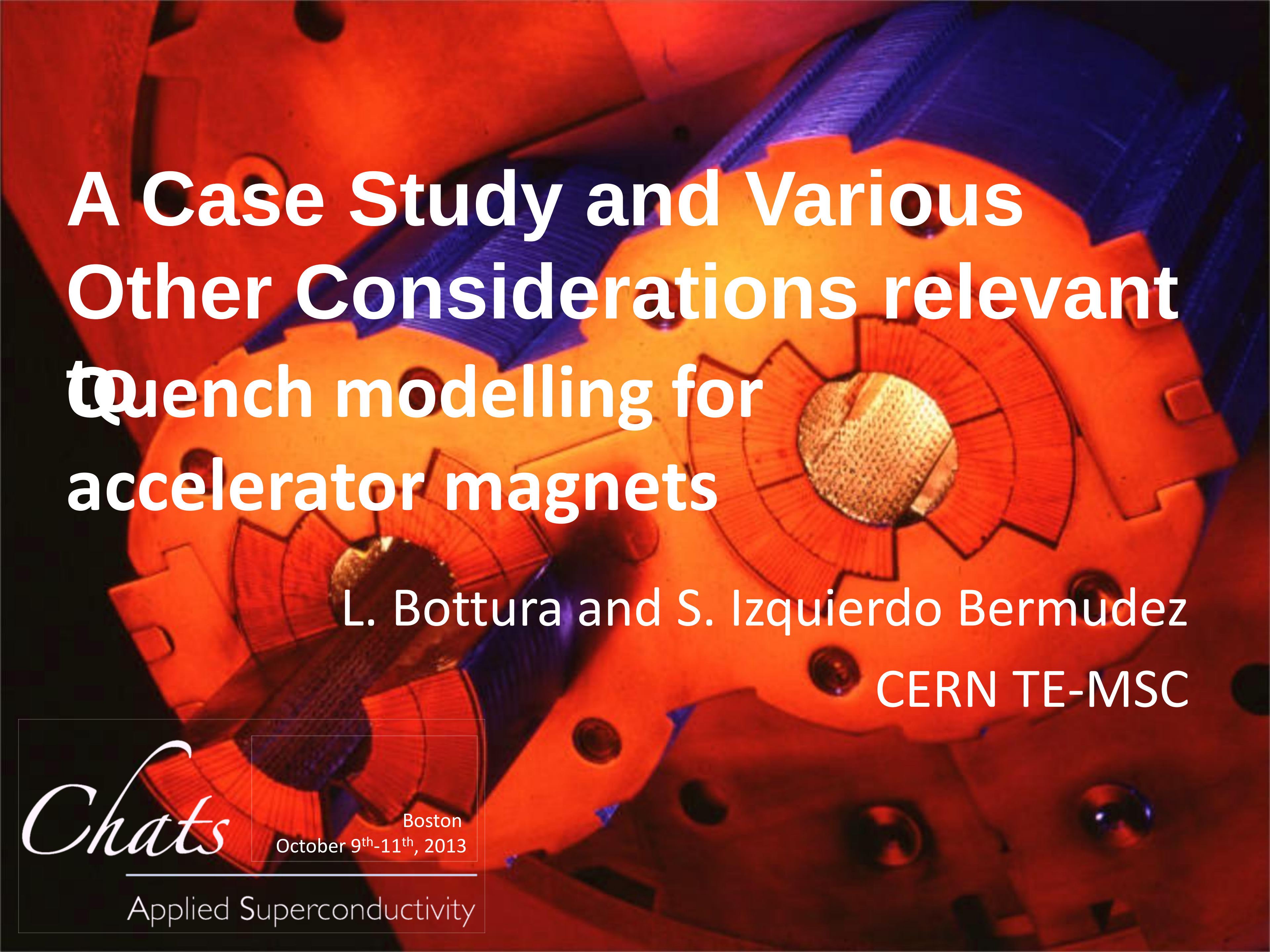


A Case Study and Various Other Considerations relevant to

Quench modelling for accelerator magnets

L. Bottura and S. Izquierdo Bermudez

CERN TE-MSC

Chats

Boston

October 9th-11th, 2013

Applied Superconductivity

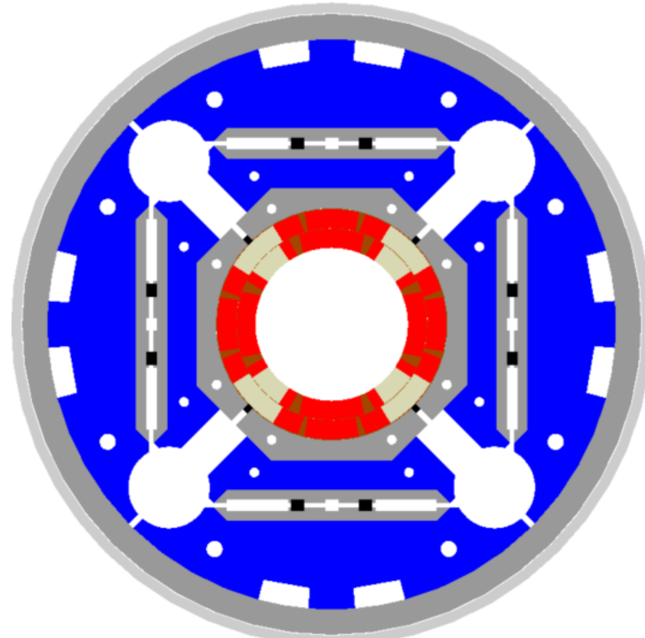
Outline

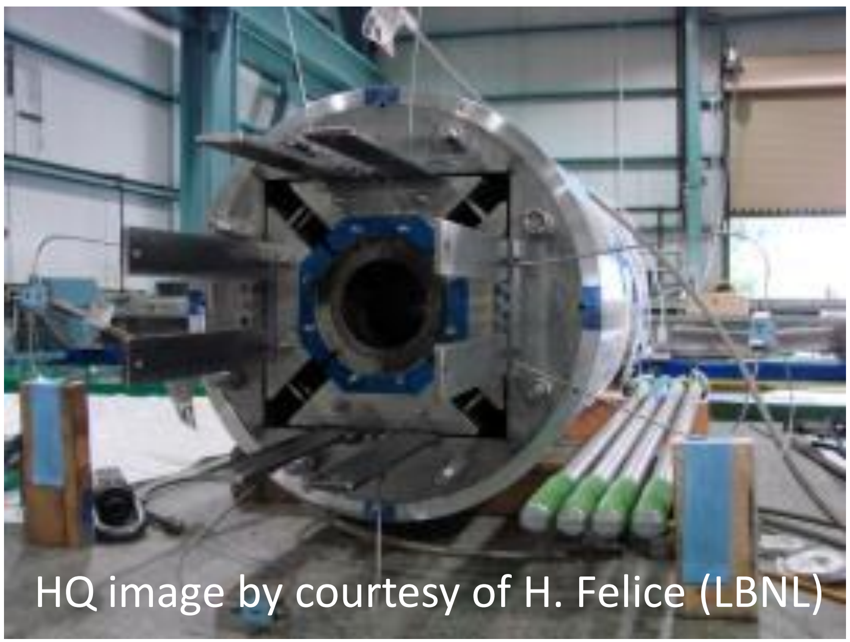
- Motivation
- Scaling analysis
- Quench modeling and issues
- A "real-life" example

An attempt to transpose experience gained in quench modelling for fusion to the domain of accelerator magnets

Motivation: MQXF for HL-LHC

Aperture	(mm)	150
Gradient	(T/m)	140
Current	(A)	17500
Temperature	(K)	1.9
Peak field	(T)	12.1

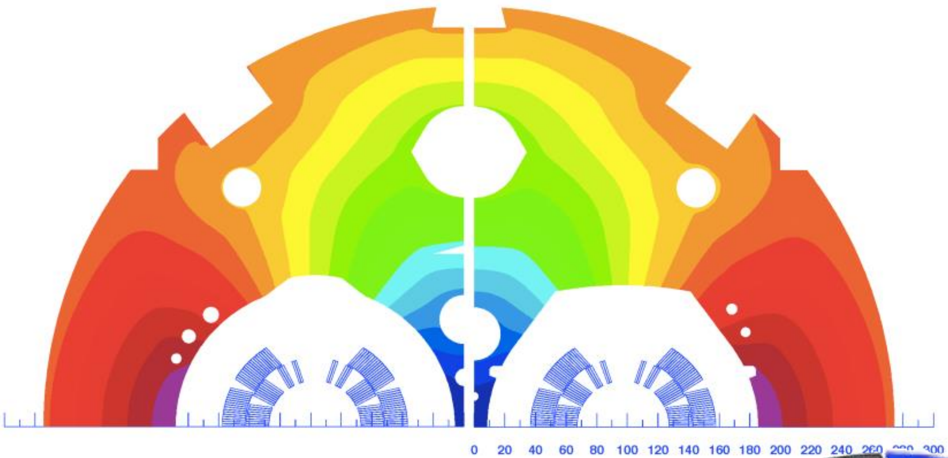




HQ image by courtesy of H. Felice (LBNL)

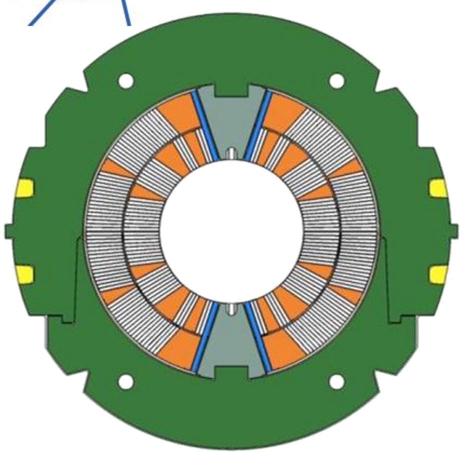
Shell-based support structure (aka *bladder-and-keys*) developed at LBNL for strain sensitive material

