Modelling of quench levels induced by steady state beam loss heat load

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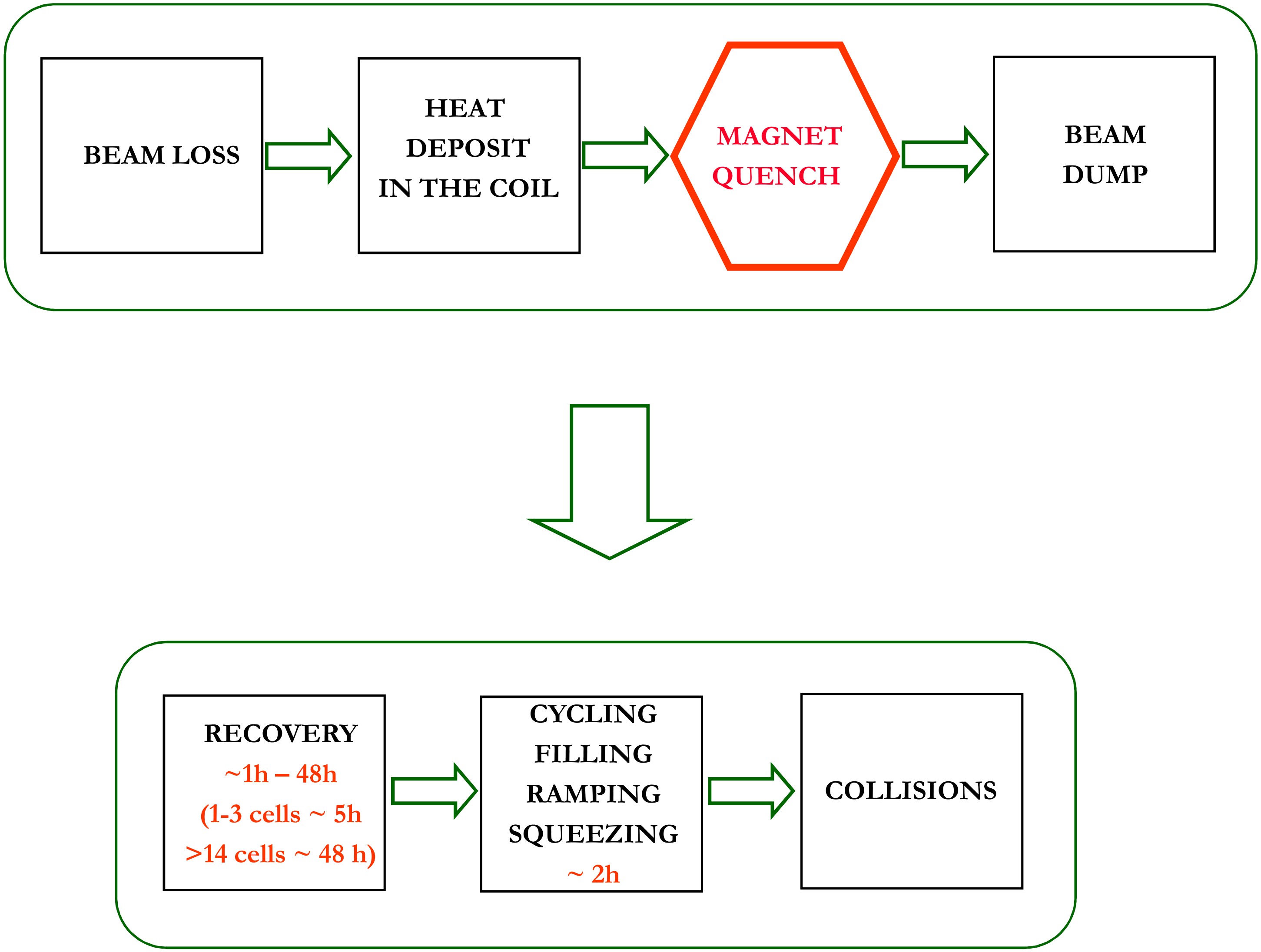
Acknowledgements: **G. D'Angelo, B. Dehning, J. Kaplon, A. Siemko, R. Van Weelderen**

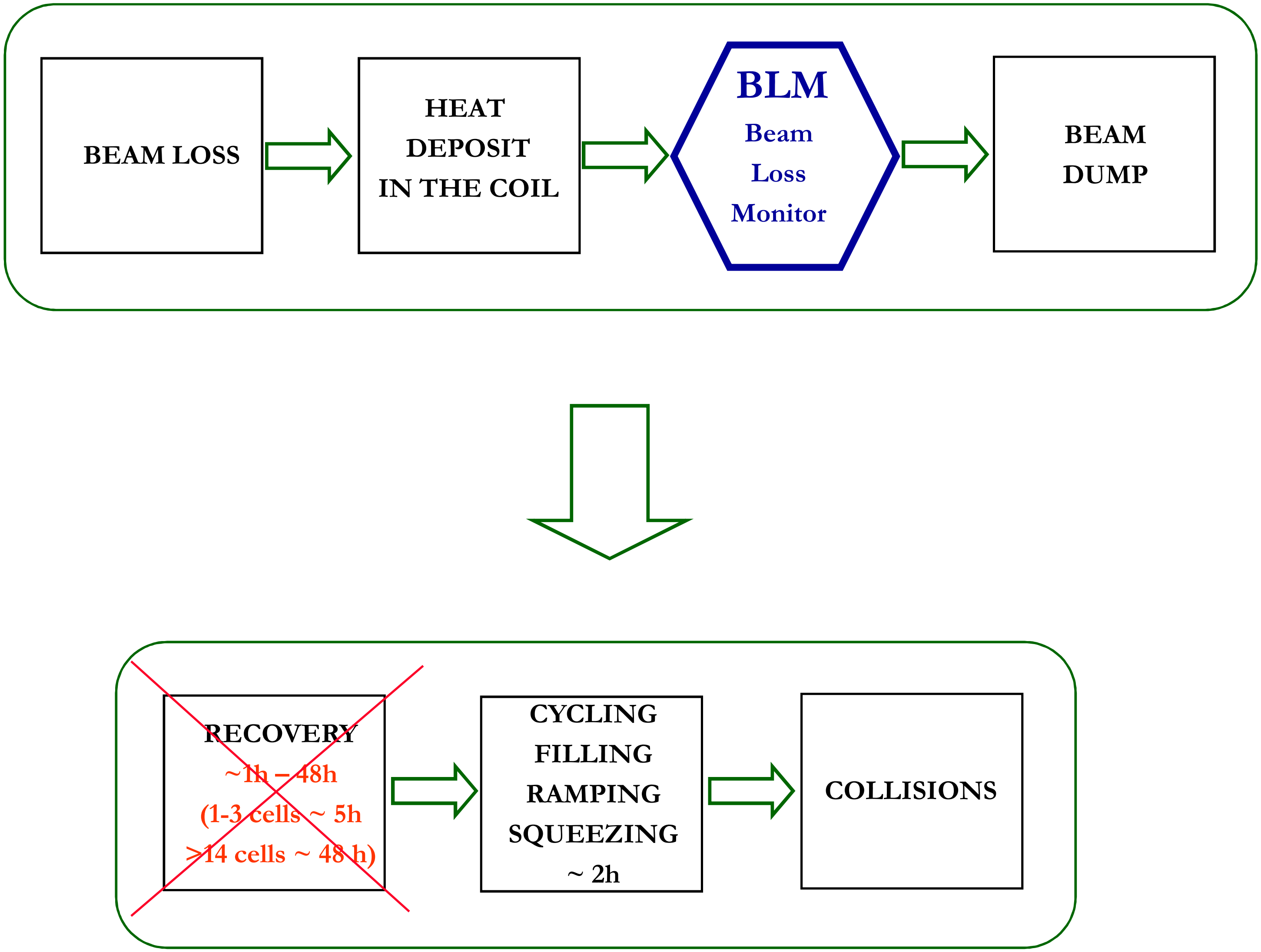
Outline

- Motivation
- Thermodynamics of magnet structure
- Network Model
- Validation of the model
- „Beam loss" simulation
- Summary and outlook

MOTIVATION
LHC beam loss protection



MOTIVATION
LHC beam loss protection



MOTIVATION
LHC beam loss protection

Optimise BLM threshold settings

(gain the time and money)

Integrated luminosity

(increase discovery potential of LHC)

Reduce of quench number

(reduce the number of thermodynamic shocks)

