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Quench Analysis of the 11 T Nb_3Sn Dipole for the LHC Luminosity Upgrade

2015
Chats

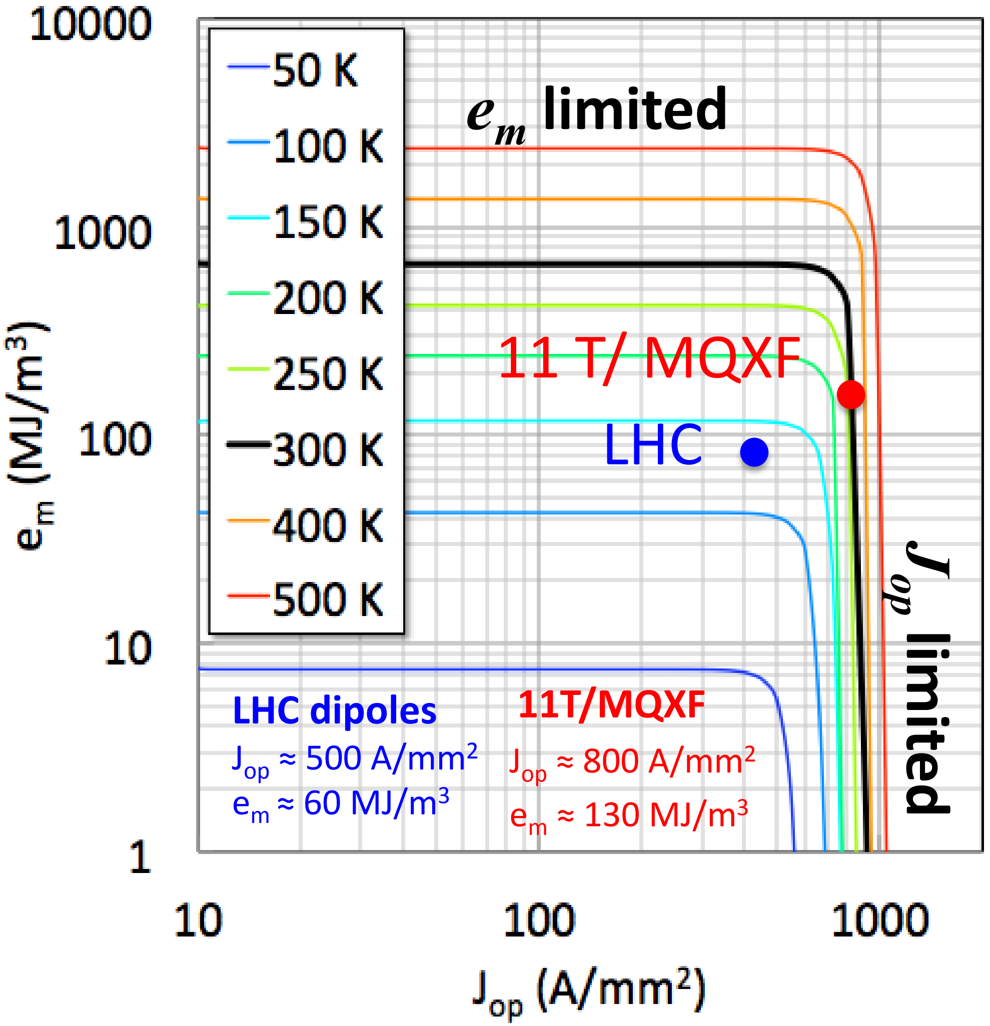
Applied Superconductivity

Conclusions From CHATS - 13

L. Bottura

http://indico.cern.ch/event/242886/contribution/18

- New accelerator magnets based on Nb_3Sn are pushing the boundary of protection
- Accurate simulation of quench transients in these magnets is crucial to the design choices, definition of priority R&D and to prove that the magnets are fit for operation
- We have today large uncertainties in the simulation results, depending on the hypotheses (inputs). It is essential to establish a good understanding of the dominating physics, and collect (new ?) data in well controlled and heavily instrumented experiments



This is a challenge for the CHATS community !!!

Contents

1. Motivation

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**

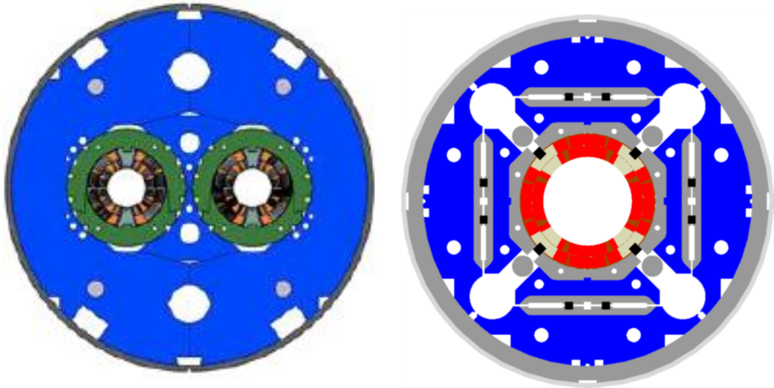
(compact winding for cost reduction)

- **Low stabilizer fraction**

(to achieve the desired margins)

- **Large temperature margin**

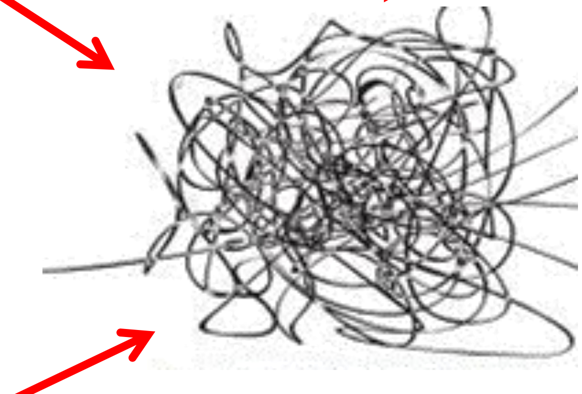
(use Nb_3Sn as superconductor)



	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. Motivation

11T and MQXF are pushing the boundary of protection,
we need a good understanding of the dominating physics!



Very different space scales

Longitudinal direction (along the cable)	few hundreds of m
Transverse direction (across the insulation)	mm

Different strongly coupled physics domains

Important dependence on very non-linear material properties

Very different time scales

Heat flow from supports and structures	1 s
Heat flow in the coil winding	10 ms
Heat flow along the cable	1 ms

Let’s try to understand it bit by bit…

2. Modelling strategy

Break the complex problem in simpler building blocks that are solved separately and then joined into a consistent solution.

The “key” ingredients are:

- **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.
- **Heat transfer from heater to coil**
  - Important because it defines the time needed to induce a distributed quench
  - Solved separately using a 2D FE COMSOL model and joined to the global solution.
- **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.

What is **not** (yet) **included** in the model:

SUPERMAGNET [Bot 2007]

- AC loss
- Other transient effects, such as change of the apparent inductance due to dI/dt

Inputs:

- Field maps and inductance from **ROXIE**

2.1 Longitudinal propagation

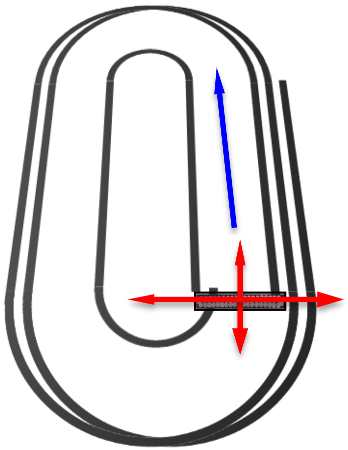
Two principal directions:

1. Longitudinal

Length scale is hundreds of m

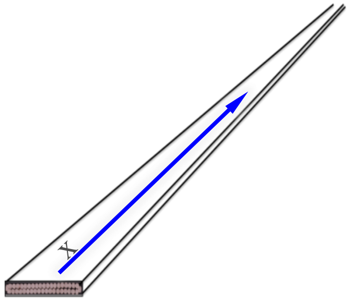
2. Transverse

Length scale is tenths of mm



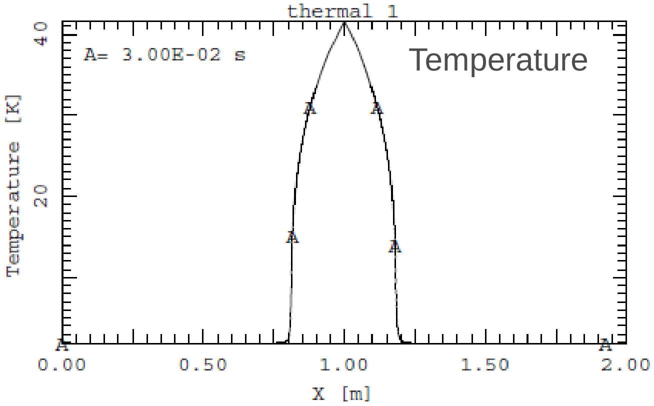
Longitudinal →

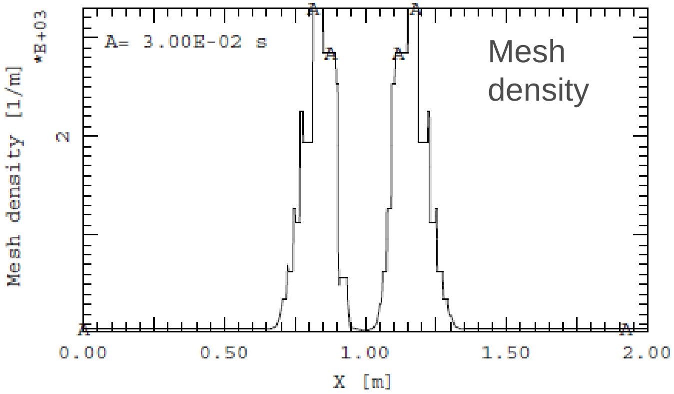
length scale: hundreds of m



The conductor is a continuum solved with accurate (high order) and adaptive (front tracking) methods:

[THEA]

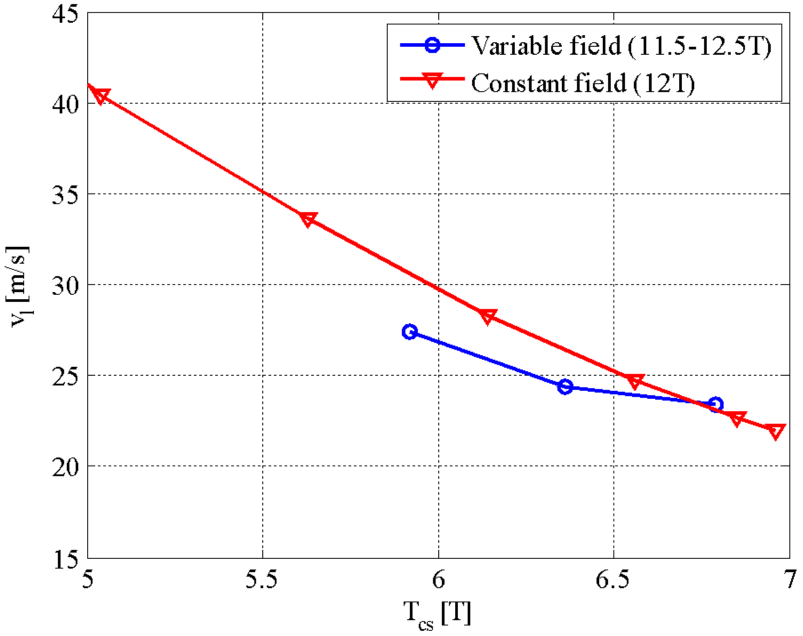




2.1 Longitudinal propagation

The **key** parameters:

- Current density on the copper (Joule Heating)
- Current Sharing Temperature (T_{cs})
- The field dependence of the material properties is less important, being T_{cs} the dominating factor affected by the field



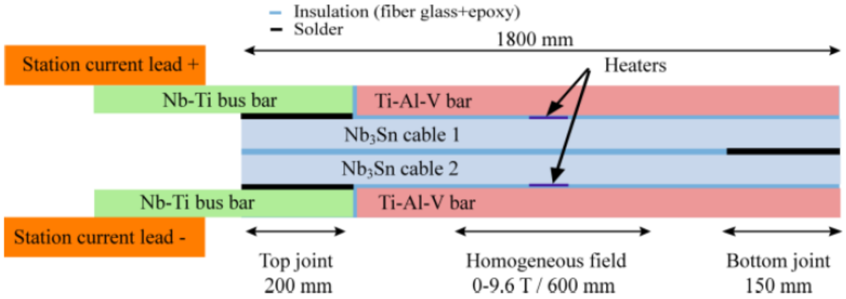
Model validation at different levels:

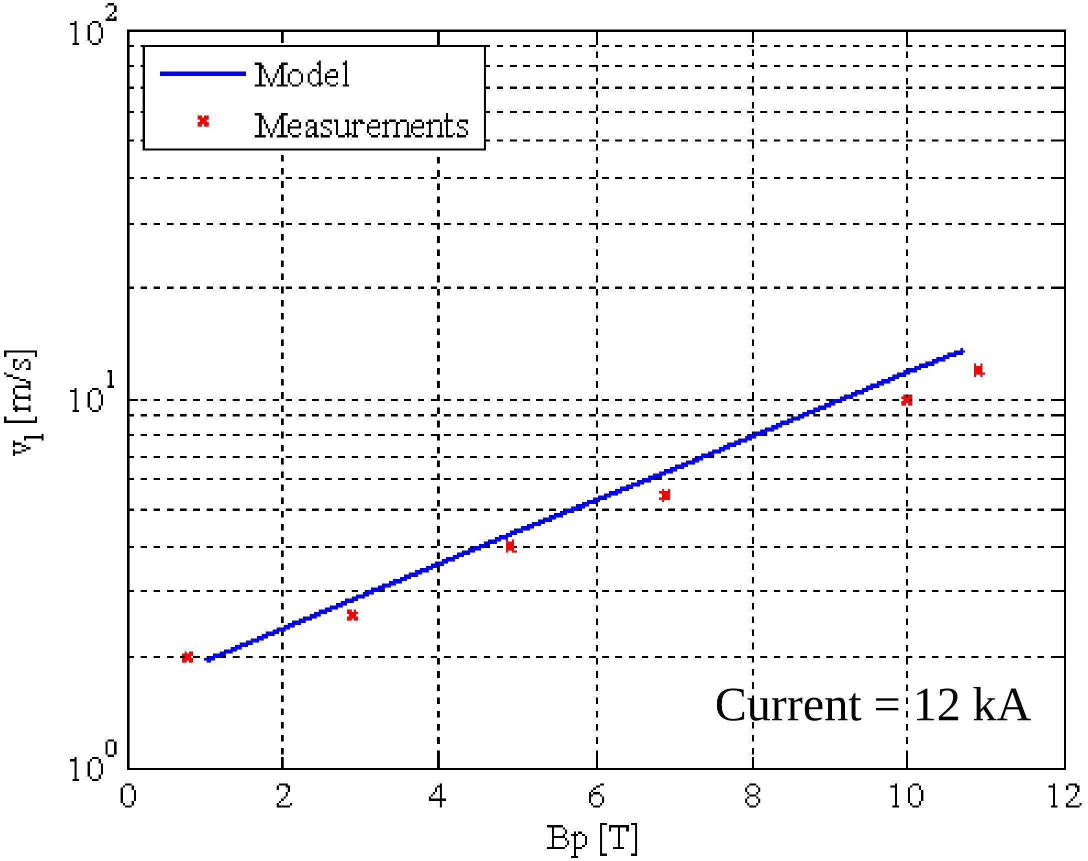
- **Cable level**: measurements on FRESCA
- **Magnet level:**
  - **R&D Magnets**: measurements on the Short Model Racetrack Coil (SMC)
  - **Magnet models**: measurements on FNAL and CERN 11T magnets.

