Beam loss induced quenches

(Update on quench limit calculations)

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Outline

- Motivation
- Thermodynamics of magnet structure
  - Magnet characteristic
  - Heat transport in the magnets
  - Characteristic of superconducting coils
- Network Model
  - Electrical equivalent
  - Superconducting cable and coil models
- Validation of the model
  - 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

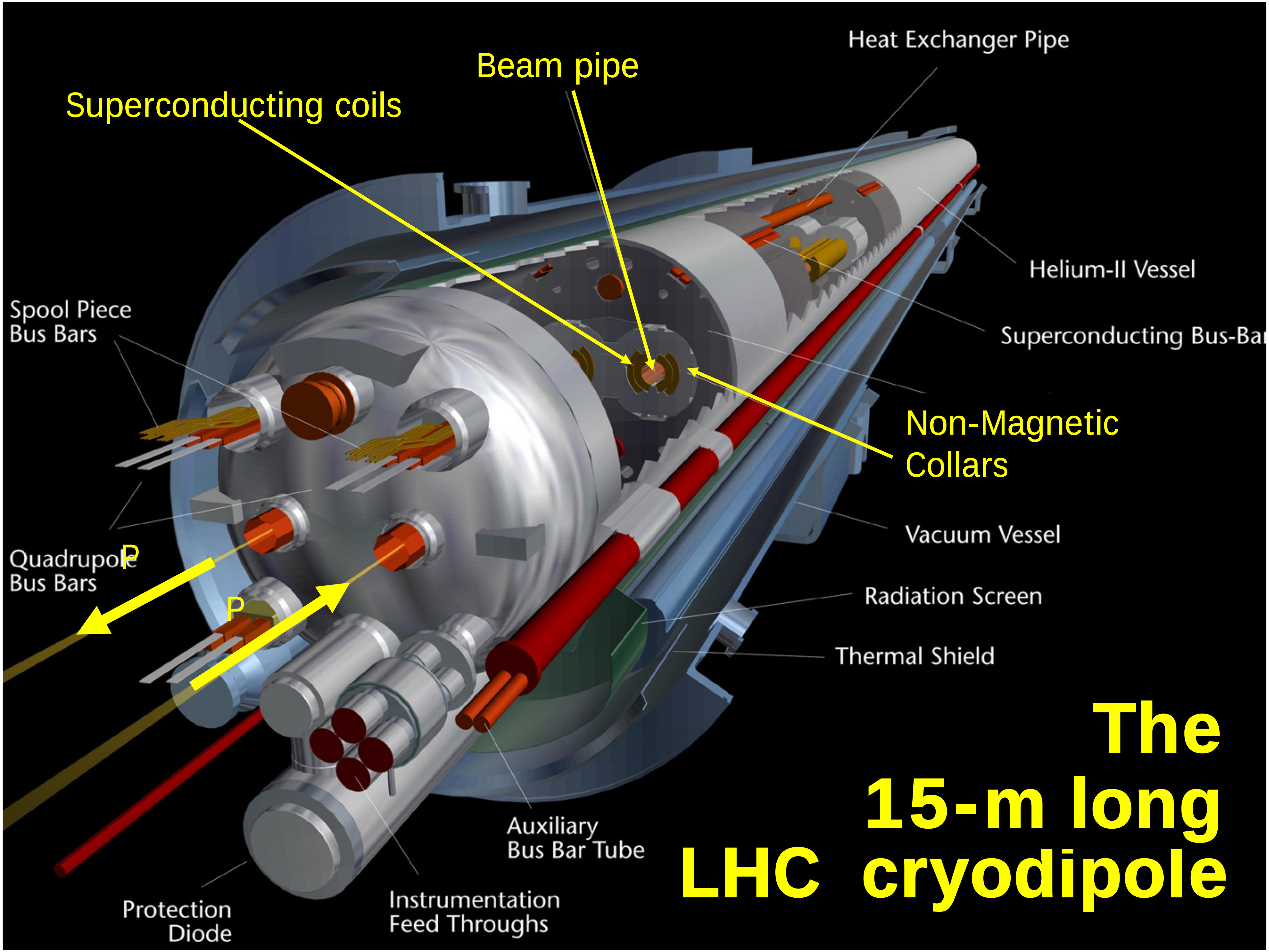
AT - MTM

Thermodynamics of magnet structure

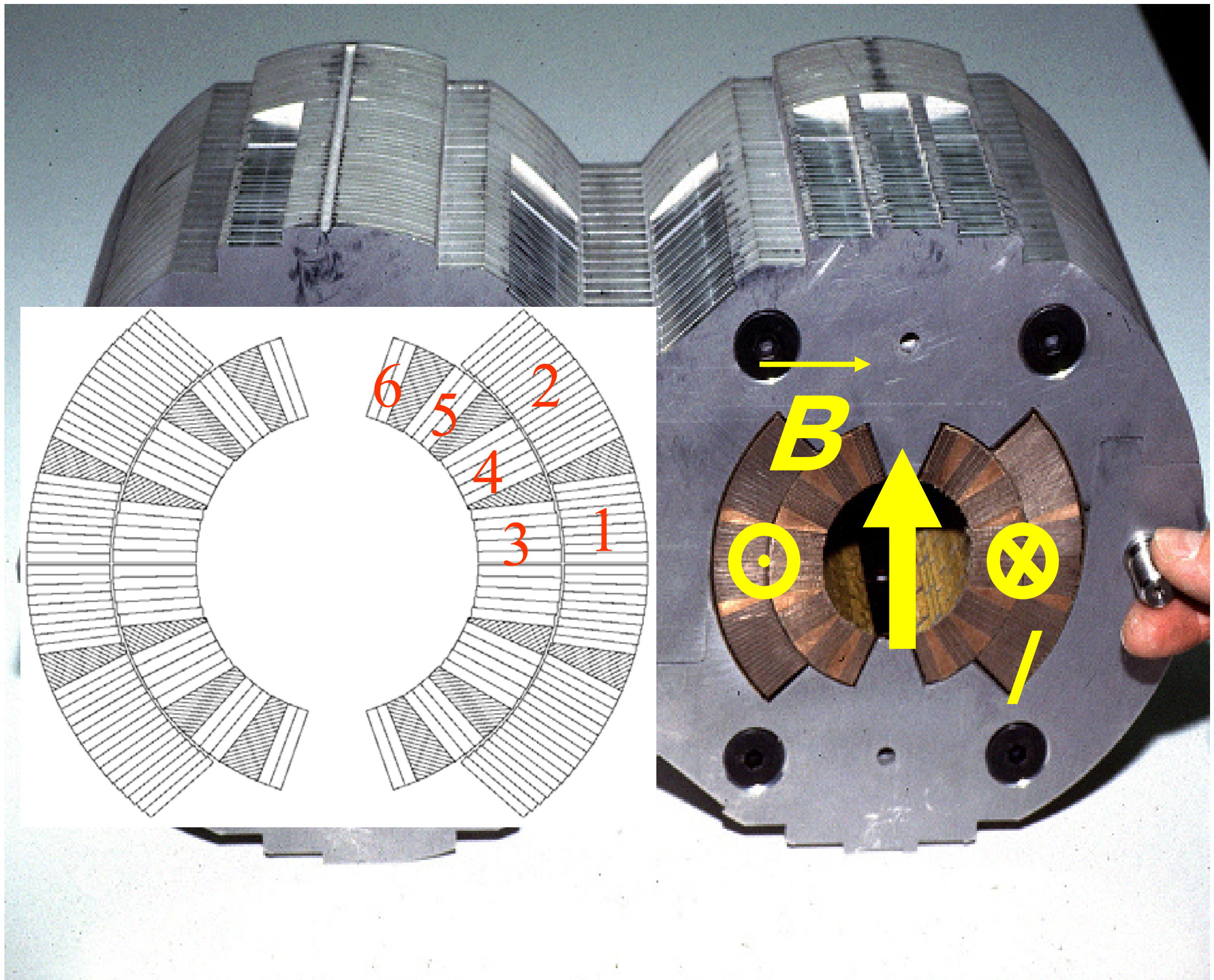
Magnet characteristic

Heat transport in the magnets

Characteristic of superconducting coils


Beam pipe
Superconducting coils
Heat Exchanger Pipe
Helium-II Vessel
Spool Piece
Bus Bars
Superconducting Bus-Bar
Non-Magnetic
Collars
Quadrupole
Bus Bars
P
P
Vacuum Vessel
Radiation Screen
Thermal Shield
Auxiliary
Bus Bar Tube
Protection
Diode
Instrumentation
Feed Throughs
The
15-m long
LHC cryodipole

Magnets chracteristic
LHC dipole magnets cross section



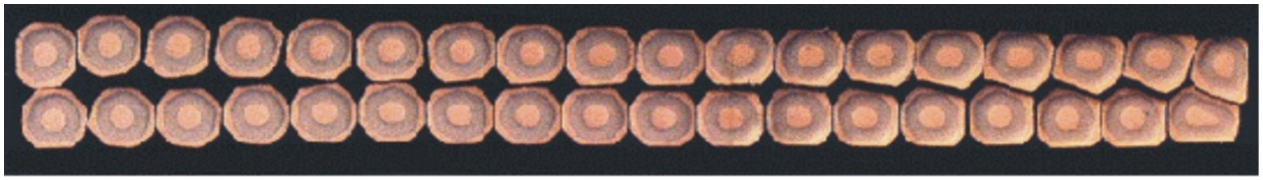
Thermodynamics of magnet structure

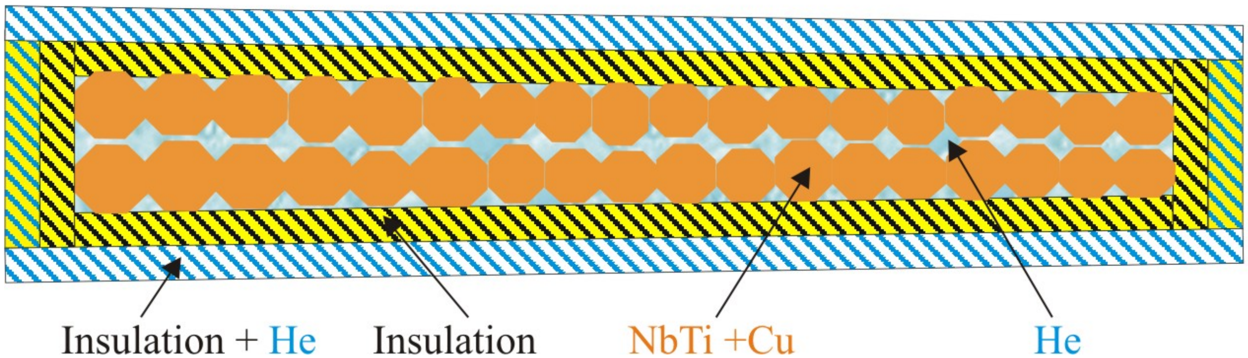
Magnet characteristic

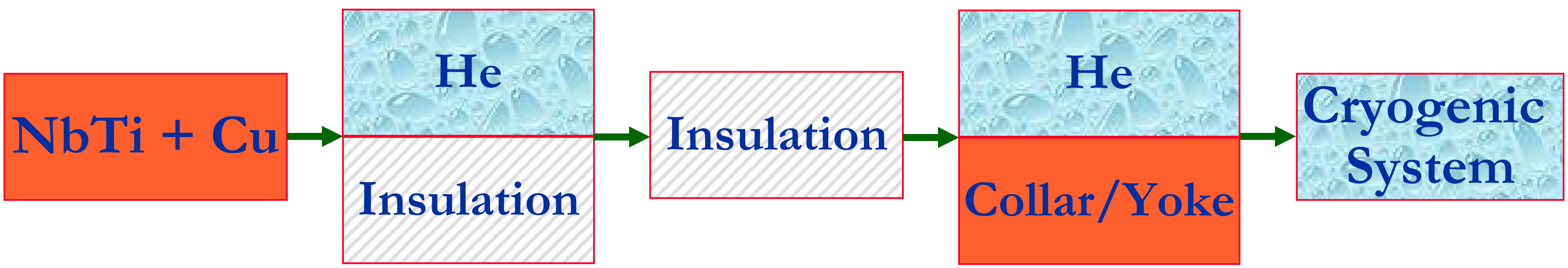
Heat transport in the magnets

Characteristic of superconducting coils

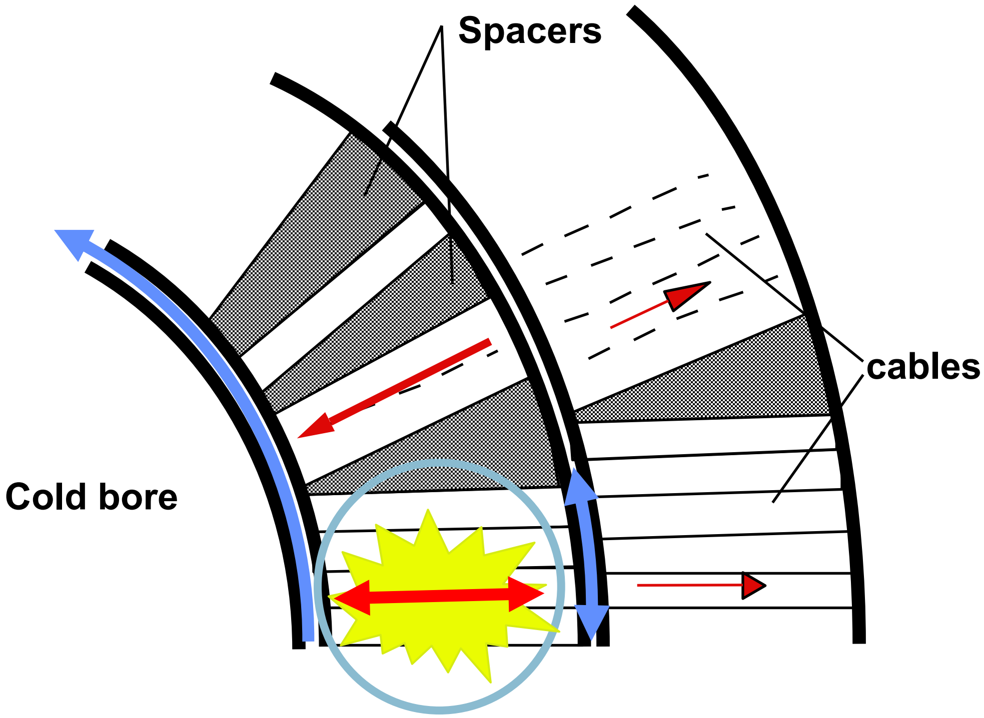
Steady state heat transport in the magnet

