Analytical Method for the Prediction of Quench Initiation and Development in Accelerator Magnets

CHATS On Applied Superconductivity Conference

Sendai, Japan. 11th December, 2017

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

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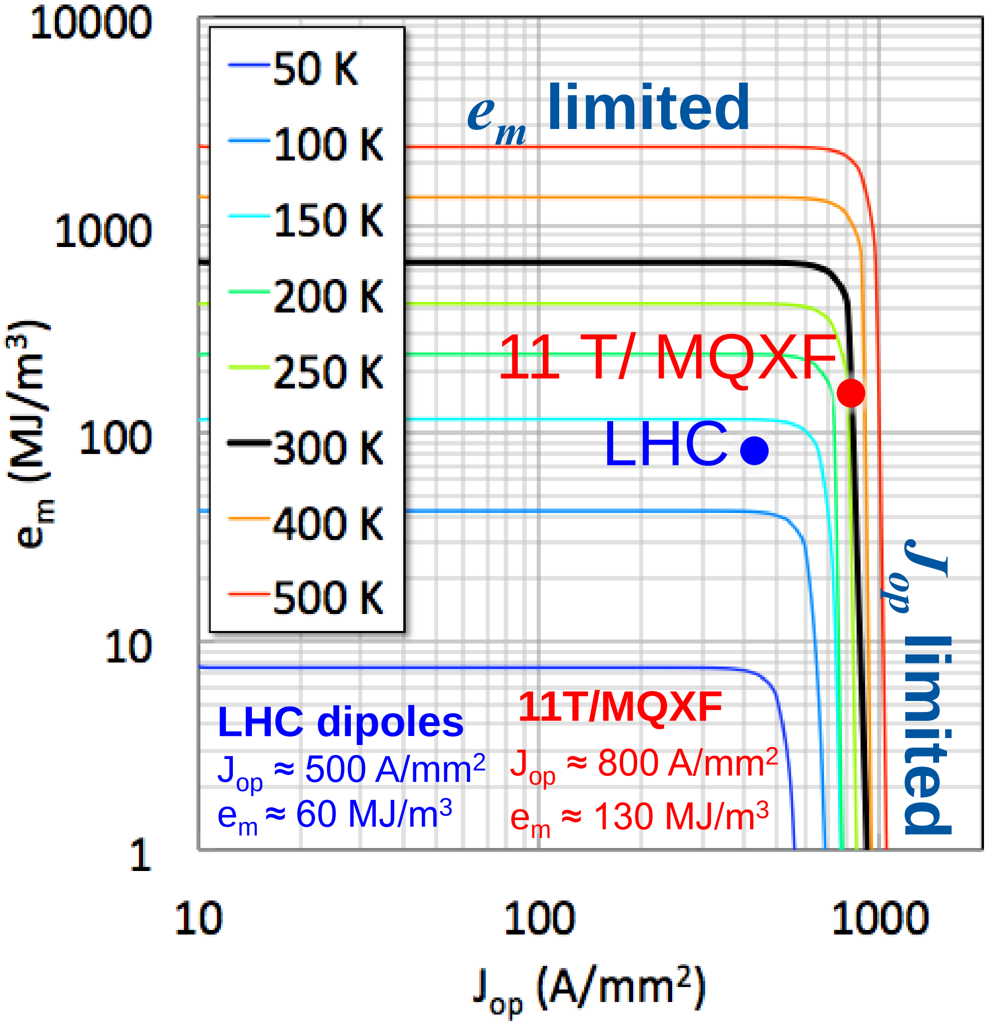
- New accelerator magnets based on Nb$_3$Sn are pushing the boundary of protection
- Accurate simulation of quench transients in these magnets is crucial to the design choices, definition of priority R&D and to prove that the magnets are fit for operation
- We have today large uncertainties in the simulation 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 !!!

https://indico.cern.ch/event/372812/contributions/1792222/

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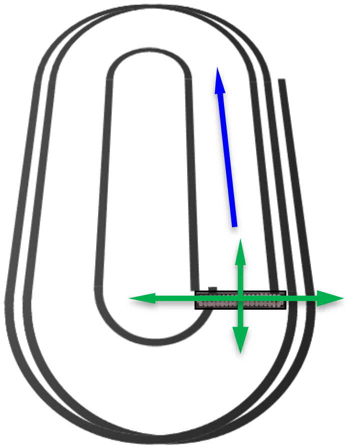
- We proposed and validated an approach to model full magnet systems with reasonable computing resources by breaking the complex problem in simpler building blocks that are solved separately and then joined into a consistent solution.

SUPERMAGNET (THEA-POWER) model

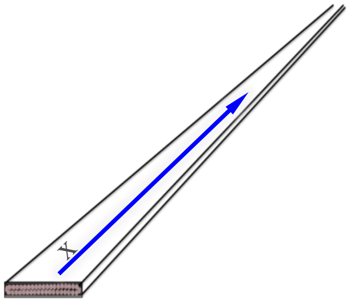
Two principal directions:

1. Longitudinal
Length scale is hundreds of m

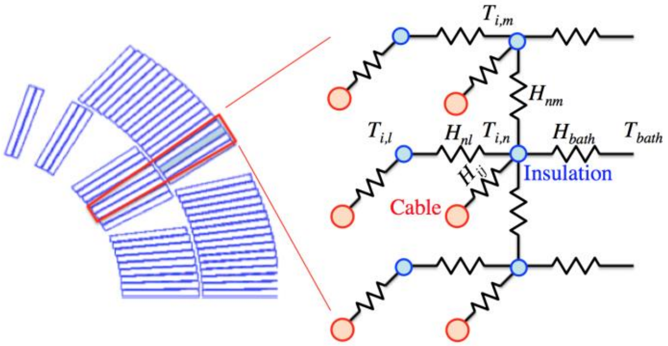
2. Transverse
Length scale is tenths of mm



Longitudinal →



Transverse→



In 2017…

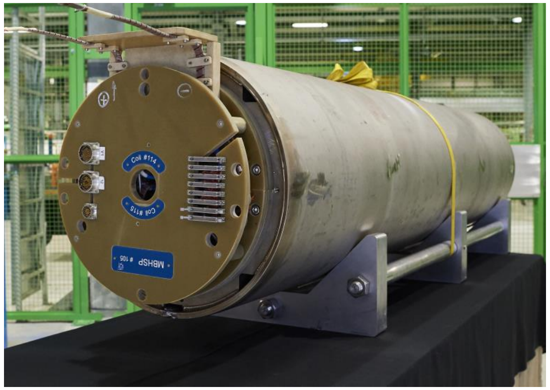
- We have built and tested at CERN two MQXF short models, six 11 T single apertures and two 11 T double aperture magnets.
  - Database to identify basic scaling relations and derive a simplified method to predict quench initiation and development in accelerator magnets.

MQXF

Inner triplet quadrupoles

11 T

Dipoles for the DS Region



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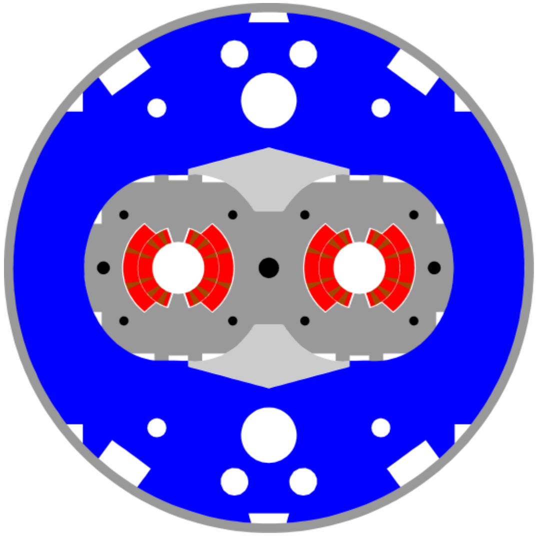
Motivation

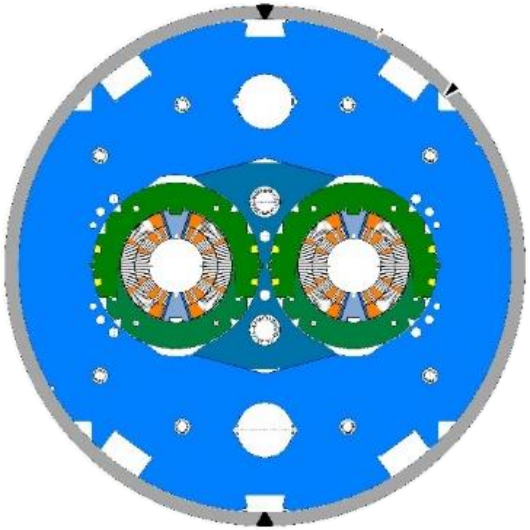
Due to the high stored energy density (130 MJ/m^3) and the low copper stabilizer fraction (55 %), quench protection in HL-LHC Nb_3Sn magnets is particularly challenging.

LHC-MB



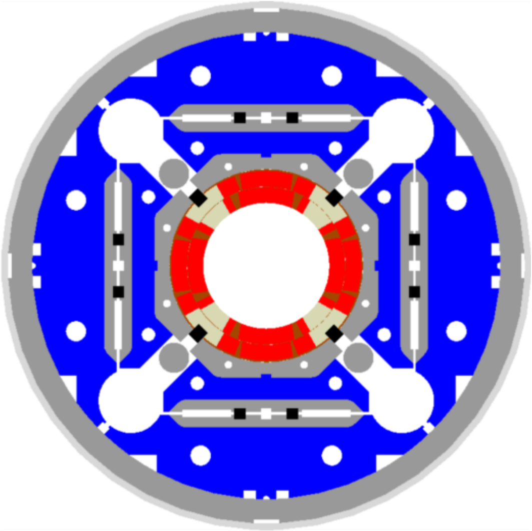
- $B_p(I_{nom})$= 8.6 T
- $J_{overall}(I_{nom})$= 356/442 A/mm^2
- $J_{cu}(I_{nom})$= 763/932 A/mm^2
- e_m (I_{nom})= 71 MJ/m^3

HL-LHC 11 T



- $B_p(I_{nom})$= 11.8 T
- $J_{overall}(I_{nom})$= 523 A/mm^2
- $J_{cu}(I_{nom})$= 1439 A/mm^2
- $e_m(I_{nom})$= 130 MJ/m^3

HL-LHC MQXF



- $B_p(I_{nom})$= 11.4 T
- $J_{overall}(I_{nom})$= 469 A/mm^2
- $J_{cu}(I_{nom})$= 1330 A/mm^2
- $e_m(I_{nom})$= 129 MJ/m^3