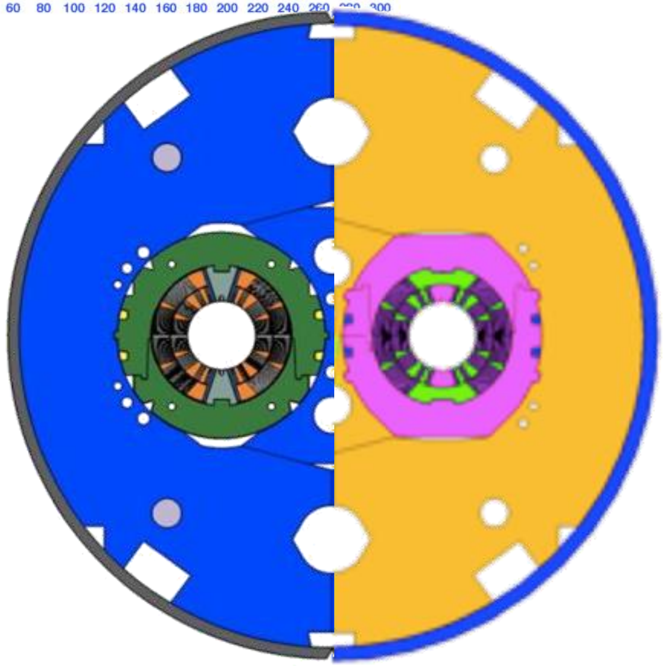
More motivation: 11 T dipole



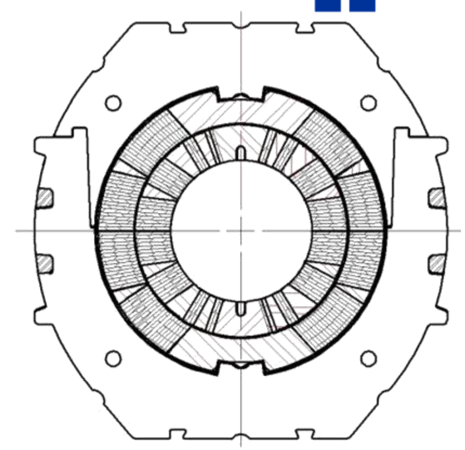
Aperture	(mm)	60
Field	(T)	10.8
Current	(A)	11850
Temperature	(K)	1.9
Peak field	(T)	11.3

Removable
pole loading





Integrated
pole loading



$J_{op} \approx 800\ A/mm^2$
$e_m \approx 150\ MJ/m^3$

By courtesy of A. Zlobin (FNAL) and M. Karppinen (CERN)

Scaling: adiabatic heat balance

- The simplest (and conservative) approximation for the evolution of the maximum temperature during a quench is to assume adiabatic behavior at the location of the hot-spot:

$$A\bar{C}\frac{\partial T_{co}}{\partial t} - \frac{\partial}{\partial x}\left(A\bar{k}\frac{\partial T_{co}}{\partial x}\right) = A\dot{q}'''_{Joule} + p_w h\left(T_{he} - T_{co}\right) \rightarrow \boxed{\bar{C}\frac{dT_{co}}{dt} = \bar{\eta}J^2}$$

- Average heat capacity: $\bar{C} = \sum_i f_i \rho_i c_i$

- Average resistivity: $\frac{1}{\bar{\eta}} = \sum_i \frac{f_i}{\eta_i}$

Scaling: hot spot temperature

- adiabatic conditions at the hot spot :

$$\bar{C}\frac{dT_{co}}{dt} = \bar{\eta} J_{op}^2$$

- can be integrated:

B.J. Maddock, G.B. James, Proc. IEE, **115** (4), 543, 1968

total volumetric heat capacity

stabilizer resistivity

cable operating current density

$$\int_{T_{op}}^{T_{max}} \frac{\bar{C}}{\bar{\eta}} dT = \int_0^\infty J^2 \, dt$$

$$\Gamma\left(T_{max}\right) = \int_{T_{op}}^{T_{max}} \frac{\bar{C}}{\bar{\eta}} dT$$

$$\int_0^\infty J_{op}^2 \, dt = J_{op}^2 t_{quench}$$

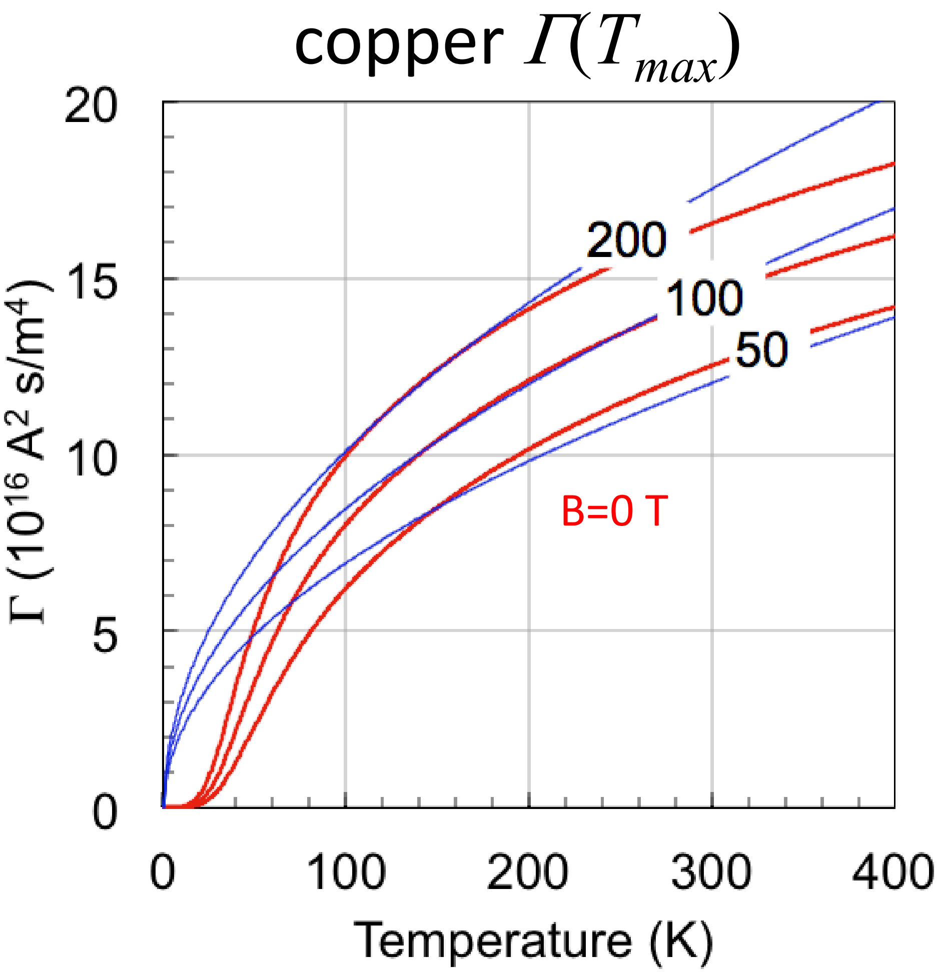
The function $\Gamma(T_{max})$ is a cable property

