Accelerator
Technology
Department

Modeling of Quench Levels Induced by Heat Deposition

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Outline

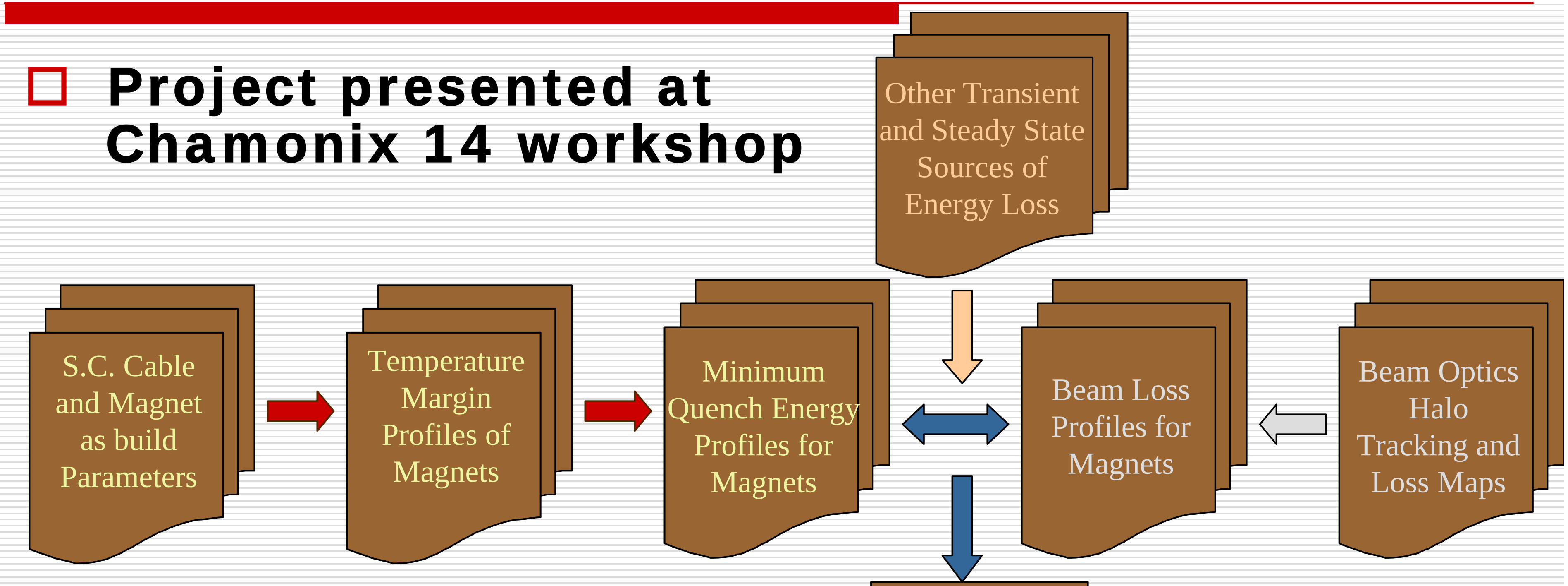
- Motivation
- Transient heat deposition modeling
- Steady state heat deposition modeling
- Outlook and conclusion

Motivation

- The LHC will operate with $3.2 \cdot 10^{14}$ protons in one beam. Already if small fraction of protons, 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 extracting the beams from the ring.
- The optimized threshold settings will assure that the beam will not be dumped too often and also that the number of quenches will be minimized. This procedure should maximize the operational efficiency and therefore maximize the integrated LHC luminosity.

