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Quench Protection Studies 11 T

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FNAL-CERN Collaboration Meeting

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1. Introduction

Main parameters for the high-field Nb_3Sn magnets for the LHC luminosity upgrade.

Comparing to the Main Bending LHC dipoles:

- **High stored energy density**

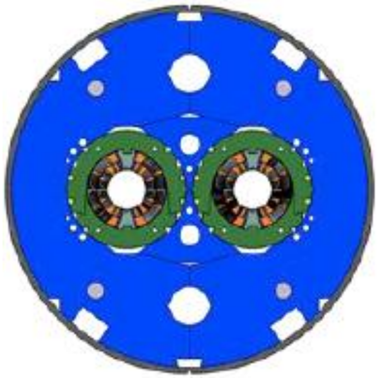
(compact winding for cost reduction)

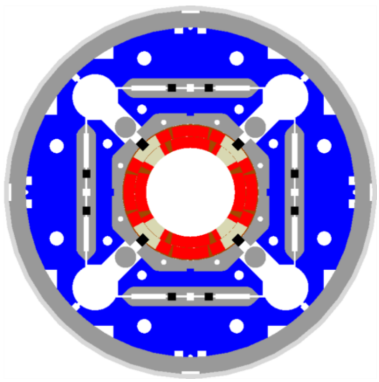
- **Low stabilizer fraction**

(to achieve the desired margins)

- **Large temperature margin**

(use Nb_3Sn as superconductor)





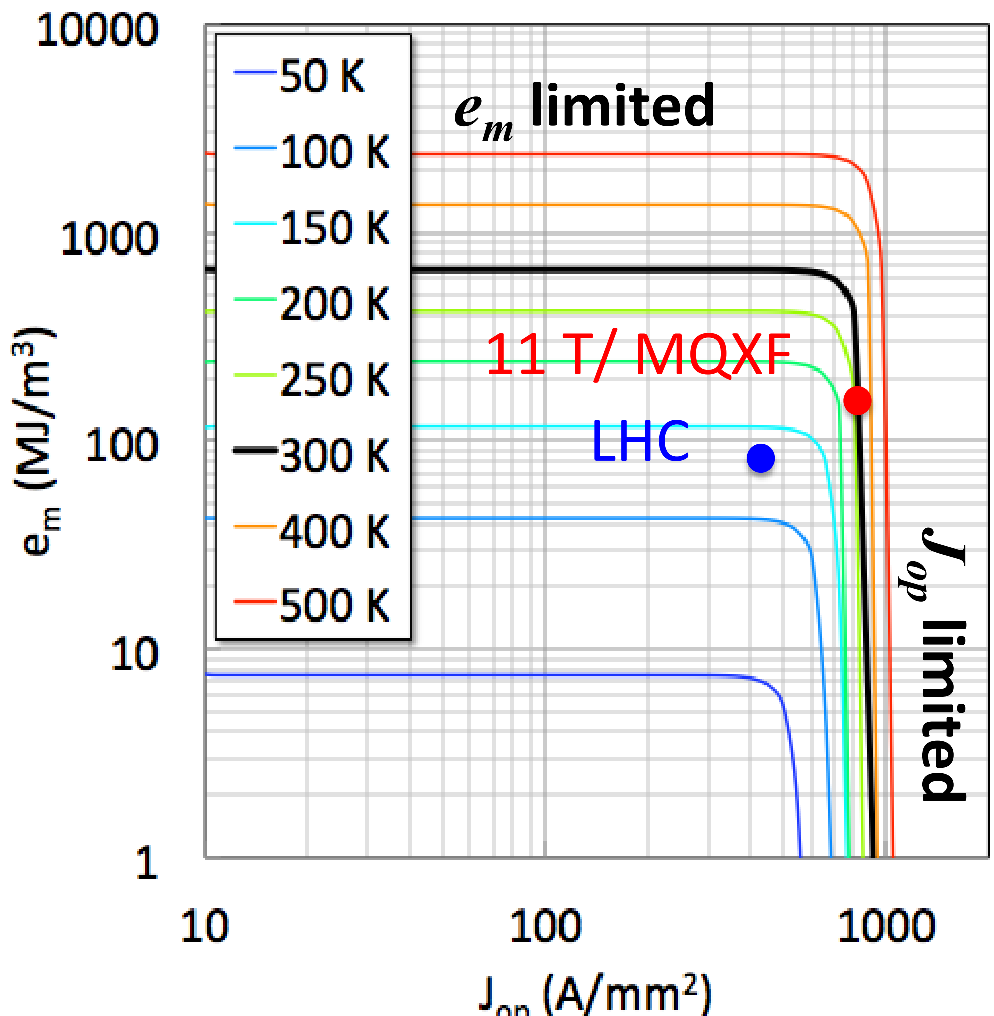
	LHC MB dipole	**DS-11T dipole**	**MQXF quadrupole**
Field (T) /Gradient (T/m)	8.3	11.2	132.5
Peak field in the conductor at I_{nom} (B_p), T	8.6	11.6	11.4
Engineering current density (J_{eng}), A/mm^2	**500**	**790**	**730**
Stored energy at $I_{nom,}$ MJ/m^3	**60**	**130**	**110**
Differential inductance at I_{nom}, mH/m	6.9	11.7	8.21
Magnetic length, m	14.3	2 x 5.3	4x4.2/2x7.15
Temperature margin, K	**1.8-6.5**	**4.5-14.5**	**5.0-14.0**

1. Introduction

One can get a relationship between the stored energy, current density and hot spot temperature under some assumptions:

- The magnetic energy is completely dissipated in the internal resistance **(self dump)**
- The whole magnet is normal at $t_{discharge}$ **(perfect heaters)**
- The current is constant until t_{quench} then drops to zero
- Wilson's Gamma and the power resistivity

L. Bottura



	DS-11T dipole	MQXF quadrupole
J_{op}, A/mm^2	790	730
e_m, MJ/m^3	130	110

CERN

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2. Longitudinal quench propagation
3. Quench heater design performance
4. Heat transfer propagation within the coil
5. Hot spot temperature
6. Sensitivity analysis
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2. Longitudinal propagation

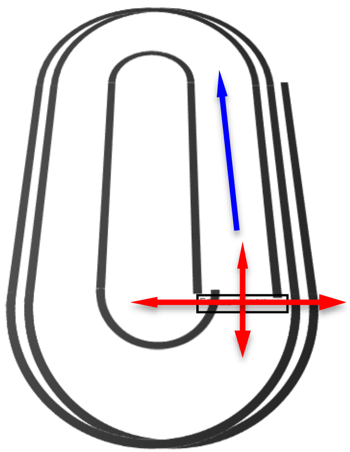
Longitudinal quench propagation

- Important because it determines the time needed to detect a normal zone
- Needs an accurate modelling. Heat equation is solved implicitly in space (finite elements) and time (multi-step finite differences) using an adaptive mesh algorithm to cope with the large disparity of length scales.

Two principal directions:

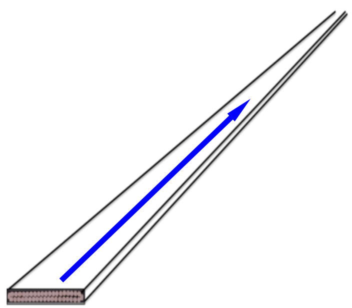
1. Longitudinal
Length scale is hundreds of m

2. Transverse
Length scale is tenths of mm



Longitudinal →

length scale: hundreds of m



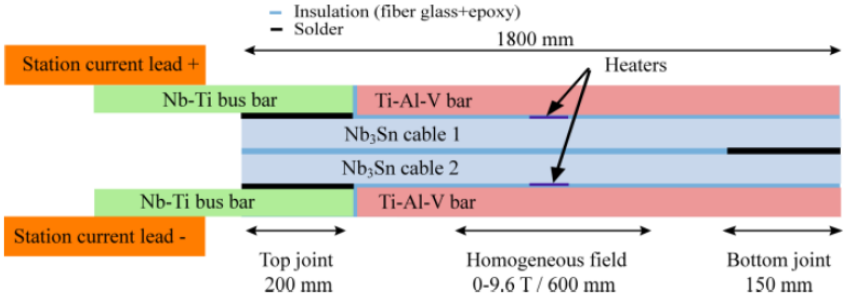
Model validation at different levels:

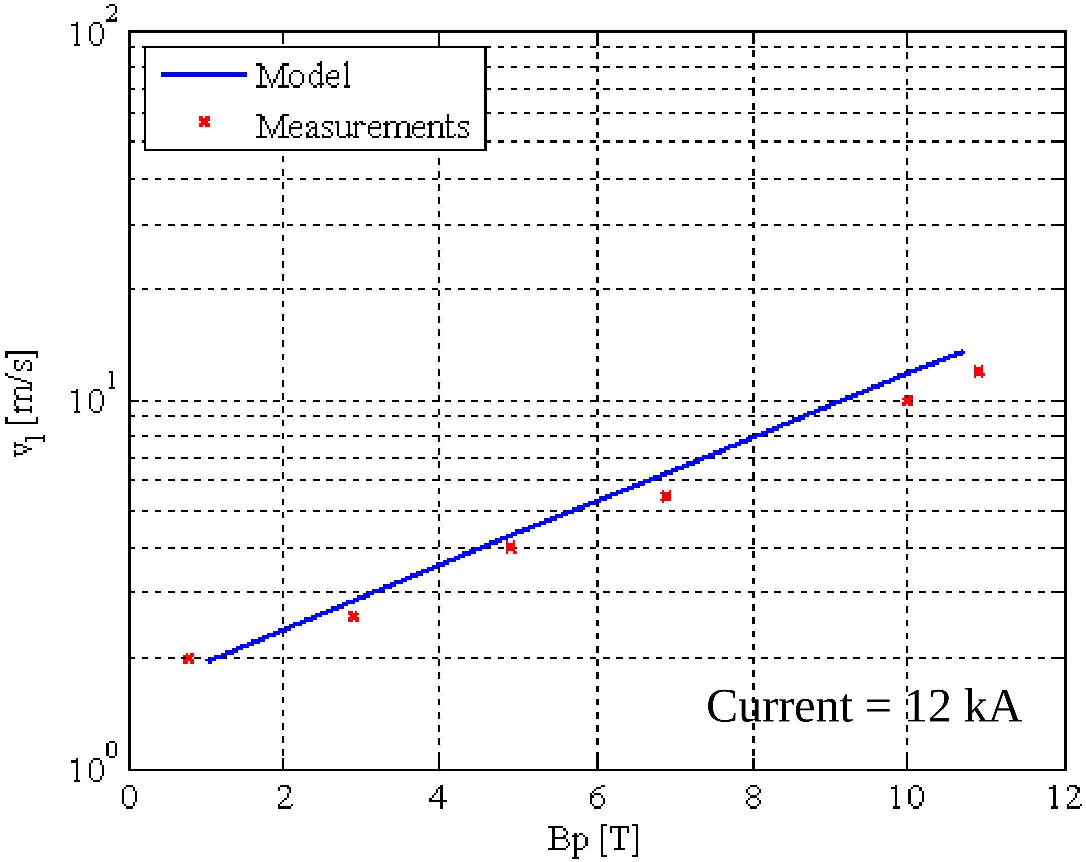
- **Cable level**: measurements on FRESCA
- **Magnet level:**
  - **R&D Magnets**: measurements on the Short Model Racetrack Coil (SMC)
  - **Magnet models**: measurements on FNAL and CERN 11T magnets.

2. Longitudinal propagation - CABLE STACK

Measurements on FRESCA cable test station

- Quench provoked by a heater at different current/field levels in a stack of two conductors
- Relative good agreement between modelled and measured data (when considering the heat capacity of the insulation)

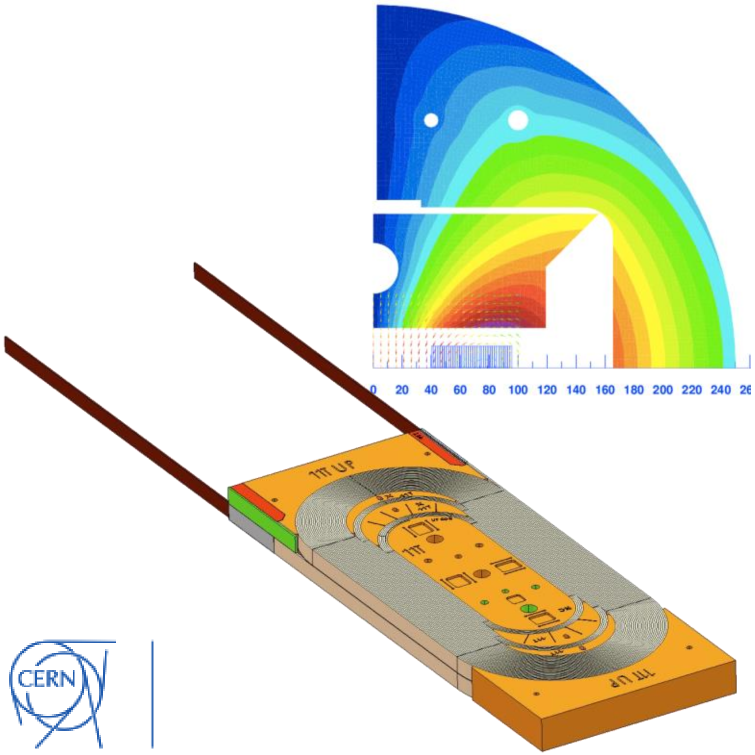


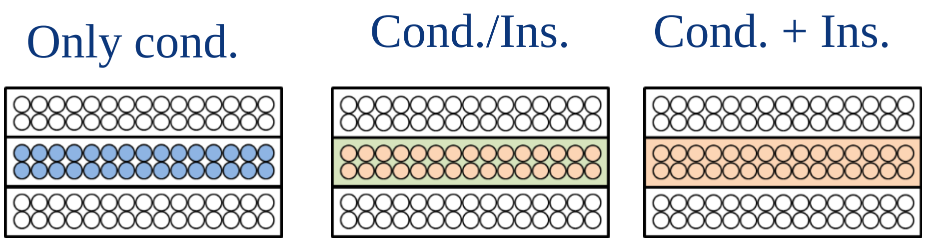


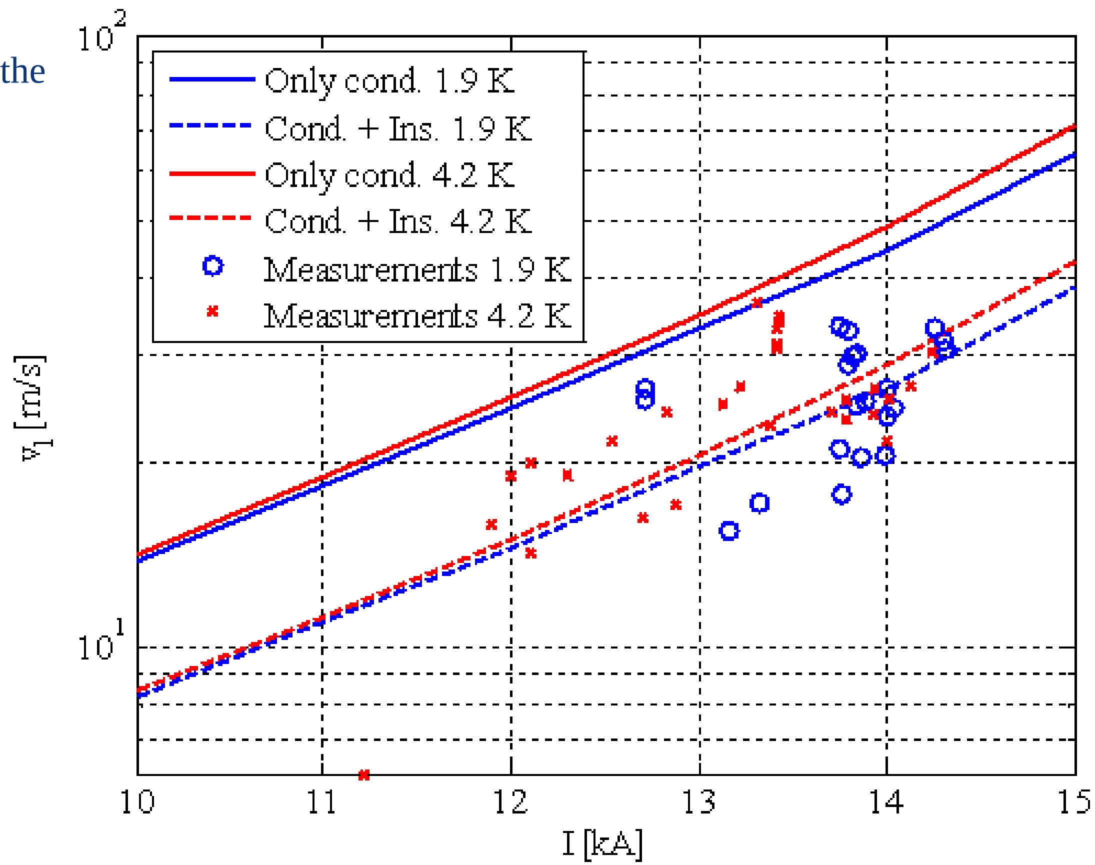
[experimental data from J. Fleiter, B. Bordini]

Measurements on Short Model Racetrack Coil (SMC)

- Coil wound using 11 T conductor.
- Natural quenches mostly in the high field region.
- Data is spread, when compared to the heater provoked quench.
- No systematic difference observed in between the SMC coil wound using S2 glass insulation and the coil wound using S2-Mica glass insulation.



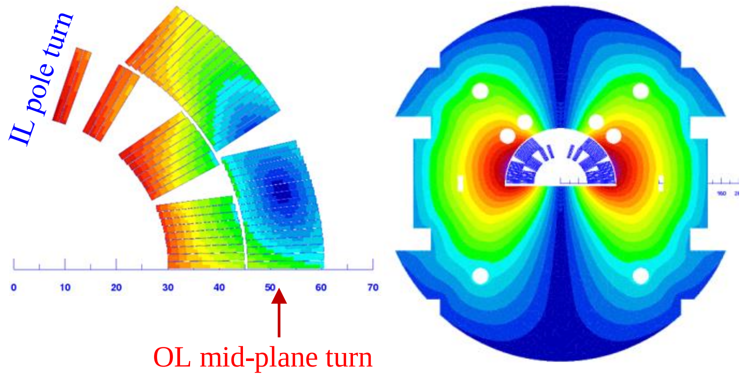


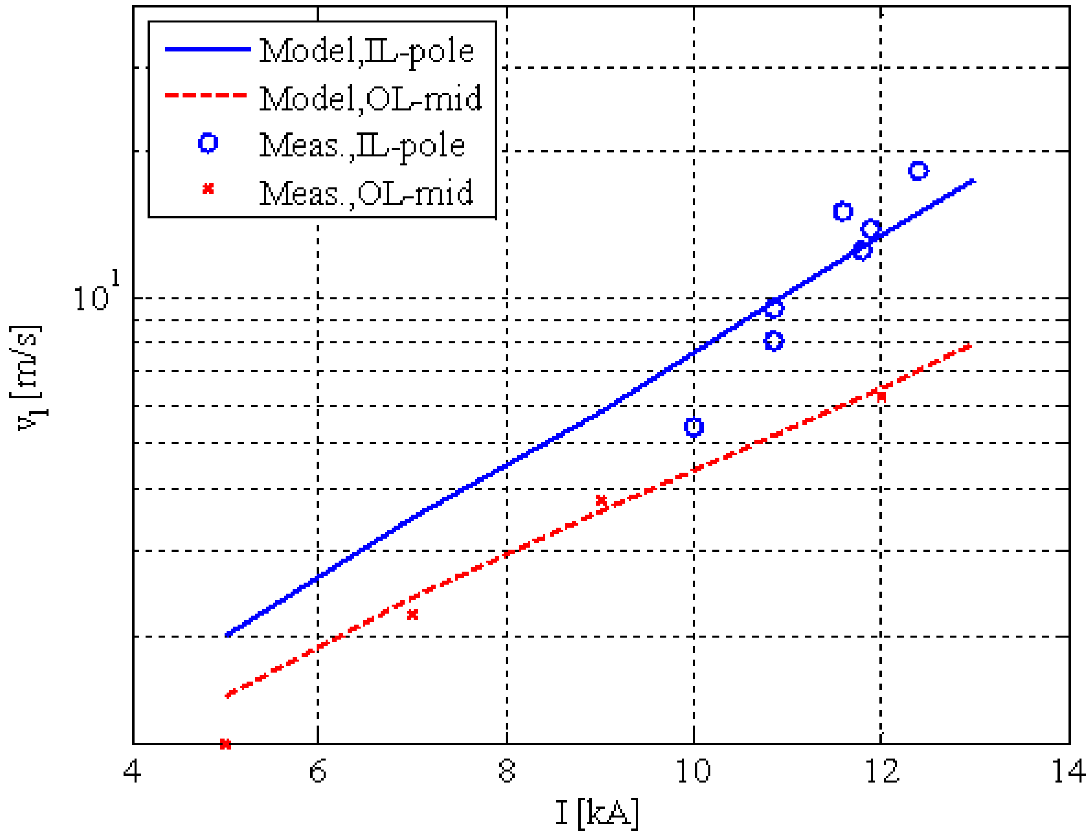


[experimental data from H. Bajas]

2. Longitudinal propagation - FNAL

Measurements on FNAL 11 T mirror magnet (MBHSM01)





Remarks:

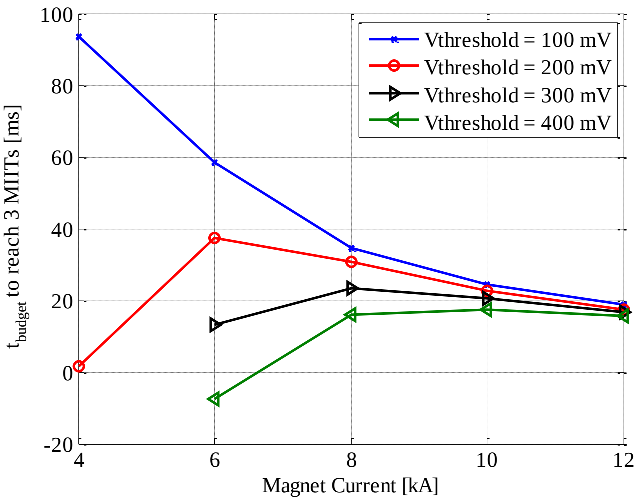
- For **spot heater provoked quenches**, measured and expected propagation velocities are well in agreement.
- For **natural quenches**, the data is scattered.