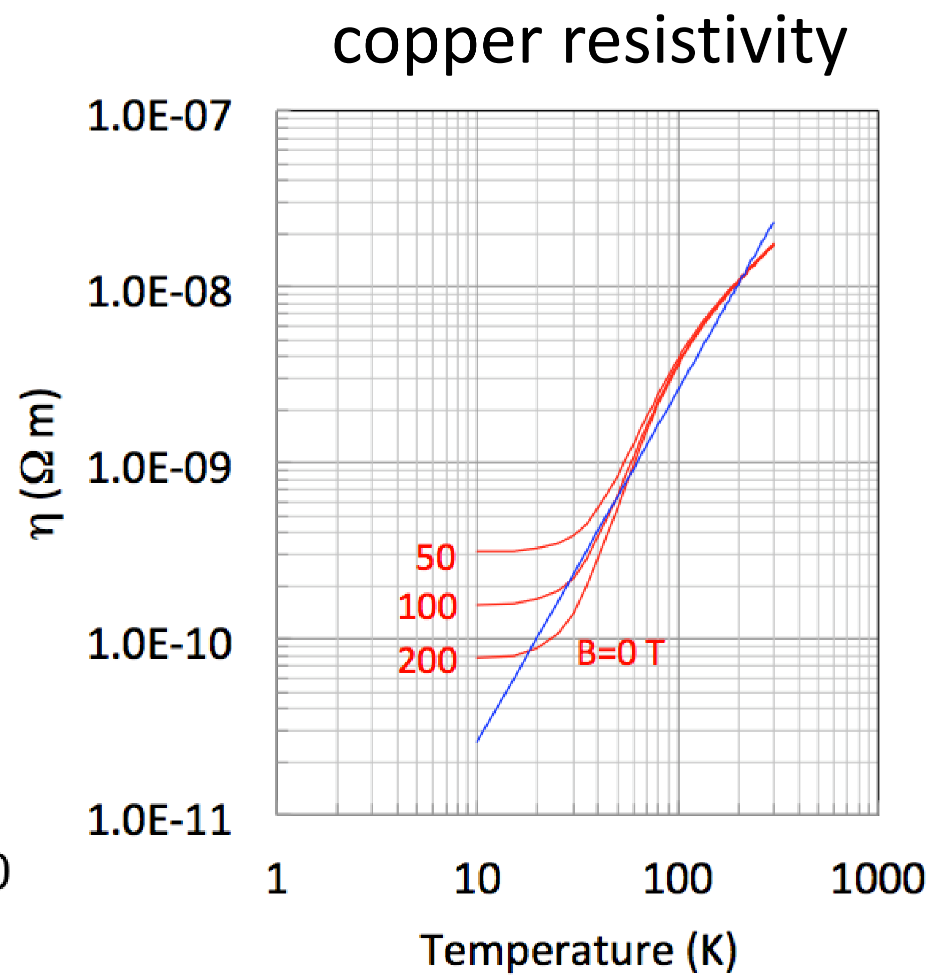
quench capital

The integral of J depends on the circuit

quench tax

Material properties



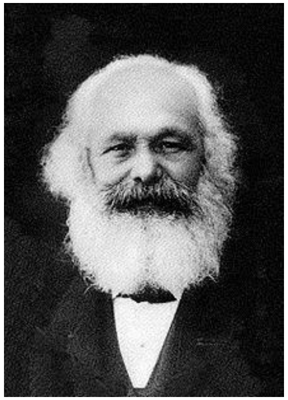


$$\Gamma(T) \approx \Gamma_0 \left(\frac{T}{T_\Gamma}\right)^{\frac{1}{2}}$$

Wilson's Gamma

Useful power approximation

$$\eta(T) = \eta_0 \left(\frac{T}{T_\eta}\right)^{n}$$

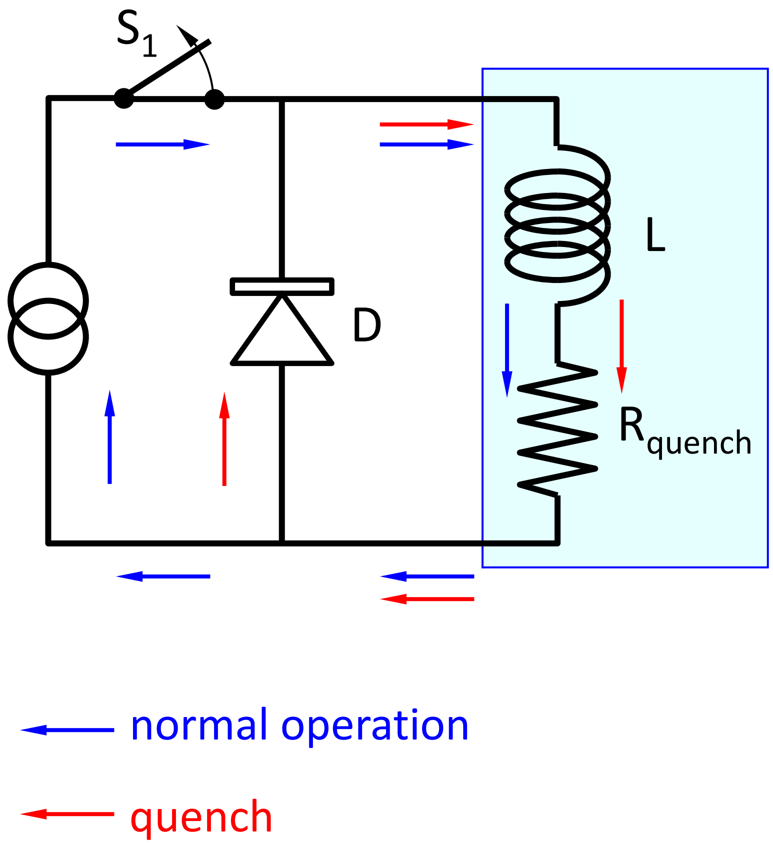


Quench Capital vs. Tax

$$\Gamma(T_{\max}) = \int_{T_{op}}^{T_{\max}} \frac{\bar{C}}{\bar{\eta}} dT = \int_0^{\infty} J^2 \, dt = J_{op}^2 t_{quench}$$

- The real problem is to determine the integral of the current waveform: how much is the quench time t_{quench} ?
- Two limiting cases:
  - **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)
  - **Self-dump:** The circuit is on a short circuit and is dumped on its internal resistance ($R_{dump} = 0$) (e.g. LHC)

"Self dump"



- The magnetic energy is completely dissipated in the internal resistance, which depends on the temperature and volume of the normal zone
- In this case it is not possible to separate the problem in quench capital and quench tax, but we can make approximations
- Assume that:
  - 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

Scaling for "self dump"

- Temperature

magnet bulk

$$T_{bulk} = \frac{T_\Gamma}{\Gamma_0^2}(2n+1)^{\frac{2}{2n+1}}\left(\frac{e_m}{\alpha}\right)^{\frac{2}{2n+1}}$$

hot-spot

$$T_{\max} = \frac{T_\Gamma}{\Gamma_0^2} J_{op}^4 \left(t_{discharge} + t_{quench}\right)^2$$

- Quench time

$$t_{quench} = (2n+1)^{\frac{1}{2n+1}}\left(\frac{e_m}{\alpha}\right)^{\frac{1}{2n+1}} \frac{1}{J_{op}^2}$$

$$\alpha = \eta_0 \left(\frac{T_\Gamma}{T_\eta \Gamma_0^2}\right)^n$$

Details as from M. Wilson, Superconducting Magnets, Clarendon Press, 1986

Scaling study for "self dump"

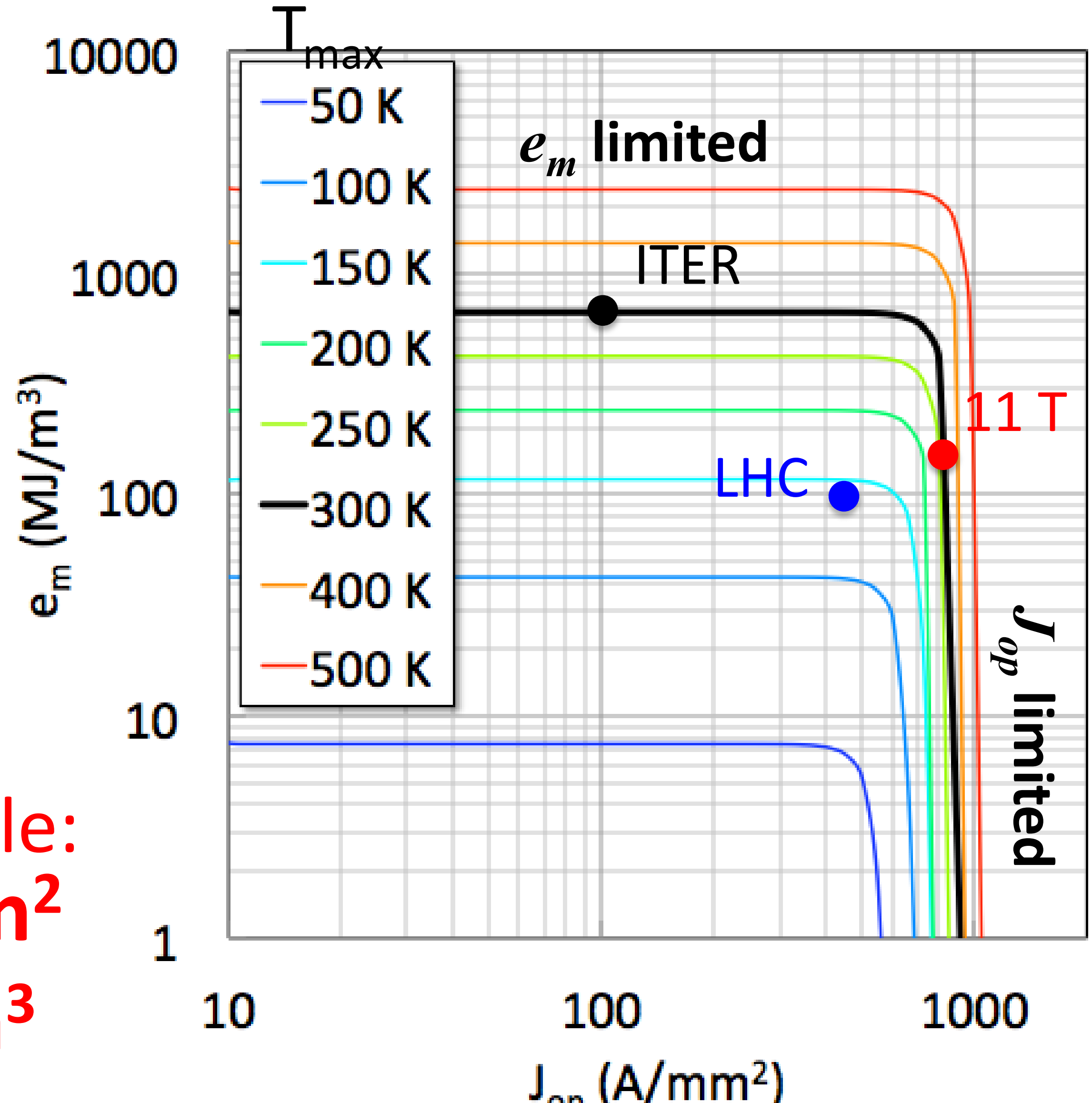
- Cu/Nb_3Sn
- $f_{Cu} \approx 0.55$
- $f_{SC} \approx 0.45$
- $I_{op} \approx 10$ kA
- $t_{discharge} \approx 0.1$ s

Remember…

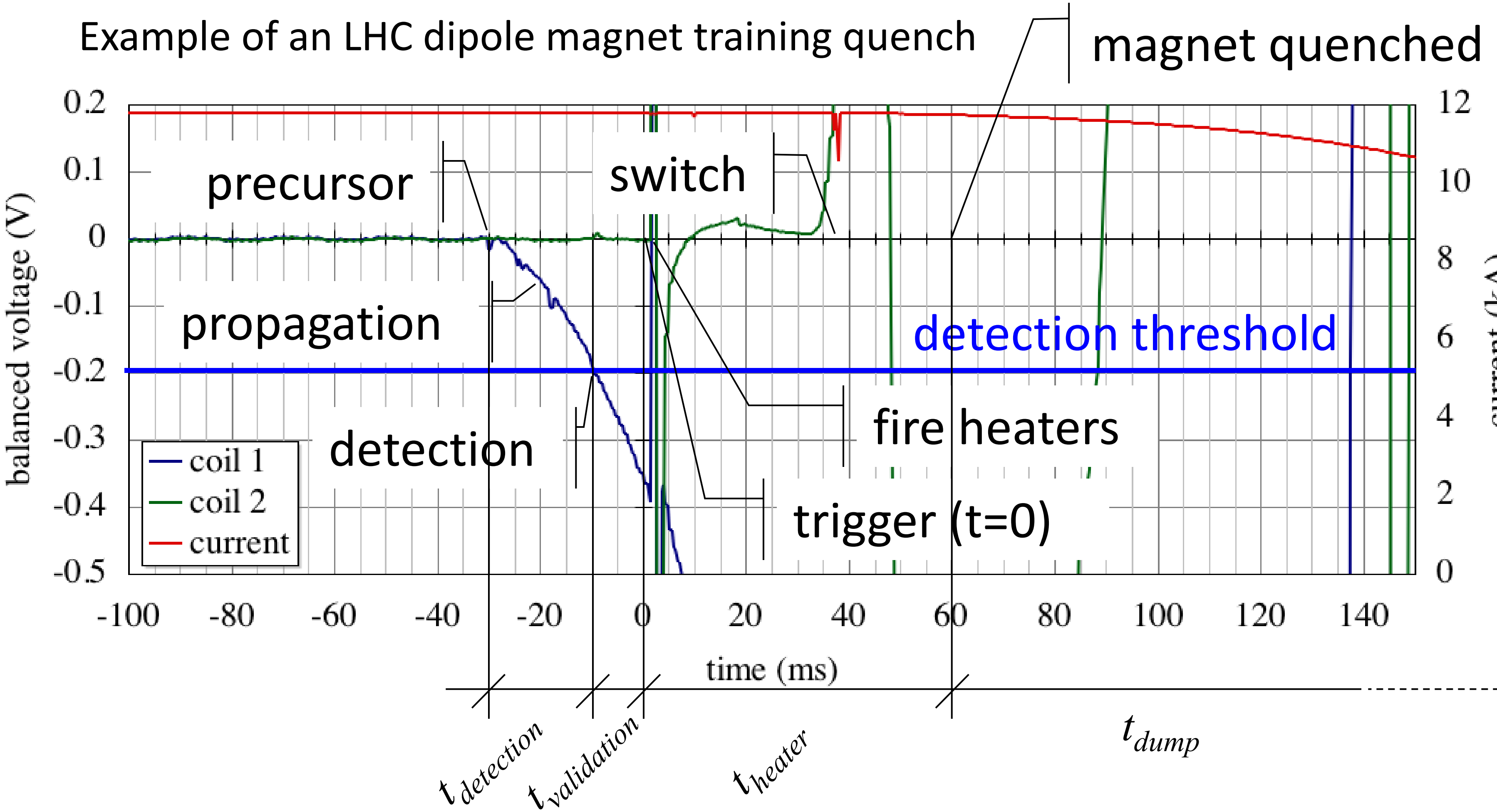
for the 11 T dipole:

$J_{op} \approx 800$ A/mm²

$e_m \approx 150$ MJ/m³



Detection, switch and dump



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

$t_{discharge}$ **≈ 50…100 ms**

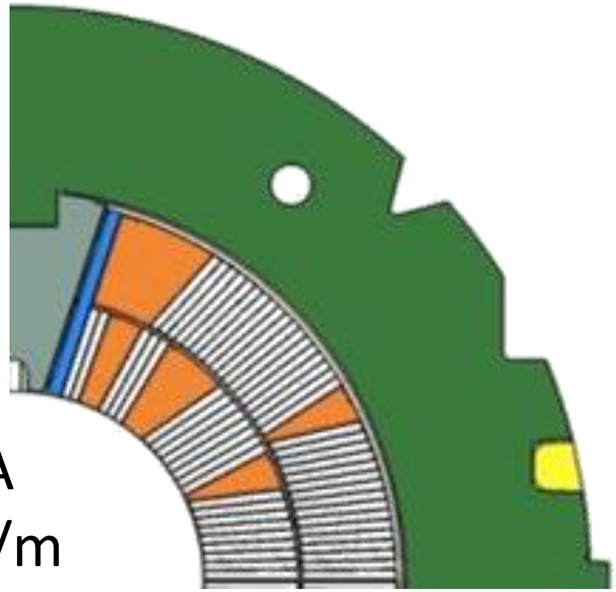
Quench (modeling) issues

- What is the time needed to detect a normal zone ? **Longitudinal quench propagation speed**

- What is the time needed to induce a distributed quench, using quench heater or comparable mechanism ? **Heater delay**

- What is the time needed for the quench to "invade" the whole magnet cross section (and the magnet tu dump) ? **Transverse quench propagation speed**

