Review of heat transfer mechanisms in superconducting magnets

Bertrand Baudouy
CEA Saclay
DSM/Dapnia/SACM/LCSE
Outline

- Different heat transfer modes to cool magnets
  - Introduction
  - Pool boiling, Static He II, Forced flow single phase, Forced flow two-phase
  - Comparison

- Heat transfer in the electrical insulation and coil: Rutherford Cable type
  - Phenomenology
  - Past Results
  - Some ideas

- Current and Possible R&D programs (NED)
  - The method
  - The experimental apparatus
  - The Tests
Introduction – Temperature margin

- 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
    - $T_{\text{conductor}} = 1.9 \text{ K}$ or $T_{\text{conductor}} \sim 4 \text{ K}$
    - [Burnod 1994]

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

- Cooling mode and thermodynamical state
  - Working temperature and stability margin (superconducting properties), Refrigeration power, Mechanical constraint (space), Size and cost

- Immersion in a stagnant liquid
  - Saturated and sub-cooled He I, Saturated or pressurized He II

- Forced flow cooling (internal or external to the cable)
  - Sub-cooled Helium, Supercritical, Superfluid, two-phase

- Two types of magnet for heat transfer point of view
  - “Dry coil” magnet: Helium in contact with the insulation or structure only
    - Conduction (cable + insulation + structure) and surface heat transfer
  - “Wet coil” magnet: Helium in contact with the insulation and the cable
    - Helium Heat transfer and conduction (cables + insulation) and Surface heat transfer

- With heat exchanger or not

- Best solution for thermal stability: helium in contact with the cable?
  - Enthalpy reserve in the cable, better heat transfer coefficient
  - Quench issue: $\Delta p$ within the insulation?
Pool boiling @ Atm pressure

- **Characteristics**
  - High heat transfer coefficient in nucleate boiling
  - Easy design
  - Heat transfer by natural convection and easily influenced by gas
  - Major (dis)advantage is $T=4.2$ K
  - Non uniform cooling due to vapor formation

- **Heat transfer**
  - 3 Regimes: Natural convection, Nucleate boiling, Film boiling
  - Highest heat transfer in nucleate boiling, no film of gas on surface
  - $q_{\text{max}} \approx 10^4$ W/m$^2$ for $\Delta T \approx 1$ K

- **Solutions to enhance heat transfer rates and thermal stability**
  - Natural convection Channels or thermosiphon to eliminate stagnant vapor zone and enhancement of heat transfer [Jones 1978]

- Typical heat loads 1 W/m and magnet length of 20 m [Van Weelder 2004]
Saturated He I forced flow

- Characteristics
  - Isothermal fluid over the cooling circuit (4.2 K)
  - High heat transfer coefficient
  - Save space and weight compared to pool boiling
  - Smaller helium content in the system
  - Two-phase flow but \( \frac{\rho_l}{\rho_v} \approx 7 \) at 4.2 K

- Heat transfer
  - Good heat transfer up to \( x=98 \% \) [Mahé 1991] et [Neuvéglise 1995]
  - \( q_{\text{max}} \approx 10^4 \text{ Wm}^{-2} \) for a SS tube of \( \Omega 10 \text{ mm} \) \( m=610^{-3} \text{ kg}^{-1}\text{s} \) and \( \Delta T \approx 1 \text{ K} \) [Mahé 1991] (titre initial de 0).
Static pressurized He II

- Characteristics
  - Lower operating T (higher performance of superconductor)
  - Improved local heat transfer
  - High heat conductivity (reduced vapor generation)
  - Bath cooled magnet and also CICC (45T Magnet @ NHMFL)
  - Double bath technique or with HX

- Heat transfer
  - $k \approx 10^5 \text{ W/m.K}$ for $\Delta T \approx 0.3 \text{ K}$, over it is He I ($k \approx 0.02 \text{ W/m.K}$)
  - Dimension of cooling channel between cable and HX
  - $q_{\text{max}} \approx 10 \text{ kW/m}^2$ for $L = 1 \text{ m}$ and $\Delta T \approx 0.35 \text{ K}$ ($15 \text{ kW/m}^2$ for He II sat)
  - Interface thermal resistance between solid and He II (Kapitza resistance)
    - Cu: $R_k = 3 \times 10^{-4} \text{ K.m}^2$/K and Kapton: $R_k = 10^{-3} \text{ K.m}^2$/K

- Performances:
  - For LHC main magnets 1 W/m and for high heat loads (inner triplets 15 W/m)
  - If Requires attention to conduction paths then extendable to 50 W/m [Van Wee deren 2004]
Forced flow He II