2.1 Longitudinal propagation - validation

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)



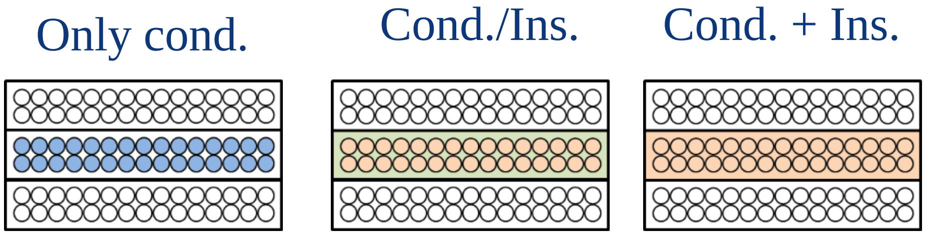


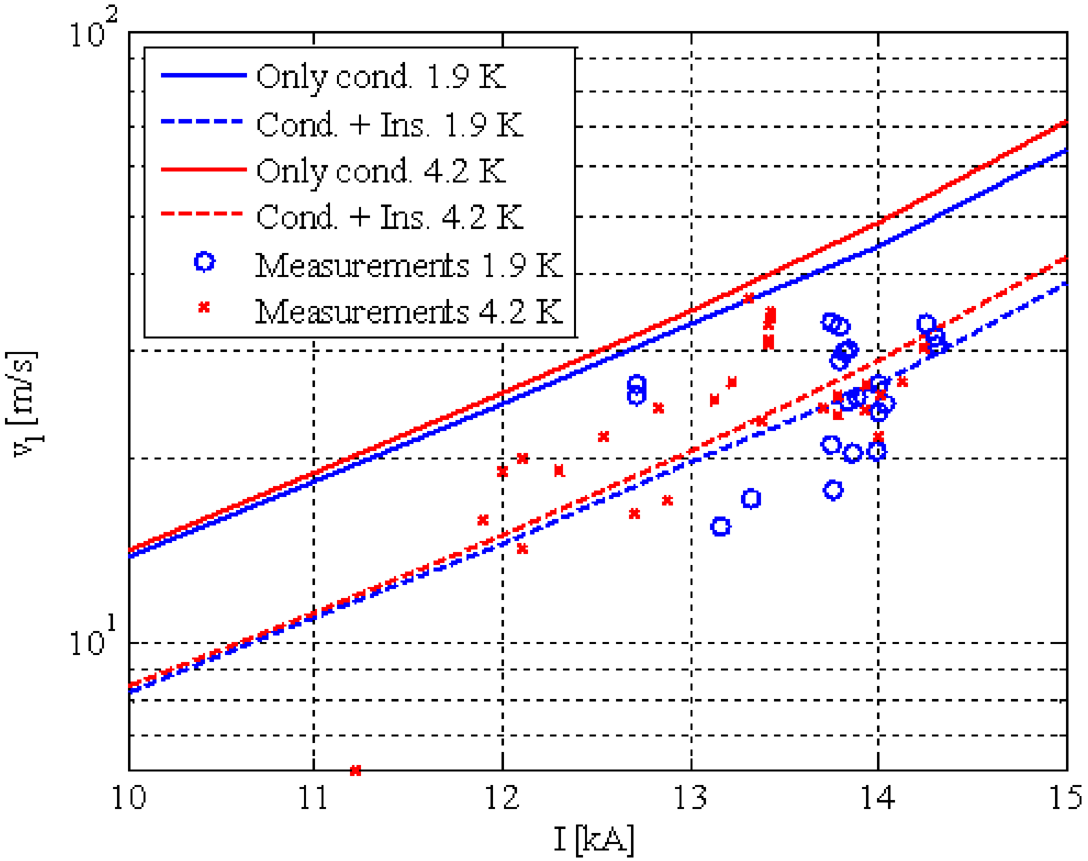
[experimental data from J. Fleiter, B. Bordini]

2.1 Longitudinal propagation - validation

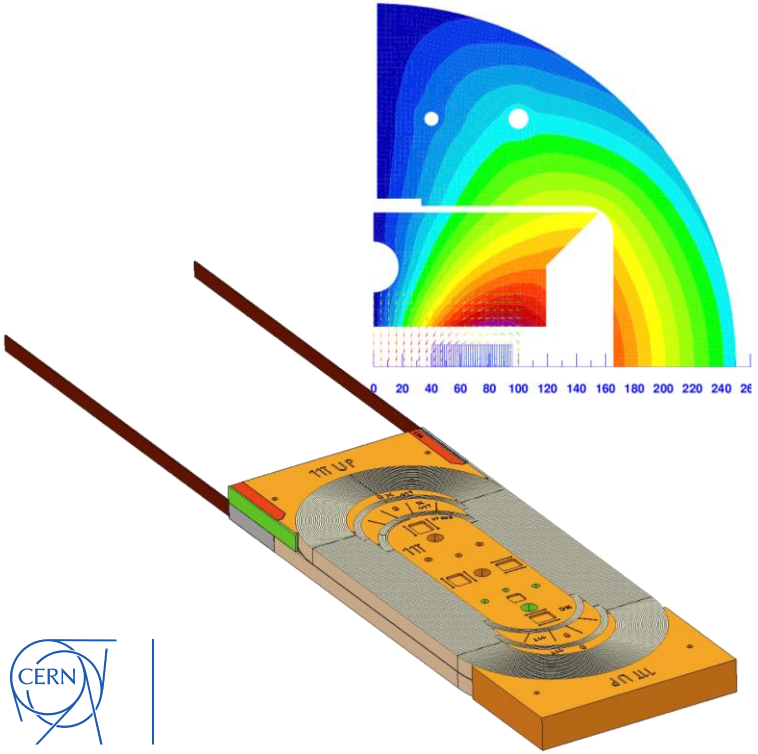
Measurements on Short Model Racetrack Coil (SMC)

- Coil wound using 11 T conductor.
- Natural quenches mostly in the high field region.
- Data is spread, when compared to the heater provoked quench.



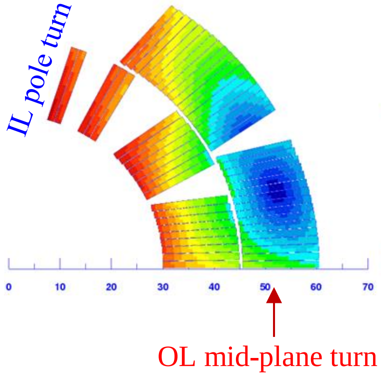


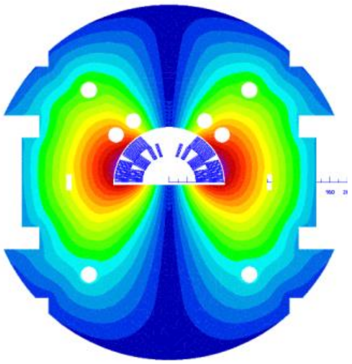
[experimental data from H. Bajas]

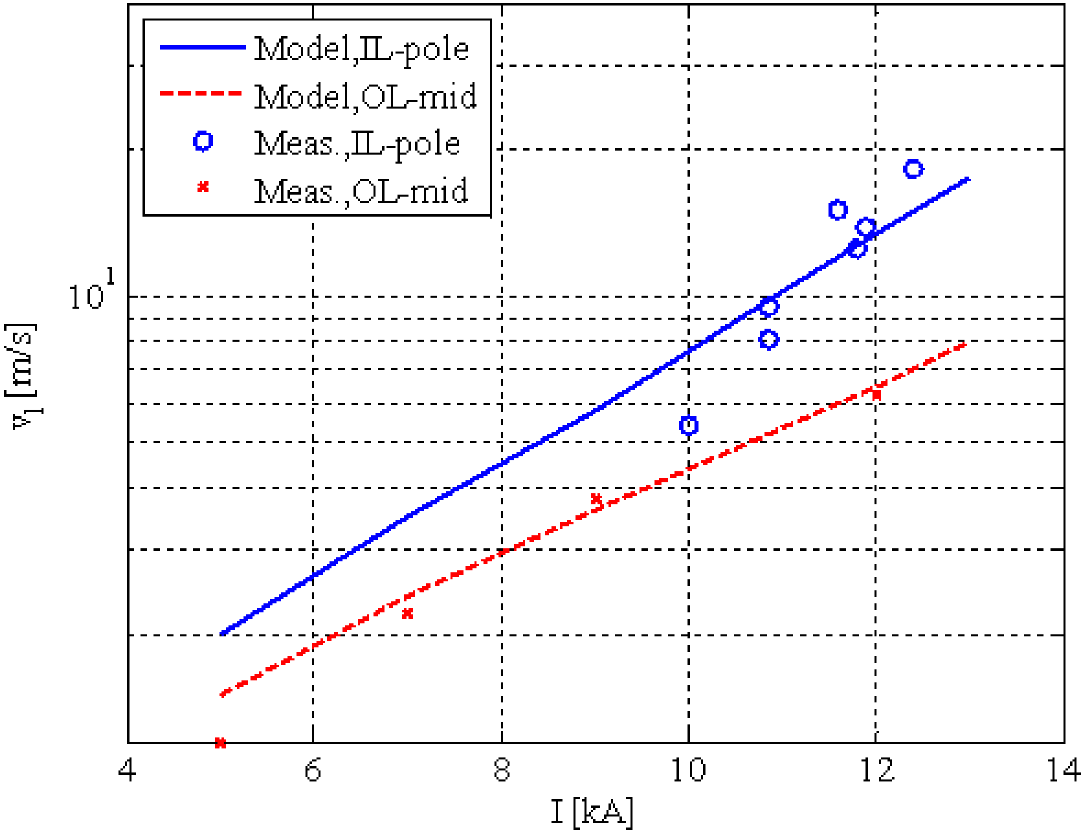


2.1 Longitudinal propagation - validation

Measurements on FNAL 11 T mirror magnet (MBHSM01)







[experimental data from G. Chlachidze]

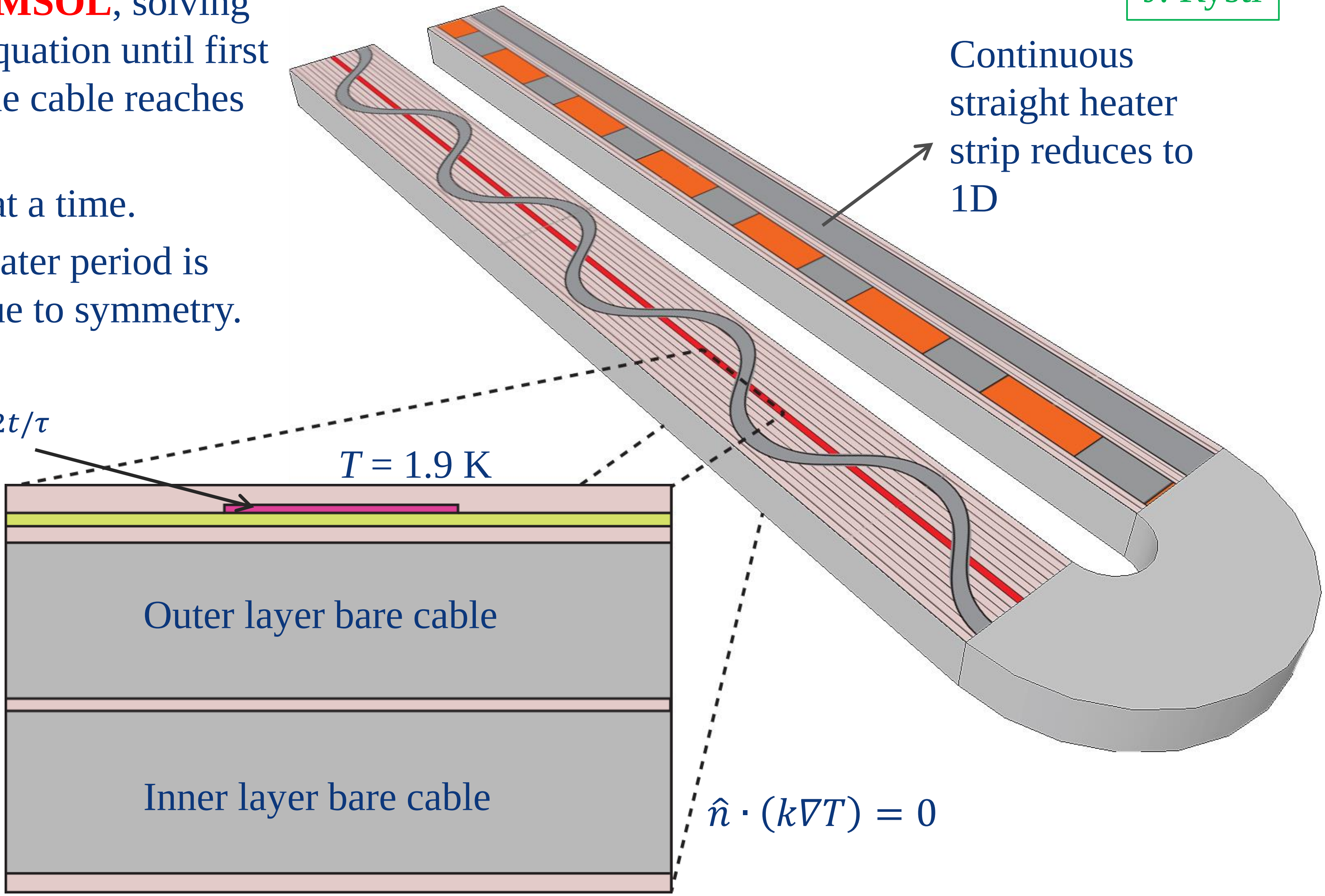
Remarks:

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

2.2 Heat transfer from heater to coil

- 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



Continuous straight heater strip reduces to 1D

$q = q_0 e^{-2t/\tau}$

$T = 1.9$ K

Outer layer bare cable

Inner layer bare cable

$\hat{n} \cdot (k \nabla T) = 0$

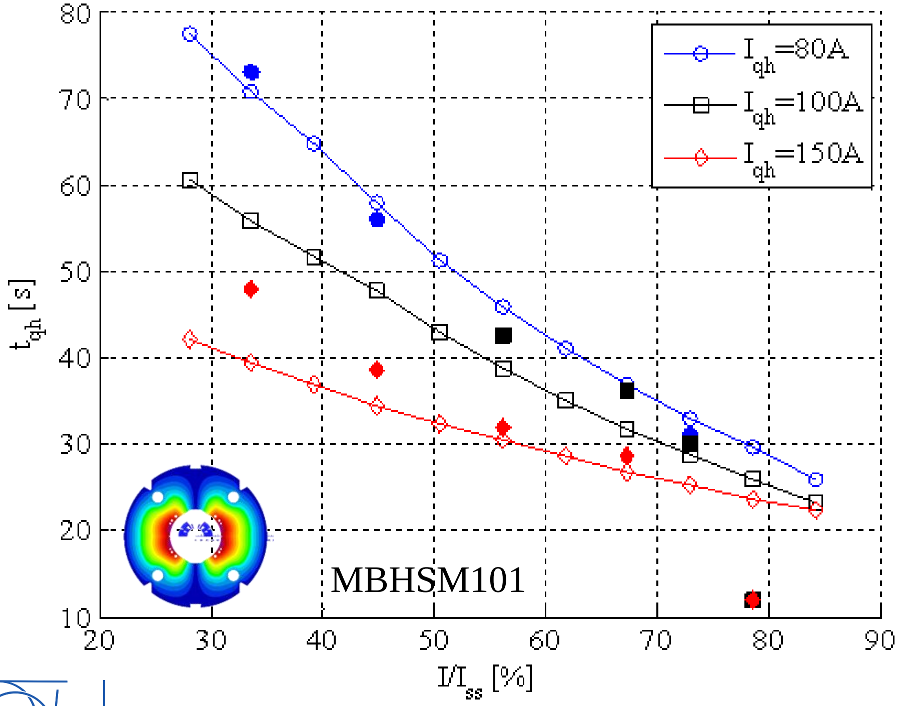
$\hat{n} \cdot (k \nabla T) = 0$

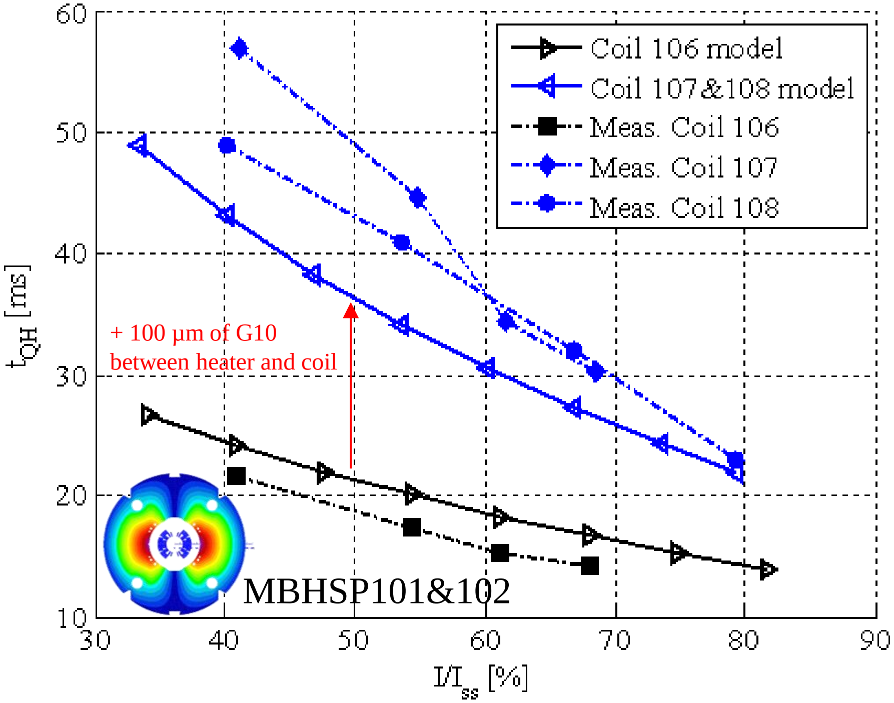
2.2 Heat transfer from heater to coil – key parameters

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



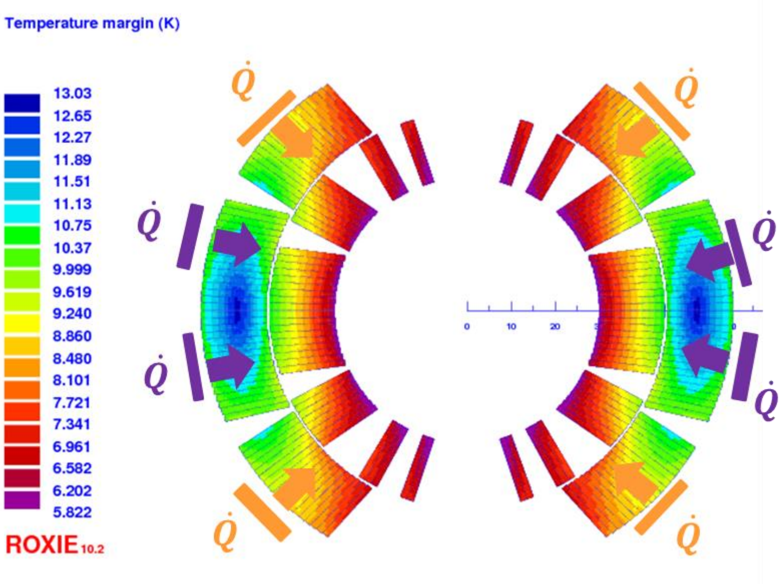


+ 100 µm of G10 between heater and coil

[experimental data from G. Willering]