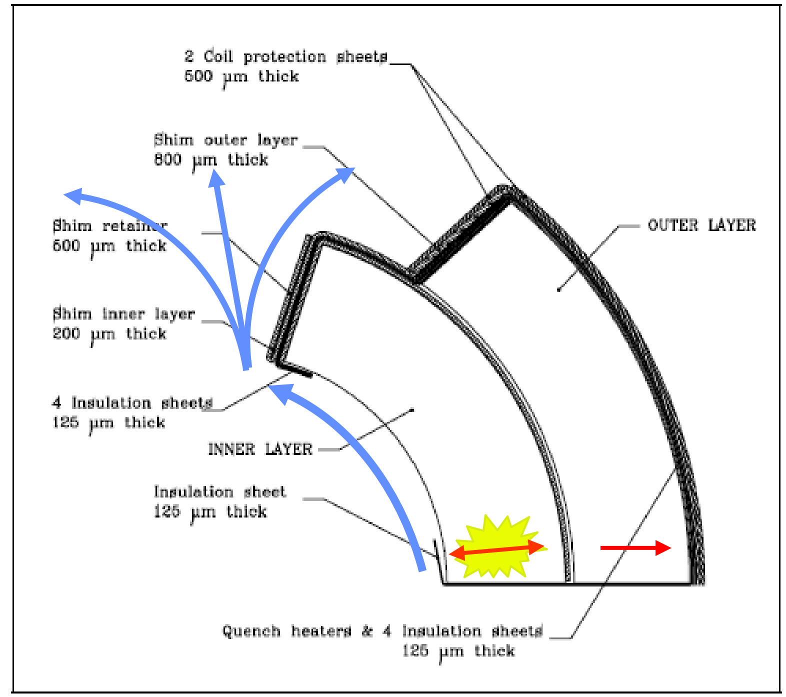






Steady state heat transport in the magnet

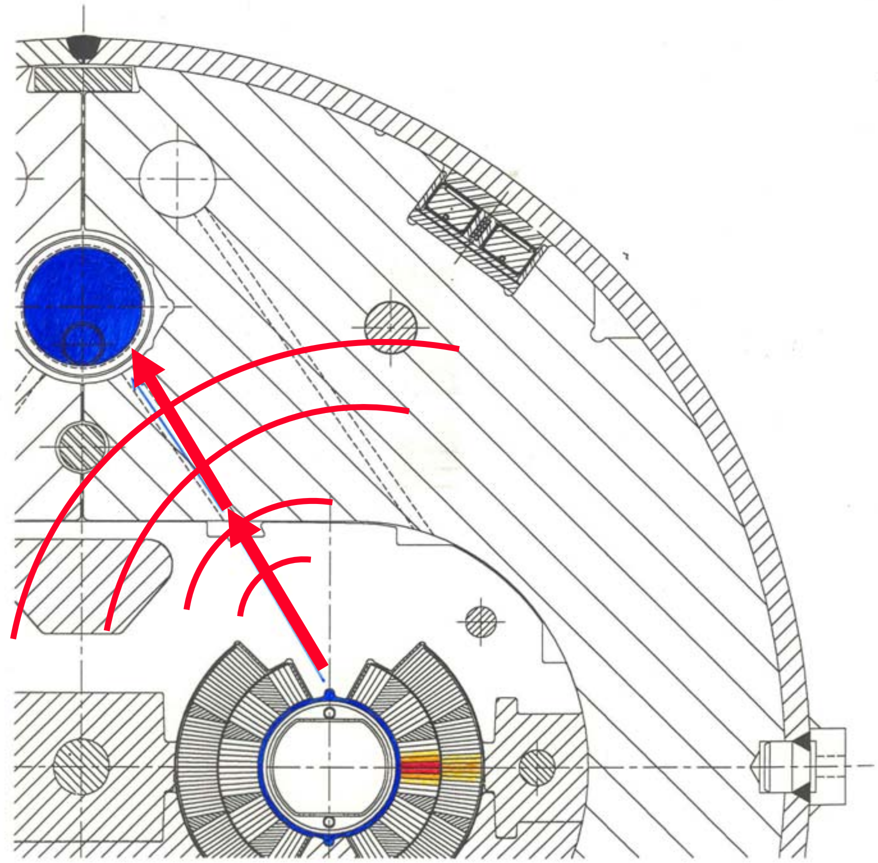




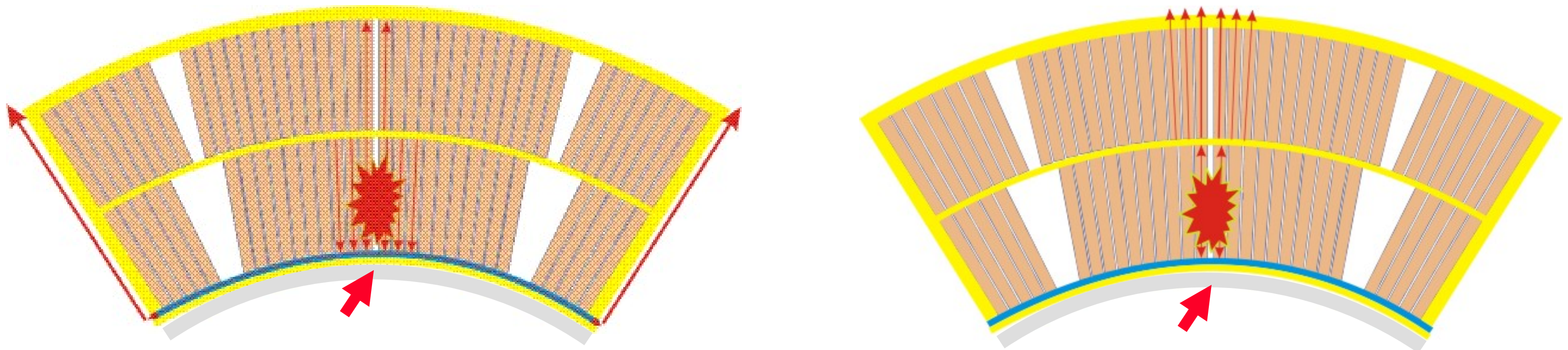
A heat transfer in the main dipole. Arrows indicate the radial path of the heat transfer in the magnet.

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=4.5K(right).

