Modeling of Quench Limit for Steady State Beam Loss

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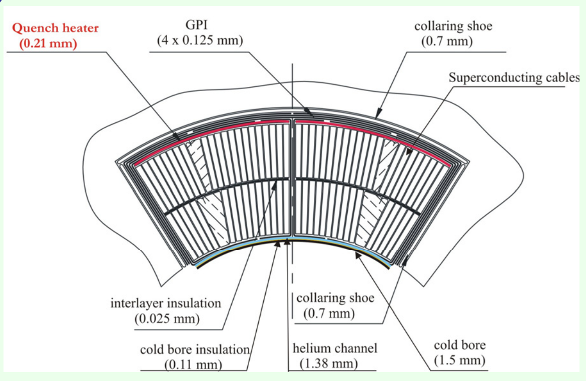
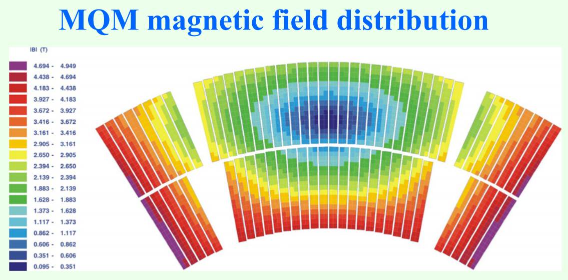
ABSTRACT: A quench is a transition of a conductor from the superconducting to the normal conducting state. Such a transition occurs in accelerator magnets if one of three parameters: temperature, magnetic field or current density, exceeds a critical value. An increase of temperature in superconductor is often caused by the lost beam particles. Particles impacting on the vacuum chamber create a shower of secondary particles which deposits their energy also in the superconducting cables of magnet coils. Energy deposition in the coils was experimentally studied making use of built-in quench heaters in the LHC magnets. The heat flow in the magnet is modeled by an electrical network and simulated using the PSPICE program. The network model was validated with measurements performed in the CERN magnet test facility. The value of quench heater DC current and corresponding coil current were calculated from the network model of heat transport in the superconducting magnets. At the occurrence of the quench the measured parameters were compared with the model values. The relative difference between measured and calculated quench values ranges from 0.6 to 15 % for all measured types of superconducting magnets.

MQM magnet coil



MQM magnetic field distribution



The analogy of the equivalent thermal circuit

Thermal circuit			Electrical Circuit		
T	[K]	**Temperature**	V	[V]	**Voltage**
Q	[J]	**Heat**	Q	[C]	**Charge**
q	[W]	**Heat transfer rate**	i	[A]	**Current**
κ	[W/Km]	**Thermal Conductivity**	σ	[1/Ωm]	**Electrical Conductivity**
R^{Θ}	[K/W]	**Thermal Resistance**	R	[V/A]	**Resistance**
C^{Θ}	[J/K]	**Thermal Capacitance**	C	[C/V]	**Capacitance**

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

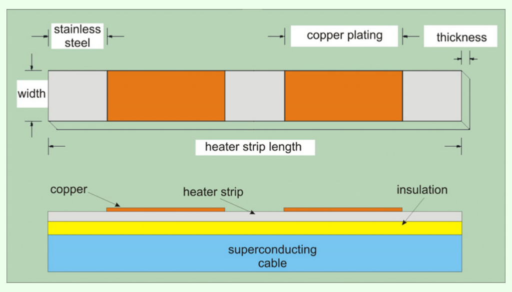
-steady-state condition *Temperature rise* ⇔ *Voltage difference*

$$\Delta T = qR^{\Theta} \quad \Leftrightarrow \quad \Delta V = iR$$

-transient condition *Heat diffusion* ⇔ *RC transmission line*

$$\nabla^2 T = R^{\Theta} C^{\Theta} \frac{\partial T}{\partial t} \quad \Leftrightarrow \quad \nabla^2 V = RC \frac{\partial V}{\partial t}$$