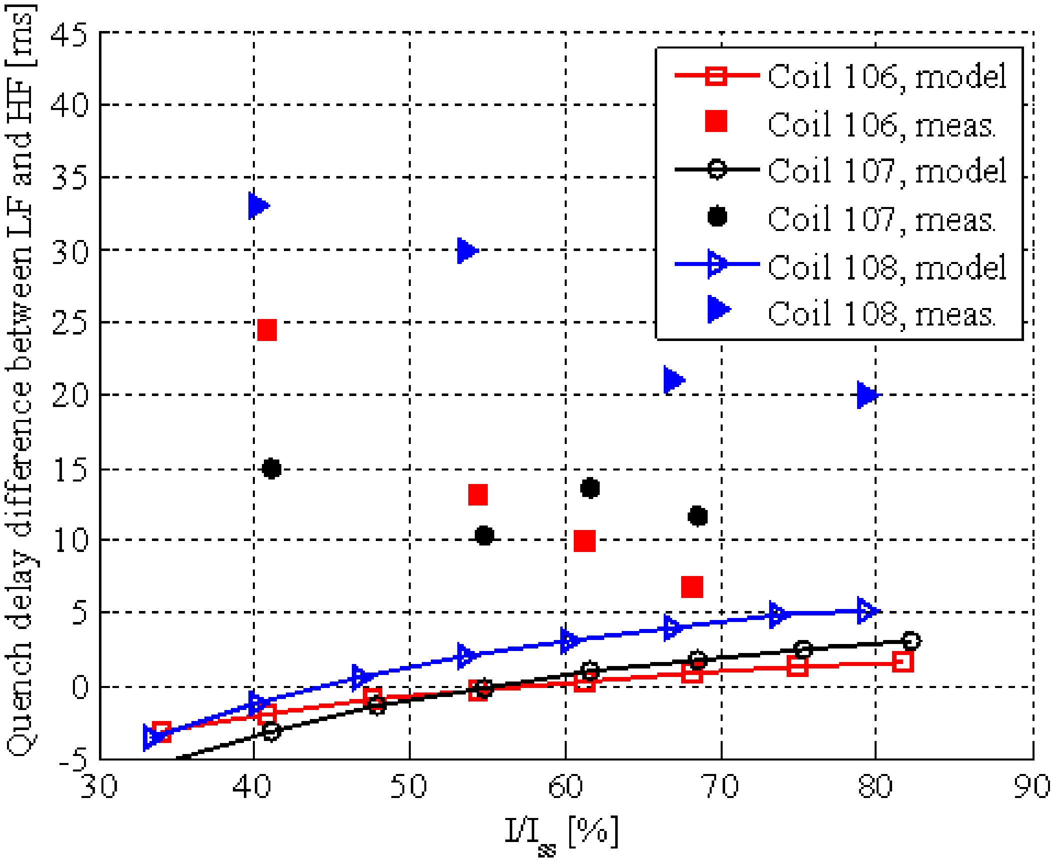
2.2 Heat transfer from heater to coil

- 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



2.3 Heat propagation within the coil

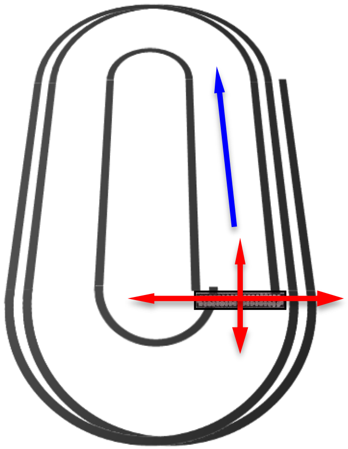
Two principal directions:

1. Longitudinal

Length scale is hundreds of m

2. Transverse

Length scale is tenths of mm



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

Power exchanged between components in the conductor

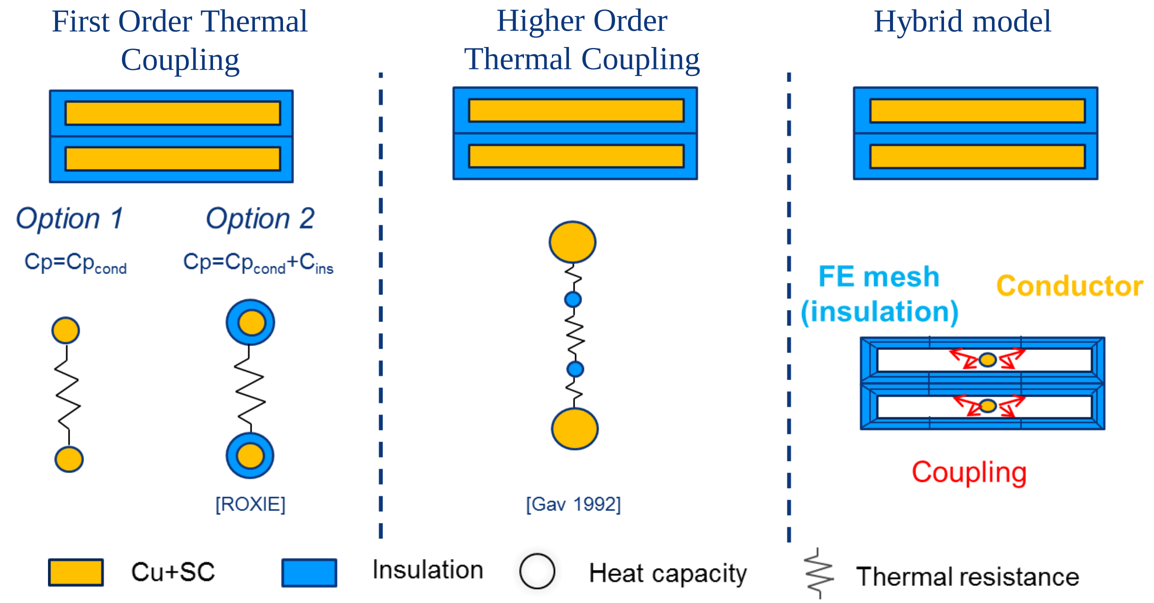
External heat perturbation

Joule heating

Transverse

Power exchange between adjacent conductors

Different approaches can be follow to model the power exchange between adjacent conductors:



First Order Thermal Coupling

Option 1

$Cp=Cp_{cond}$

Option 2

$Cp=Cp_{cond}+C_{ins}$

[ROXIE]

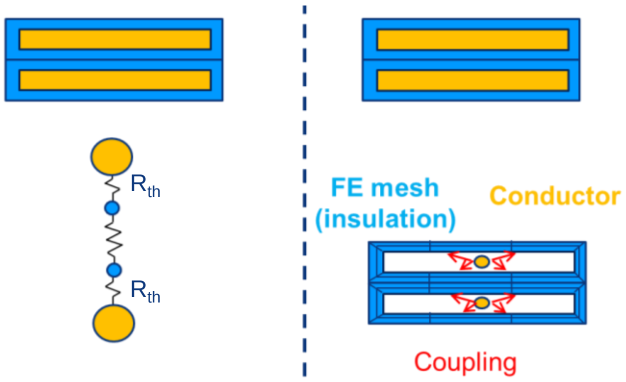
Higher Order Thermal Coupling

[Gav 1992]

Hybrid model

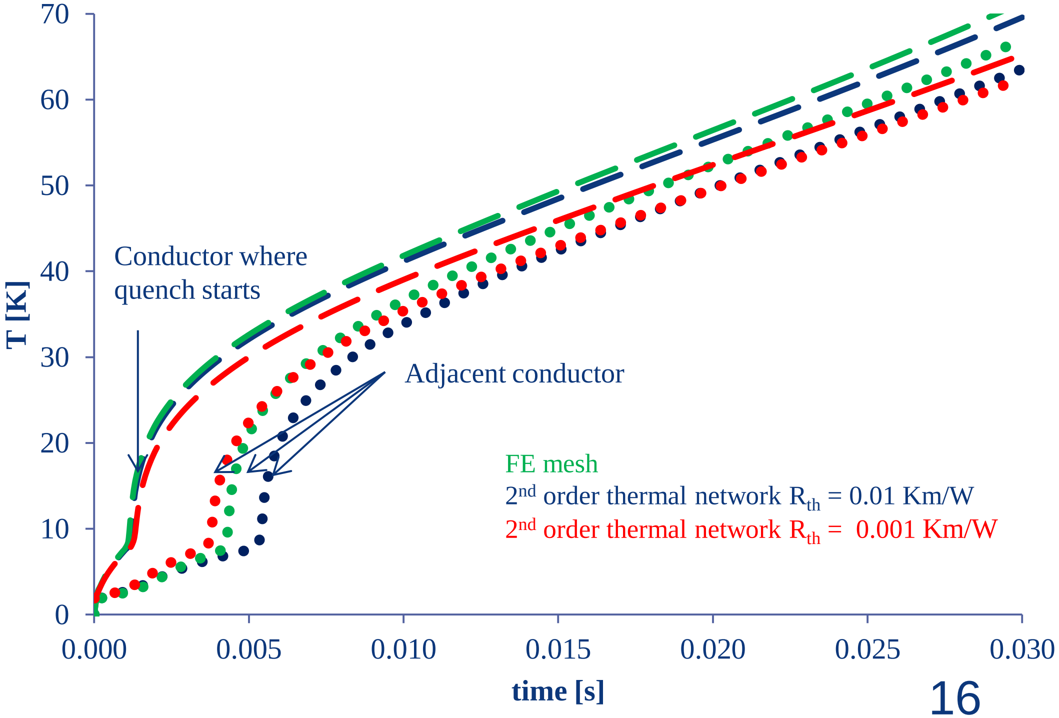
2.3 Network model vs. hybrid model

Hybrid model with explicit coupling: conditionally stable. Small heat capacity and large thermal conductance requires small time steps for the stability of the coupling, gets numerically heavy to model a full magnet!



Network model: conductor and insulation are independent nodes connected through a thermal resistance (R_{th}) . The degree of thermal separation among the components depends on this thermal contact (which is not well known):

- **Small R_{th}**, conductor and insulation are in good thermal contact, lumping the effect of the hole insulation (faster transverse quench propagation and lower T_{max})
- **Large R_{th}**, larger temperature gradient between conductor and insulation (slower transverse quench propagation and larger T_{max})

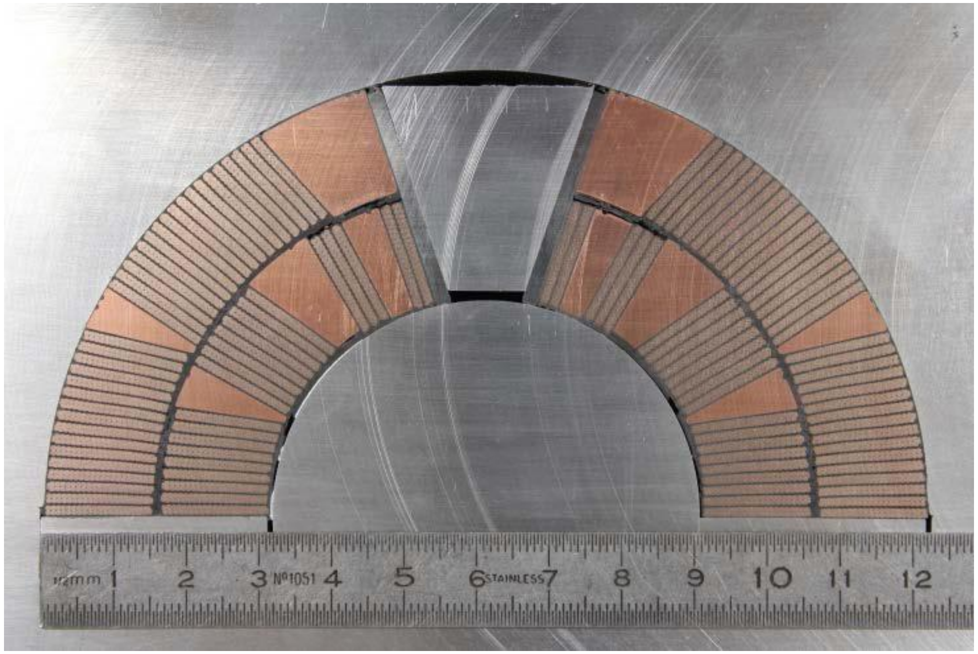


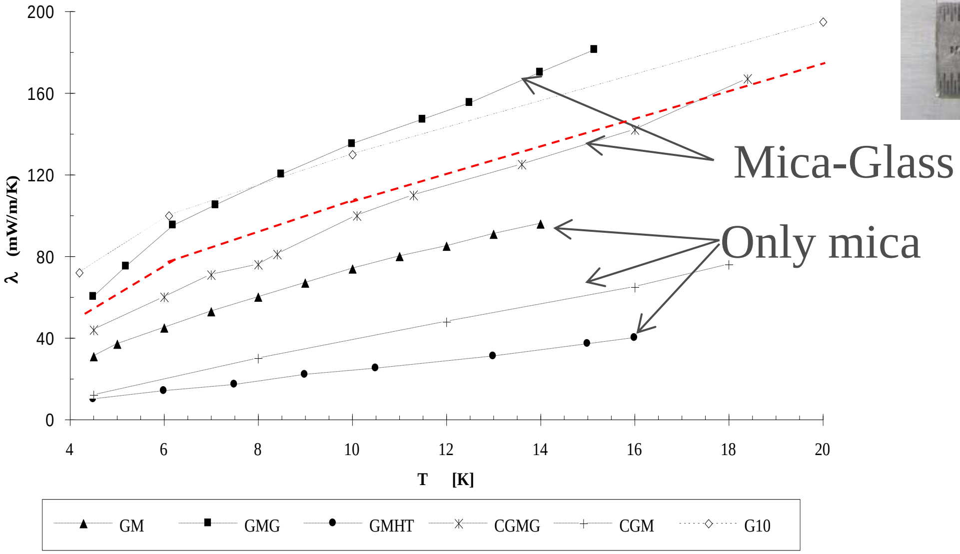
2.3 Thermal network - validation

Case study DS-11T dipole.
Insulation scheme:

- 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.





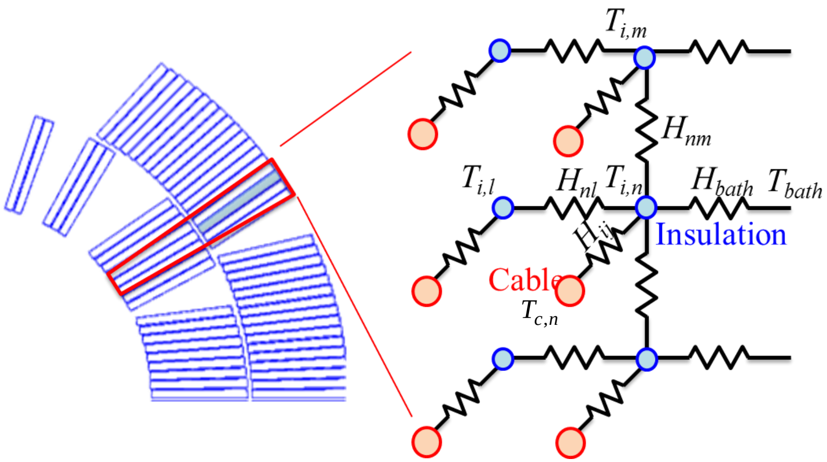
The thermal properties of the insulation in the model are "**G10**", although measurements are on-going at CERN - Cyrolab to have experimental data on the thermal diffusivity for the specific 11T magnet insulation.

Big uncertainties in terms of geometry and material properties!