The project of quench level modeling

- Project presented at Chamonix 14 workshop



Other Transient and Steady State Sources of Energy Loss

S.C. Cable and Magnet as build Parameters

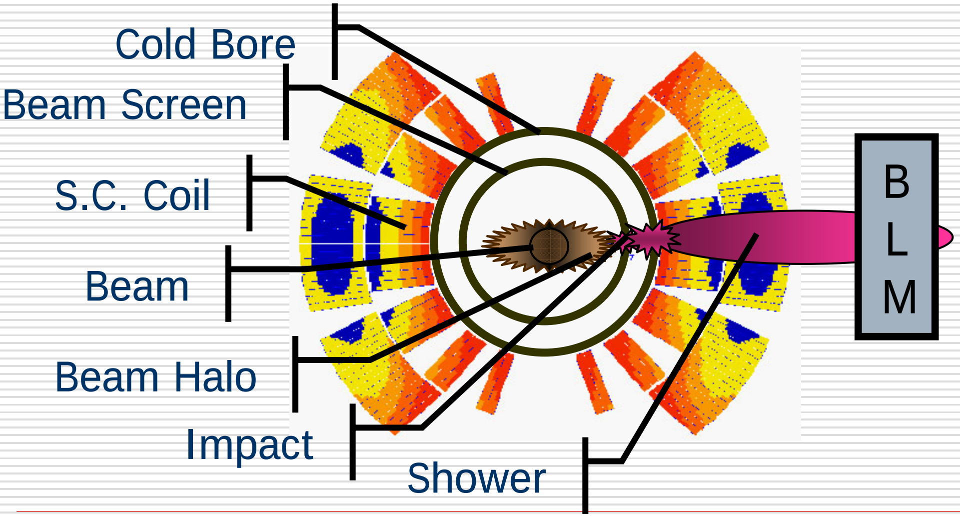
Temperature Margin Profiles of Magnets

Minimum Quench Energy Profiles for Magnets

Beam Loss Profiles for Magnets

Beam Optics Halo Tracking and Loss Maps

Predictive Tool to Prevent Premature Dump of the Beam Due to Beam Loss

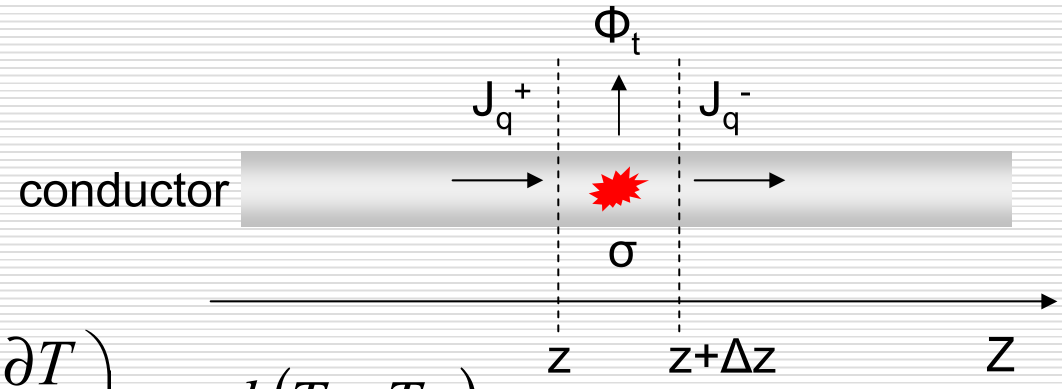


- Need of DB with as build magnet parameters
- Need of new simulation tools
- Need of tools allowing rapid iterations

Transient heat deposition modeling - 1S model

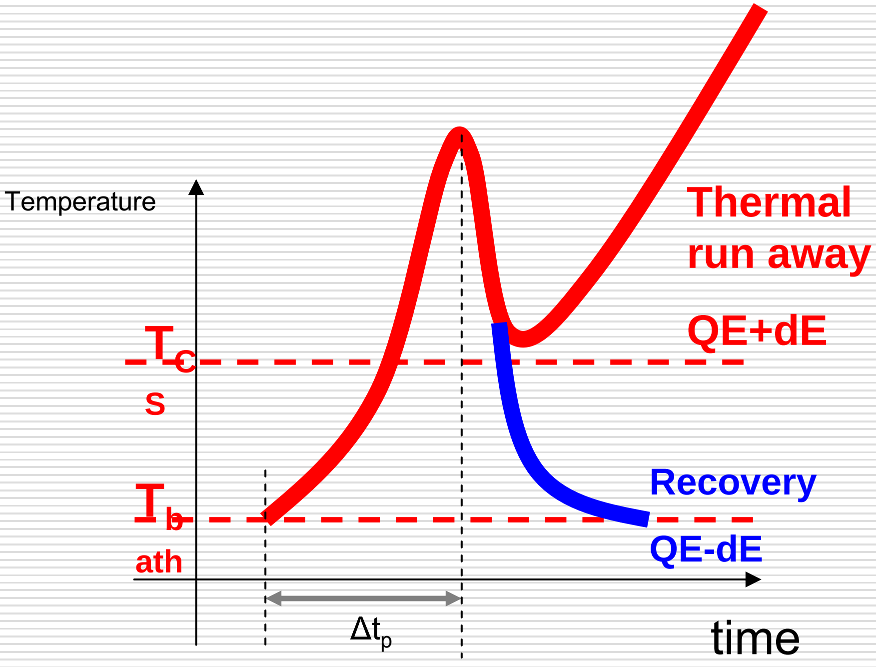
The internal energy balance can be expressed as:

$$\dot{u} = -\mathrm{div}\cdot j_q + \sigma - \Phi_t$$



$$A\rho C\frac{\partial T}{\partial t} = \dot{q} + \dot{q}_{Joule} + \frac{\partial}{\partial z}\left(Ak\frac{\partial T}{\partial z}\right) - p_w h(T - T_H)$$

- ☐ SPQR "1S Model" was used
- ☐ It allows Enthalpy Limit Calculations for transient perturbations
- ☐ It allows to assess impact of various parameters: pulse duration, heated length, magnet current, etc.