Thermodynamics of magnet structure

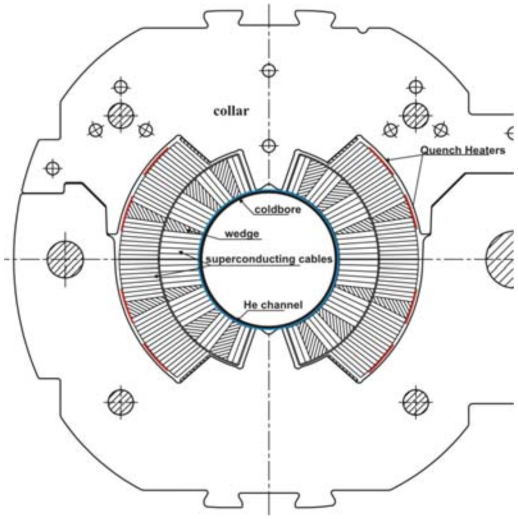
Magnet characteristic

Heat transport in the magnets

Characteristic of superconducting coils

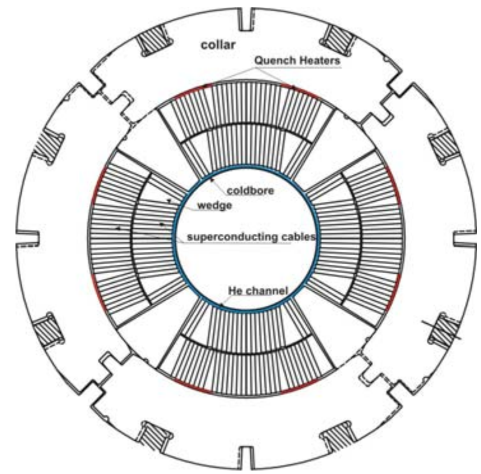
Magnets coil

Arc magnet



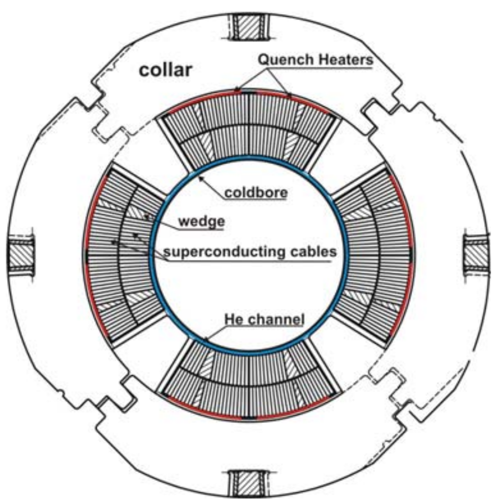
MB

Arc magnet



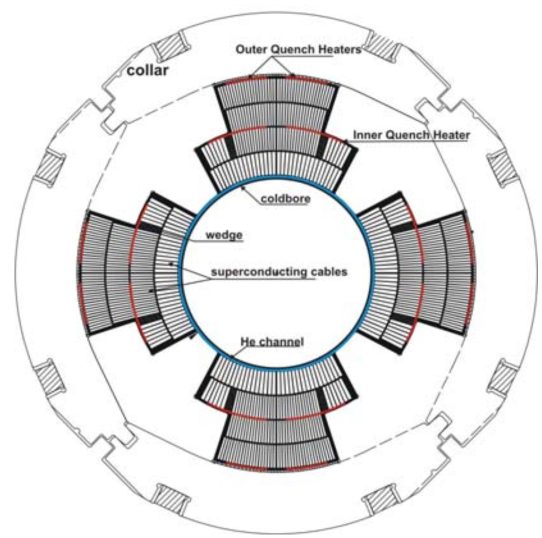
MQ

LSS magnet



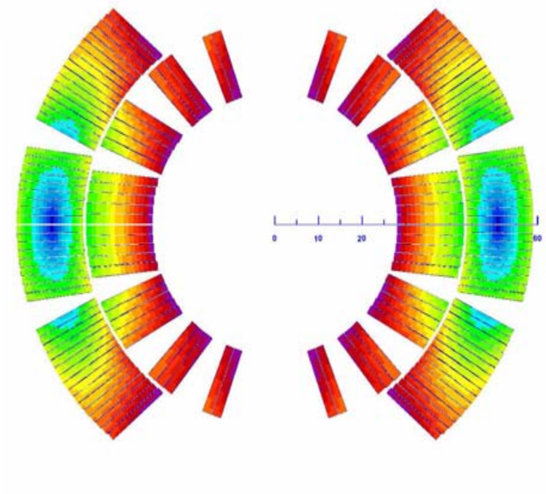
MQM

LSS magnet

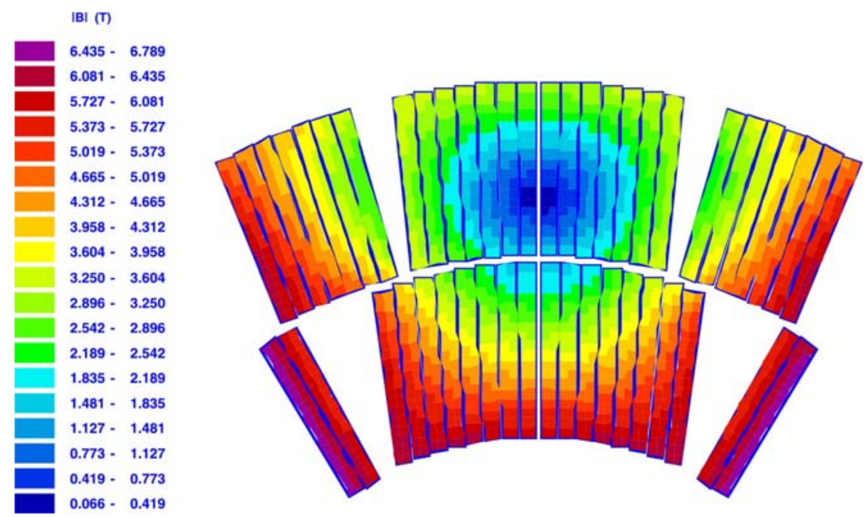


MQY

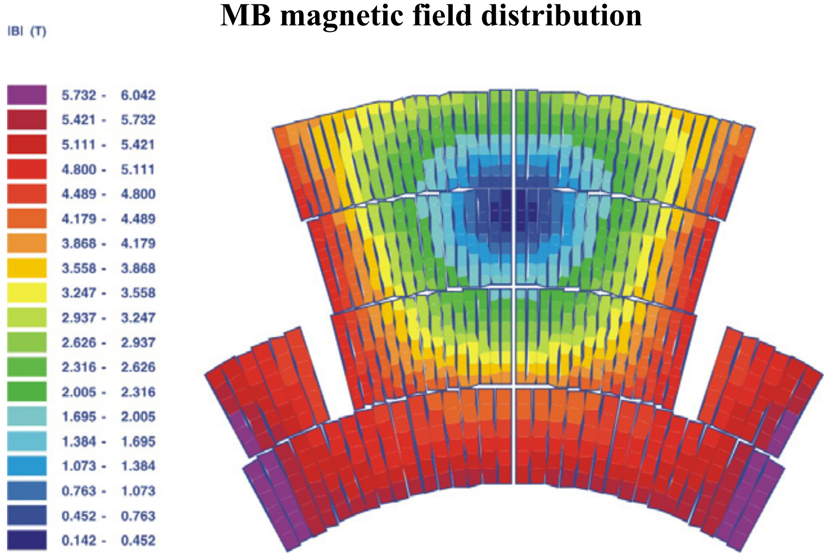
Magnetic field distribution in the coils



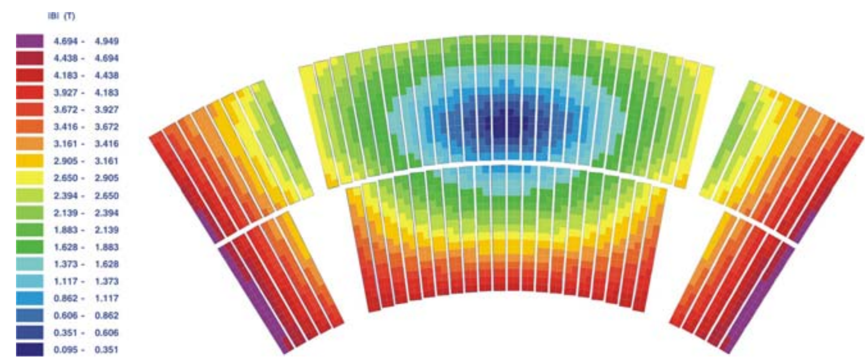
MB magnetic field distribution



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

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*

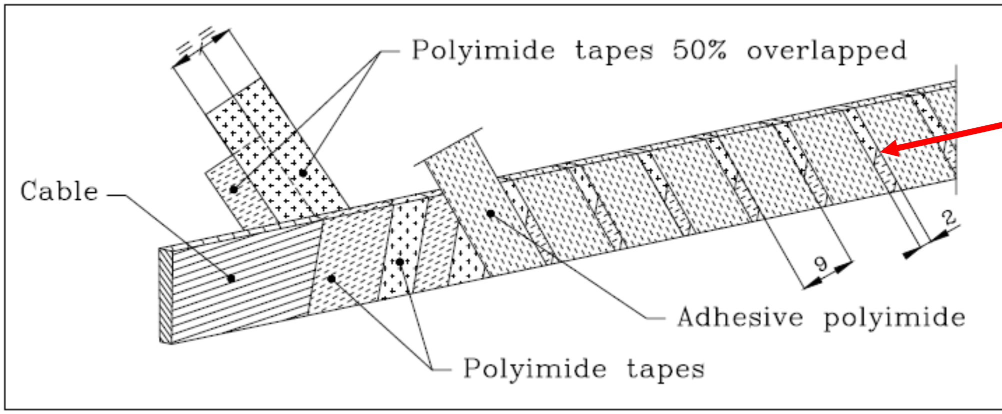
$$\nabla^2 T = R^{\Theta} C^{\Theta} \frac{\partial T}{\partial t} \quad \Leftrightarrow \quad \nabla^2 V = RC \frac{\partial V}{\partial t}$$

Network Model

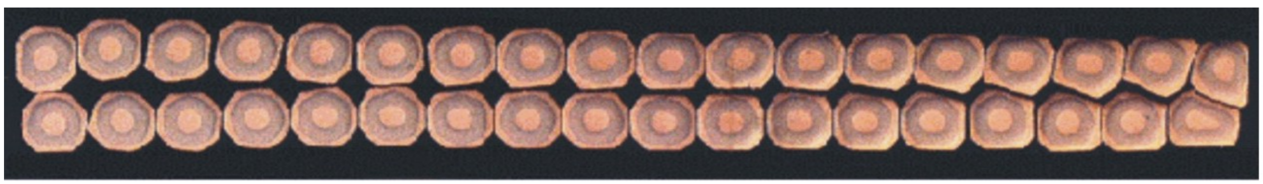
Electrical equivalent

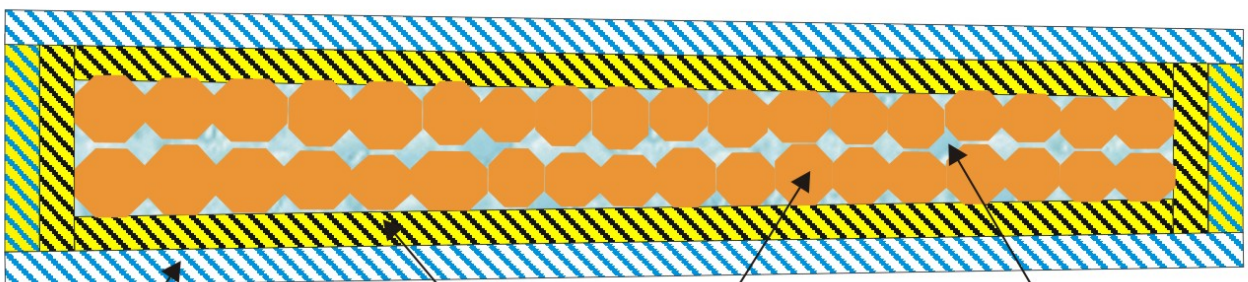
Model of the superconducting cable and coils

"WET" superconducting cable modeling



μ-channel





Cable modeling

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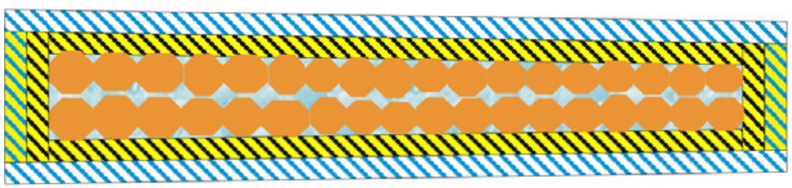
Cable



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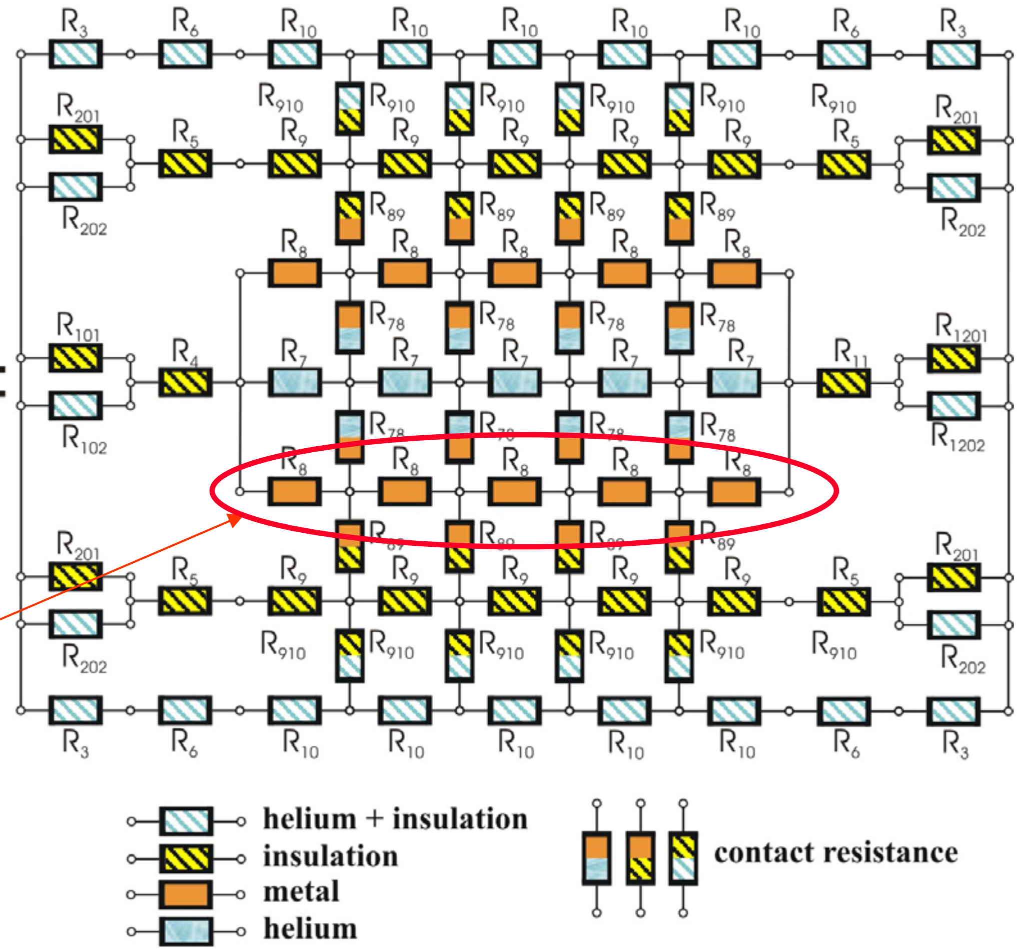
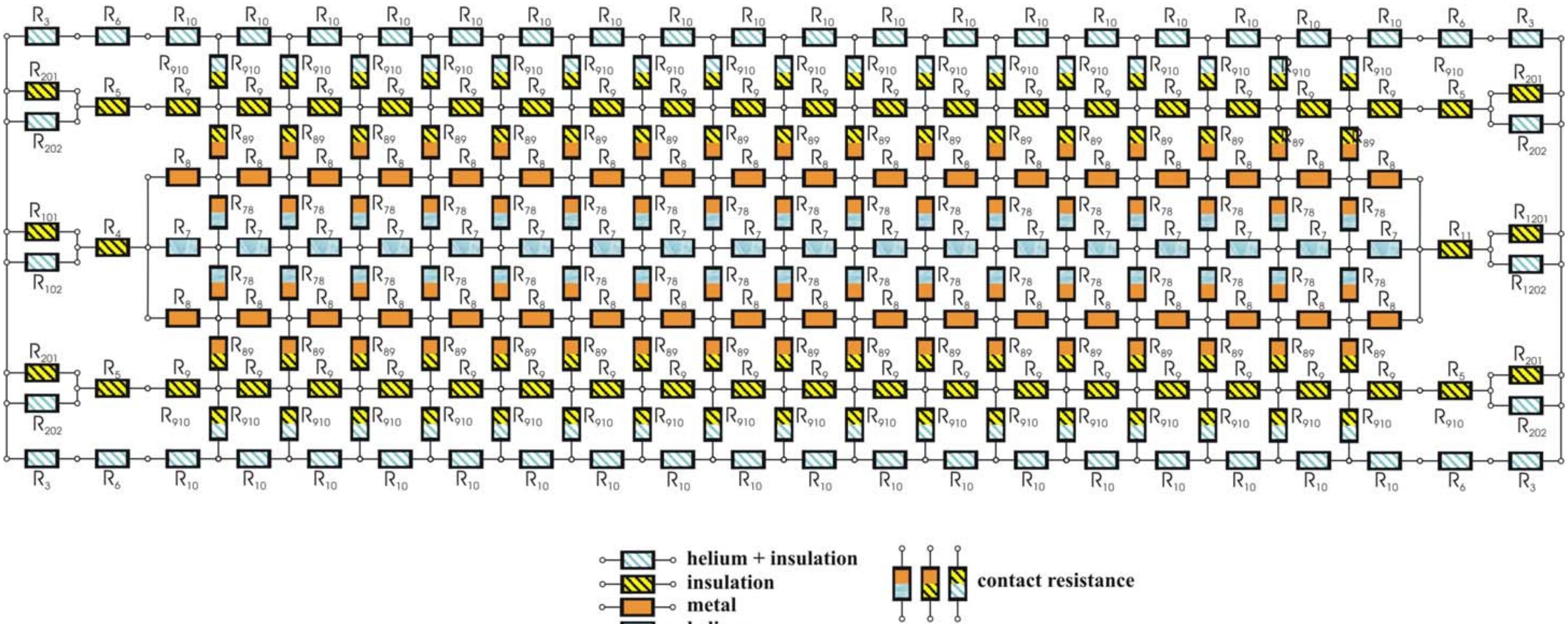
Network model of the cable