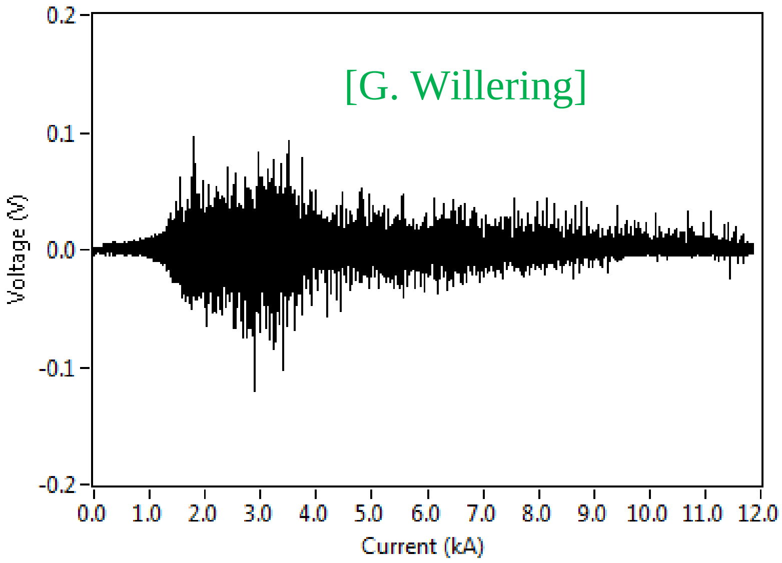
[experimental data from G. Chlachidze]

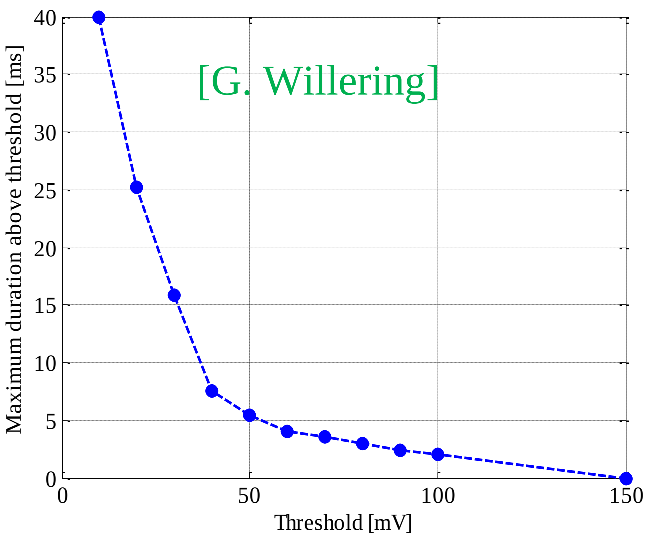
2. Quench detection

- An increased on the voltage threshold from 100 mV to 400 mV has a dramatic impact on the magnet protection at low current level as the longitudinal quench propagation is very slow.
- Important to have a good characterisation of the flux jumps to define the safest way to detect the quench at low magnet currents (longer validation delay keeping a low detection threshold or keep the same validation delay and increase the threshold).

$$t_{budget} = \frac{MIITs}{I^2} - t_{detect}(V_{threshold})$$







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1. Motivation
2. Longitudinal quench propagation
3. **Quench heater design and performance**
4. Heat transfer propagation within the coil
5. Hot spot temperature
6. Sensitivity analysis
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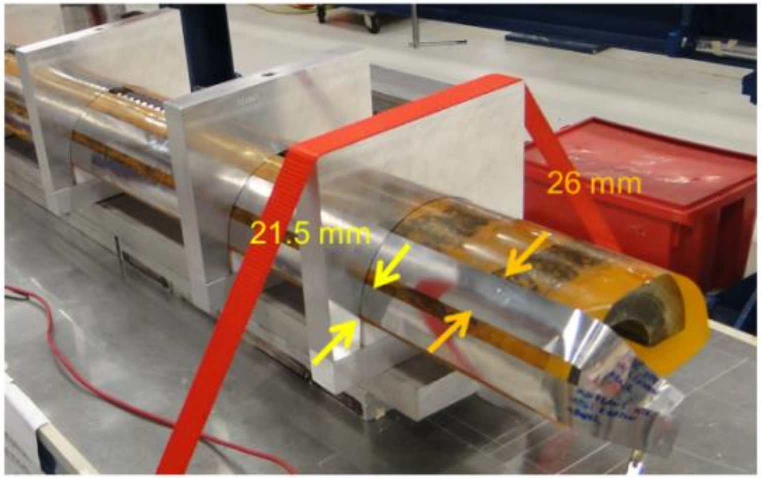
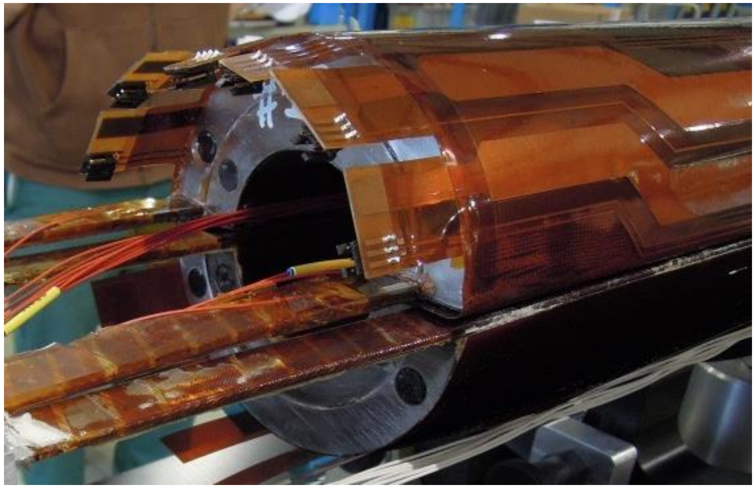
3. Quench heater design

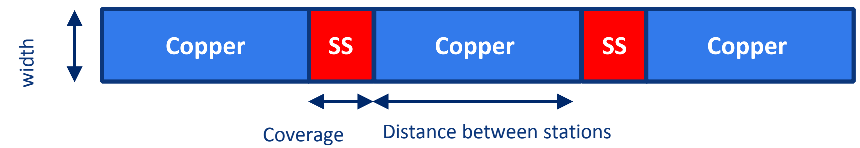
- Both for FNAL and CERN, heaters are only present in the **outer layer,** and they are glued on the outer coil surface after impregnation.
- The main difference between CERN and FNAL is that heaters are **copper plated** to reduce the overall strip resistance (max. voltage across the heaters +-450 V). CERN design can be extended to a 5.5 m magnet.
- The thickness of the Kapton insulation between heater and coil is also different:
  - FNAL: 1x0.076 mm or 2x0.076 mm
  - CERN: 0.050 mm + ~ 0.025 mm of glue

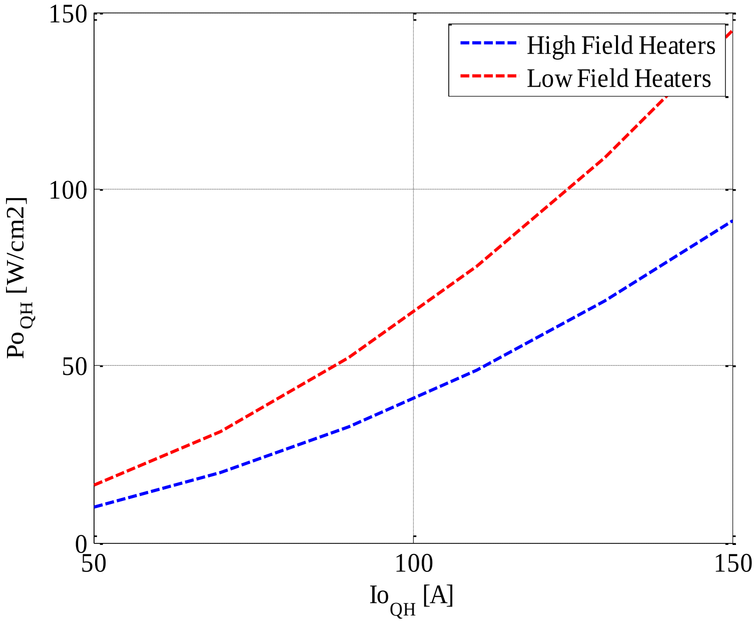




3. Quench heater design

- Width of the heaters and distance between heater stations has been optimized to quench the coil in an uniform way.

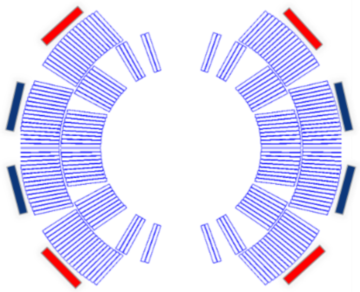


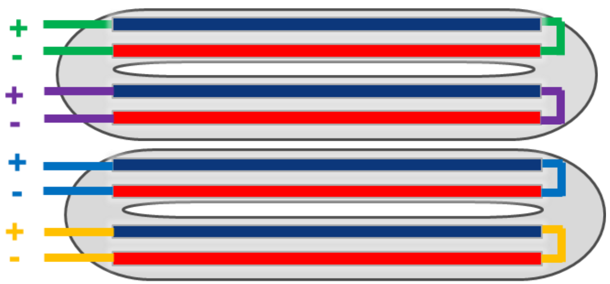


	Low field heater strip	High field heater strip
Coverage (mm) (Stainless steel part)	*50*	
Distance Between Stations (mm) (Copper plating)	*90*	*130*
Width (mm)	*19*	*24*
Stainless steel thickness (mm)	*0.025*	
Copper plating thickness (mm)	*0.005*	

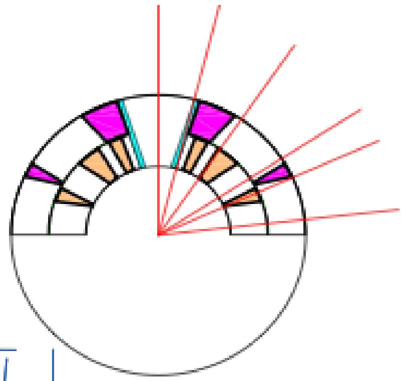
3. Heater design

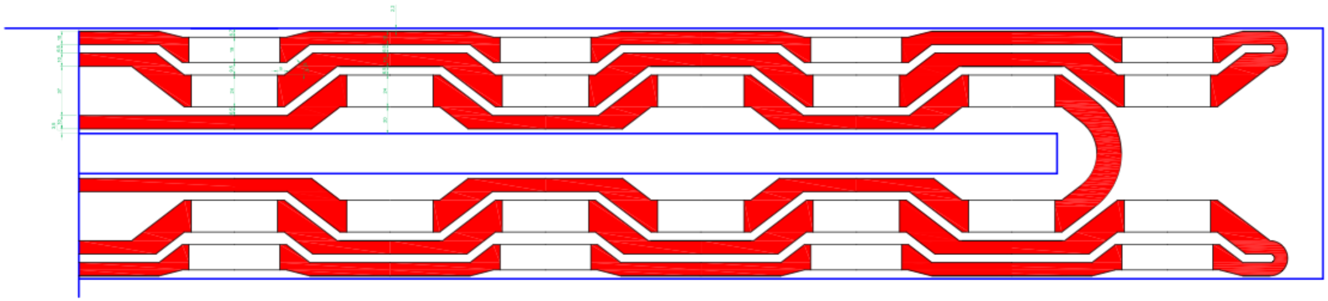
- The baseline design considers 4 heater circuits per aperture for redundancy (could be increased up to 8 per aperture).





- To provide redundancy to the system, a extra circuit could be integrated in the outer layer trace.





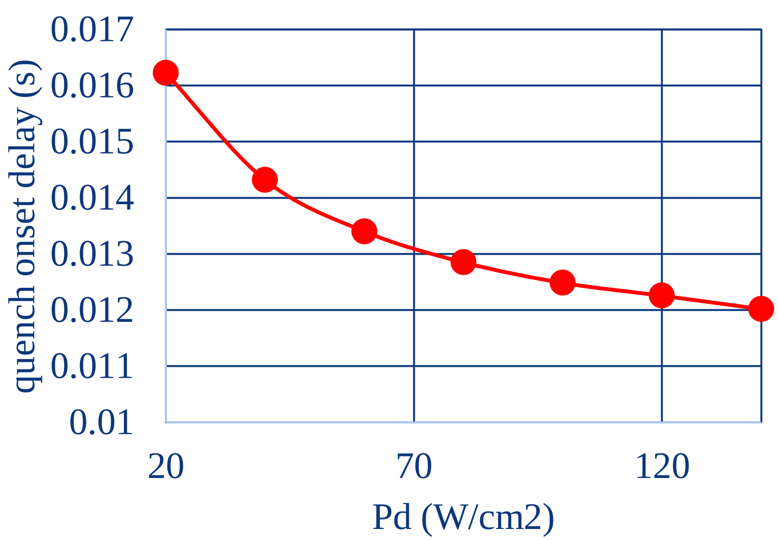
3. Heater design – Inter-Layer Heaters

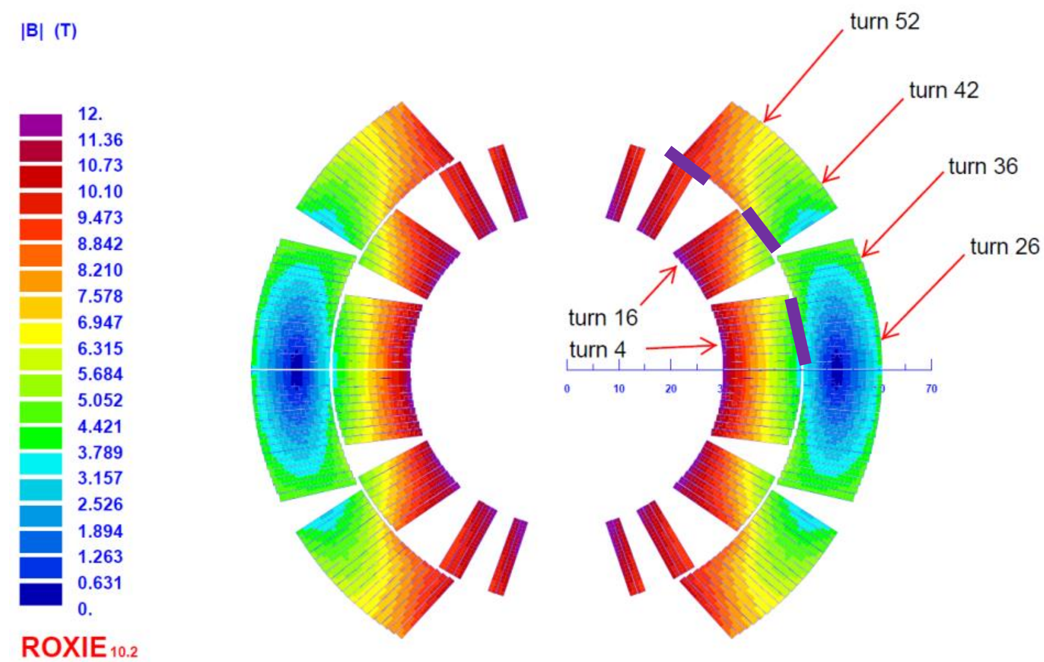
Limitations:

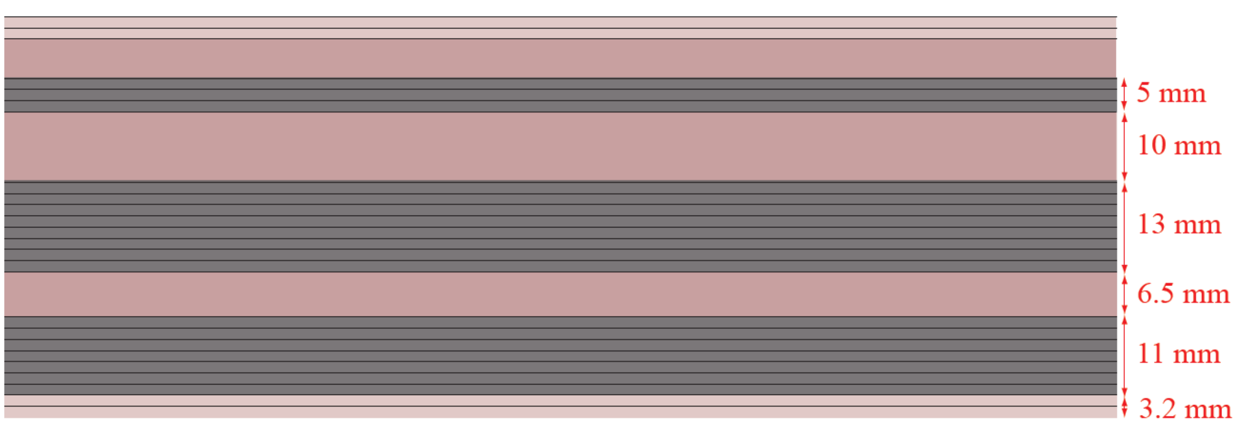
Voltage < 450 V

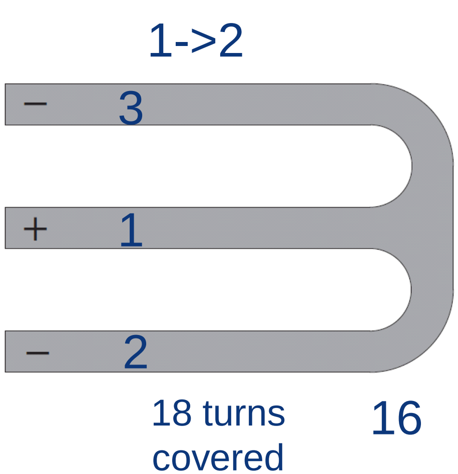
Current < 150 A

Preferred power density 50-100W/cm^2





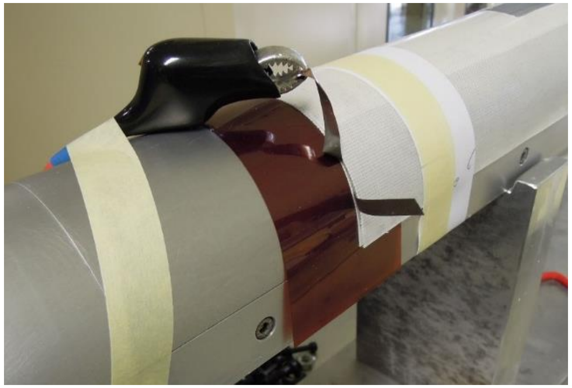




3. Heater design – Inter-Layer Heaters

Techincal challenges for the Inter-Layer Quench heaters:

- Electrical integrity
  - Quench heaters integrated in coil 110 show a great electrical perfomance
    - After coil impregnation, up to 8 kV without failure. At 9 kV, failure at the connection level (on the inter-layer assembly before installing it in the coil the breakdown voltage about 1.5 kV)

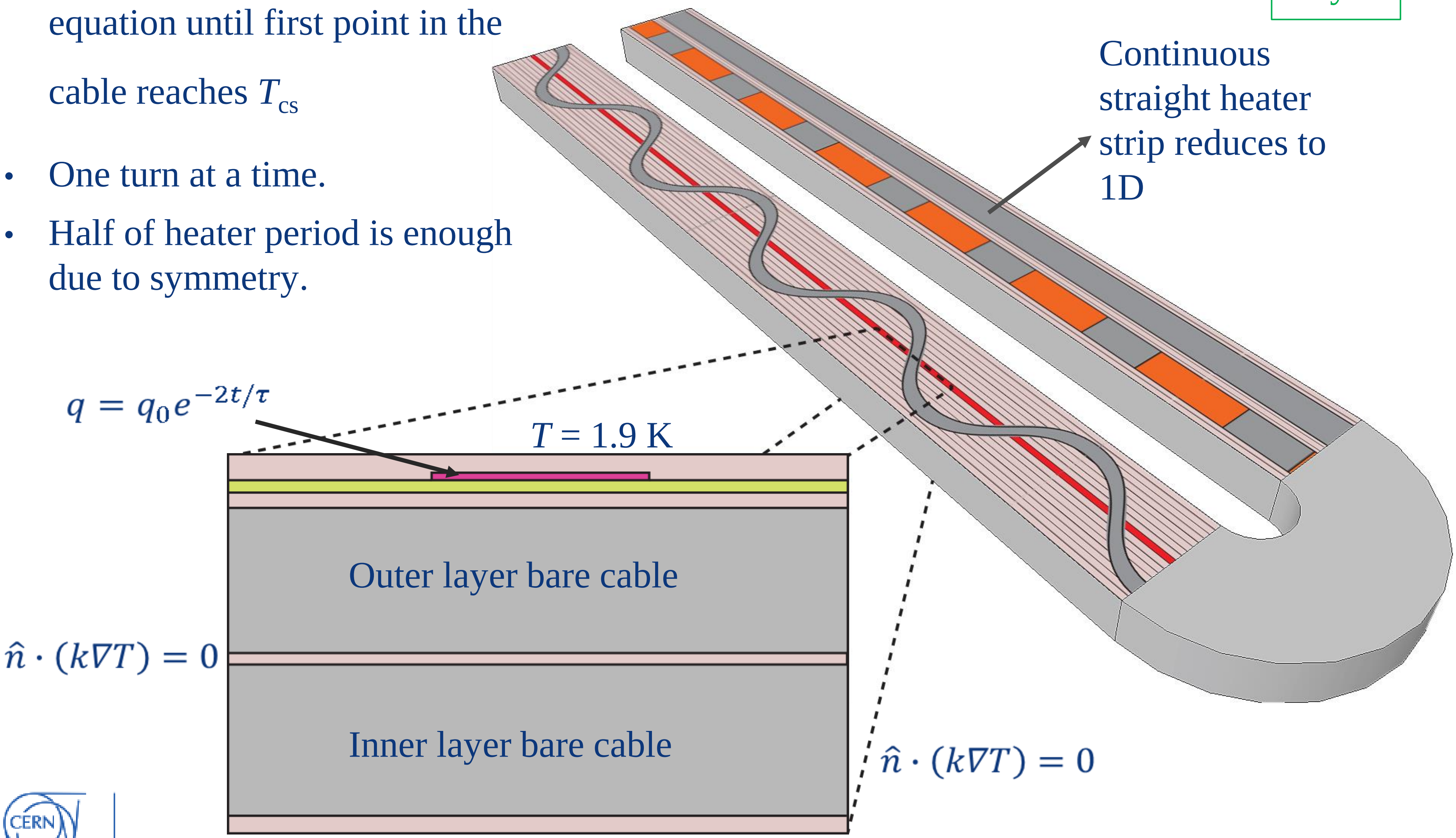


- For 5.5 m magnet:
  - 5.5 m mica sheet?
  - How to reduce the overal strip resistance? With the copper plating technique we use in the outer layer heaters, we need a layer of Ni in between stainless and copper, but during heat treatment the nickel diffuses to the copper increasing the resistance ofthe copper plating section by a factor 5 at room temperature.

3. Modelling quench heater delay

- 2D/1D FEM simulation using **COMSOL**, solving the heat equation until first point in the cable reaches T_{cs}
- One turn at a time.
- Half of heater period is enough due to symmetry.