The challenge

Beam energy

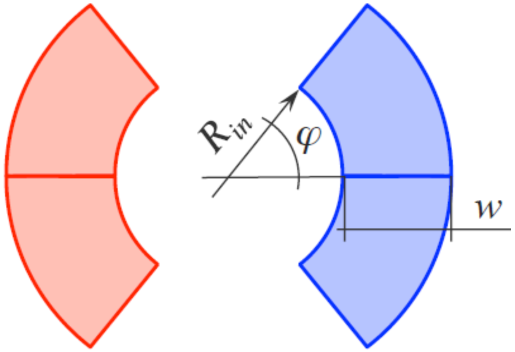
Bending radius

$$E\ [GeV] = 0.3\ B[T]\ \rho[m]$$

Dipole field

- Our aim: largest feasible and economic B to reduce the accelerator radius
- But large field means…
  - Large current density (J) , since we want to keep them as compact (cheap) as possible

$$B = \frac{2\mu_0}{\pi}\ J\, w\, sin(\varphi)$$



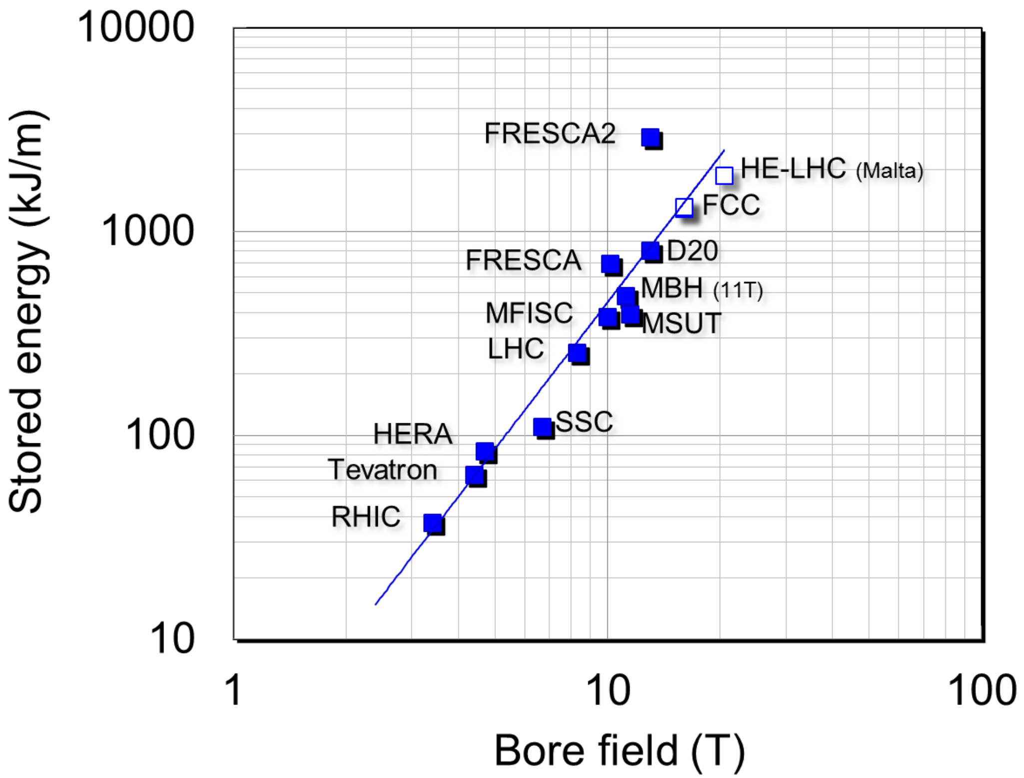
  - Large stored energy

$$\frac{E}{l} = \frac{\pi B^2 R_{in}^2}{\mu_0}\left[1 + \frac{2}{3}\frac{w}{R_{in}} + \frac{1}{6}\left(\frac{w}{R_{in}}\right)^2\right]$$

The challenge

- High field magnets get more and more challenging to protect if we want to keep them compact (high J).
- What are the actual limits?

$$\frac{E}{l} = \frac{\pi B^2 R_{in}^2}{\mu_0}\left[1 + \frac{2}{3}\frac{w}{R_{in}} + \frac{1}{6}\left(\frac{w}{R_{in}}\right)^2\right]$$



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Protection of accelerator magnets

Two limiting cases in terms of magnet protection strategy:

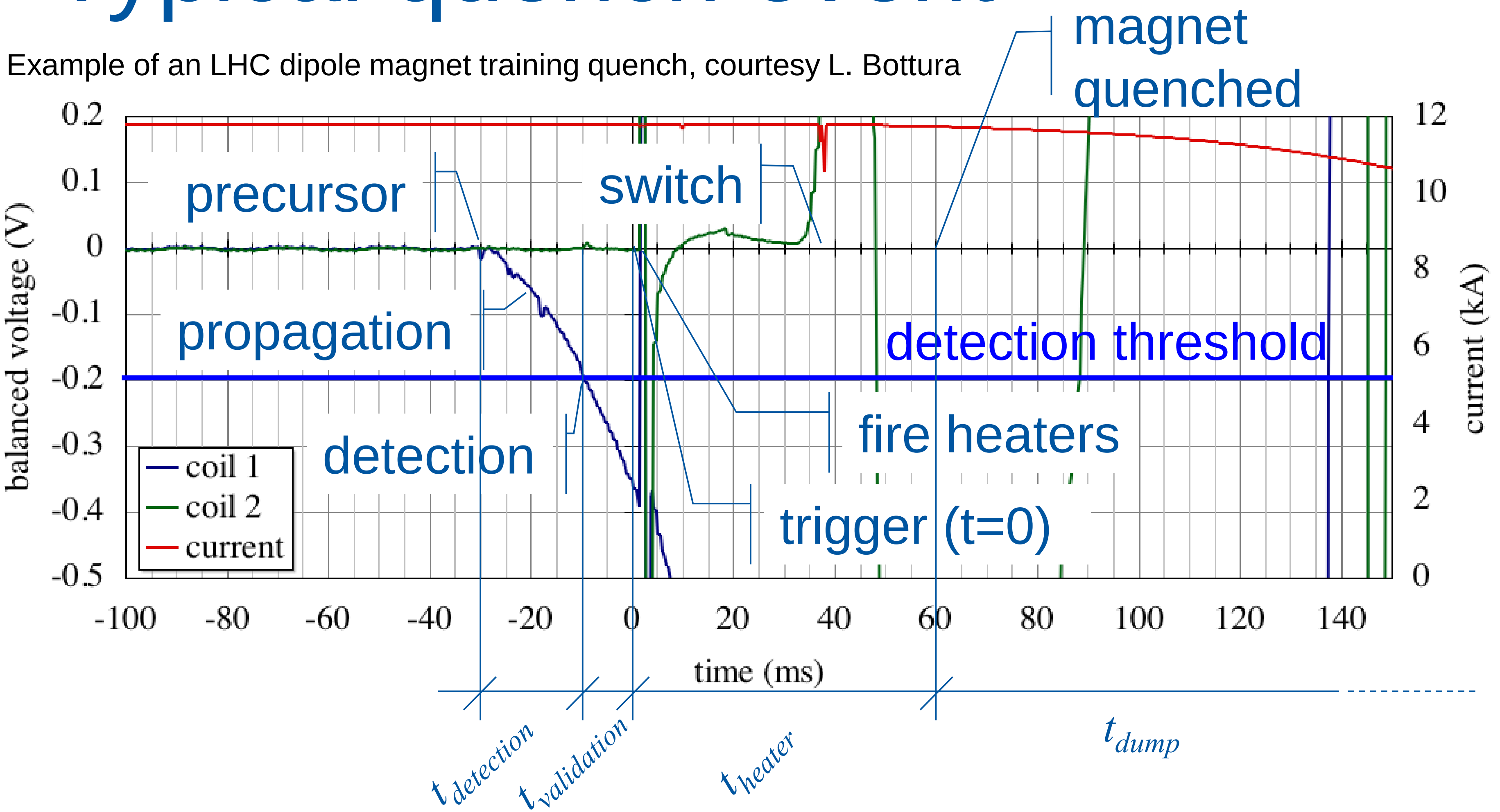
1. **External-dump**: The magnet is dumped externally on a large resistance ($R_{dump} >> R_{quench}$) as soon as the quench is detected (e.g. ITER)

2. **Self-dump:** The circuit is on a short circuit and is dumped on its internal resistance ($R_{dump} = 0$) (e.g. LHC). Actually, external dump is not an option for a chain of accelerator magnets.
   Typical $J_{Cu} \approx 1000\ldots1250$ (A/mm^2)
   Meaning $dT/dt \approx 1000\ldots2000$ (K/s)
   We need to dump quickly! $\tau(300\ \text{K}) \approx 0.15\ldots0.3$ (s)
   $I_{op} \approx 15$ (kA)
   $E/l \approx 1000$ (kJ/m)

$$\frac{\mathbf{V}}{\mathbf{l}} \approx \frac{\mathbf{2E}/_{\mathbf{l}}}{\boldsymbol{\tau}\mathbf{I_{op}}} = \mathbf{500\ldots1000\ V/m}$$

Typical quench event

Example of an LHC dipole magnet training quench, courtesy L. Bottura



magnet quenched

precursor

switch

propagation

detection threshold

detection

fire heaters

trigger (t=0)

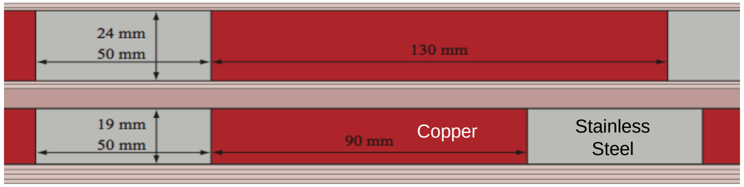
$$t_{quench} \approx t_{detection} + t_{validation} + t_{heater} + f\,t_{dump}$$

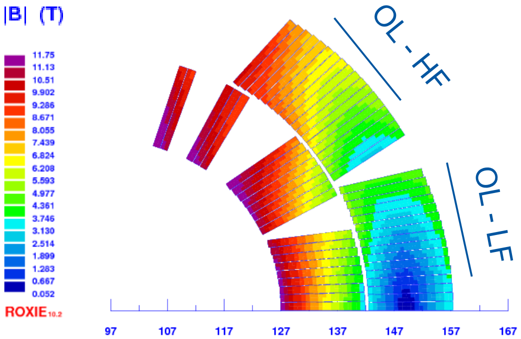
Quench heater based protection

Principle: temperature rise in the conductor through the heating of metal strips attached to the coil.