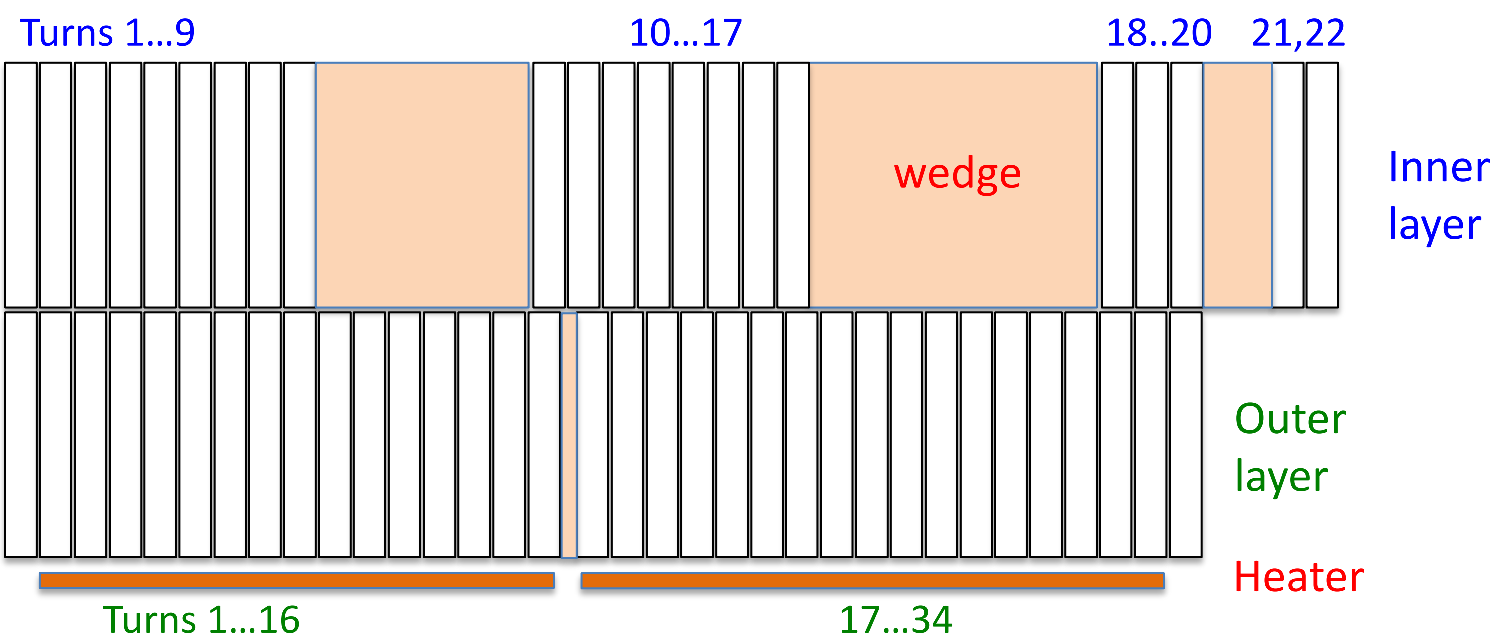
Quench model for a 11 T dipole



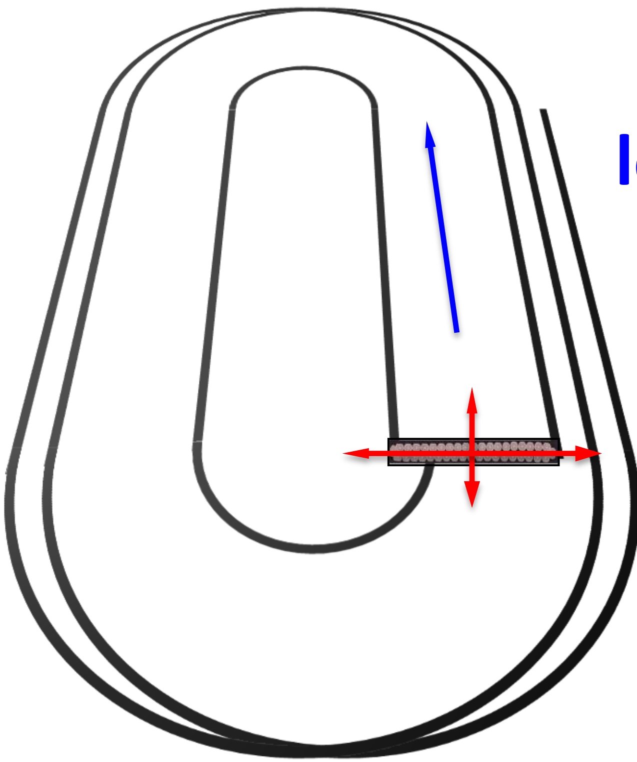
6 blocks coil
2 layers/pole
56 turns

I_{op} = 11850 A
L/l = 6.8 mH/m

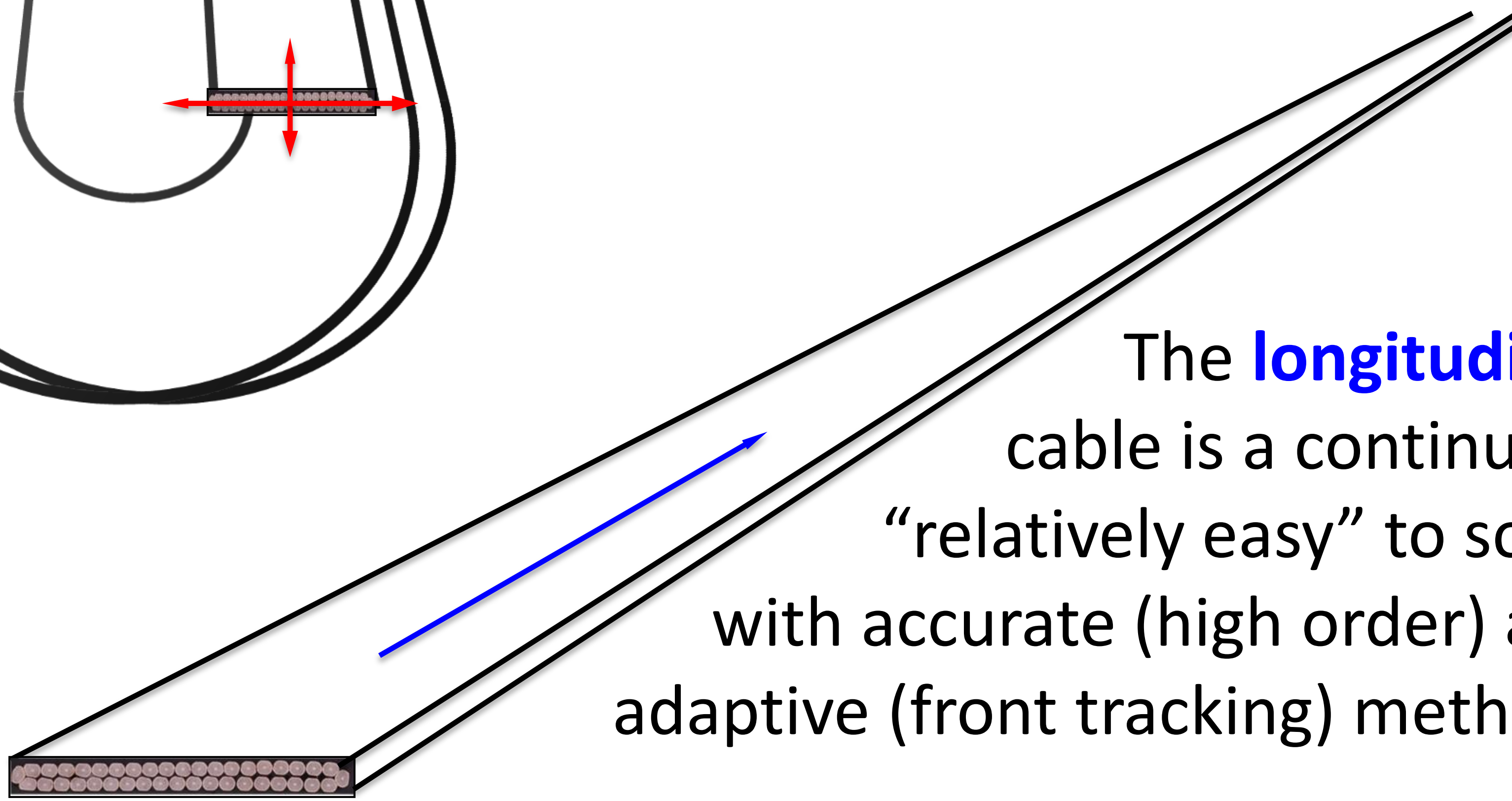
40 Nb_3Sn strands
14.7 mm x 1.25 mm
0.1 mm insulation
A_{Nb_3Sn} = 7.2 mm^2
A_{Cu} = 8.2 mm^2
$A_{epoxy\text{-}glass}$ = 5.5 mm^2



Quench modeling – unfolding

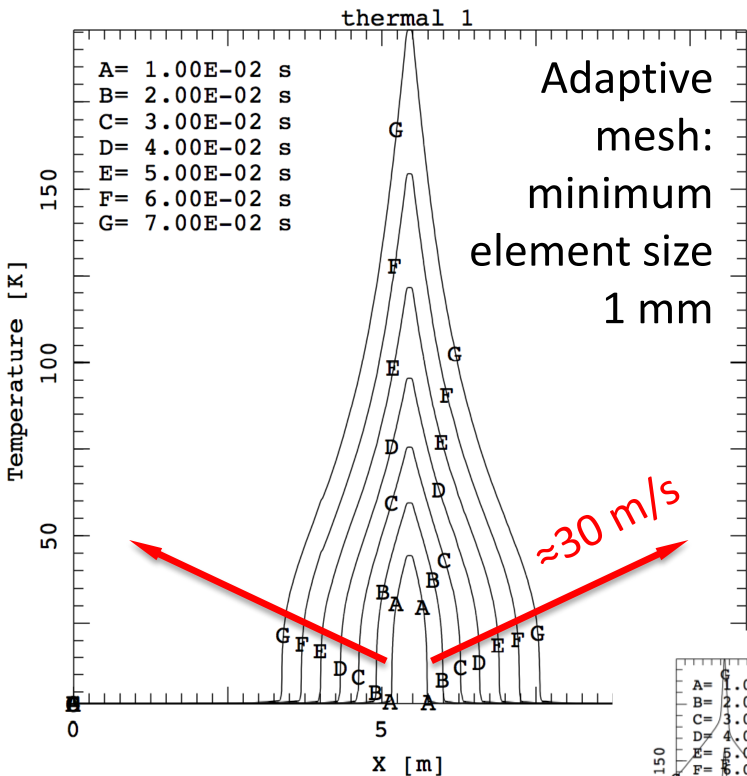


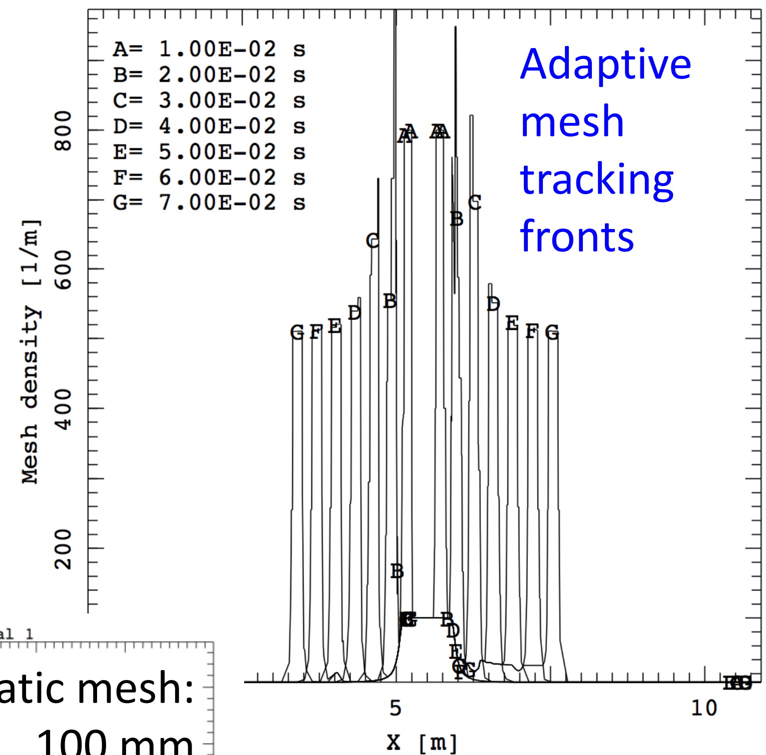
Identify in the winding the **longitudinal** and **transverse** (principal) directions

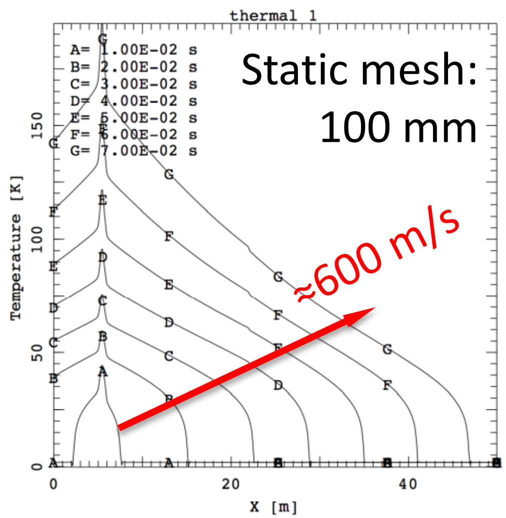


The **longitudinal** cable is a continuum "relatively easy" to solve with accurate (high order) and adaptive (front tracking) methods