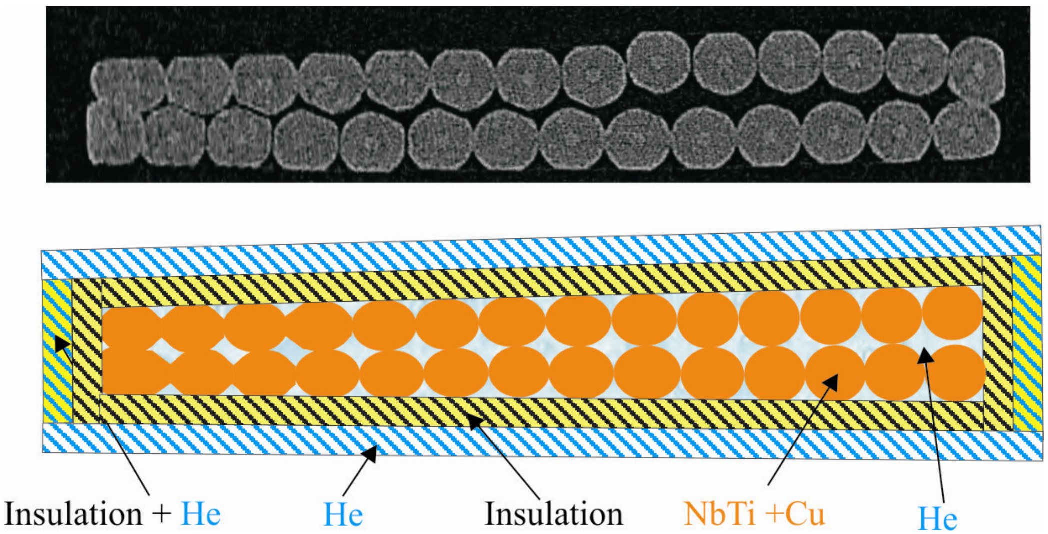
Thermodynamics of magnet structure

Heat transport in the magnets
Characteristic of superconducting coils

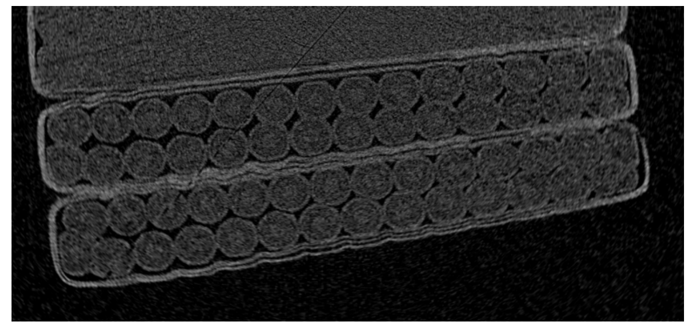
Thermodynamics of magnet structure

Heat transport in the cable

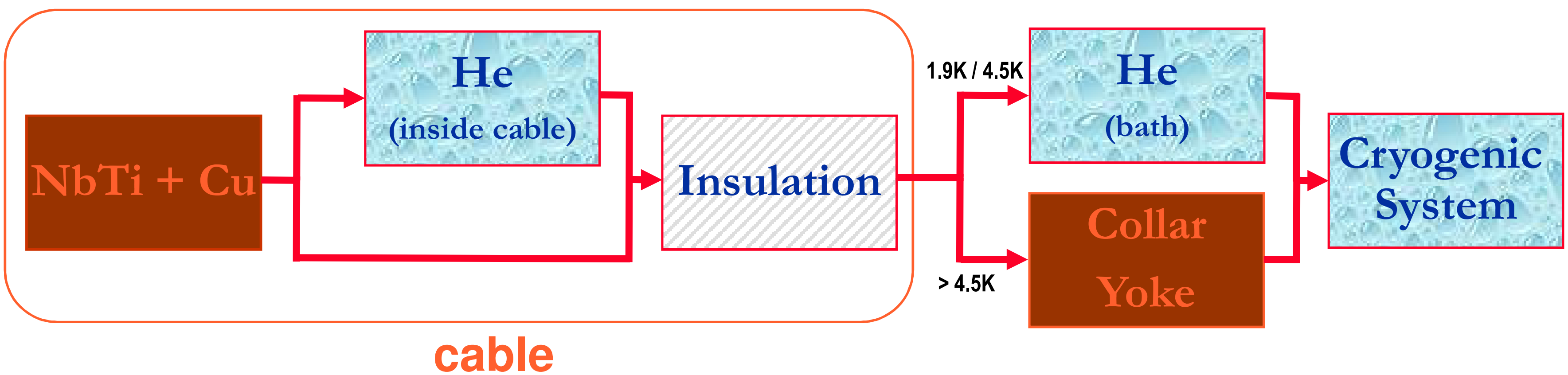
Rutheford type cable



MB magnet – inner layer

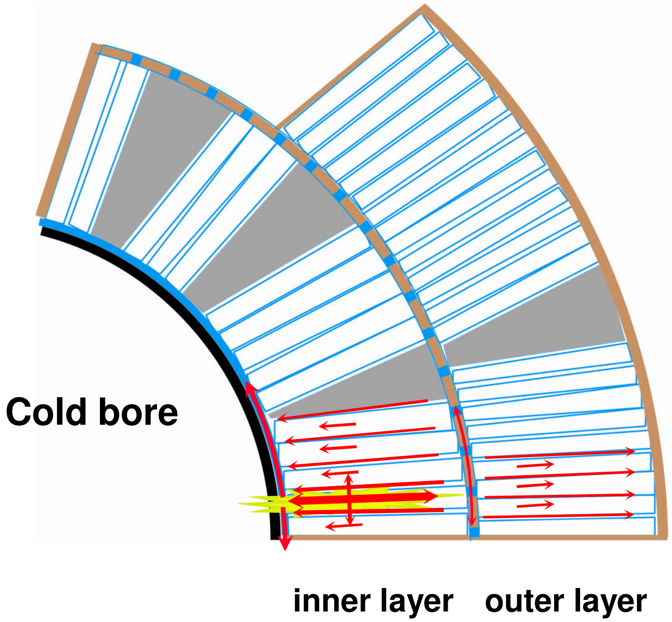


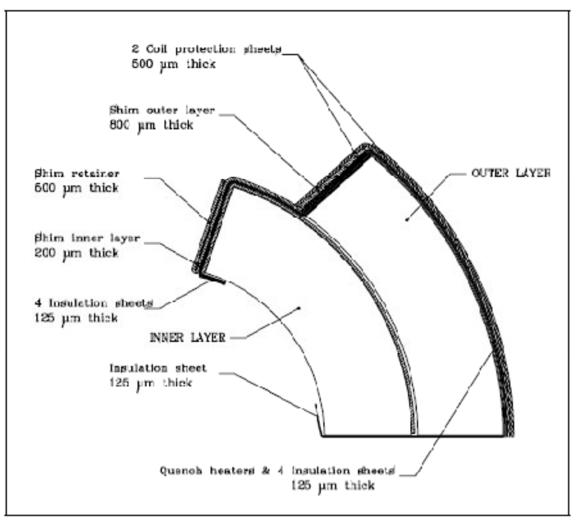
Courtesy C. Scheuerlein



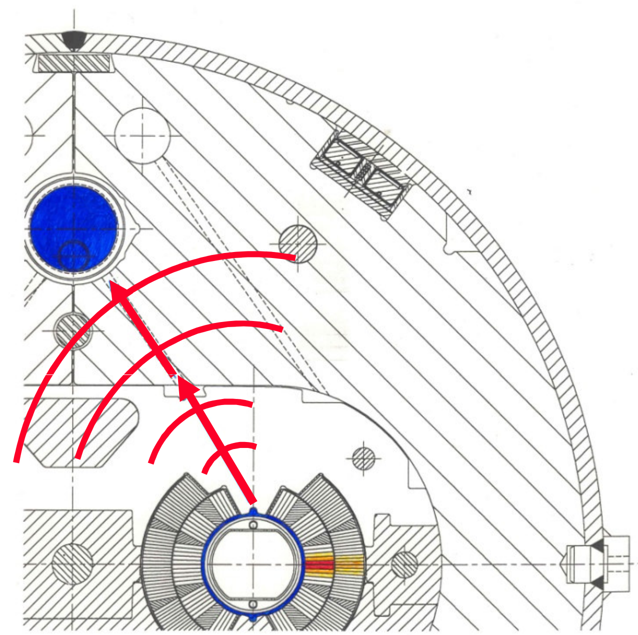
Thermodynamics of magnet structure

Heat transport in the coil at 1.9K





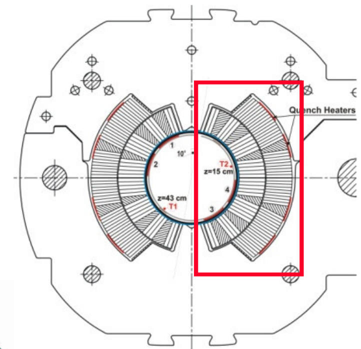
A heat transfer in the main dipole

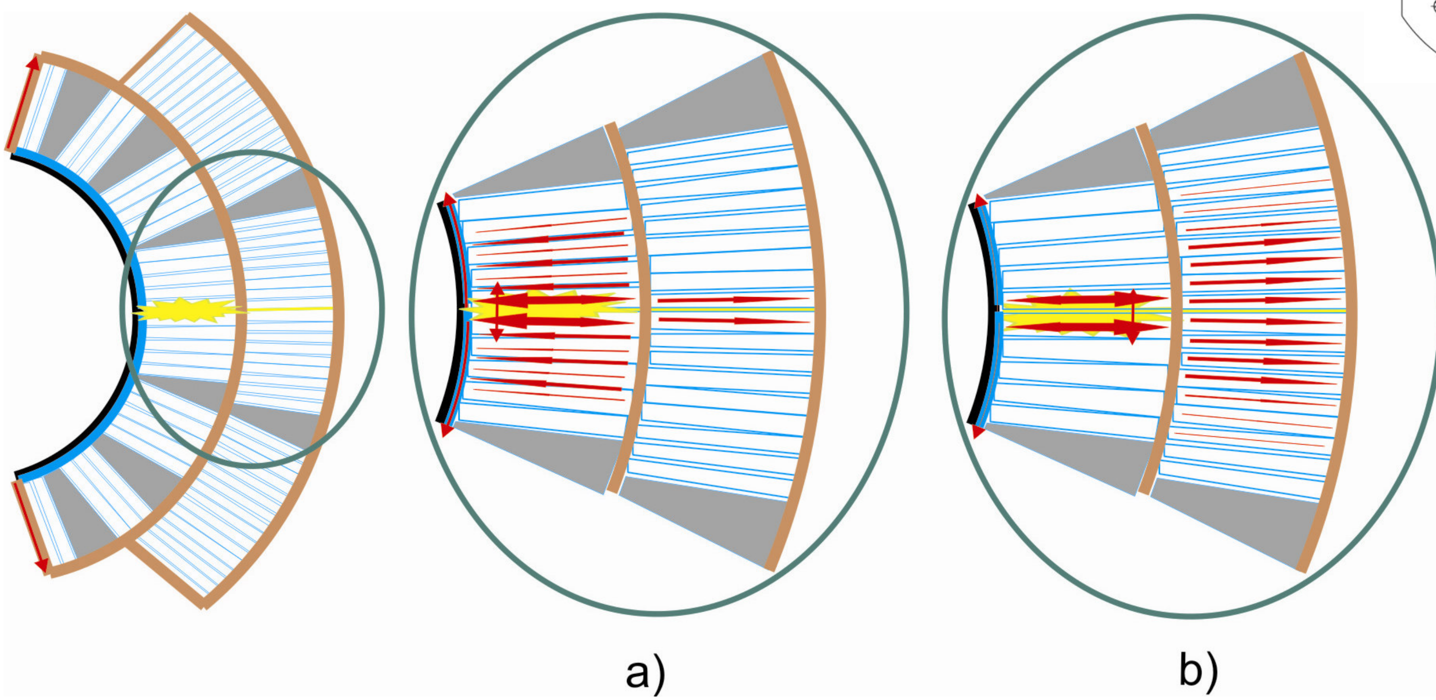


- **Heat transfer from the conductor to the cold source defines the temperature margin**
- **Electrical insulation is the largest thermal barrier at 1.9 K against cooling**

Thermodynamics of magnet structure

Heat transfer in the magnet coil

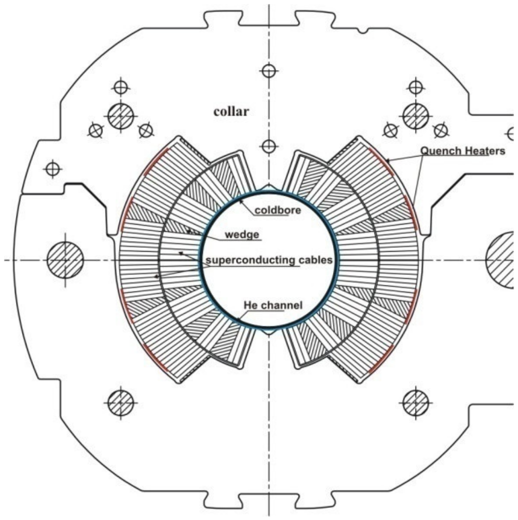




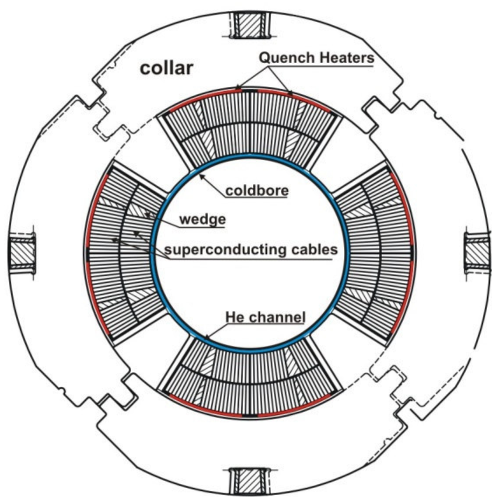
A sketch of the heat transfer in the magnet at nominal operations (a) and at quench limit (b).

Thermodynamics of magnet structure

MB – arc magnet, T_b=1.9 K



MQM – LSS magnet, T_b=1.9/4.5 K



HEAT FLOW LIMITS

➢ heat flow barriers

- cable insulation
- interlayer insulation (MQM)
- ground insulation
- helium channel around cold bore (for temperatures above 2.16 K)

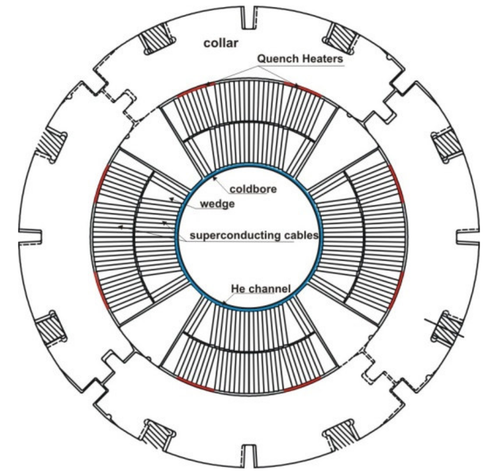
➢ bath temperature 1.9 K

- Transition HeII → HeI: helium channels are blocked = less effective heat evacuation due to the changing of heat evacuation path

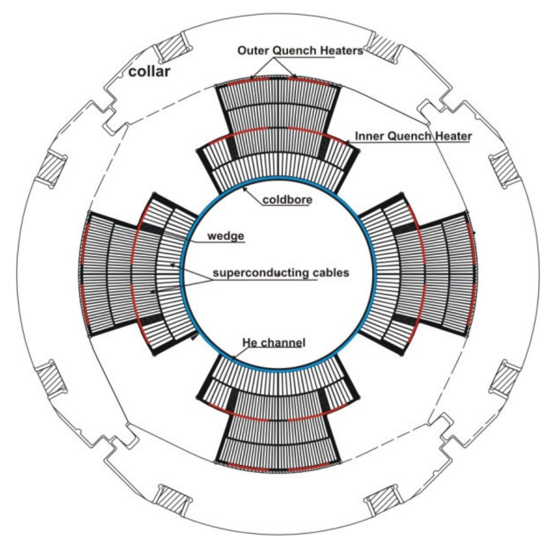
➢ bath temperature 4.5K

- lower temperature margin (worst case: MQM 0.45K)
- Helium channels does not play dominating role (heat conduction of He I and polyimide is the same order)