11 T Heater Lay-Out (only outer layer heaters)

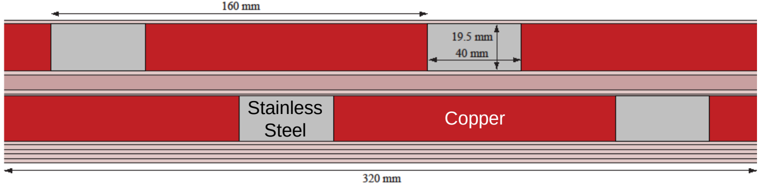
Outer layer heater design



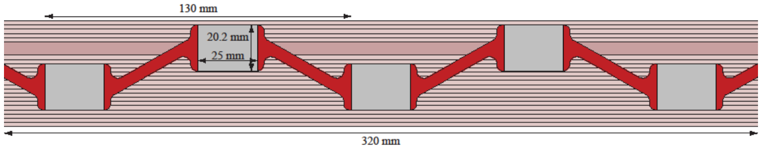


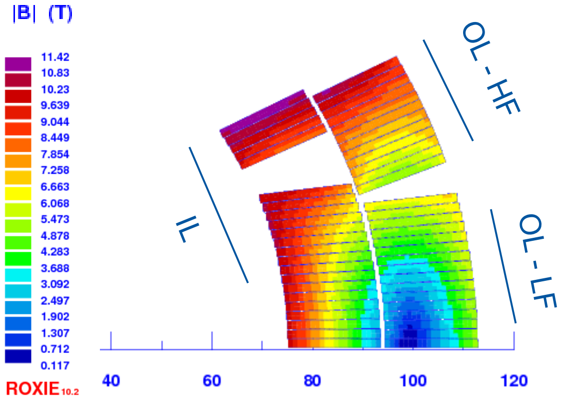
MQXF Heater Lay-Out (heater in the inner and outer layers)

Outer layer heater design



Inner layer heater design





Protection limit

- Ideal case: all magnet is quenched at the quench start

Assuming adiabatic conditions

$$\frac{E}{V} = \int_{T_{op}}^{T} \overline{C}(T)dT$$

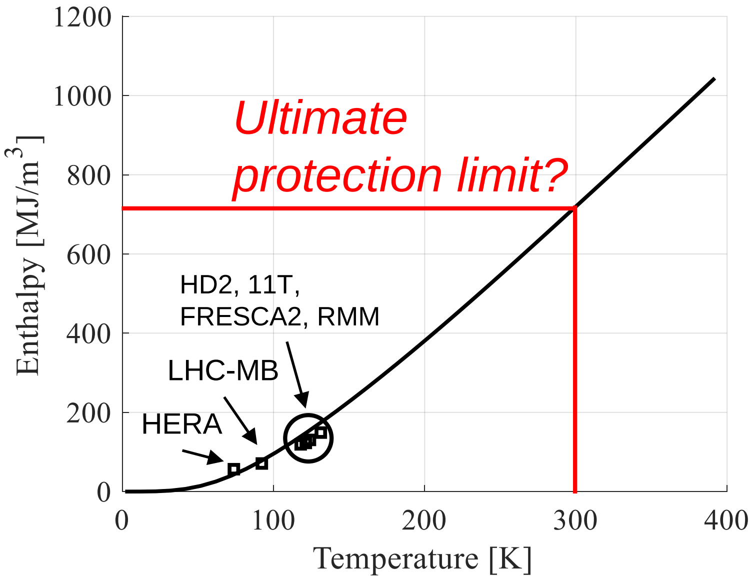
$$\frac{E}{V}$$

Magnet stored energy per unit volume.

$$\overline{C}(T) = \sum_i f_i \rho_i \, c_i$$

Volumetric heat capacity of the cable

i = copper, superconductor and insulation.



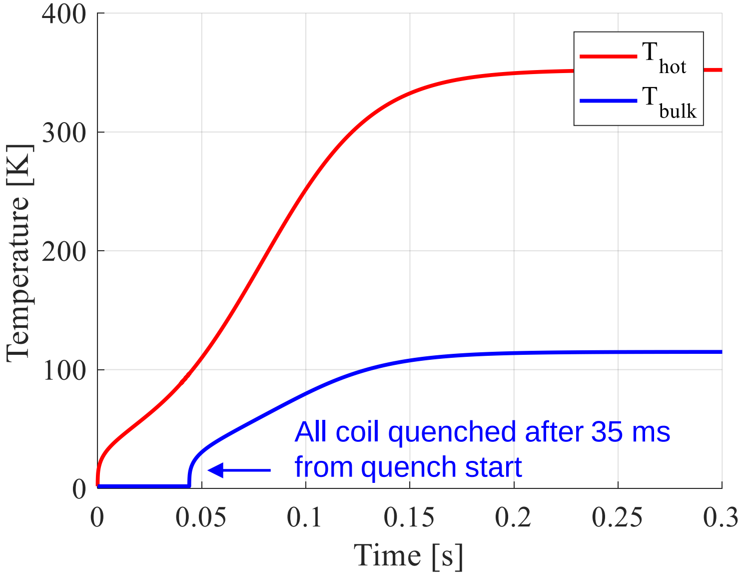
Enthalpy of the strand volume (neglecting the insulation)

- Reality: we need time to detect, validate and quench the magnet.

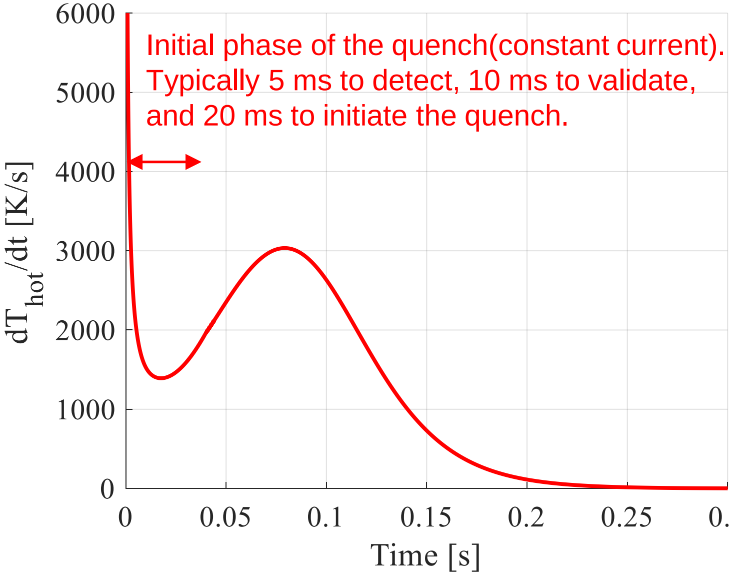
Detection and quench initiation

- The time needed to detect, validate and quench the coil is very expensive in terms of temperature rise. And here is where current density become critical!

$$\frac{dT_{hot}}{dt} = \frac{I^2}{(A_{Cu} + A_{SC} + A_{ins}) \cdot A_{Cu} \cdot \Gamma(T,B)} \qquad \Gamma(T,B) = \frac{\overline{C}(T)}{\eta_{Cu}(T,B)}$$



All coil quenched after 35 ms from quench start



Initial phase of the quench(constant current). Typically 5 ms to detect, 10 ms to validate, and 20 ms to initiate the quench.

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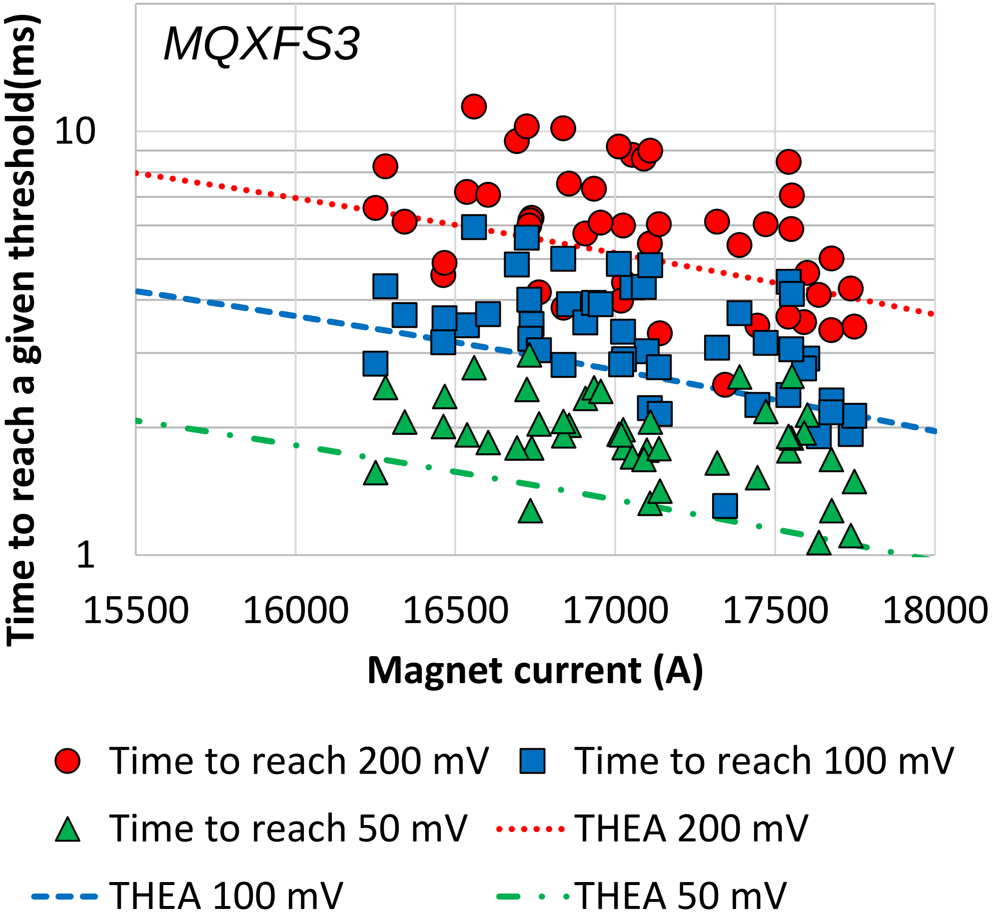
Quench detection – experiment

- During magnet training, the study of the voltage growth in the initial phase of the quench is used to built statistics on the time needed to detect the quench.

- Even if the data is scattered (different quench location/type), it can be used to identify the basic relations.