J. Rysti

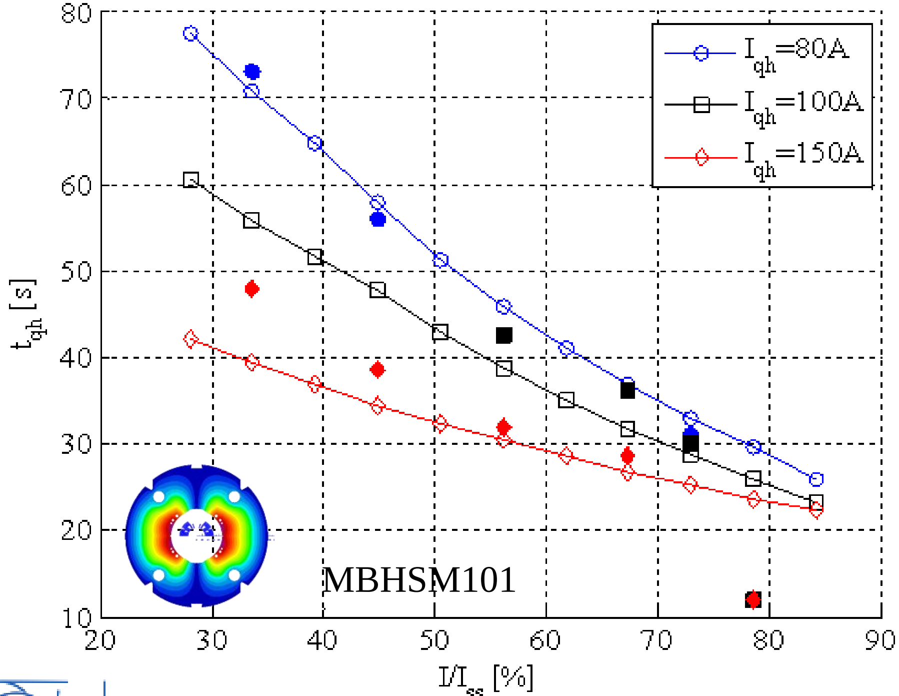


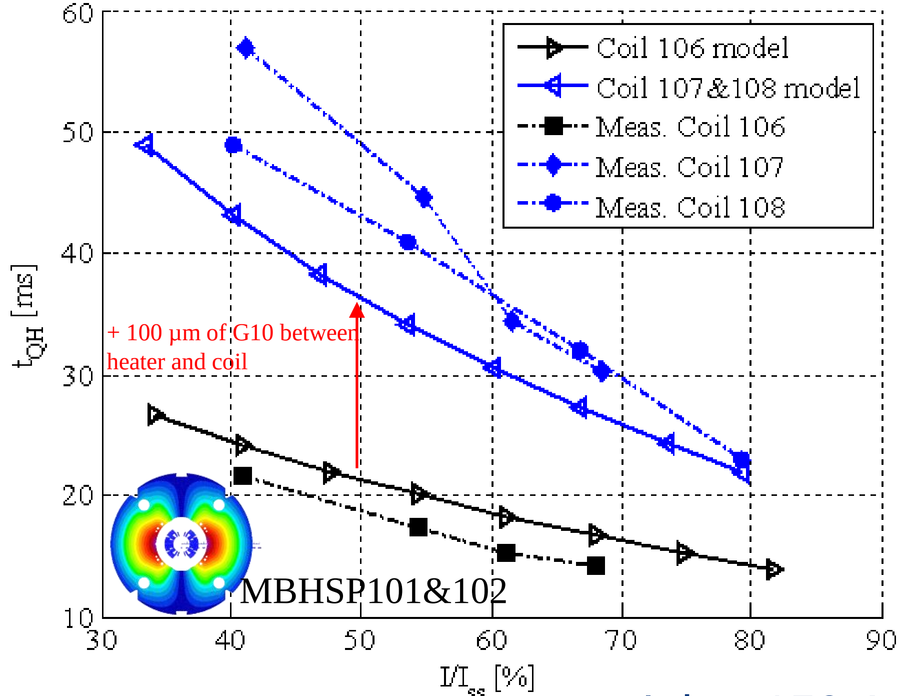
3. Quench heater delays - CERN

Key parameters for the heater delay:

- **Power dissipated on the heaters**.
- Thickness of the **insulation from heater to coil**.

Agreement ~ 20 % between measured and expected heater delays, although discrepancy increases at low magnet current



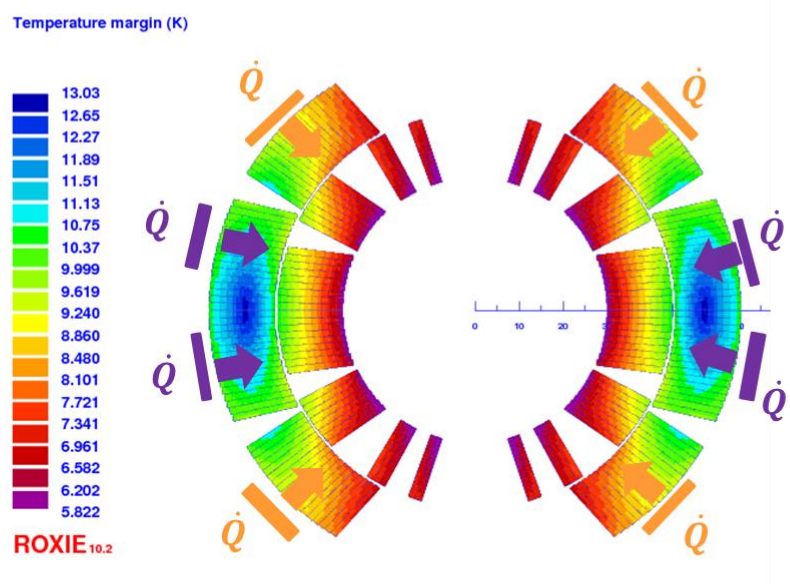


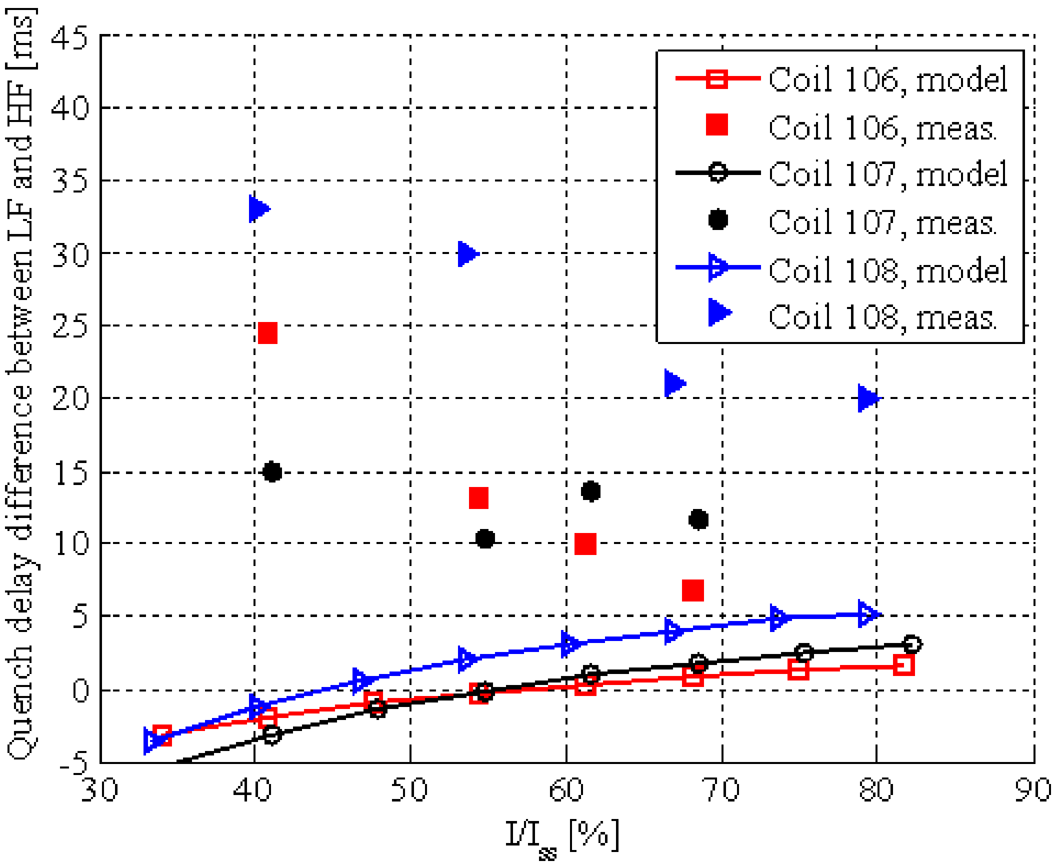
Iqh = 150 A

[experimental data from G. Willering]

3. Quench heater delays - CERN

- Even if the agreement between measurements and model is reasonable good for the heater delay in the high field area, the delay to quench the low field block is longer than expected.
- It varies significantly from coil to coil to coil
  - Coil manufacturing?
  - Test data interpretation?

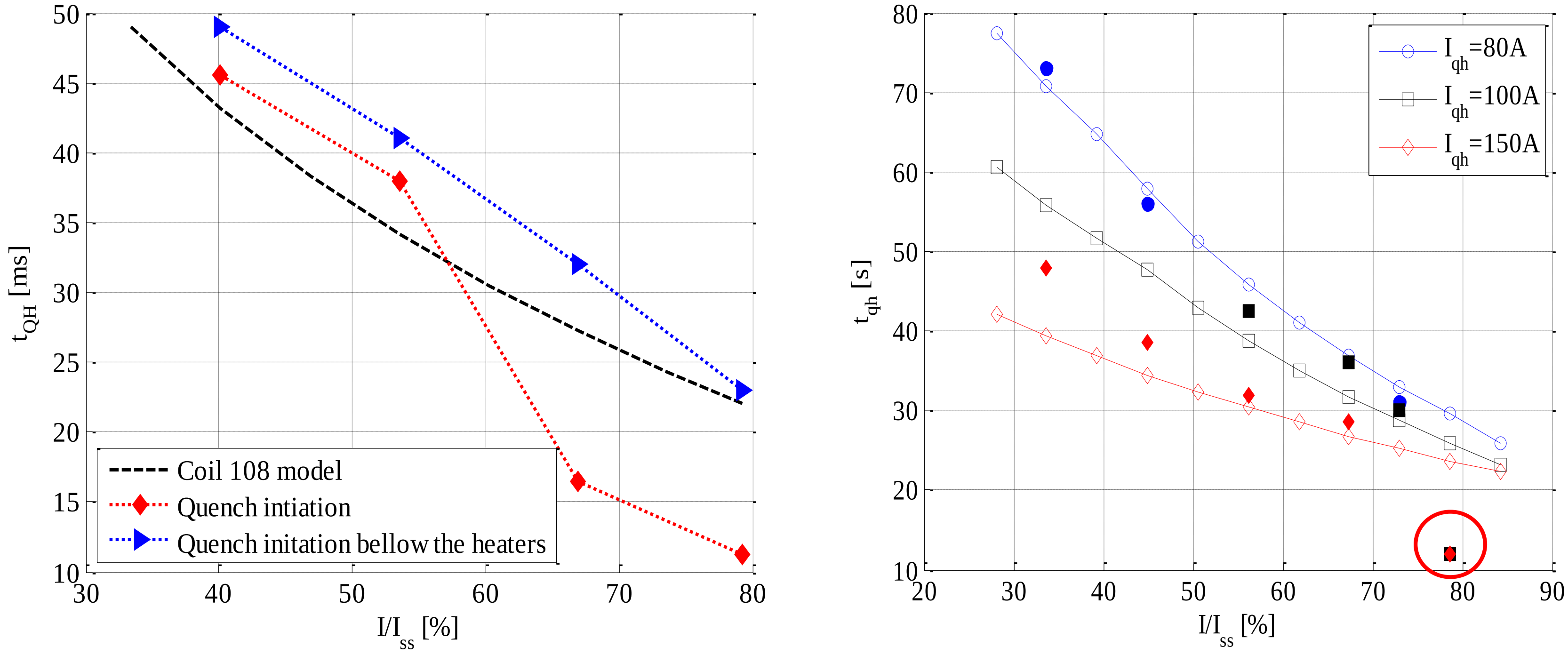




Quench heaters on the high field blocks
Quench heaters on the low field blocks

3. Quench heater delays - CERN

- At high magnet currents, a fast quench starts after quench heater firing. The conductor where the quench starts is not bellow the heaters, so it is difficult to explain it through thermal heat conduction from heater to coil.
- The same effect was observed in coil 105, tested in single coil configuration.



3. Quench heater delay - comparison to FNAL

FNAL MBHSM% insulation between heater and coil:

- 0.125 mm of glass on the outer, impregnated with the coil
- 0.076 mm of kapton between heater and coil

CERN MBHSM101 insulation between heater and coil:

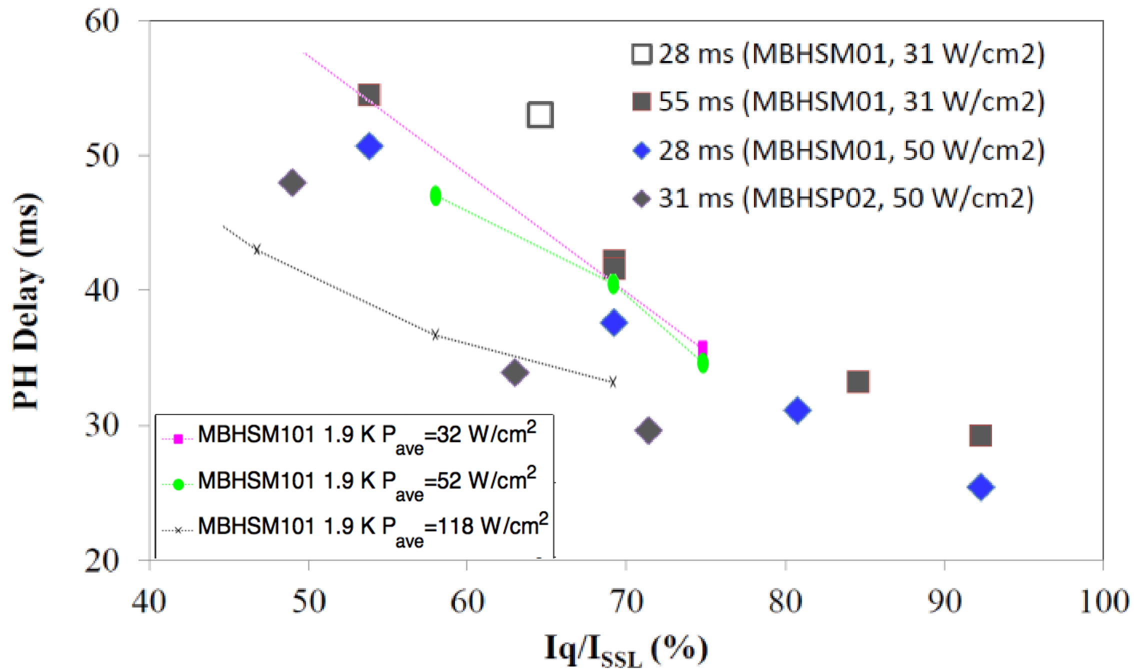
- 0.200-0.250 mm of glass on the outer, impregnated with the coil
- 0.050 mm of kapton between heater and coil + about 0.025 mm glue

CERN MBHSP101 insulation between heater and coil:

- Coil 106: no glass on the outer during impregnation
- 0.050 mm of kapton between heater and coil + about 0.025 mm glue

Comparable delays

Shorter delays



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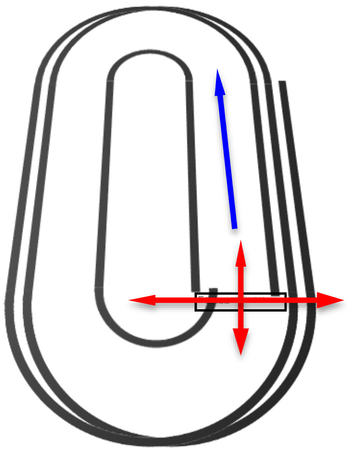
4. Heat propagation within the coil

Two principal directions:

1. Longitudinal
Length scale is hundreds of m

2. Transverse
Length scale is tenths of mm



$$\sum_k A_k \rho_k C_k \frac{\partial T_i}{\partial t} - \frac{\partial}{\partial x}\left(\sum_k A_k k_k \frac{\partial T_i}{\partial x}\right) = \sum_j H_{ij}\left(T_j - T_i\right) + \dot{q}_i + \dot{q}_{Joule,i} + \dot{q}_{adj,i}$$

Power exchanged between components in the conductor

External heat perturbation

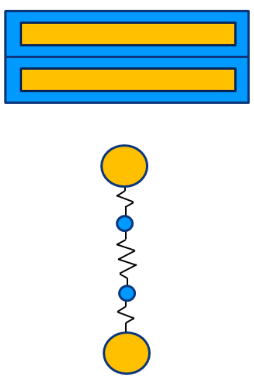
Joule heating

Transverse
Power exchange between adjacent conductors

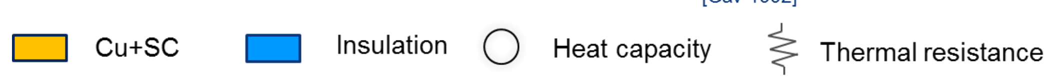
- **Heat propagation within the coil**
  - Important because it determines the time needed to quench the whole magnet cross section
  - Longitudinal conductor model coupled explicitly with a 2nd order thermal network.

- **Key parameters**
  - Degree of thermal coupling between conductors.
  - Thermal properties of the insulation.

2nd order Thermal Coupling Conductor - Insulation



[Gav 1992]

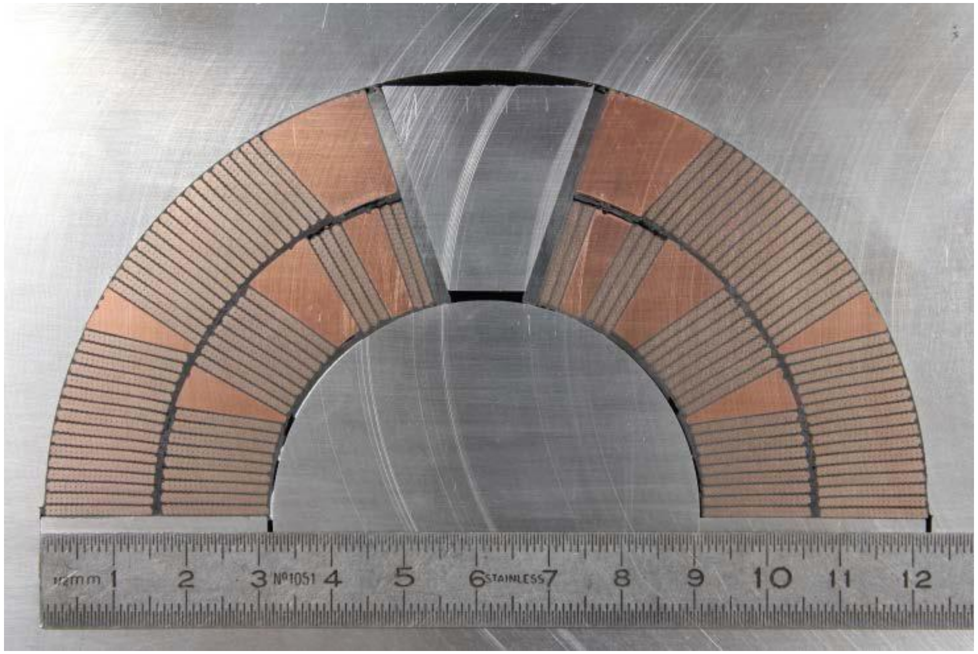


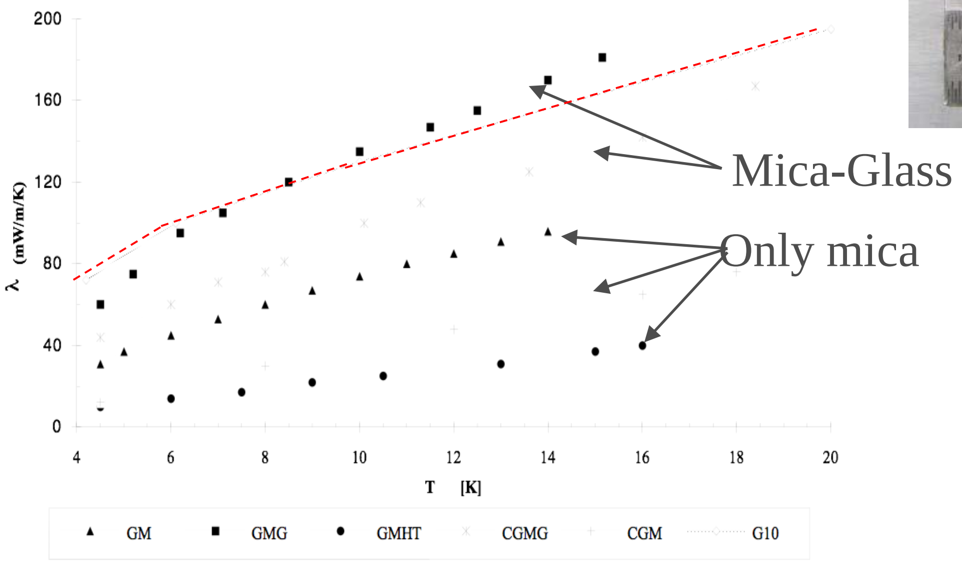
4. Heat propagation with in the coil

Insulation scheme for CERN 11 T:

- Cable insulation: 80-µm-thick C-shaped Mica film and a braided sleeve made of S2-glass fibers (total thickness after reaction = 100-µm)
- Inter layer insulation: 500 µm of S2-Glass, cured using ceramic CTD-1202X

The insulation follows the same reaction treatment as the Nb3Sn (210 ºC 48h, 400 ºC 48h and 650 ºC 50 h), and then it is vacuum impregnated with the epoxy resin CTD-101K.





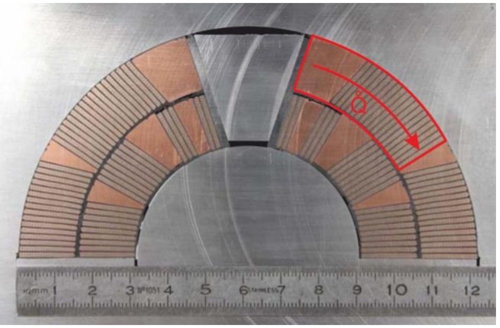
Big uncertainties in terms of geometry and material properties!

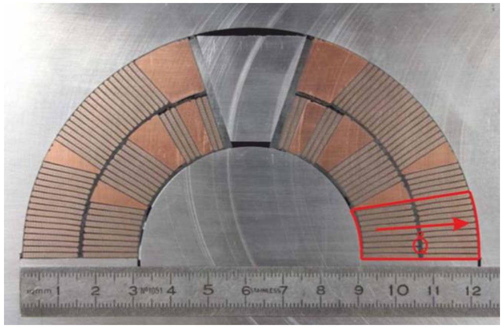
The thermal properties of the insulation in the model are "**G10**", although measurements are on-going at CERN - Cyrolab to have experimental data on the thermal diffusivity for the specific 11T magnet insulation.

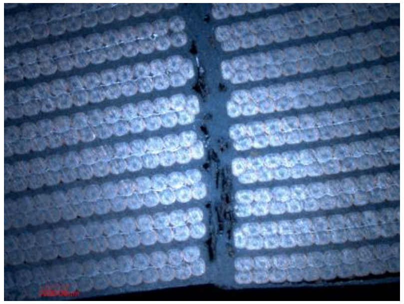
Reference: Thermal Conductivity of Mica/glass Insulation for Impregnated Nb3Sn Windings in Accelerator Magnets*
Andries den Ouden and Herman H.J. ten Kate
Applied Superconductivity Centre, University of Twente, POB 217, 7500 AE Enschede, The Netherlands

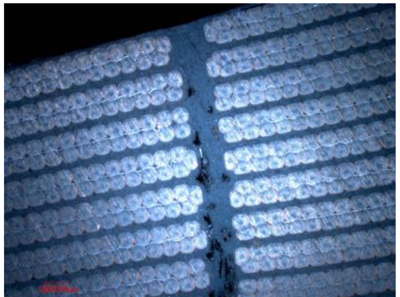
4. Measurements on coil thermal conductivity

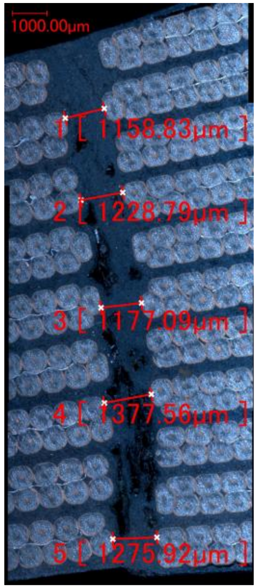
- Measurements performed on the azimuthal and radial coil direction.
- Image analysis on coil cross-section to have an accurate measurement of the actual thickness of insulation.
- The equivalent thermal conductivity of the insulation is ~ 2-3 times lower than G10.
- Next steps:
  - Measurements on heat capacity
  - Measurements on a stack of mica-glass insulation and only glass insulation.











