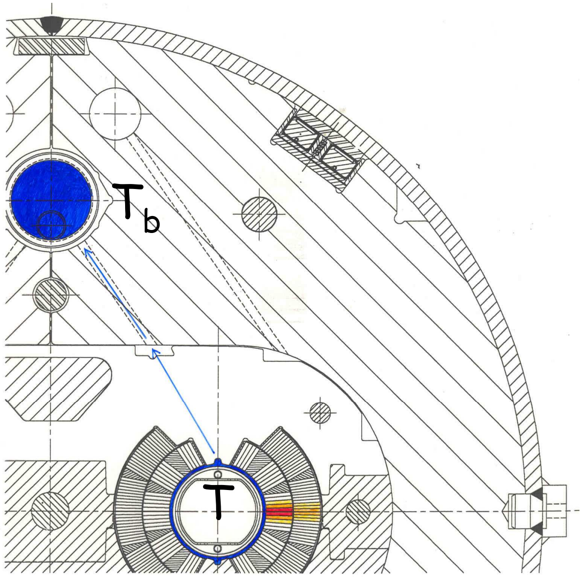


A. Sato, MiMS





Accelerator magnets



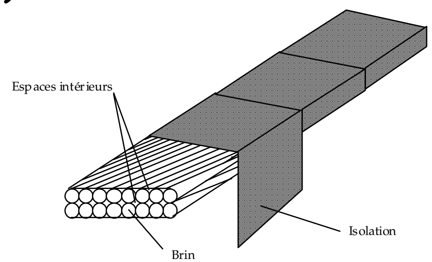
- "Wet" magnets with "heat exchanger"
  - Large internal losses and smaller stored energy
  - Cooling Source : Internal tube flow
  - Single phase coolant in contact with conductor

- Heat transfer between the conductor and the cooling source determines the temperature margin, $\Delta T = T_b - T$

- **Electrical insulation constitutes the largest thermal barrier**

- Heat transfer R&D on the LHC insulation (90's) (Dapnia (C. Meuris) and KEK)
  - Permeability increase in the insulation to create heat paths
  - Creation of space between the insulations and the conductors
  - Removal of epoxy resin impregnation ("dry" magnet)

- **Little work on the materials**
  - Conductive doping, holes or porosity



Accelerator magnets : LHC

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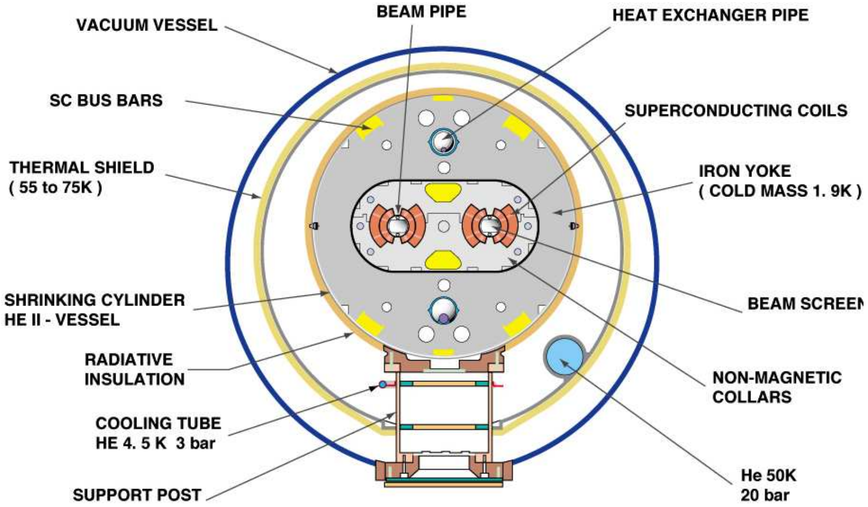
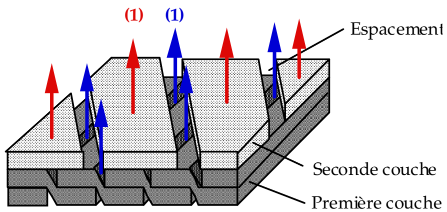
- He II cooling
  - Two-phase He II for the exchanger
  - Stagnant He II for the magnet
- "Beam losses" in LHC
  - 10 mW/cm^3 or 0.4 W/m (cable)
  - **ΔT<0.3 K with permeable insulation**
  - ΔT~4 K with monolithic insulation

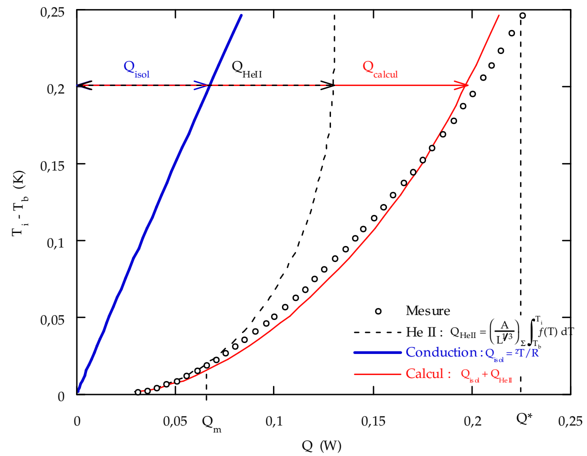


- Electrical Insulation is
  - Historically: double wrapping
    - Polyimide with 50% overlap
    - Fiberglass + epoxy resin with spacing

  - LHC Insulation : triple polyimide wrapping
    - First 2 wrappings without overlap
    - 3rd wrapping with spacing

- A thermal Insulation
  - Kapton/ Kapton : 120 µm thick
  - Ø~10 µm, channel length of ~mm
  - **He II + Conduction**