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

2.3 Thermal network - validation

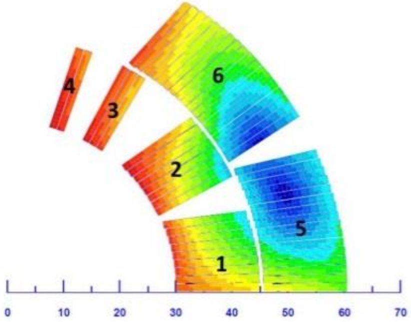
$\dot{q}_{adj,i} = H_{nm}(T_{i,m} - T_{i,n})$ $\dot{q}_{adj,c} = H_{ij}(T_{i,n} - T_{c,n})$



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

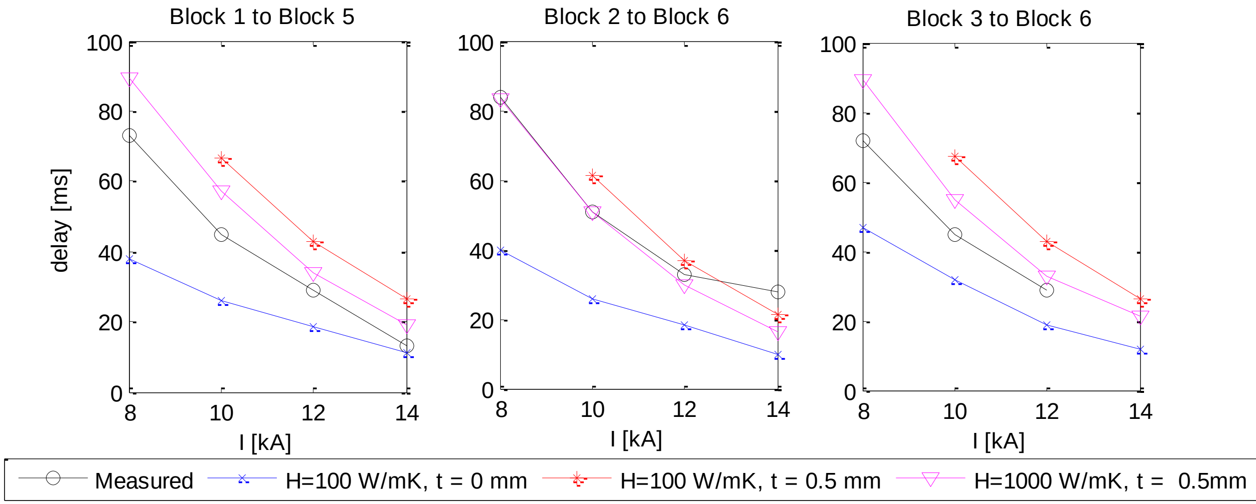
1. Internal thermal conductance in the conductor **H_{ij} = 100 W/mK** (R_{th}=0.01 mK/W), inter-layer insulation thickness **t = 0 mm**
2. Internal thermal conductance in the conductor **H_{ij} = 100 W/mK** (R_{th}=0.01 mK/W), inter-layer insulation thickness **t = 0.5 mm**
3. Internal thermal conductance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



Data from [G. Willering]

Outer layer to inner layer delay

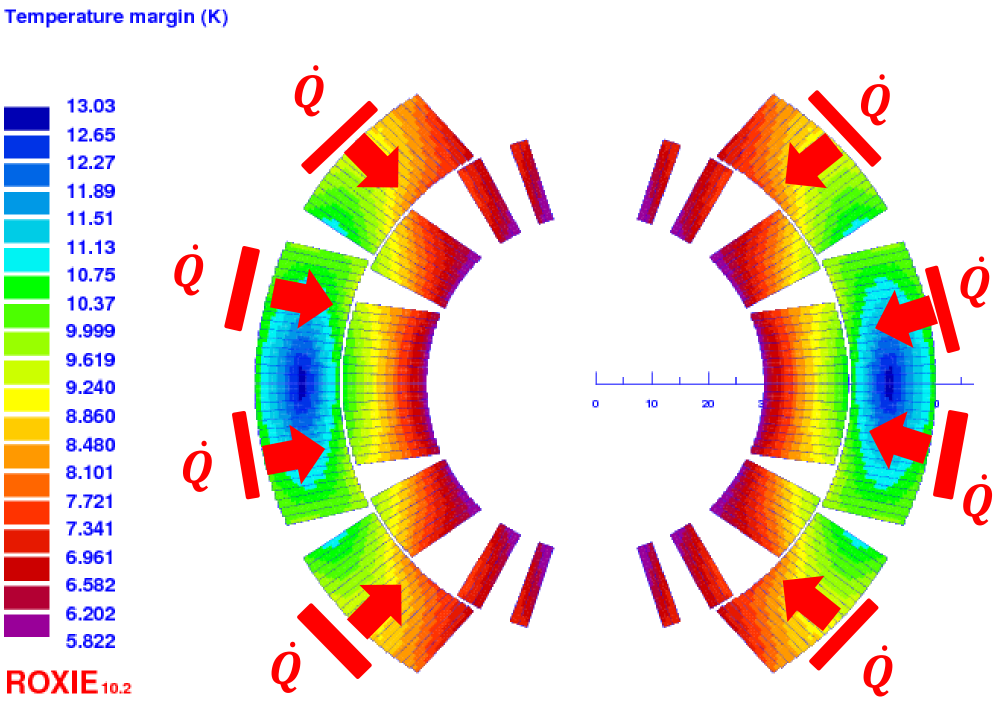


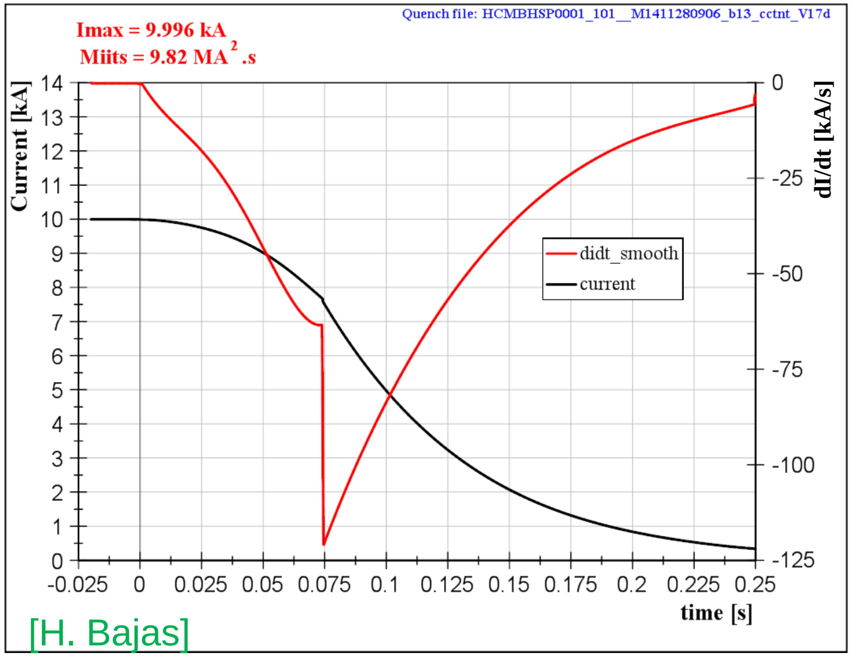
2.4 Hot spot temperature - validation

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]

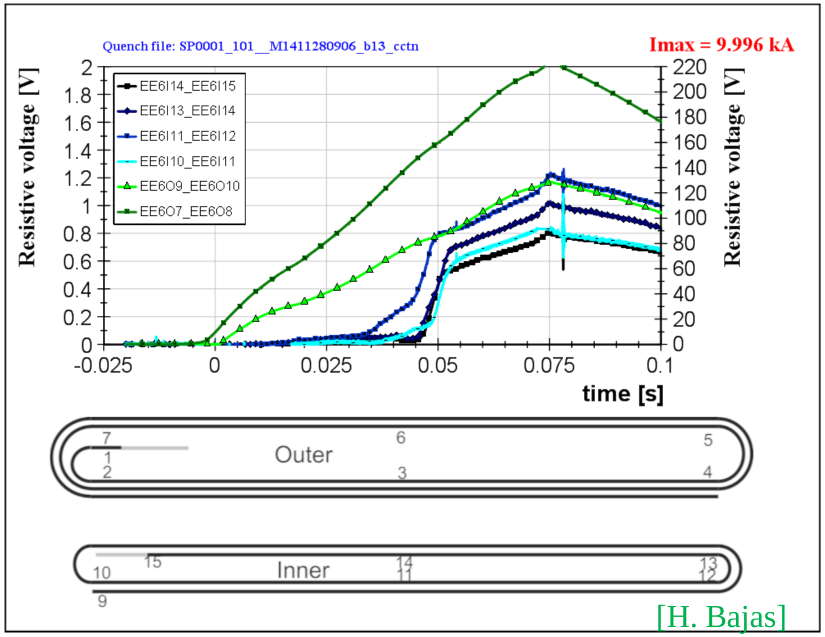
$$T(t) = \Phi\left(\rho_{\exp}(t) - \frac{C_0}{RRR} - m_r\, B(t)\right)$$



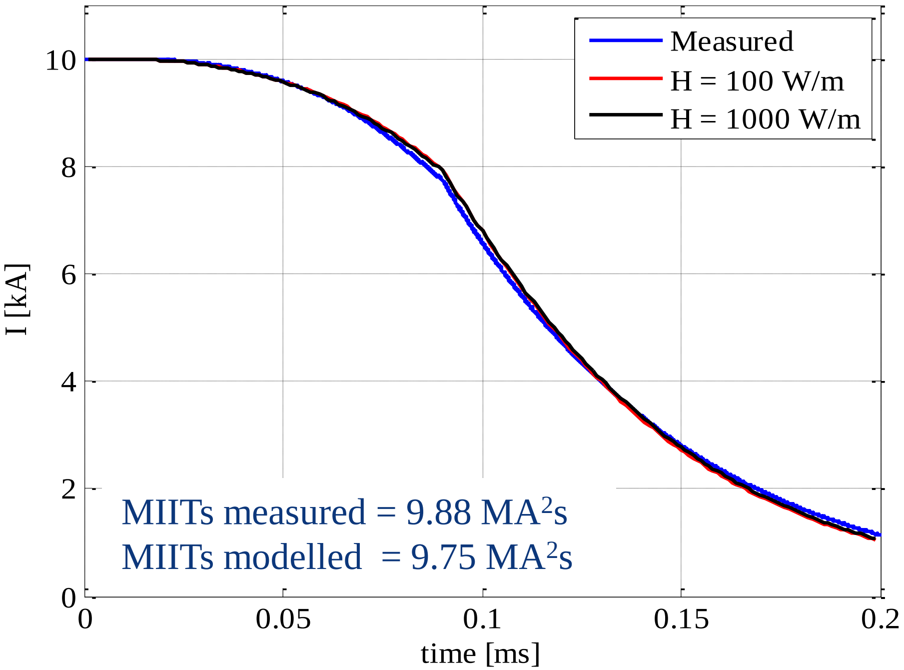


[H. Bajas]

2.4 Hot spot temperature - validation



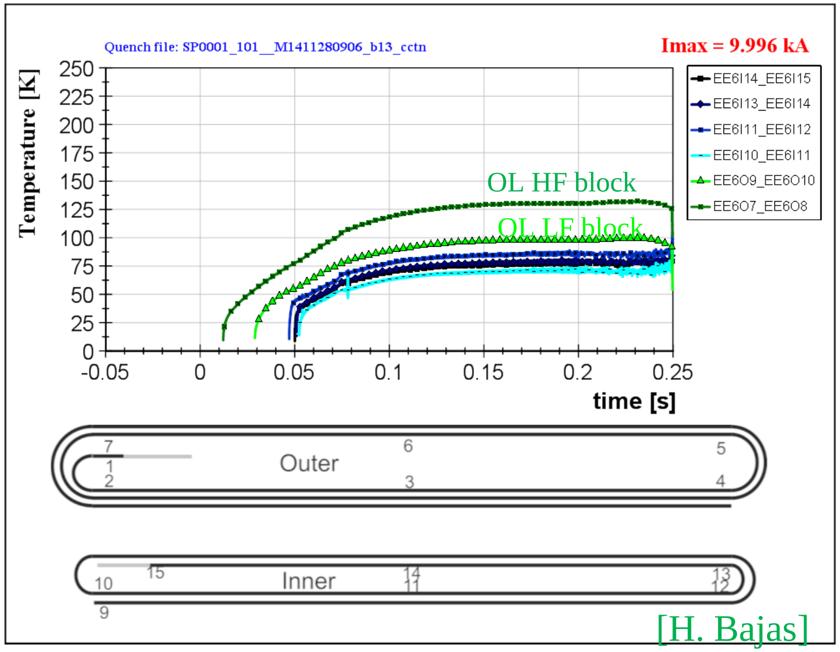
[H. Bajas]



MIITs measured = 9.88 MA^{2}s
MIITs modelled = 9.75 MA^{2}s

	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

2.4 Hot spot temperature - validation

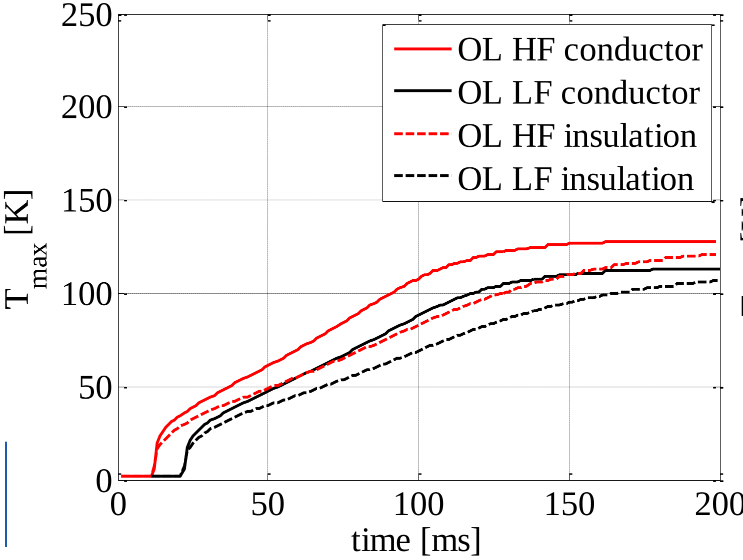


[H. Bajas]

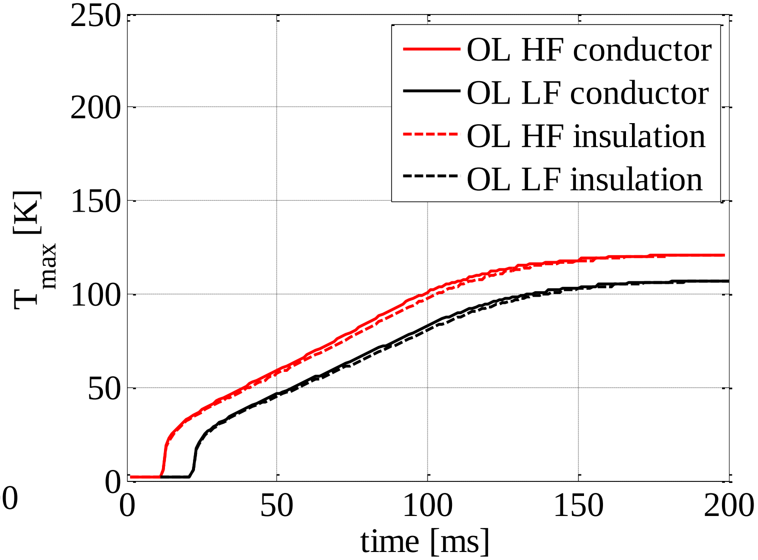
Temperatures predicted by the model are pretty close to those defined experimentally by [H. Bajas]

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

H = 100 W/m



H = 1000 W/m



3. Sensitivity analysis

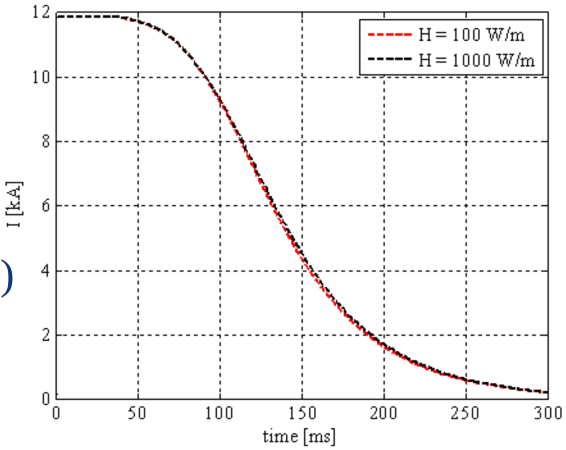
How different parameters affect the hot spot temperature?

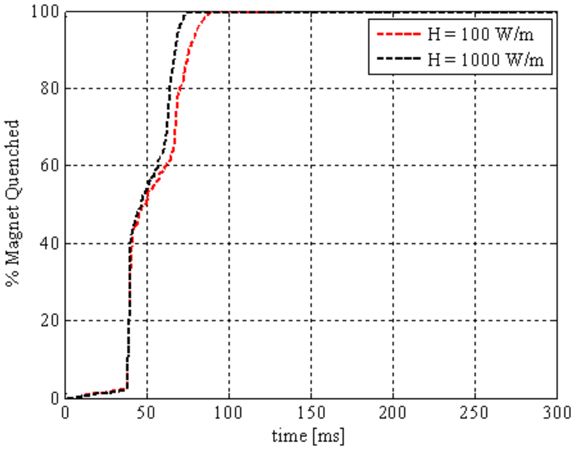
- Conductor where quench starts
- Conductor parameters
  - Copper to superconductor ratio
  - RRR
- Time to detect and validate the quench
- Insulation thickness from heater to coil
- Numbers of heater failure

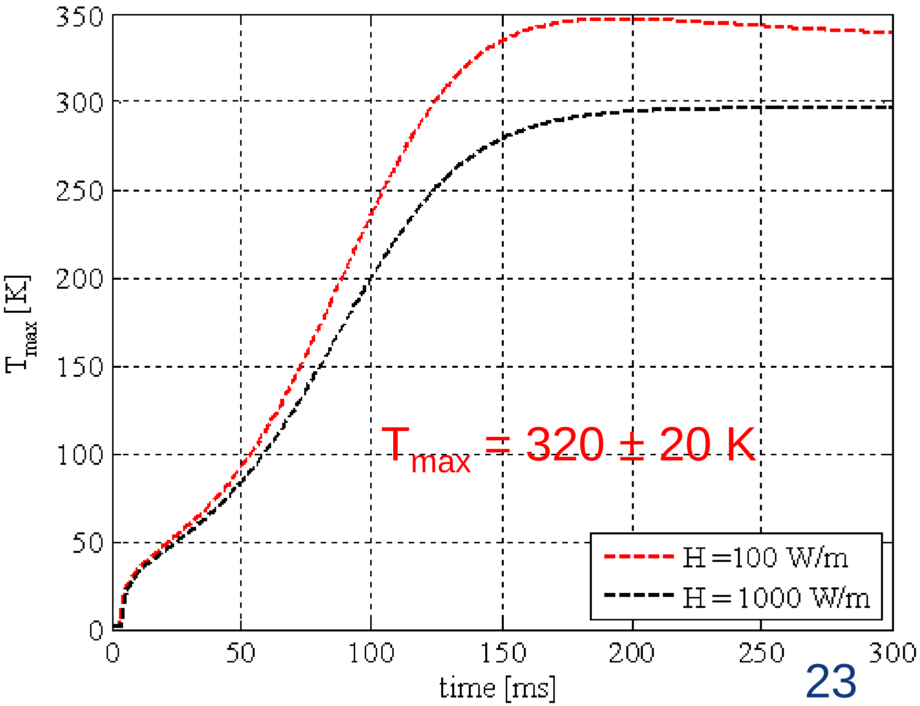
2.4 Hot spot temperature – Reference case