4. Thermal properties of the coil

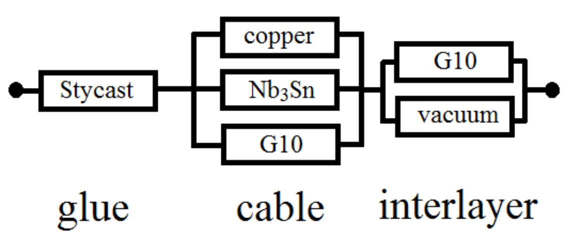
- Put a known heat flux $\dot{Q}$ through the sample and measure the temperature difference ΔT.
- Thermal conductance:

$$C \equiv \frac{\dot{Q}}{\Delta T} \qquad \text{[W/K]}$$

- Thermal conductivity:

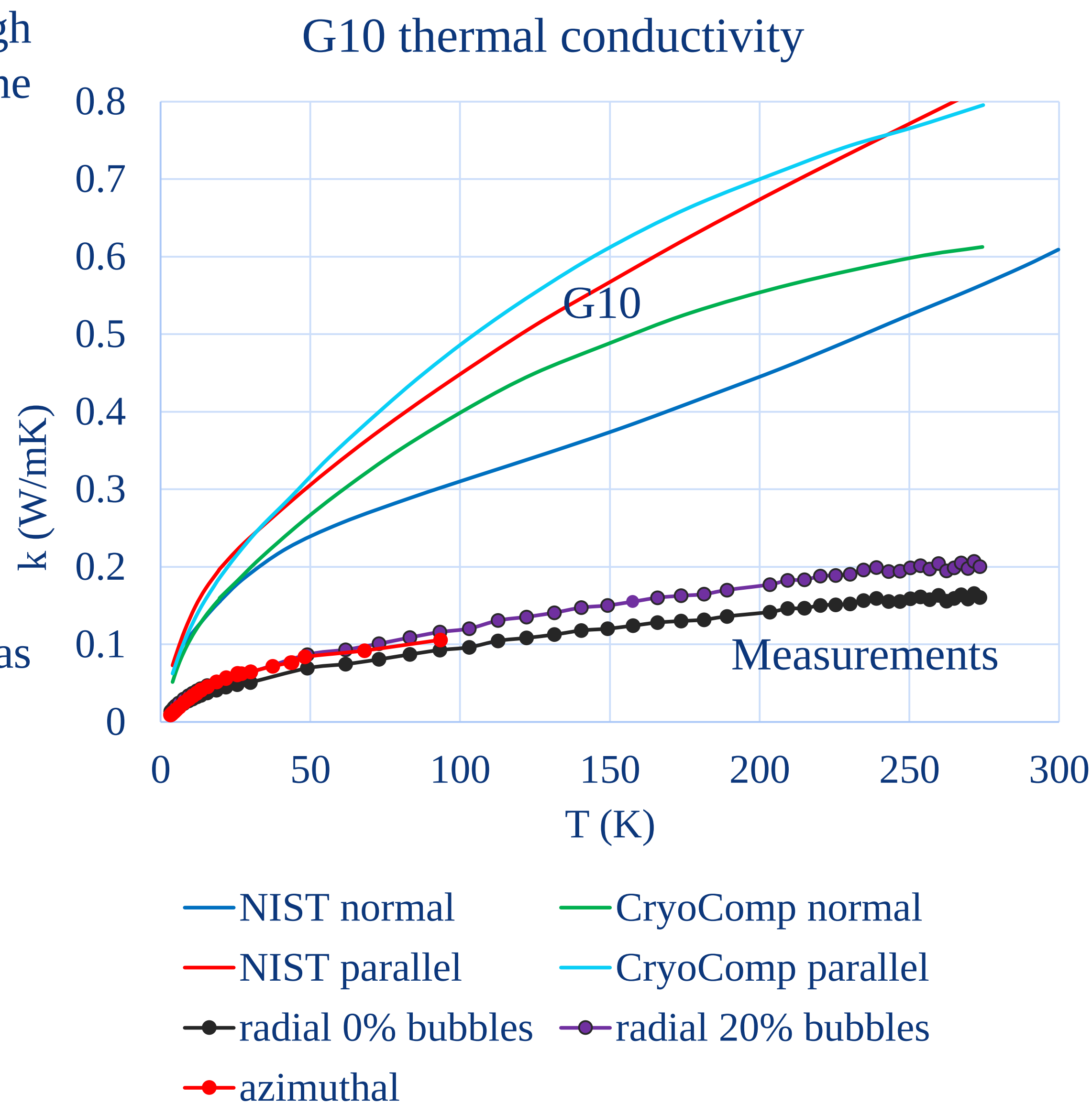
$$\dot{Q} = -kA\frac{dT}{dx} \Rightarrow k = \frac{CL}{A} \qquad \text{[W/mK]}$$

- Thermal resistors behave as electrical ones ($R = 1/C$).

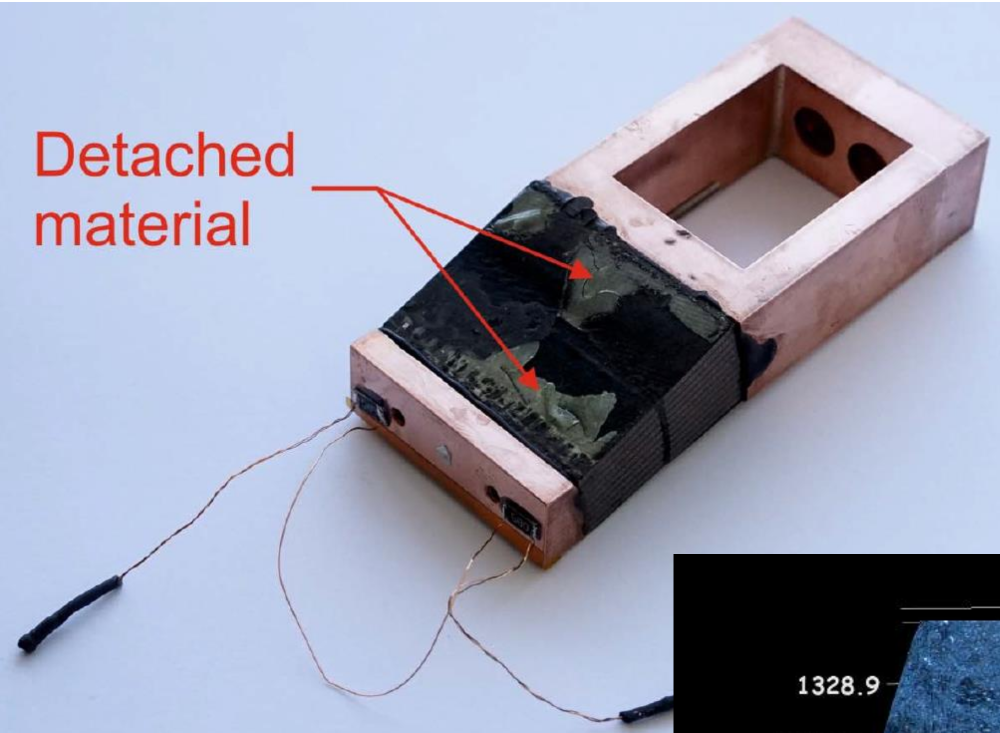


$$R = R_1 + R_2 + \dots + R_N \qquad \text{series}$$

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_N} \qquad \text{parallel}$$



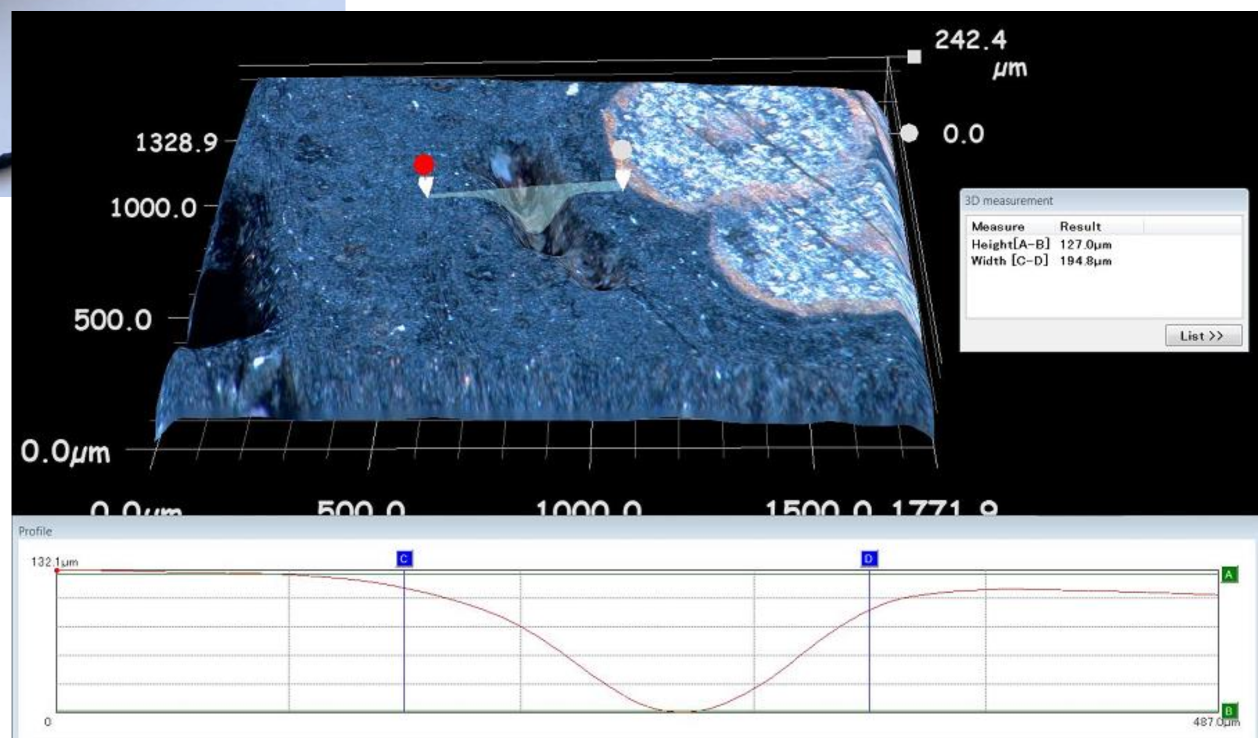
4. Measurements on thermal conductivity



Some observations…

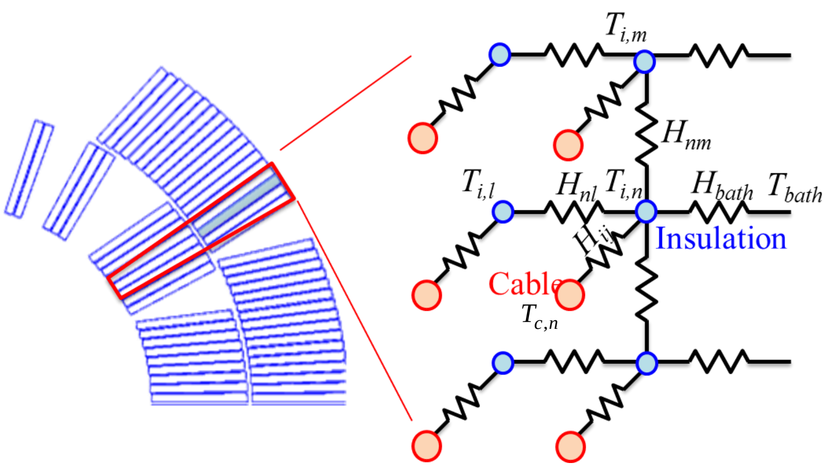
- After cool-down, measurement, and warm-up, some material peeled off from the specimen surface:

- Inter layer is full of voids (about 20 %?)



4. Layer to layer propagation

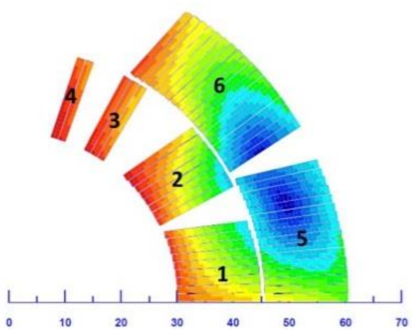
$$\dot{q}_{adj,i} = H_{nm}(T_{i,m} - T_{i,n}) \qquad \dot{q}_{adj,c} = H_{ij}(T_{i,n} - T_{c,n})$$



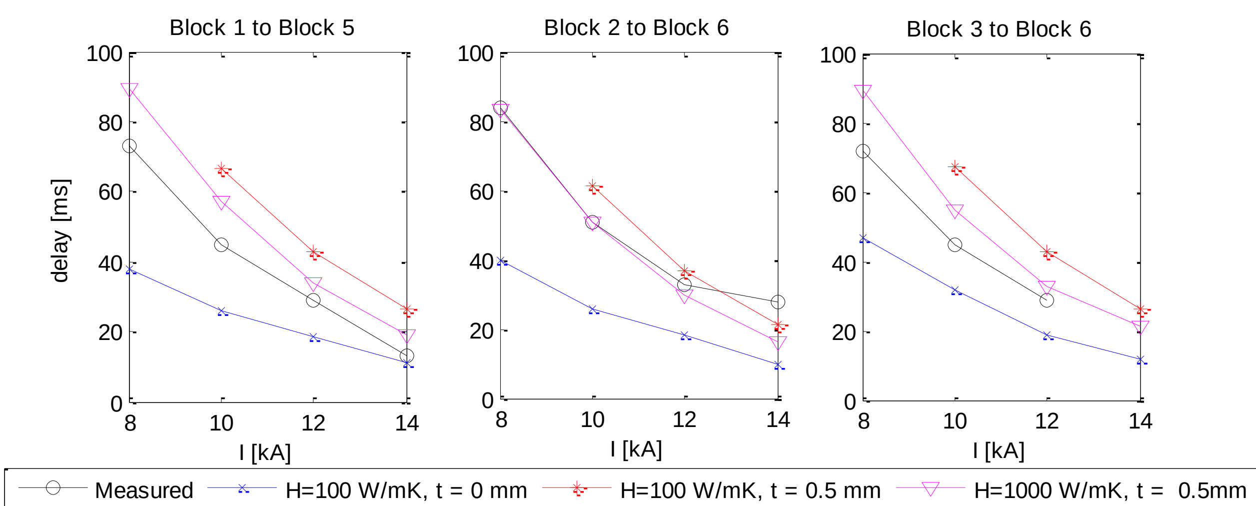
Measurements on outer layer to inner layer propagation delay can help to understand the level of thermal coupling among conductors. Three cases are explored:

1. Internal thermal conductance in the conductor **H_{ij} = 100 W/mK** (R_{th}=0.01 mK/W), inter-layer insulation thickness **t = 0 mm**
2. Internal thermal conductance in the conductor **H_{ij} = 100 W/mK** (R_{th}=0.01 mK/W), inter-layer insulation thickness **t = 0.5 mm**
3. Internal thermal conductance in the conductor **H_{ij} = 1000 W/mK** (R_{th}=0.001 mK/W), inter-layer insulation thickness **t= 0.5 mm**

MBHSM101
(CERN single coil assembly)



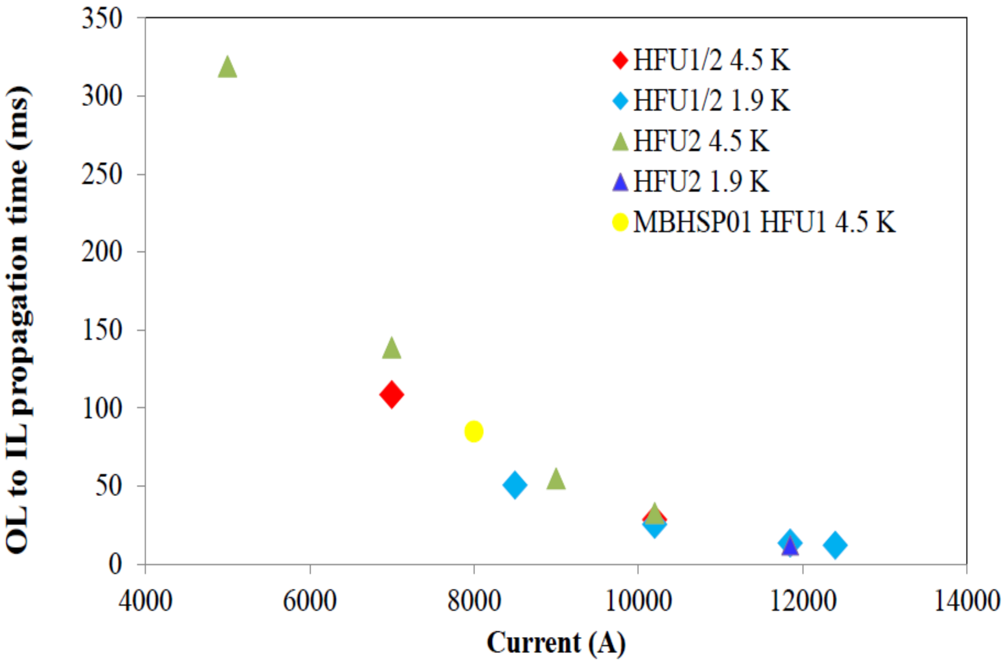
Outer layer to inner layer delay

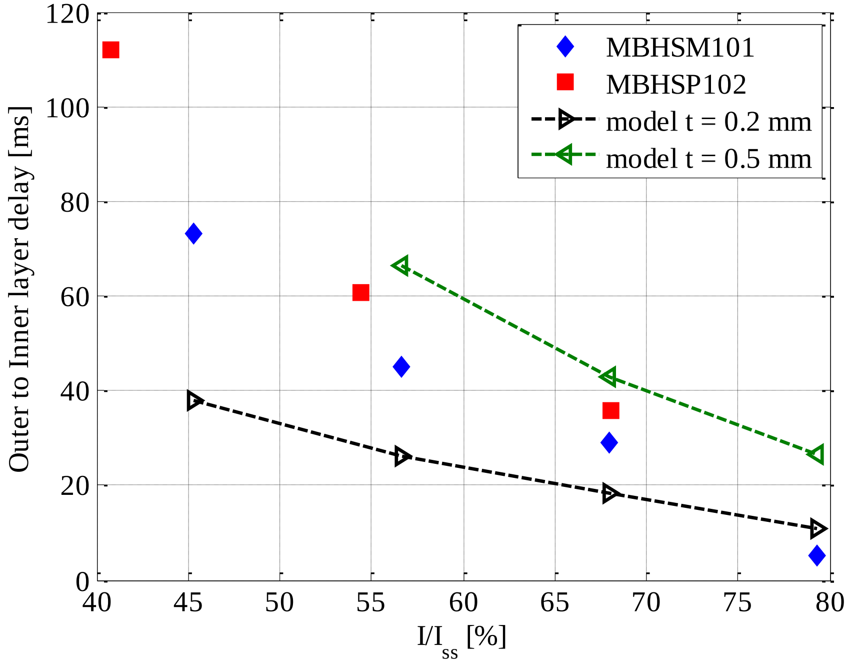


Data from [G. Willering]

4. Layer to layer quench propagation

- Measurements are consistent at CERN and FNAL

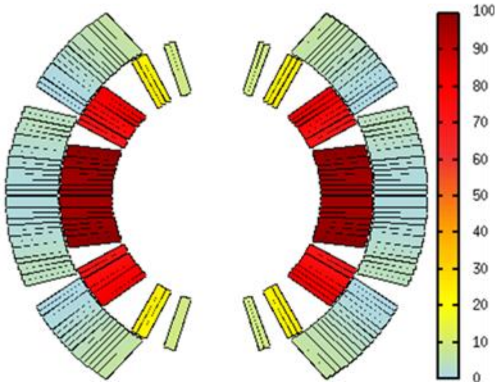




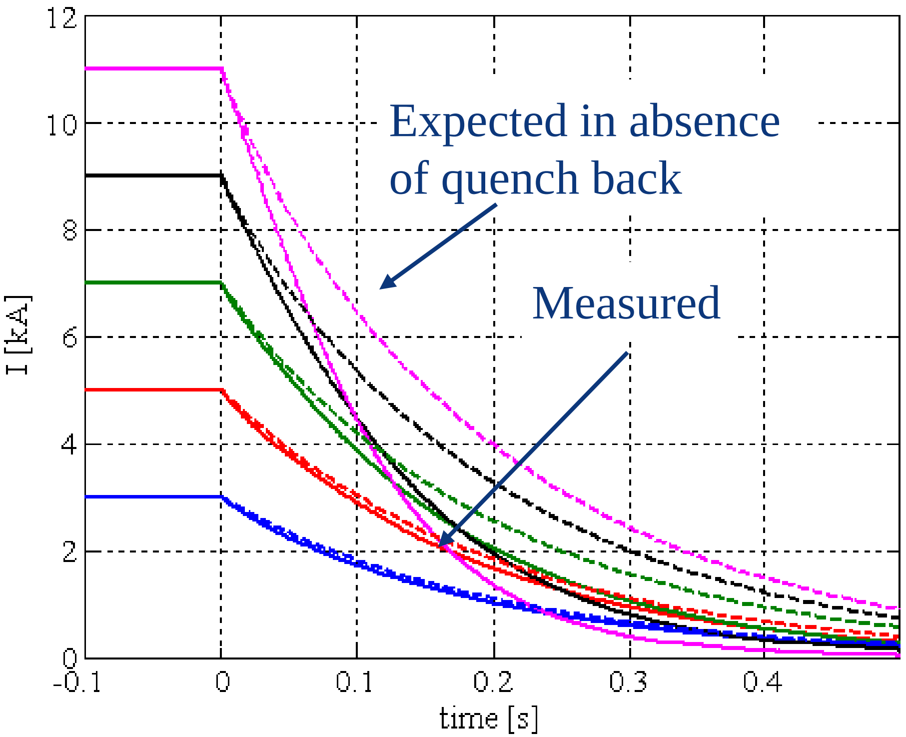
4. Fast Energy Extraction Tests

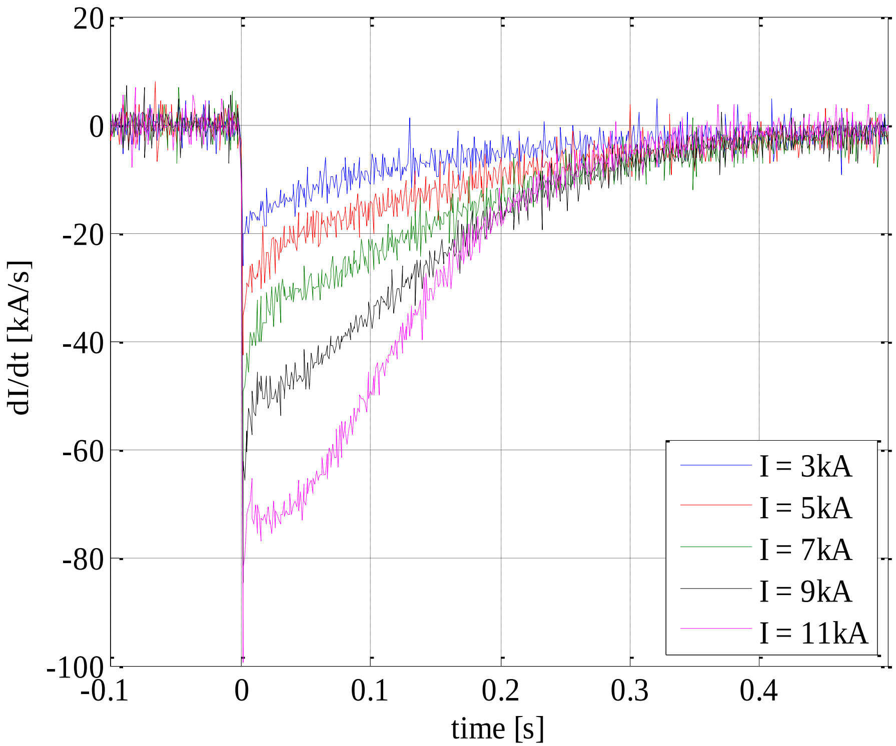
AC loss help to the quench propagation from outer to inner layer. In order to asses the contribution of AC losses:

- Fast energy extraction tests using 60 mΩ
- Quench observed due to AC losses at currents > 6 kA
- Rc~ 5 μΩ and τ ~ 5 s.