MQ – arc magnet, T_b=1.9 K



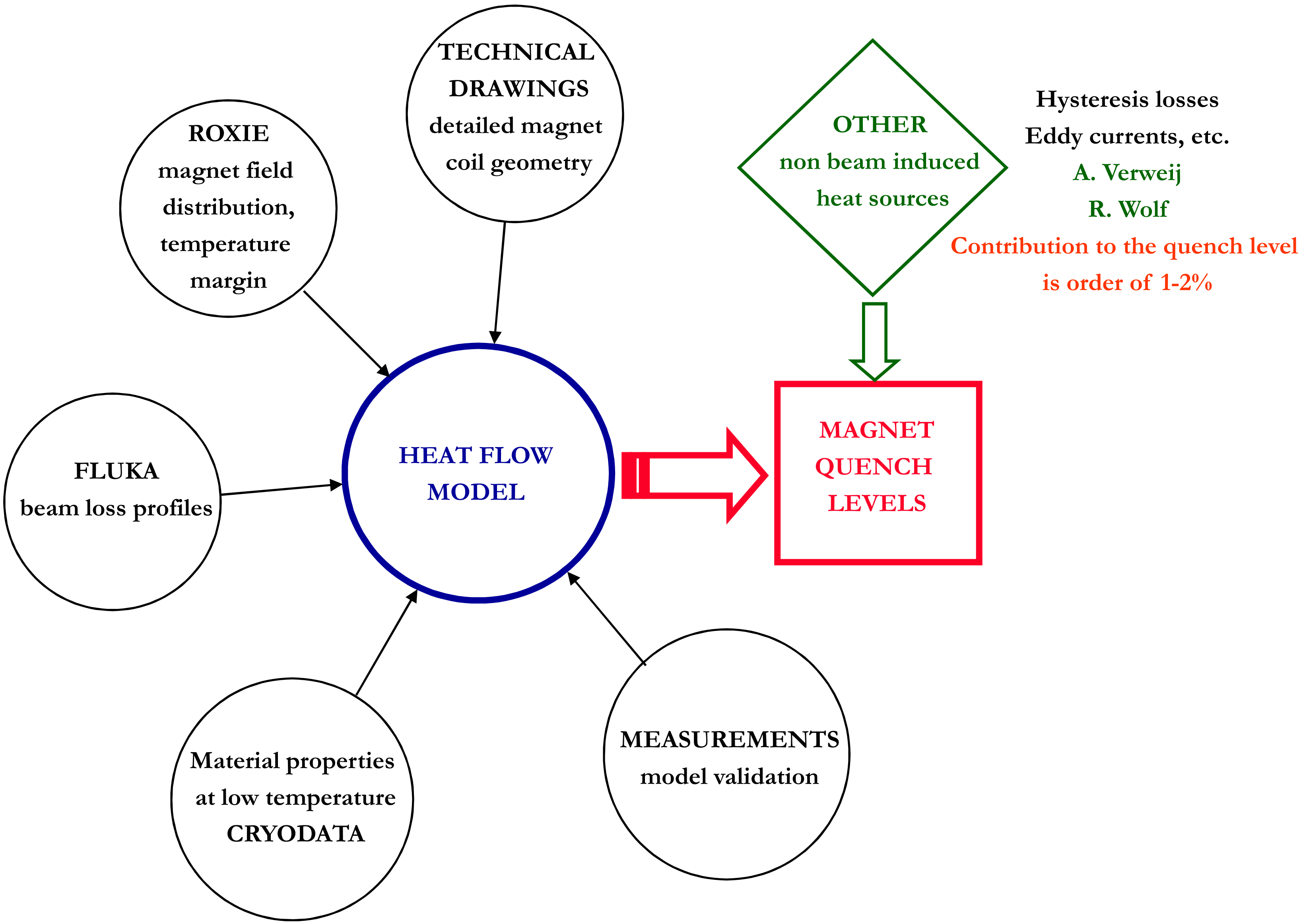
MQY – LSS magnet, T_b=4.5 K



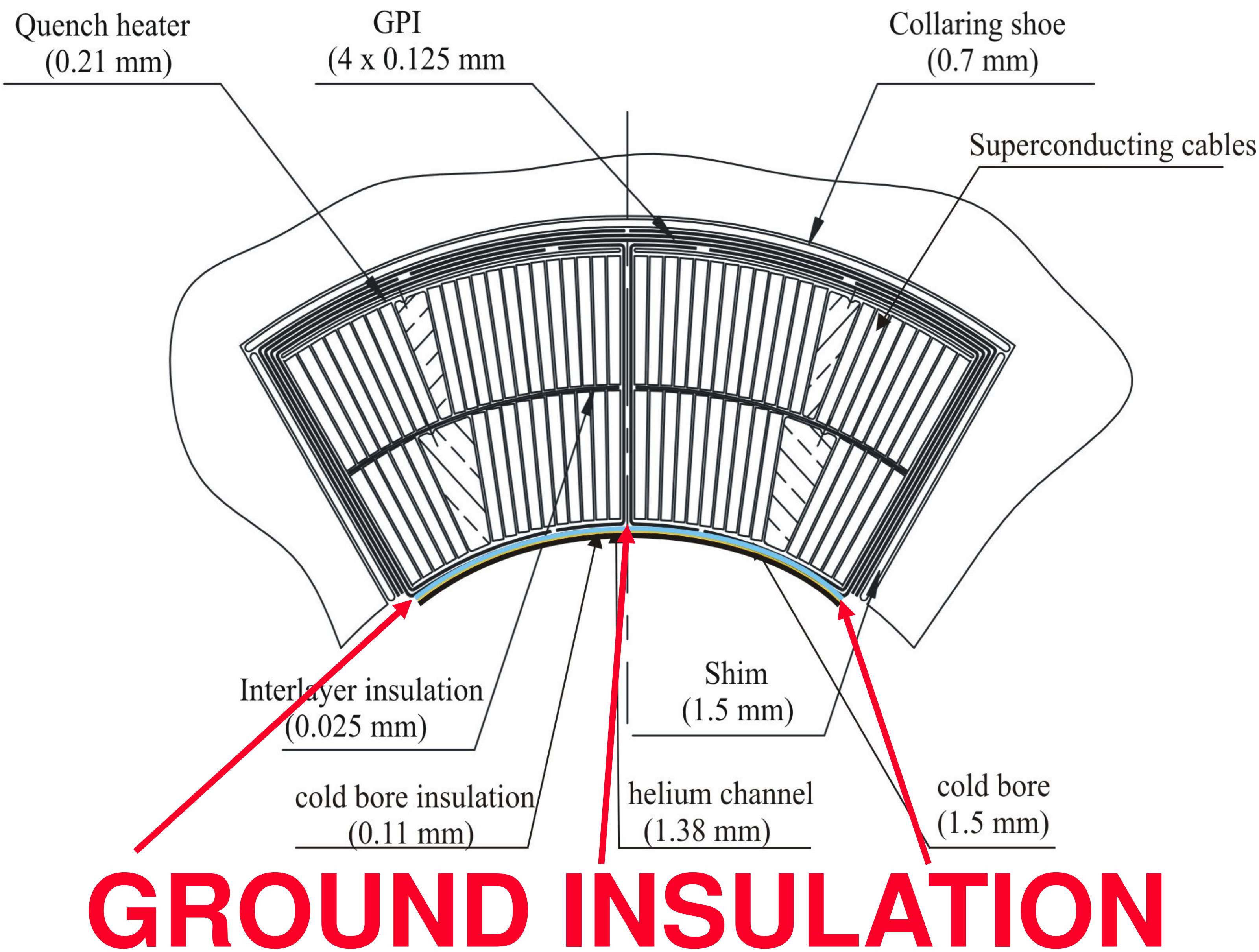
Network Model

Model construction
Model of the superconducting cable and coils
Simulations

Network Model - Model Construction

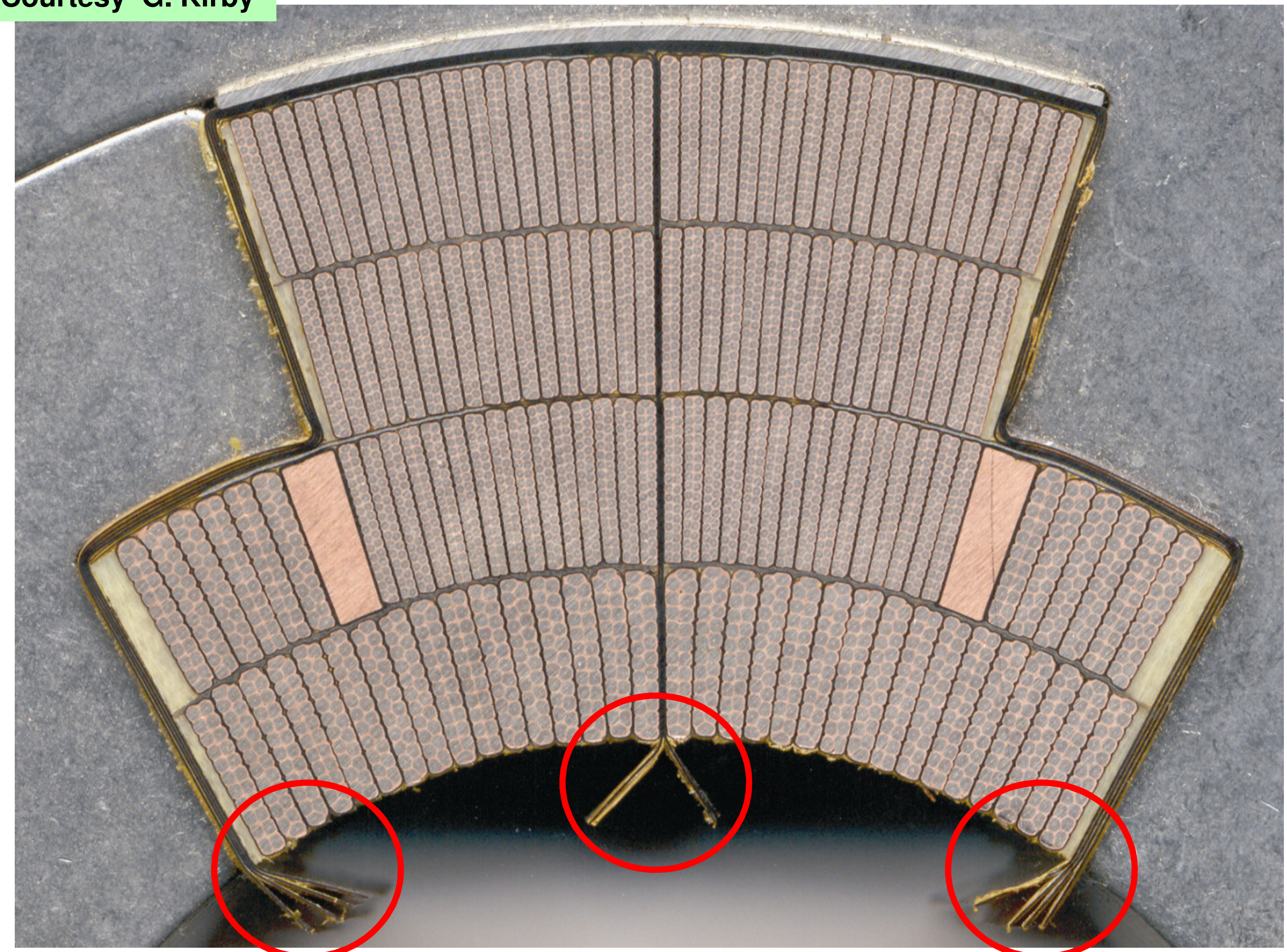


Network Model - Model Construction



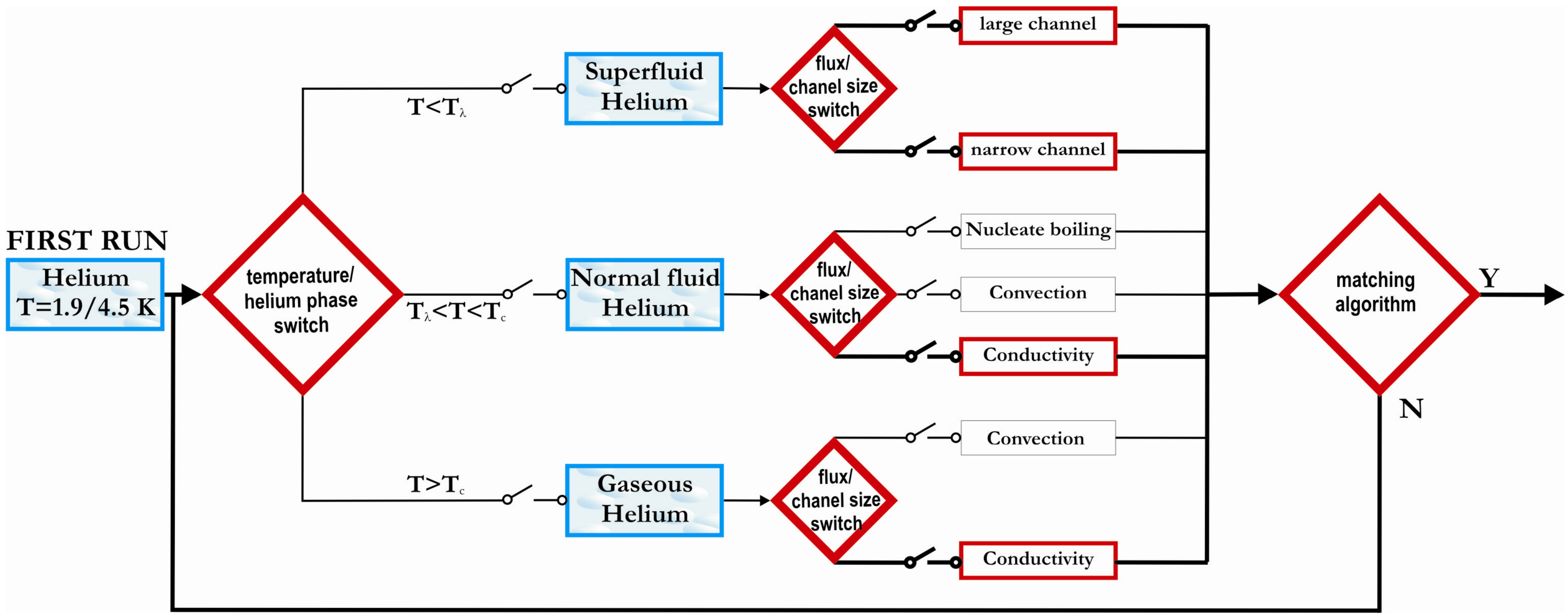
Network Model - Model Construction

Courtesy G. Kirby



Network Model - Model Construction

Helium in the Network Model



The volumes occupied by helium in the magnet are considered as:

-the narrow channels,

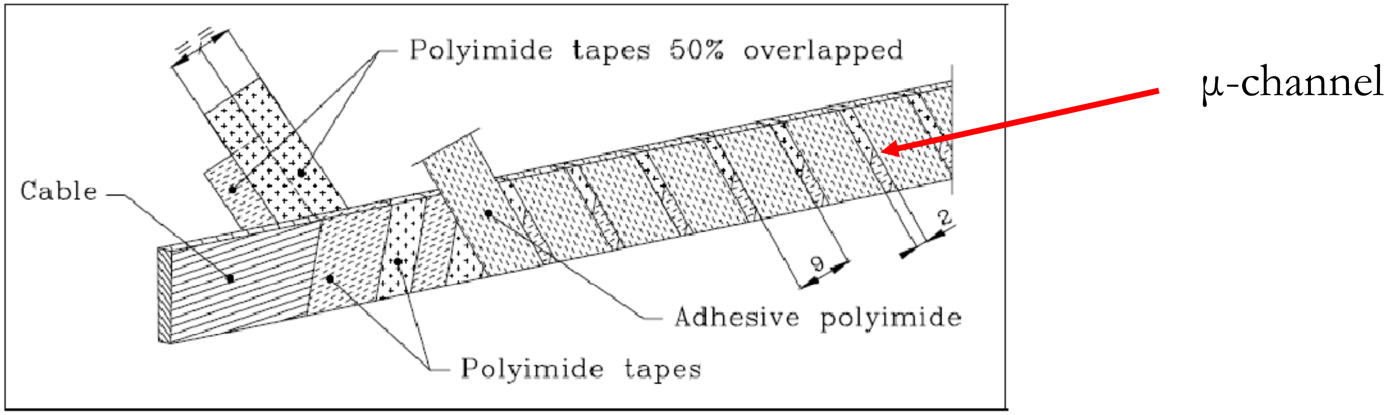
-semi-closed volumes = inefficient inlet of fresh helium.