Longitudinal propagation speed



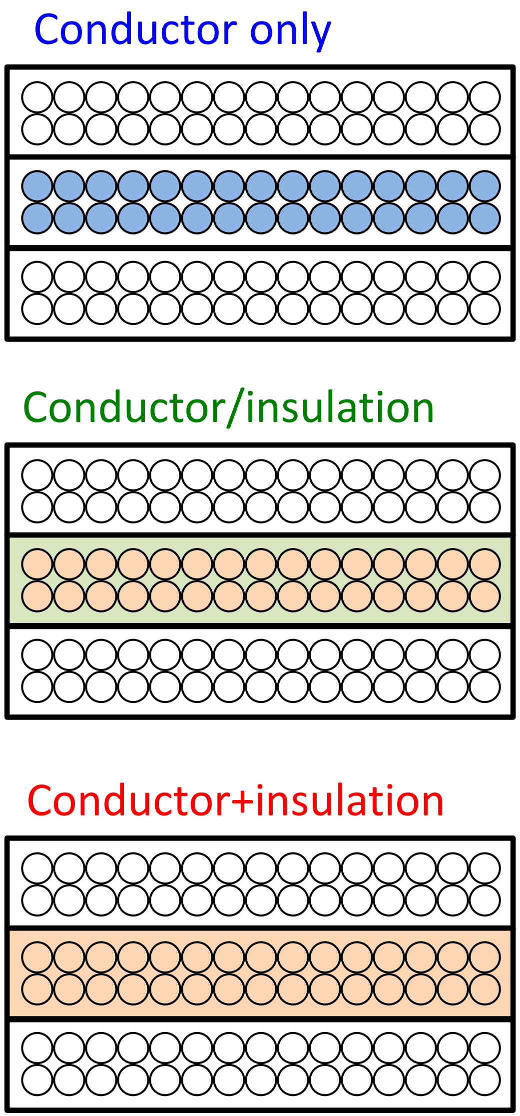


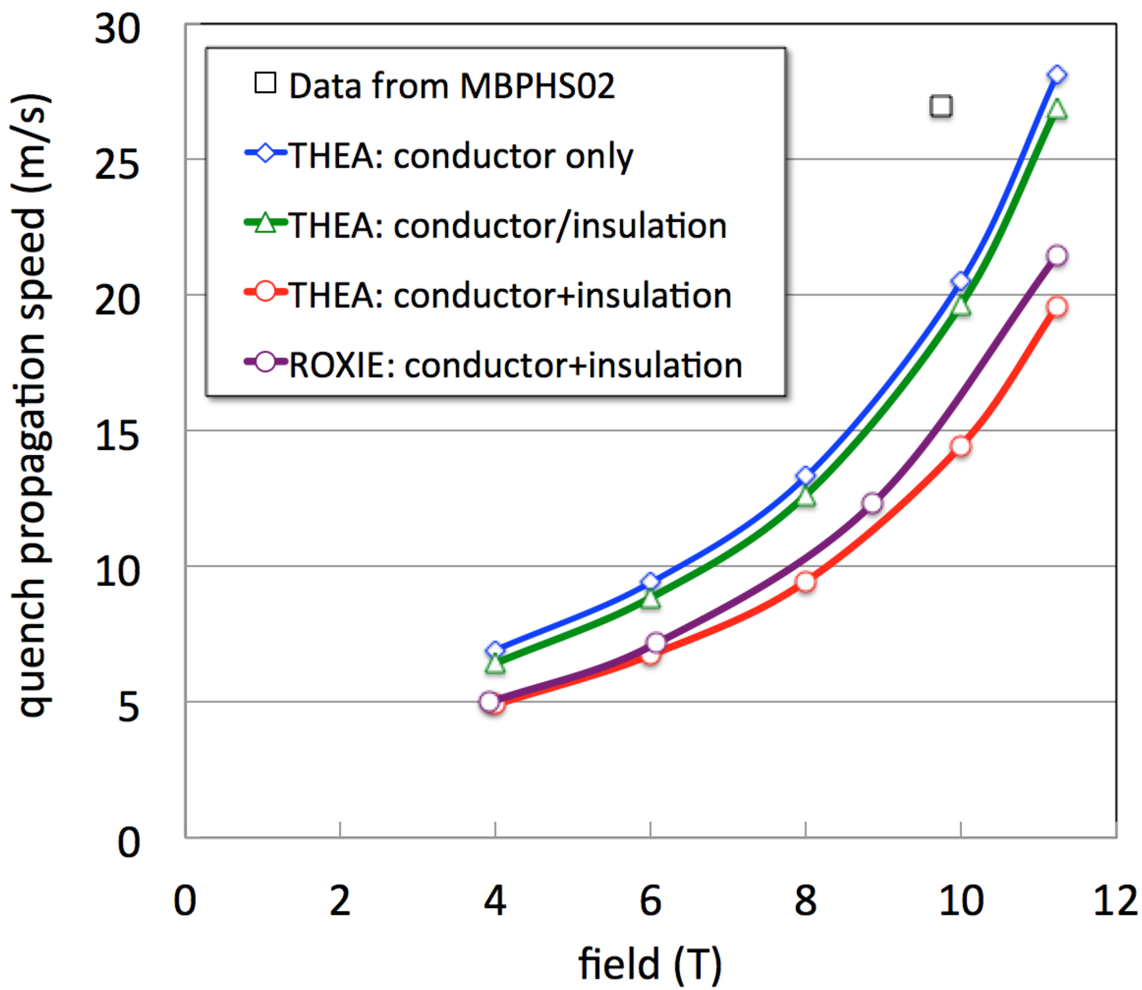


Example of a quench in a Nb_3Sn 11 T cable triggered over 10 cm in a high field (11 T) zone (uniform field assumed)

Small mesh size and/or adaptive meshing are a must for quench analysis

Longitudinal propagation

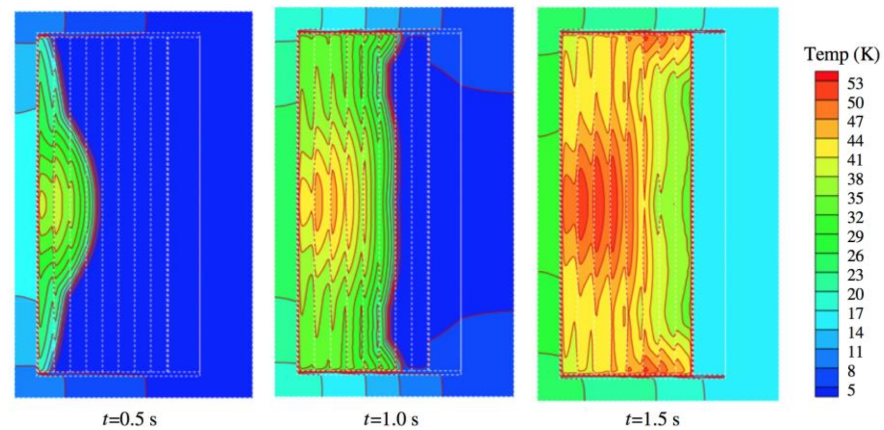




Appropriate subdivision is important to resolve relevant temperature gradients

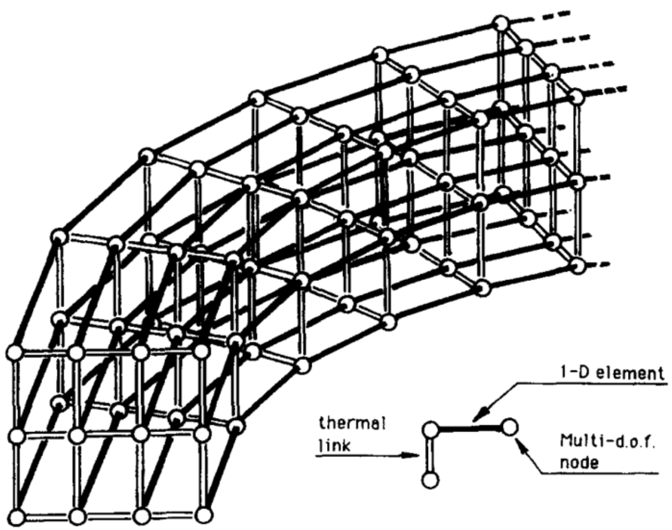
Quench model – thermal coupling

- Continuum models
  - 3-D mesh of the magnet system allows for a natural treatment of geometry
  - Examples:
    - OPERA-quench (MICE)
    - ANSYS (e.g. LBNL, FERMILAB)
    - COMSOL (e.g. TUT)



X.L. Guo et al., Cryogenics 52 (2012) 420–427

- Network models
  - Simplified connectivity and thermal resistances
  - Examples:
    - SARUMAN and following (LB)
    - Gavrilin, 1992
    - ROXIE (S. Russenschuck, B. Auchmann, N. Schwerg)
    - …



L. Bottura, O.C. Zienkiewicz, Cryogenics 32 (1992) 659-667

First order thermal coupling

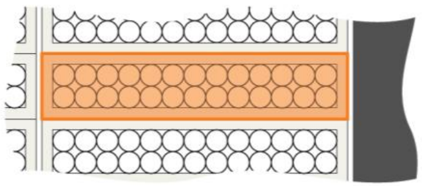
$$\rho_{\mathrm{D}}(T)c'_{\mathrm{V}}(T,B)\frac{\mathrm{d}T}{\mathrm{d}t} = P + \nabla\cdot(\kappa_{\mathrm{T}}(T,B)\nabla T).$$

Convection not considered -> cooling by helium mass flow can not be taken into account

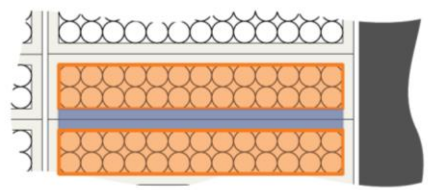
Finite volumes and linear approximations:

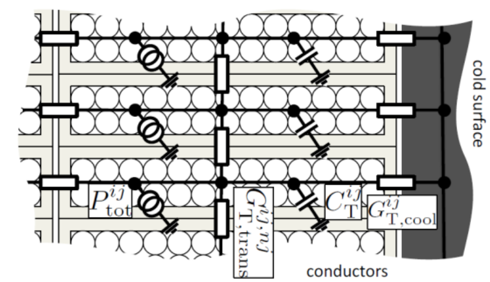
Transverse direction

Heat capacity:
includes conductor + insulation

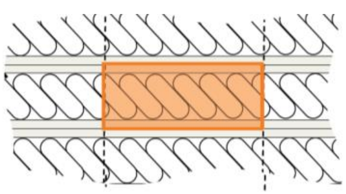


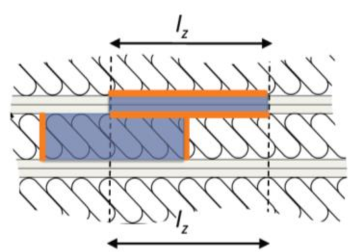
Thermal conductance and heat fluxes:
Conductor without insulation. Uniform temperature in the conductor and linear temperature distribution in between them