- Characteristics
  - Same advantages of Static pressurized He II
  - Applied when He II static cooling is not sufficient
  - Internally cooled magnets
  - Needs specific pumps, HX, more complicated cooling scheme

- Heat transfer
  - Kapitza resistance not a function of velocity [Kamer 1988]
  - Classical Frictional $\Delta p$ up to $Re \approx 10^7$ [Fuzier 2001]
  - Transition velocity for advection effect (1 m/s for $\Delta T=0.1$ K @ 1.8 K) [Van Sciver 1998]
  - Negative JT coefficient (0.2 m/s for 100 m)
    - CICC : $D_h=0.5$ mm $\Delta p=75$ kPa (150 mK)
    - Smooth tube : $D_h=10$ mm $\Delta p=1$ kPa (5 mK)
  - Pumps add heat loads on the system
  - Parallel hydraulic channel may help

- Not applied for accelerator magnets [Van Weeldeeren 2004]
Forced flow supercritical helium

- **Characteristics**
  - Comparable heat transfer coefficient to pool boiling
  - Single phase flow (no vapor formation)
  - Adjustable heat transfer with mass flow (temperature optimization)
  - Can be « plugged » to refrigeration plant and use of cooling from 300 K
  - Internally cooled conductor, For CICC, better electrical insulation

- **Heat transfer**
  - Classical heat transfer Nu [Giarratono 1971], q≈10^4 W/m² for ΔT≈1 K
  - JT coefficient positive or negative
  - Pressures are P≈3-8 bar, ΔP≈1-2 mbar per magnet
  - T≈4.4 K, ΔT≈50-150 mK per magnet

- **Performances** [Van Weelderen 2004]:
  - Typical heat loads are ≈2 W per magnet (RHIC)
  - 6 W per magnet (cross flow in SSC)
Comparison of cooling modes

- **Pool boiling** (~1 W/m)
  - Liquid-vapour phases, vertical liquid heat conduction paths and ullage space necessary

- **Forced convection of superfluid helium** (~1 W/m)
  - Single phase, circulation pump needed, no accelerator implementation yet

- **Forced convection of supercritical helium** (~1-10 W/m)
  - Easy to implement for low heat loads, Single phase Mass flows of O(W/0.1 kg/s), High heat load possible at the expense of T-margin and high ΔP, Cross-flow construction needed for high heat loads

- **Static pressurized He II** (~1-10 W/m)
  - With a two-phase flow of saturated helium II (bayonnet heat exchanger) heat loads of O(10W/m), High conductivity avoids “dead spots”, Concept certainly extendable to heat loads of about 50W/m
Heat transfer in superconducting coil

- Heat transfer in a coil
- Insulations
- Phenomenology
- Past results
- Insulation for GSI
- “Comparison”
- Some ideas

(a) Première couche
(b) Seconde couche
(c) Canaux débouchants
   Conduits inter-conducteur
   Grande face
   Petite face

Transverse gaps
Second wrapping
Primary wrapping
Longitudinal multi-channels in dry woven tape
Evolution of 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] [Kimura 1998]
- First 2 wrappings with no overlap
- Last wrapping with a gap
- Apical $R_{th}$ Kapitza and $k$ @ 2 K
  Just tested at Saclay

Innovative insulation for $\text{Nb}_3\text{Sn}$ magnet
- Fiberglass tape + Ceramic precursor
- Smaller Porosity ($d$~0.1 $\mu$m, $\varepsilon$?, $th=400$ $\mu$m)
- $k \approx 4 \times 10^{-2}$ W/K.m ($k_{\text{kapton}} \approx 10^{-2}$ W/K.m) @ 2 K

Courtesy of F. Rondeaux (CEA) [Puissegur 2004]
Heat Transfer : Phenomenology

Meuris 1999
Results: The different configurations

- Epoxy Resin or glue on both side of the layer fills up the helium path
- Dry fiber thermally decouples the conductors
- Very small paths for He for polyimide insulations with gaps due to overlapping
Results: The insulation is participating

- Study on conventional insulations
  - d ~ 10 µm, channel length ~ mm
  - He II in // conduction + Kapitza

\[ Q_{\text{HeII}} = A \int_{T_b}^{T_i} f(T) \, dT \]

\[ Q_{\text{isol}} = \frac{\Delta T}{R} \]

For Large \( \Delta T \), He II HT < Conduction HT

[Baudouy 2001] and [Kimura 1999]
Results : Conclusions

Heat power in central conductor J2 (mW)