Transient heat deposition - 1S model results

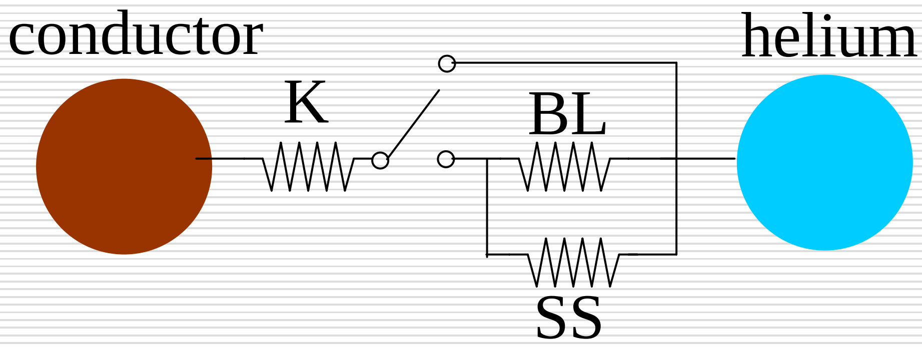
- All types of SC magnets built for LHC at CERN were calculated
- Entalpy Limit Calculations for transient perturbations
- Results published in EDMS Id 750204 AT-MTM-IN-2006-021

Entalpy [mJoule/cm^3]

		Beam energy = 450 GeV		Beam energy = 7000 GeV	
Magnet	**Temp**	**Fast perturbation <100 µs**	**Slow perturbation >100 ms**	**Fast perturbation <100 µs**	**Slow perturbation >100 ms**
MB Type-1	1.9K	*31,29*	*148,53*	*0,93*	*56,26*
MB Type-2	1.9K	*29,24*	*141,21*	*0,90*	*53,70*
MQ Type-3	1.9K	*29,45*	*150,69*	*1,41*	*72,09*
MQM Type-7	1.9K	*30,31*	*127,78*	*1,06*	*50,11*
MQM Type-7	4.5K	*28,22*	*47,58*	*1,63*	*6,35*
MQY Type-5	4.5K	*28,43*	*48,55*	*2,46*	*8,78*
MQY Type-6	4.5K	*32,06*	*57,76*	*4,95*	*15,84*
Orbit correctors					
MCB corr-1	1.9K	*23,21*	*23,21*	*4,77*	*4,77*
MCBC corr-2	1.9K	*23,13*	*23,13*	*4,20*	*4,20*
MCBC corr-2	4.5K	*21,60*	*21,60*	*5,69*	*5,69*
MCBY corr-2	1.9K	*23,30*	*23,30*	*5,21*	*5,21*
MCBY corr-2	4.5K	*21,51*	*21,51*	*5,28*	*5,28*
MCBXH corr-4	1.9K	*33,11*	*33,11*	*10,91*	*10,91*
MCBXV corr-4	1.9K	*33,22*	*33,22*	*11,66*	*11,66*
Multipole correctors					
MCD corr-3	1.9K	*32,88*	*32,88*	*10,65*	*10,65*
MCO corr-2	1.9K	*23,72*	*23,72*	*7,64*	*7,64*
MCOSX corr-2	1.9K	*23,98*	*23,98*	*9,46*	*9,46*
MCOX corr2	1.9K	*23,98*	*23,98*	*9,37*	*9,37*
MCS corr-3	1.9K	*32,99*	*32,99*	*12,27*	*12,27*
MCSSX corr-2	1.9K	*23,98*	*23,98*	*9,50*	*9,50*
MCSX corr-2	1.9K	*23,81*	*23,81*	*7,02*	*7,02*
MCTX corr-2	1.9K	*23,30*	*23,30*	*4,89*	*4,89*
Lattice correctors					
MO corr-3	1.9K	*32,76*	*32,76*	*10,55*	*10,55*
MQS corr-3	1.9K	*32,20*	*32,20*	*5,81*	*5,81*
MQSX corr3	1.9K	*32,20*	*32,20*	*6,32*	*6,32*
MQT corr-3	1.9K	*32,20*	*32,20*	*5,81*	*5,81*
MQTLI corr-3	1.9K	*32,20*	*32,20*	*5,81*	*5,81*
MS corr-3	1.9K	*32,08*	*32,08*	*5,00*	*5,00*
MSS corr-3	1.9K	*32,08*	*32,08*	*5,00*	*5,00*
Q6 at IP6					
MQTLH corr-3	4.5K	*29,72*	*29,72*	*5,69*	*5,69*