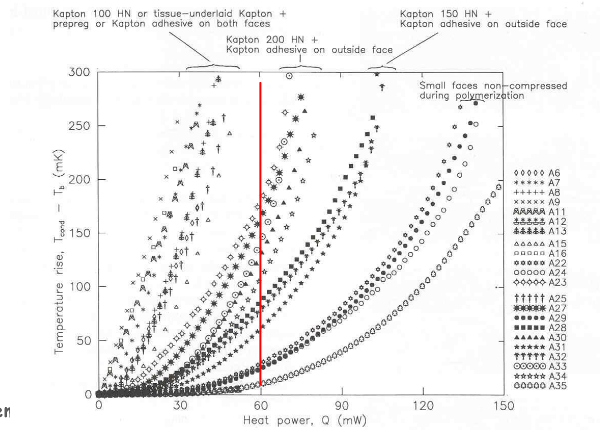


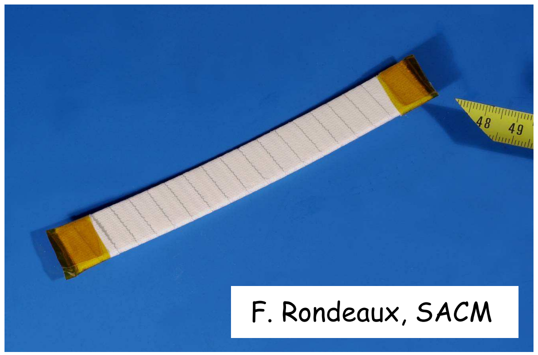
Accelerator magnets : Beyond LHC

- "Beam losses" of LHC upgrade with Nb_3Sn Magnets
  - 50 to 80 mW/cm^3 or 2 to 3 W/m (cable) → ΔT?

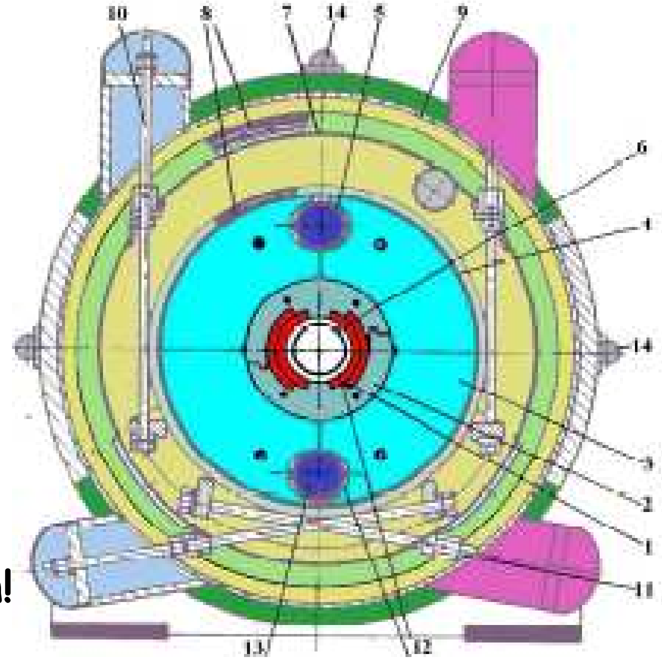
- **Innovative ceramic insulation (under development)**
  - Thermal treatment (insulation+Nb_3Sn, easier and less costly construction)
  - Fiberglass + ceramic precursor (CEA patent)
  - Heat transfer considerations
    - Higher heat transfer rate, larger He Volume in the insulation (Cp) and heat exchange surface increase (matrix participation)

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





Pulsed magnets at GSI



- Cooling
  - He two phase flow at 4.2 K & 1 bar
  - Supercritical helium flow
    - 4,4 K at 3 bar and 5 g/s
- "AC losses"
  - SIS 300 (UNK) 1 T/s → 0.6 W/m
  - ΔT ~ 2 K with impermeable insulation
  - **ΔT ~ 200 mK with permeable insulation!**
- Insulation **with Holes**?
  - 2 layers of Polyimide 25 µm with adhesive (50 % overlap)
  - **26% of the surface in contact with He**
- **R&D to be done on insulation heat transfer**
  - Tests at SACM in 2007
  - In supercritical, static He (3 bars)

M. Wilson, GSI

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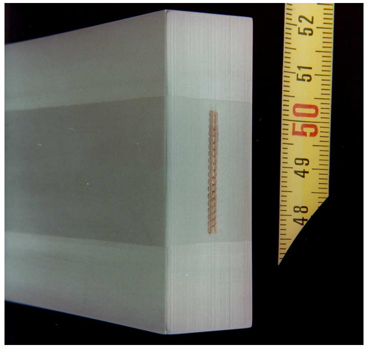
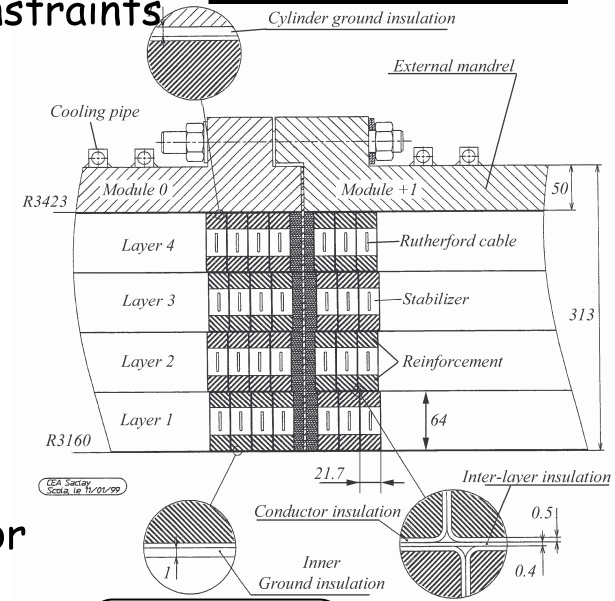
Detector Magnets

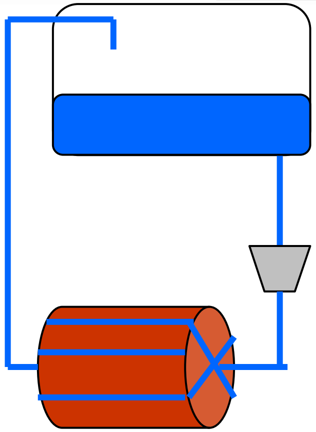
- Large scale magnet
  - Larger stored energy and smaller thermal losses
  - Large thermal stabilizer Cross-sectional needed
  - T_{max} and ∇T to minimize the mechanical constraints