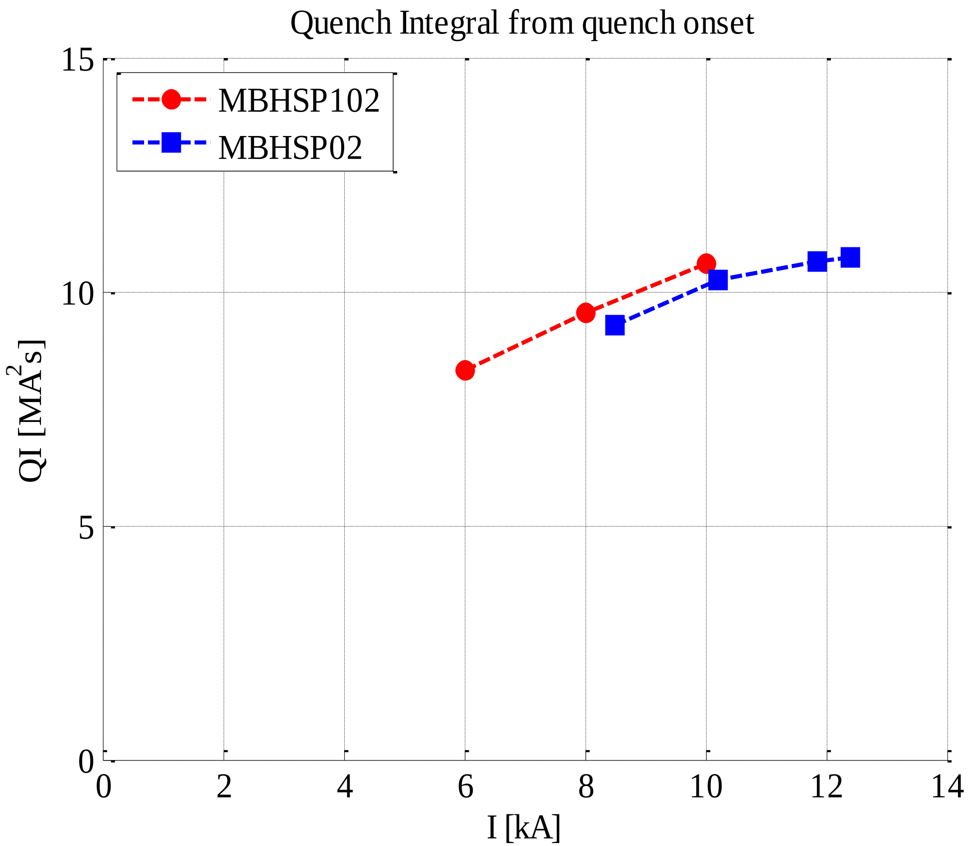
Normalized power dissipated [%] in the coil due to inter-strand coupling currents





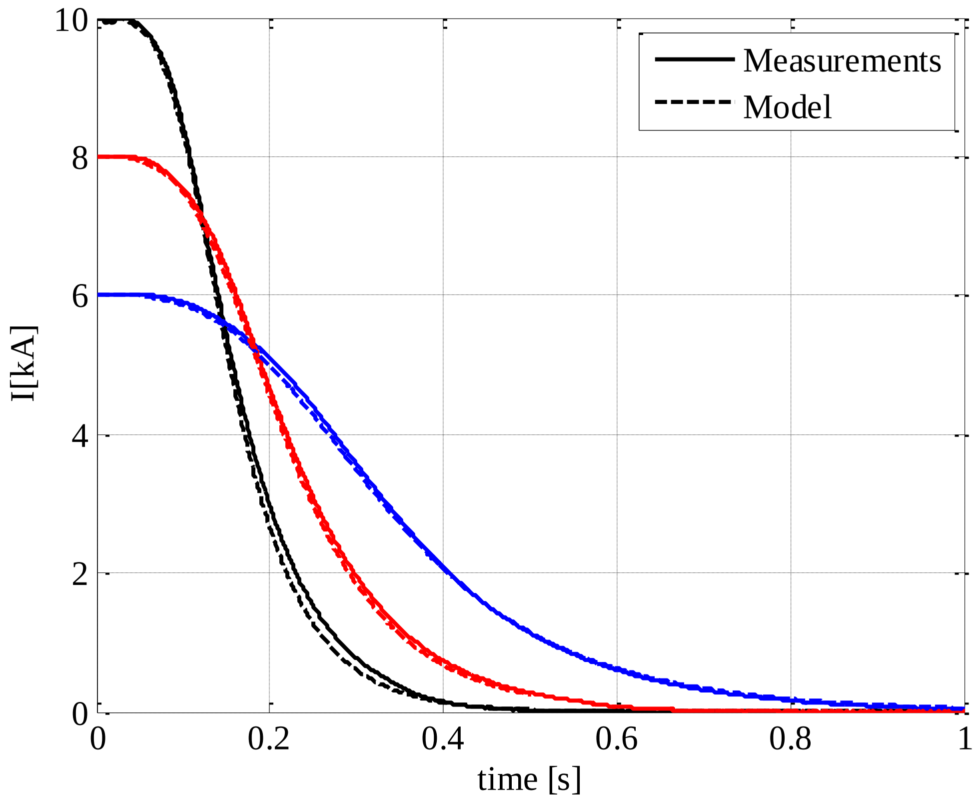
4. Quench integral (QI) studies

- Test set up:
  - Manual trip of a quench using the protection heaters at different current levels
  - Dump resistor delayed by 1000 ms
- QI from the moment the quench is detected is very close in FNAL (MBHSP02) and CERN (MBHSP102) magnets.



4. Quench integral studies

- Agreement better than 5 % between measured and expected current decay at the different current levels.



Contents

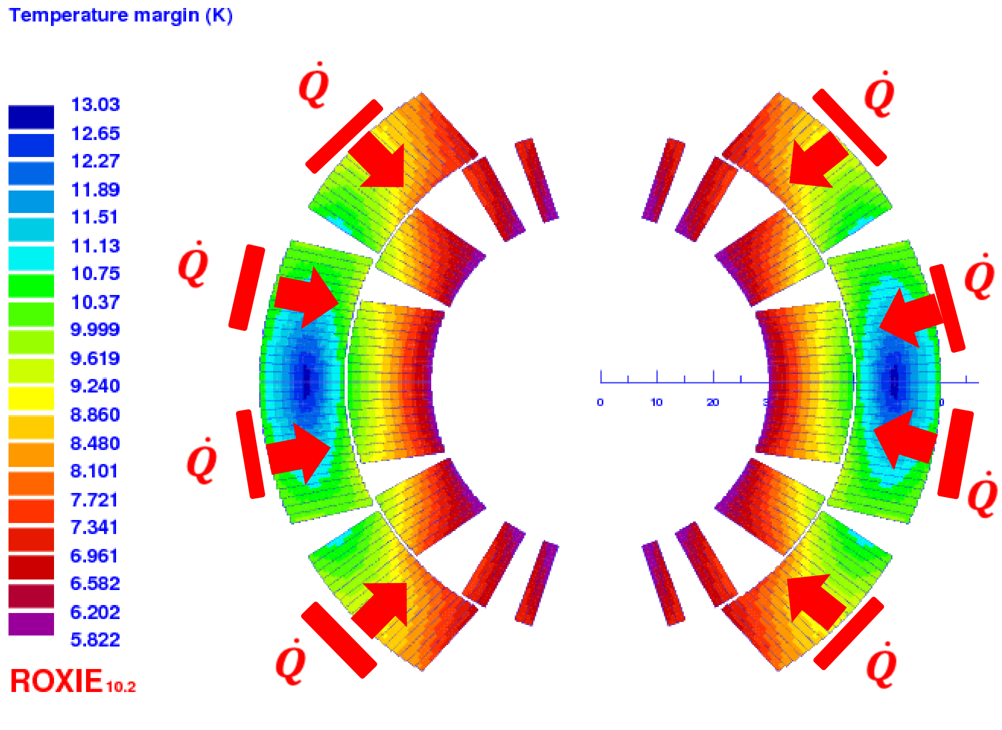
1. Introduction
2. Longitudinal quench propagation
3. Quench heater design performance
4. Quench propagation within the coil
5. Hot spot temperature
6. Sensitivity analysis
7. Summary

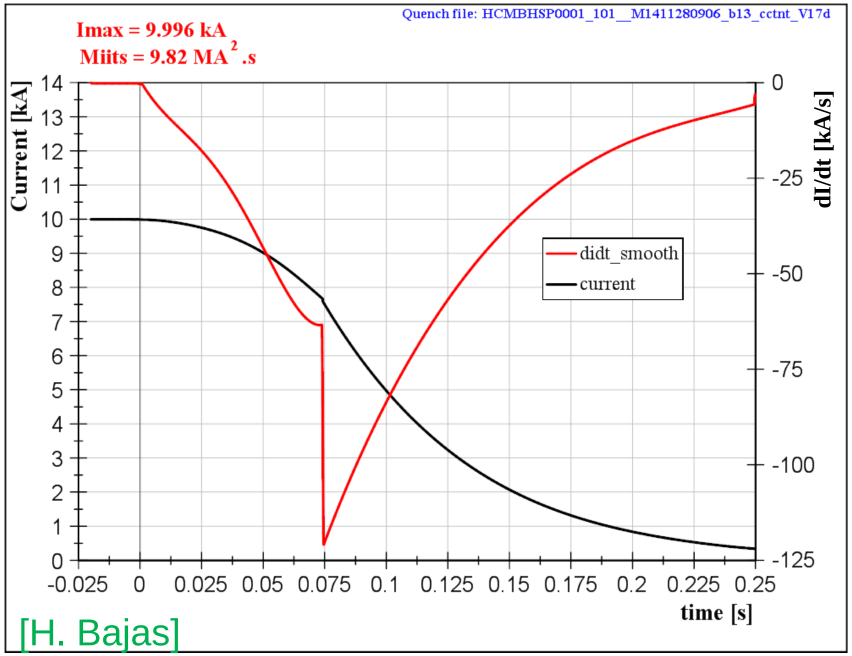
5. Hot spot temperature

Case study:

- Quench heater provoked quench at 10 kA in MBHSP101 (first CERN 11T aperture)
- Dump resistor = 80 mΩ, delayed 90 ms
- Temperature compared to the one obtained based on the voltage measured during quench in the different segments [H. Bajas]

$$T(t) = \Phi\left(\rho_{\exp}(t) - \frac{C_0}{RRR} - m_r\, B(t)\right)$$

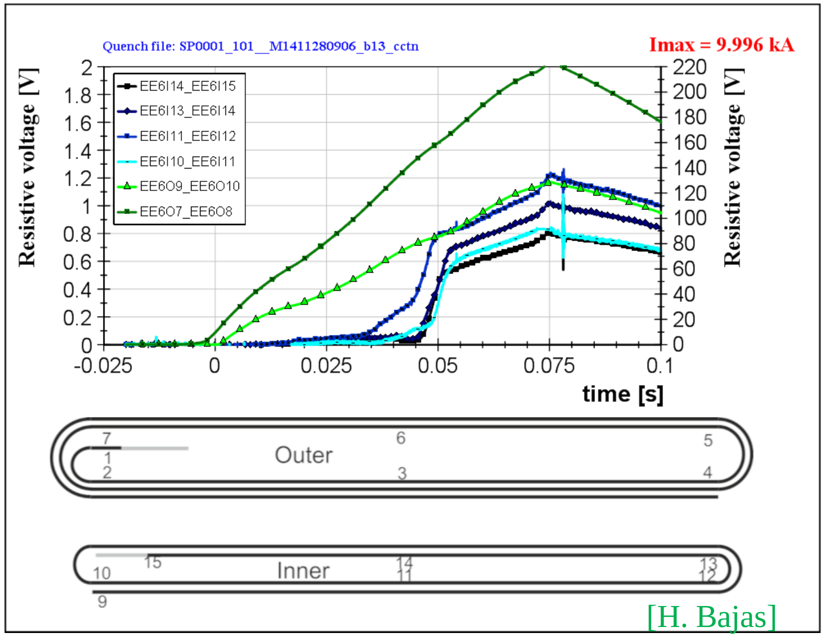




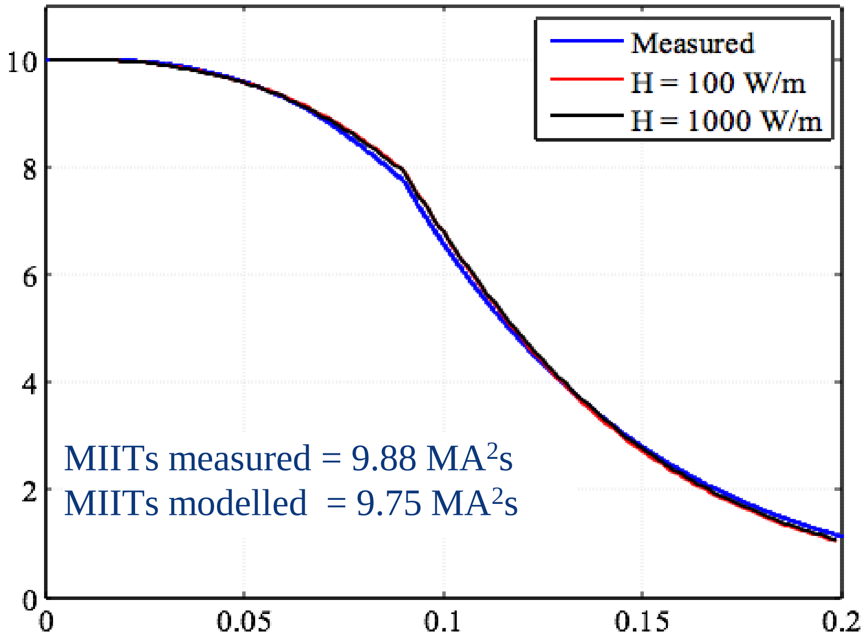
[H. Bajas]

5. Hot spot temperature

- Measured and computed current decay and delays are in good agreement.

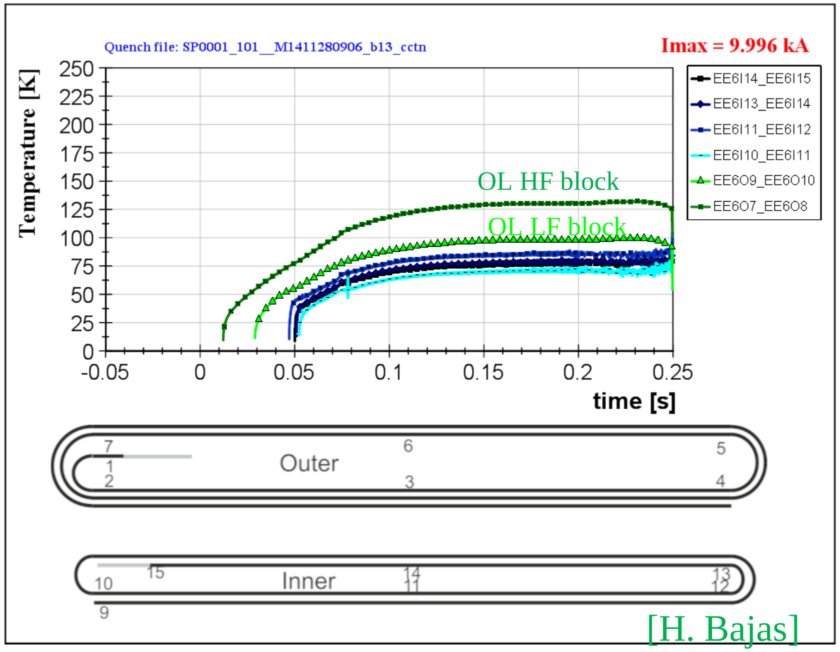


[H. Bajas]



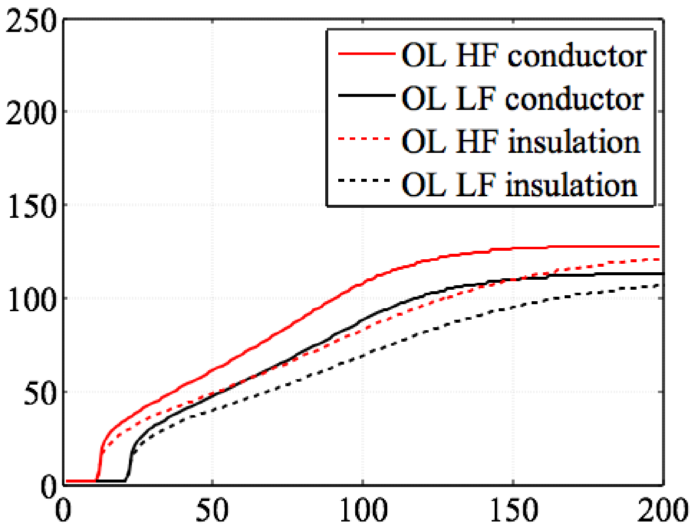
	Coil 106		Coil 107	
Heater delays (10 kA)	**Model (ms)**	**Measured (ms)**	**Model (ms)**	**Measured (ms)**
High Field Block	14	13	25	~ 26
Low Field Block	18	16	31	xx

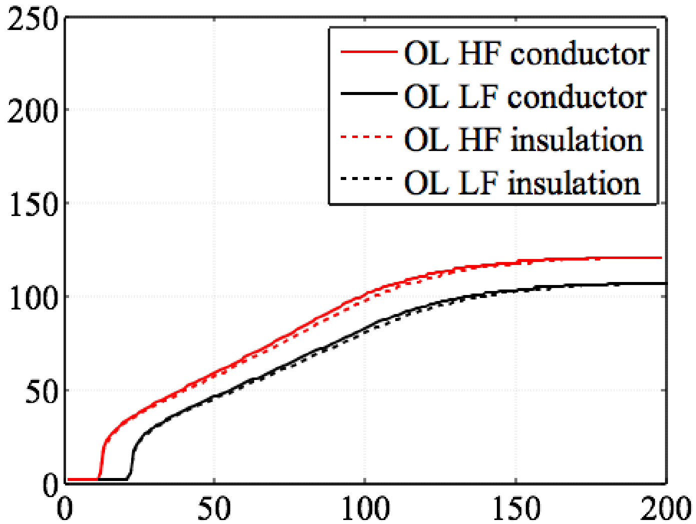
5. Hot spot temperature



Temperatures predicted by the model are pretty close to those defined experimentally by [H. Bajas]

T [K]	Outer Layer- High field block	Outer Layer- Low field block
Measured	125	100
Model H = 100	128	113
Model H = 1000	121	107





Contents

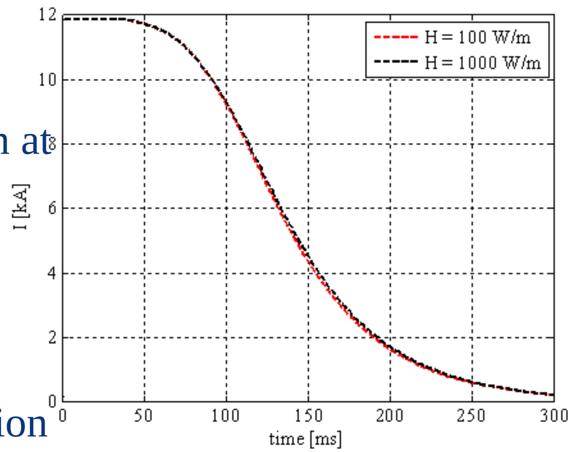
How different parameters affect the hot spot temperature?

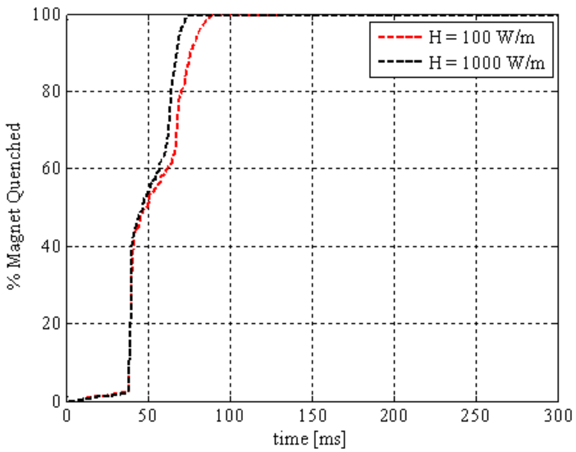
- Conductor where quench starts
- Conductor parameters
  - Copper to superconductor ratio
  - RRR
- Time to detect and validate the quench
- Insulation thickness from heater to coil
- Numbers of heater failure

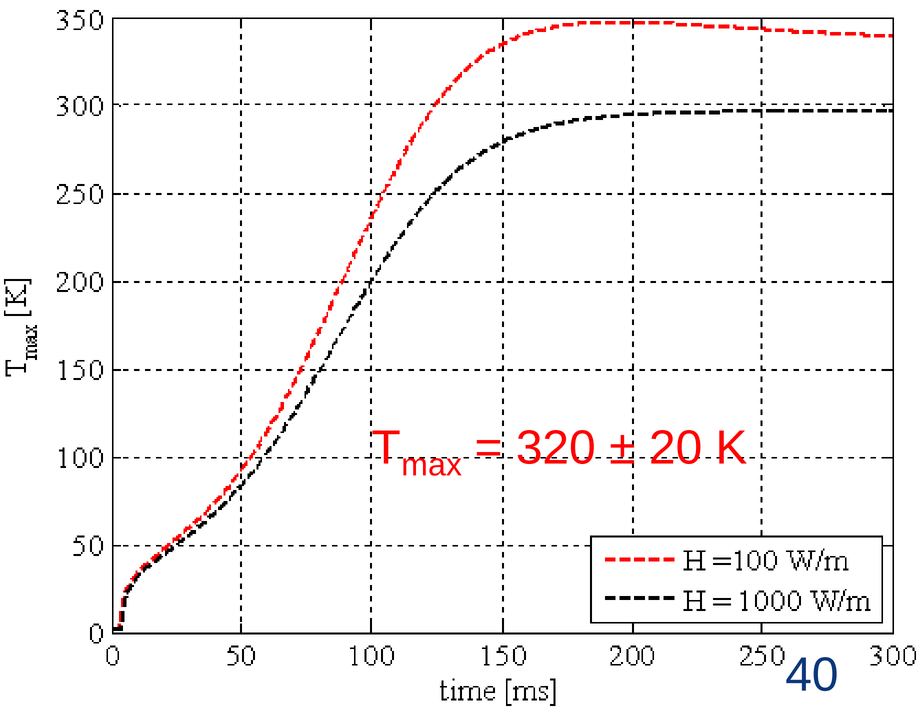
2.4 Hot spot temperature – Reference case

Reference case:

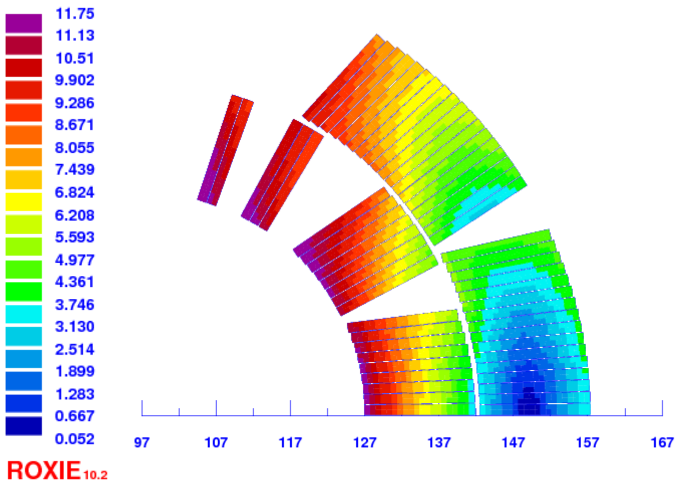
- Quench starting in the high field region at nominal current (11.85 kA)
- 100 mV threshold, 10 ms validation
- 5 ms heater firing delay
- Assumed 100 µm G10 outer wrap between heaters and coil. Total insulation from heater to coil (heater delay ~20 ms):
  - 50 µm of kapton
  - 100 µm G10 outer wrap
  - 100 µm G10 conductor insulation
- Nominal conductor parameters, RRR=100
- All quench heaters fired
- Two different cases for transverse thermal coupling:
  - Hij=100 W/Km
  - Hij=1000W/Km

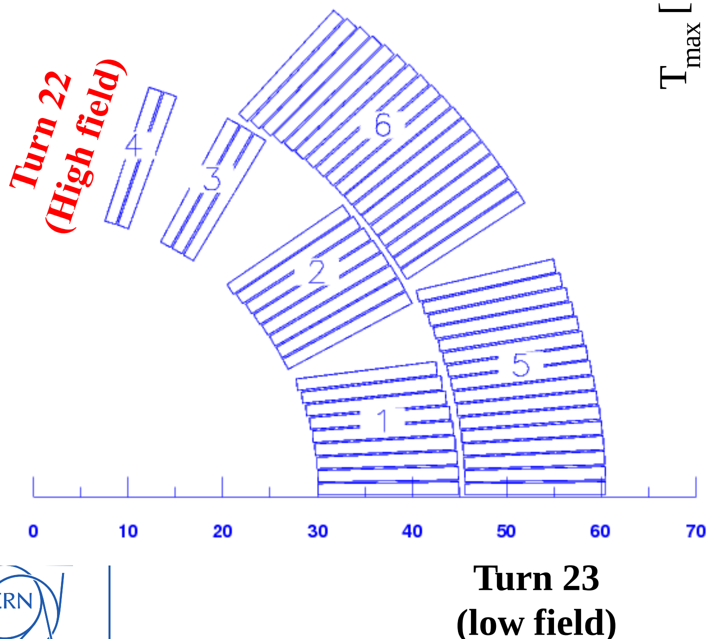


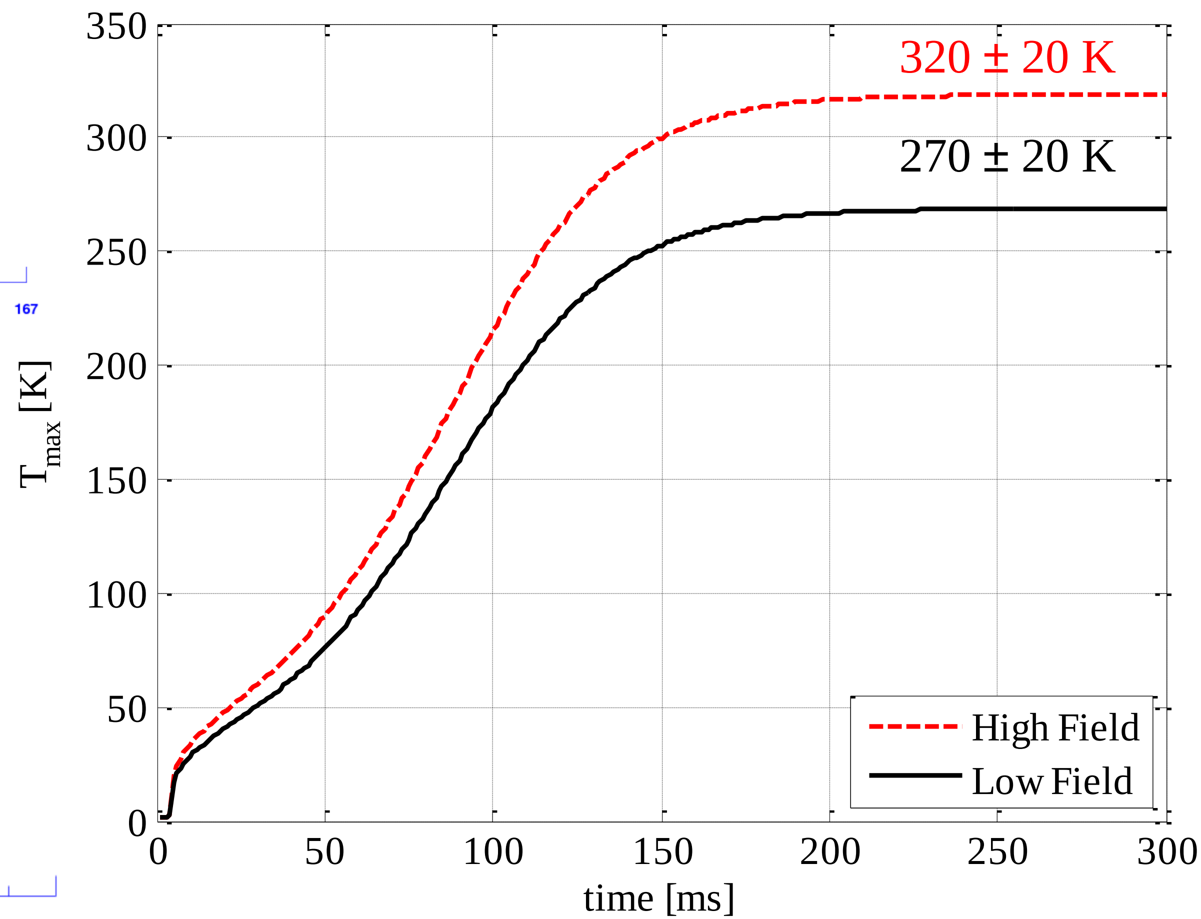




Conductor where quench starts







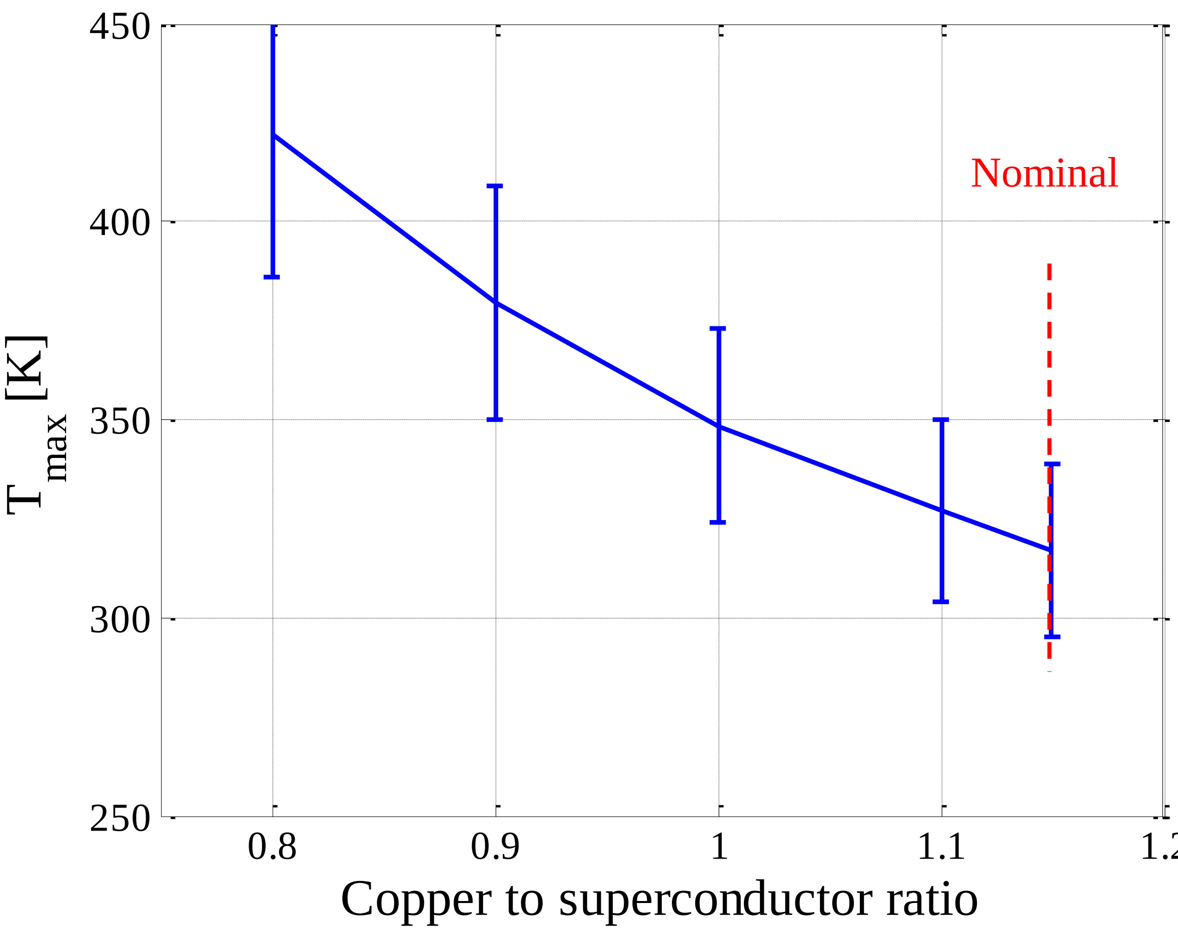
Copper to superconductor ratio

The amount of copper in the strand is ~1/2 of the copper in the MB-LHC dipoles:

	MB LHC inner layer	MB LHC outer layer	DS-11T
Total cable area, mm^2	33.52	27.04	22.67
Cu area, mm^2	15.53	13.43	8.23
SC area, mm^2	9.41	6.89	6.84

Further decrease of the amount of copper implies a non-negligible increase of the hot spot temperature

(~ 25K from Cu/Sc = 1.1 to 1.0)

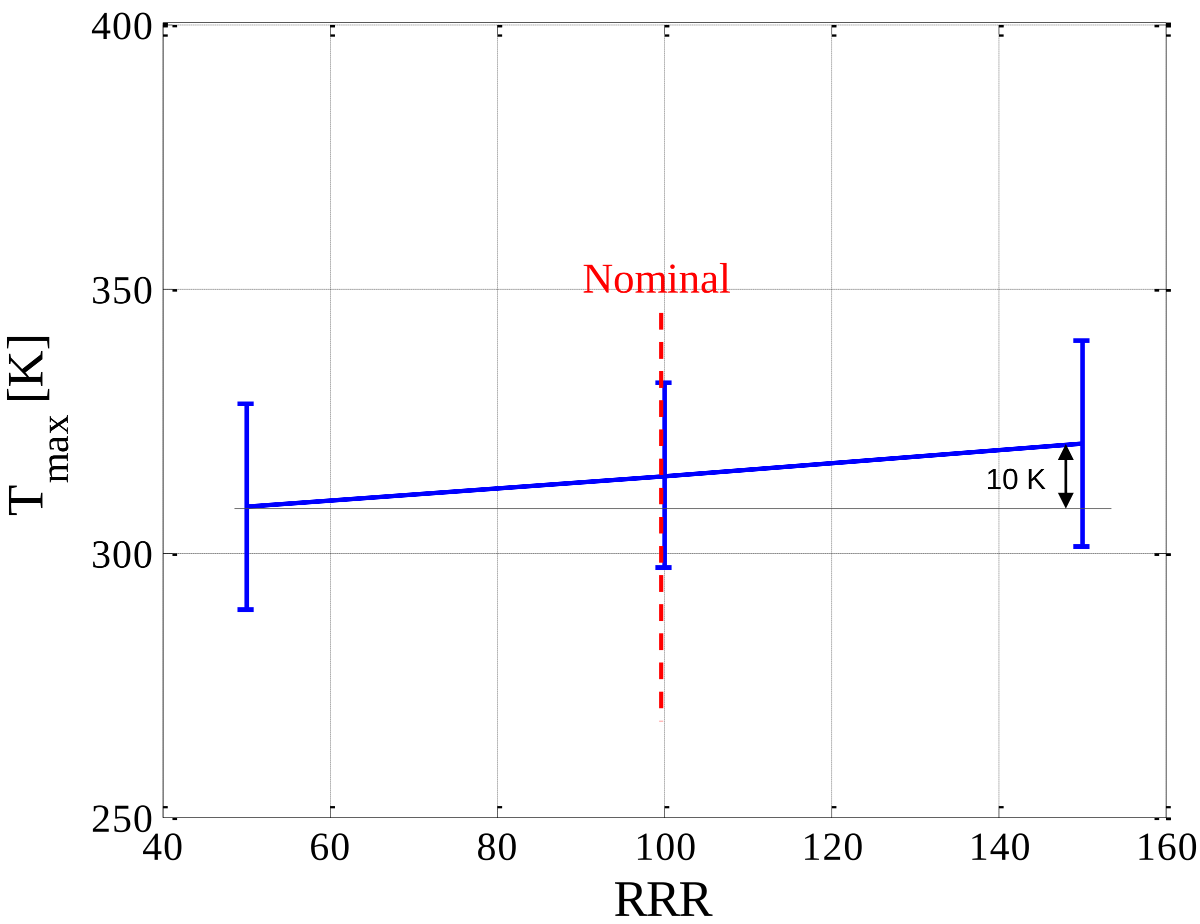


RRR

The net effect of the RRR on the hot spot is small, as there is a “double effect” that is compensated:

- Low RRR, higher hot spot for the same MIITs, but as the coil resistance build up is faster, the decay is faster → lower MIITs in case of quench

- High RRR, lower hot spot for the same MIITs, but as the coil resistance build up is slower, the decay is slower → more MIITs in case of quench



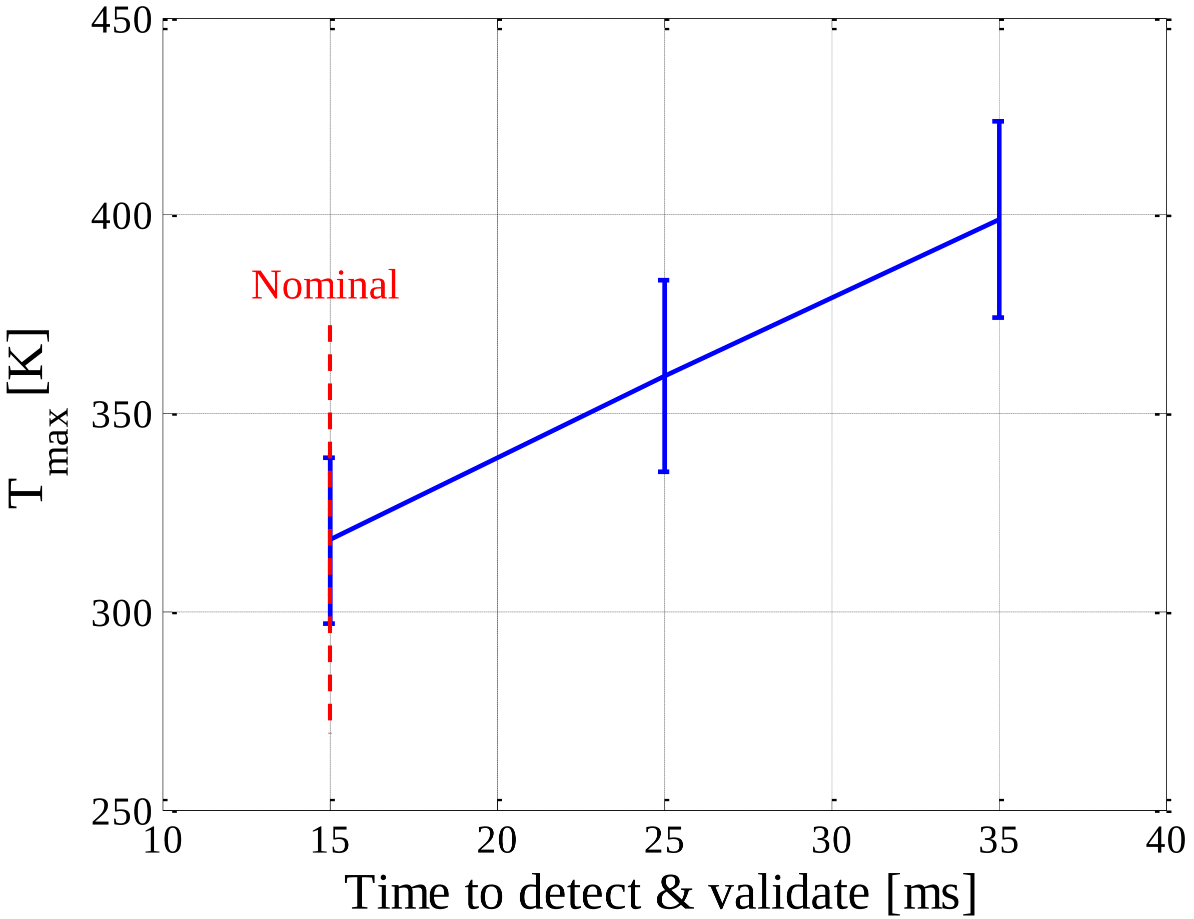
Time to detect and validate the quench

A quick detection of the quench is a must!

ΔT_{max}~ 45 K for Δt_{detect}~10 ms

Efforts needed to:

- Confirm **100 mV threshold and 10 ms validation** is a reasonable assumption for LHC operation
- Confirm that **5 ms for heater firing delay** is a reasonable assumption for LHC operation and that not further reduction is possible by improving the heater firing units.



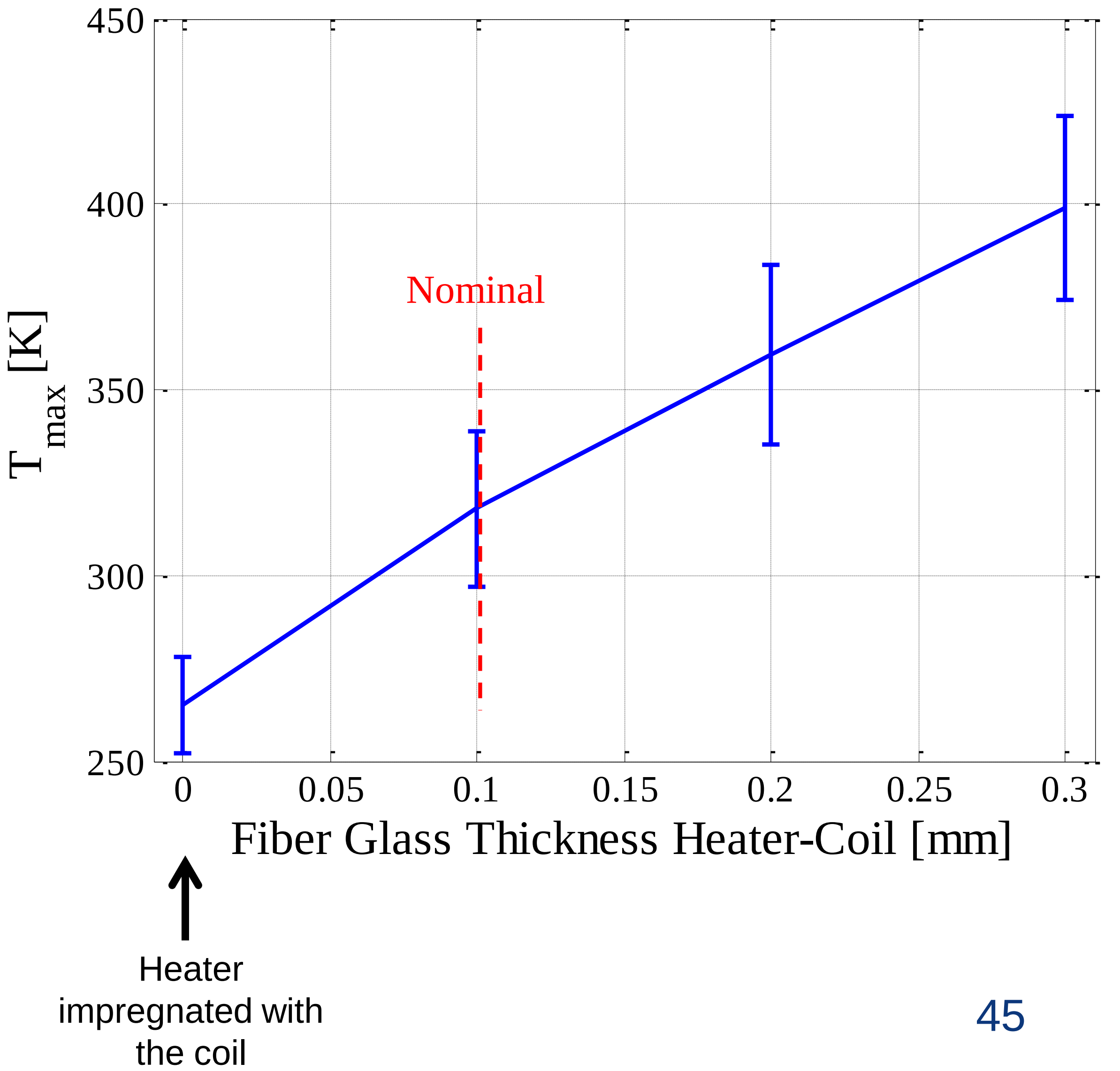
Insulation thickness from heater to coil

Minimize the thermal insulation between heater and coil is important:

ΔT_{max}~ 45 K for Δth_{G10}~0.1 mm

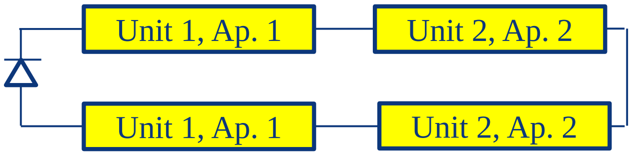
For the current design, quench heaters are glued on the coil after impregnation, so a minimum layer of 0.1 mm glass is required.

Activities are on-going to **impregnate the heaters** with the coil to improve the quench heaters performance.