Transient heat deposition modeling – 0D model

- Lack of proven models of heat transfer from conductors to HeII, including HeII/HeI transition, Kapitza resistance, boundary layer, etc.
- A simplified “0D model” estimates better than “1S model” contribution of helium enthalpy
  - *See talk of L. Bottura*



$$A\rho C\frac{\partial T}{\partial t} = \dot{q} + \dot{q}_{Joule} - p_w h\left(T - T_{He}\right)$$

$$T_{He} < T_\lambda \rightarrow h^{HeII}$$

$$T_{He} > T_\lambda \rightarrow h^{HeI}$$

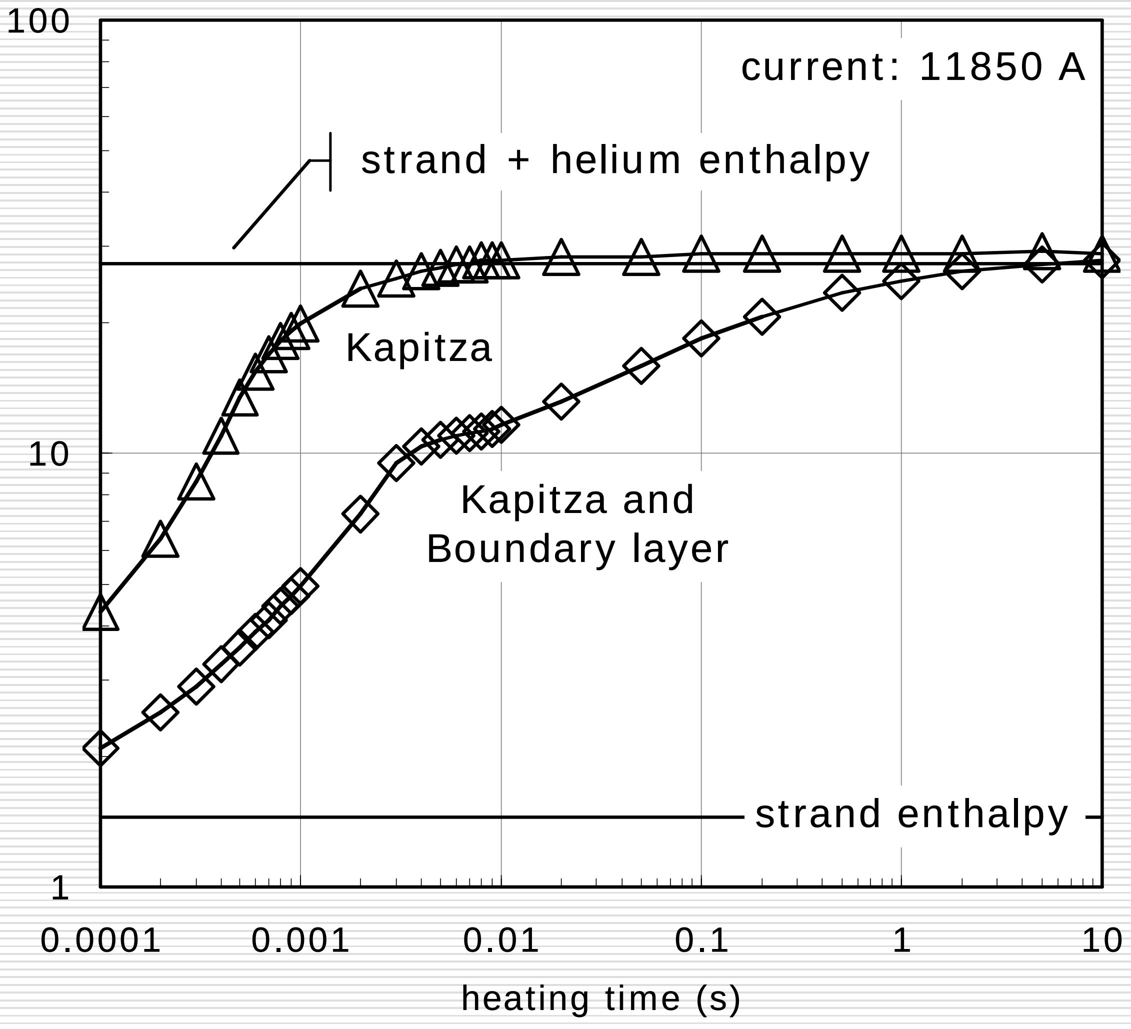
Equivalent heat transfer coefficient

$$Q = h\cdot\left(T - T_{He}\right)$$

$$h^{HeII} = h_K$$

$$h^{HeI} = \tilde{h}_{BL} + \tilde{h}_{SS}$$

Transient heat deposition – 0D model results



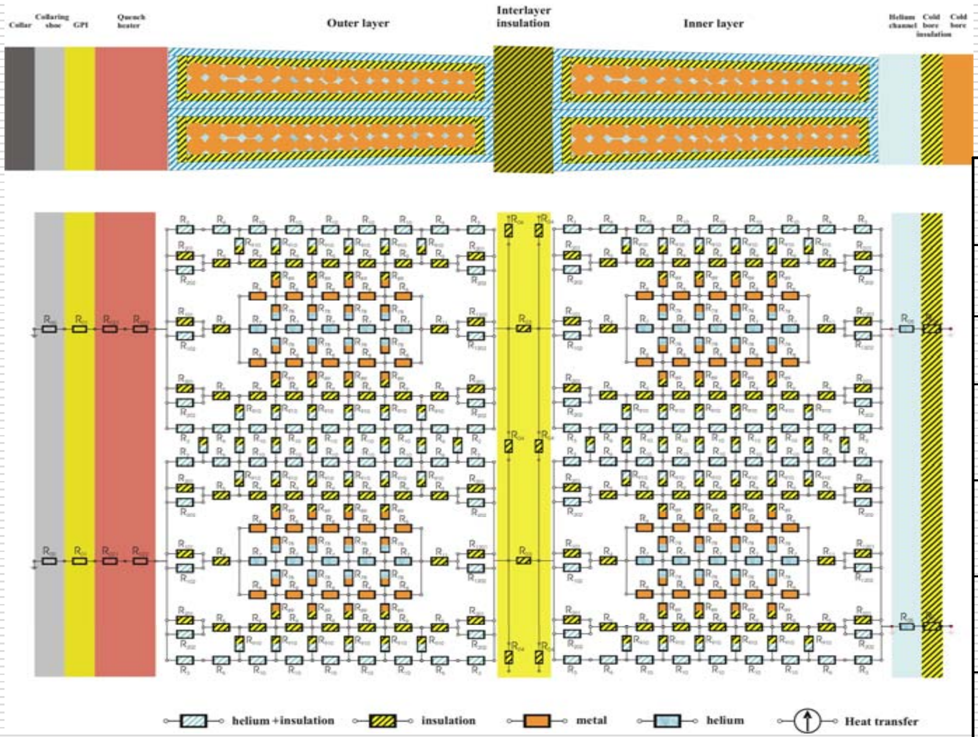