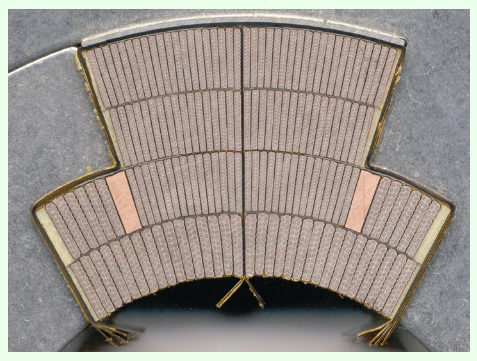
Characteristic of quench heater strip design for the LHC magnets



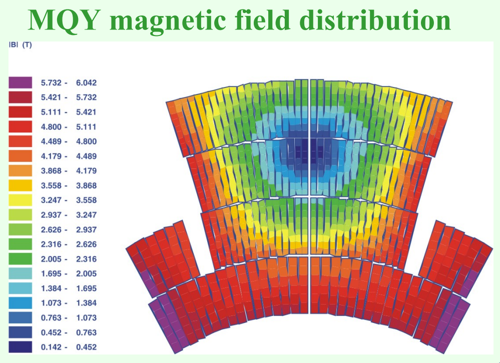
Quench heaters are installed to protect magnet coils against overheating and excessive voltages. They are made of stainless steel with the copper plating cycle to reduce their resistance. The strips are positioned along the coil. They are heated by the capacitor bank discharged after quench detection. The heat is transferred through thin polyimide insulation layer into the coil and provokes quench. The Stainles Steel/Copper ratio is different for all types of magnets as indicated in the table.

Magnet type	Length [mm]	Width [mm]	Thickness [mm]	Pattern L_{ss} [mm]	Pattern L_{Cu} [mm]	Number of Strips in Series
MQM	3511	21	0.025	120	170	4
MQMC	2506	21	0.025	125	100	4
MQML	4916	21	0.025	140	350	4
MQY - outer	3528	15	0.025	100	250	4
MQY - inner	3528	21	0.025	130	190	4