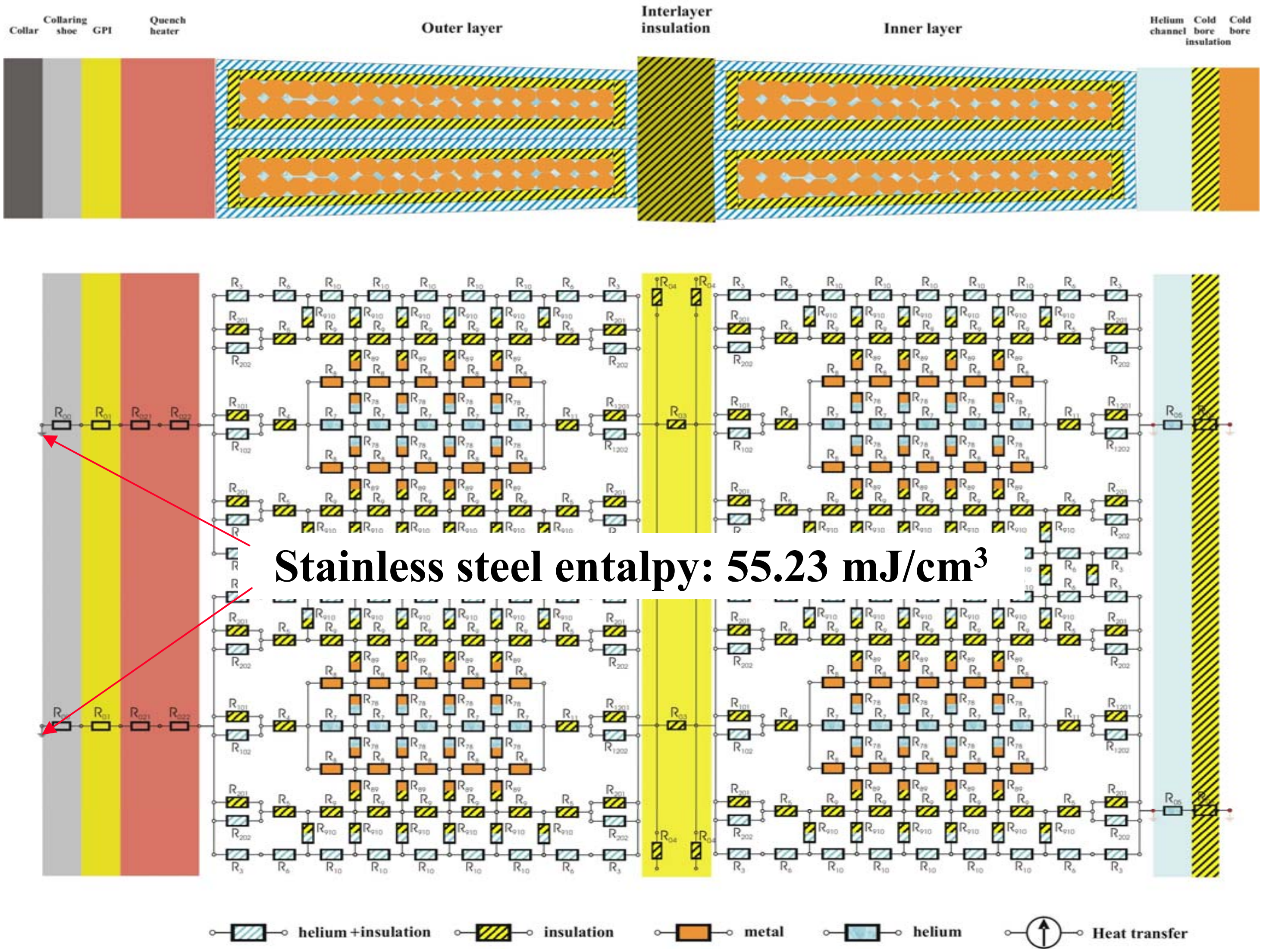
5 block discretization

Cable model – 36 strands

Network model of the cable - 36 strands model



Coil modeling



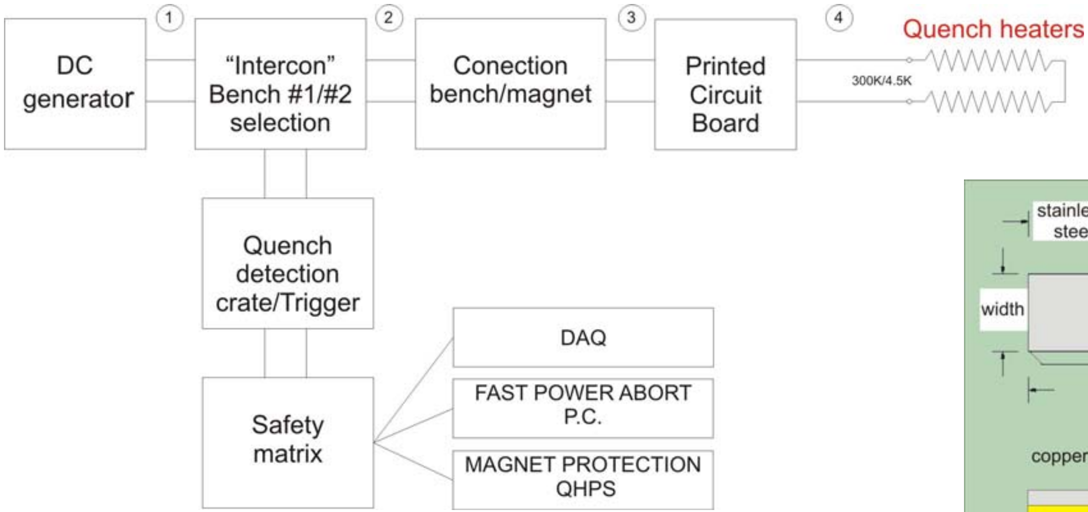
Stainless steel entalpy: 55.23 mJ/cm^3

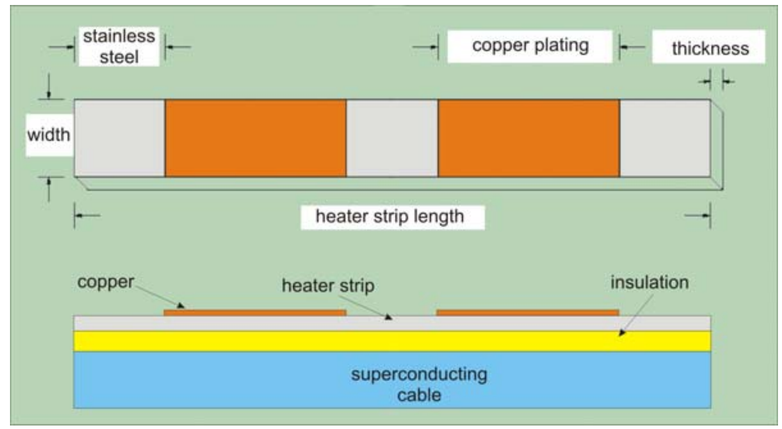
Validation of the model

Measurements in SM18

Evaluation of the network model quality

Measurements in SM 18

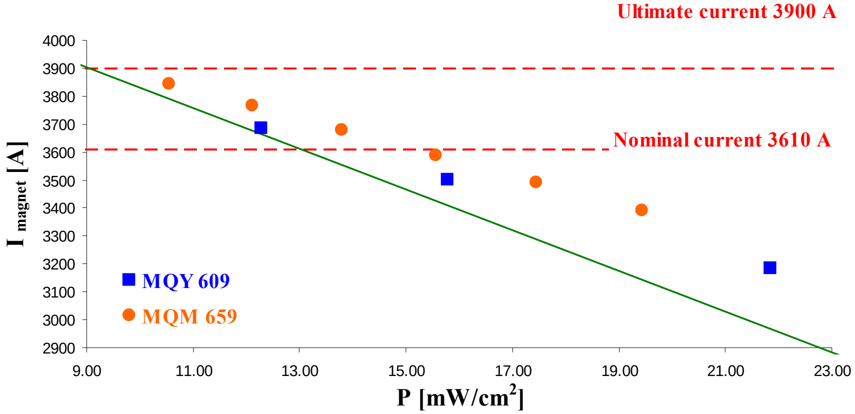




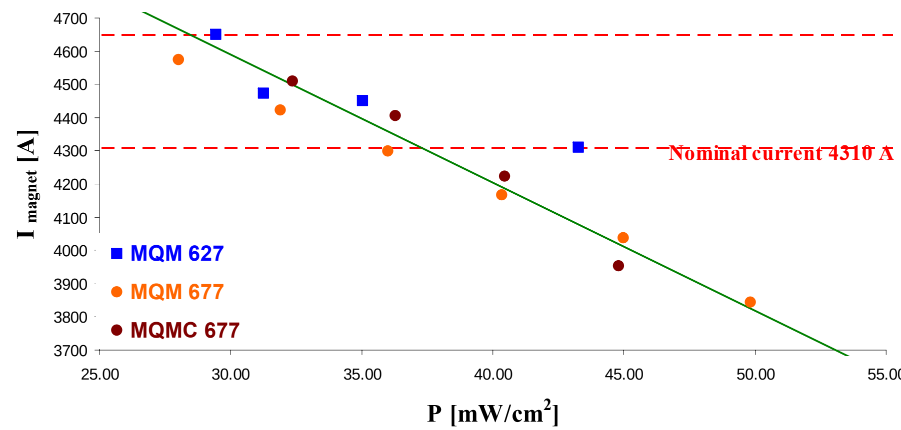
- **Two methods of measurement**
  - I_{coil} =const, increase of I_{QH} with a step of 0.1 A
  - I_{QH} =const, wait 300 second for staeady state, then ramp of I_{coil}
- **Second method is better for steady state heat transport**
- **3 MQM's and 2 MQY's at 4.535K have been tested**