Quench detection model

- Voltage growth $(V(t))$:

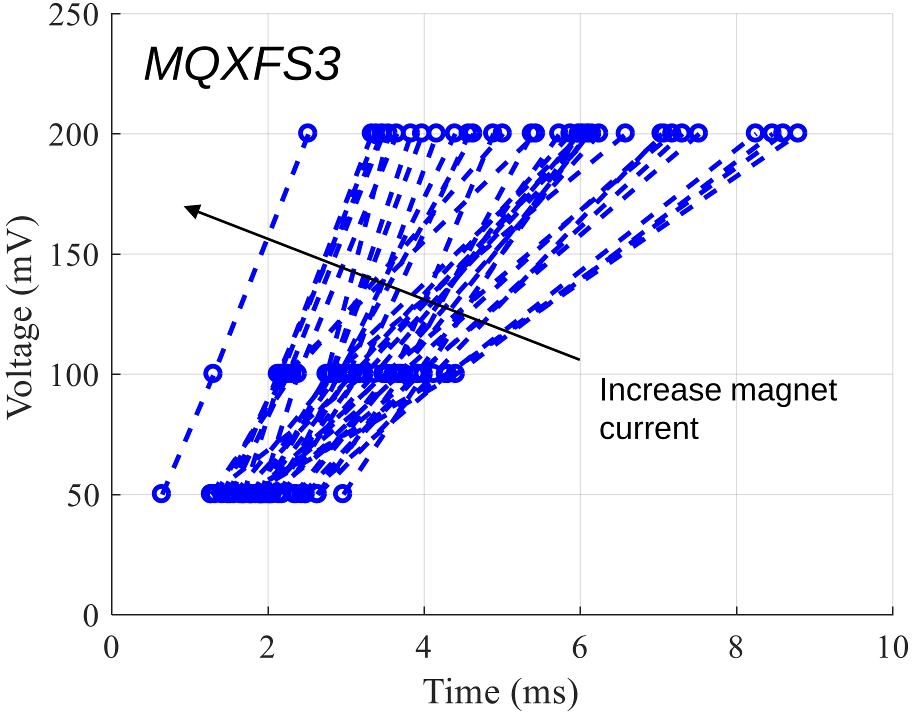
$$V(t) = 2J_{op}\int_0^{v_Q t} \bar{\eta}\,(T(x,t))dx$$

- Quench propagation in the initial phase

$$v_Q = \frac{J_{op}}{\bar{C}}\sqrt{\frac{\bar{\eta}\bar{k}}{(T_{joule} - T_{op})}} = \beta J_{op}$$

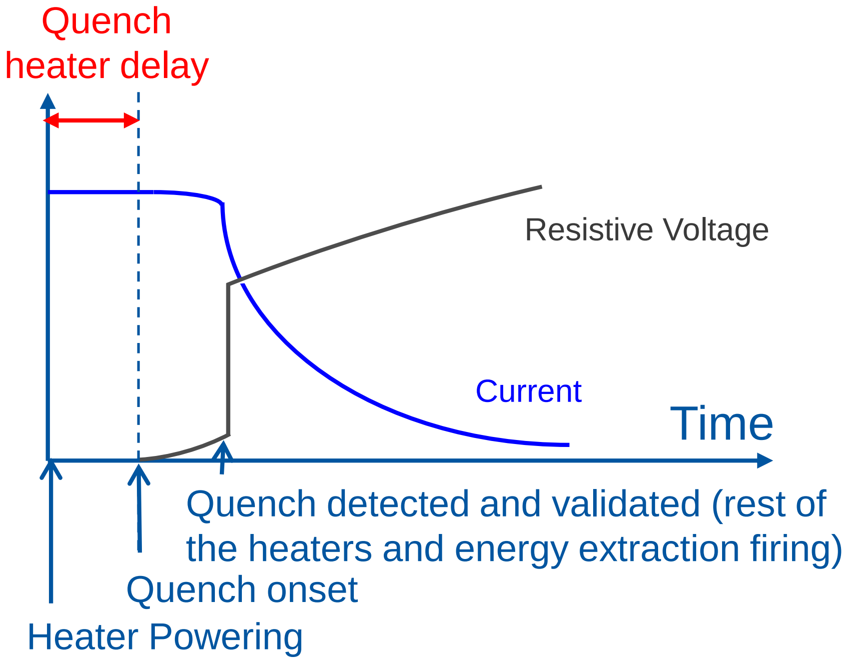
- The resistivity of the stabilizer is approximately constant for T < 20 K (η_{low}) → constant voltage rise with time.

$$V(t) = 2J_{op}\int_0^{v_Q t} \eta_{low}\,dx = 2\eta_{low}\beta J_{op}^2 t$$



Quench initiation - experiment

- Magnet ramped to a specific current level.
- Quench induced on the magnet, through the firing of a heater strip.
- Upon quench detection, firing of the rest of the quench protection elements (energy extraction and rest of the heater strips)



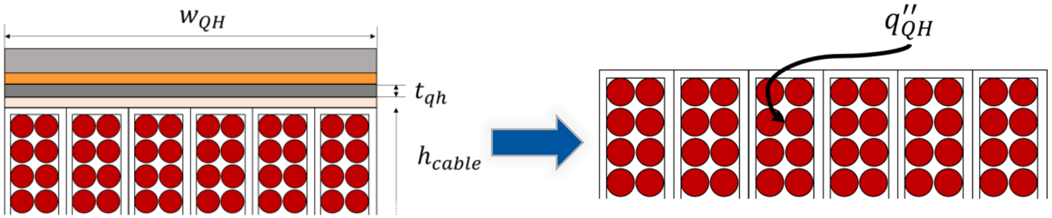
Quench detected and validated (rest of the heaters and energy extraction firing)

Quench onset

Heater Powering

Quench initiation - model

Simplest approach: assume all the energy dissipated in the quench heater strips is invested on heating up the coil.



$$\boxed{\overline{C}\,\frac{\partial T_{cond}}{\partial t} = q''_{QH}}$$

$$\rightarrow\; t^{*}_{qh} = t\left(T_{cond} = T_{cs}\right)$$

Volumetric heat capacity of the insulated cable

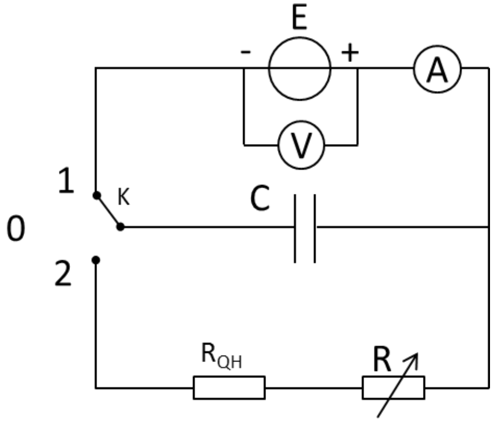
$$\overline{C}(T) = \sum_i f_i \rho_i \, c_i$$

Volumetric heating of the protection heater strips

η_{SS}	Stainless steel resistivity
w_{qh}, th_{qh}	Heater width/thickness
h_{cable}	Cable height
R, C, I	Resistance, Capacitance and Current of the heater circuit

$$Q_0 = \frac{\eta_{SS} I_{QH}^2}{w_{QH}^2 \, th_{QH} \, h_{cable}}$$

$$q''_{QH} = Q_0 e^{-2t/RC}$$

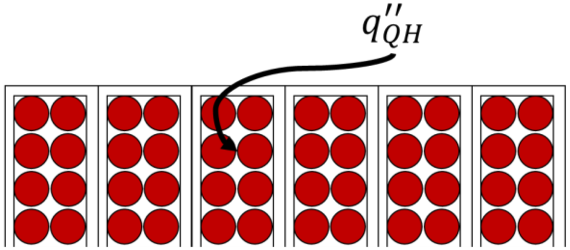


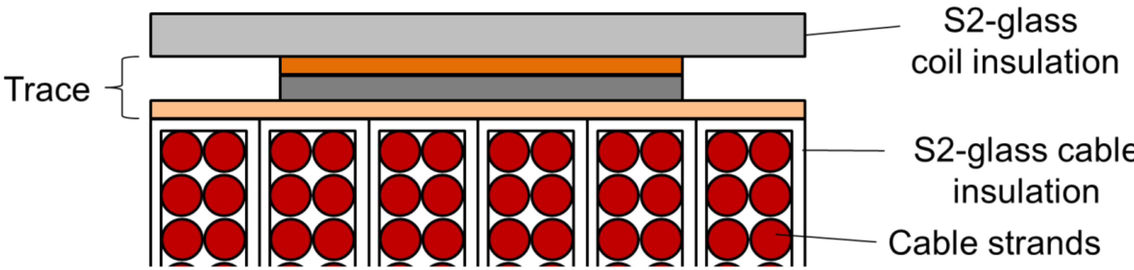
Quench heater circuit

Quench initiation - model

- But reality is rather far from the assumption that the heater energy is deposited directly on the coil
  - Let's allow ourselves to have two scaling parameters (a,b) to coil to account for:
    - Part of the quench heater energy is dissipated on the bath.
    - The heat has to diffuse through the coil insulation layers.

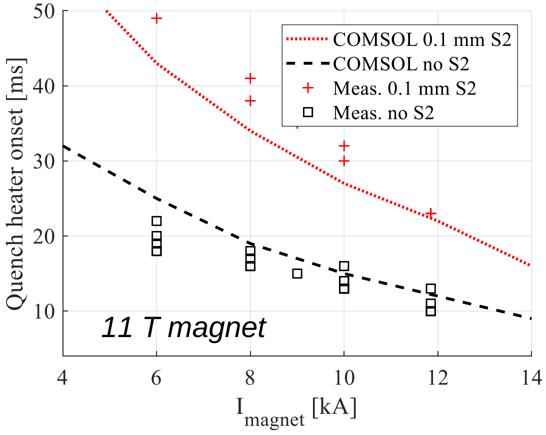
$$t_{qh} = t^{*}_{qh} \cdot a + b$$

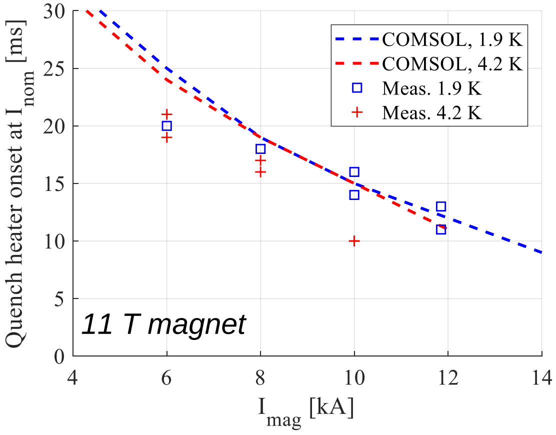


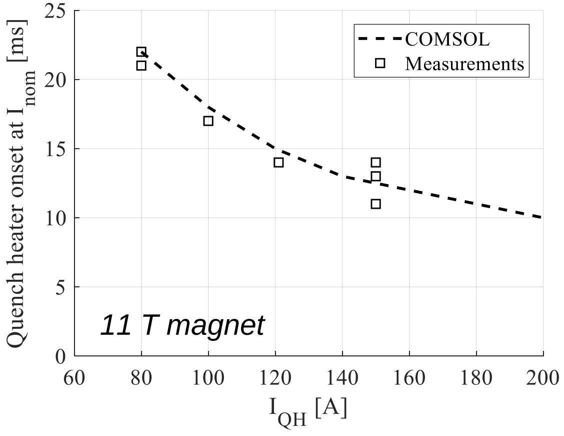


Quench initiation

- Experimental data available for:
    - Different insulation layouts
    - Different bath temperature
    - Different heater powering conditions







- And a model in COMSOL which reproduces rather good the experimental results…

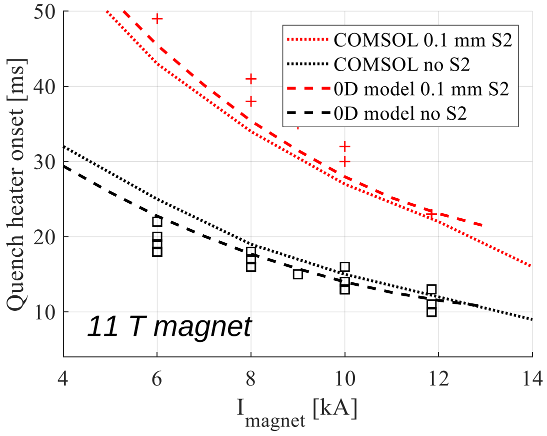
Quench initiation – validation

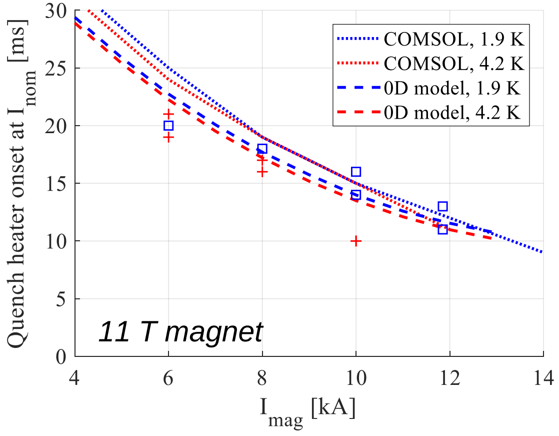
- The proposed 0d adiabatic approximation is “good enough” to fit the experimental and COMSOL model data with:

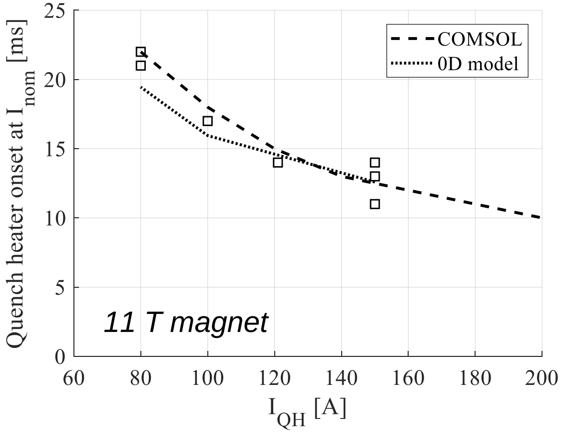
$$t_{qh} = t^{*}_{qh} \cdot a + b\;;\; a = 70 \cdot t_{trace2coil}[mm];\ \mathrm{b} = 100 \cdot t_{trace2coil}[mm]$$

where $t_{trace2coil}$ is the insulation from the trace to coil. In the case of the 11 T:

- 0.1 mm S2 glass – Mica conductor insulation
- In some magnets, an additional layer of S2 glass protection

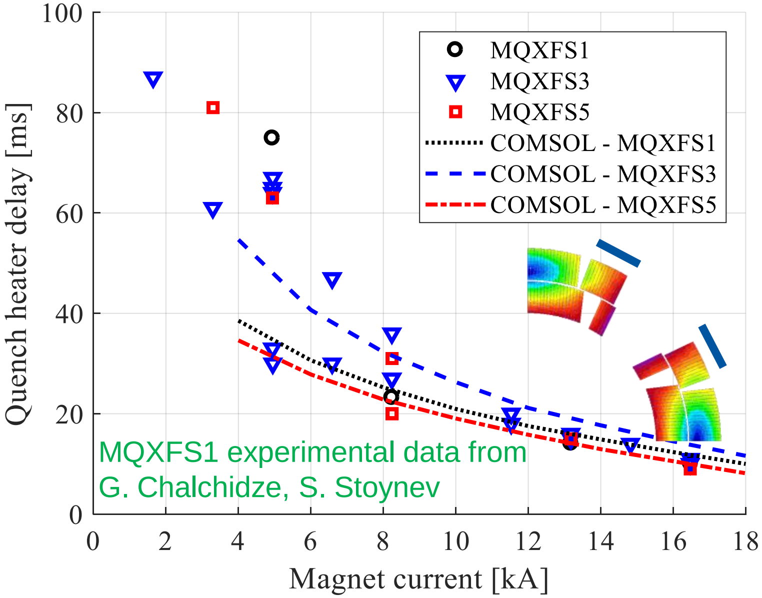




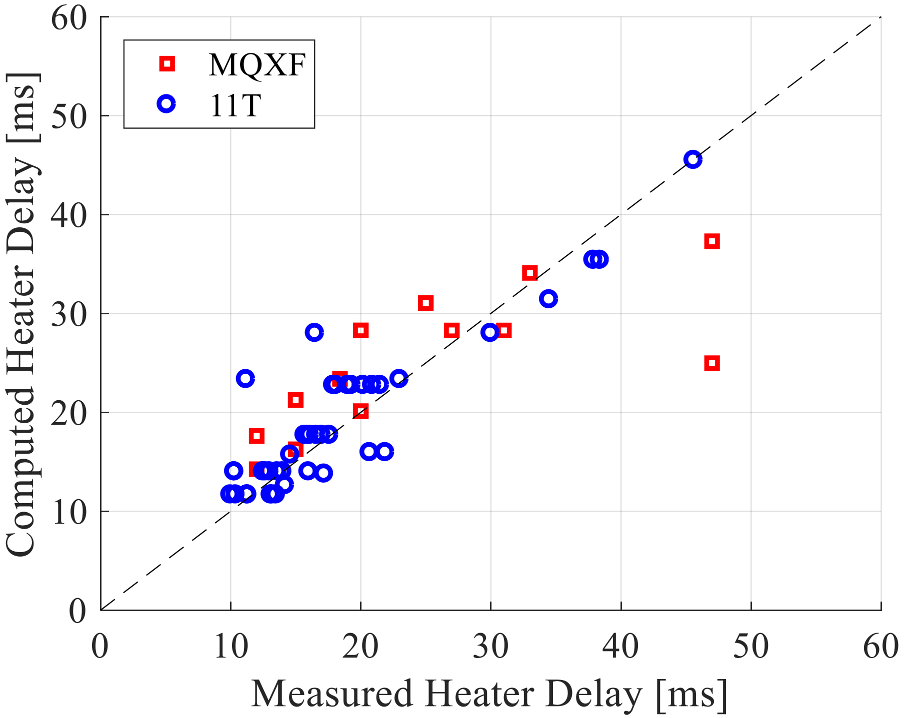


Quench initiation model

- Measured and computed delays correlate, although significant deviations are observed in several cases
  - The original measured data is also scattered, in particular at low field level.

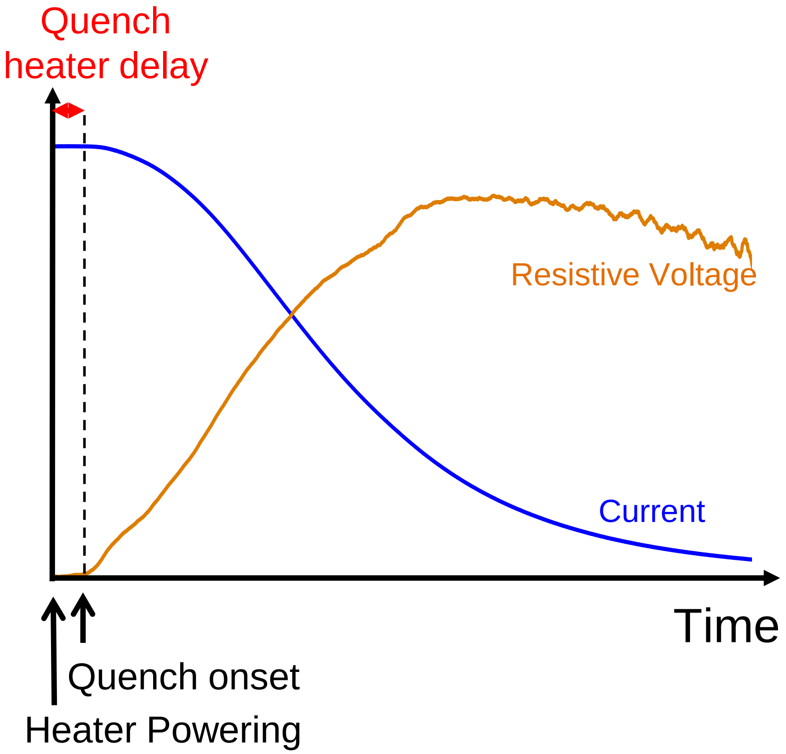


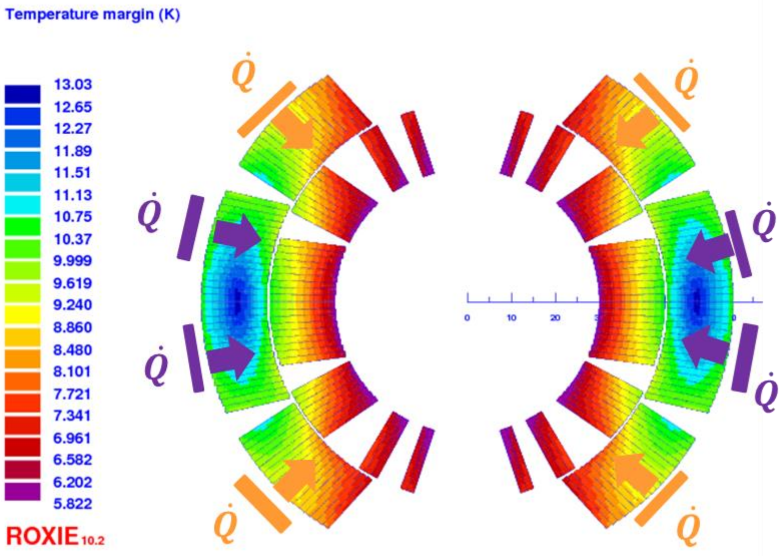
MQXFS1 experimental data from G. Chalchidze, S. Stoynev



Quench dump

- Magnet ramped to a specific current level.
- Quench induced on the magnet, through the firing of OL or OL+IL heaters.
- Study of the current decay, resistance growth and temperature rise.





Quench dump model

- Assumptions:
  - Adiabatic conditions.
  - Average field in the coil turns (computed using ROXIE, function of the magnet current).
  - Non linear inductance (Ld) (computed using ROXIE , function of the magnet current).
  - The magnet is completely or partially quenched at the minimum quench heater delay.

$$A\overline{C}\frac{\partial T_{cond}}{\partial t} = Aq''_{joule} \rightarrow \overline{C}\frac{\partial T_{cond}}{\partial t} = \eta_{Cu} J^2$$

$$L_d \frac{\partial I}{\partial t} + RI = 0$$

Average heat capacity:

$$\overline{C}(T) = \sum_i f_i \rho_i \, c_i$$

Electrical resistivity of the stabilizer (Cu)