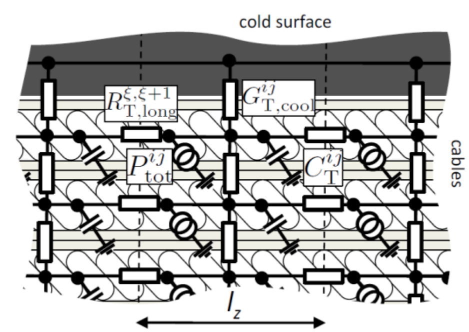




Longitudinal direction



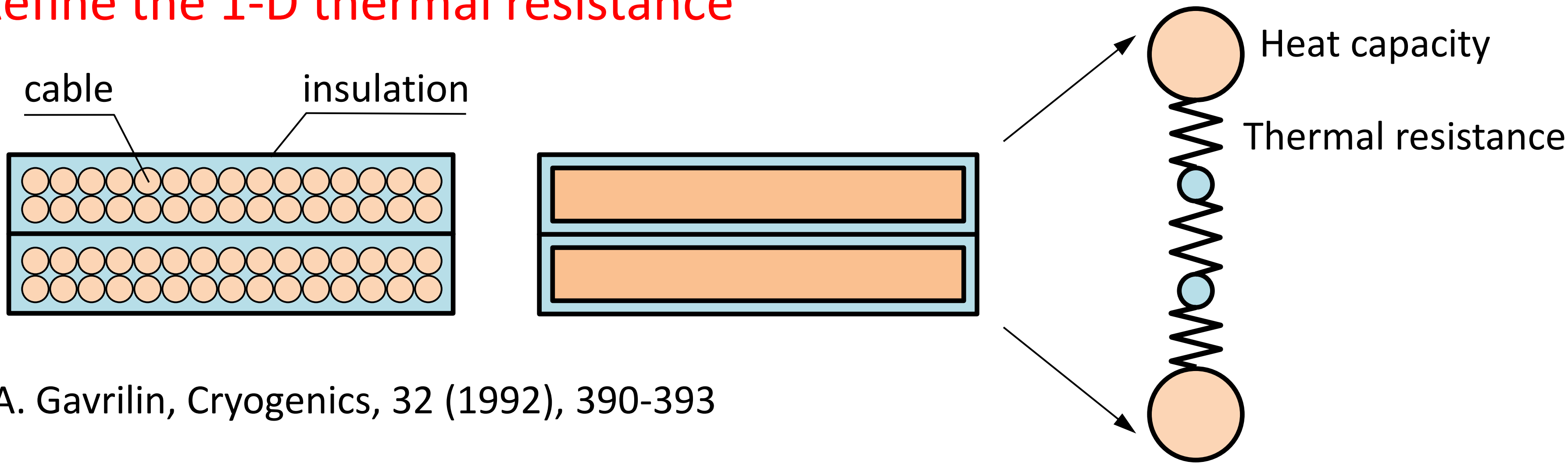




Implementation in ROXIE, N. Schwerg, B. Auchmann, S. Russenschuck

Higher order thermal coupling

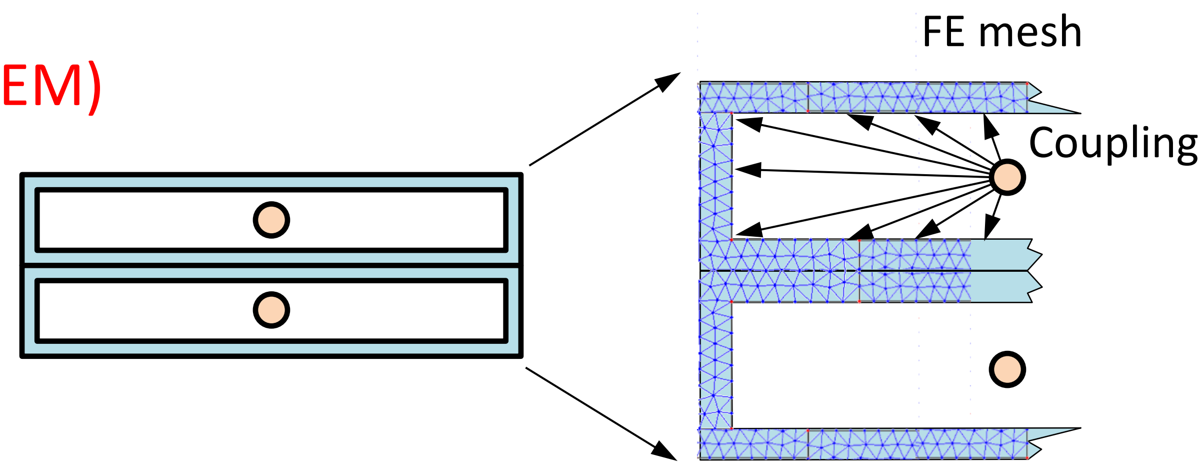
Refine the 1-D thermal resistance



A. Gavrilin, Cryogenics, 32 (1992), 390-393

Hybrid model (DOF<->FEM)

SUPERMAGNET
VINCENTA
4C



This would be great, but how to make it work in case of quench ?!?

Coupling to circuit model

From MT-23 4OrCa-01

Circuit models and magnetic fields

- *A wealth of models and codes are available for the simulation of*
  - *Current transients in a circuit made by an arbitrary number of inductances, resistances (capacitances, current and voltage sources, passive and active non-linear components, ...)*
  - *Magnetic field generated by arbitrary current distributions in space (steady state and transient, in presence of magnetic materials, ...)*
- *Consistent modelling is important, e.g.*
  - *current waveform in case of quench with no dump*
  - *AC-loss induced quenchback*

Coupling is "easy", as the time scales of the circuit response are naturally long (large inductances, and small resistances)

Case study: simulations performed

Quench of MBPS01, 1 m long, single aperture, 11 T dipole model
Magnet running at 11850 A, quench triggered by QH

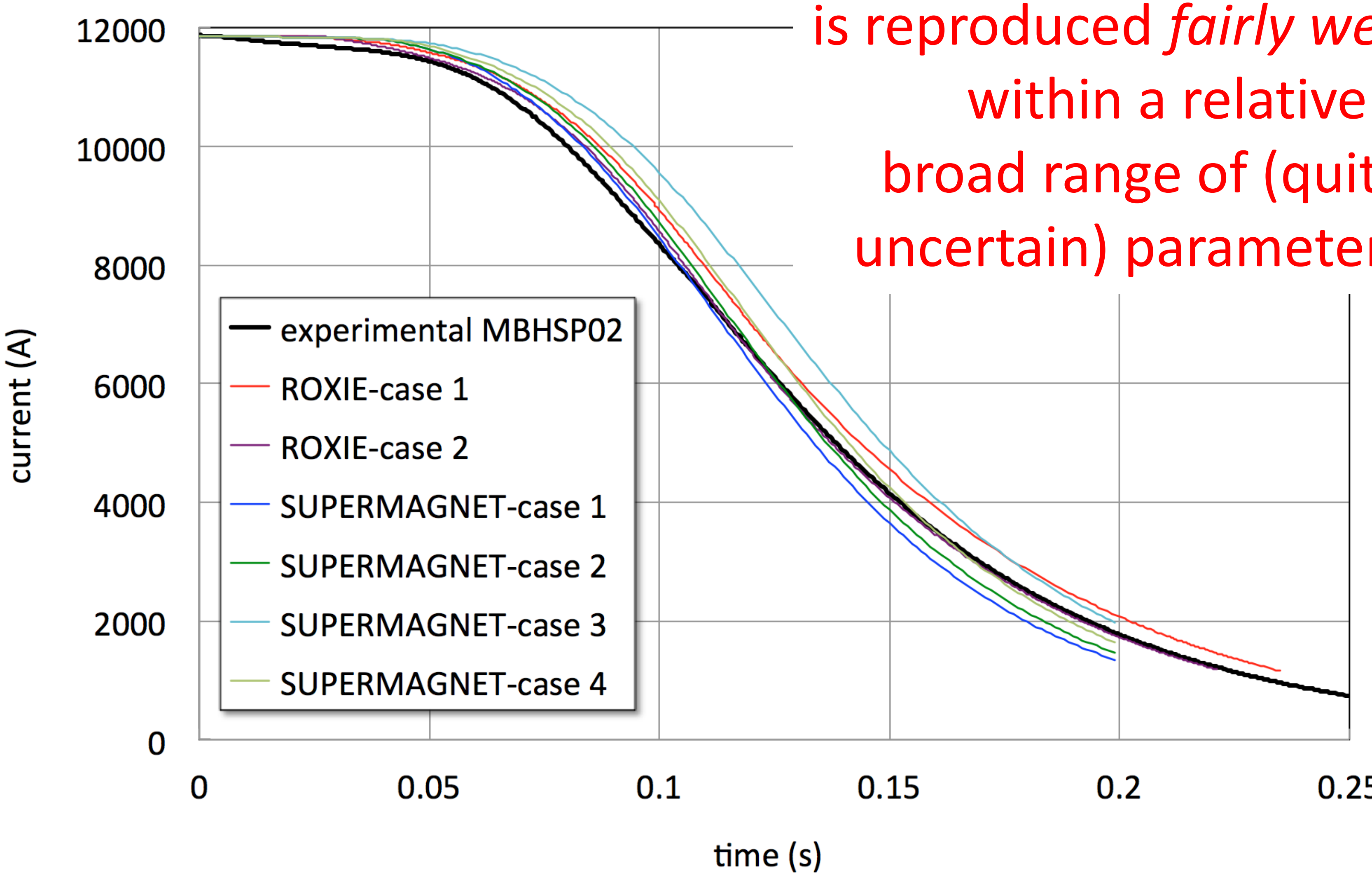
- ROXIE
  - 3-D slice simulation, scaled by the length
    - 1-D model of the cable
    - 2-D thermal network, first order thermal coupling
  - Self-consistent current and field model
  - Case 1: QH powered with nominal power (LF: 70.5 W/cm^2; HF: 45.5 W/cm^2)
  - Case 2: OL temperature raised above Tcs after measured QH delay
- SUPERMAGNET
  - 3-D model of the complete magnet
    - 1-D simulation of cable, adaptive mesh
    - 2-D thermal network, second order coupling
  - Self-consistent current calculation, scaled field
  - *Quench triggered at the HF pole turn, detected (100 mv, 10 ms)*
  - QH modelled as power input to OL with 25 ms delay

case	IT t_{ins} (mm)	IL t_{ins} (mm)	QH power (W/m)
1	0.2	0.2	400
2	0.2	0.4	400
3	0.2	0.2	100
4	0.2	0.4	200

