Thermodynamics Modeling of New LHC Quadrupole Magnet

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**Motivation**

**Heat sources in the accelerator magnets**

**Thermodynamics of magnet structure**
- Heat evacuation path and heat flow barriers
- Helium in the magnet

**Modeling of heat flow in the magnets**
- Network model construction
- Helium modeling
- Model validation

**New inner triplet phase I simulation status**

**New inner triplet phase II simulation status**

**Conclusions**

**Future plans**
MOTIVATION

Particles coming from proton-proton collision debris impacts the inner triplet magnets
→ energy deposition in the coils.

Heat flow paths and heat flow barriers identification in the magnet
→ need to give a feedback to the magnet designers.

Phase I LHC upgrade → enhanced insulation scheme → open helium paths between the bath and the cable
→ necessary studies of magnet thermodynamics

Thermal studies of LARP Nb$_3$Sn LHC upgrade phase II magnets
→ implement method used in phase I magnet studies
Heat sources in the LHC magnets

- Debris of the proton-proton interactions at accelerator interaction regions
- Interaction of lost protons with collimators
- Physics processes - BFPP (ion beam case)
- Accidental beam losses

**Transient losses ~ns to ~ms**
- Enthalpy of the cable materials (~ns)
- Heat transfer to helium volume inside the cable (~μs)
- Enthalpy of the cable (~ms)

**Steady-state losses**
- Transfer of the heat from cable to the heat reservoir (~s)
- Magnet structure is vital

References:
D. Bocian, CERN AT-MTM note, EDMS 750204
P.P. Granieri, (D. Bocian), et al., CERN-LHC-PROJECT-Report-1089
D. Bocian et al., CERN-AB-2008-006
HEAT FLOW BARRIERS

- cable insulation
- interlayer insulation
- ground insulation
- helium channel around cold bore
  For temperatures above 2.16 K: transition $\text{HeII} \rightarrow \text{HeI}$: helium channels are blocked = less effective heat flow due to the changing of heat evacuation path

A sketch of the heat transfer in the magnet at nominal operations (a) and at quench limit (b).
NETWORK MODEL

- ROXIE magnet field distribution, temperature margin
- TECHNICAL DRAWINGS detailed magnet coil geometry
- FLUKA beam loss profiles
- Material properties at low temperature CRYODATA
- OTHER non beam induced heat sources
- MAGNET QUENCH LEVELS
  - Hysteresis losses
  - Eddy currents, etc.
  - A. Verweij
  - R. Wolf
  - Contribution to the quench level is order of 1-2%
  - MEASUREMENTS model validation
Network Model

coil model
The volumes occupied by helium in the magnet are considered as:
- narrow channels,
- semi-closed volumes = inefficient inlet of fresh helium.

The steady heat load, heat up the helium in the semi-closed volumes:
- Helium temperature well above superfluid helium temperature at $T_b = 1.9K$
- Critical helium temperature reached already below the calculated quench limit
Network Model Validation

Model validation

**EXPERIMENT**

- Heat source
  - quench heaters
  - inner heating apparatus

**MAGNET**

- measured quench current

**VALIDATION**

- predicted quench current

**END**

**HEAT SOURCE MODEL**

- heat

More details:


**MB magnet at 1.9K**

- measurements
- simulation

**Network Model Validation**

**MQM magnets at 4.5 K**

- Ultimate current 4650 A
- Nominal current 4310 A

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New inner triplet phase I simulation status

The nominal LHC cable insulation:
- two 11 mm tapes overlapping by 50%
- one 9 mm tape with 2 mm spacing

Nominal parameters for current and phase I design of LHC inner triplet

<table>
<thead>
<tr>
<th></th>
<th>Current design</th>
<th>Phase I design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature [K]</td>
<td>1.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Nominal gradient [T/m]</td>
<td>205</td>
<td>120</td>
</tr>
<tr>
<td>Aperture diameter [mm]</td>
<td>70</td>
<td>120</td>
</tr>
<tr>
<td>Quadrupole length [m]</td>
<td>5.5 / 6.37</td>
<td>10</td>
</tr>
</tbody>
</table>

The enhanced insulation:
- one 9 mm tape with 1 mm spacing
- four 2.5 mm tapes with 1.5 mm spacing
- one 9 mm tape with 1 mm spacing


Nominal parameters for current and enhanced LHC cable insulation

<table>
<thead>
<tr>
<th></th>
<th>Nominal</th>
<th>Enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cable 1</td>
<td>Cable 2</td>
</tr>
<tr>
<td>Radial thickness</td>
<td>0.150</td>
<td>0.150</td>
</tr>
<tr>
<td>Azimuthal thickness</td>
<td>0.120</td>
<td>0.130</td>
</tr>
</tbody>
</table>
New inner triplet phase I simulation status