Energy margin as from the 0D model at nominal operating conditions, as a function of the time for the deposition of the heating perturbation.

Two different cooling models were considered: a simplified heat transfer based on the Kapitza resistance, and a more appropriate model that includes the Kapitza resistance as well as the transition to helium I and the formation of a boundary layer around the strand.

The enthalpy of the cable components, either excluding or including the helium fraction in the cable is also reported.

L. Bottura, M.Calvi. A.Siemko.
"Stability of the LHC Cables"
Cryogenics 46 (2006) 481-493

Steady State Heat Deposition - Network Model



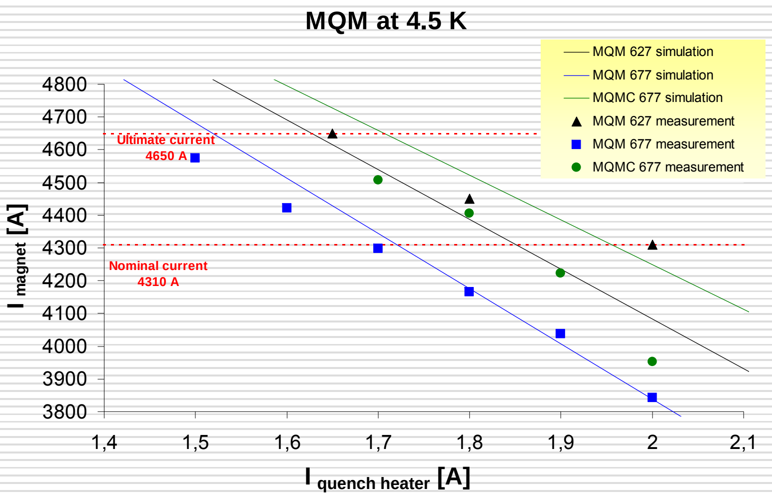
- ☐ The electrical equivalent of the thermal circuit is used