Results of the measurements with QH

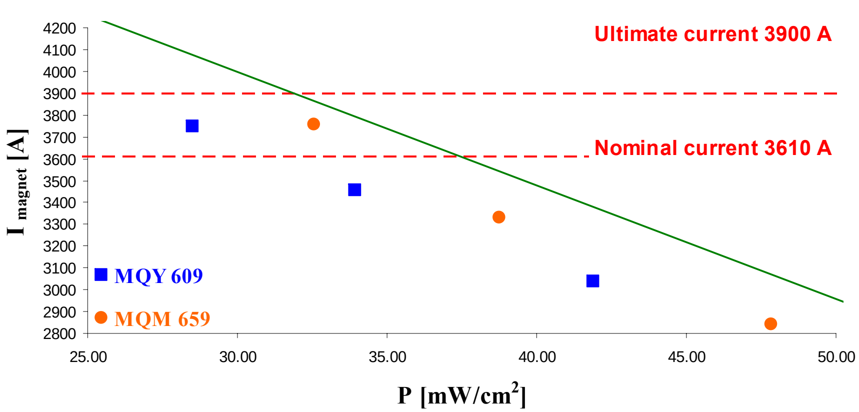
MQY inner quench heater



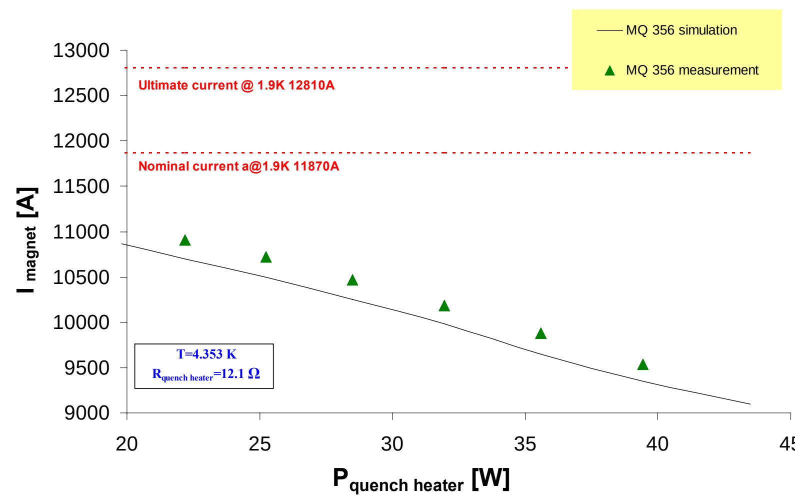
MQM magnets at 4.5 K



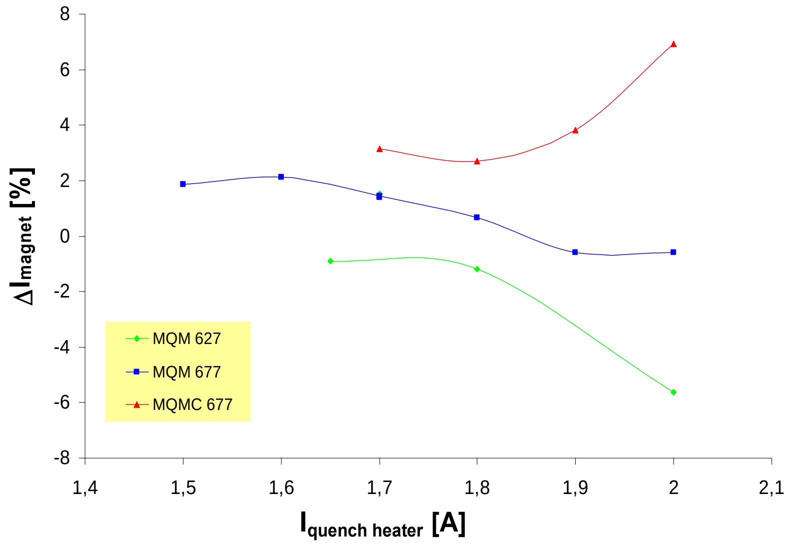
MQY - outer quench heater

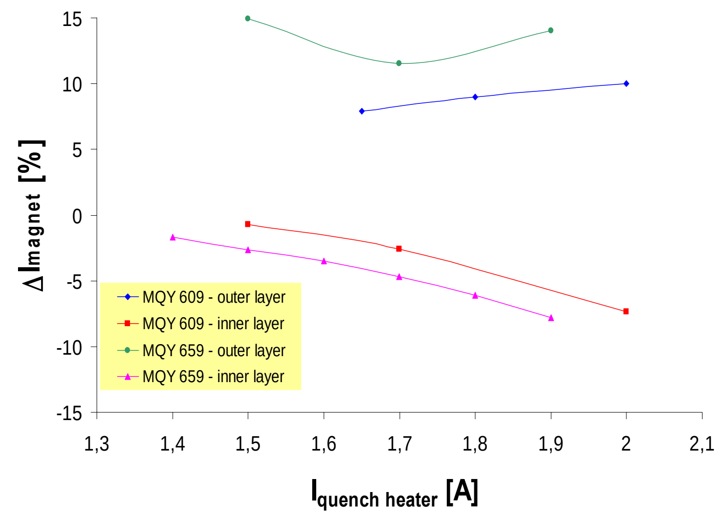


MQ at 4.5 K



Results of the measurements with QH
Relative difference

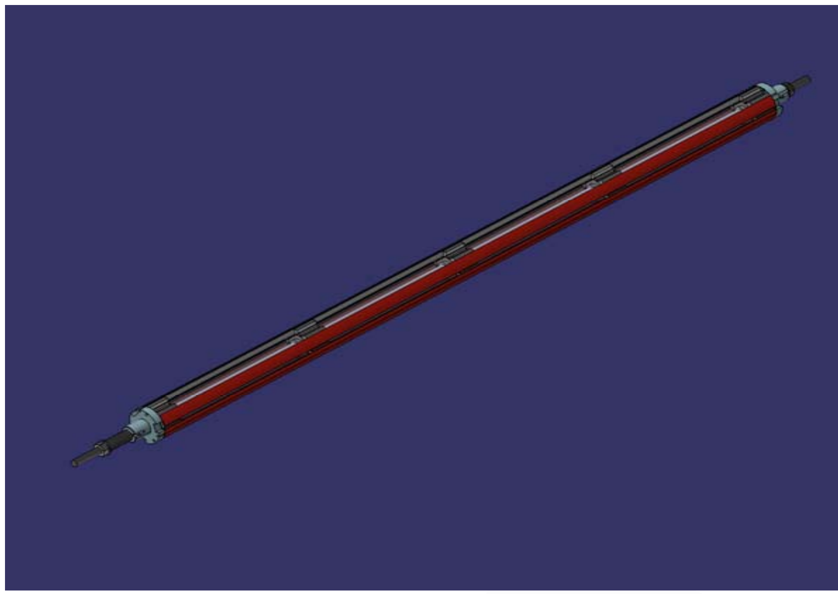


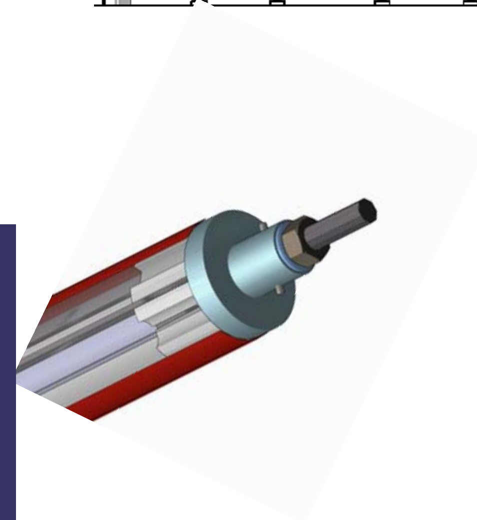


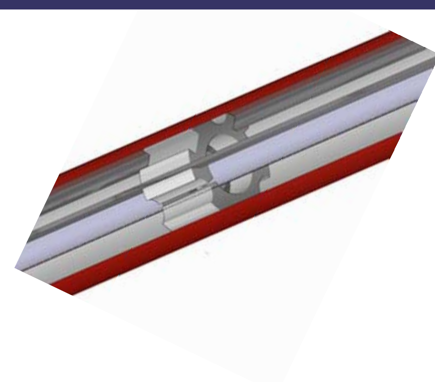
The results show very good agreement of the measurements with simulations.

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 Aparatus







Internal Heating Aparatus in the coil

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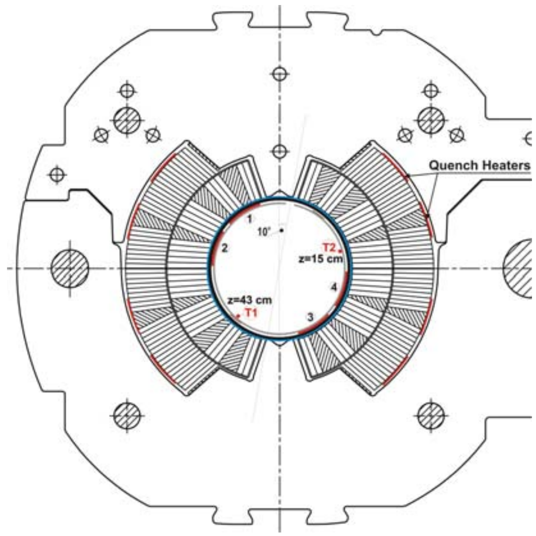
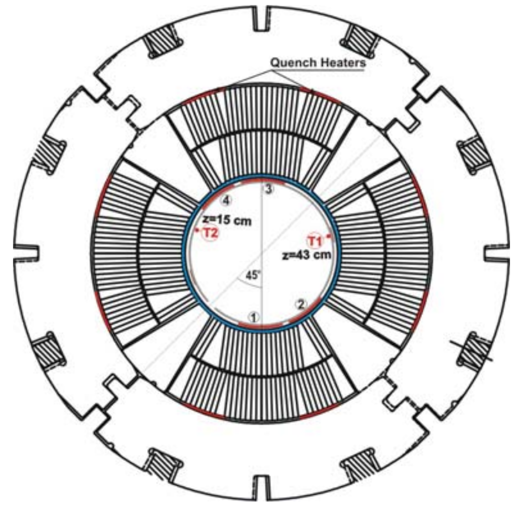
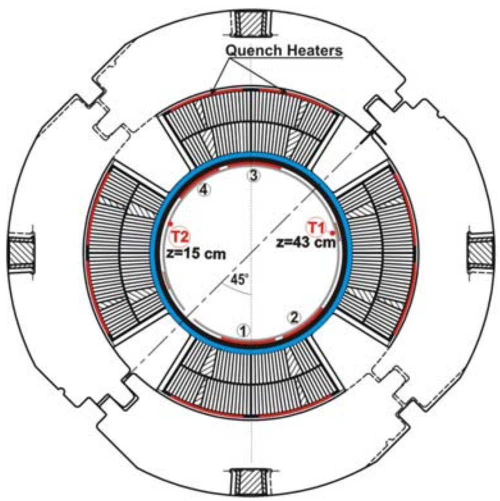


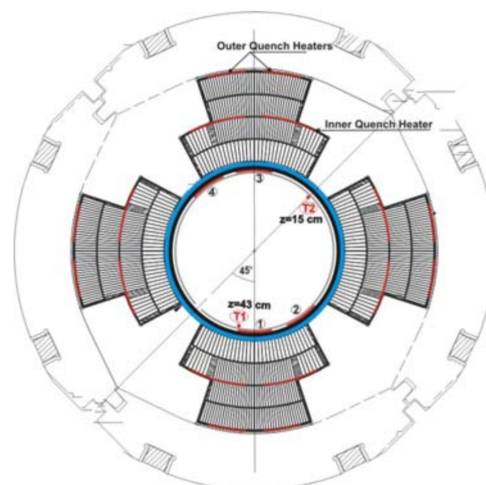
Main Dipole - MB



Main Quadrupole - MQ



MQM

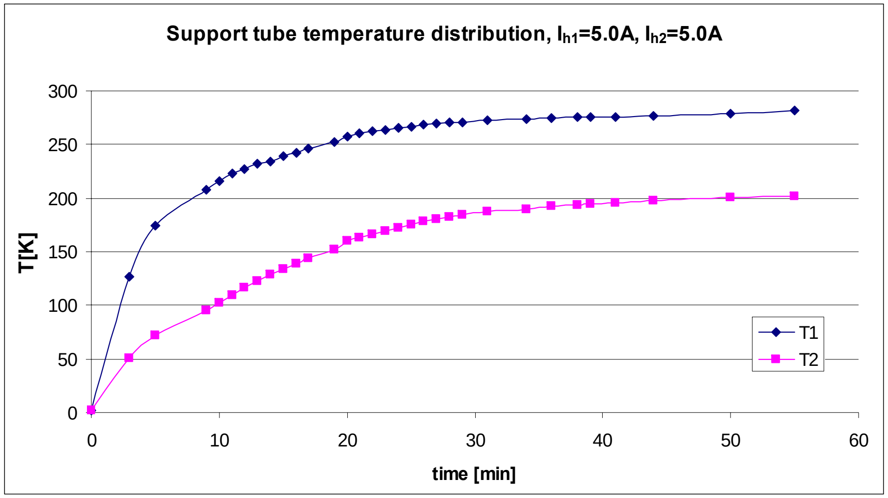


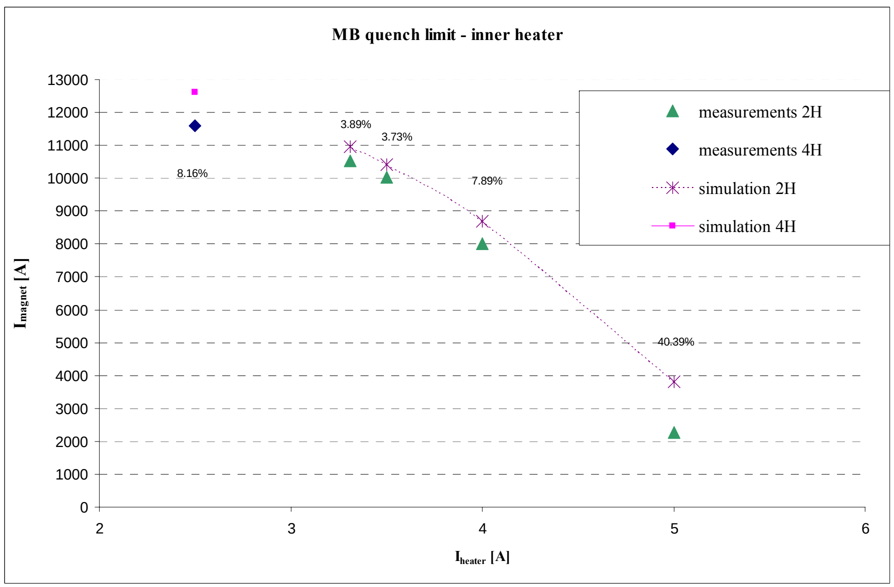
MQY

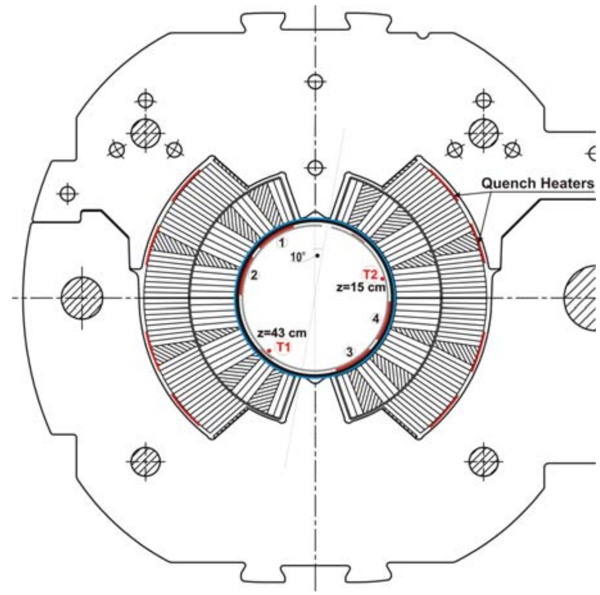
Results of the measurements with IHA

PRELIMINARY RESULTS

AT - MTM







Main Dipole - MB

ADDITIONAL MEASUREMENTS ARE NECESSARY

Validation of the model

Measurements in SM18

Evaluation of the network model quality

Evaluation of the Network Model
Matching Algorithm

Matching algorithm have been developed to match the heat conduction parameters to the temperature profile in the magnet coil