Case description (DS-11T magnet):

- 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

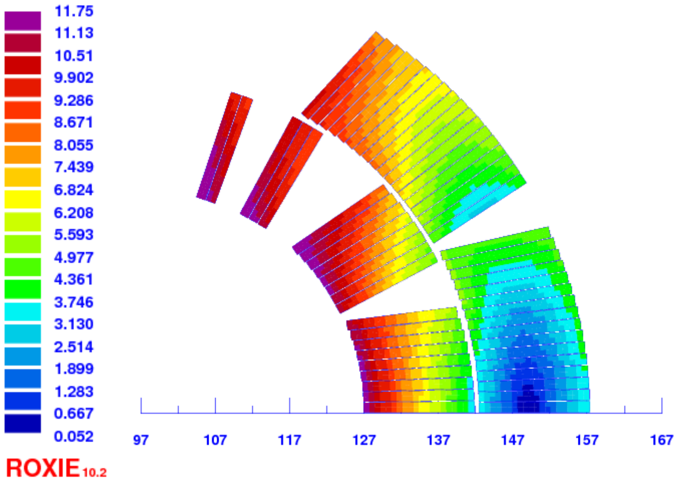


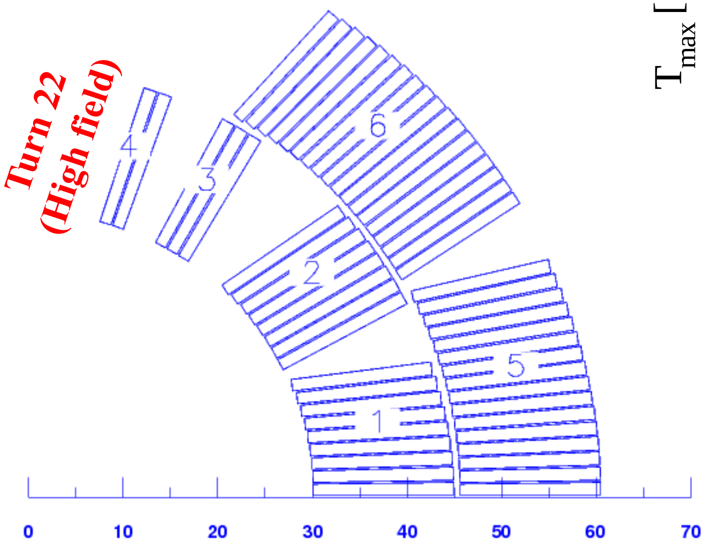




T_{max} = 320 ± 20 K

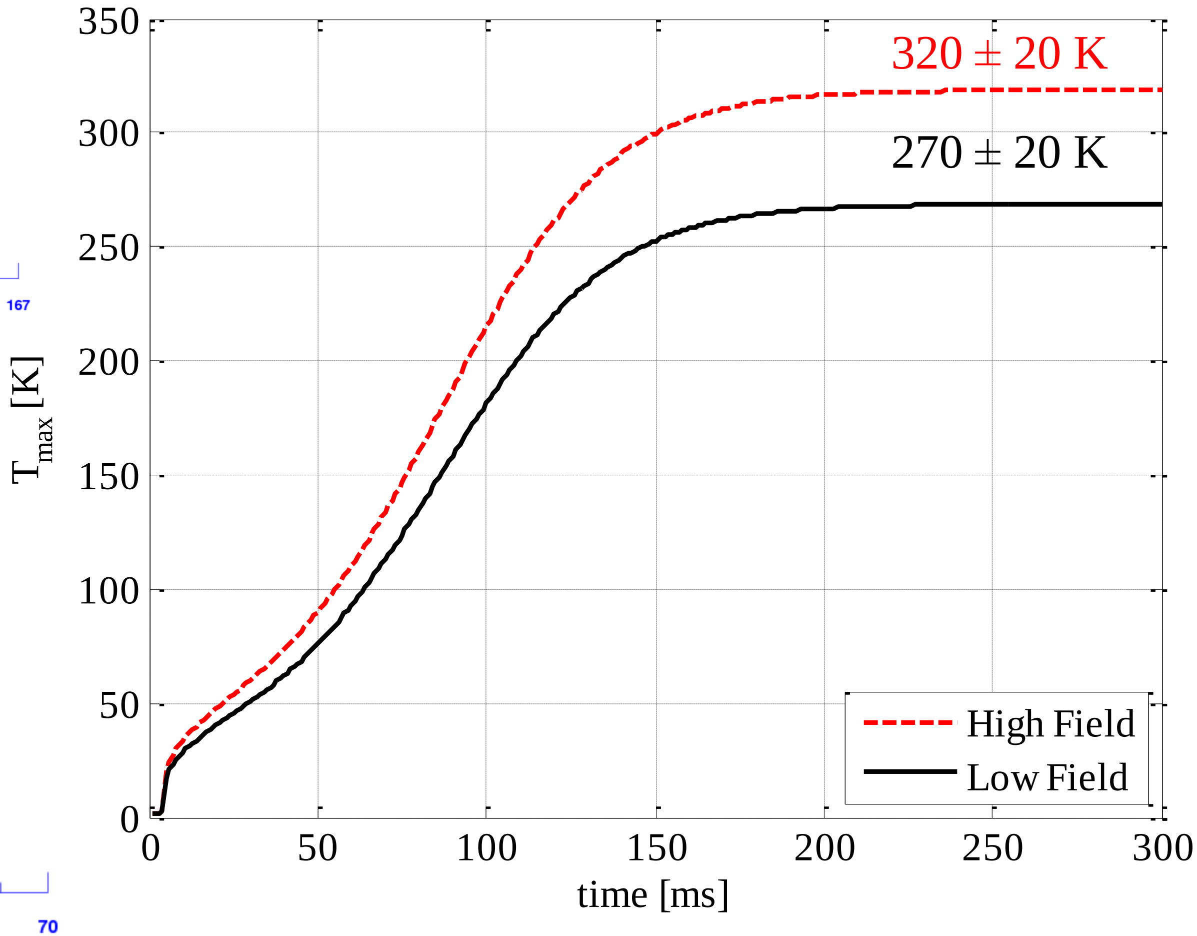
Conductor where quench starts





Turn 22 (High field)

Turn 23 (low field)



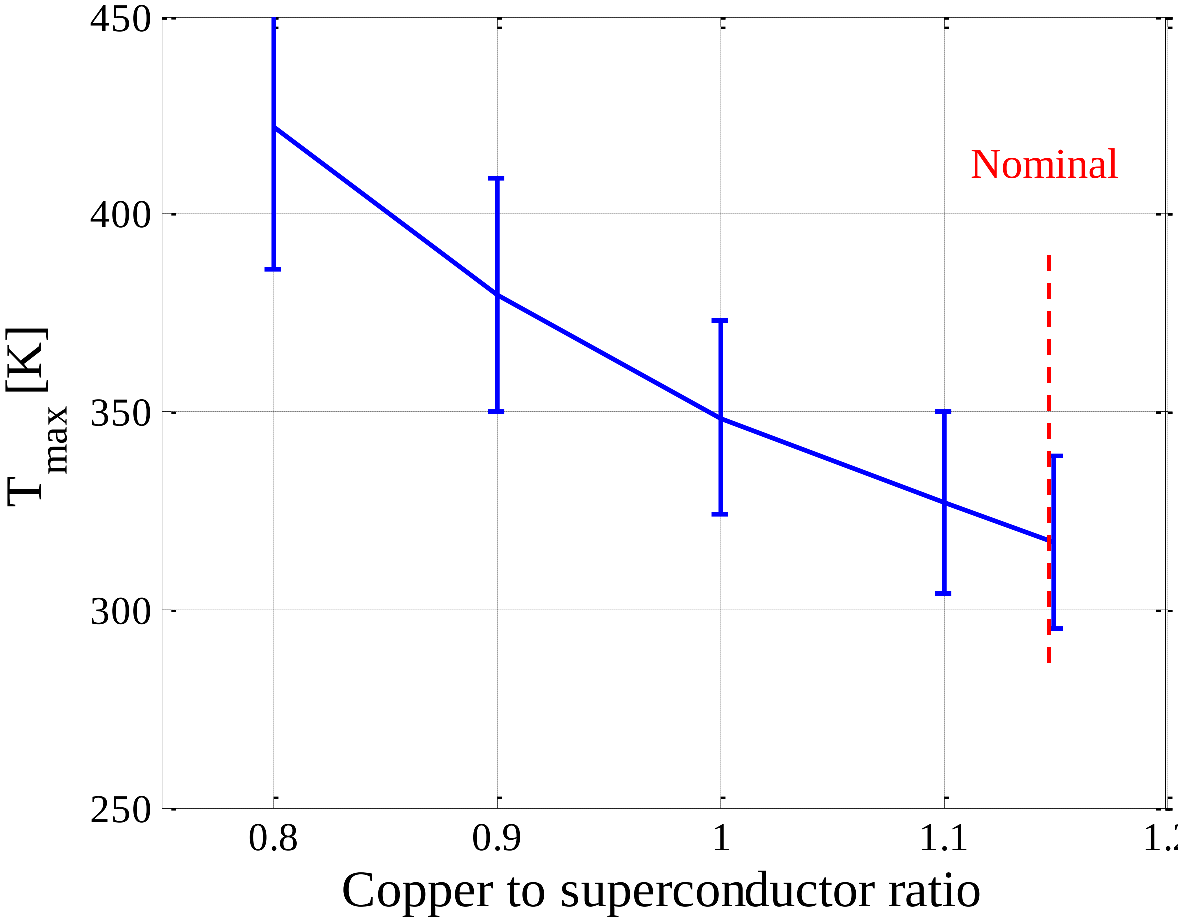
Copper to superconductor ratio

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, 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

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)

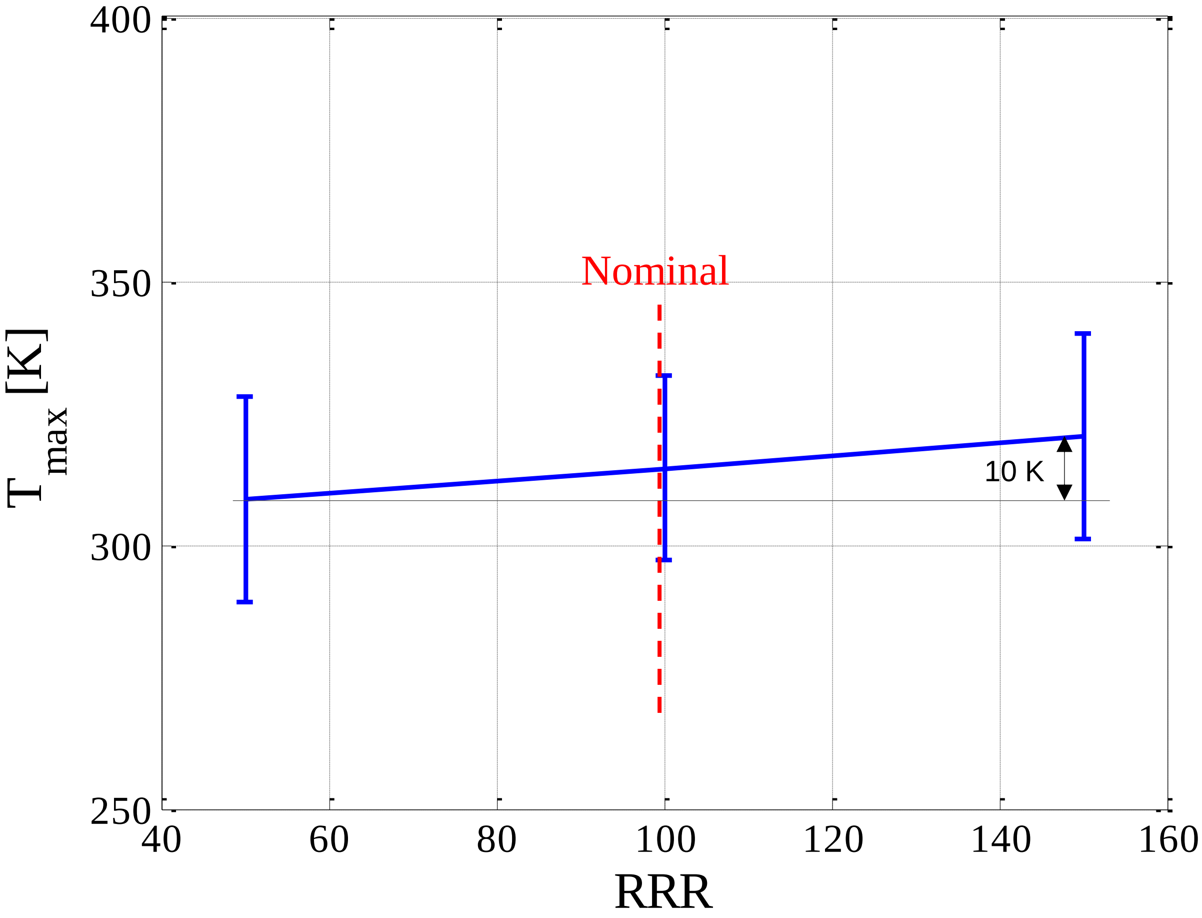


RRR

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



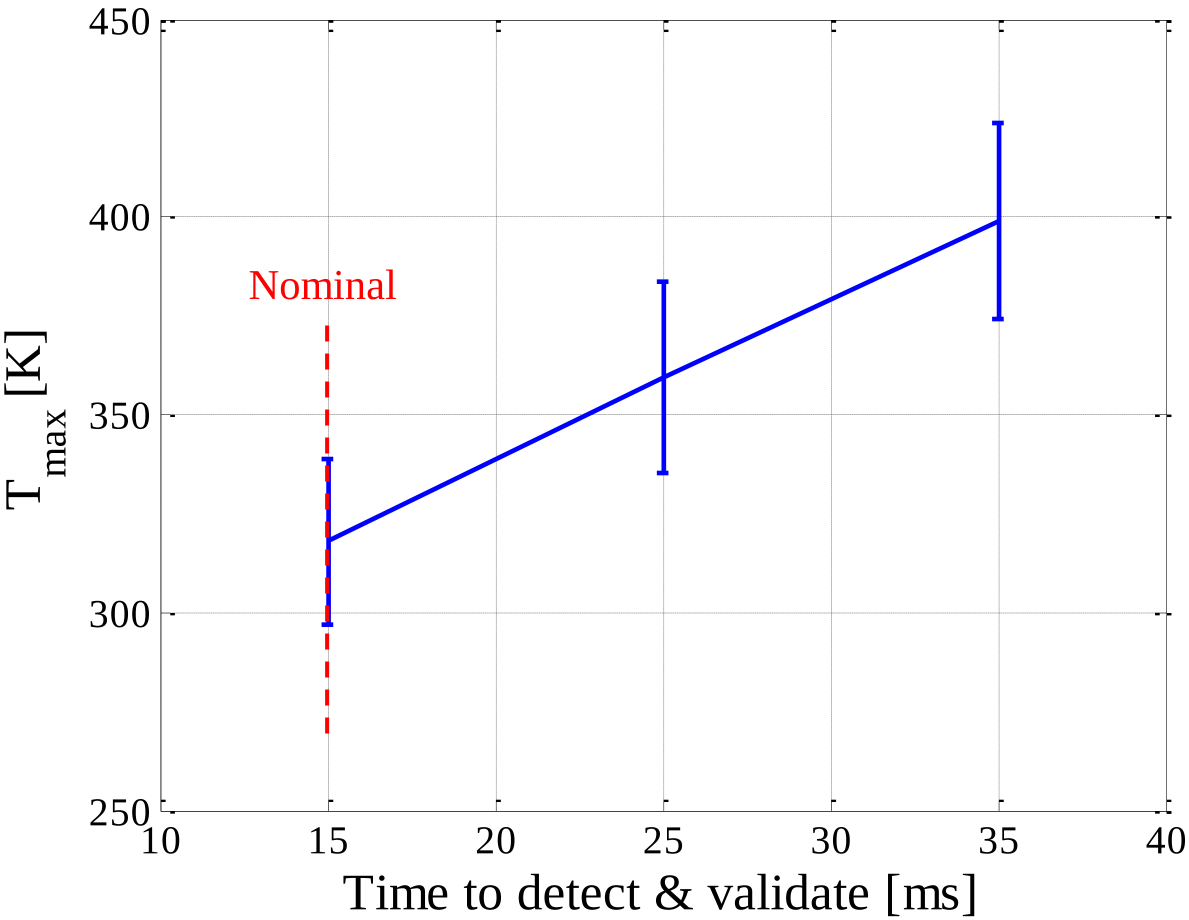
Time to detect and validate the quench

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.