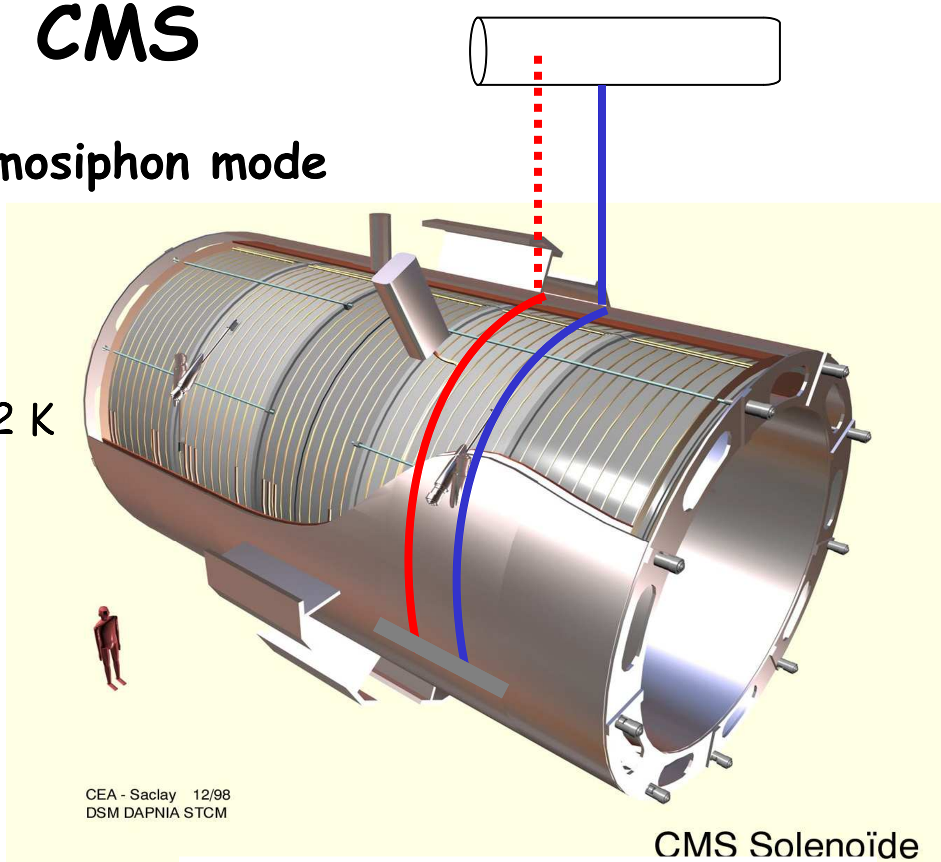
- Dry" magnet
  - Reduced quantity of cryogen
  - High purity aluminum stabilized conductor
  - Fully impregnated coil with epoxy resin

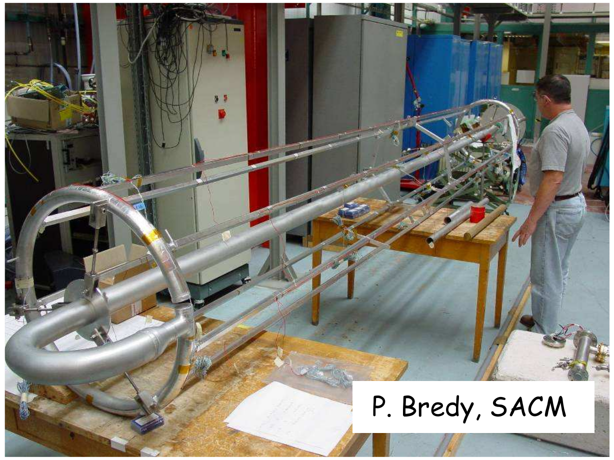
- Heat transfer
  - Cold source : He reservoir / phase separator
  - Two-phase flow of He I in external tubes
    - Forced flow or natural two-phase flow



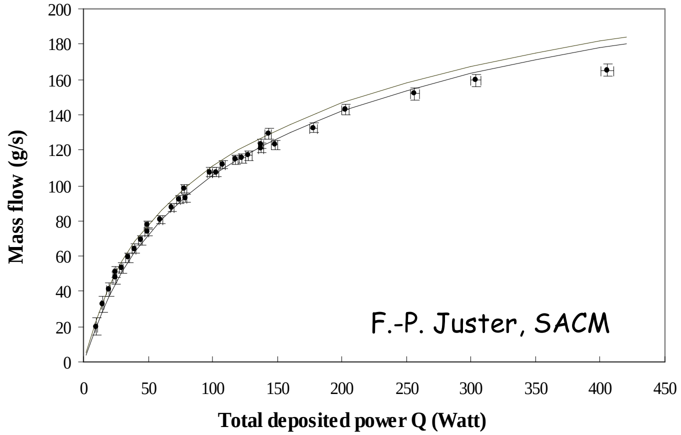
Detector Magnets : CMS

- Two-phase convection in **thermosiphon mode**
  - Solenoid with "vertical parts"
- Heat transfer
  - 4.5 K at 1.25 bars
  - Tests at CERN ΔT=0.1 K et 0.2 K



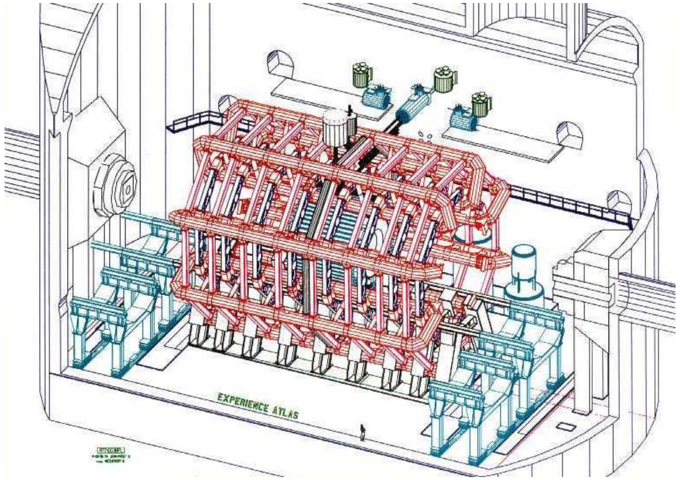


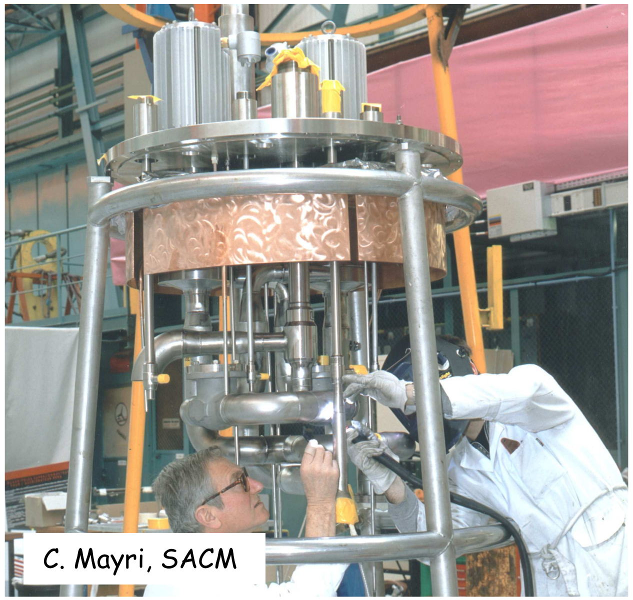
- R&D done on "Thermosiphon" flow
  - Validation Homogeneous model
  - "Large scale" experimental validation