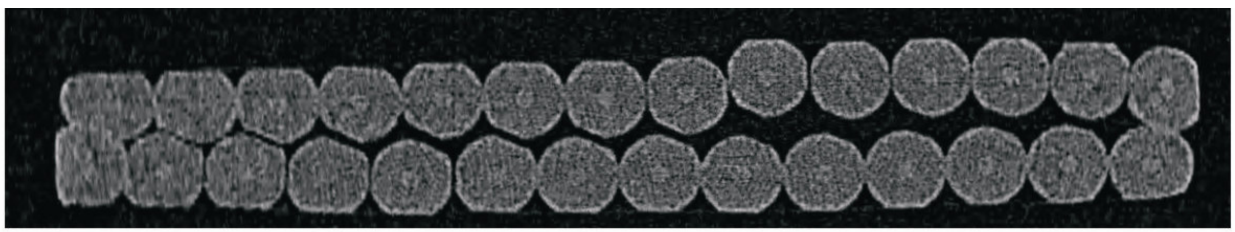
The steady heat load, heat up the helium in the semi- closed volumes:

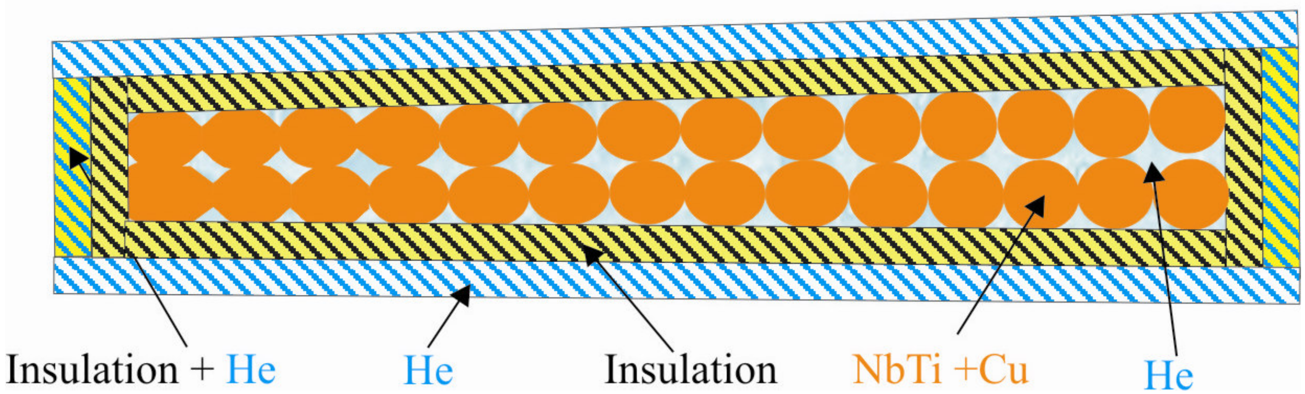
-Helium temperature well above critical temperature at T_b=4.5K