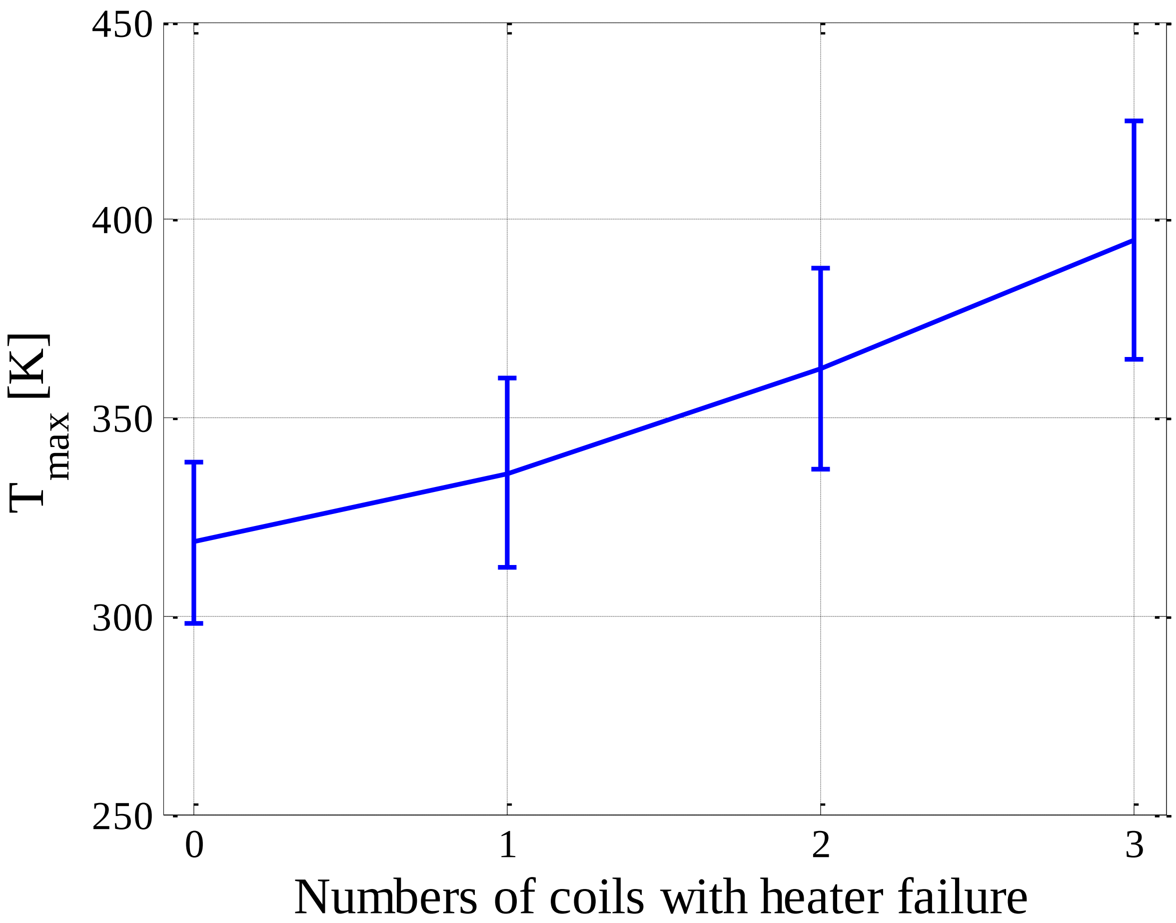


Numbers of heaters failure

- Baseline circuit configuration: 2 units of 5.5 m connected in series and protected with an unique diode



- For this analysis, we consider that **all the heaters in a coil fail** (very pessimistic scenario as the baseline configuration considers 2 quench heater circuits per coil, and the possibility to have 4 quench heater circuits per coil is being explored)



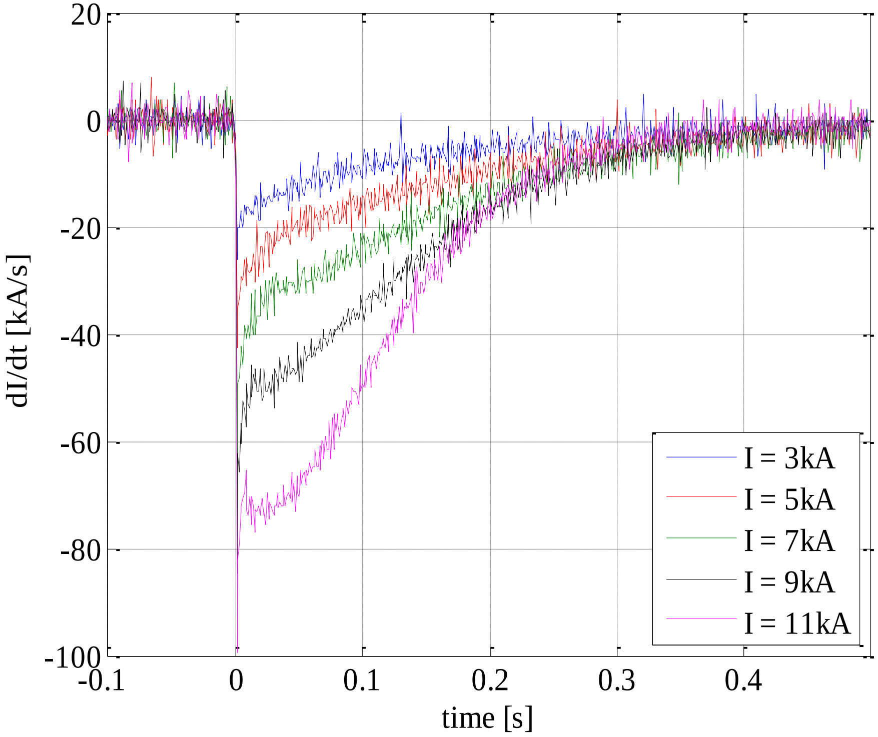
Summary

- FNAL and CERN measurements on quench protection are comparable.
- The baseline quench protection scheme based on outer layer heater can protect the magnet, keeping the hot spot temperature below 350 K.
- As regards LHC Operation:
  - Detailed study needed to define how to protect the magnet in case of symmetric quench keeping a fast detection.
  - In all the heaters in two coils (out of eight) fail, the hot temperature increases above 350 K. In order to provide redundancy to the system, different options are “available”:
    - Additional heater circuit on the outer layer
    - Inter layer heaters
    - CLIQ

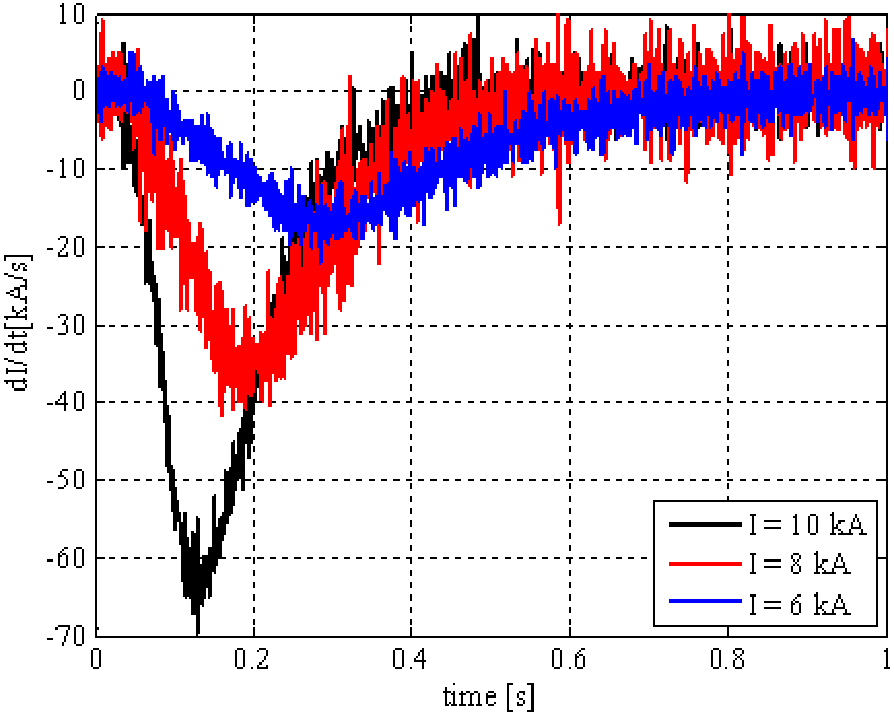
Additional slides

Energy extraction tests

Measured dI/dt on MBHSP102 during the fast energy extraction test using a 60 mΩ dump resistor.



Measured dI/dt on MBHSP102 for the magnet protected only with quench heaters.



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Nominal conductor parameters

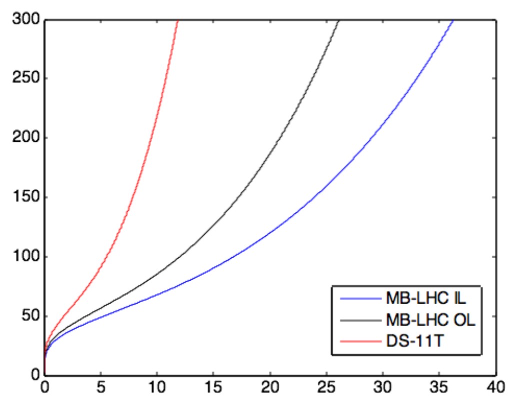
Strand diameter	0.7000 ± 0.003 mm
Nominal sub-element diameter (according to billet design)	*< 50 µm*
Copper to non-Copper volume ratio	*1.15 ± 0.10*
Strand twist pitch	*14 ± 2 mm*
Strand twist direction	*right-handed screw*
RRR (after recommended Heat Treatment)	*> 100*
n-value @ 15 T and 4.2 K	*> 30*

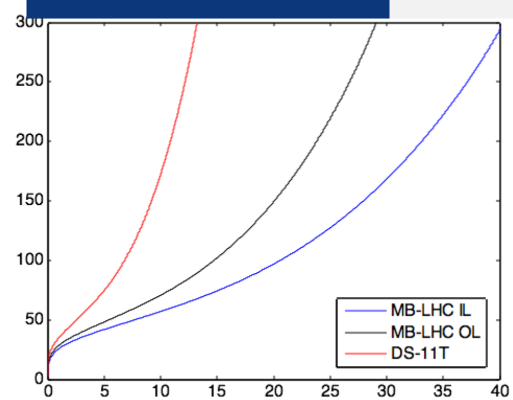
two different field levels (12

. Heat capacity of insulation

Comparison LHC-MB dipole and DS-11T dipole cable parameters

	MB inner layer	MB outer layer	DS-11T
Total cable area, mm²	*33.52*	*27.04*	*22.67*
Cu area, mm²	*15.53*	*13.43*	*8.23*
SC area, mm²	*9.41*	*6.89*	*6.84*
Insulation area, mm²	*4.83*	*4.70*	*3.25*
Void area, mm²	*3.75*	*2.03*	*4.00*





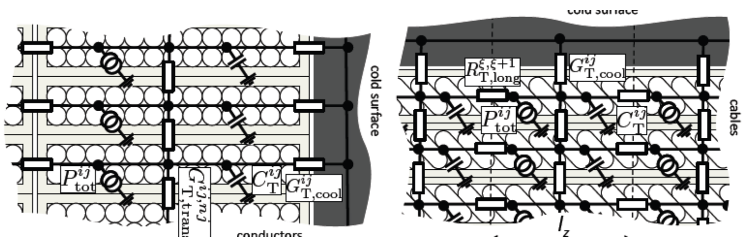
$$MIITs = A_{total} A_{Cu} \int_{T_0}^{T_\infty} \frac{C_p^{ave}(T)}{\rho_{Cu}(T)} dT$$

$$C_p^{ave}(T) = \frac{A_{Cu} \cdot C_p^{Cu} + A_{SC} \cdot C_p^{SC}}{A_{Cu} + A_{SC}}$$

ROXIE vs SUPERMAGNET

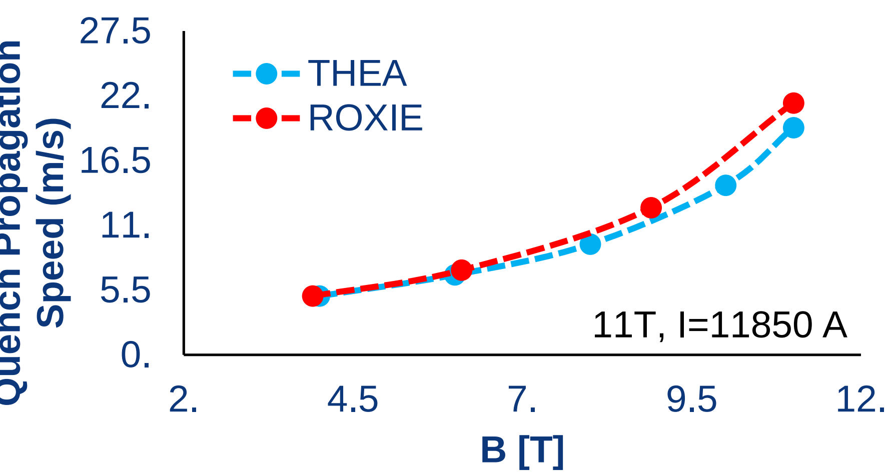
ROXIE QUENCH MODULE [Sch 2010]

Couples magnetic, electrical and thermal.
First order thermal network (2D (XSec) + 1 (z*))



*Requires small element size (<1mm) in the longitudinal direction to converge in terms of longitudinal quench propagation velocity

Under the same assumptions…very close propagation velocity (not the case for T_{max}!)

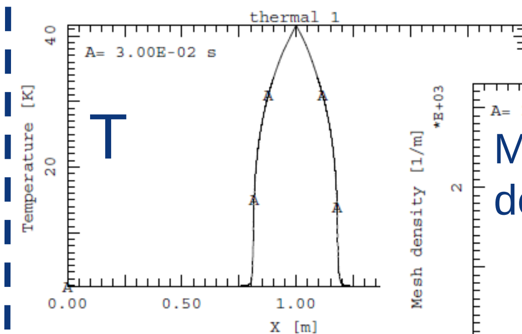


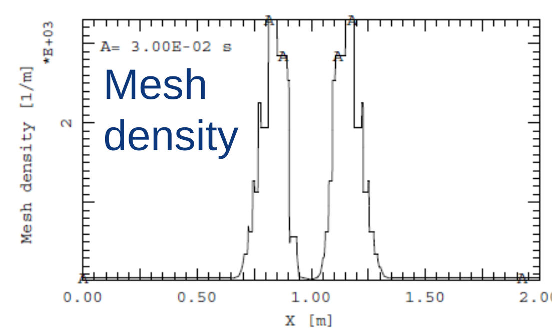
SUPERMAGNET [Bot 2007]

Built by different blocks with an unified interface for data exchange.

THEA [Bot 2010]

Thermal, Hydraulic and Electric analysis of superconducting cables
Adaptive mesh tracking





HEATER [Bot 2010]

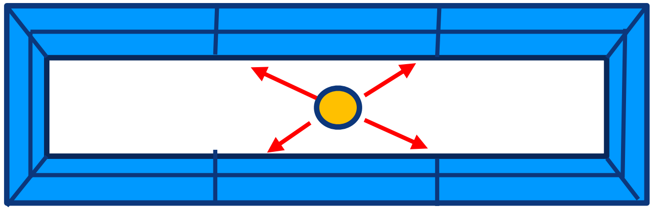
FE heat conduction

POWER [Bot 2004]

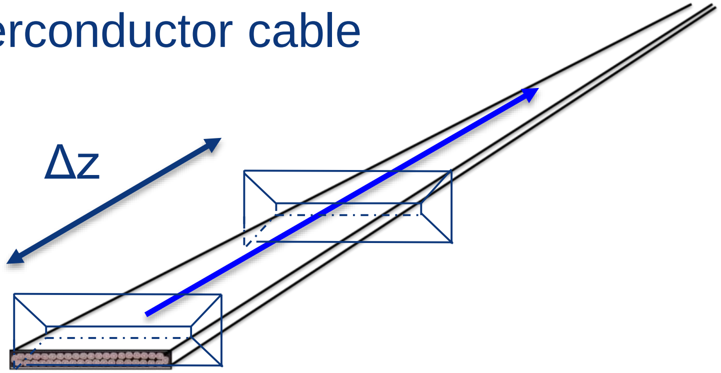
Electric network simulation of magnetic systems

Coupling heat conduction domains

HEATER : Heat conduction in the insulation is solved in 2D cross sections
THEA: Thermal and Electrical analysis of the superconductor cable

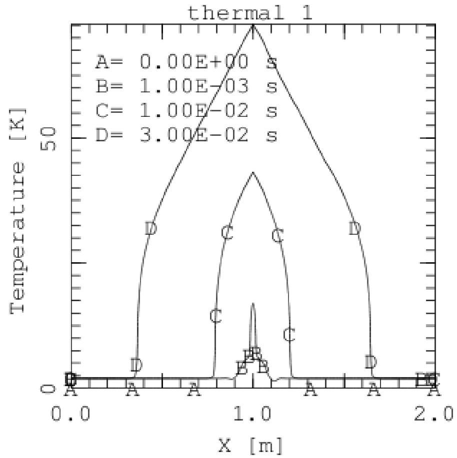


2D quadrilateral elements with 4 nodes and first order shape function

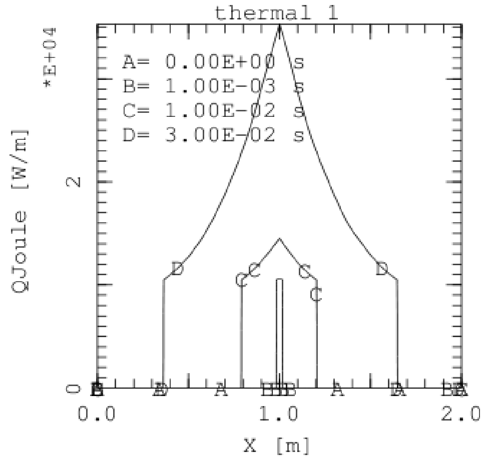


Explicit coupling → conditionally stable. Small heat capacity and large thermal conductance requires small time steps for the stability of the coupling

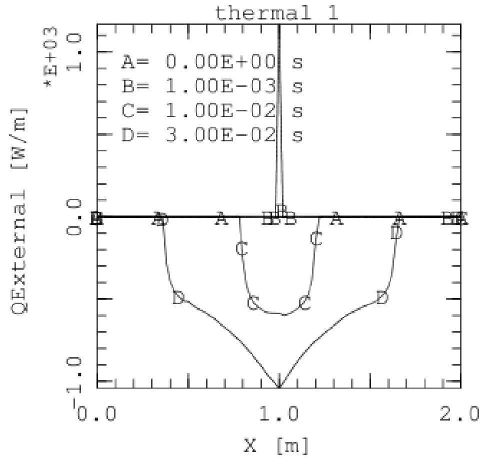
Example: HEATER : Δz=20 mm t_{step}=[10^{-6} 10^{-3}] s
THEA : Δz=0.3mm-100mm t_{step}=[10^{-7} 10^{-4}] s



Temperature in the SC



Joule heating

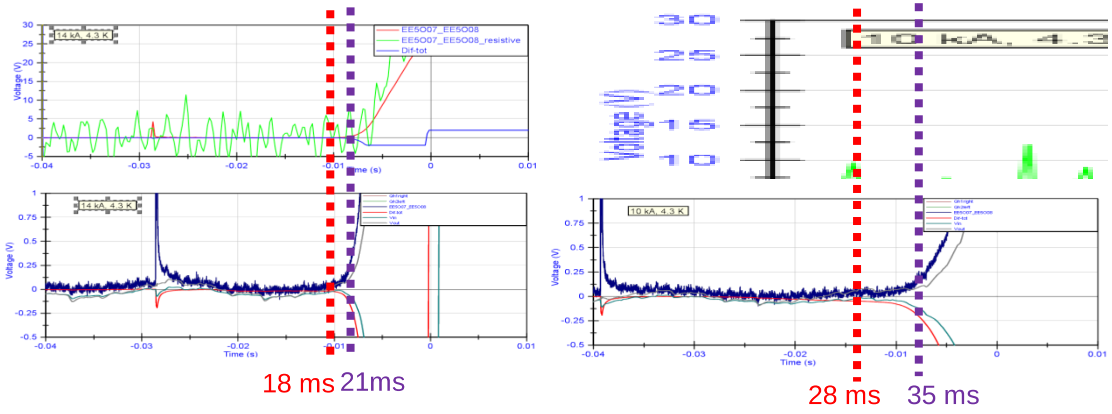


Heat flow from/to the insulation

Heater efficiency

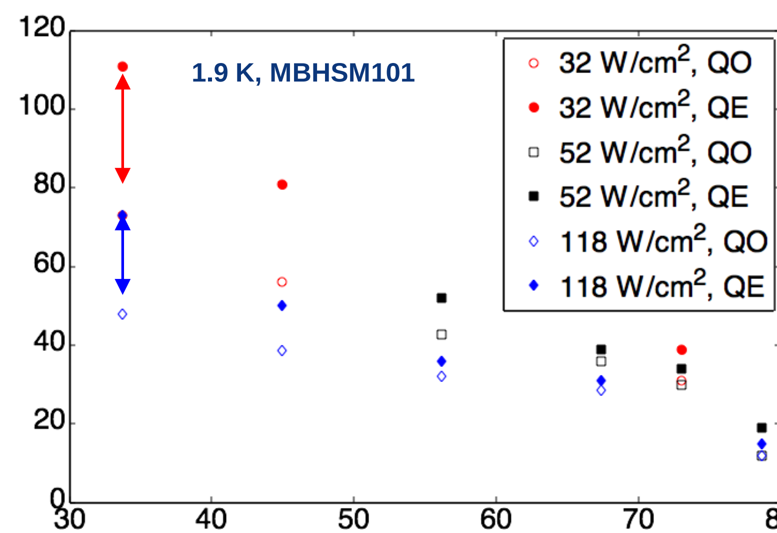
2 times to look at:

- **Quench heater onset (QO):** start of the quench
- **Quench heater efficient (QE):** time where slope of the resistive voltage cross the "time" axis



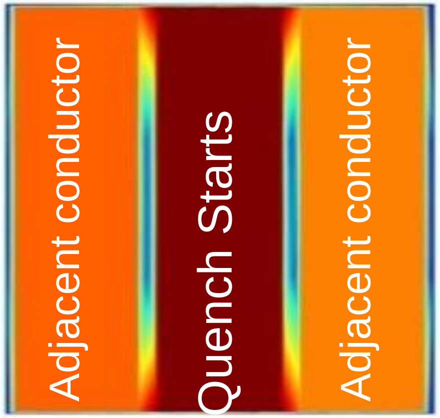
Remarks:

- At high current, the difference between **QO-QE** is very small, but at lower current there is an important offset to keep into account.
- The difference between quench onset and quench efficient increases for low heater power density.



