Beam loss induced quenches
(Update on quench limit calculations)

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Outline

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  - Heat transport in the magnets
  - Characteristic of superconducting coils
- **Network Model**
  - Electrical equivalent
  - Superconducting cable and coil models
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  - Measurements in SM 18
  - Evaluation of the network model quality
- **“Beam loss” simulation**
- **Non “beam loss” heat sources**
- **Transient beam loss simulation**
  - Network Model
  - 0D model
- **Summary and outlook**
Motivation

- Quench is transition of the superconductor from the superconducting to the normal state. Such a transition invariably occurs in accelerator magnets if one of the three parameters: temperature, magnetic field or current density, exceeds a critical value.

- Quench limit calculation in terms of external energy deposition is vital for accelerators making use of superconducting magnets.

- These studies are important for the LHC operation and efficiency of protection system, BLM calibration and design and operation of collimators.
Thermodynamics of magnet structure

Magnet characteristic

Heat transport in the magnets

Characteristic of superconducting coils
LHC Dipole Magnets

15-m long LHC cryodipole
Magnets characteristic
LHC dipole magnets cross section
Thermodynamics of magnet structure

Magnet characteristic

Heat transport in the magnets

Characteristic of superconducting coils
Steady state heat transport in the magnet

- Insulation + He
- Insulation
- NbTi + Cu
- He

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Steady state heat transport in the magnet

A heat transfer in the main dipole. Arrows indicate the radial path of the heat transfer in the magnet.
Heat transfer in the magnets

- Heat transfer from the conductor to the cold source define the temperature margin
- Electrical insulation is the largest thermal barrier at 1.9 K against cooling
Heat transfer in the magnets

A simple sketch of the heat transfer in the magnet

at $T=1.9\ K$ (left) and $T=4.5\ K$ (right).
Thermodynamics of magnet structure

Magnet characteristic

Heat transport in the magnets

Characteristic of superconducting coils
Magnets coil

Arc magnet

MB

LSS magnet

MQM

MQ

LSS magnet

MQY
Magnetic field distribution in the coils

MB magnetic field distribution

MQ magnetic field distribution

MQY magnetic field distribution

MQM magnetic field distribution
Network Model

Electrical equivalent

Model of the superconducting cable and coils
## Electrical equivalent

### 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]</td>
<td>( V ) [V]</td>
</tr>
<tr>
<td>( Q ) [J]</td>
<td>( Q ) [C]</td>
</tr>
<tr>
<td>( q ) [W]</td>
<td>( i ) [A]</td>
</tr>
<tr>
<td>( \kappa ) [W/Km]</td>
<td>( \sigma ) [1/Ωm]</td>
</tr>
<tr>
<td>( R^\theta ) [K/W]</td>
<td>( R ) [V/A]</td>
</tr>
<tr>
<td>( C^\theta ) [J/K]</td>
<td>( C ) [C/V]</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**  
  \( \nabla^2 T = R^\theta C^\theta \frac{\partial T}{\partial t} \)  \( \Leftrightarrow \)  \( \nabla^2 V = RC \frac{\partial V}{\partial t} \)
Network Model

Electrical equivalent

Model of the superconducting cable and coils
“WET” superconducting cable modeling

μ-channel

Insulation + He  Insulation  NbTi + Cu  He
Cable modeling

Network model of the cable

5 block discretization
Coil modeling

Stainless steel enthalpy: 55.23 mJ/cm$^3$
Validation of the model

Measurements in SM18

Evaluation of the network model quality
Two methods of measurement

- $I_{coil} =$const, increase of $I_{QH}$ with a step of 0.1 A
- $I_{QH} =$const, wait 300 second for steady state, then ramp of $I_{coil}$

Second method is better for steady state heat transport

3 MQM's and 2 MQY's at 4.535K have been tested
Results of the measurements with QH

MQY inner quench heater

Ultimate current 3900 A
Nominal current 3610 A

MQM magnets at 4.5 K
Ultimate current 4650 A
Nominal current 4310 A

MQY - outer quench heater

Ultimate current 3900 A
Nominal current 3610 A

MQ at 4.5 K

Ultimate current @ 1.9K 12810A
Nominal current @ T=1.9K 11870A

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The results show very good agreement of the measurements with simulations. The relative difference between measured and calculated quench values are ranging from 0.6 to 15 % for all measured types of superconducting magnets at 4.5 K.
Internal Heating Apparatus
Internal Heating Apparatus in the coil

Main Dipole - MB

Main Quadrupole - MQ

MQM

MQY
Results of the measurements with IHA

**PRELIMINARY RESULTS**

**Support tube temperature distribution, I_h1=5.0A, I_h2=5.0A**

![Graph showing temperature distribution over time](image1)

**MB quench limit - inner heater**

![Graph showing quench limit vs. heater and magnet current](image2)

**ADDITIONAL MEASUREMENTS ARE NECESSARY**
Validation of the model

Measurements in SM18

Evaluation of the network model quality
Matching algorithm have been developed to match the heat conduction parameters to the temperature profile in the magnet coil.

\[ \Delta T = 0.1K \quad \text{– accuracy level} \]
\[ \Delta T_i = T_i - T_{i-1} \]