- Critical helium temperature reached already below the calculated quench limit

Network Model - Cable modelling

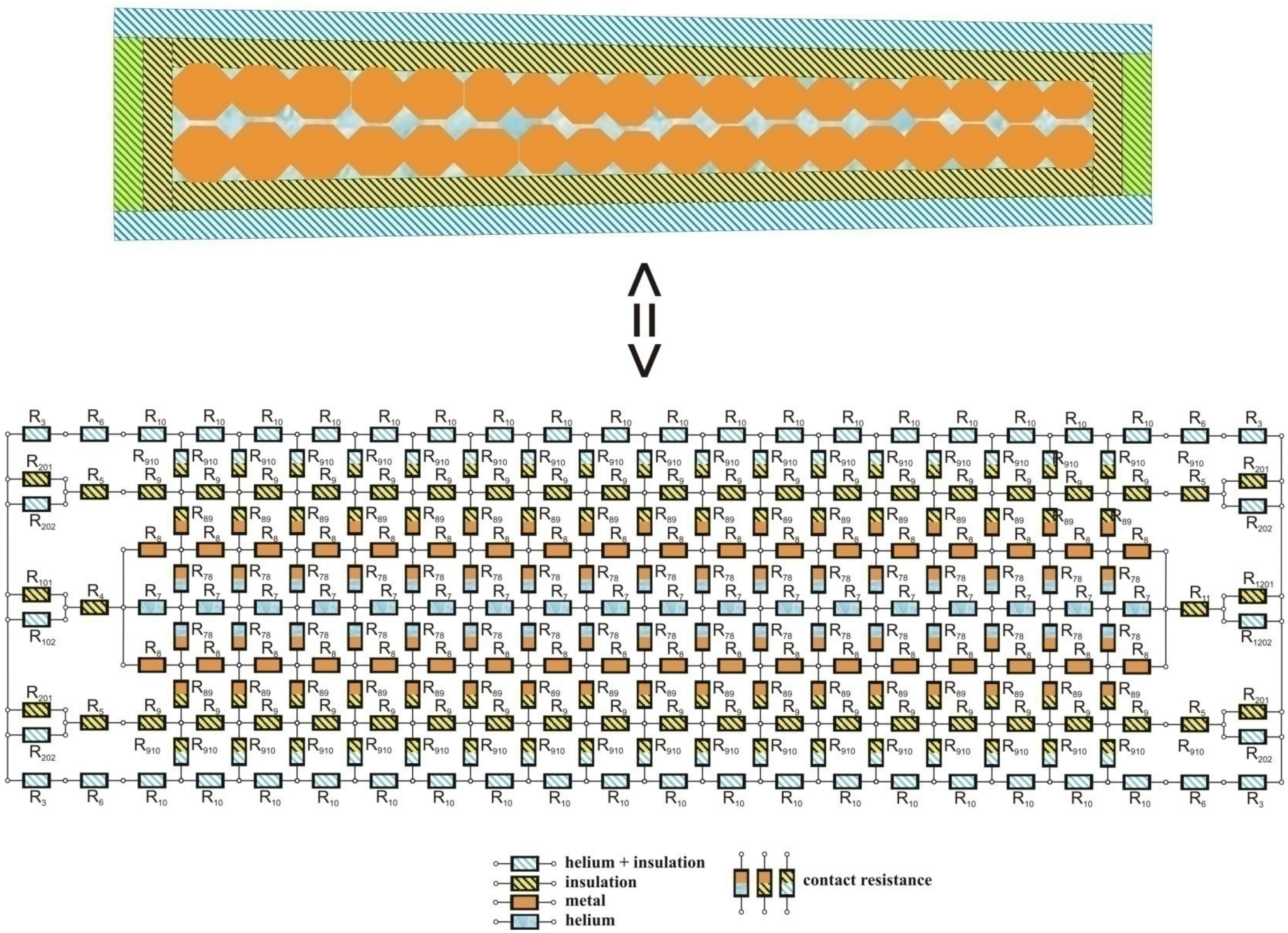




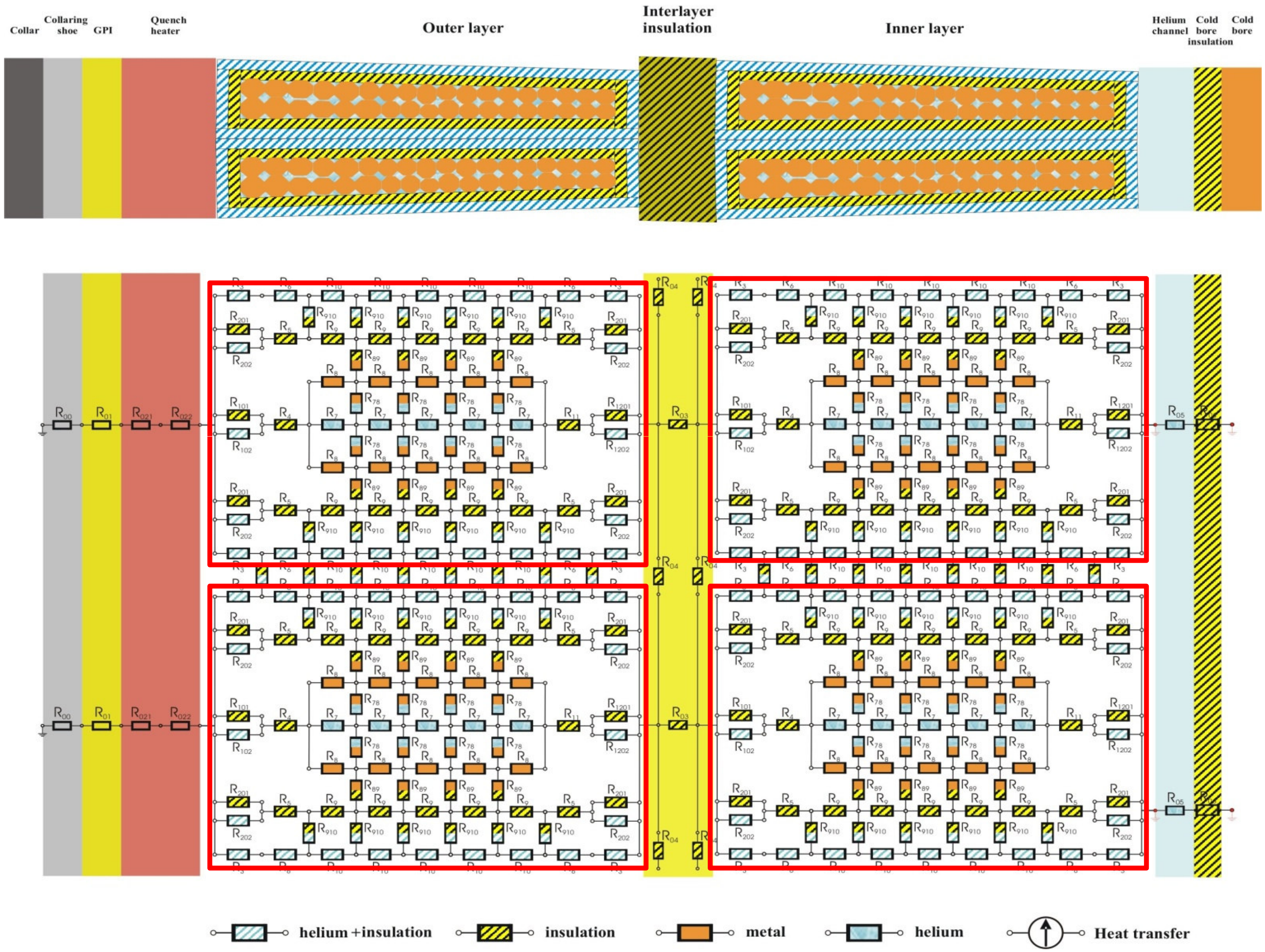


Network Model - Cable modelling

Network model of the superconducting cable



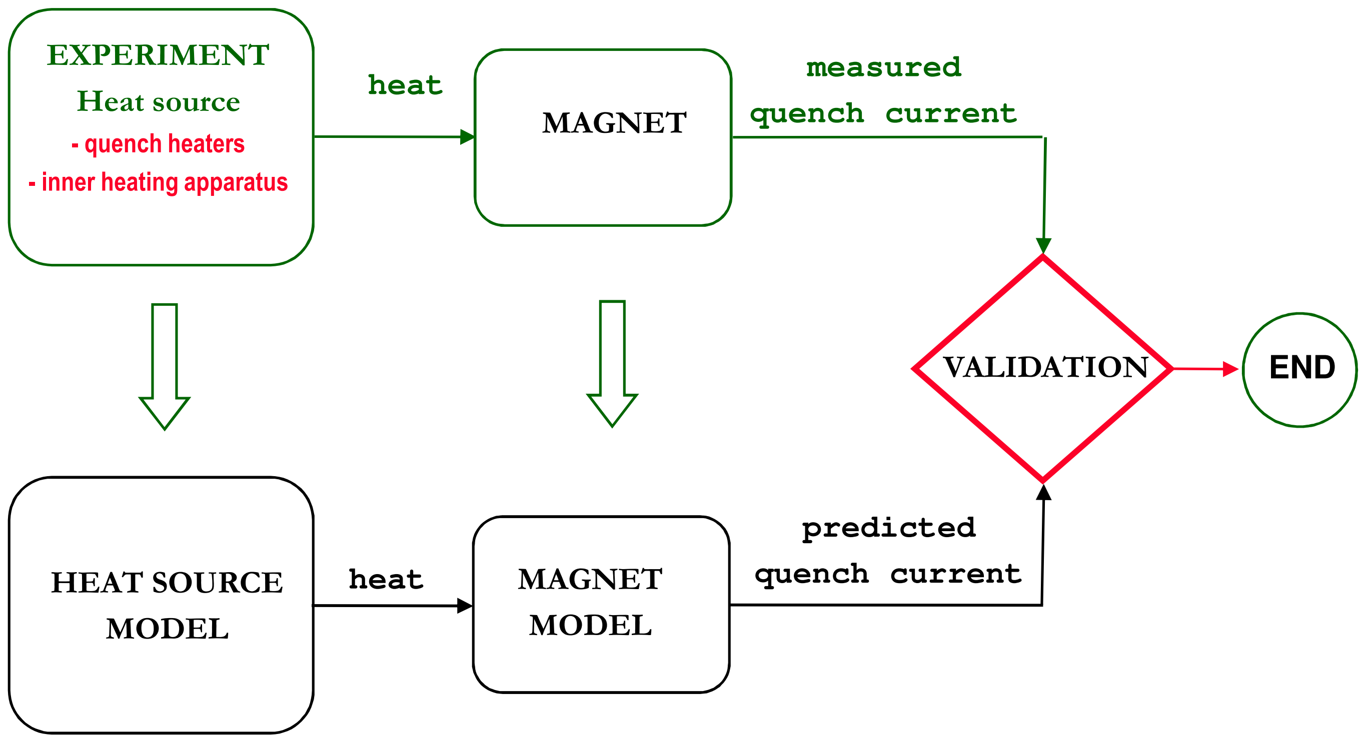
Network Model - Coil modelling



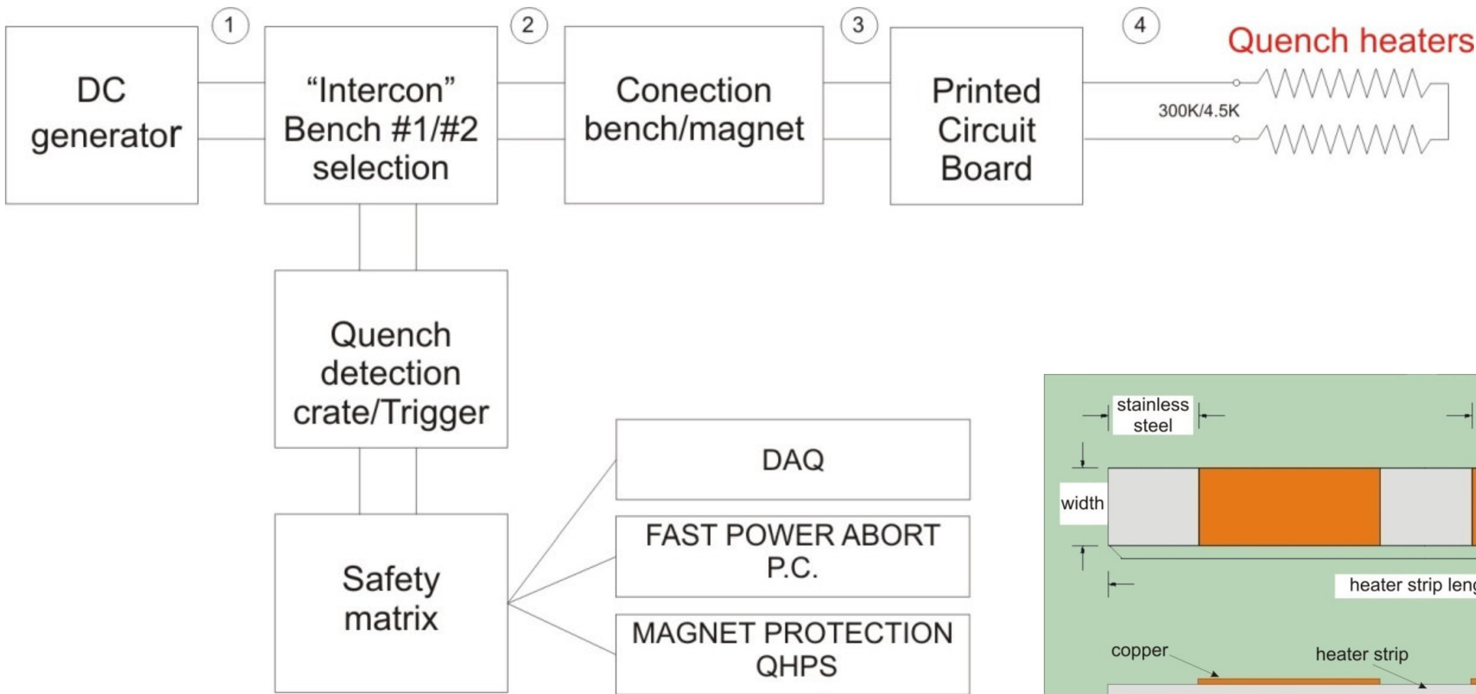
Validation of the model

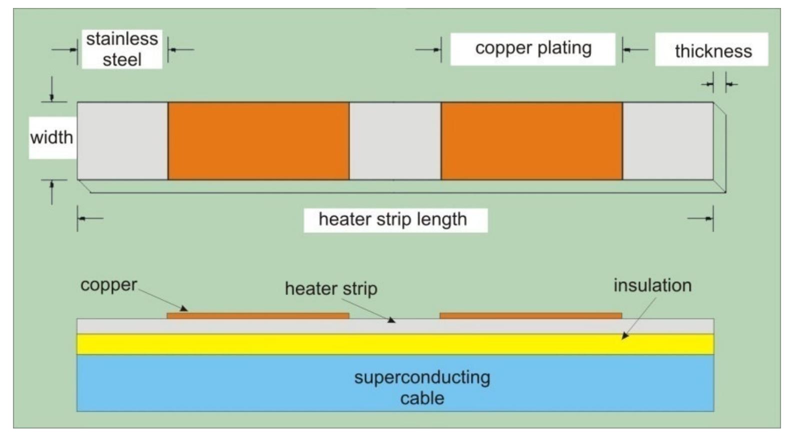
Measurements in the CERN test facility

Validation of the Network Model



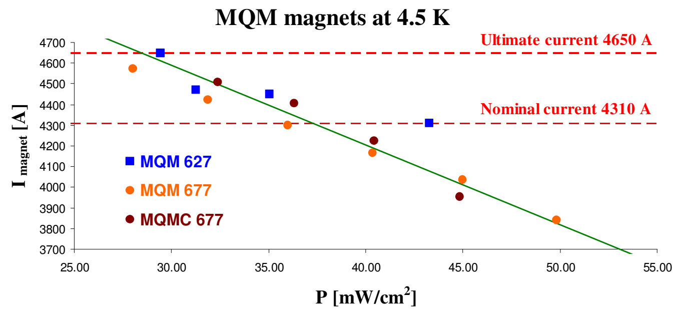
Validation of the Network Model with quench heaters

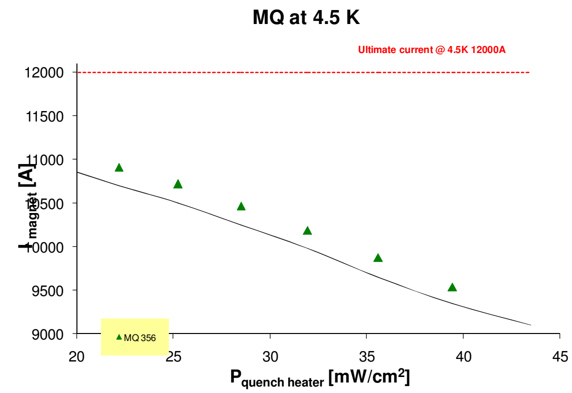


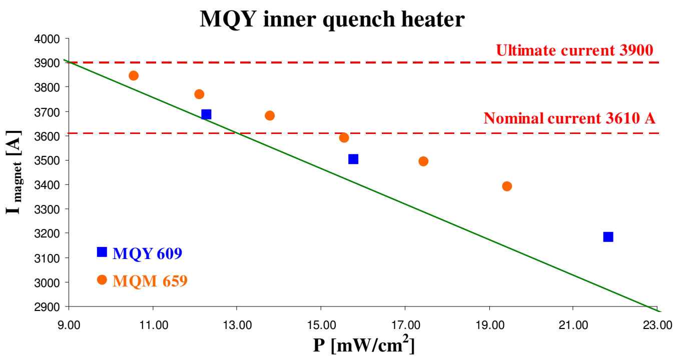


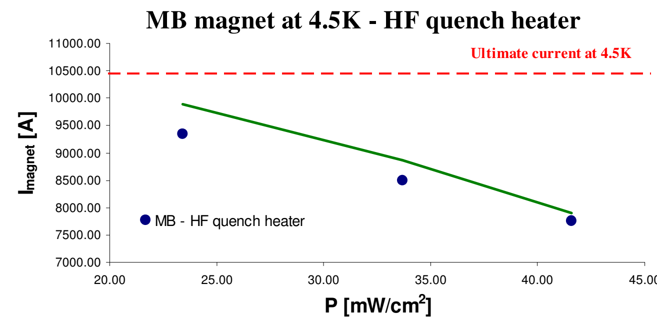
- **Two methods of measurement**
  - I_{coil} =const, increase of I_{QH} with a step of 0.1 A
  - I_{QH} =const, slow ramp of I_{coil} up to the quench after 300 s of coil heating
- **3 MQM, 2 MQY, MQ and MB have been tested at 4.5 K**

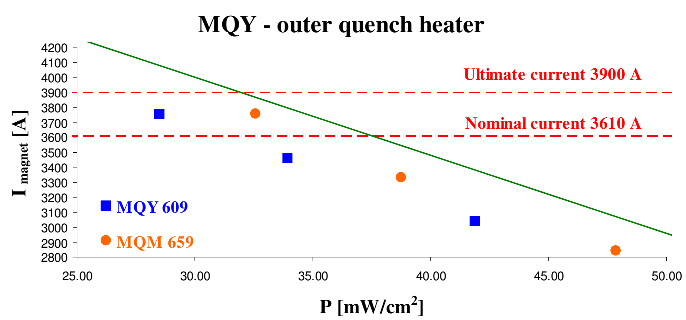
Validation of the model with quench heaters

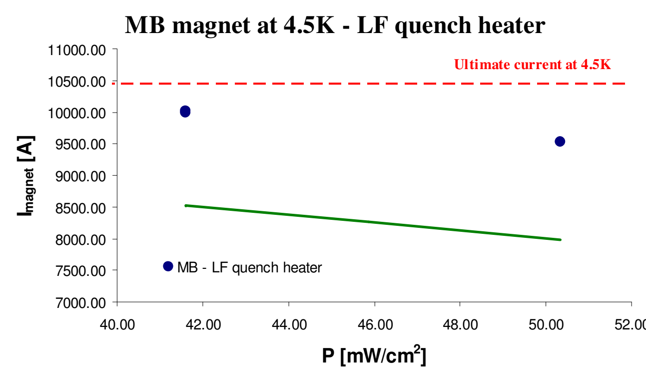




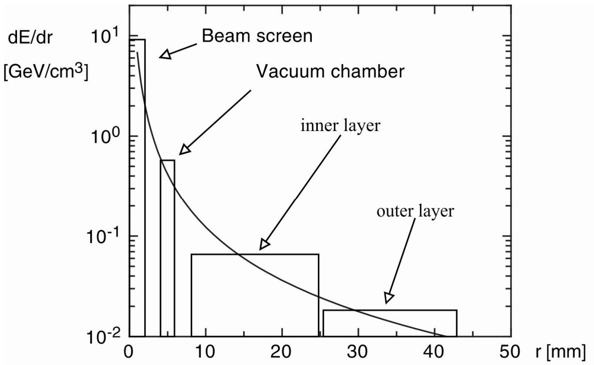






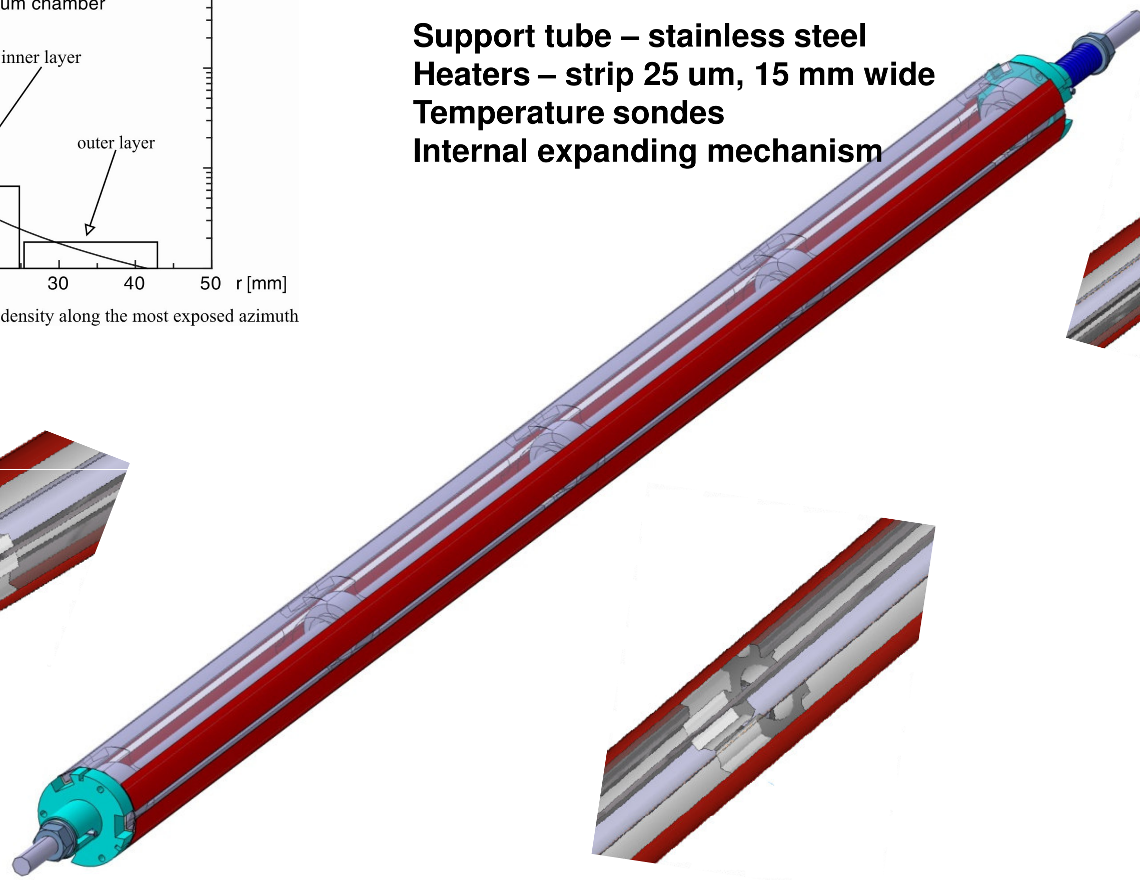


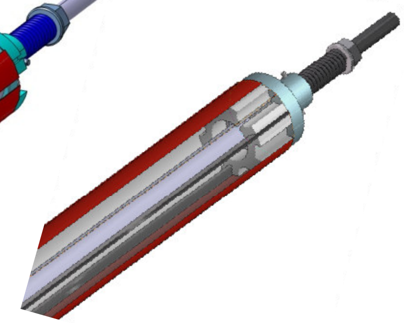
Validation of the model – internal heater