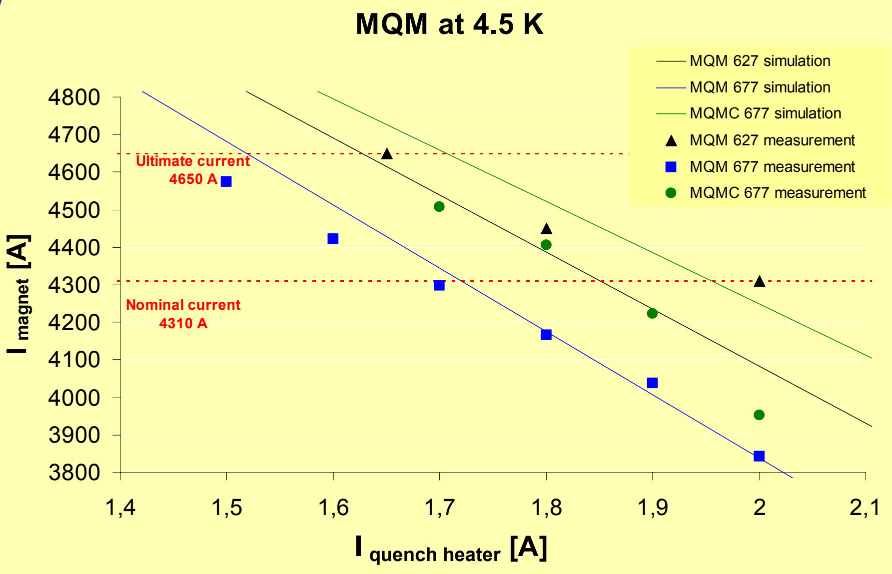
MQY magnet coil



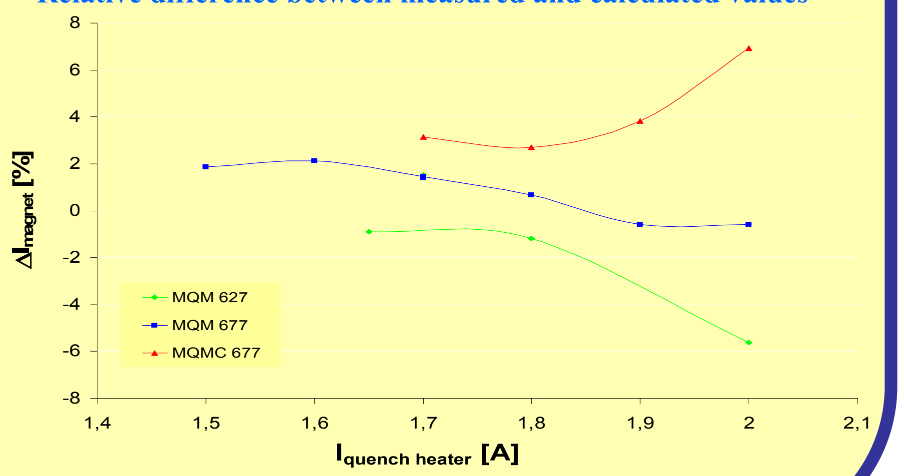
MQY magnetic field distribution



MQM magnet model validation

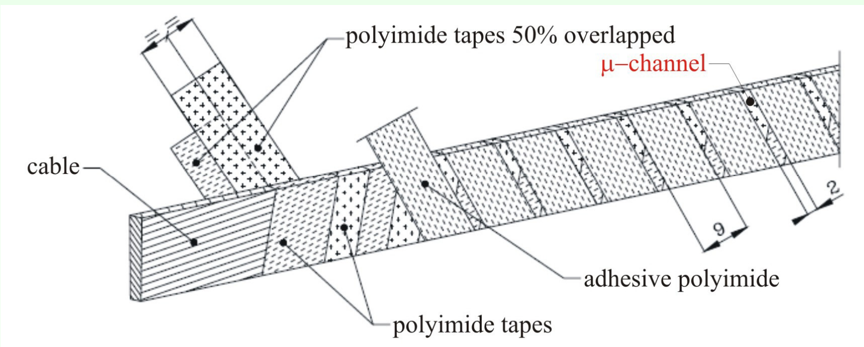


Relative difference between measured and calculated values

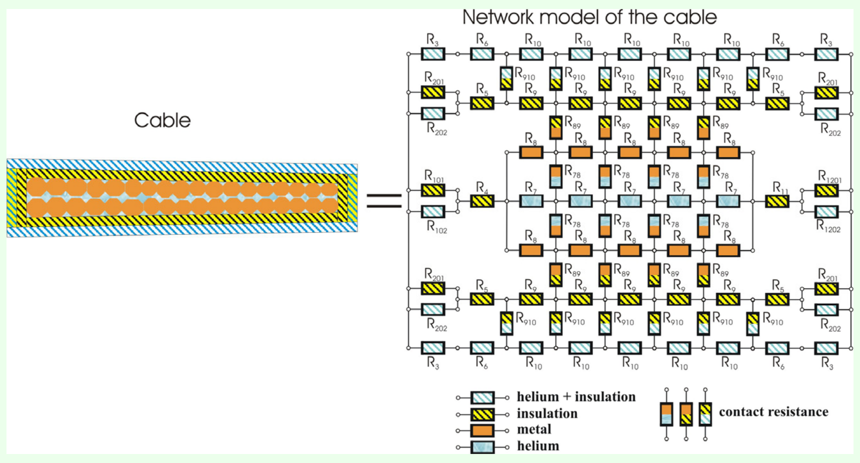


THE NETWORK MODEL

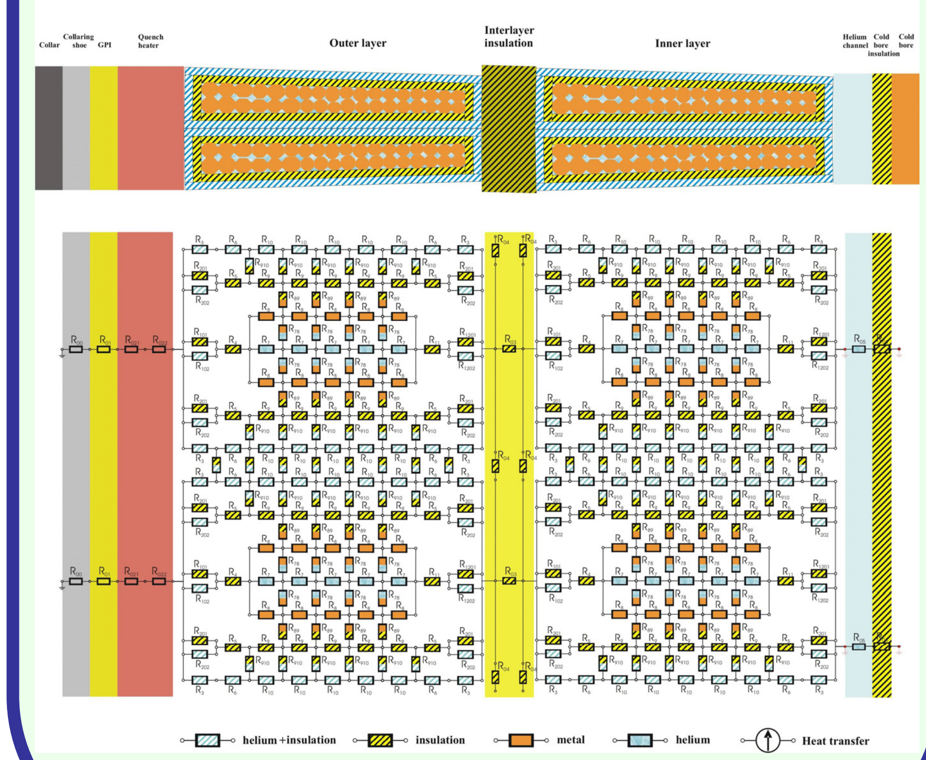
The power dissipation in the superconductiong magnet component leads to a complex process of the heat conduction. In many cases a simplified model for heat transfer is sufficient. The network model uses a well-known method, where an electrical circuit is used to model the thermal quantities. The cable has been subdivided in thermal resistance elements to study the heat flow inside its structure. The coil is modeled using the cable model unit.