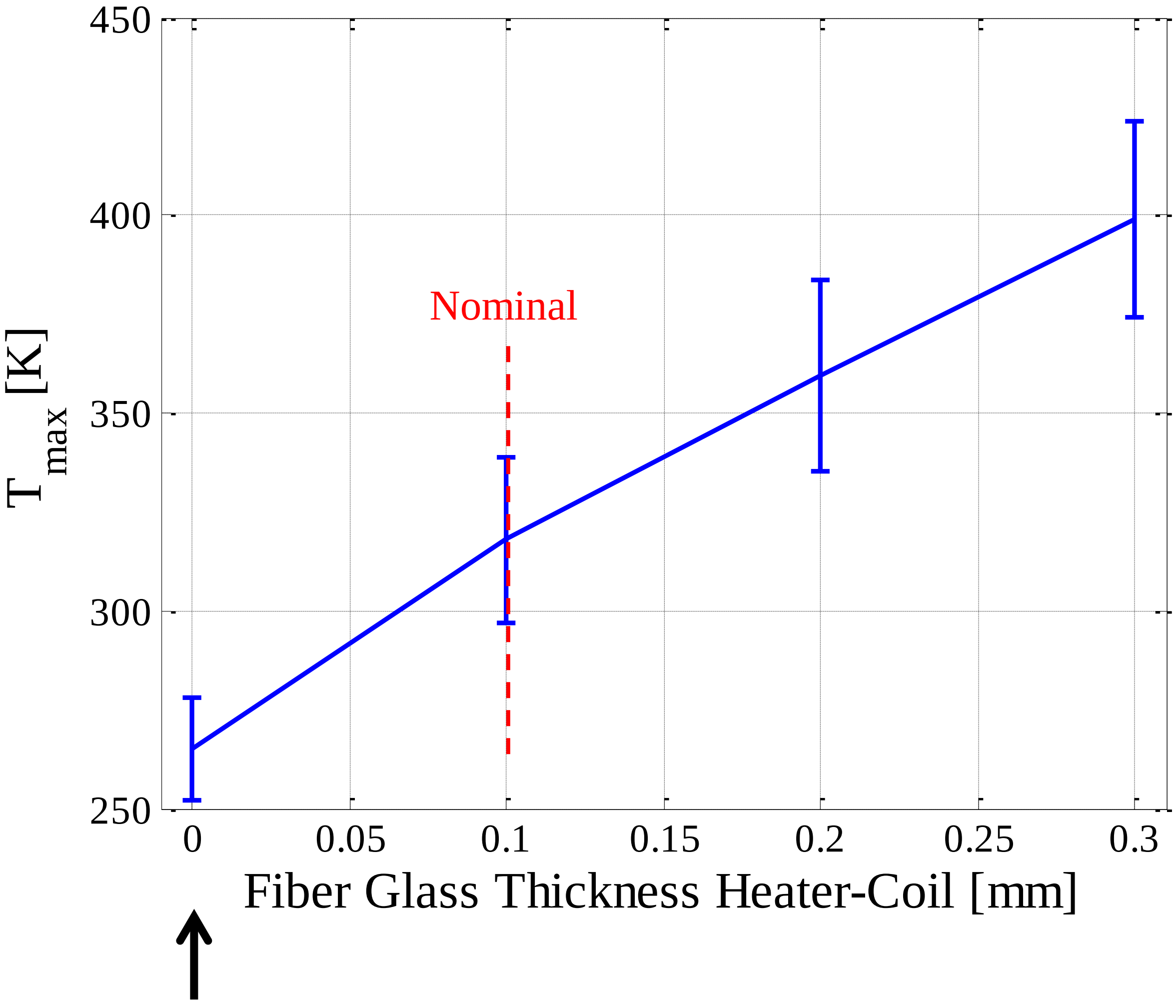
Insulation thickness from heater to coil

Minimize the thermal insulation between heater and coil is important:

$\Delta T_{max} \sim 45$ K for $\Delta th_{G10} \sim 0.1$ 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.

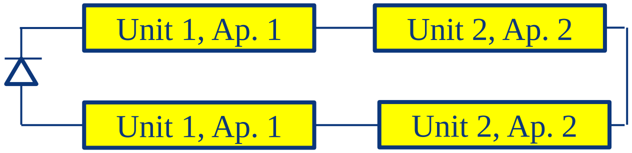
Activities are on-going to **impregnate the heaters** with the coil to improve the quench heaters performance.



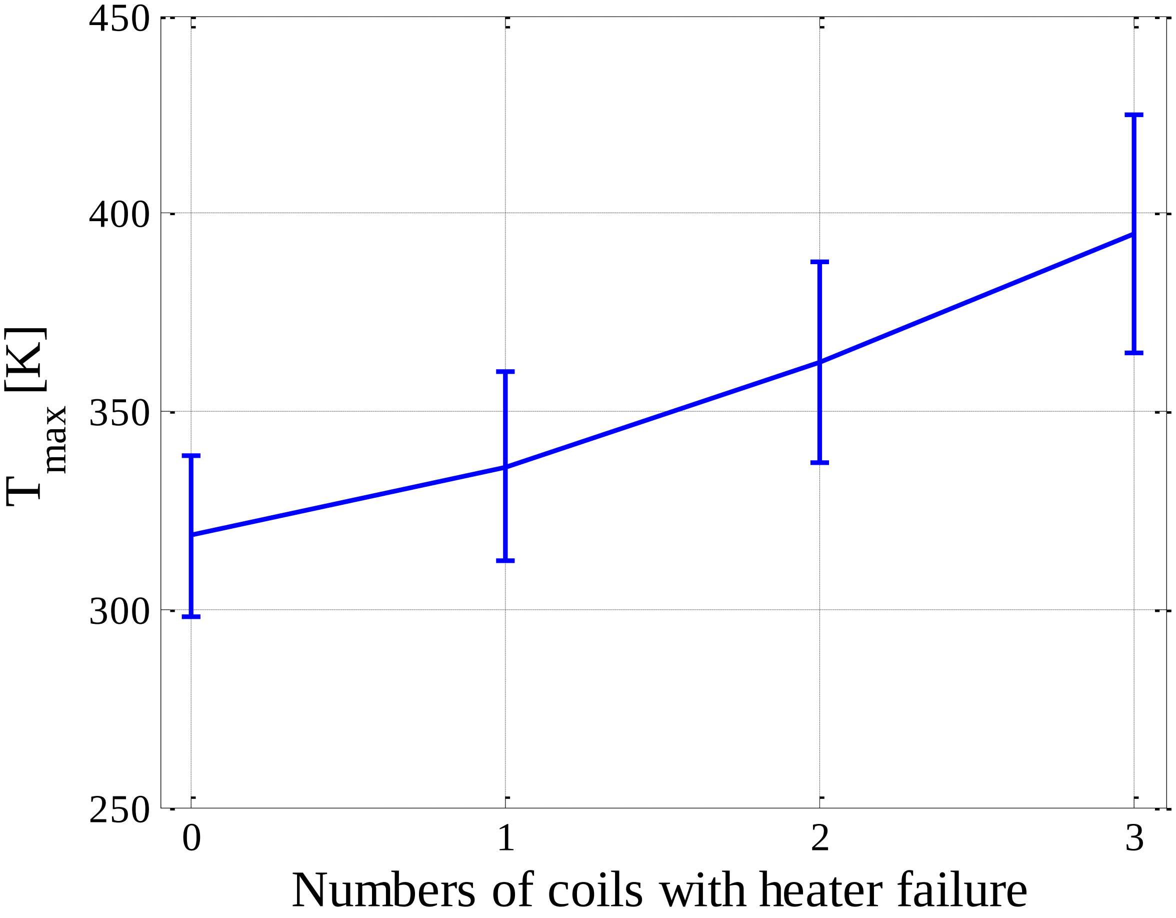
Heater impregnated with the coil

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

- Nb_3Sn magnets for the Hi-Luminosity upgrade are pushing the boundary of protection so it is essential to establish a good understanding of the dominating physics.
- Here we present an approach to model full magnet systems with reasonable computing resources by breaking the complex problem in simpler building blocks that are solved separately and then joined into a consistent solution.
- We still have uncertainties (geometry, properties, anisotropy) that we try to reduce/understand by comparing the model to experimental data.
- **Next steps:**
  - Study the effect of **AC loss** and other transient effects, such as change of the **apparent inductance** due to dI/dt
  - Resistive, inductive, capacitive effects in the circuit (non-linear components such as cold diodes, **internal voltages**)

Additional slides

REFERENCES

- MATERIAL PROPERTIES

  - [Man 2011] G. Manfreda, Review of ROXIE's Material Properties Database for Quench Simulation
  - [TD Note ----] TD Note 00-041, Material properties for quench simulation
  - [Dav ----] A. Davies, Material properties data for heat transfer modelling in Nb3Sn magnets

- EXPERIMENTAL DATA

  - [Mar 2012] M. Marchevsky. Quench Performance of HQ01, a 120 mm Bore LARP Quadrupole for the LHC Upgrade

- MODELLING

  - [Bot 2004] Power. User’s Guide. CryoSoft, Ver. 2.0; 2004
  - [Bot 2007] SuperMagnet. User’s Guide. CryoSoft, Ver. 1.0; 2007
  - [Bot 2010] Thea. User’s Guide. Cryosoft, Ver. 2.1; 2010
  - [Bot 2010] Heater. User’s Guide. Cryosoft, Ver. 2.0; 2010
  - [Bot 2013] L. Bottura, Magnet Quench 101, WAMSDO CERN 2013
  - [Gav 1992] A. Gavrilin, Cryogenics, 32 (1992), 390-393
  - [Rus 2008] S. Russenschuck. Field Computation for Accelerator Magnets
  - [Sch 2010] Numerical Calculation of Transient Field Effects in Quenching Superconducting Magnets. PhD Thesis

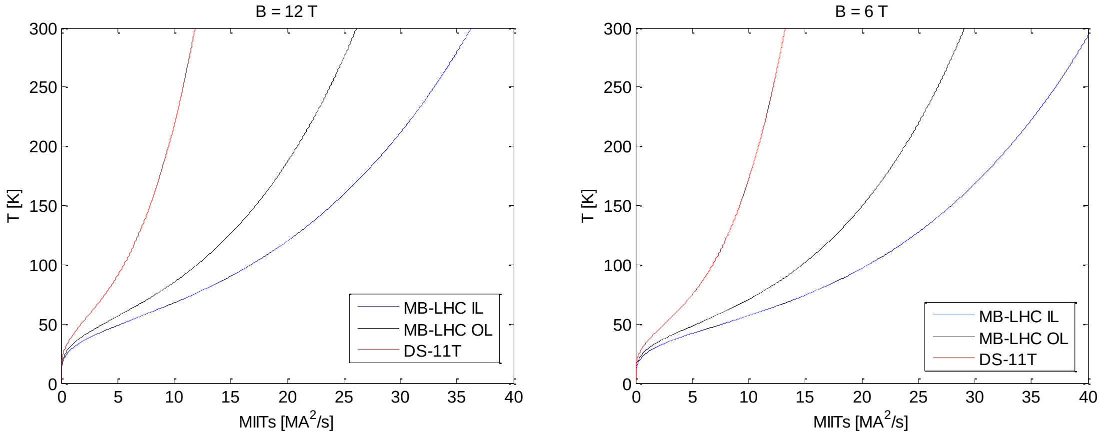
Nominal conductor parameters

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

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

	MB inner layer	MB 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
Insulation area, mm^2	4.83	4.70	3.25
Void area, mm^2	3.75	2.03	4.00

MIITs vs T_{max} under for two different field levels (12T (left) and 6T (right)) using NIST material properties database. Heat capacity of insulation not consider for the MIITs calculation



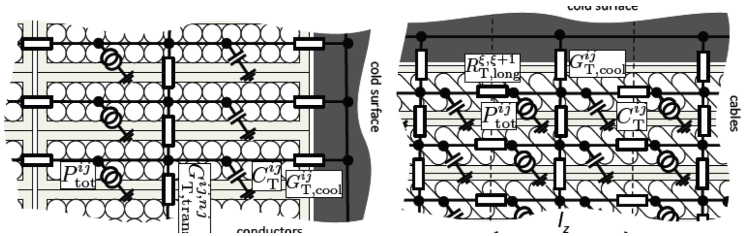
$$MIITs = A_{total} A_{Cu} \int_{T_0}^{T_\infty} \frac{C_p^{ave}(T)}{\rho_{Cu}(T)} dT \qquad C_p^{ave}(T) = \frac{A_{Cu} \cdot C_p^{Cu} + A_{SC} \cdot C_p^{SC}}{A_{Cu} + A_{SC}}$$

ROXIE vs SUPERMAGNET

ROXIE QUENCH MODULE [Sch 2010]

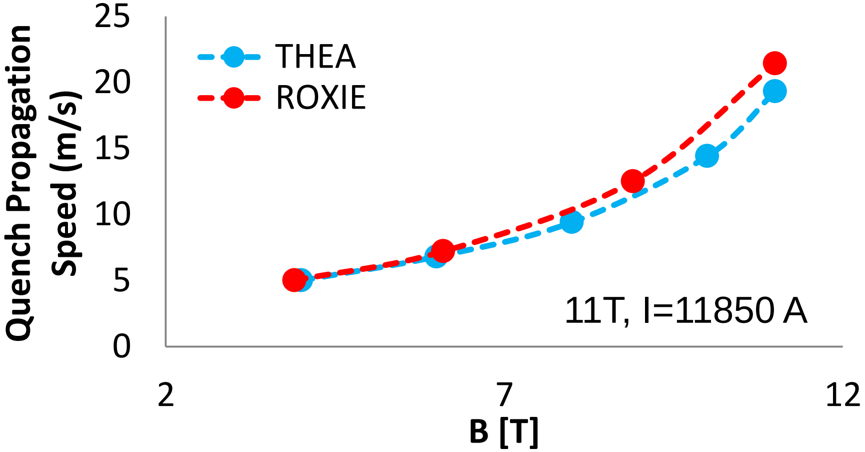
Couples magnetic, electrical and thermal.

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}!)



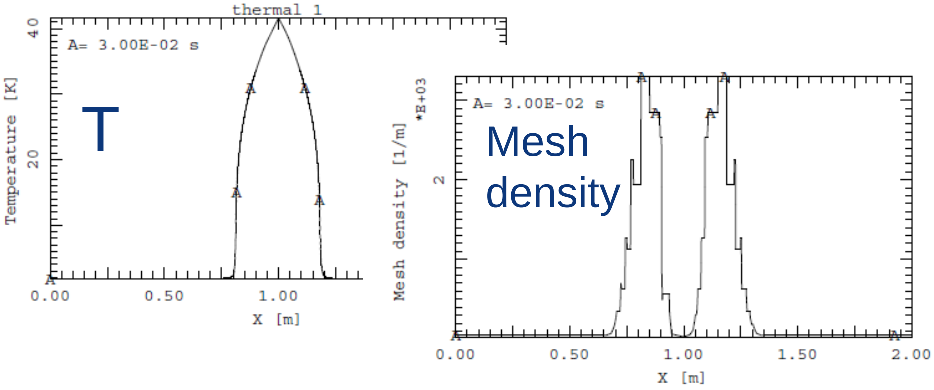
SUPERMAGNET [Bot 2007]

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]__

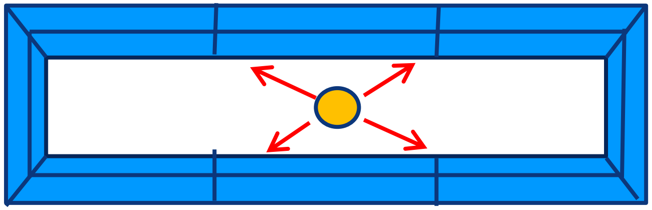
FE heat conduction

__POWER [Bot 2004]__

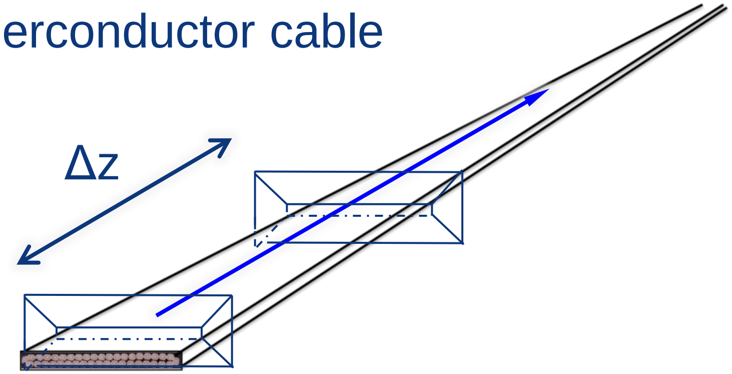
Electric network simulation of magnetic systems

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

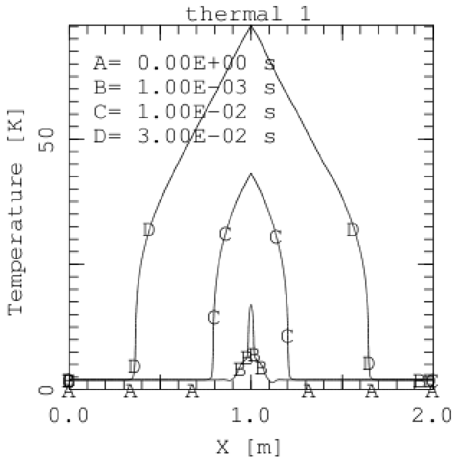


2D quadrilateral elements with 4 nodes and first order shape function

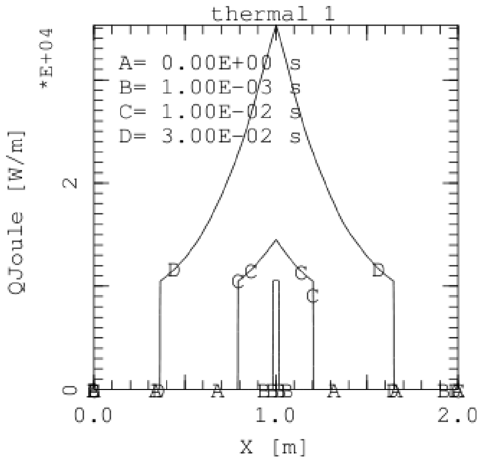


Explicit coupling → conditionally stable. Small heat capacity and large thermal conductance requires small time steps for the stability of the coupling

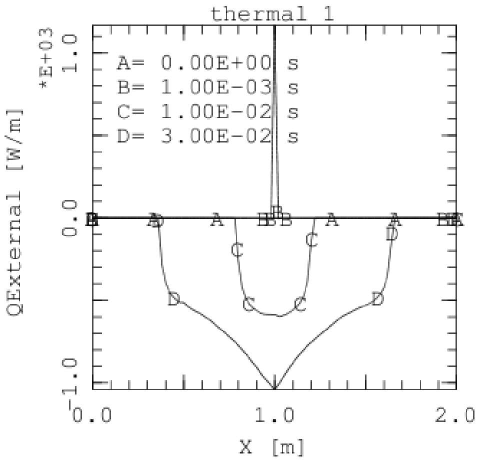
Example: HEATER : Δz=20 mm t_{step}=[10^{-6} 10^{-3}] s
THEA : Δz=0.3mm-100mm t_{step}=[10^{-7} 10^{-4}] s