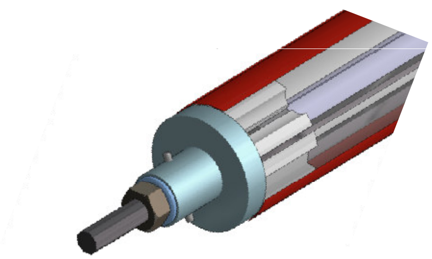


The maximum radial energy density along the most exposed azimuth

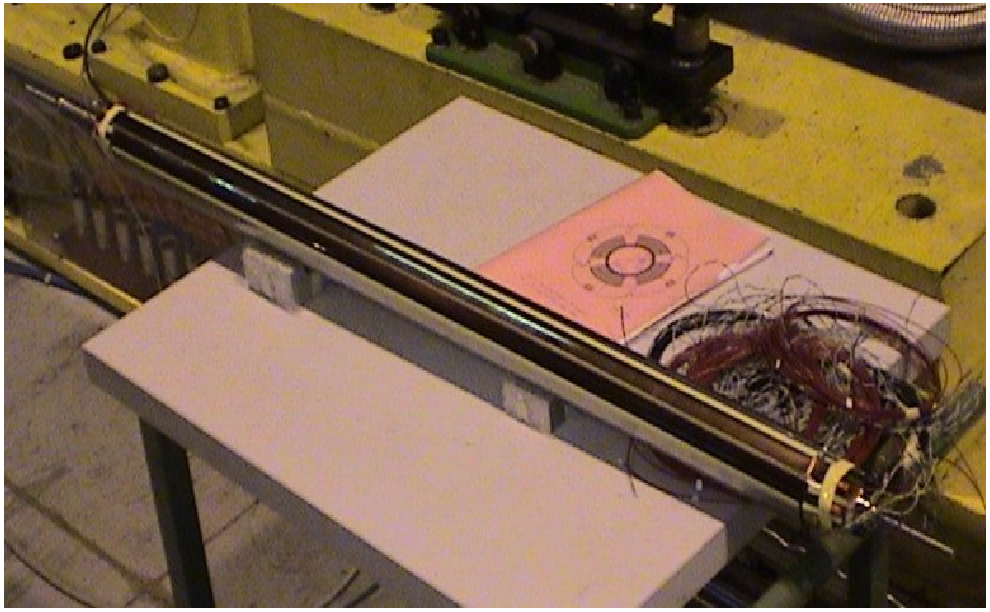
Support tube – stainless steel
Heaters – strip 25 um, 15 mm wide
Temperature sondes
Internal expanding mechanism

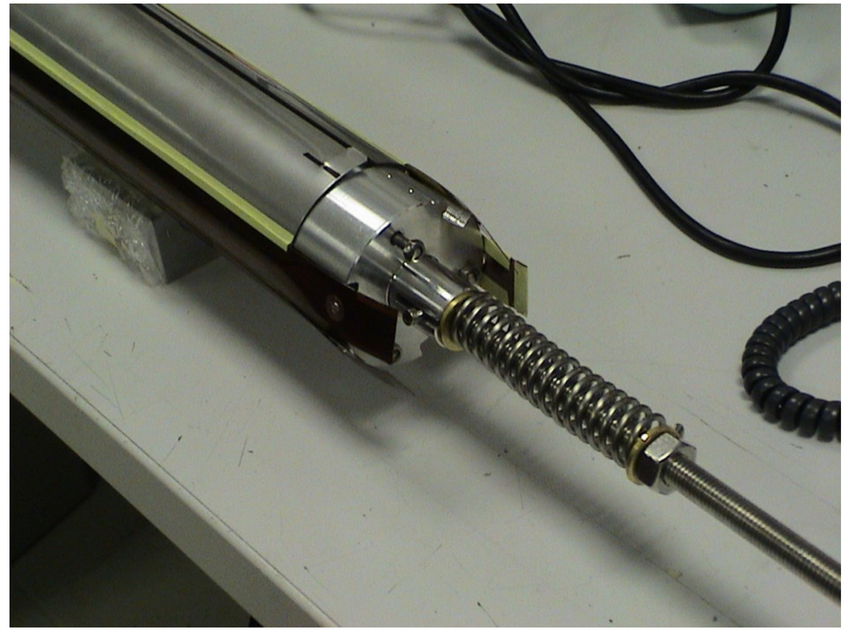


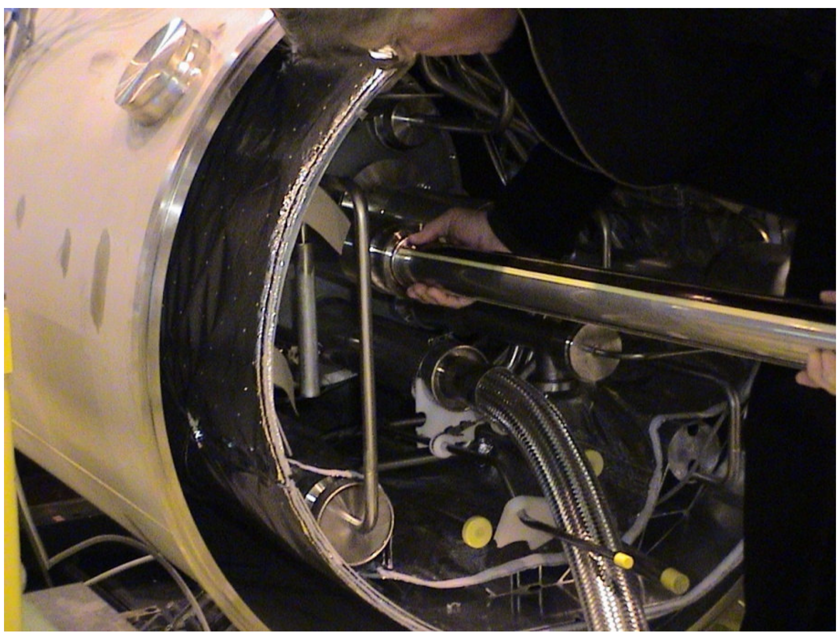


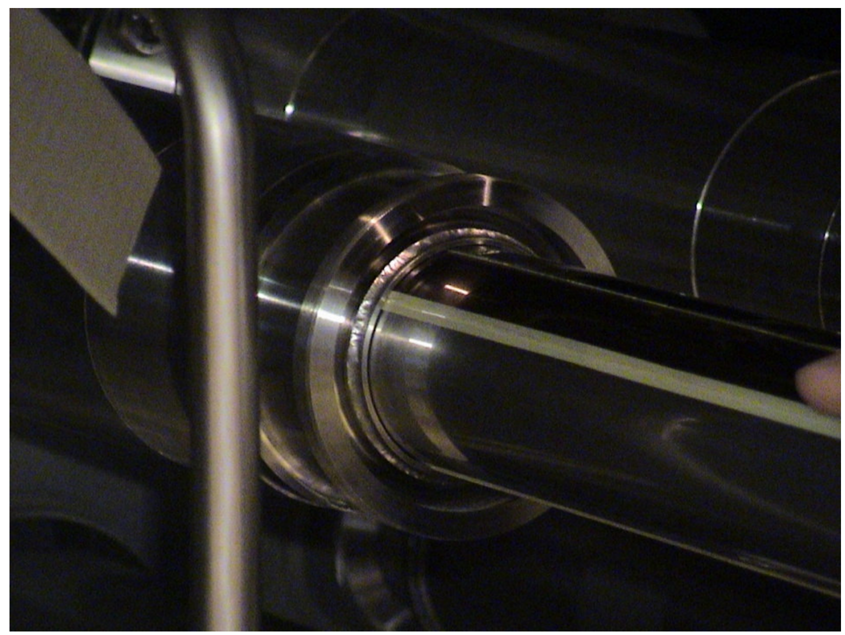


Validation of the model – internal heater

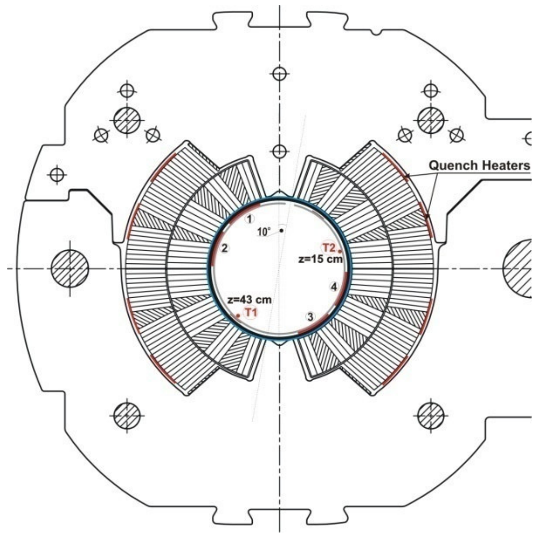




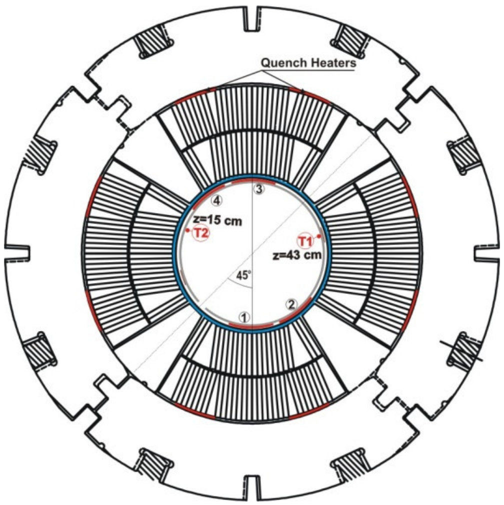




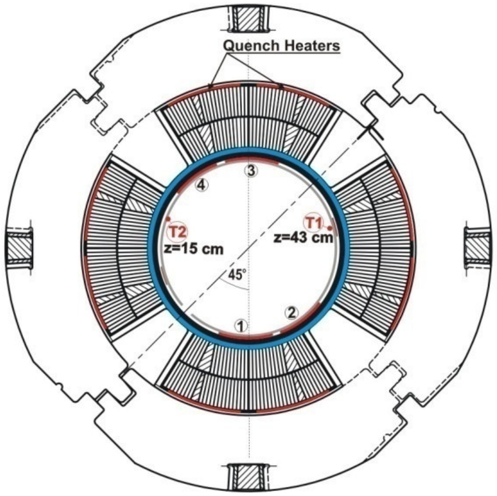
Validation of the model – internal heater