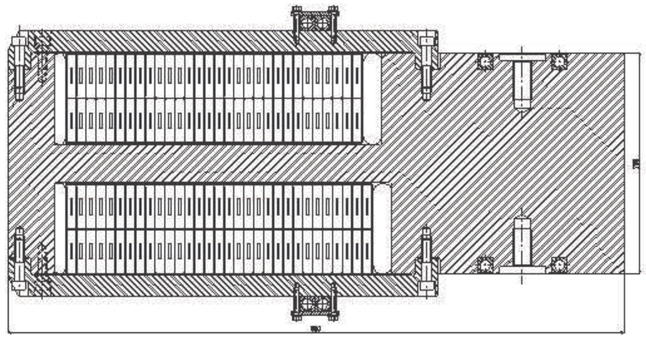
Detector Magnets : ATLAS

- Helium two-phase **forced convection**
  - Toroid with long horizontal parts
- Heat transfer
  - 4.5 K at 1.5 bars
  - $\Delta T=0.15$ K et $\Delta p=0.2$ bars



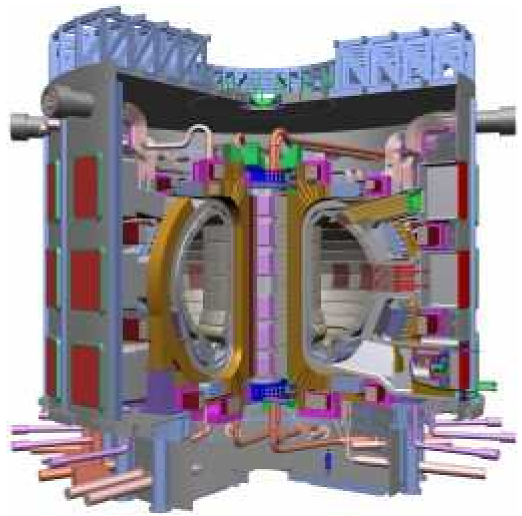


C. Mayri, SACM



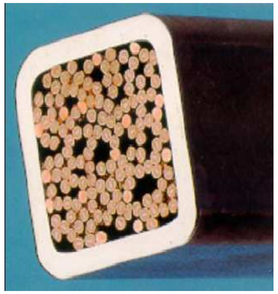
- R&D done at Saclay on circulator
  - 0.1 kg/s$\rightarrow$1.2 kg/s
  - Tests of 0.6 kg/s circulators

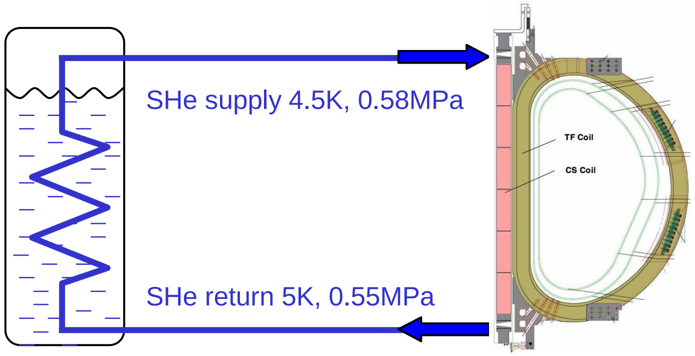
Magnets for fusion

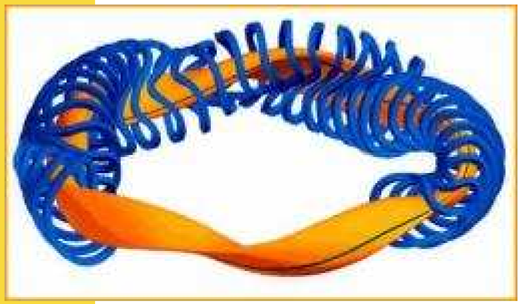


- **Large losses** due to plasma and radiation
- **Direct cooling** with Cable in conduit conductor

- ITER
  - Enormous, known and tested technology
  - Supercritical helium flow at 4.5 K and 6 bars