Temperature rise at S2 (mK)

He I

$T_b = 2.2$ K

configuration a
configuration b
configuration c
The insulation for GSI magnet

- GSI001: a conductive insulation
  - Inner layer: Polyimide 25 µm thick with adhesive on one side (50% overlap)
  - Outer layer: Polyimide 24 µm thick with adhesive on both side (50% overlap)

- UNK magnets PF insulation: A classic
  - Inner layer: Polyimide 20 µm thick with twist pitch of 5 mm
  - Outer layer: Prepreg fiber glass 100 µm thick with 1 mm gap

- UNK magnets PP insulation: An all Polyimide Insulation
  - Inner layer: Polyimide 20 µm thick with twist pitch of 5 mm
  - Outer layer: Polyimide 40 µm thick with adhesive on both side, 1 mm gap

- UNK magnets PFM insulation: A classic improved for He II
  - Inner layer: Polyimide 20 µm thick with twist pitch of 5 mm
  - Outer layer: Prepreg fiber glass 100 µm thick with 5 mm gap
Comparison

Test in boiling He I

Kapton 100 HN or tissue-underlaid Kapton + prepreg or Kapton adhesive on both faces

Kapton 200 HN + Kapton adhesive on outside face

Kapton 150 HN + Kapton adhesive on outside face

Small faces non-compressed during polymerization

Temperature rise, $T_{\text{cond}}$, vs. heat power, $Q$, (mK)

- PF
- PP
- PFM
Heat transfer in He I and He II

- A6- Conducteur central; $T_b = 1.897$ K
- A6- Conducteur voisin; $T_b = 1.897$ K
- A16- Conducteur central; $T_b = 1.901$ K
- A16- Conducteur voisin; $T_b = 1.901$ K
- A16- Conducteur central; $T_b = 2.357$ K

$T_{\text{cond}} - T_b$ (K)

$Q$ (W)

$\Delta T$

$Q_{\text{Faisceau}}$
Small face with holes

- Artificial permeability with 6 holes of $\Phi 200 \mu$ [Baudouy 1996]
- Holes reduce permeability and $R_{th}$ of small face and of the insulation

- Small $\Delta T$, heat transfer through the holes
- High $\Delta T$, heat transfer through holes and conduction

[Wilson 2002]
Ideas for insulation in non He II

- Work needed on the material itself
  - Thermal conductivity of Kapton, Apical, Peek?
  - Can it be enhanced?
  - Other insulation system?

- Increase heat transfer between the cable layer
  - Porous second layer like for NED or dry fiber glass
  - Has to be tested in He I or She

- Increase the Heat transfer through the small face
  - No epoxy resin and minimum amount of polyimide glue
  - Large overlap gap for second layer
  - Optimized overlap for the second layer
  - Direct contact between helium and the conductor is good
  - has to be tested in He I or SHe

- Increase the helium in the cable
  - Central core in porous material?
NED R&D program: Method

- Stack experiment
- 1D transverse HT (Drum set-up)
- 1D longitudinal HT (Conduit experiment)

Stack = Drum + Conduit

1D transverse HT through the small face
1D longitudinal HT (and transverse!) through the large face
NED R&D program: Experimental apparatus

- Stack of five insulated conductors under mechanical constraint
- Conductor = CuNi Strands Ø 0.8 mm (w=11 mm x t=1.5 mm)

Drum experiment for 1D steady-state measurement

Courtesy of N. Kimura (KEK)
NED R&D program: The tests

- Two types of insulation are considered
  - glass fiber tape, vacuum-impregnated with epoxy resin
  - “innovative” insulation (glass fiber tape + ceramic)

- At least four cooling schemes can be envisioned
  - pool boiling He I at 4.2 K and 1 atm
  - superfluid helium at 1 atm
  - He I at 4.35 to 4.5 K and 1.2 to 1.7 atm
  - Static supercritical helium?

Courtesy of F. Rondeaux (CEA)
References

- R. Van Weelderen, NED presentation, CERN, 08/07/2004
- H. Kamer, Proceedings of ICEC 12, p. 299-304, 1988
- [Giarratono 1971]
Phase diagram of helium

- Solide
- He II (liquide)
- He I (liquide)
- Gaz

- T=2,163
  p=1
- T=1,76
  p=29,7
- T=4,2
  p=1
- T=2,172
  p=0,05
Heat transfer curves

- $R_k$ Kapton
- $\text{He II, 1 m}$
- Forced $\text{He II}$
- $\text{He I, }\varnothing10\text{ mm, }m=610^{-3}\text{ kgs}^{-1}$