IF(\(\Delta T_i = \Delta T\)) THEN „finish iteration”

IF(\(\Delta T_i < 0\)) THEN
\[ T_i = T_{i-1} - \frac{\Delta T_i}{2} \]
ELSE
\[ T_i = T_{i-1} - \frac{\Delta T_i}{2} \]
ENDIF
HF quench heater - temperature distribution

\[ \Delta T = 0.1K/0.01K \quad I_{\text{magnet}} = 8668/8870 \, A, \quad I_{HF} = 3A, \quad T_b = 1.9K \]

Temperature margin at 8870

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LF quench heater - temperature distribution

\[ I_{\text{magnet}} = 10245 \, \text{A}, \quad I_{\text{LF}} = 3\, \text{A}, \quad T_b = 1.9\, \text{K} \]

Temperature margin at 10245
„Beam loss” simulations
Quench limit for the “real” beam loss depends on the beam loss profiles.

Heat flow distribution in the coil will be different compared to the “quench heater” and IHA simulations.

A simple simulation of beam loss are presented on the next slides.

The updated result for typical “beam loss profile” in MQM, MQY and MB magnet are presented.
„Beam loss” profiles in magnets

Homogenous beam loss profile

Concentric beam loss profile

Gaussian beam loss profile

Limited area beam loss
MQM quench limit for nominal current (4310 A) ⇒ 6 \([\text{mW/cm}^3]\)
MQM quench limit for ultimate current (4650 A) ⇒ 4 \([\text{mW/cm}^3]\)
MQM quench limit for nominal current (4310 A) and naive homogeneous heat deposit in profile 3, 4 and 5 ⇒ 3 \([\text{mW/cm}^3]\)

MQY quench limit for nominal current (3650 A) ⇒ 8 \([\text{mW/cm}^3]\)
MQY quench limit for ultimate current (3900 A) ⇒ 5 \([\text{mW/cm}^3]\)
MQY quench limit for nominal current (3650 A) and naive homogeneous heat deposit in profile 3, 4 and 5 ⇒ 2 \([\text{mW/cm}^3]\)

\[ T_b = 4.5 \text{K} \]
Homogenous beam loss-temperature distribution

$I_{\text{magnet}} = 12057 \, \text{A}, \, T_b = 1.9 \, \text{K}$

- Iteration 1
- Iteration 2
- Iteration 3
- Iteration 4
- Iteration 5
- Iteration 6

- Temperature margin
- Quenching cable
- Inner layer
- Outer layer

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Homogenous beam loss-temperature distribution

$I_{\text{magnet}} = 12057 \, \text{A}, \, T_b = 1.9 \, \text{K}$

- Temperature margin
- Quenching cable
- Inner layer
- Outer layer
Beam loss profile in MB magnet

PRELIMINARY RESULTS

Beam loss profile with homogenous heat deposition

MB dipole simulations – preliminary results – no cold bore
- 10500 A → Quench Limit ~ 150 mW/cm³
- 11300 A → Quench Limit ~ 105 mW/cm³
- 12100 A → Quench Limit ~ 77 mW/cm³

MB dipole simulations – preliminary results – with cold bore
- 10500 A → Quench Limit ~ 20 mW/cm³
- 11300 A → Quench Limit ~ 15 mW/cm³
- 12100 A → Quench Limit ~ 10 mW/cm³

This numbers should not be taken as a reference numbers for MB magnets.
"Beam loss" profile in MB magnet

PRELIMINARY RESULTS

LHC Project Note 44

1-outer layer
factor = 1

2- inner layer
factor = 6

3 - cold bore
factor = 50

Concentric beam loss profile

Temperature margin distribution

Quench limit at 7300A
31 mW/cm³

Quench limit at 12200A
12.6 mW/cm³

Temperature in the coil at I=7300A, ΔI_{simulation}

Heat flow map at I=7300A
Ongoing work

"Non beam loss" heat loads
Transient beam loss
Non beam loss heat loads

A. Siemko, 14th “Chamonix Workshop”, January 2005

♦ Heat generated by electrical sources

- For main dipole during ramp (R. Wolf) [J/m]
  - Hysteresis loss 240
  - Inter-strand coupling (Rc = 7.5 μΩ) 45
  - Inter-filament coupling (τ = 25ms) 6.6
  - Other eddy currents (spacers, collars..) 4
  - Resistive joints (splices) 30

- Total (per meter) ~325

The first estimations shows contribution at the level of 0.5 mW/cm³

A detailed studies are ongoing (A. Verweij, R. Wolf)
Network Model is developed and work is ongoing

The first results should be available in few months

In the network model R is replaced by RC (low pass filter)
Transient beam loss – 0D Model

P.P. Granieri et al.

0D Model is developed and work is on going
The agreement between measurements and simulations is in worse case at the level of 15% at 4.5K.

The better understanding of magnet thermodynamics is achieved.

The validation of the model at 1.9 K is ongoing.

On going - transient losses simulations.

The simulations of „realistic“ beam loss - including cold bore (1.5 and 1.75 mm) are required.

Continuation of measurement in SM18 on MB, MQ and MQM magnets is required.