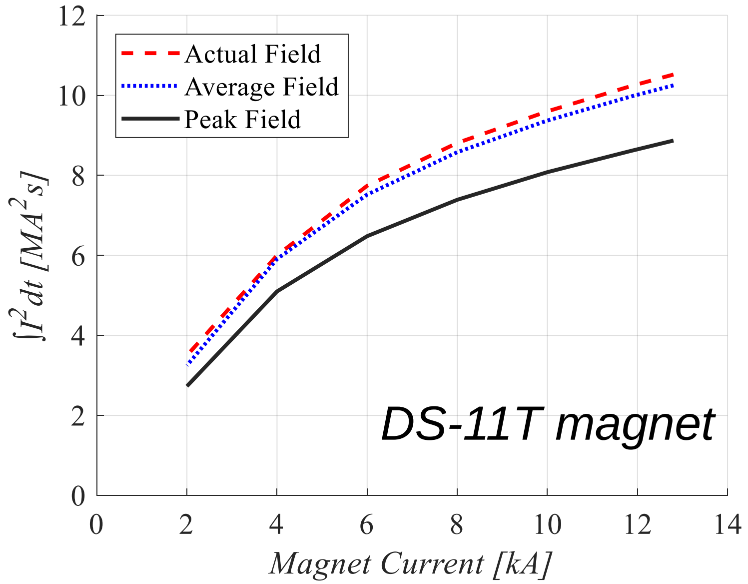
$$\eta_{Cu}(B, RRR, T)$$

Dump model - Field

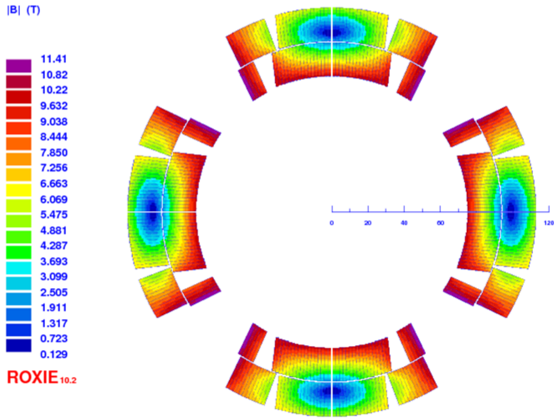
- Defining quench integral (QI) as:

$$QI = \int I^2 dt$$

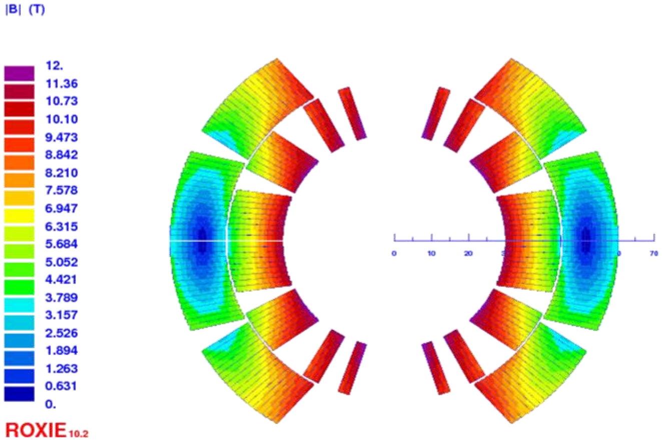
- The average field in the coil is a good enough approximation for the estimation of the quench integral.
- Quench load is underestimated if instead of the average the coil peak field is considered.



	MQXF	11 T
$\frac{B_{OL}}{B_p}$	0.50	0.48
$\frac{B_{IL}}{B_p}$	0.66	0.73



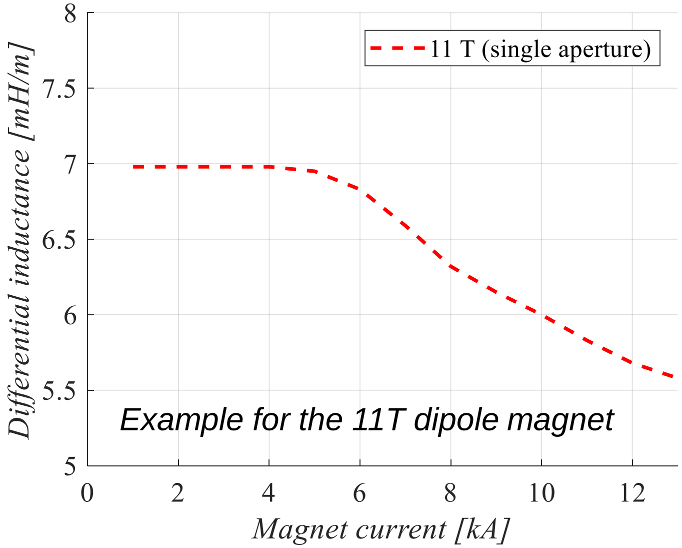
MQXF – Field profile at nominal current

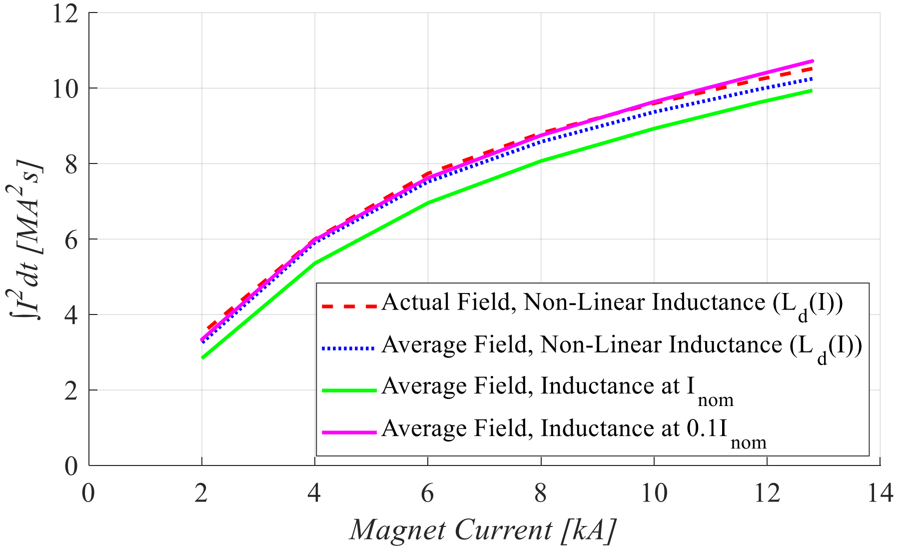


11 T – Field profile at nominal current

Dump model - Inductance

- The magnet inductance is around 20 % lower at nominal current than at low field due to iron saturation effect
  - The field dependence of the inductance cannot be neglected for a good estimation of the quench load!


Example for the 11T dipole magnet



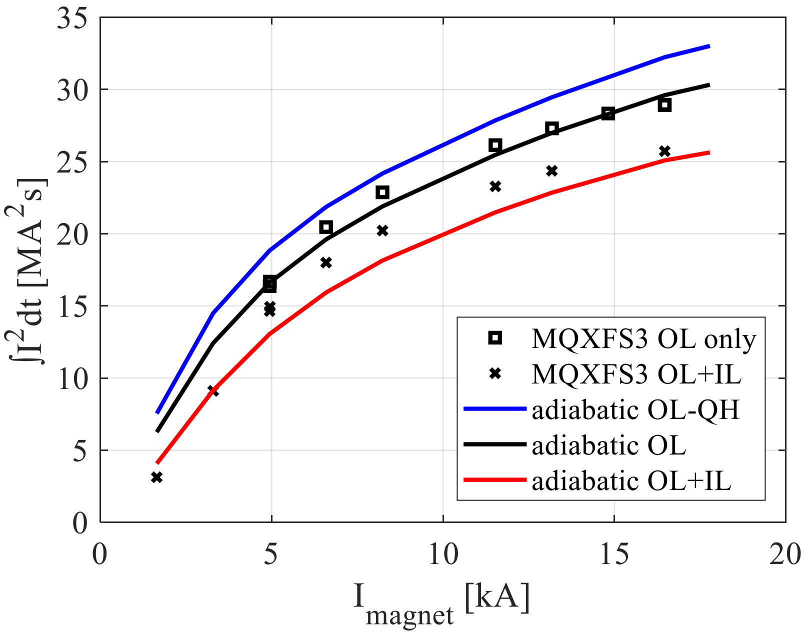
Dump model – Quench delay

- In order to simplify the problem, all the turns are assumed to quench at the same heater delay.

- Two different cases:
  - All the magnet is quench at the minimum quench heater delay, for the case inner and outer layer heaters are protecting the magnet.
  - Only the outer layer turns quench at the minimum quench heater delay, for the case only outer layer heaters are protecting the magnet

- Of course this is not reality (every turn will quench at a different delay), but we just want to check if it is a good enough approximation

Quench integral from heaters powering in MQXFS3



OL-QH: only turns in contact with the outer layer quench heaters quench
OL: all outer layer turns quench
OL+IL: all outer layer and inner layer turns quench

Quench Integral ($\int I^2 dt$)

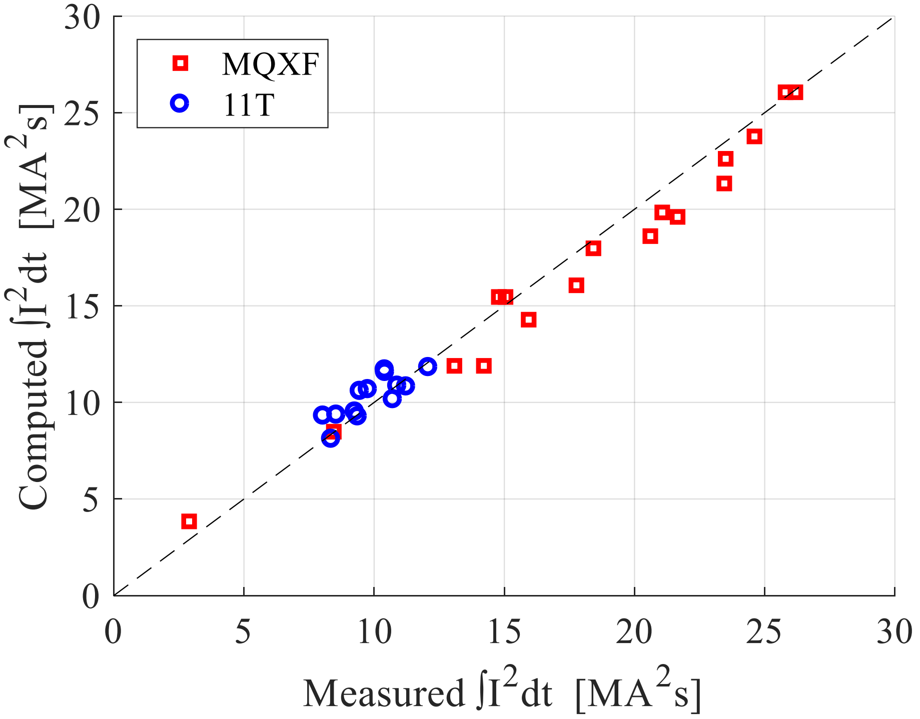
- During the test we measure current (I)
- In the adiabatic 0d model

$$\boxed{I(t) = I(t-1)e^{-dt\cdot R(T,B)/L_d}}$$

$$R(T,B) = \frac{\eta_{Cu}(T,B(I))L_{quench}}{A_{Cu}}$$

$$\frac{dT}{dt} = \frac{I^2}{(A_{Cu}+A_{SC}+A_{ins})\cdot A_{Cu}\cdot \Gamma(T,B)}$$