Temperature in the SC



Joule heating

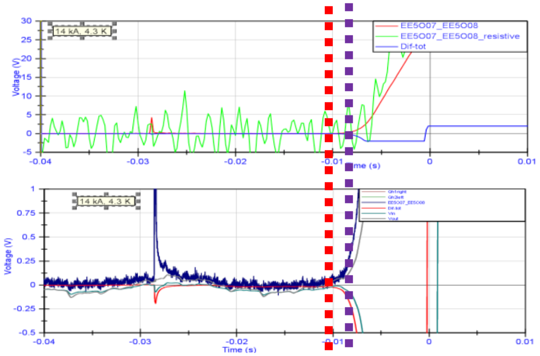


Heat flow from/to the insulation

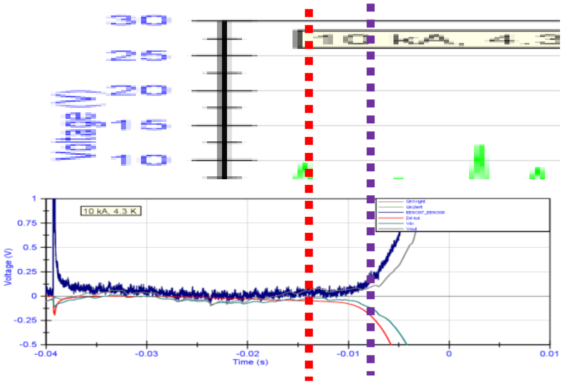
Heater efficiency

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



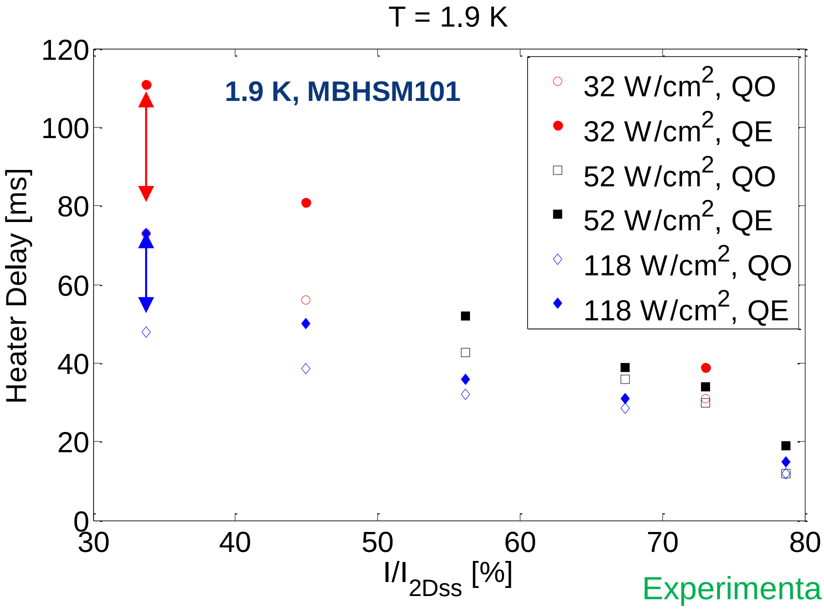
18 ms 21ms



28 ms 35 ms

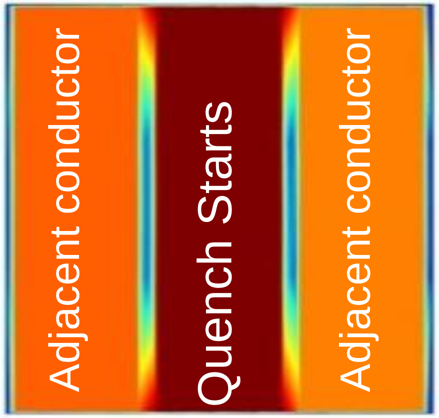
Remarks:

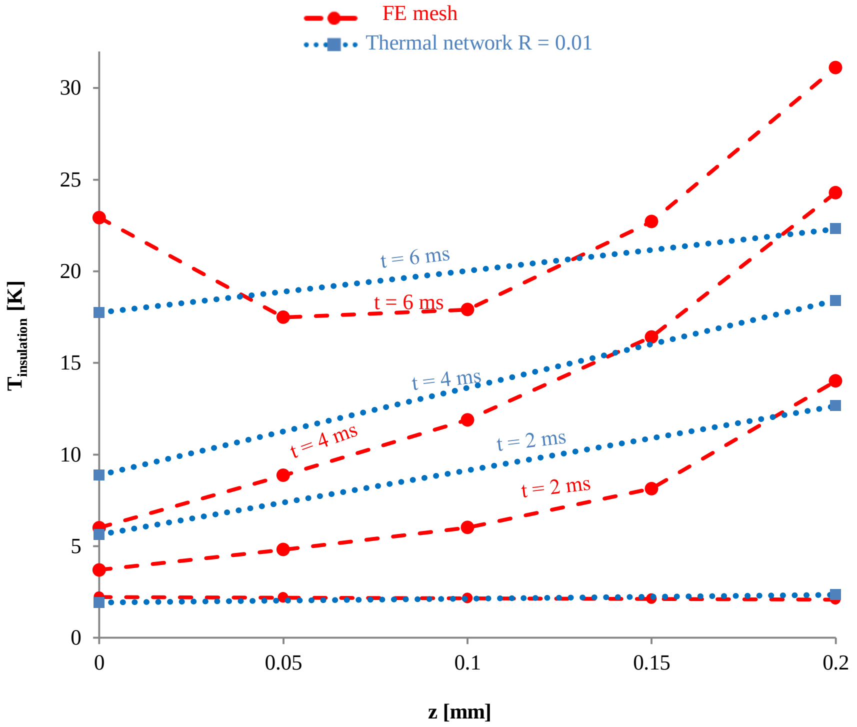
- At high current, the difference between **QO**-**QE** is very small, but at lower current there is an important offset to keep into account.
- The difference between quench onset and quench efficient increases for low heater power density.



Experimental data from G. Willering

Network model vs. hybrid model

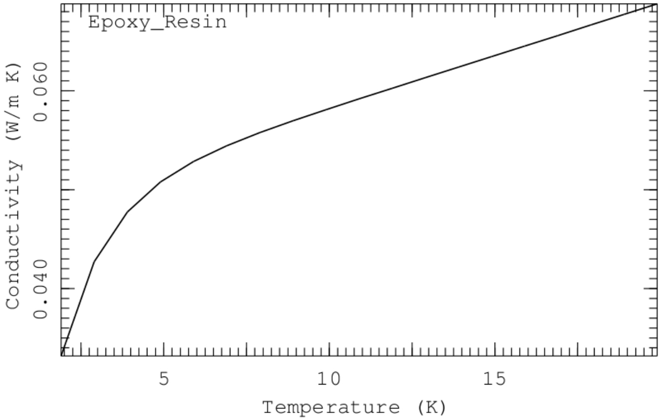




Thermal resistance

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

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



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

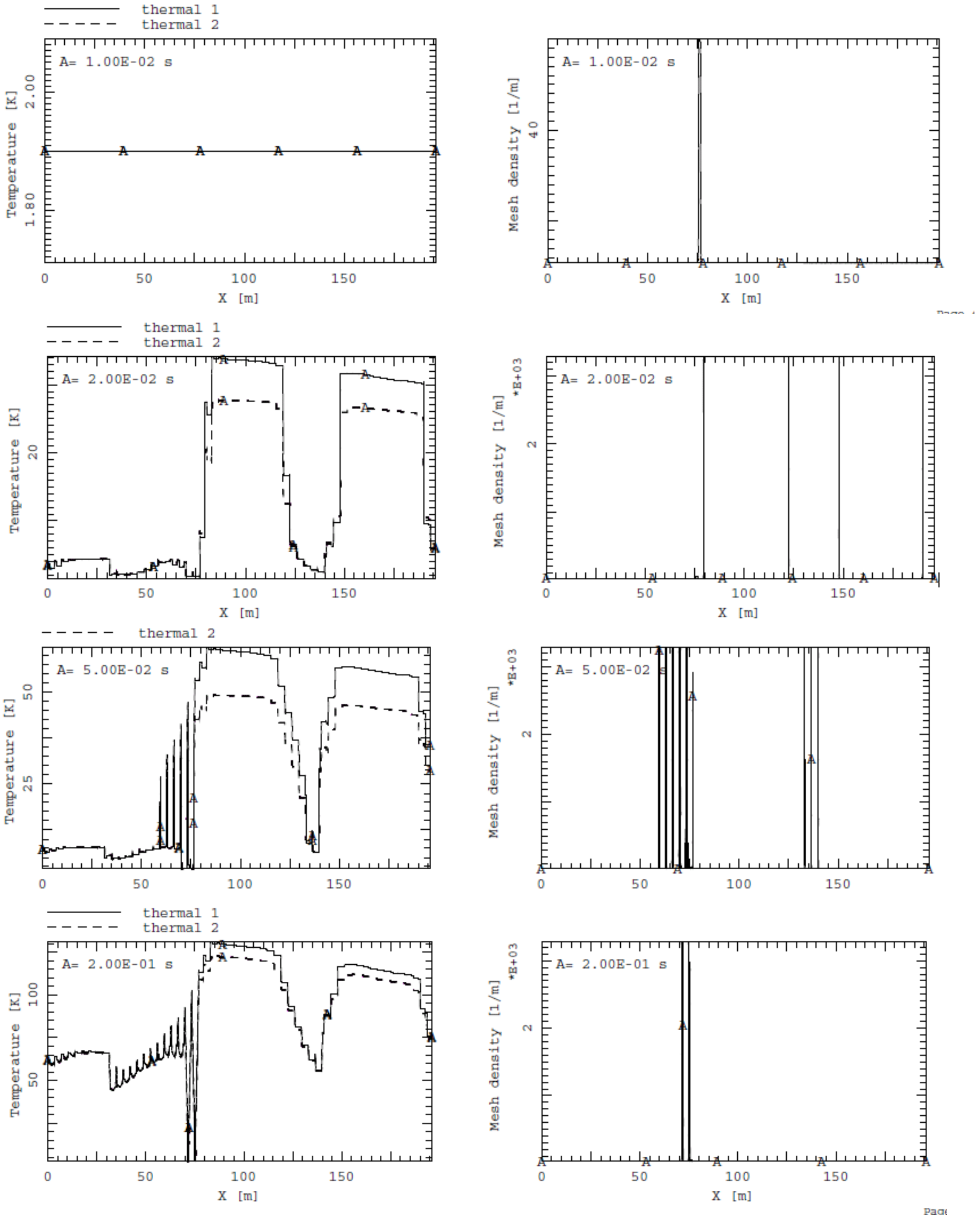
k = 0.05 W/mK, tins = 0.1 mm

- R_{th} = 0.03 mK/W

k = 0.05 W/mK, tins = 0.01 mm

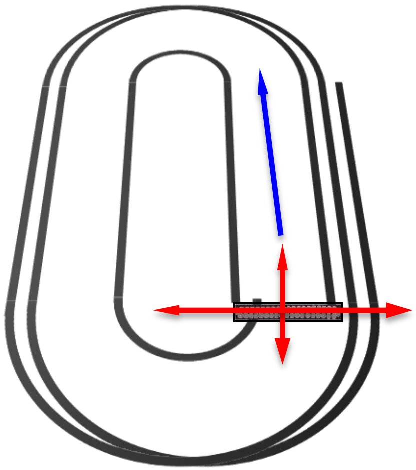
- R_{th} = 0.003 mK/W

Temperature profile & mesh density H = 100, coil 106



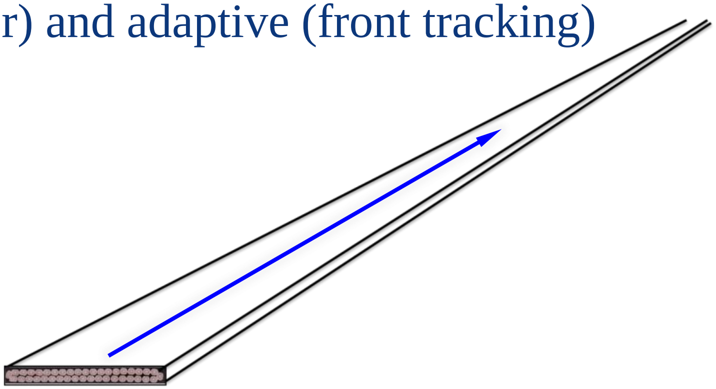
Modelling: length scale

2 Principal directions:
longitudinal and **transverse**



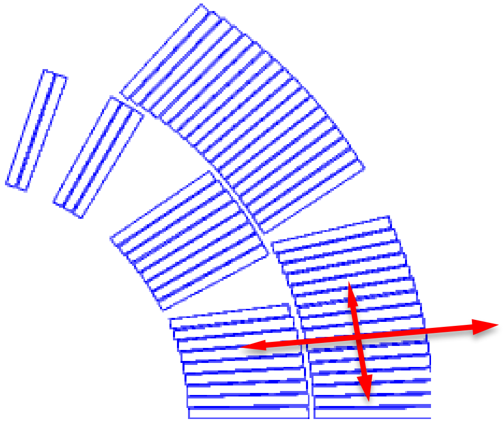
Longitudinal → length scale: hundreds of m