ΔT=0.1K – accuracy level

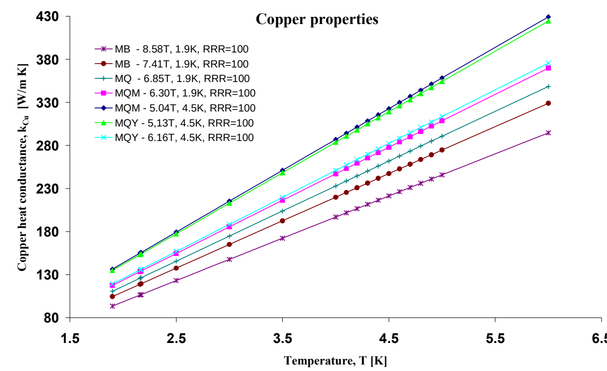
$\Delta T_i = T_i - T_{i-1}$

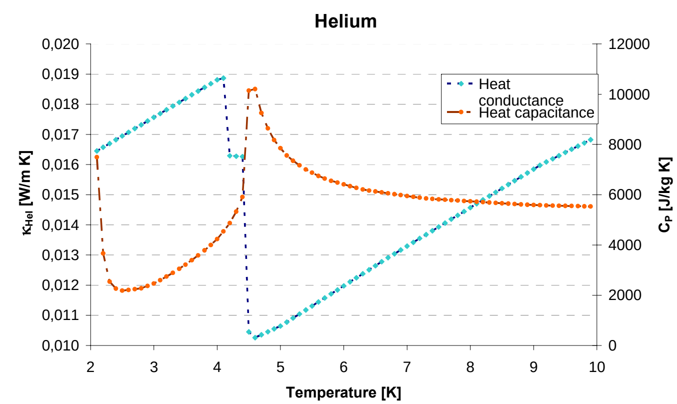
IF($\Delta T_i = \Delta T$) THEN „finish iteration"

IF($\Delta T_i < 0$) THEN $T_i = T_{i-1} - \Delta T_i/2$

ELSE $T_i = T_{i-1} - \Delta T_i/2$

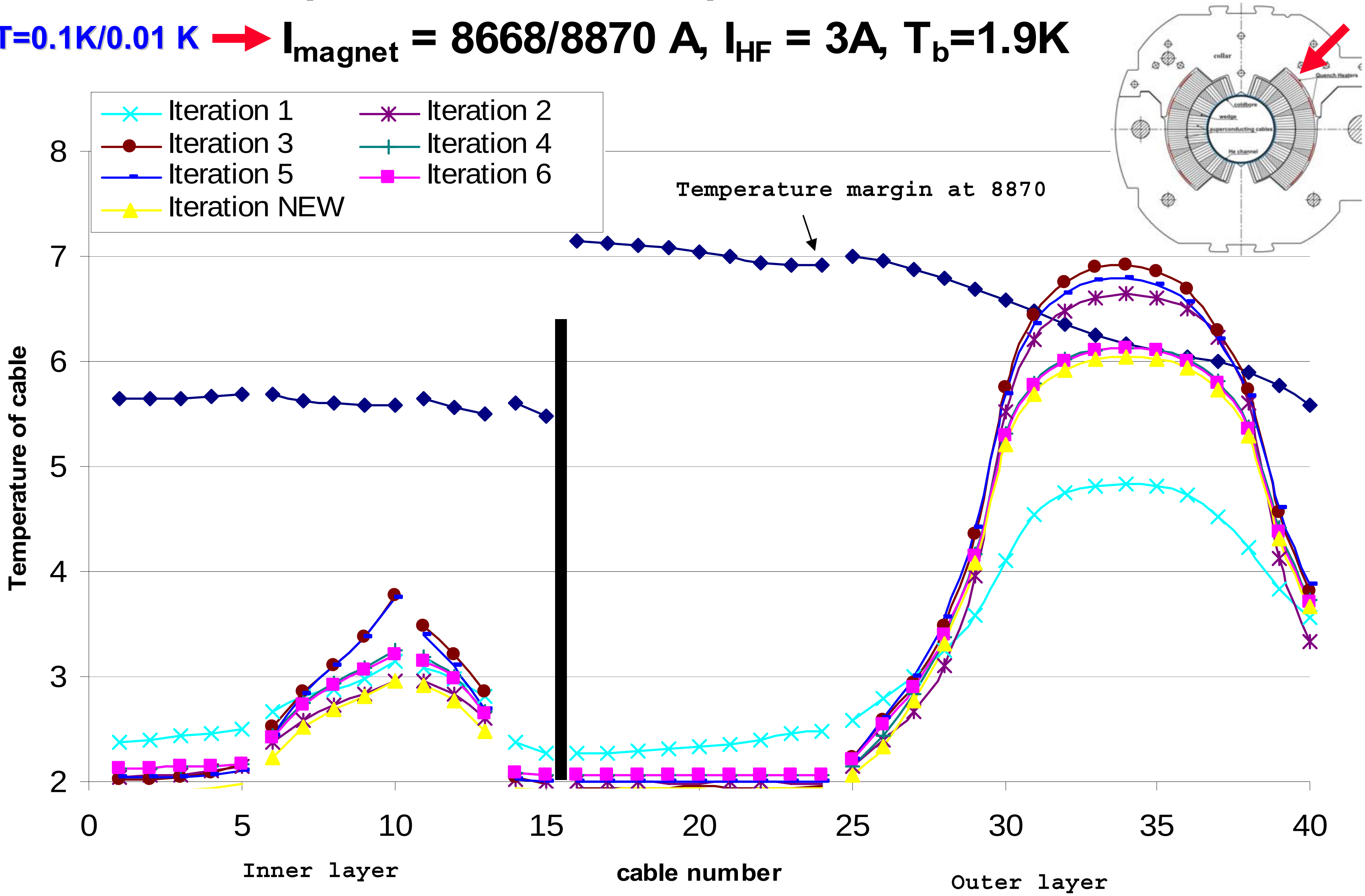
ENDIF





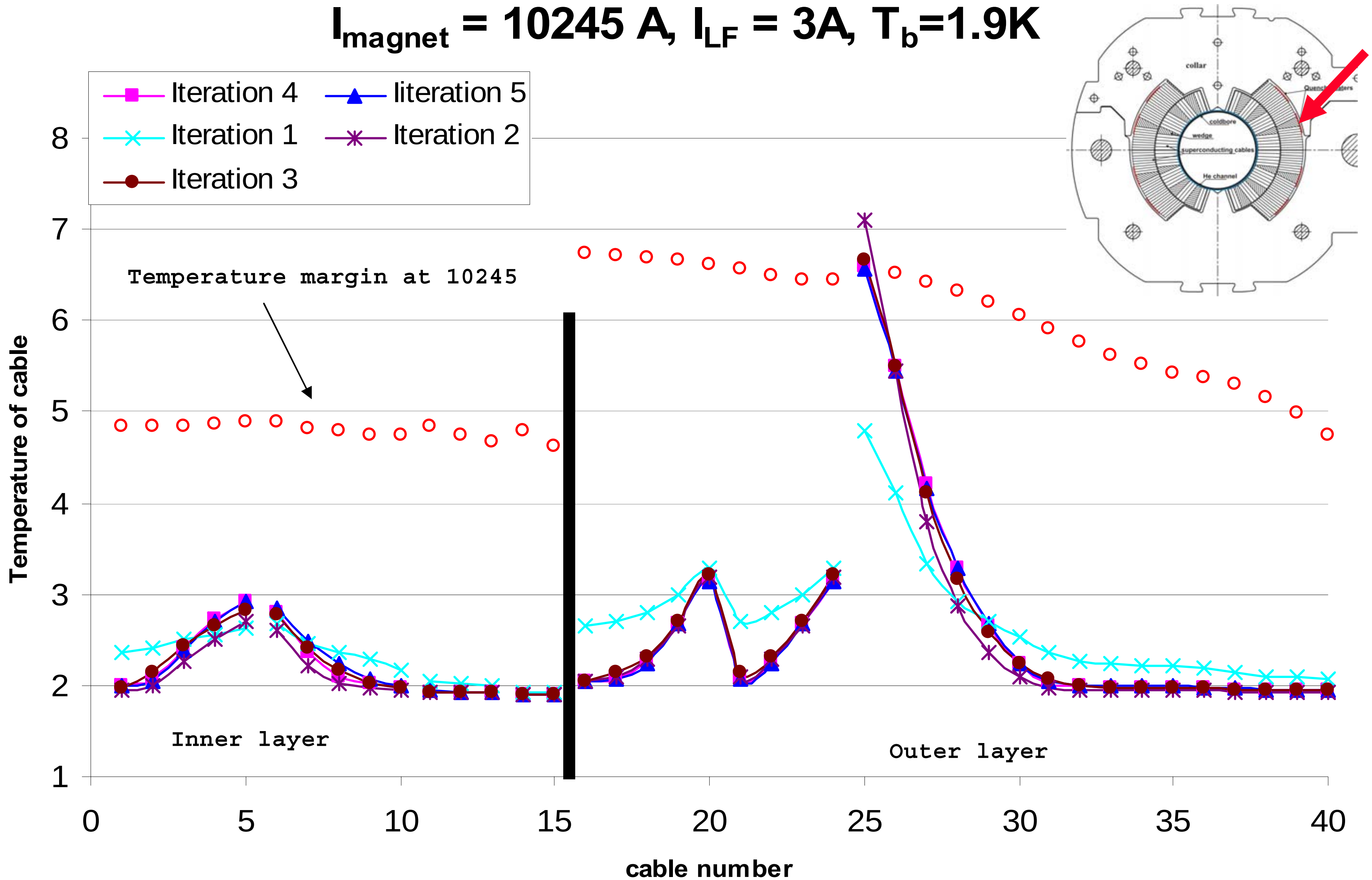
HF quench heater - temperature distribution

ΔT=0.1K/0.01 K → I_{magnet} = 8668/8870 A, I_{HF} = 3A, T_b=1.9K



LF quench heater - temperature distribution

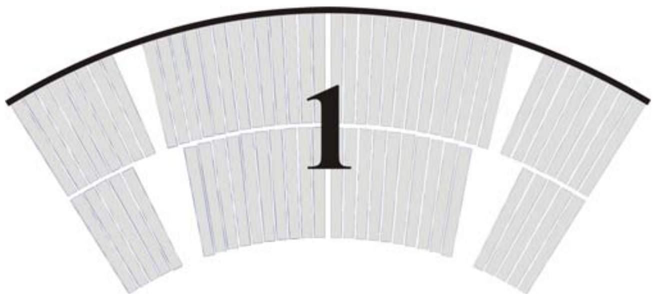
I_{magnet} = 10245 A, I_{LF} = 3A, T_b=1.9K



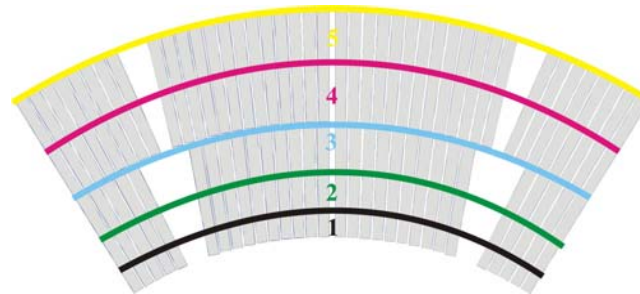
„Beam loss" simulations

- Quench limit for the „real" beam loss depends on the beam loss profiles
- heat flow distribution in the coil will be different compare 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