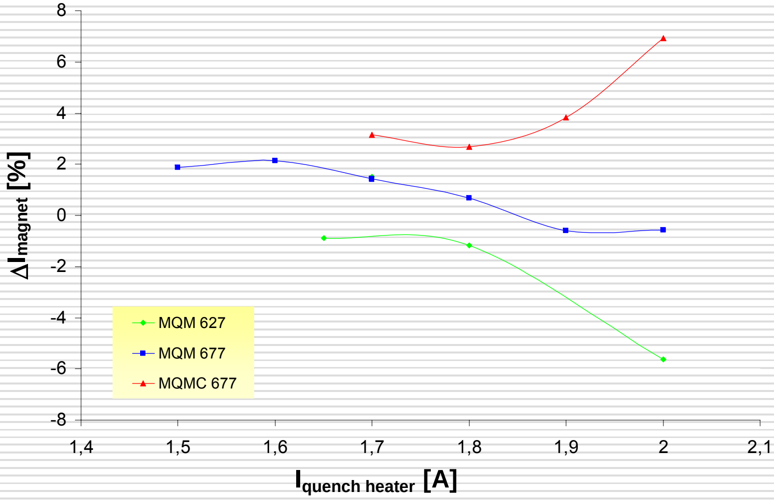
Thermal circuit			Electrical Circuit		
T	**[K]**	**Temperature**	V	**[V]**	**Voltage**
Q	**[J]**	**Heat**	Q	**[C]**	**Charge**
q	**[W]**	**Heat transfer rate**	i	**[A]**	**Current**
κ	**[W/Km]**	**Thermal Conductivity**	σ	**[1/Ωm]**	**Electrical Conductivity**
R^{Θ}	**[K/W]**	**Thermal Resistance**	R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

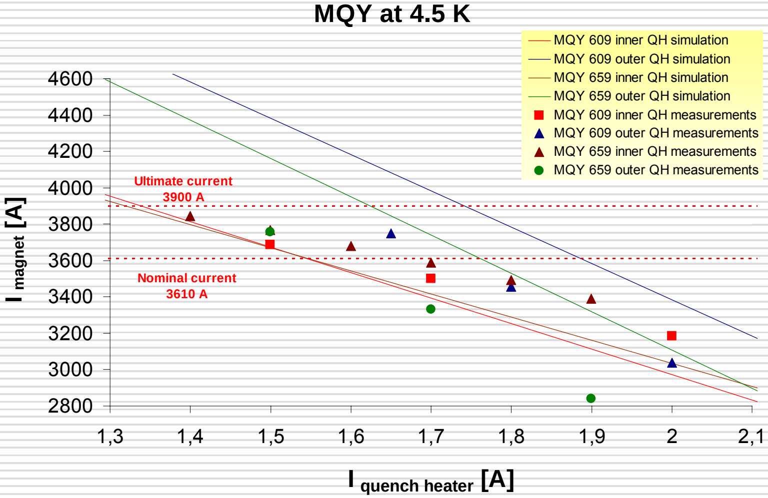
- ☐ PSPICE software is used to implement the magnet models and solve the equations
- ☐ Models of most of the magnets under concern were developed

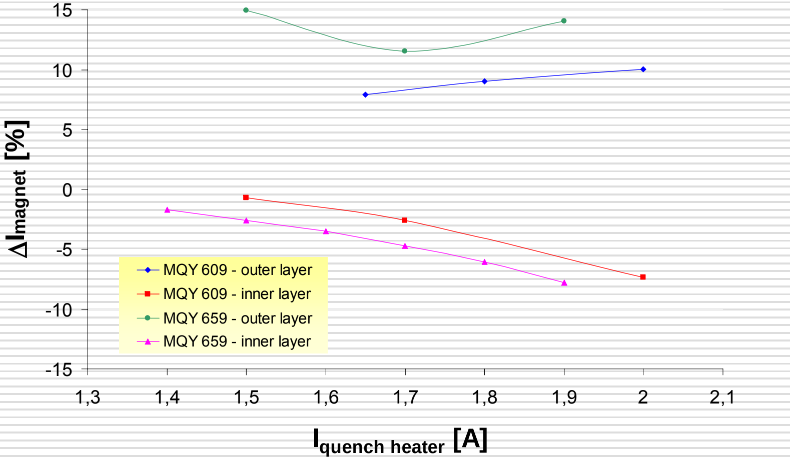
Steady State - Network Model Validation

- ☐ Series of quench heater provoked quenches were performed on MQM and MQY in order to validate the models at 4.5K