Superconducting cable sketch

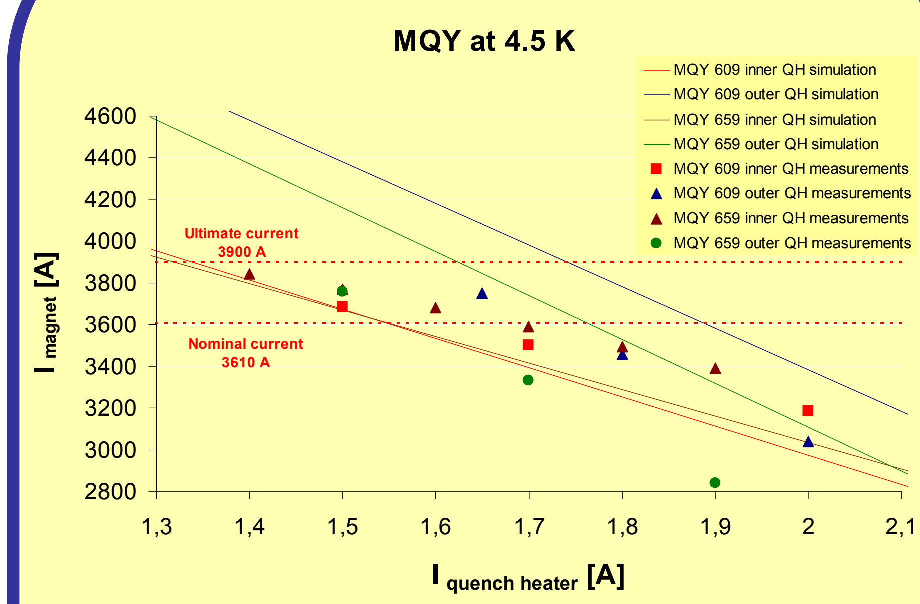


Superconducting cable network model

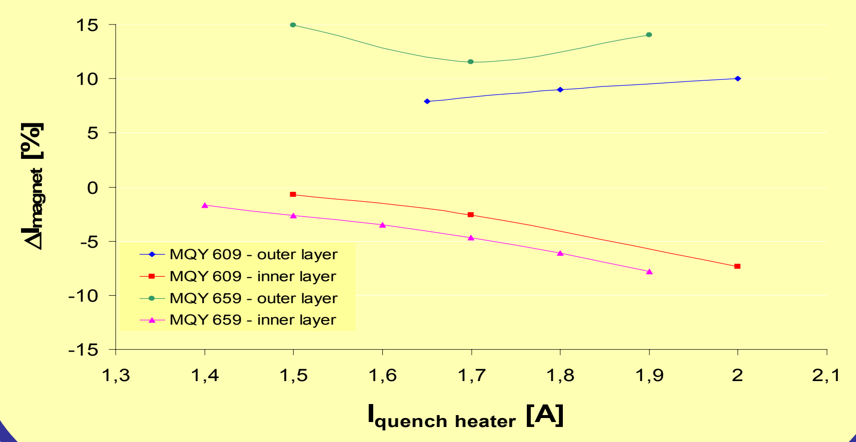


Superconducting magnet coil network model

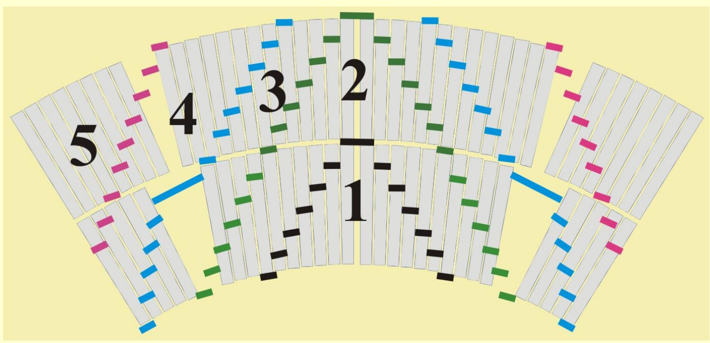
MQY magnet model validation



Relative difference between measured and calculated values



RESULTS



An example of beam loss profiles in MQM magnet

Gaussian heat deposit profiles

- MQM quench limit for nominal current (4310 A) ⇒ *6 [mW/cm³]*
- MQM quench limit for ultimate current (4650 A) ⇒ *4 [mW/cm³]*
- MQY quench limit for nominal current (3610 A) ⇒ *8 [mW/cm³]*
- MQY quench limit for ultimate current (3900 A) ⇒ *5 [mW/cm³]*

Homogeneous heat deposit

- MQM quench limit for nominal current (4310 A) ⇒ *3 [mW/cm³]*
- MQY quench limit for nominal current (3610 A) ⇒ *2 [mW/cm³]*

CONCLUSIONS

The LHC operates with $3.2\cdot10^{14}$ protons in one beam. Already if a small fraction of the beam, of the order of 10^7 protons per second, is lost locally and resulting shower energy deposited in the coil, a quench will occur. The knowledge of the quench level will allow optimizing the collimation system design and setting appropriate initial threshold values for beam loss monitors triggering the extraction of the beams from the ring. The optimized threshold settings will assure that the beam will be dumped only if it is necessary and also that the number of quenches will be minimized. This procedure should maximize the operational efficiency and therefore maximize the integrated LHC luminosity.

From the performed measurements and simulations it could be concluded that:

- ✓ *The developed heat transport network model is working correctly at 4.5 K.*
- ✓ *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.*
- ✓ *Proposed model can be used for the quench limit calculation of other LHC magnets working at 4.5 K*

OUTLOOK:

- ✓ *Validation of the model at 1.9 K (is on going)*
- ✓ *Non-linear objects in the model are desired to improve the precision of the results and to simulate the superfluid helium behavior*
- ✓ *Transient loss simulation are under investigation*

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