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

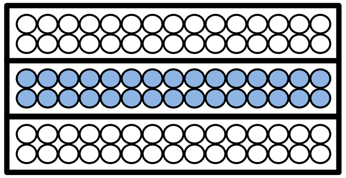


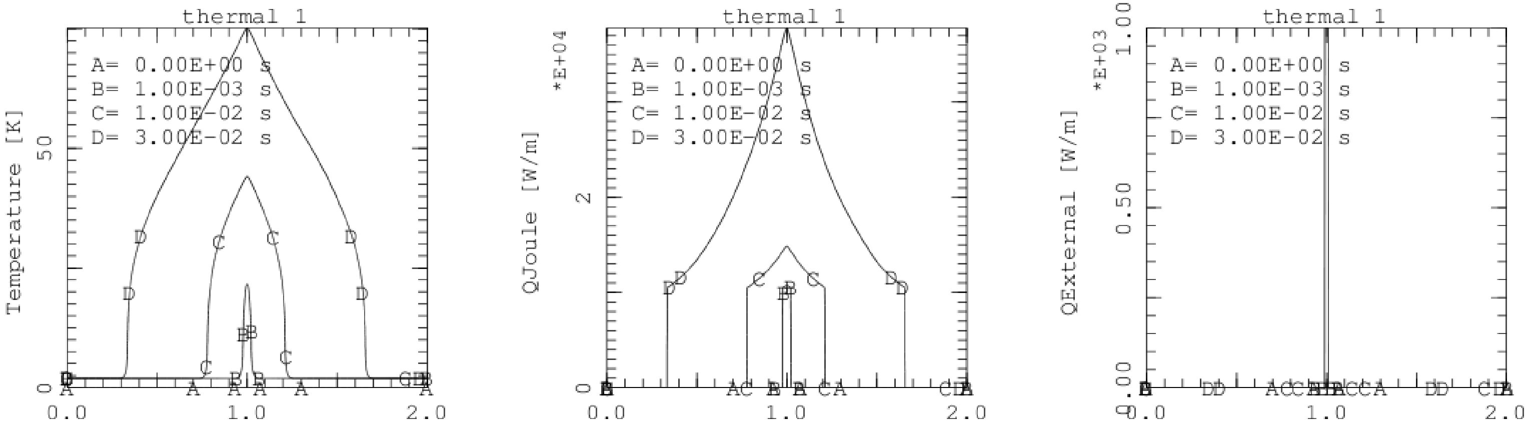
Transverse → length scale: mm

Heat diffusion across the insulation

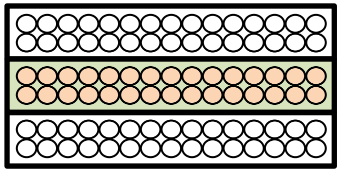


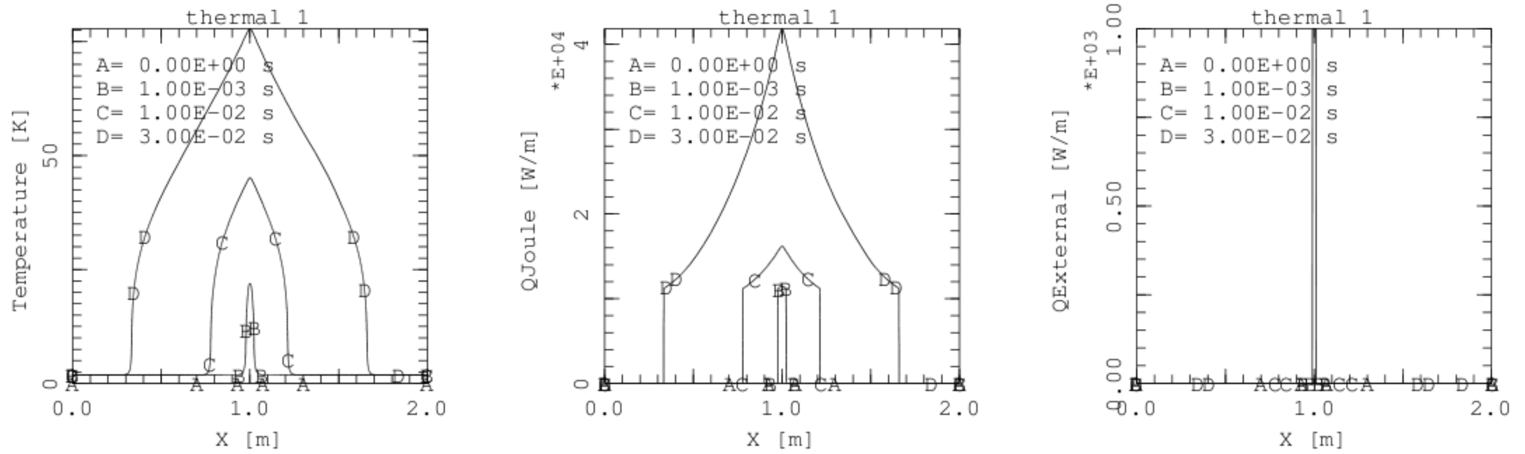
Conductor only



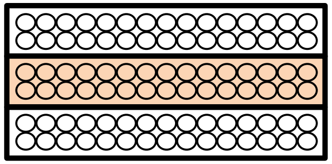


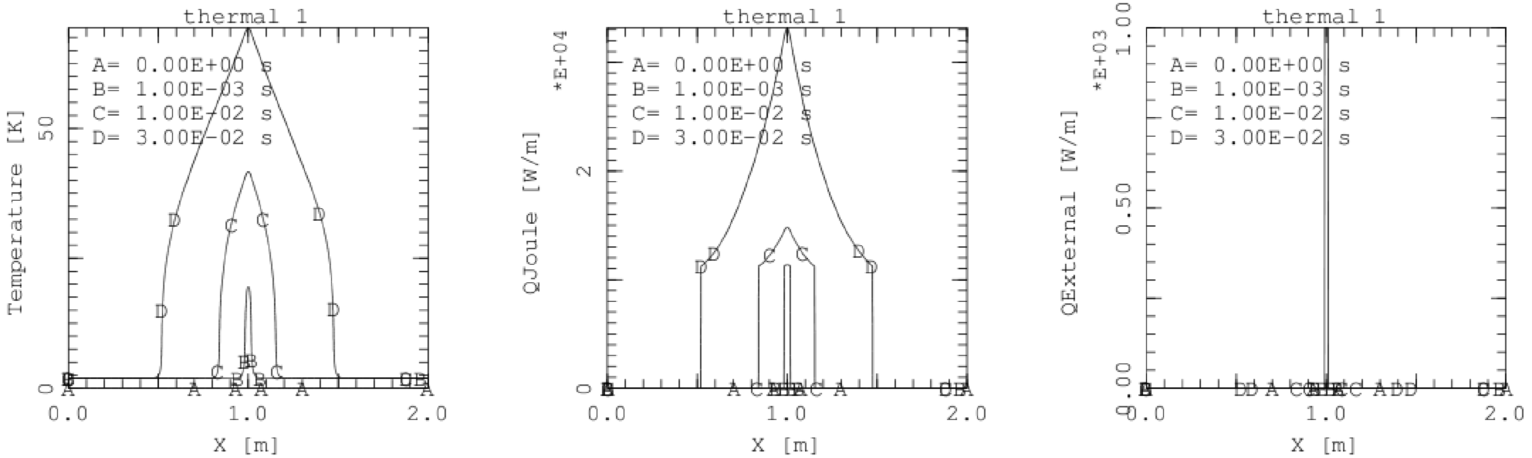
Conductor /insulation



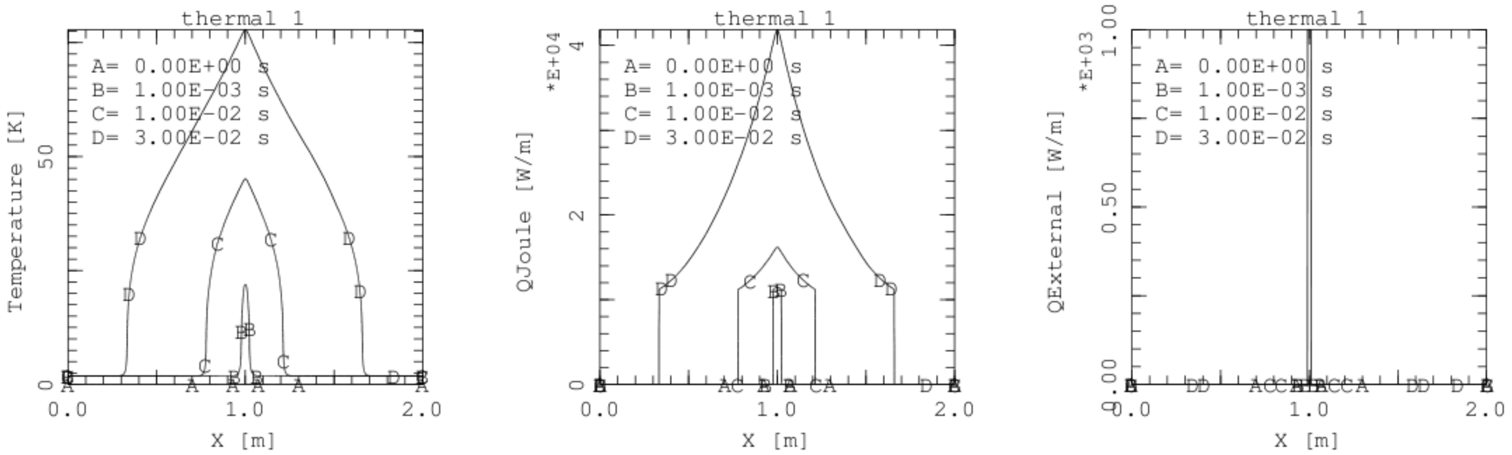


Conductor +insulation

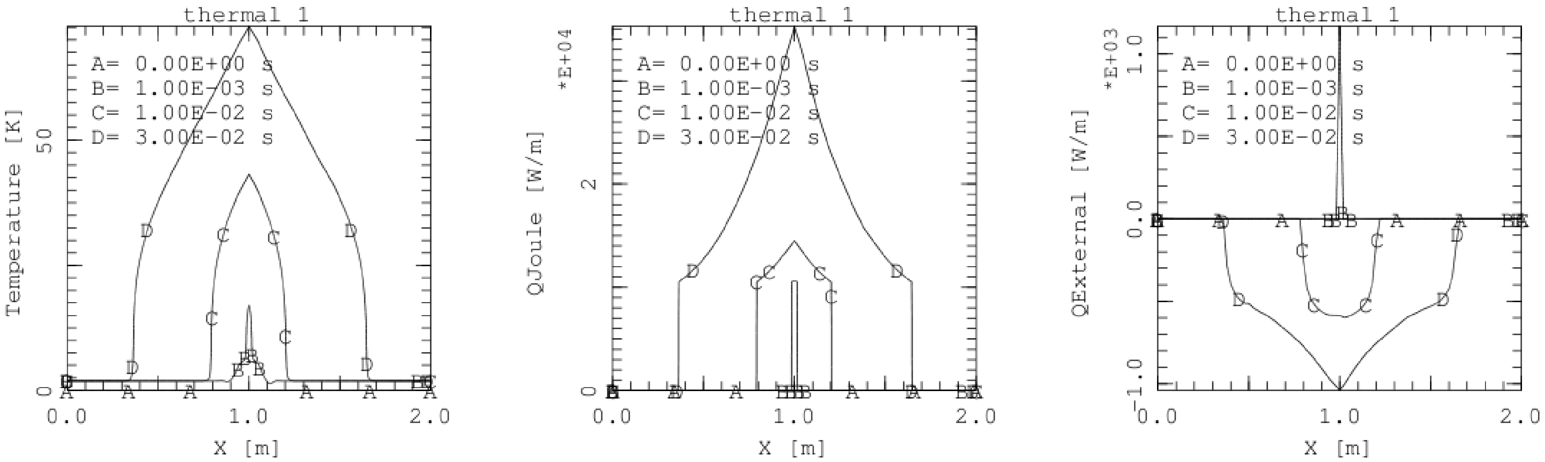




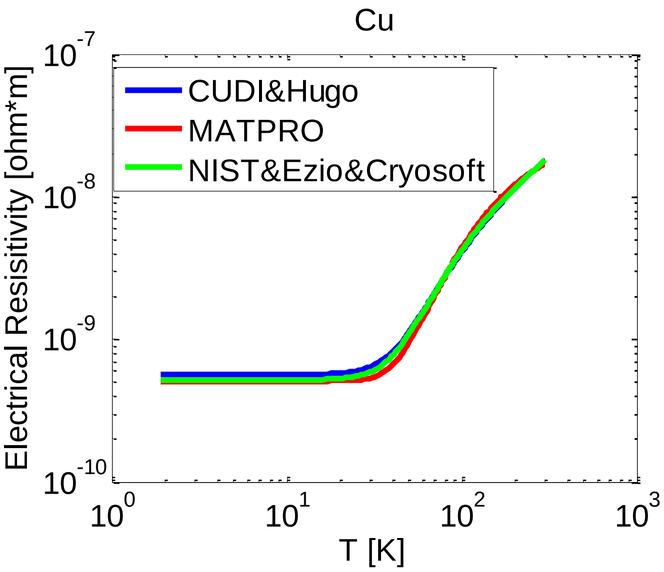
Network

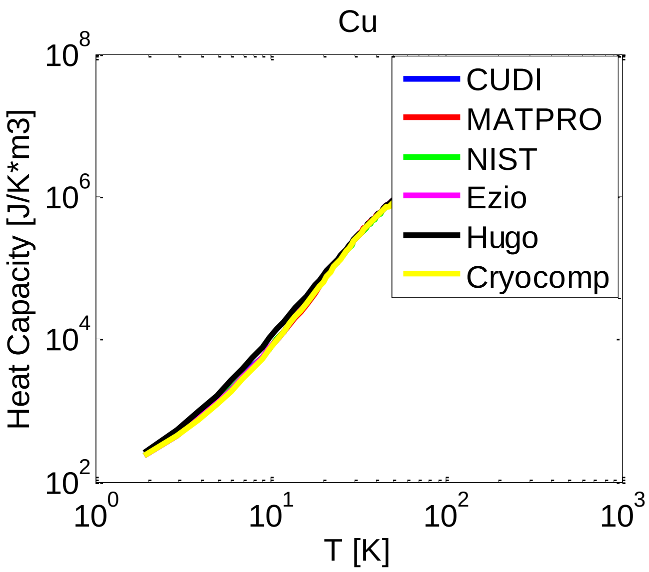


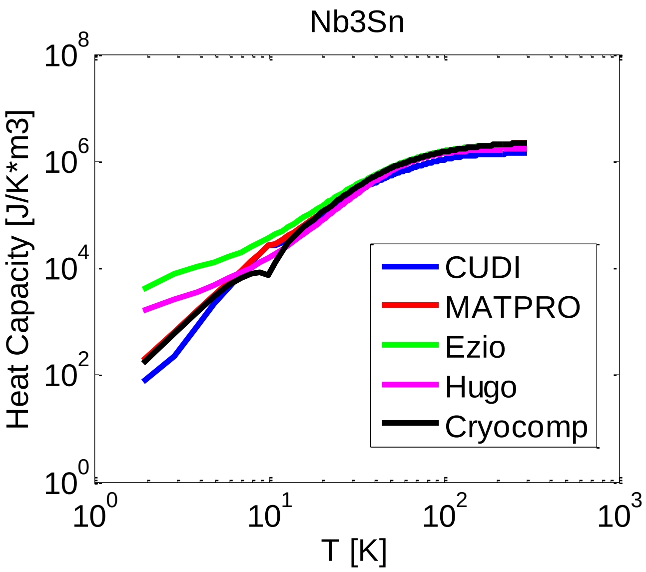
FE mesh

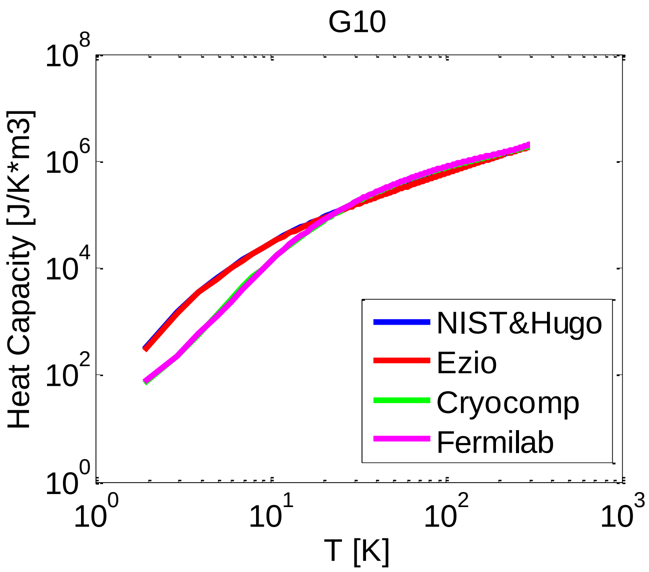


Material Properties

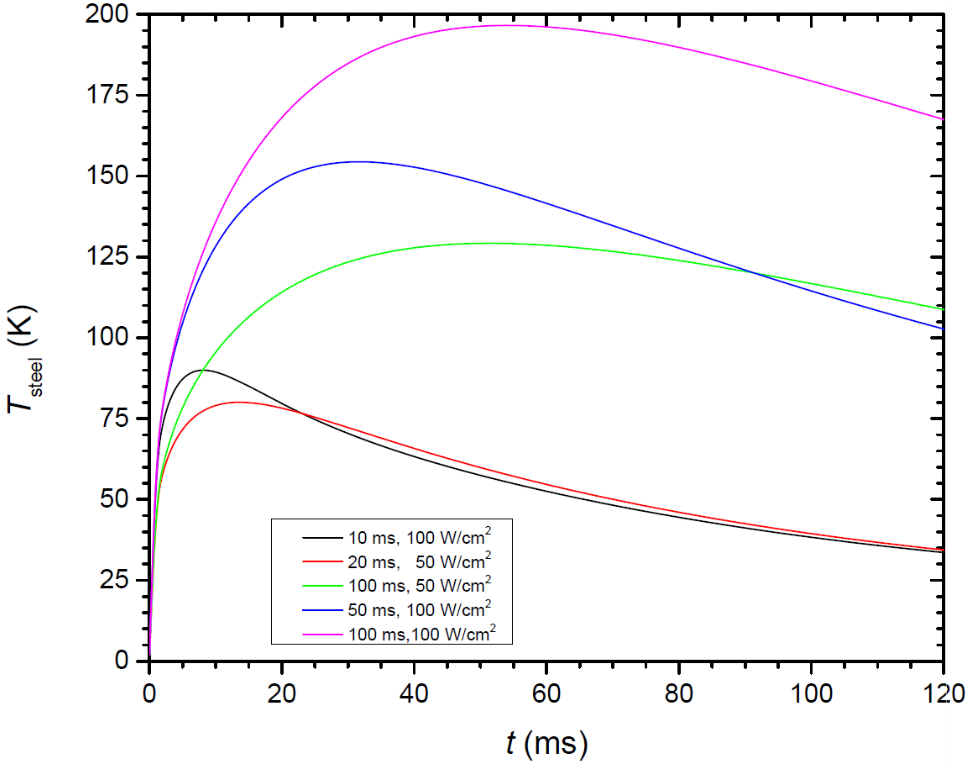


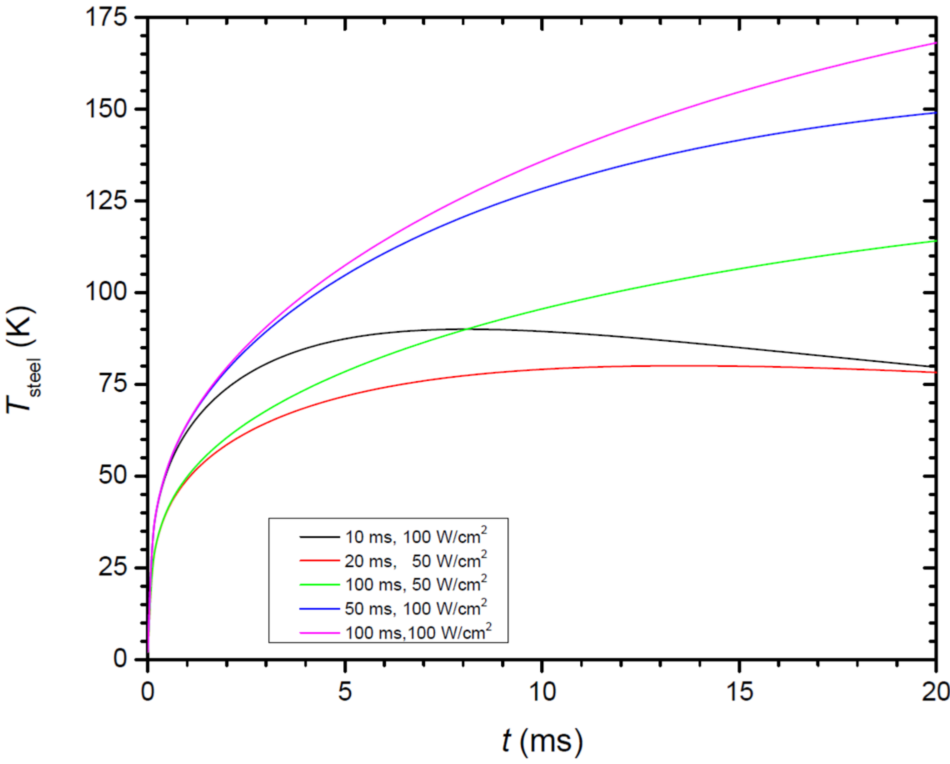






QH temperature rise





Training quench SMC – 11T