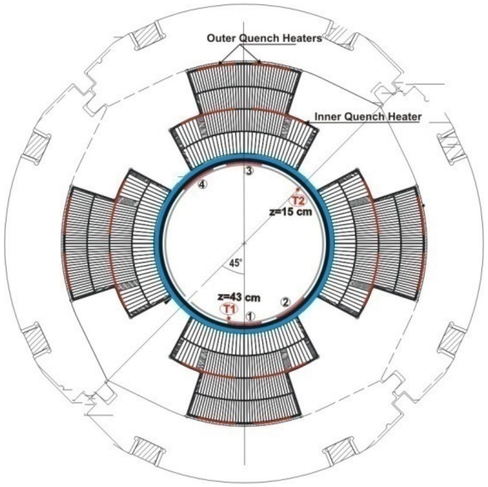
Main Dipole - MB



Main Quadrupole - MQ

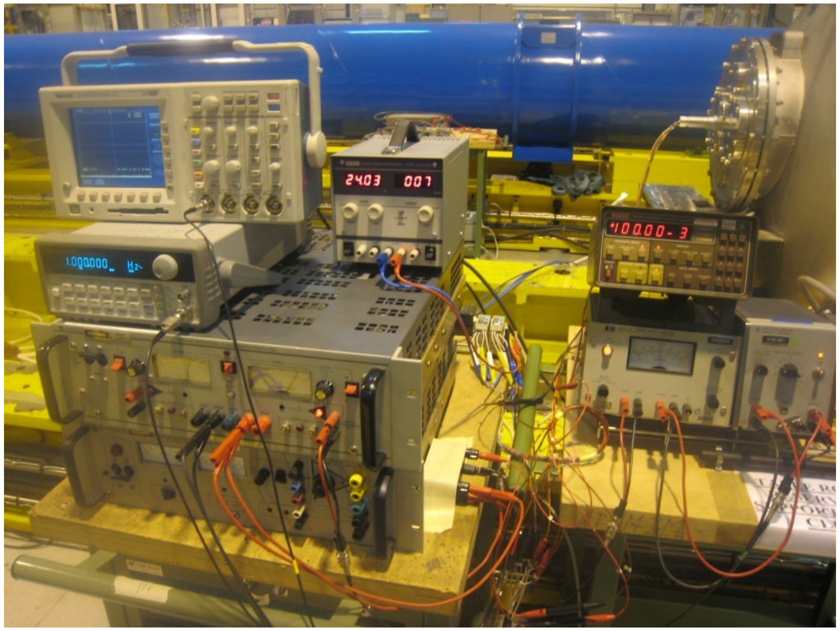


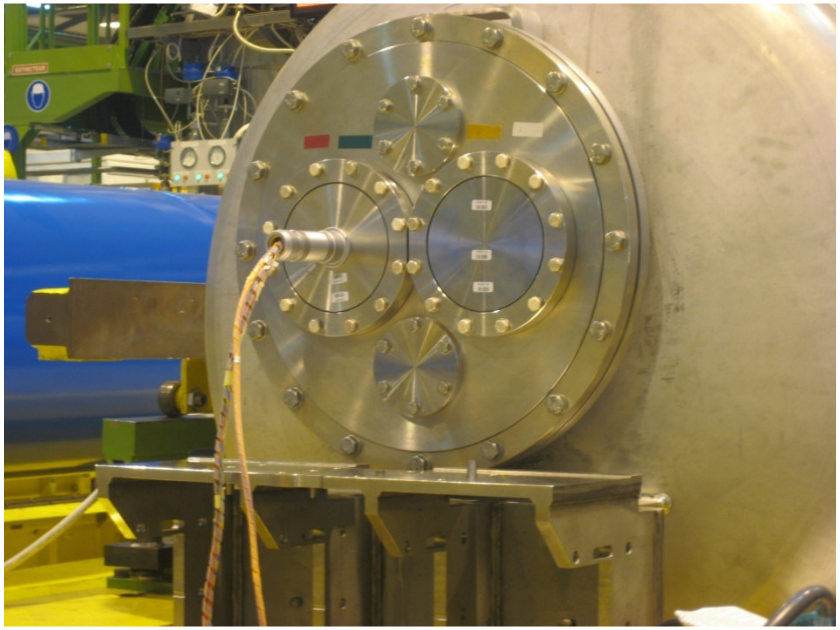
MQM

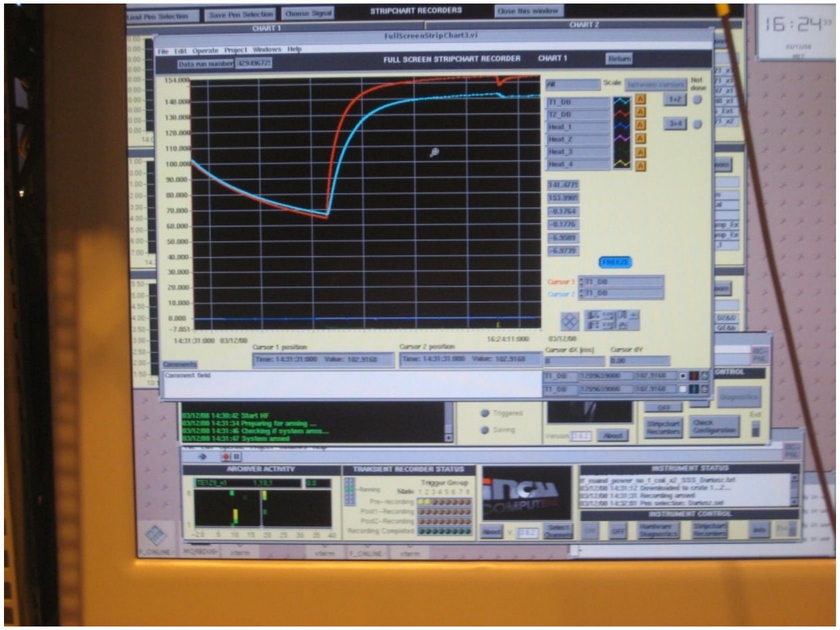


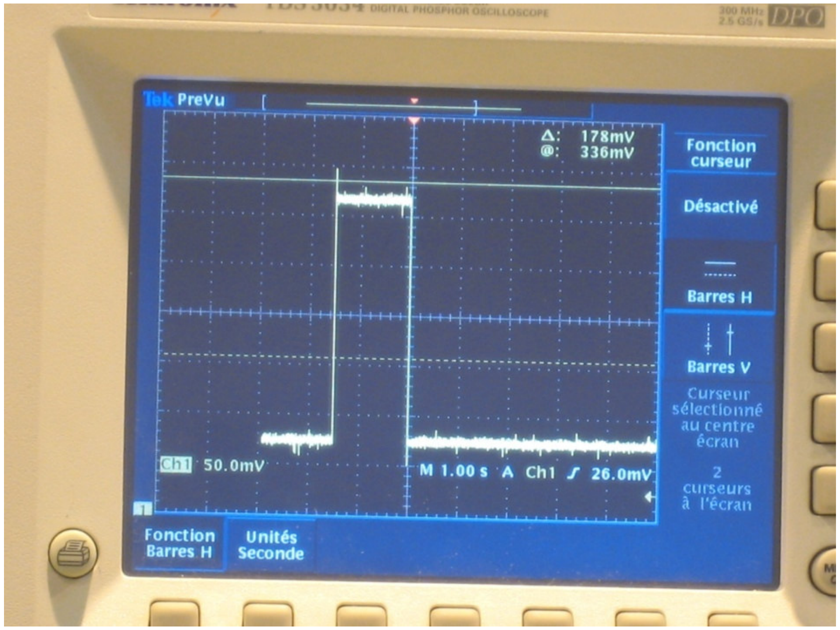
MQY

Validation of the model – internal heater

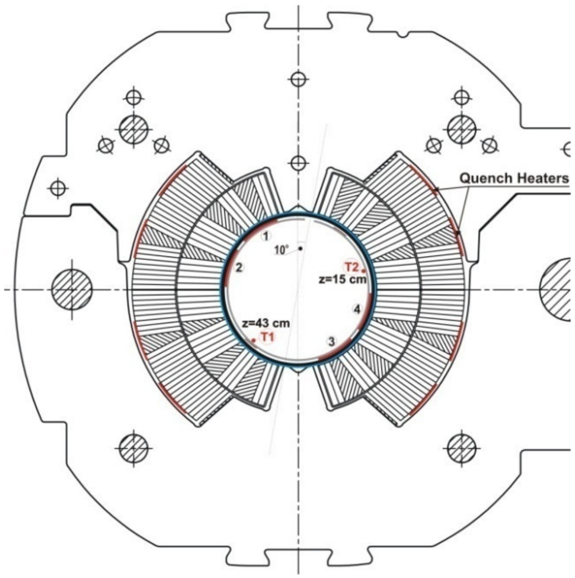


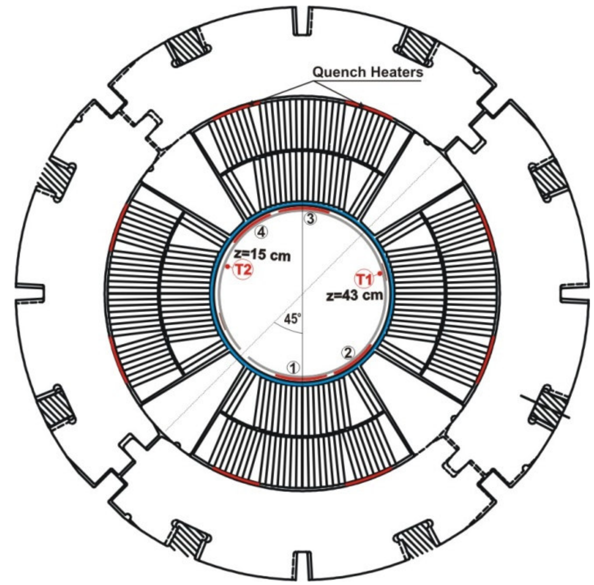




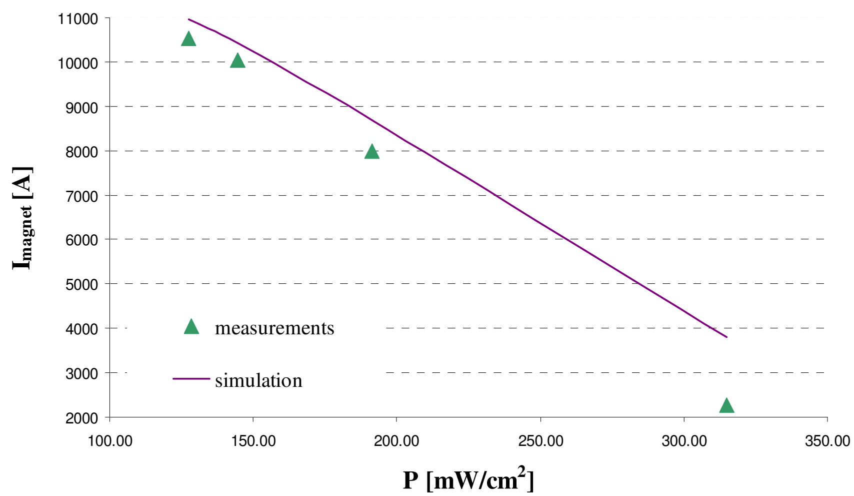


Validation of the model – inner heater

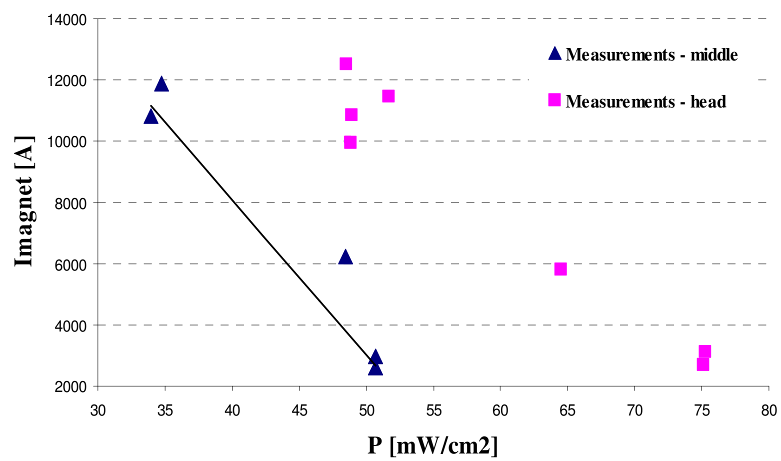




MB magnet at 1.9K - Inner Heating Apparatus



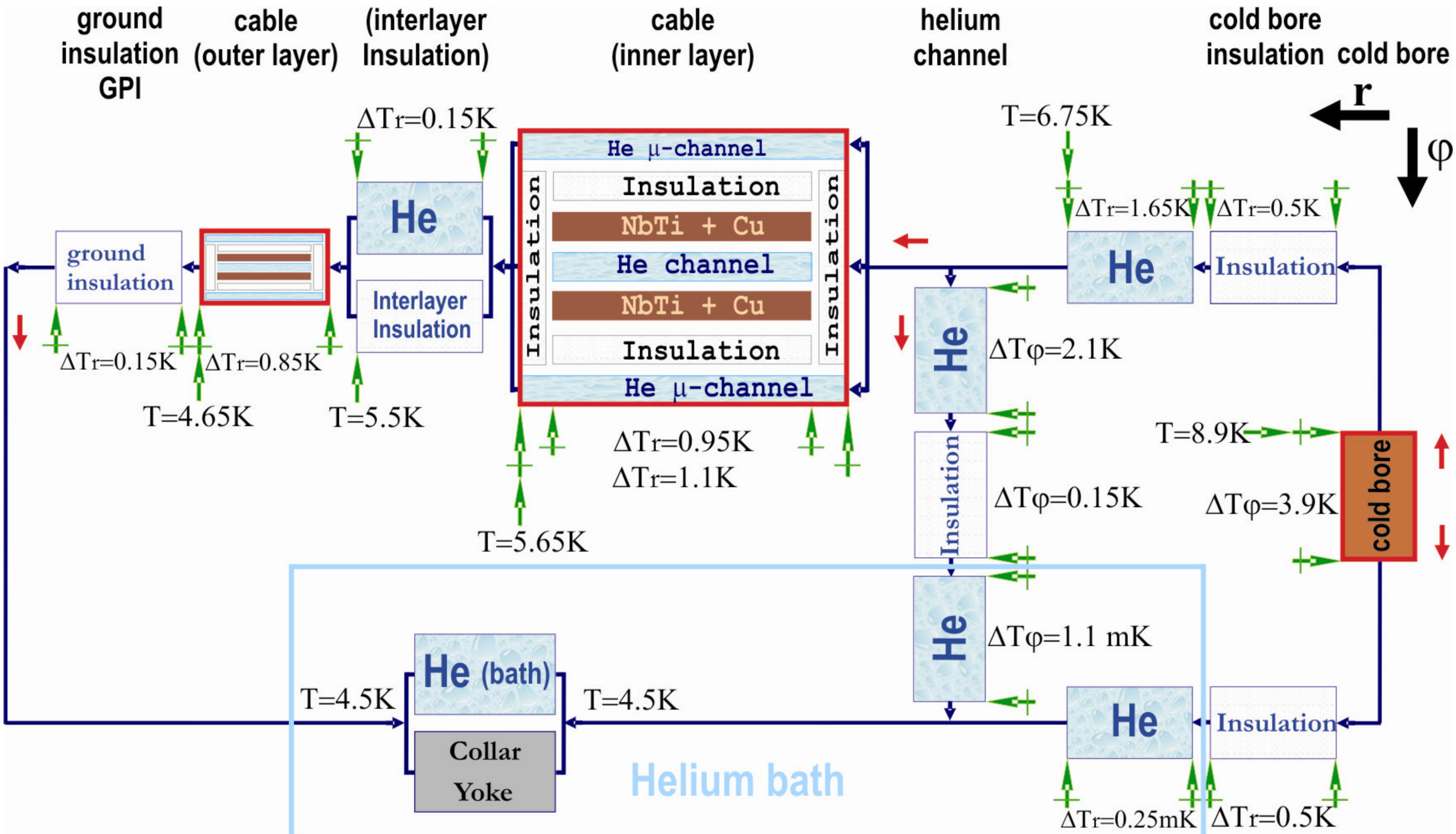
MQ magnet at 1.9 K - Inner Heating Apparatus



Network Model

Quench limit simulations

Network Model – Quench limit simulations

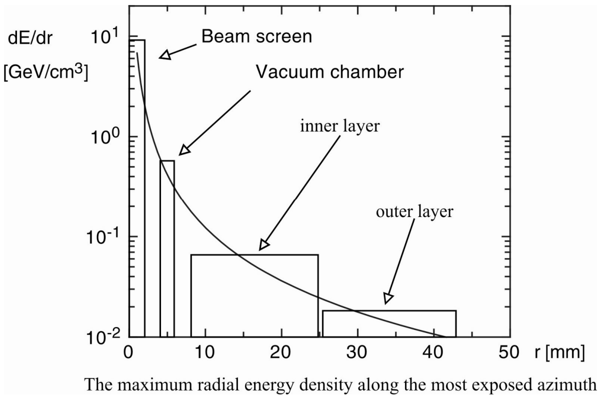


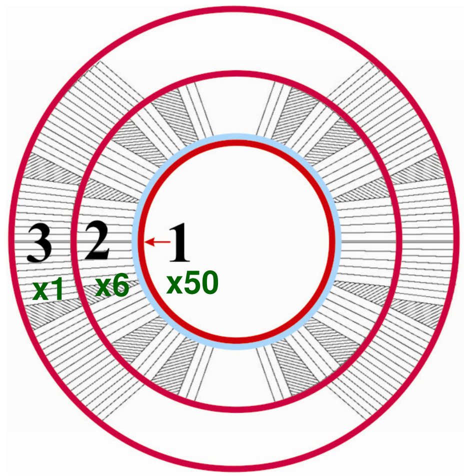
Network Model – Quench limit simulations