$B(I), L_d\ (I)$ input function from ROXIE



- Good correlation between measurements and model

All MQXF and 11 T measurements

Magnet Resistance

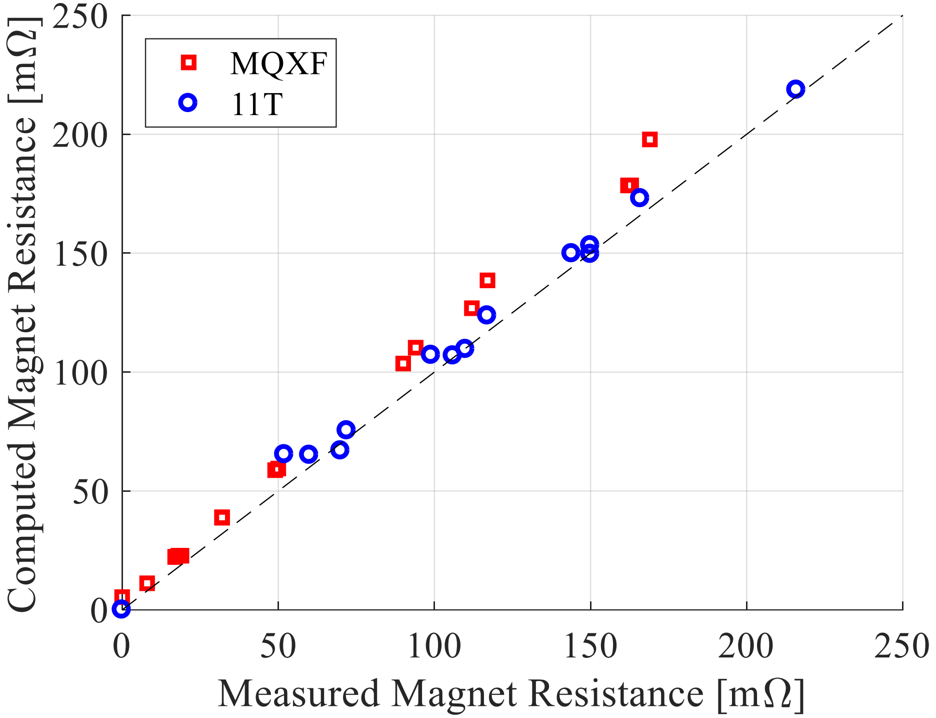
- During the test we measure voltage an inductance of each coil in the magnet.
- Resistive voltage and magnet resistance can be easily derived:

$$V_{res}(t) = V_{tot} - L_d \frac{dI}{dt} \qquad R(t) = \frac{V_{res}(t)}{I(t)}$$

- In the adiabatic 0d model

$$R(T,B) = \frac{\eta_{Cu}(T,B) L_{quench}}{A_{Cu}}$$

- Good correlation between measurements and model



All MQXF and 11 T measurements

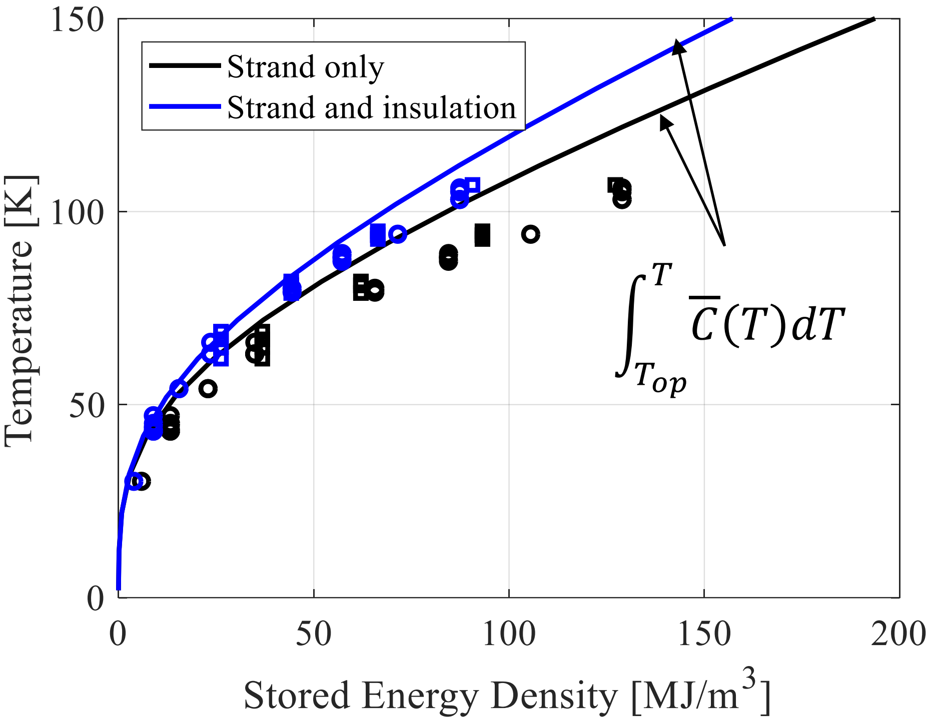
Average Temperature

- Average temperature rise in the coil can be determined through the measured resistive voltage:

$$\frac{V_{res}(t)}{I(t)} = \frac{\eta_{Cu}(T, B, RRR)L_{quench}}{A_{Cu}}$$

- At the end of the discharge, the average magnet temperature is close to the coil enthalpy.

$$\frac{E}{V} = \int_{T_{op}}^{T} \overline{C}(T)dT$$



All MQXF and 11 T measurements

Contents

1. Motivation
2. Protection of accelerator magnets
3. Scaling analysis
    1. Quench detection model
    2. Quench initiation model
    3. Quench dump model
4. Summary

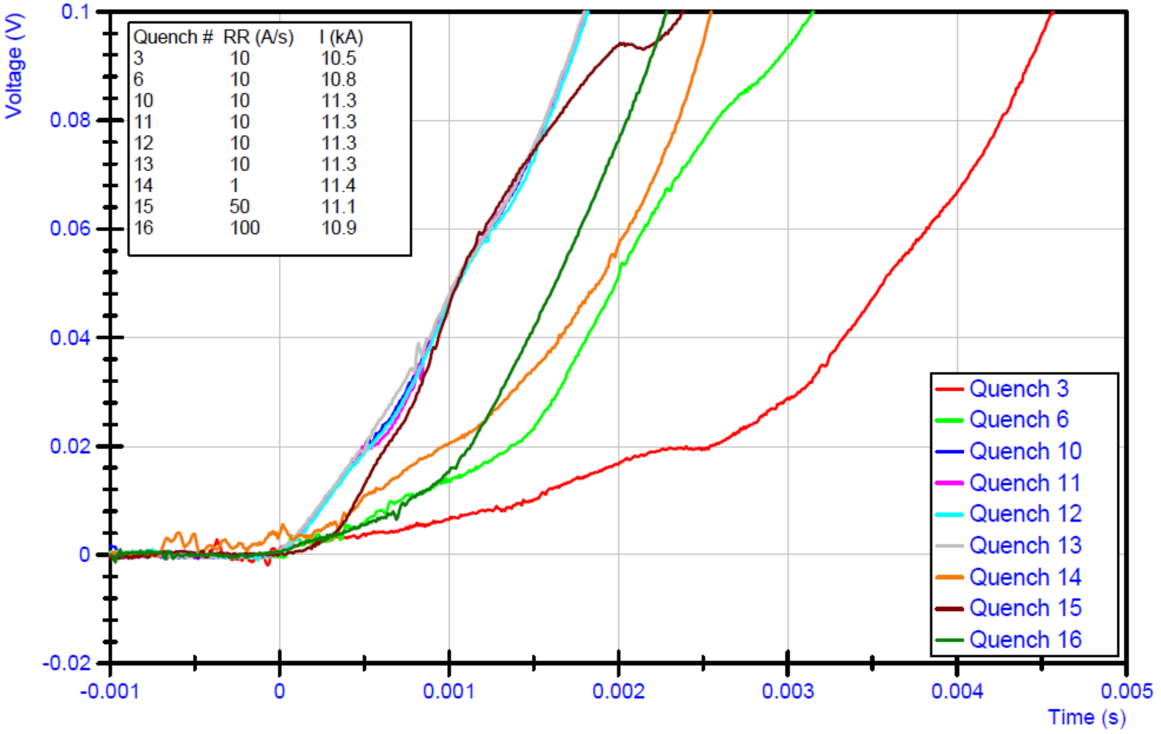
Summary

- An analytical model for the prediction of quench initiation and development in accelerator magnets is presented.

- Experimental measurements on MQXF and 11 T short model magnets validate the assumptions, providing simple relations for the estimation of the peak and average temperature, current decay and resistance growth in high field accelerator magnets during quench.