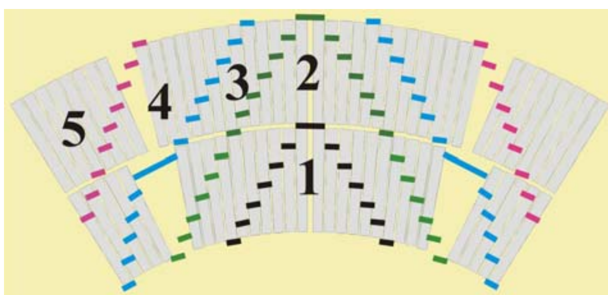
„Beam loss” profiles in magnets



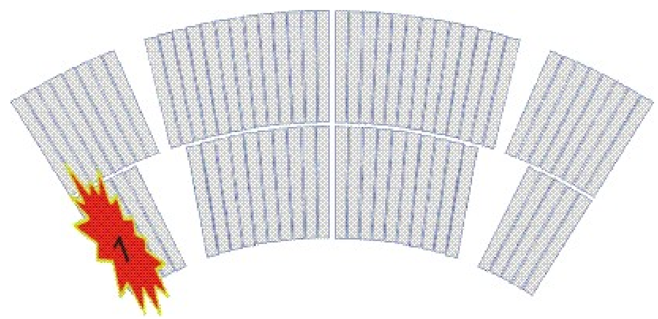
Homogenous beam loss profile



Concentric beam loss profile

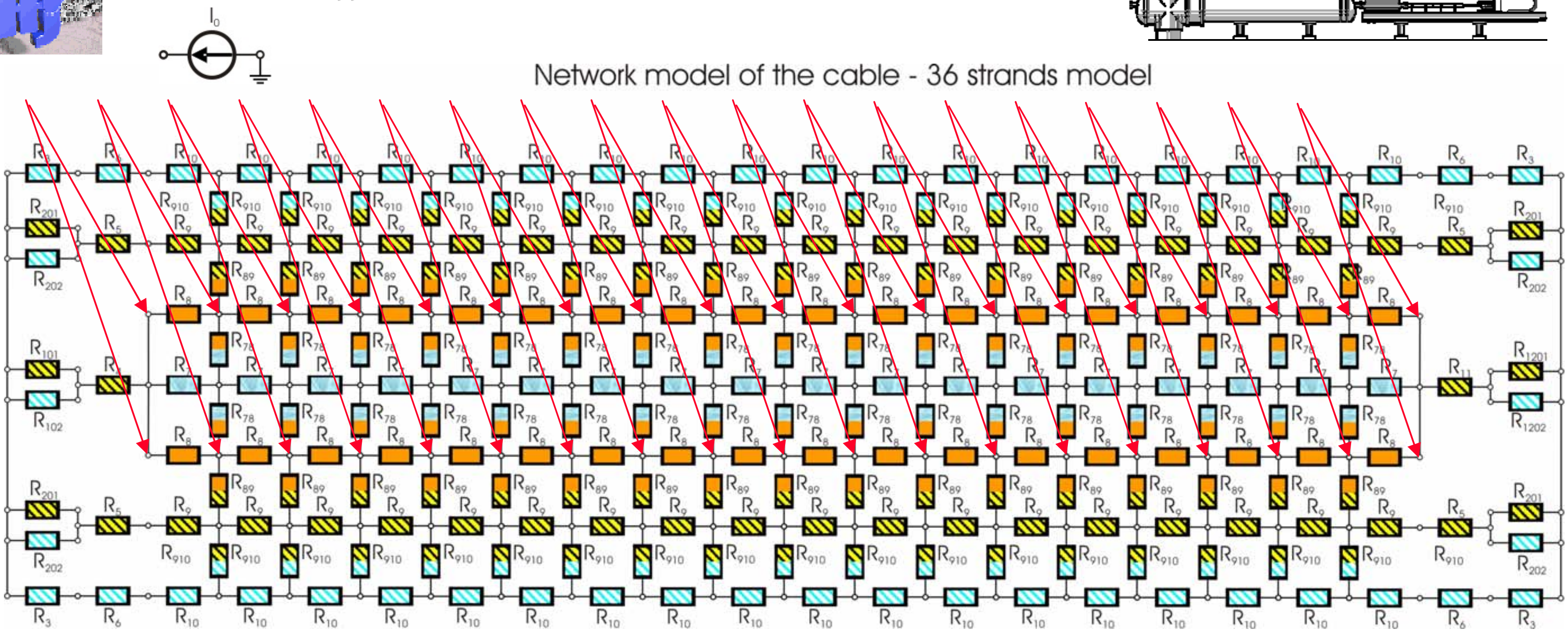


Gaussian beam loss profile



Limited area beam loss

„Beam loss” simulation



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 naive homogeneous heat deposit in profile 3, 4 and 5 ⇒ *3 [mW/cm^3]*

MQY quench limit for nominal current (3650 A) ⇒ *8 [mW/cm^3]*

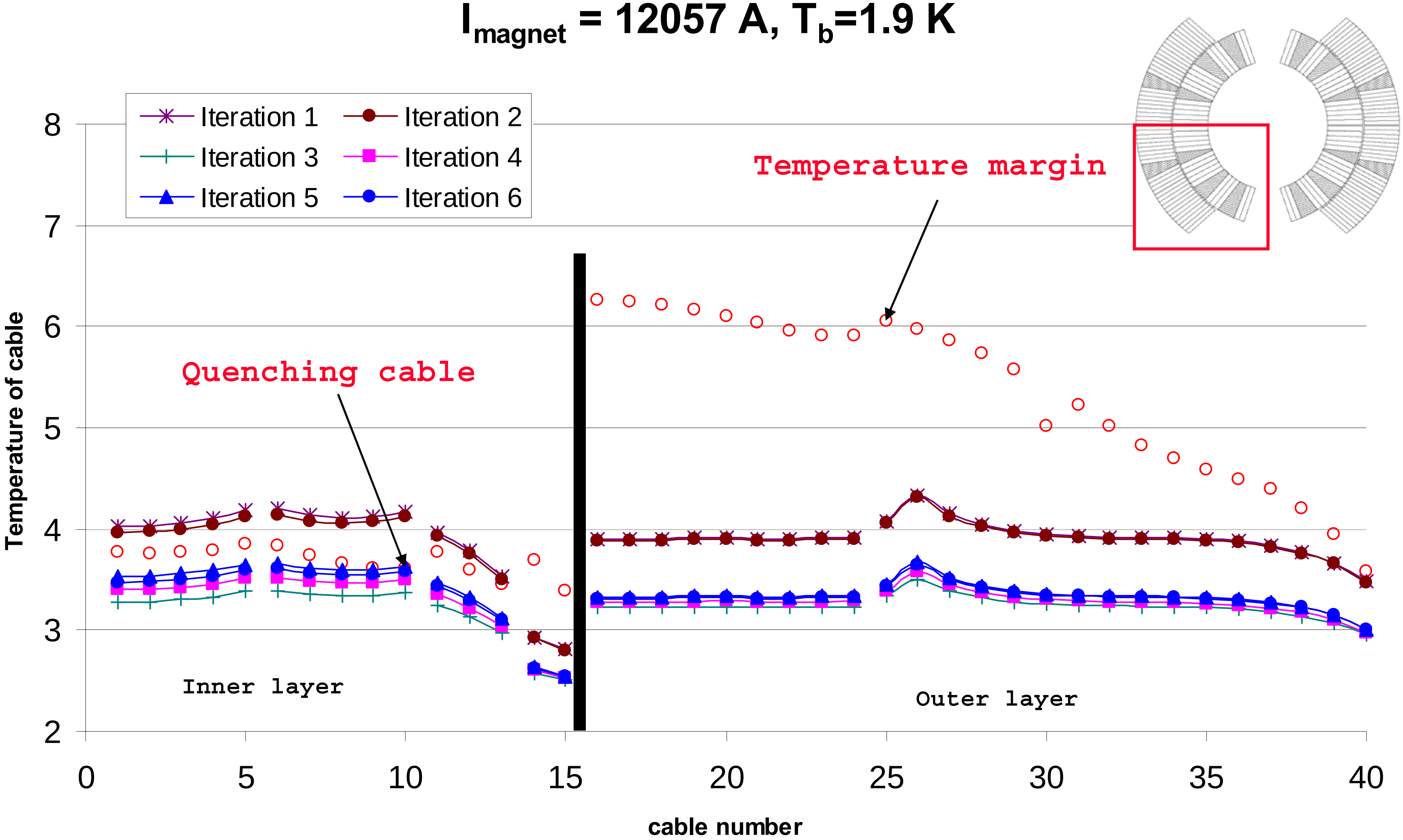
MQY quench limit for ultimate current (3900 A) ⇒ *5 [mW/cm^3]*

MQY quench limit for nominal current (3650 A) and naive homogeneous heat deposit in profile 3, 4 and 5 ⇒ *2 [mW/cm^3]*

T_b=4.5K

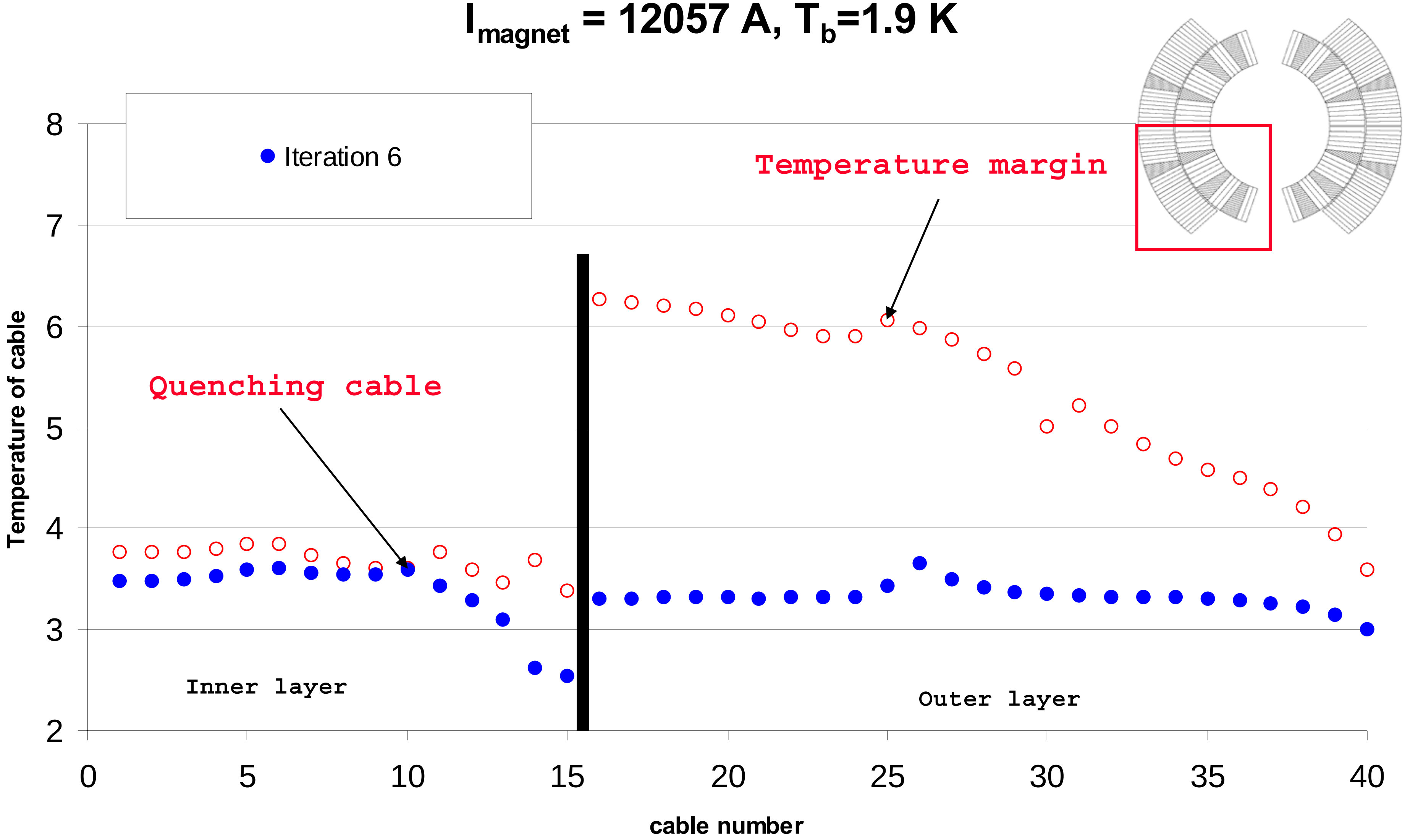
Homogenous beam loss-temperature distribution