Experimental data from G. Willering

Network model vs. hybrid model



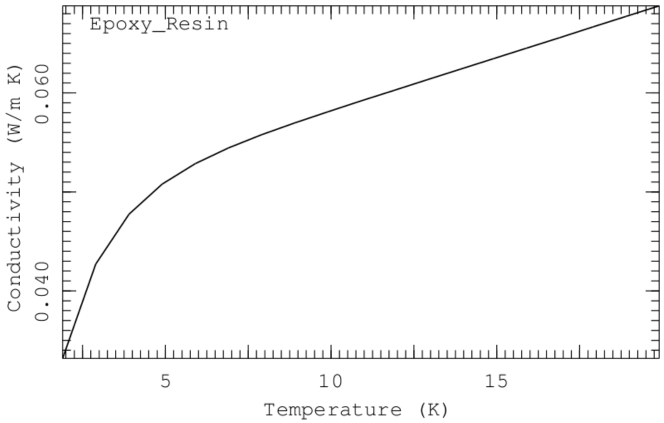
FE mesh
Thermal network R = 0.01

t = 6 ms
t = 6 ms
t = 4 ms
t = 4 ms
t = 2 ms
t = 2 ms

Thermal resistance

$$R_{th} = \frac{1}{hp}[Km/W]$$

$$h = k/(t_{ins}/2)$$



$$p = 2(w+t) \approx 30mm$$

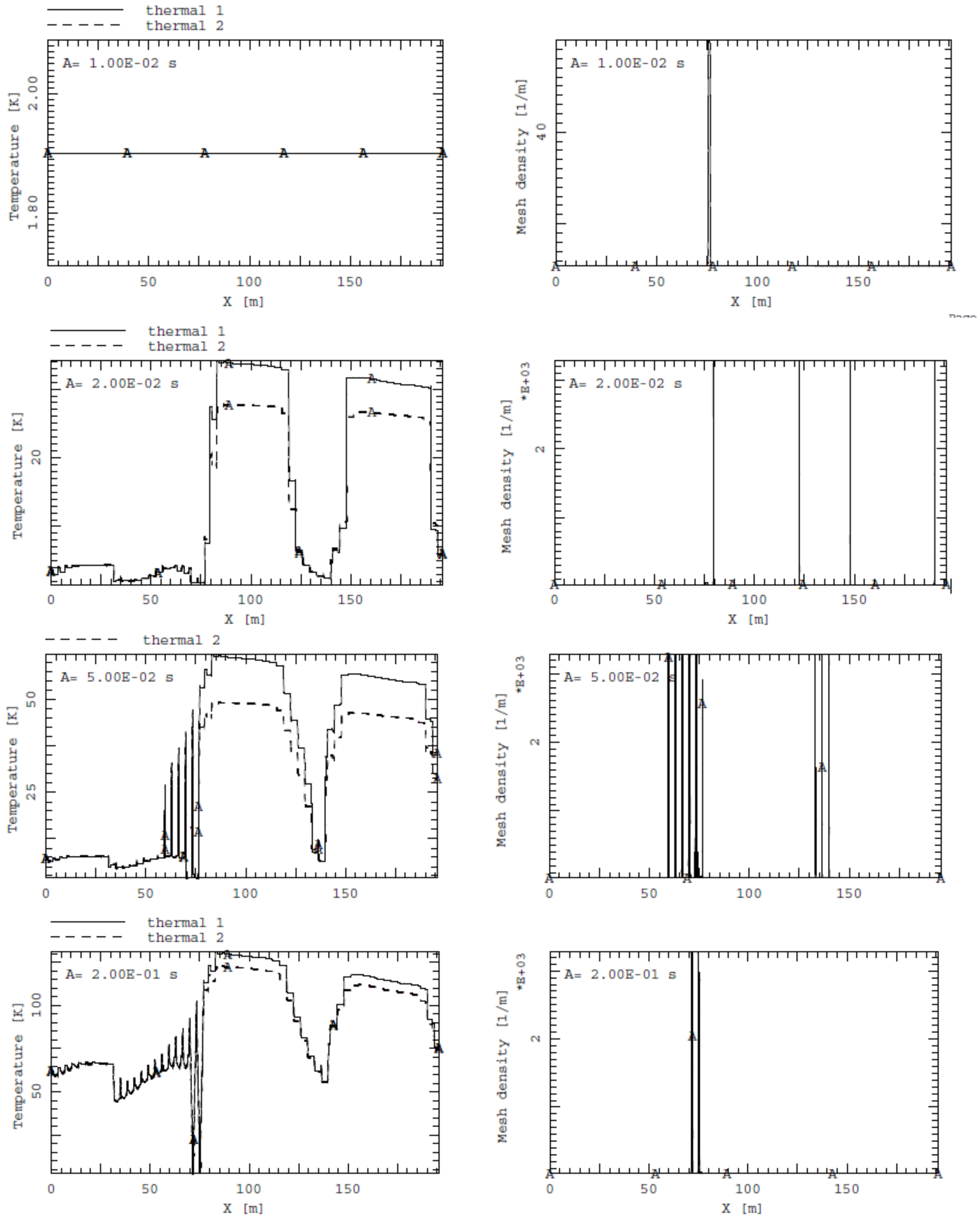
k = 0.05 W/mK, tins = 0.1 mm

- R_{th} = 0.03 mK/W

k = 0.05 W/mK, tins = 0.01 mm

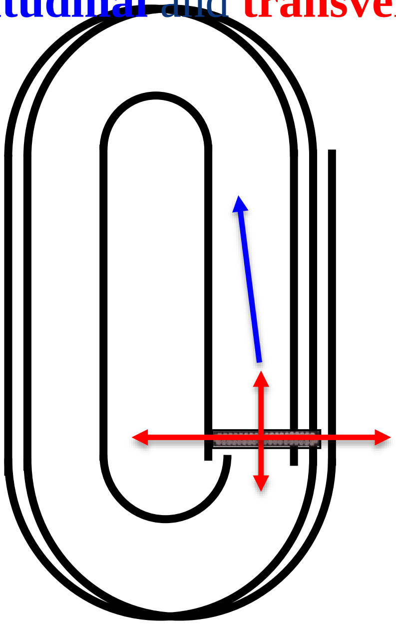
- R_{th} = 0.003 mK/W

Temperature profile & mesh density H = 100, coil 106



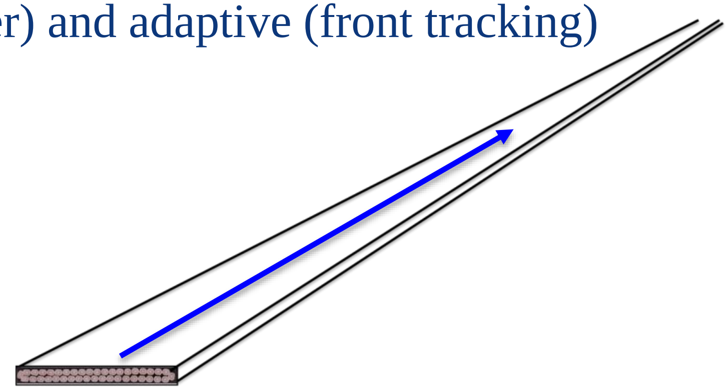
Modelling: length scale

2 Principal directions:
longitudinal and **transverse**



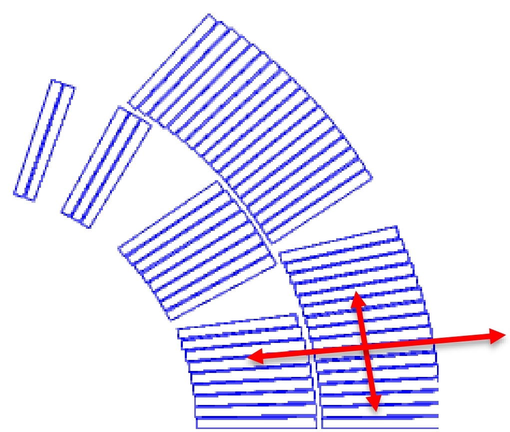
Longitudinal → length scale: hundreds of m

Cable is a continuum "relatively easy" to solve with accurate (high order) and adaptive (front tracking) methods

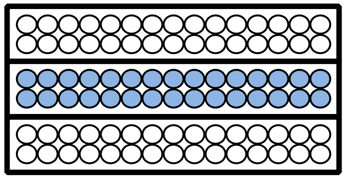


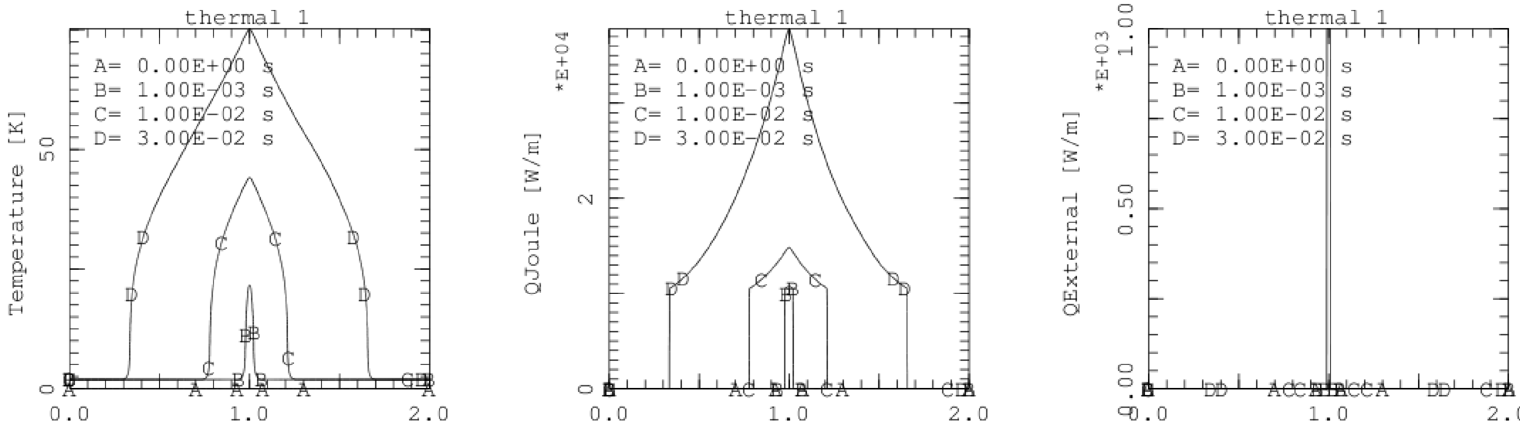
Transverse → length scale: mm

Heat diffusion across the insulation

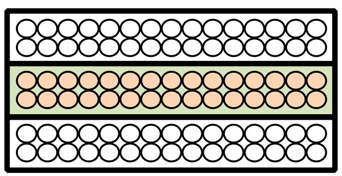


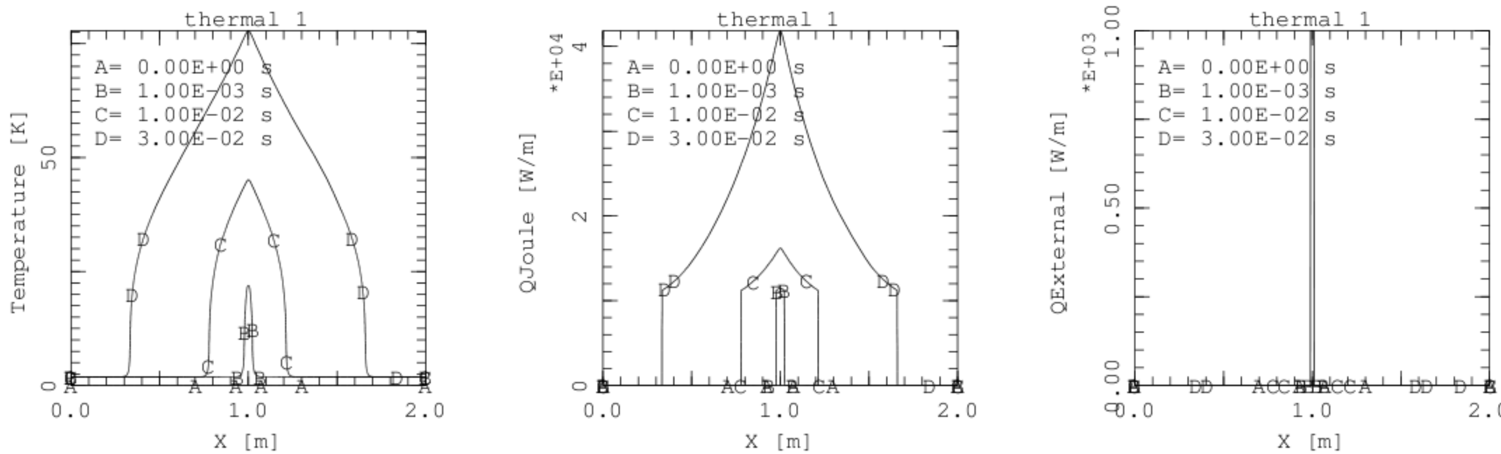
Conductor only



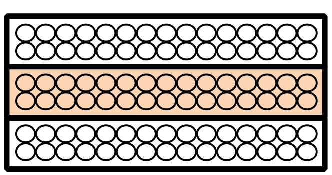


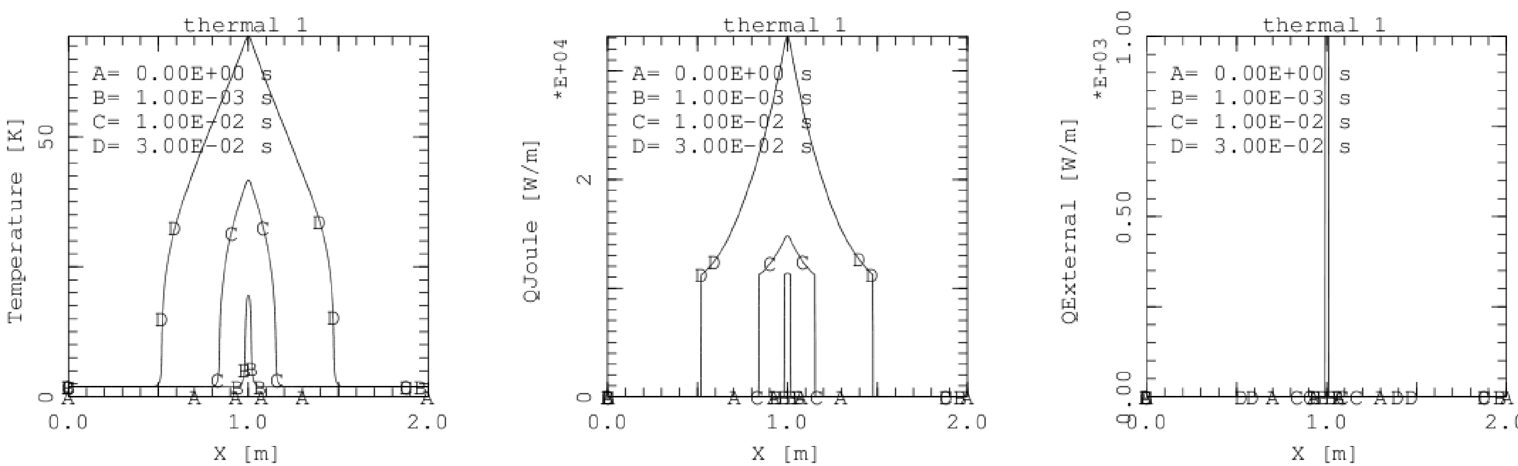
Conductor /insulation





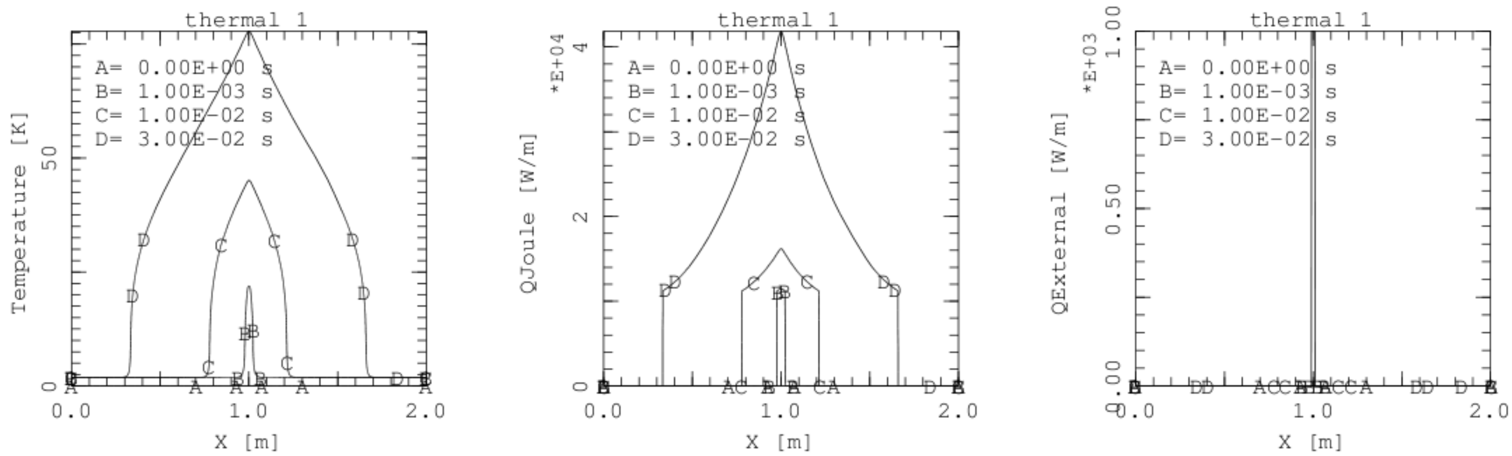
Conductor +insulation



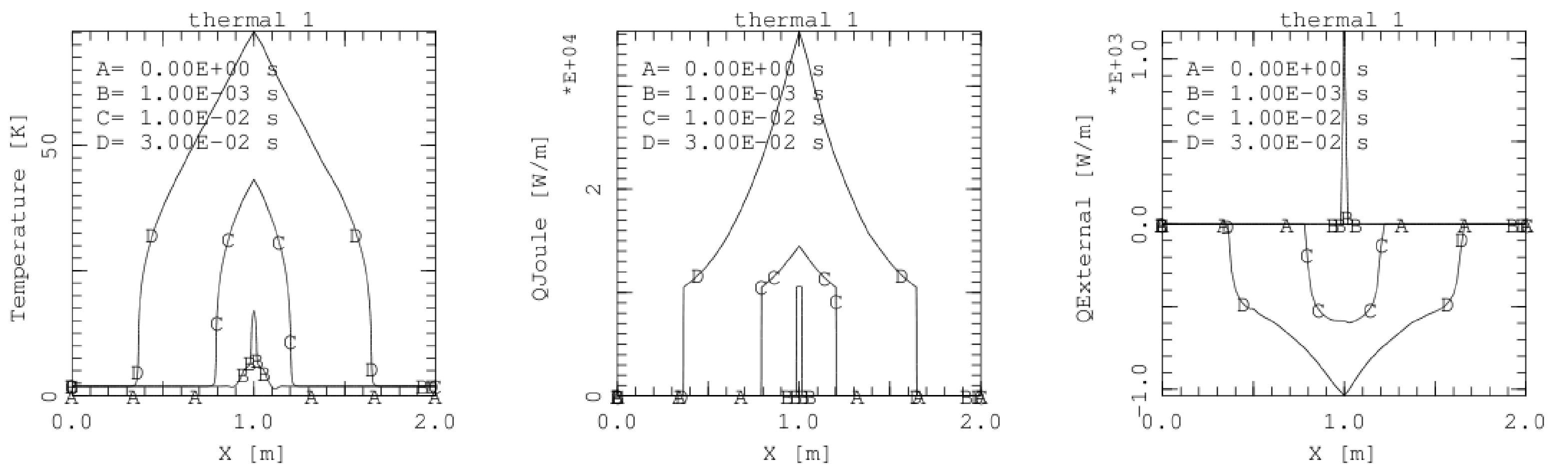


CERN

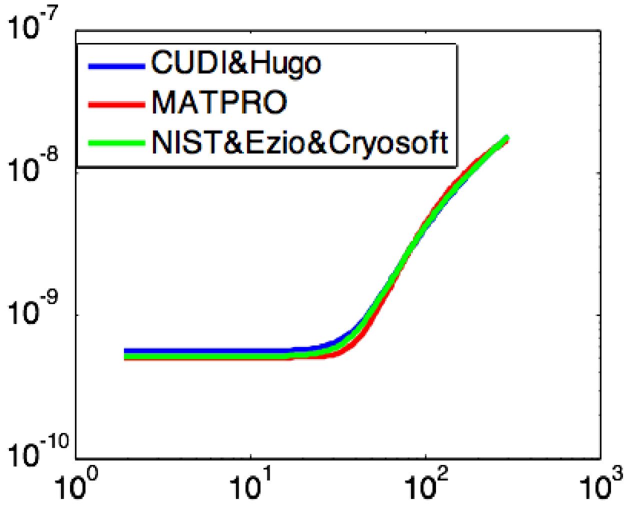
Network



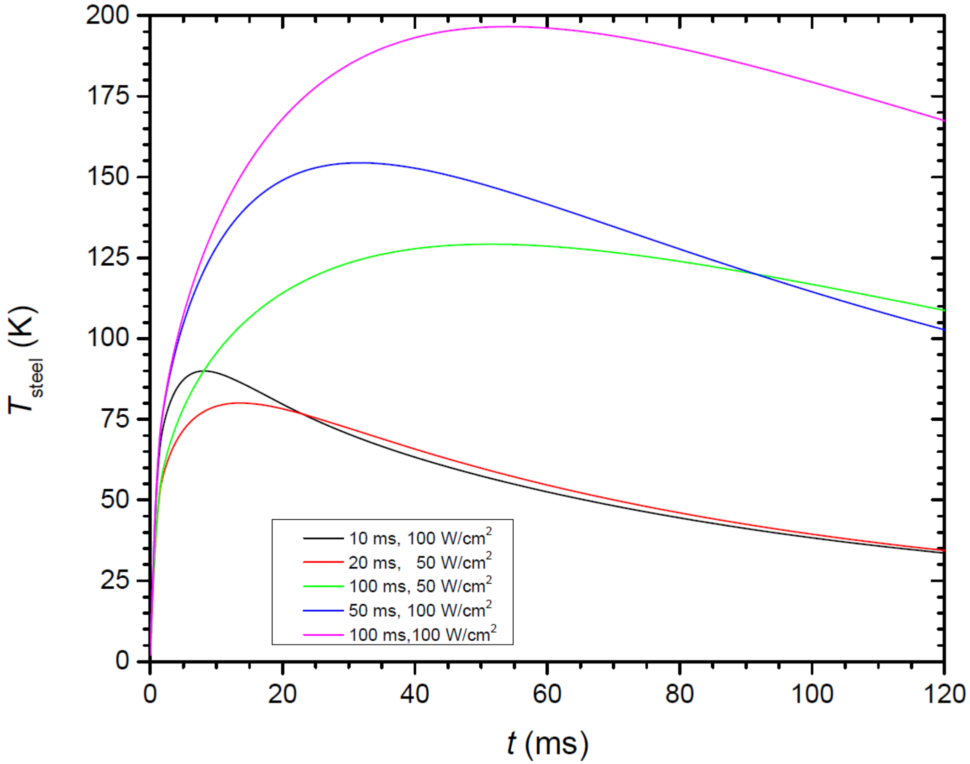
FE mesh

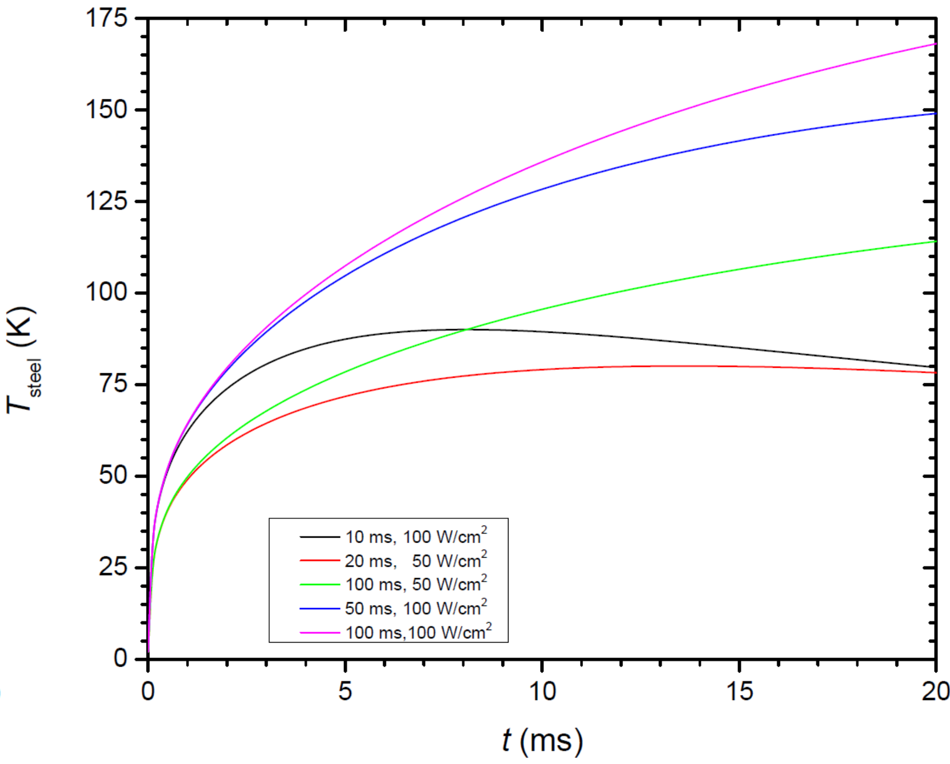


Material Properties



QH temperature rise





Training quench SMC – 11T