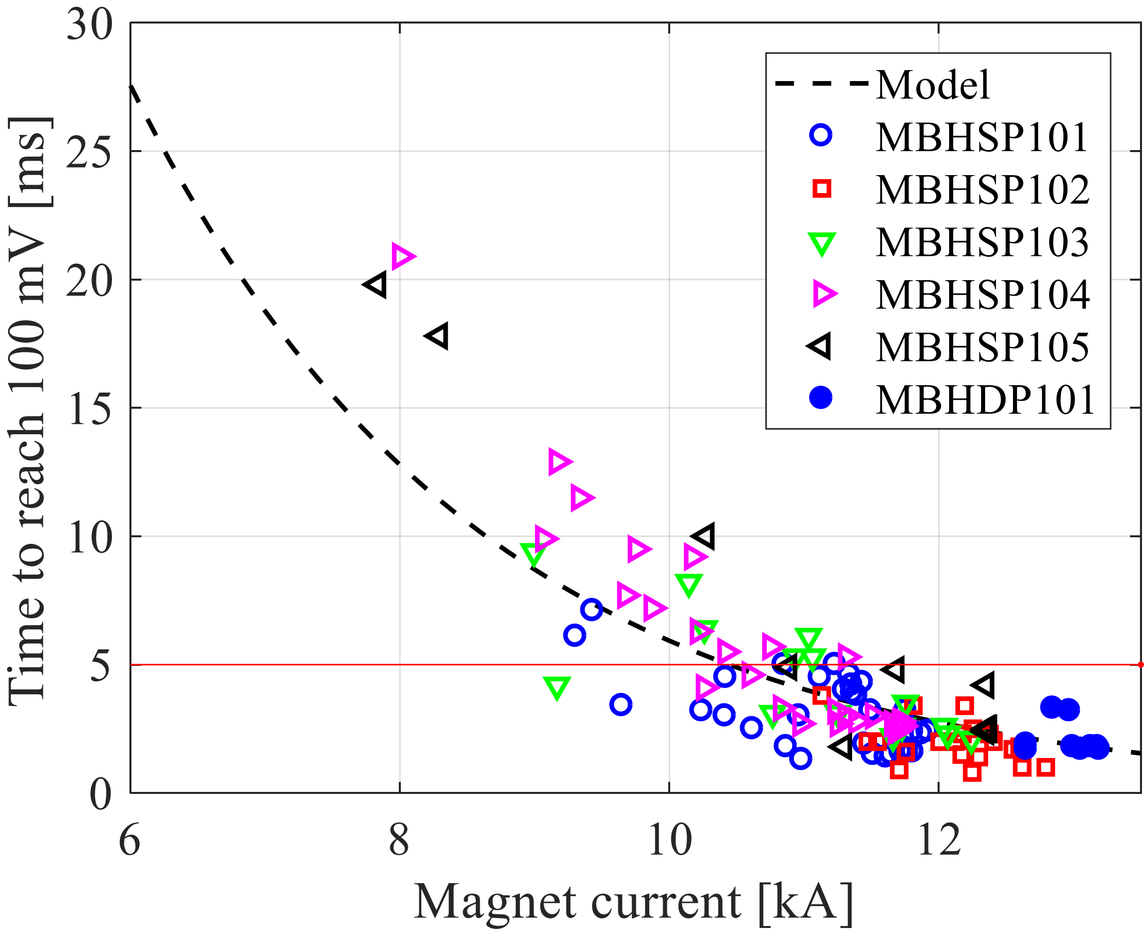
Additional slides

11 T – MBHSP106 quenches

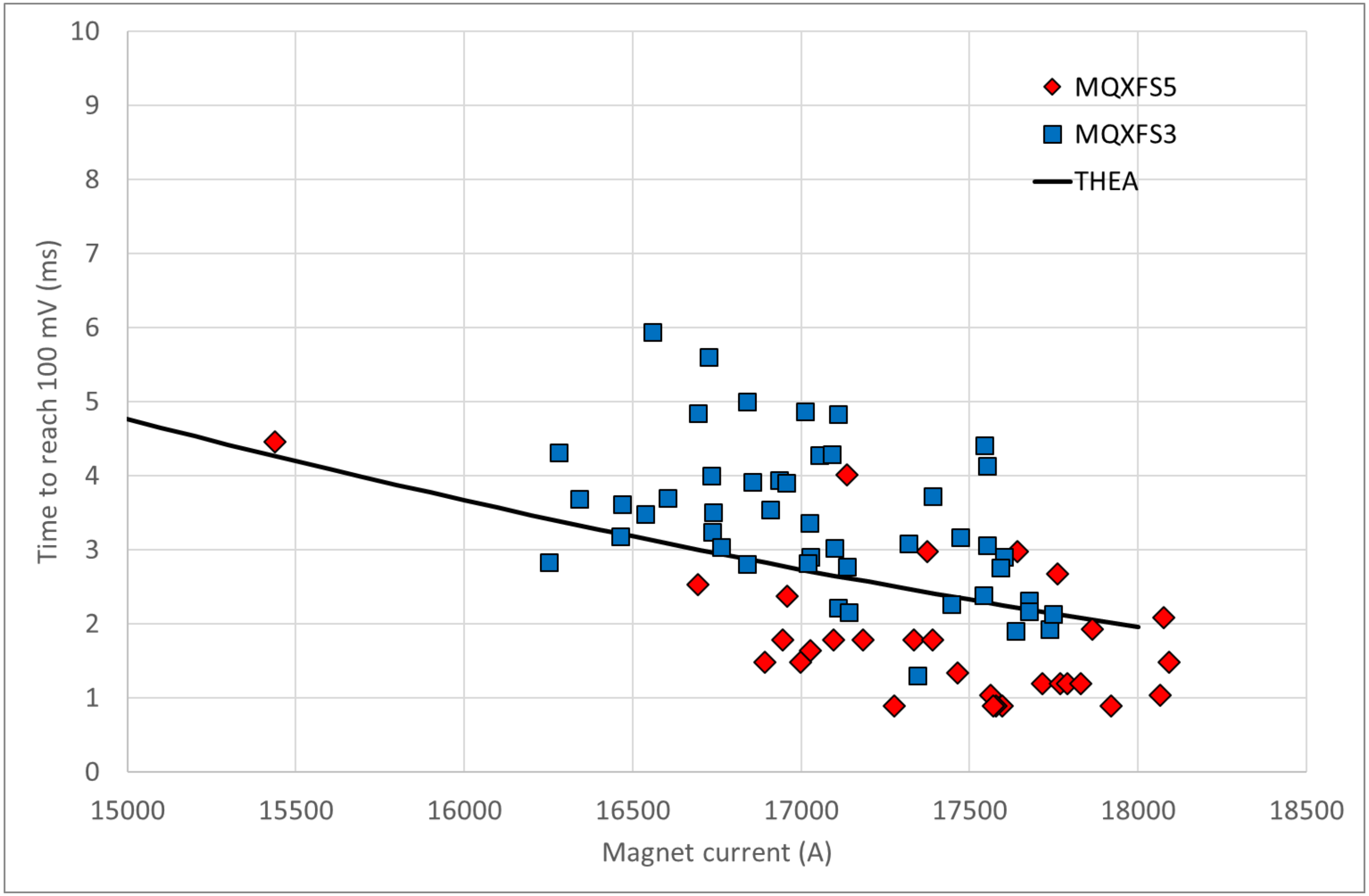


Quench #	RR (A/s)	I (kA)
3	10	10.5
6	10	10.8
10	10	11.3
11	10	11.3
12	10	11.3
13	10	11.3
14	1	11.4
15	50	11.1
16	100	10.9

Detection – 11 T



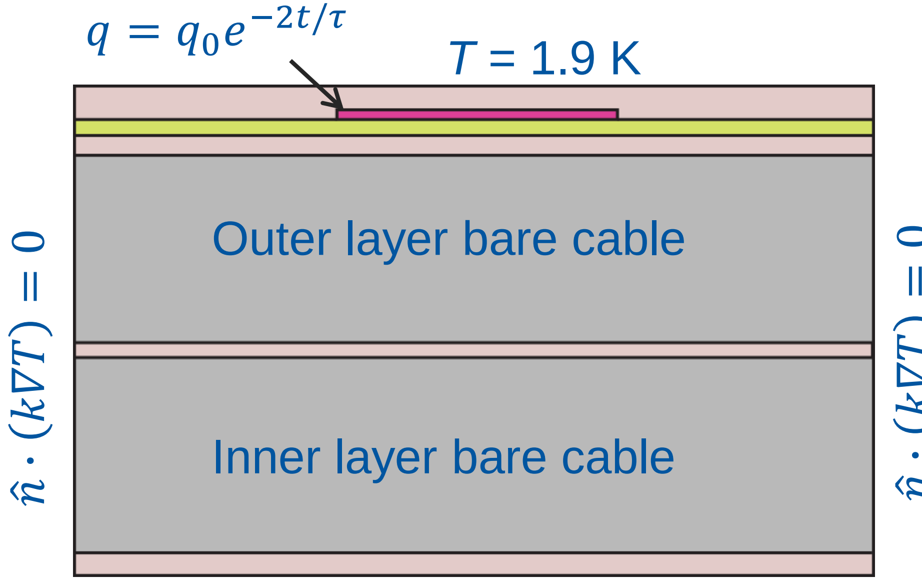
Detection - MQXF



COMSOL quench heater model

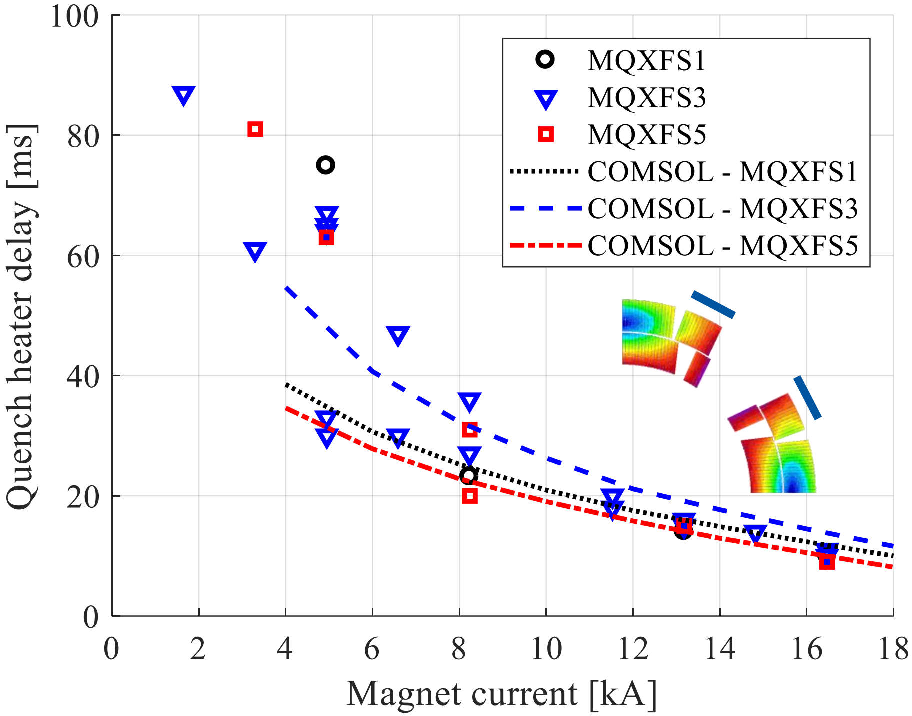
The model

- 2D FEM simulation (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.
- Field profile in the conductor imported from ROXIE

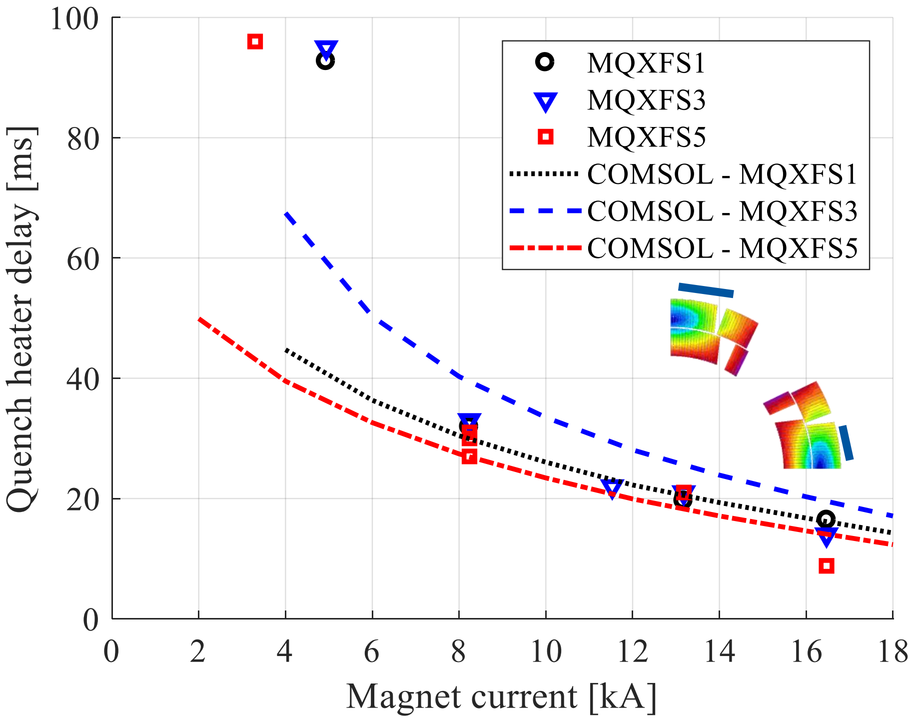


MQXF heater delay

Outer Layer – High Field Block



Outer Layer – Low Field Block



Experimental data from G. Chalchidze, S. Stoynev and H. Bajas.