I_{magnet} = 12057 A, T_b=1.9 K

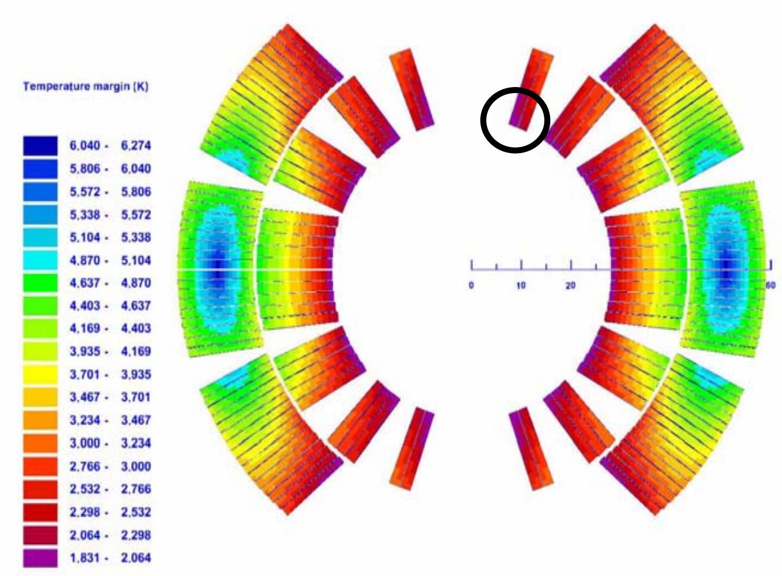


Homogenous beam loss-temperature distribution

I_{magnet} = 12057 A, T_b=1.9 K



„Beam loss" profile in MB magnet
PRELIMINARY RESULTS



This numbers should not be taken as a reference numbers for MB magnets

- **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**

„Beam loss" profile in MB magnet
PRELIMINARY RESULTS

LHC Project Note 44

1-outer layer

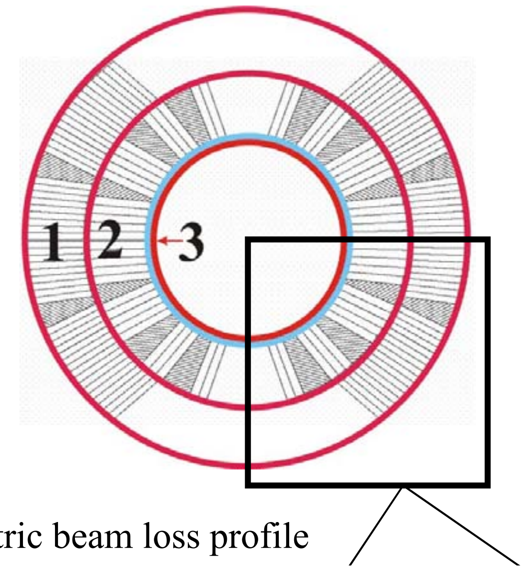
factor = 1

2- inner layer

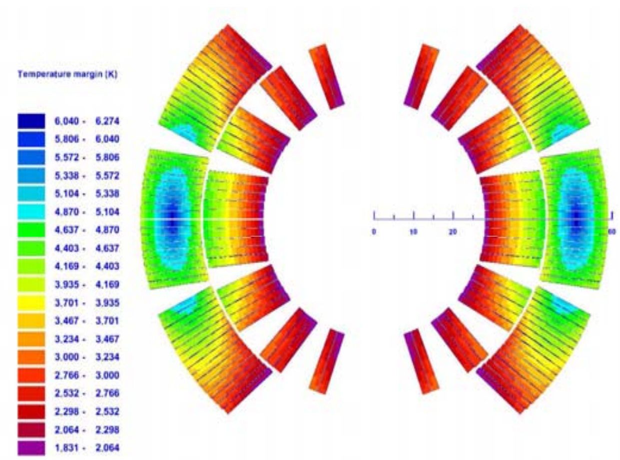
factor = 6

3 - cold bore

factor = 50



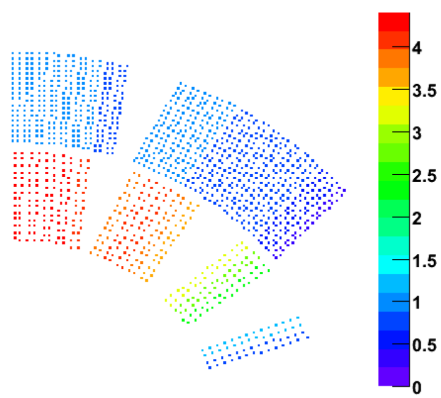
Concentric beam loss profile



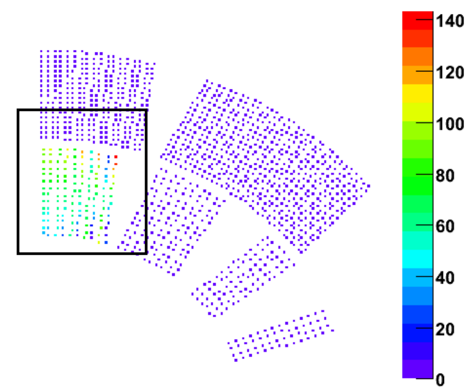
Temperature margin distriution

Quench limit at 7300A
31 mW/cm³

Quench limit at 12200A
12.6 mW/cm³



Temperature in the coil at I=7300A, $\Delta T_{simulation}$



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 $\mu\Omega$)	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/cm^3

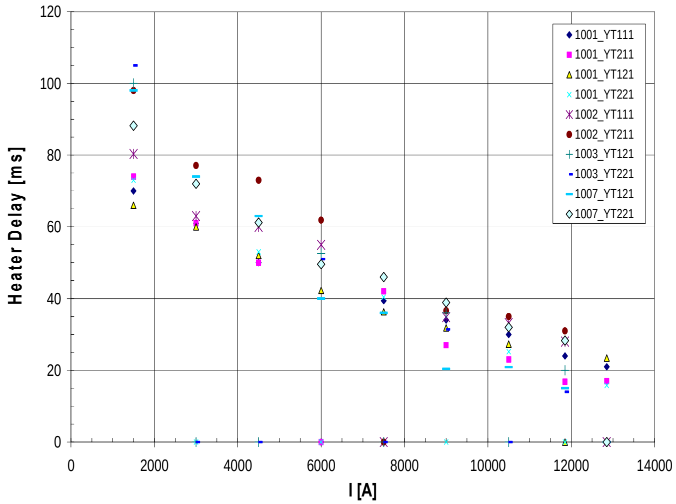
A detailed studies are ongoing (A. Verweij, R. Wolf)

Transient beam loss - Network Model

D. Bocian & P. Xydi

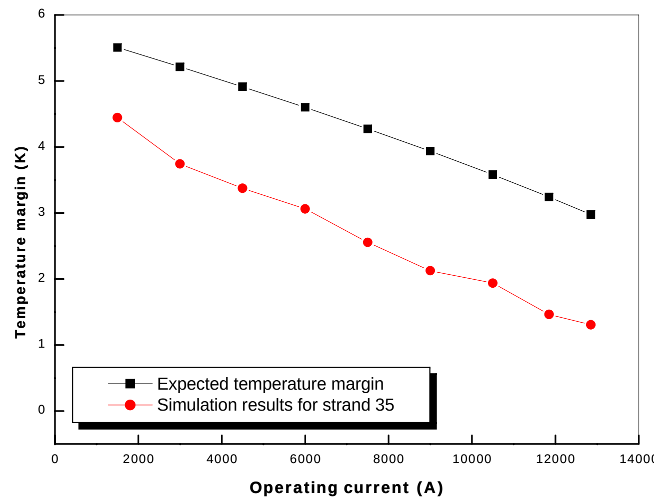
AT - MTM

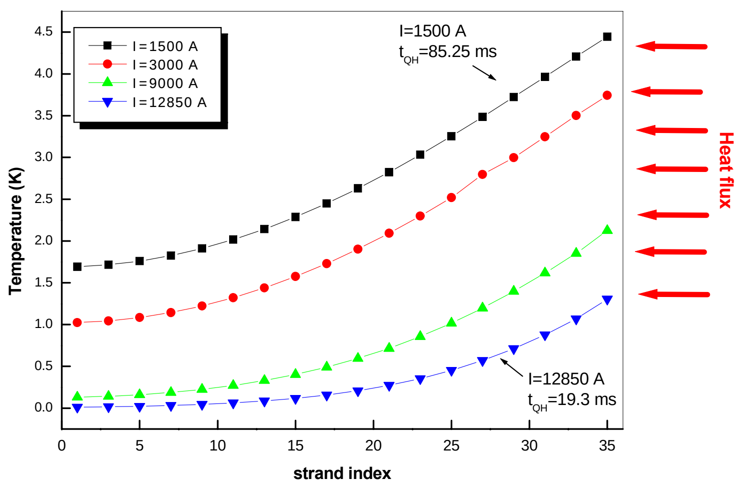
P. Pugnat



In the network model R is replaced by RC (low pass filter)

Preliminary results

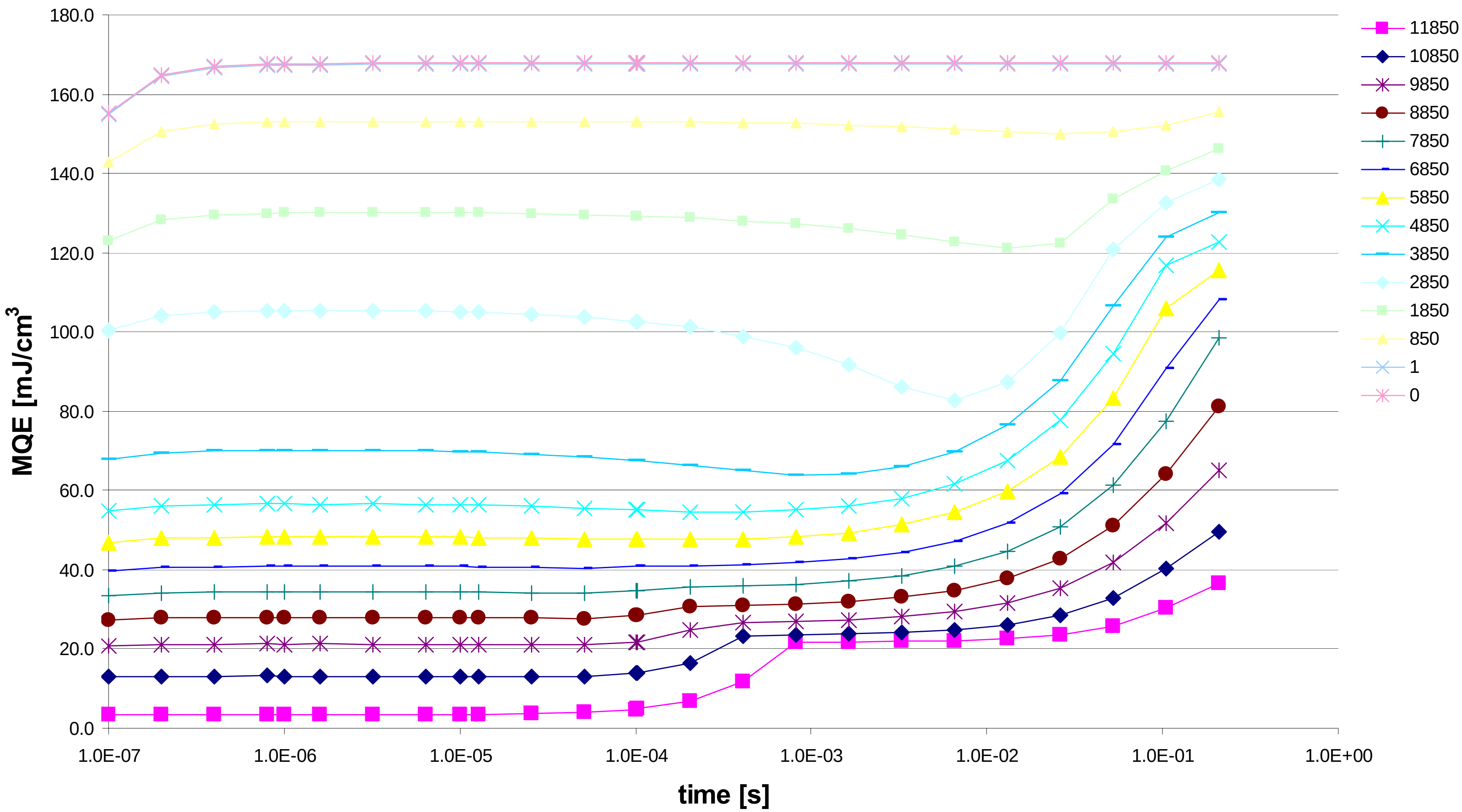




Network Model is delevoped and work is on going

The first results should be available in few months

0D Model is delevoped and work is on going



Conclusions and requirements

- 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 achived
- The validation of the model at 1.9 K is ongoing
- On going – transient losses simulations
- The simualtions 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.