MQM at 4.5 K

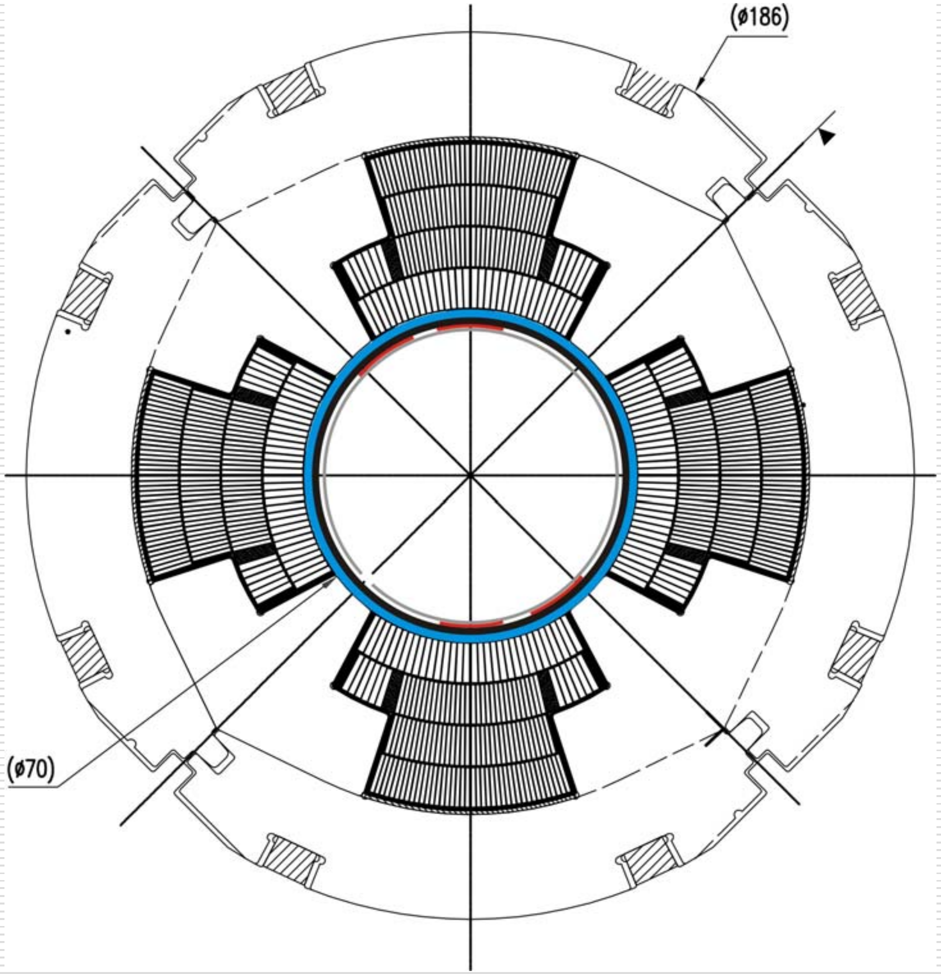


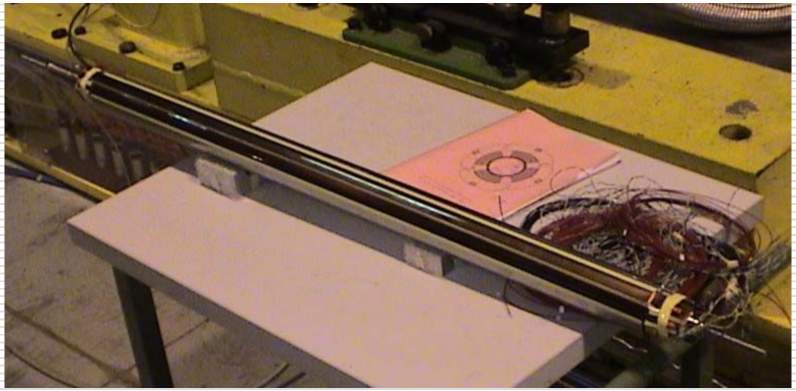

MQY at 4.5 K

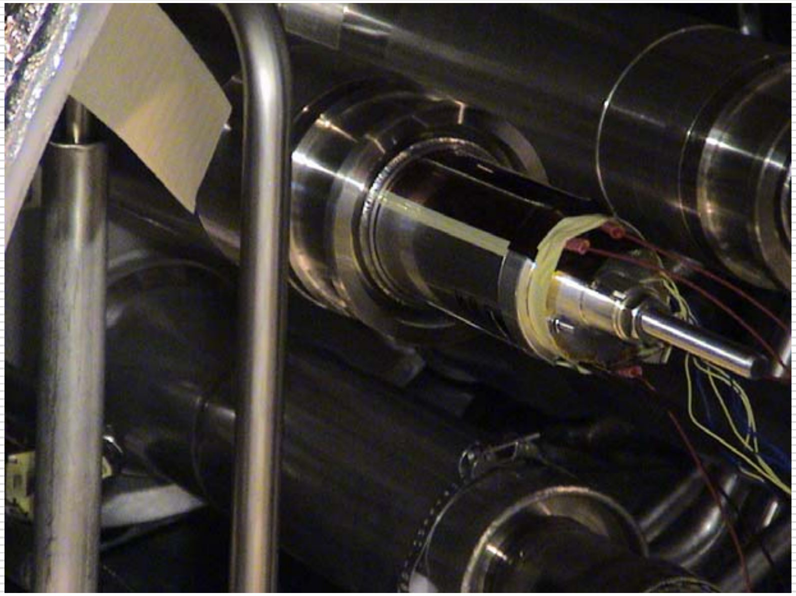


Steady State - Network Model Validation at 1.9K

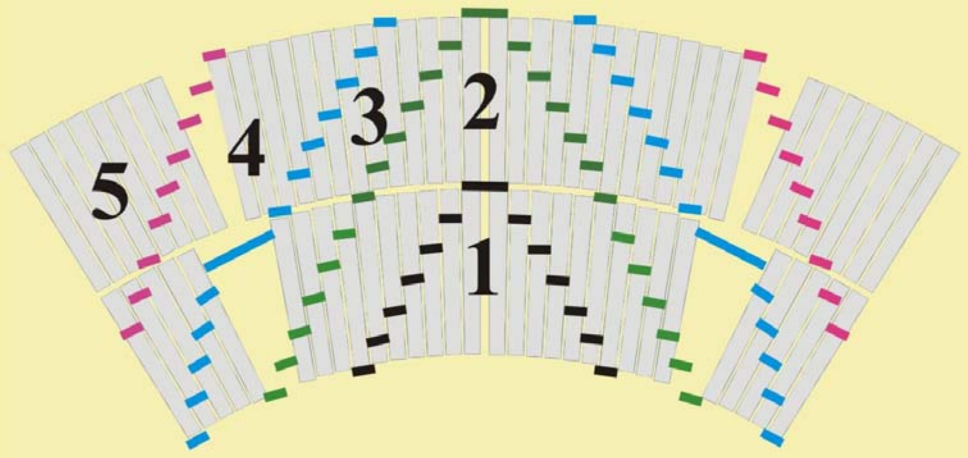
- New “internal” quench heater to provoke quenches was recently developed with the aim to simulate better the beam loss and to validate the network models at 1.9K







Steady State - Network Model First Results



- MQM quench limit for nominal current (4310 A) ⇒ *6 [mW/cm^3]*
- MQM quench limit for ultimate current (4650 A) ⇒ *4 [mW/cm^3]*
- MQM quench limit for nominal current (4310 A)
  and homogeneous heat deposit ⇒ *3 [mW/cm^3]*
- MQY quench limit for nominal current (3610 A) ⇒ *8 [mW/cm^3]*
- MQY quench limit for ultimate current (3900 A) ⇒ *5 [mW/cm^3]*
- MQY quench limit for nominal current (3610 A)
  and homogeneous heat deposit ⇒ *2 [mW/cm^3]*

- Heat transport network model was first exploited for MQM and MQY magnets working at 4.5 K
- The simulation results show strong dependence of quench levels on:
  - beam loss profile
  - distribution of dissipated energy

Outlook and Conclusion

- The SPQR “1S model” and “0D model” were used to asses the enthalpy limits for fast and slow transient heat pulses for all build at CERN LHC magnets
- Transient loss model development is at present on stand-by, but should be resumed in December

- Steady State heat transport network models were developed for all relevant magnets and validated at 4.5 K
  - The results show very good agreement of the measurements with simulations. The relative difference between measured and calculated quench values ranges from 0.6 to 15 % for all measured types of superconducting magnets at 4.5 K

- Network model was used to calculate the first quench limits for MQM and MQY in case of typical beam loss distribution
  - The shape of the perturbation (beam loss profile) is mandatory to perform realistic stability margin calculations
  - Present network model can be used for the quench limit calculation of other magnets working at 4.5 K

- In near future:
  - Validation of the magnet models at 1.9 K (ongoing)
  - If validation successful – simulation of quench levels for magnets working at 1.9K.
  - Non-linear objects in the model are desired to improve the model and simulate better superfluid helium

- Available resources:
  - 1 part time fellow + 1 student (from December)