A combining particle tracking, FLUKA shower simulations in a single magnet coil

The inner triplet quadrupole FLUKA simulations were ran with a thick Beam Screen (BS) in Q1 (10.15 mm extra stainless steel shield added to the usual 2mm thick BS).

\[ L = 2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

Energy deposits in selected bin of magnet cross section with peak value. Magnet has been divided longitudinally into 108 bins (~10 cm)
Temperature distribution in the magnet

Temperature jump due to normal fluid helium heat conduction decrease

Temperature jump due to superfluid to normal fluid phase transition

Temperature jump due to normal fluid helium zone expansion in the channel around cold bore
New inner triplet phase I simulation status

Quench limit in the phase I quadrupole magnet

Cable insulation and helium channel around cold bore are the most critical parameters limiting heat flow from the magnet coil at steady state heat load.

Temperature increase in the coil at nominal heat load for nominal and enhanced LHC cable insulation.
New inner triplet phase II simulation status

Work presented by V. Kashikhin on CECICMC09.

The COMSOL simulation included:
- energy deposits in the coil
- cable material and insulation.

The simulation did not included:
- helium in the magnet (channel around cold bore)
- energy deposits in the coldbore

Courtesy N. Mokhov

Arrow indicates phase II nominal luminosity

L = 2.5 * 10^{34} \text{ cm}^{-2} \text{s}^{-1}

The COMSOL simulation included:
- energy deposits in the coil
- cable material and insulation.

The simulation did not included:
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N_{b_3}s_{n}

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Conclusions

The analysis of thermal behaviour of the phase I quadrupole magnet was presented.

The heat flow paths and heat flow barriers were identified with the thermal network simulation.

There is significant impact on magnet performance from energy deposits in cold bore.

The size of helium channel around cold bore and cable insulation are the most critical parameters.
Future Plans

- Implementation of the thermal network to phase II Nb$_3$Sn magnet is needed to calculate quench limits and compare with phase I simulation.

- The analysis of impact of helium channel around cold bore is necessary to optimize the channel width.
  
  - An experiment devoted to study of helium channel around cold bore is welcome

- Possible use of network model to study different Nb$_3$Sn cable insulation properties, for instance radiation hardness.
Modeling of Nb$_3$Sn coil length change during heat treatment

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B. Walsh / NHMFL, M. Wake / KEK

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Introduction

Presented results are the part of general studies leading to understanding coil elements behavior during heat treatments.

Work has been divided into several steps:

I. Collection of relevant data and material properties for simulations
II. Preparation and conduct of necessary measurements
III. FEM simulation of the strand/cable/coil behavior during reaction
IV. Feedback to the coil fabrication technology
Observed cable shrinkage was:

- 0.85 mm for 5 kg load
- 0.65 mm for 15 kg load.

Extrapolation to 0 kg load shows a 0.95 mm cable shrinkage.

Cable sample: LARP Nb₃Sn
Strand: 54/61
Sample length: 104 cm

Target temperature: 210°C
Heating time at 210°C: 360 min.
Temperature ramp time: 2h 19min
Cooling time: 1h
Strand sample measurement

Sample preparation:

- Weld the ends of strand sample.
- Resize the ends of strands to fit required diameter.
- Chosen sample length ~ 48 mm Nb₃Sn strand.

- measurement of ΔL after HT - done
- measurement during HT - in progress

<table>
<thead>
<tr>
<th>Results of nominal LQ heat treatment of strand sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
</tr>
<tr>
<td>Sample 1</td>
</tr>
<tr>
<td>Sample 2</td>
</tr>
<tr>
<td>Sample 3</td>
</tr>
</tbody>
</table>

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BACKUP TRANSPARENCIES
The analogy of the equivalent thermal circuit

<table>
<thead>
<tr>
<th>Thermal Circuit</th>
<th>Electrical Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T$ [K] Temperature</td>
<td>$V$ [V] Voltage</td>
</tr>
<tr>
<td>$Q$ [J] Heat</td>
<td>$Q$ [C] Charge</td>
</tr>
<tr>
<td>$q$ [W] Heat transfer rate</td>
<td>$i$ [A] Current</td>
</tr>
<tr>
<td>$\kappa$ [W/Km] Thermal Conductivity</td>
<td>$\sigma$ [1/Ωm] Electrical Conductivity</td>
</tr>
<tr>
<td>$C^\Theta$ [J/K] Thermal Capacitance</td>
<td>$C$ [C/V] Capacitance</td>
</tr>
</tbody>
</table>

The analogy between electrical and thermal circuit can be expressed as:

-steady-state condition \( \Delta T = qR^\Theta \) \( \Leftrightarrow \) \( \Delta V = iR \)

-transient condition \( \nabla^2 T = R^\Theta C^\Theta \frac{\partial T}{\partial t} \) \( \Leftrightarrow \) \( \nabla^2 V = RC \frac{\partial V}{\partial t} \)
A. Siemko, 14th “Chamonix Workshop”, January 2005

• **Heat generated by electrical sources**
  
  – For main dipole during ramp (R. Wolf)  
    • Hysteresis loss  240  
    • Inter-strand coupling ($R_c = 7.5 \, \mu\Omega$)  45  
    • Inter-filament coupling ($\tau = 25$ ms)  6.6  
    • Other eddy currents (spacers, collars..)  4  
  
  • Resistive joints (splices)  30  
  
  – Total (per meter)  ~325

The first estimations show contribution at the level of 0.5 mW/cm$^3$

A detailed studies are ongoing (A. Verweij, R. Wolf)
Helium in the magnet

Superfluid helium

The heat flow in He II is calculated according formulae [Claudet et al., CRYOGENIE et ses applications en supraconductivite, IIF/IIR]

\[ \frac{Q}{s} = \left[ \frac{X(T_c) - X(T_h)}{l} \right]^{0.29} \left[ \frac{W}{cm^2} \right] \]

and \( X(T) \) is an experimental results fitting

\[ X(T) = 520 \left[ 1 - e^{-\left[3^{(2.16-T)^{2.5}}\right]} \right] \]

The heat conductivity of superfluid helium is very high at low heat currents, but since it is non-linear it can be much reduced at high heat currents.

(W. F. Vinen. Superfluidity. CERN CAS School on Superconductivity, 1995.)

At high heat currents the superfluid helium in the channel can „quench” resulting in transition to the normal fluid helium means that heat evacuation from the coil is reduced significantly resulting in quenching of the magnet.

Normal fluid and gaseous helium

In case of channels inside of the cable and \( \mu \)-channels which are of the order of 0.2 mm and 0.07 mm respectively, a typical nucleate boiling flux becomes much lower than that for helium bath which is 10 000 W/m\(^2\) [1]. The gaseous phase in the narrow channels is described by a constant heat transfer coefficient and is of the order of 70 W/m\(^2\)/K as extrapolated from [2]. The convective heat transfer in steady state mode is restricted to heat fluxes not greater than a few mW/cm\(^2\) [3] as it is only relevant for large volumes. In case of helium inside the cable and in the \( \mu \)-channels this mode is negligible.


Fig. 6.2. Typical heat transfer relationship for pool boiling liquid.

Fig. 2 Steady state boiling helium heat transfer characteristics in narrow cooling channels.
## Cable parameters

Table 1: Cables parameters

<table>
<thead>
<tr>
<th></th>
<th>unit</th>
<th>Inner layer</th>
<th>Outer layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>w</td>
<td>mm</td>
<td>15.100</td>
<td>15.100</td>
</tr>
<tr>
<td>thick in</td>
<td>mm</td>
<td>1.736</td>
<td>1.362</td>
</tr>
<tr>
<td>thick out</td>
<td>mm</td>
<td>2.064</td>
<td>1.598</td>
</tr>
<tr>
<td>rad. insulation</td>
<td>mm</td>
<td>0.160</td>
<td>0.160</td>
</tr>
<tr>
<td>az. insulation</td>
<td>mm</td>
<td>0.135</td>
<td>0.145</td>
</tr>
<tr>
<td>n. strand</td>
<td></td>
<td>28</td>
<td>36</td>
</tr>
<tr>
<td>strand diameter</td>
<td>mm</td>
<td>1.065</td>
<td>0.825</td>
</tr>
<tr>
<td>Cu/Sc ratio</td>
<td></td>
<td>1.65</td>
<td>1.95</td>
</tr>
<tr>
<td>$I_{ss}$</td>
<td>A</td>
<td>14800 (10T)</td>
<td>14650 (9T)</td>
</tr>
<tr>
<td>$\Delta I_{ss}/\Delta B$</td>
<td>A/T</td>
<td>4680 (10T)</td>
<td>4050 (9T)</td>
</tr>
</tbody>
</table>
New inner triplet E deposits simulation

MARS

L=2.5*10^{34} \text{ cm}^{-2}\text{s}^{-1}

FLUKA

Peak Energy Deposit in coil

Peak Energy Deposit in cold bore
New inner triplet phase II simulation status

Work presented by V. Kashikhin on CECICMC09.

Arrow indicates nominal luminosity

`\text{NbTi}`

`\text{Nb}_3\text{Sn}`