1 - cold bore - factor = 50

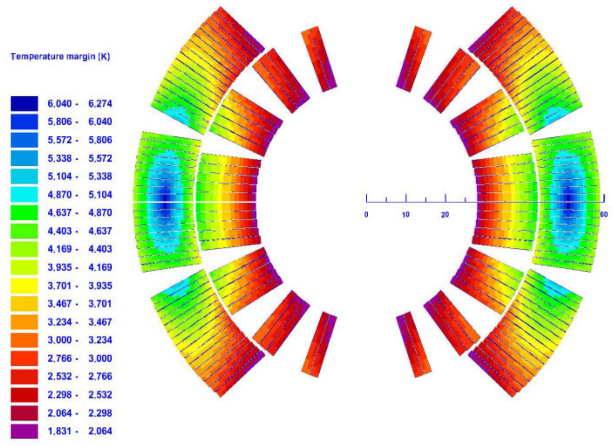
2 - inner layer - factor = 6

3 - outer layer - factor = 1





Concentric beam loss profile



Temperature margin distriution, ΔT

LHC Project Note 44 (2006)

FLUKA simulations

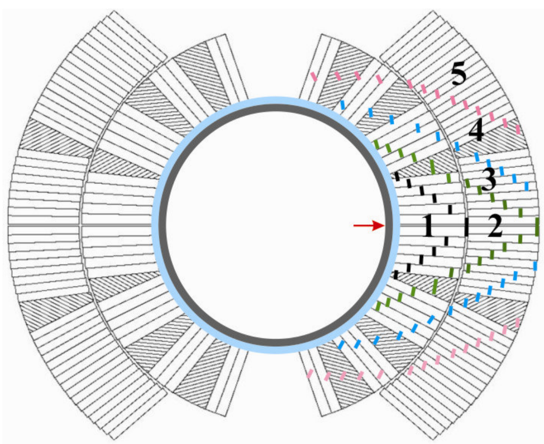
1 - factor = 1

2 - factor = 1.0/3.0

3 - factor = 0.4/3.0

4 - factor = 0.1/3.0

5 - factor = 0.03/3.0



Gaussian beam loss profile

Quench limit at 11850A

Concentric - 12 mW/cm³

Gaussian - 17 mW/cm³

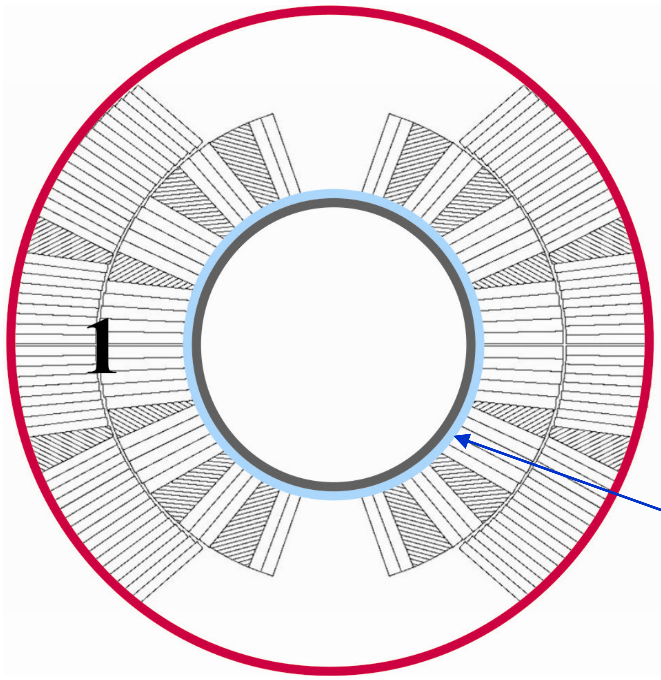
Quench limit at 12840A

Concentric - 10 mW/cm³

Gaussian - 14 mW/cm³

Network Model – Quench limit simulations

Homogenous beam loss profile in MB magnet
STUDY CASE – cold bore heated/not heated



- **Beam loss profile with homogenous heat deposition**
- **no heat load to the cold bore**
  - 10500 A → Quench Limit ~ 150 mW/cm³
  - 11850 A → Quench Limit ~ 100 mW/cm³
  - 12100 A → Quench Limit ~ 72 mW/cm³
- **with heat load to the cold bore**
  - 10500 A → Quench Limit ~ 20 mW/cm³
  - 11850 A → Quench Limit ~ 14 mW/cm³
  - 12840 A → Quench Limit ~ 9mW/cm³

This is effect of heat flow decrease in the helium channel around cold bore

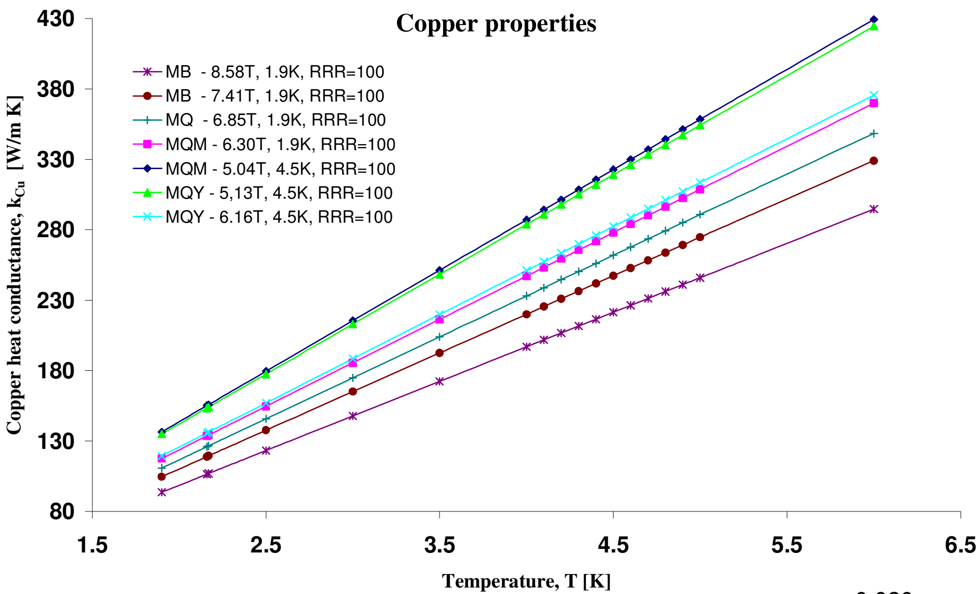
A better cooling of the cold bore is needed to increase quench level

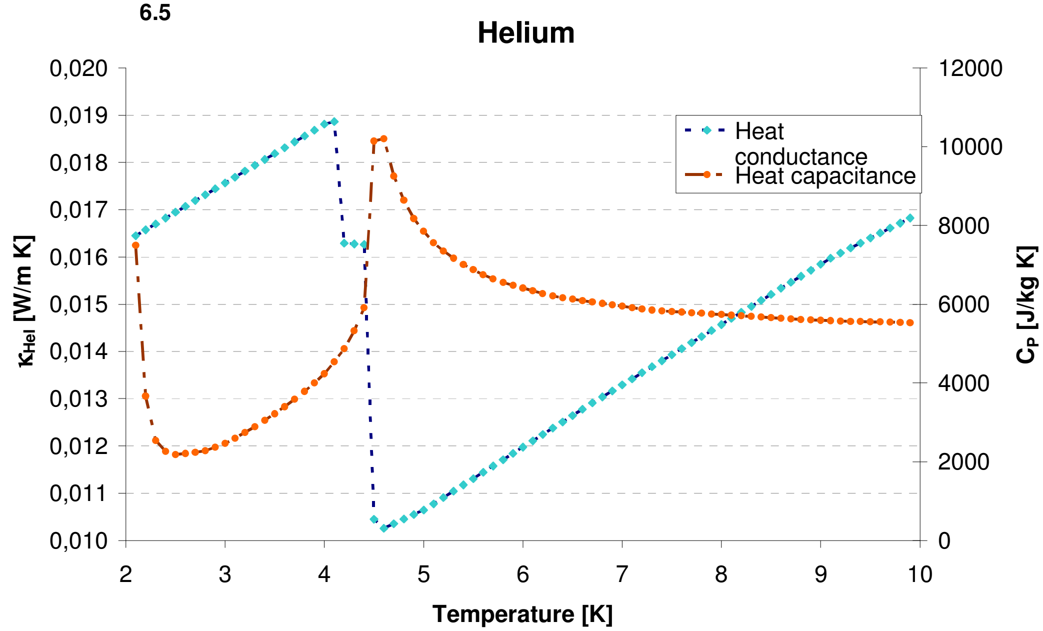
Summary and outlook

- Quench limit for the „real" beam loss depends on the beam loss profiles
  - Two most realistic beam loss scenarios are considered:
    Gaussian and concentric (factor ~2 difference)
- The validation of the model with MQM, MQY, MQ and MB magnet at 4.5K were performed successfully.
  - The agreement between measurements and simulations is in worse case of order of 20%.
- The measurements on MB and MQ at 1.9K are very successful
  - Internal Heating Apparatus allows to quench MB magnet in the range from 1kA to 12 kA.
- Quench level for the typical beam losses scenarios are calculated
- Transient loss simulations and validations with measurements – first results with so-called impulse mode are available.

Additional transparencies

Heat conductivity





Motivation I
Gain time by optimised threshold settings

- **Scenarios**
  1. Threshold too high ⇒ quench of the magnets
     (ideally: no beam loss induced quenches)
  2. Threshold too low ⇒ beam abort

  Scenario 1

  After 3 quenches change threshold value (by trial and error)

  ⇒ lost time: 3 recovery times (minimum 3x5h=15 hours)

  Scenario 2

  After 3 aborts change threshold value (by trial and error)

  ⇒ lost time: 3 false aborts (3x2h=6 hours)

- **9 different main magnets family ⇒**

  ⇒ ~10 kCHf/hour of LHC operation

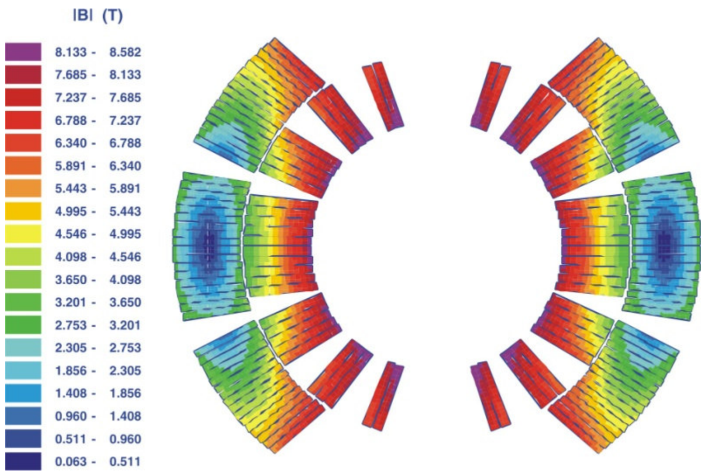
  ⇒ assuming one threshold setting change per magnet

MB, MQ, MQM @ 1.9K, MQM @ 4.5K, MQY
MQTL
MQXA, MQXB, MBR

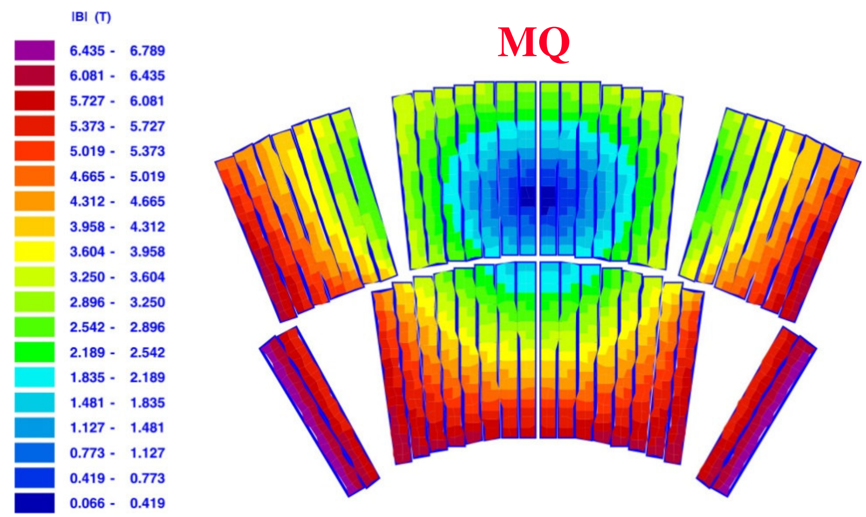
135 h makes $1.35 \cdot 10^6$ CHF

Magnetic field distribution in the coils

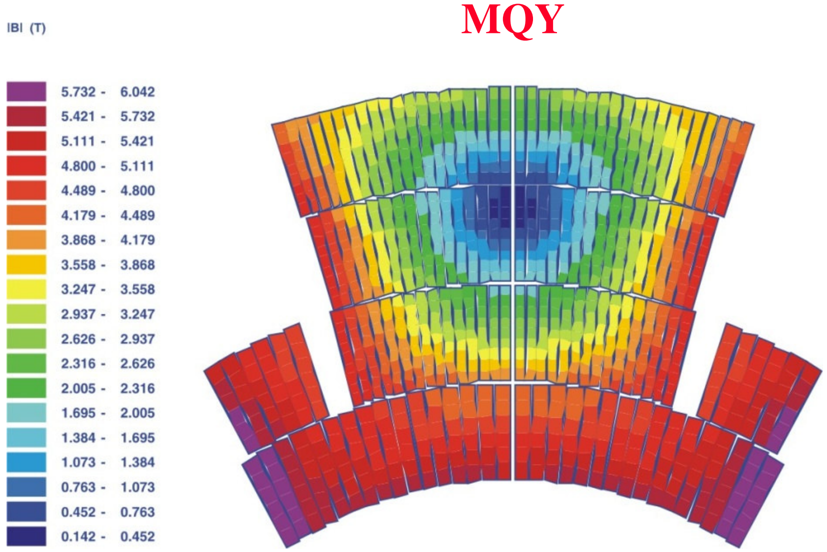
MB



MQ



MQY



MQM