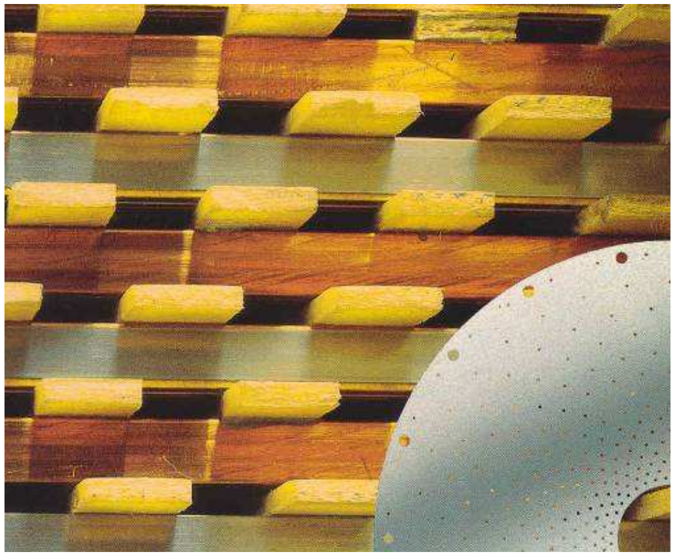


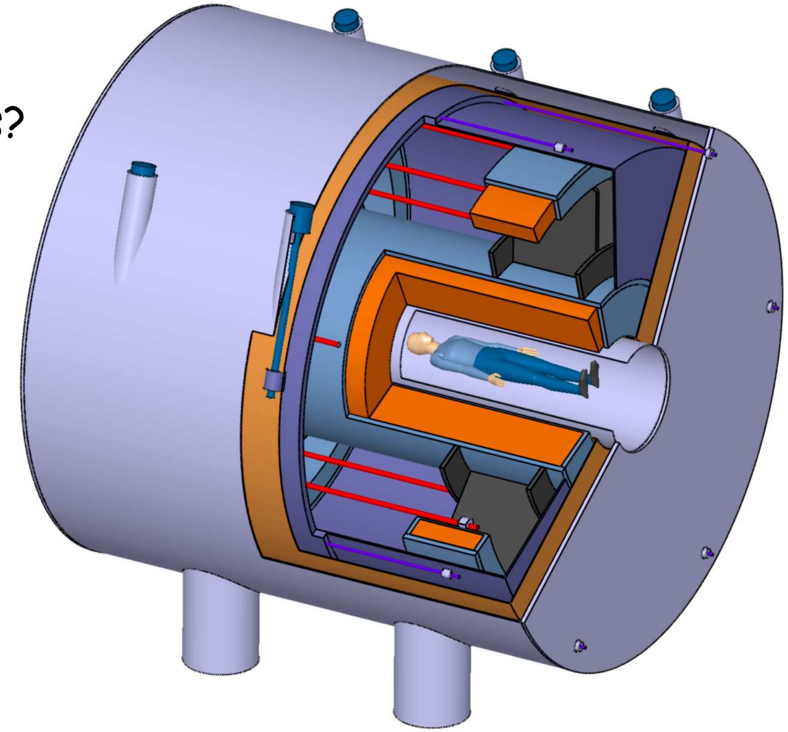


- W7X
  - Supercritical helium at 3.8 K and 6 bars max
  - Experimental testing facility at Saclay
    - 4.5 K to 7.6 K, p=6 to 10 bars and I≈18 kA
  - **Largest experimental data base on CICC cooled magnet in operation at Saclay**

Magnet for life science

- “Wet” and “cryostable” magnet
  - Cold source : He II static helium
  - Large He II bath (volume ~ 1000 l)
  - No perturbation of the medical environment!
- Heat transfer
  - T=1.8 K at 1.25 bars
  - Insulator/separator of conductors creates channels
  - Channel heat transfer know in He II
- Transient heat transfer and hydraulics?





Design limits and future needs

- "Wet" magnets cooled with single phase submitted to phase change
  - Iseullt ou LHC
  - Pressure rise due to magnet quench

  Development of experimental and theoretical thermo hydraulics models

- Next generation of accelerator magnets

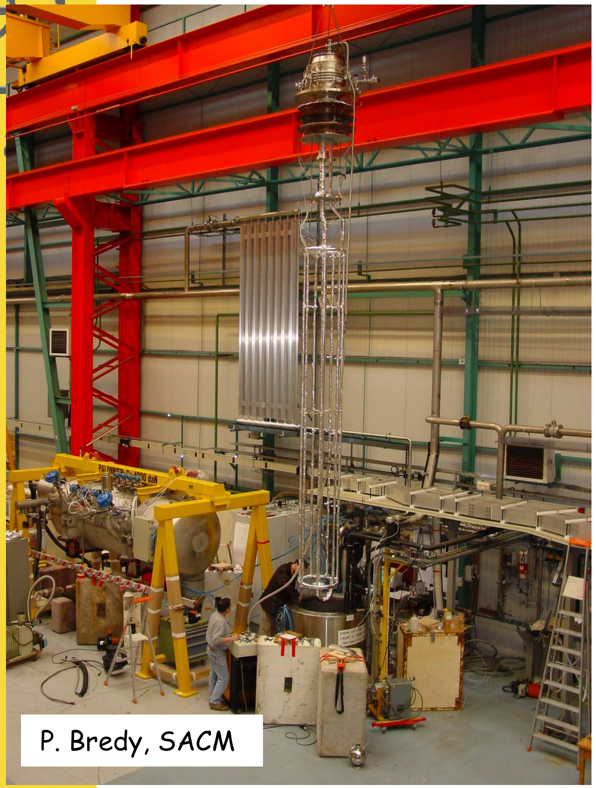
  Improvement of heat transfer in the magnet (Insulation et design)

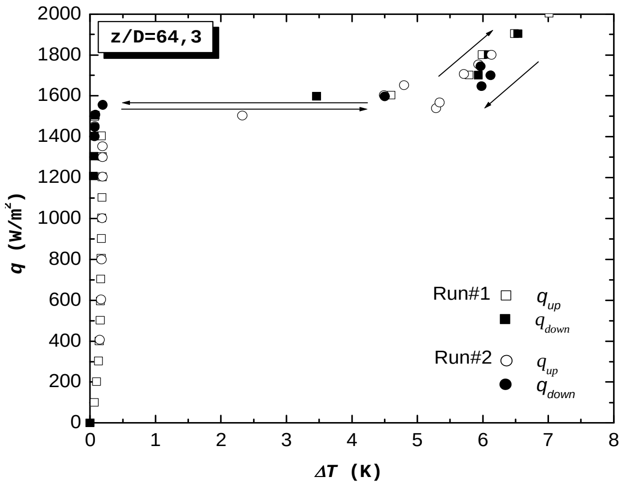
- HTS magnets / Single unit magnet
  - Cryocooler and fluid coupling

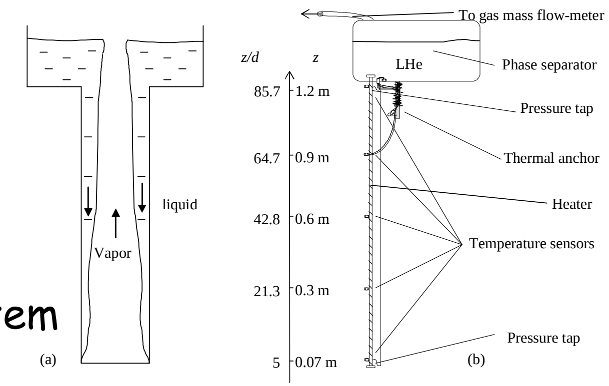
  Autonomous cooling device : cryocooler + fluid

Cryogenics R&D at Dapnia (1/3)

- Fluid dynamics and heat transfer in a He two-phase thermosiphon (CMS)
  - 1 m Experimental loop (Fundamental flow properties, models, 1 PhD)
  - 9 m Experimental loop (Large scale)



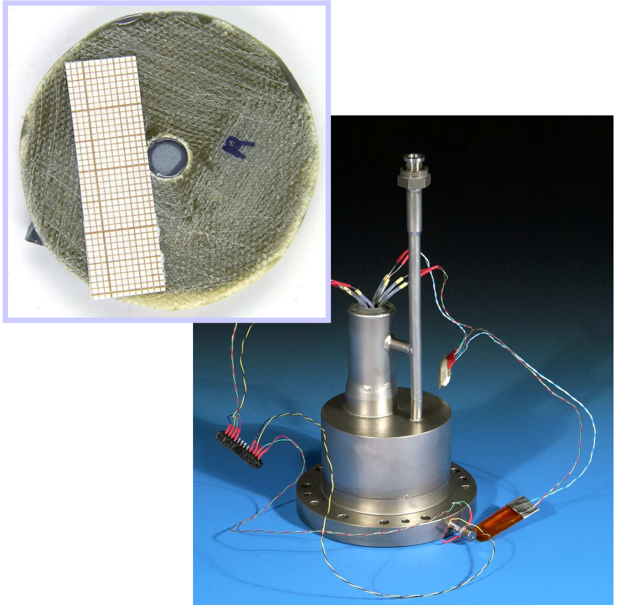




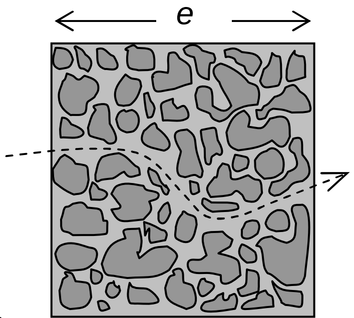
- Helium "Heat pipe" development
  - Internal R&D interne for autonomous system
    - Cryocooler + fluids

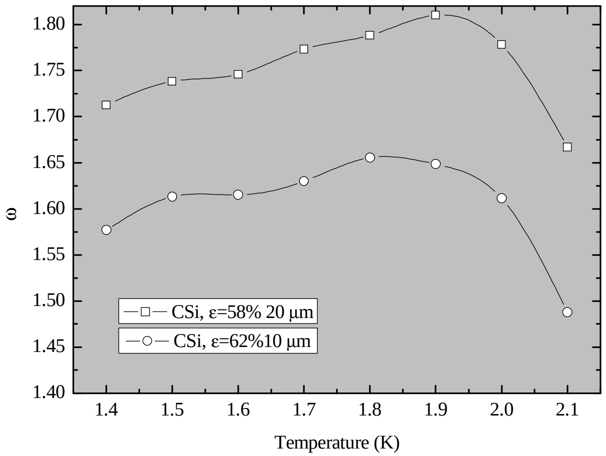
Cryogenics R&D at Dapnia (2/3)

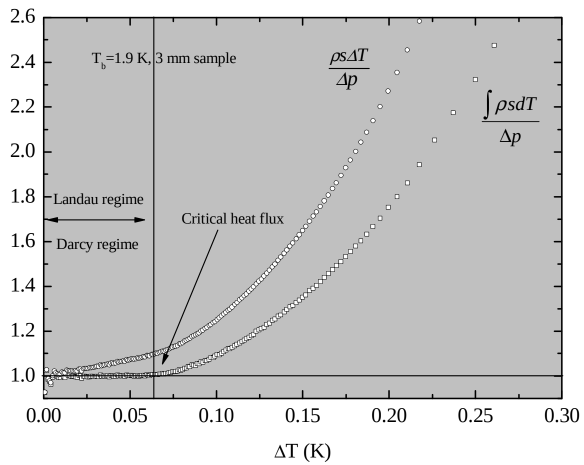
- He II Heat transfer in porous media
  - Tests on porous "scaled" sample



- Fundamentals on transport properties
  - Permeability K(T)
  - Tortuosity ω



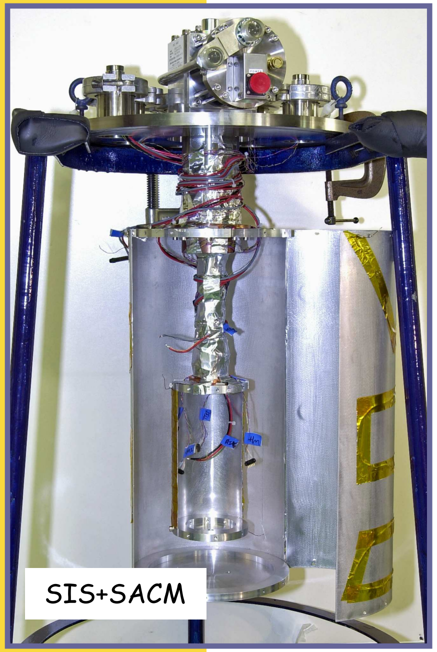


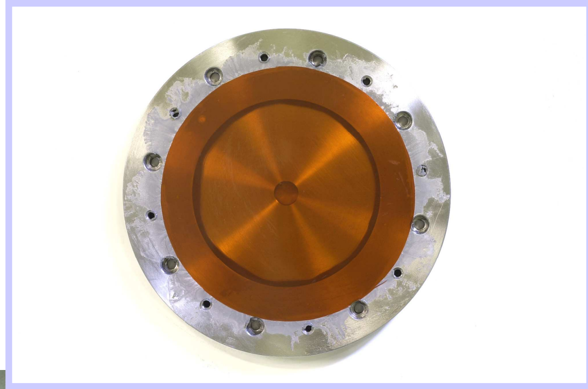


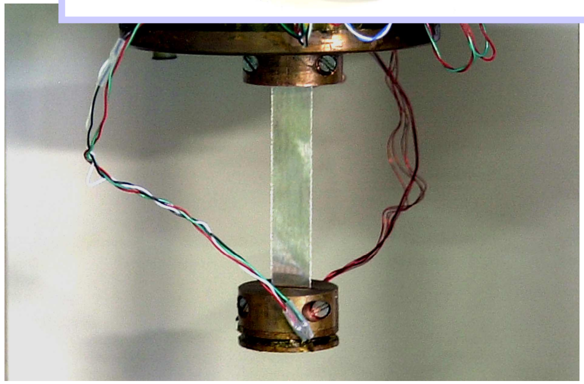
$$\Delta p = \left[\int \rho s \vec{\nabla} T \right] \neq \rho s \Delta T$$

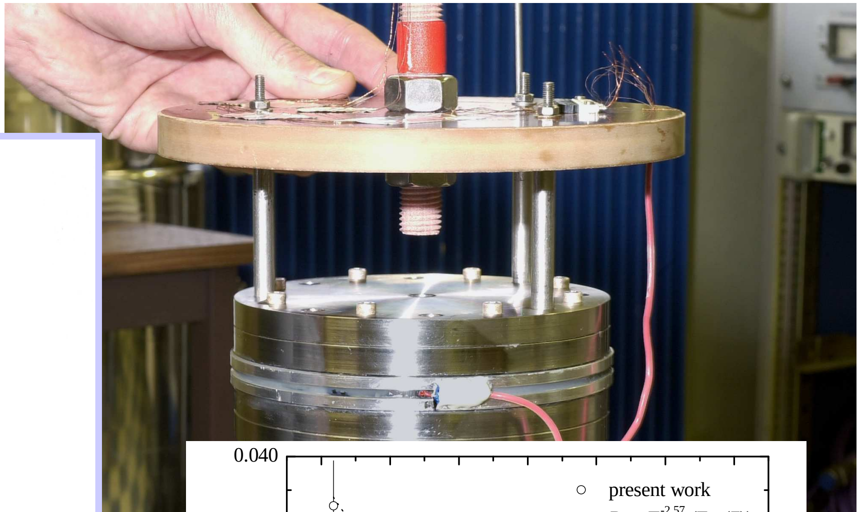
Cryogenics R&D at Dapnia (3/3)

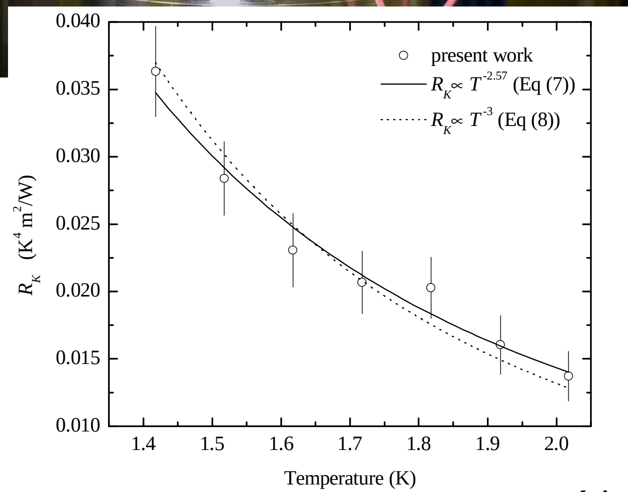
- Thermal properties of materials
  - Kapitza resistance and thermal conductivity in He II
    - Kapton, Mylar, Apical, …
- Thermal conductivity and diffusivity (4 K à 300 K)
  - Insulators and conductors





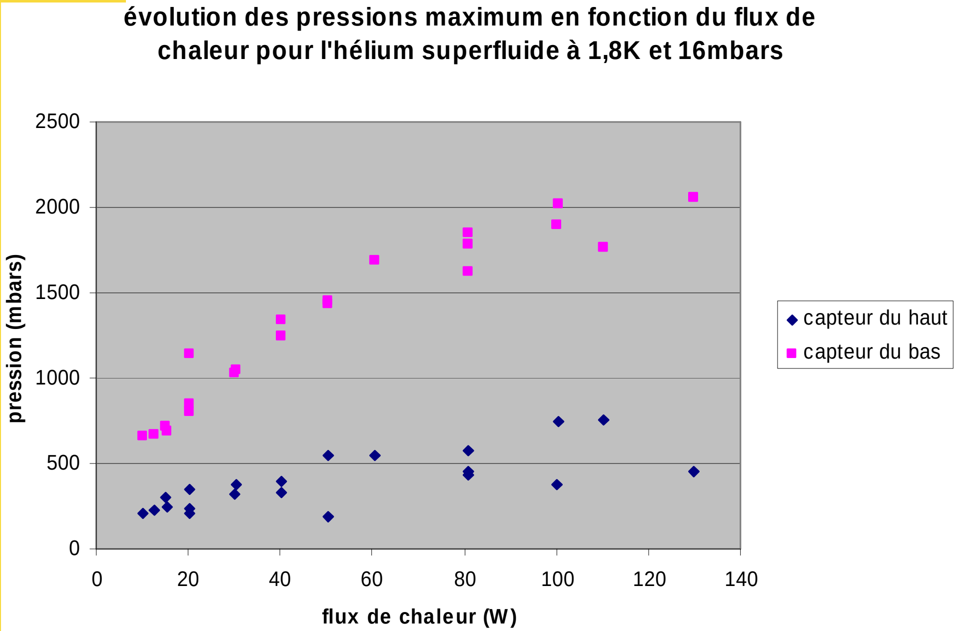


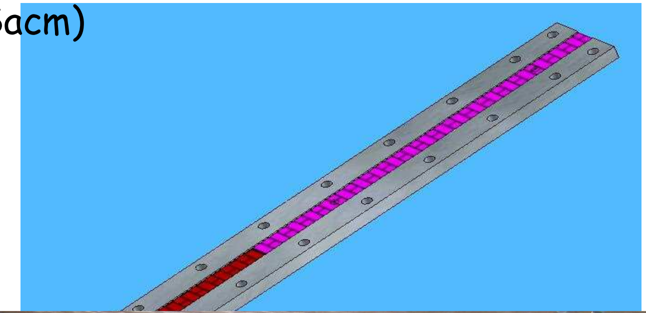


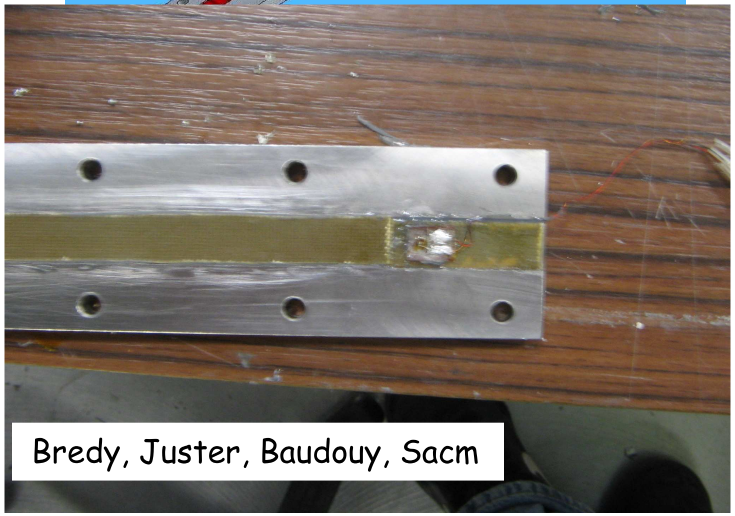


R&D propositions (1/3)

- Pressure rise in magnets due to quench (transient thermo-hydraulics)
  - In the frame work of Iseult and SEHT
    - First experimental rig and first results on channel pressure rise in He II
    - Analytical work in progress (C. Meuris, Sacm)





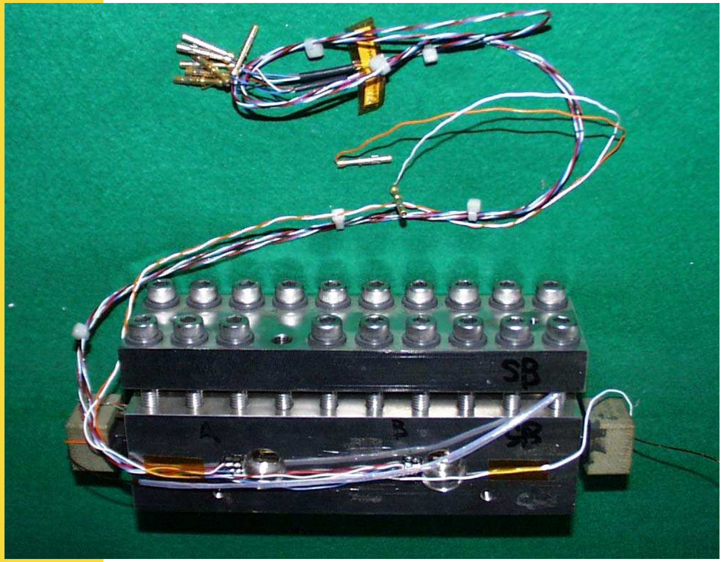


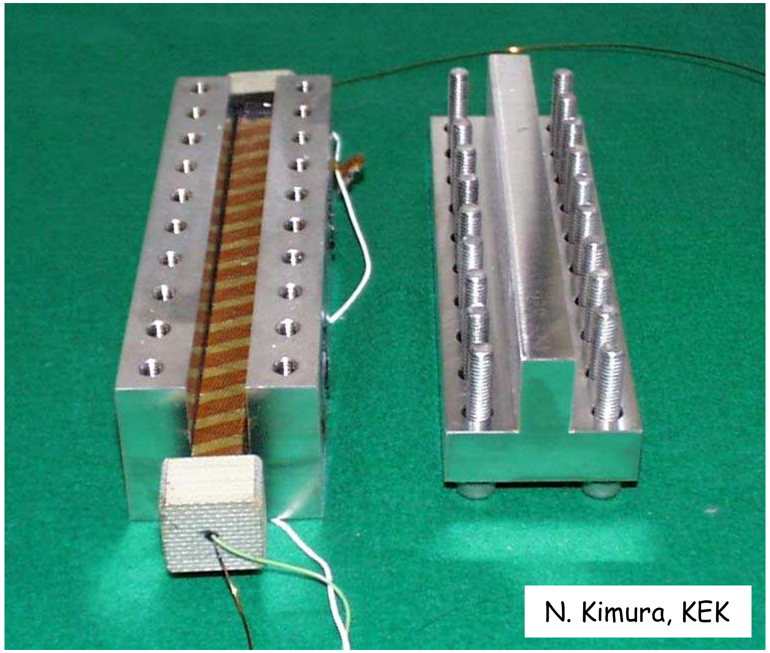
Bredy, Juster, Baudouy, Sacm

To be continued… and generalized to accelerator magnet

R&D propositions (2/3)

- He II heat transfer through innovative insulation
  - Experimental and theoretical work on "scaled" porous media
    - NIFS, IMFT
  - Experimental work and modeling on stack of conductors (coil) (NED)
    - KEK, CERN, WTU





N. Kimura, KEK

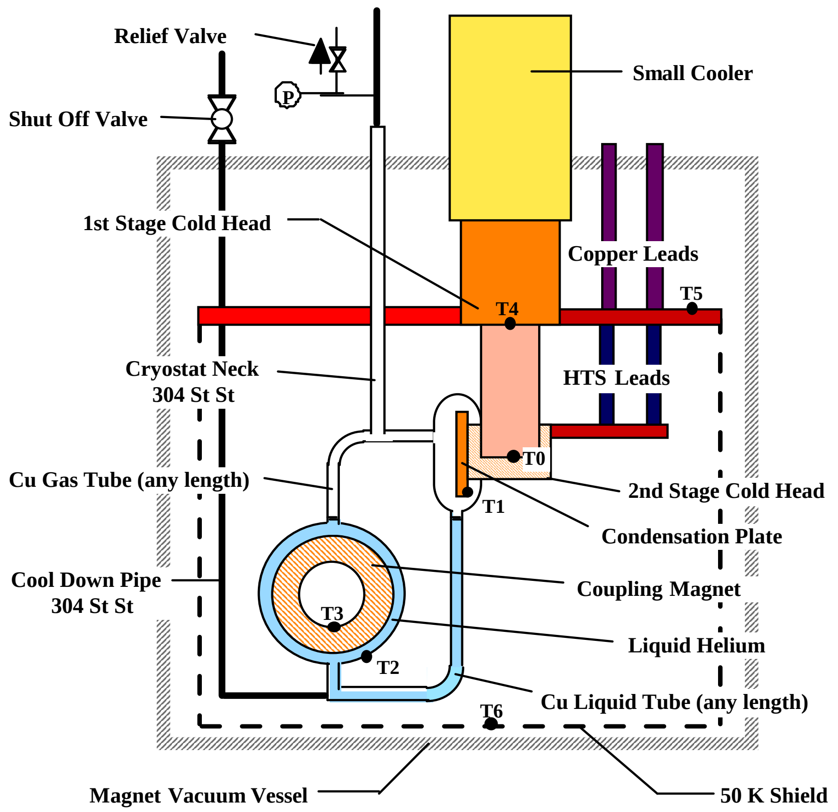
- **To be continued in the framework of NED or any another…**

dapnia

saclay

R&D propositions (3/3)

- Autonomous loop with cryocooler and fluids
  - For small magnet, Targets and magnet for other scientific communities



Mice

- **To be started… to be in the train…**