Quench simulation – 1

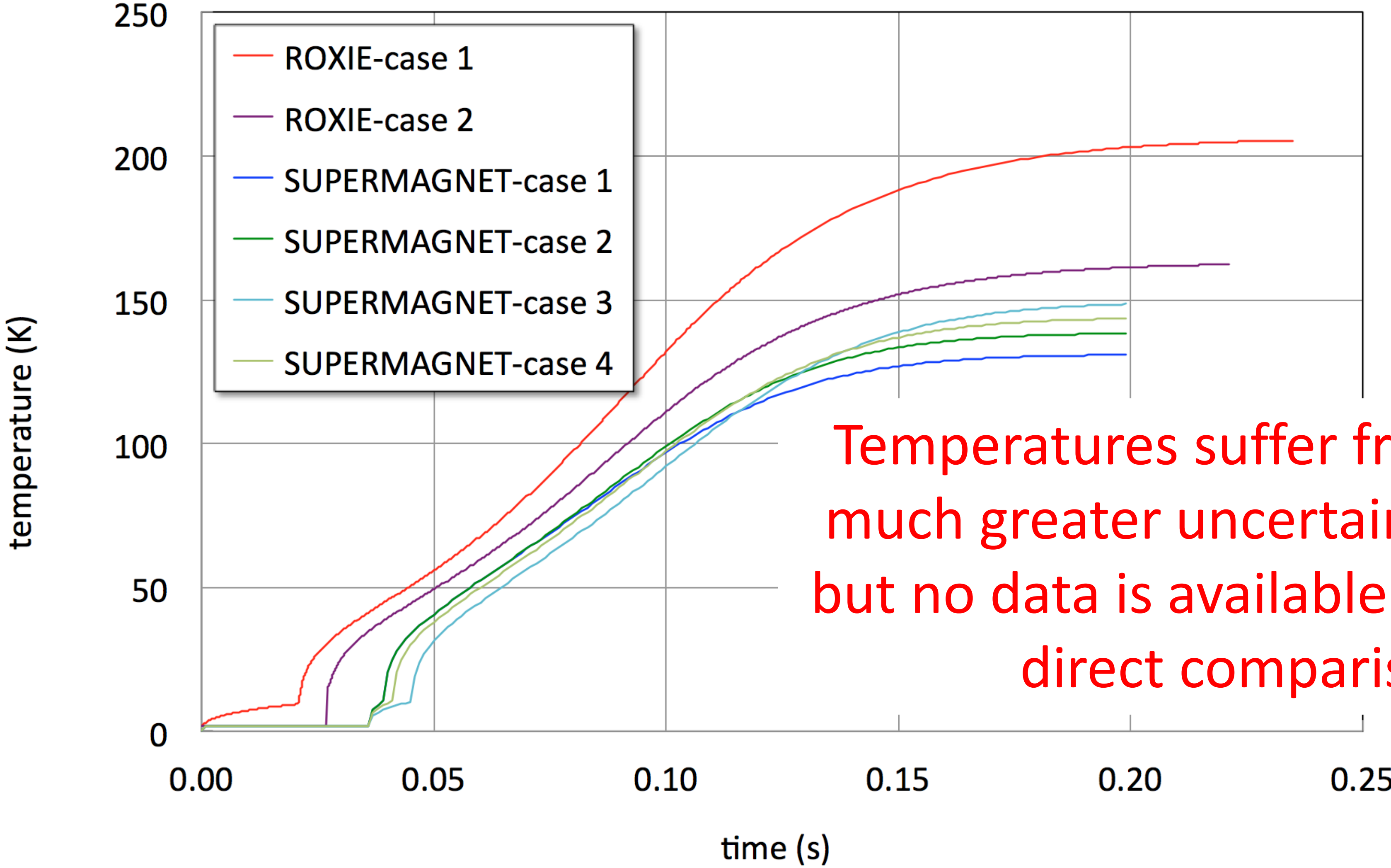
- Current vs. time

The current waveform is reproduced *fairly well* within a relatively broad range of (quite uncertain) parameters



Quench simulation – 2

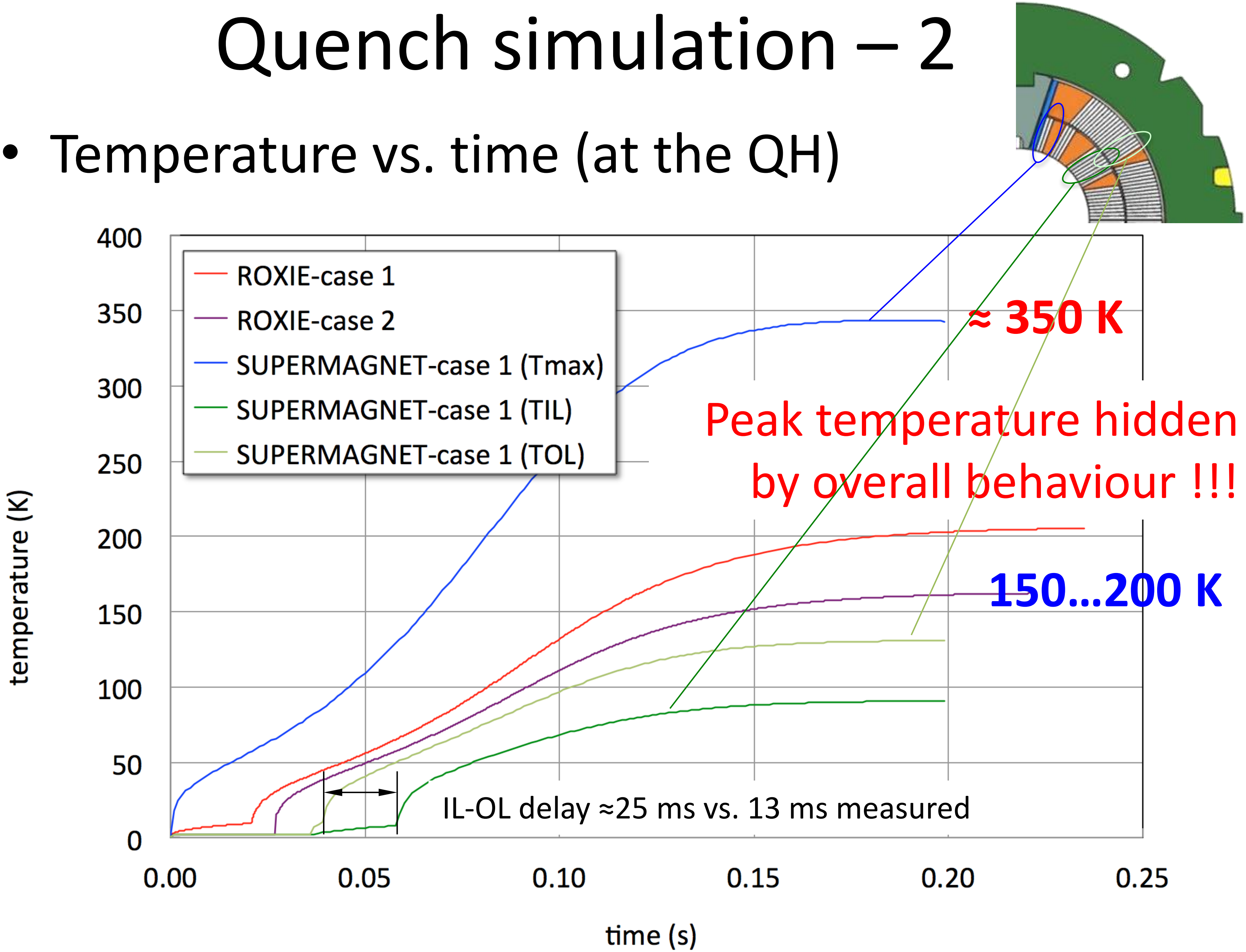
- Temperature vs. time (at the QH)



Temperatures suffer from much greater uncertainty, but no data is available for direct comparison

Quench simulation – 2

- Temperature vs. time (at the QH)



Lots of further details

- Transverse heat transfer (geometry, properties, anysotropy) – measure !
- Numerical stability, convergence, consistence
- Quench heater efficiency (geometry, heat diffusion)
- Effect of cooling (helium bath, superfluid, flows ?)
- Quench-back (AC loss distribution in the coil and structure)
- Resistive, inductive, capacitive effects in the circuit (non-linear components such as cold diodes, internal voltages)

A daunting problem ?

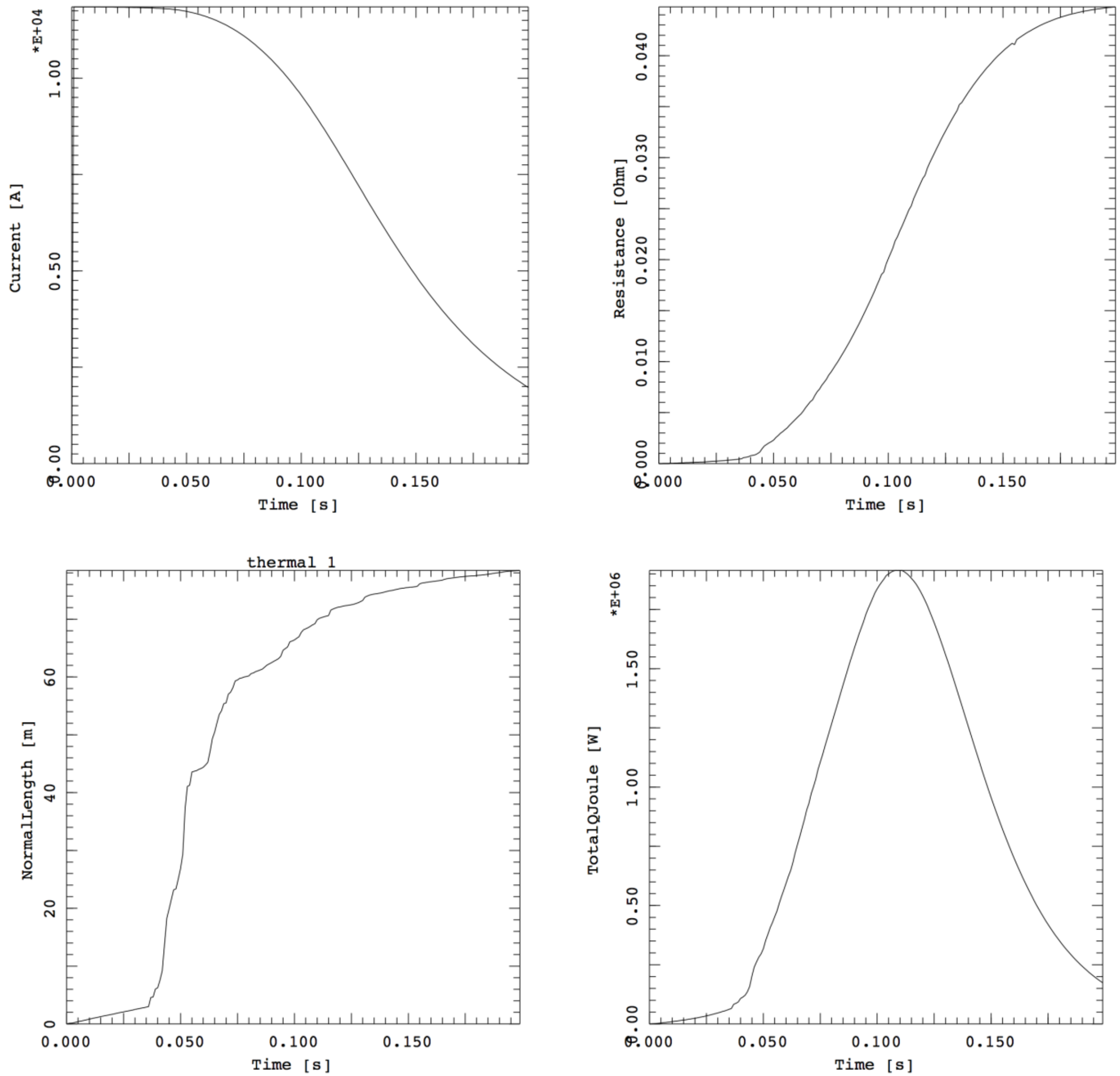
A wonderful playground

Conclusions

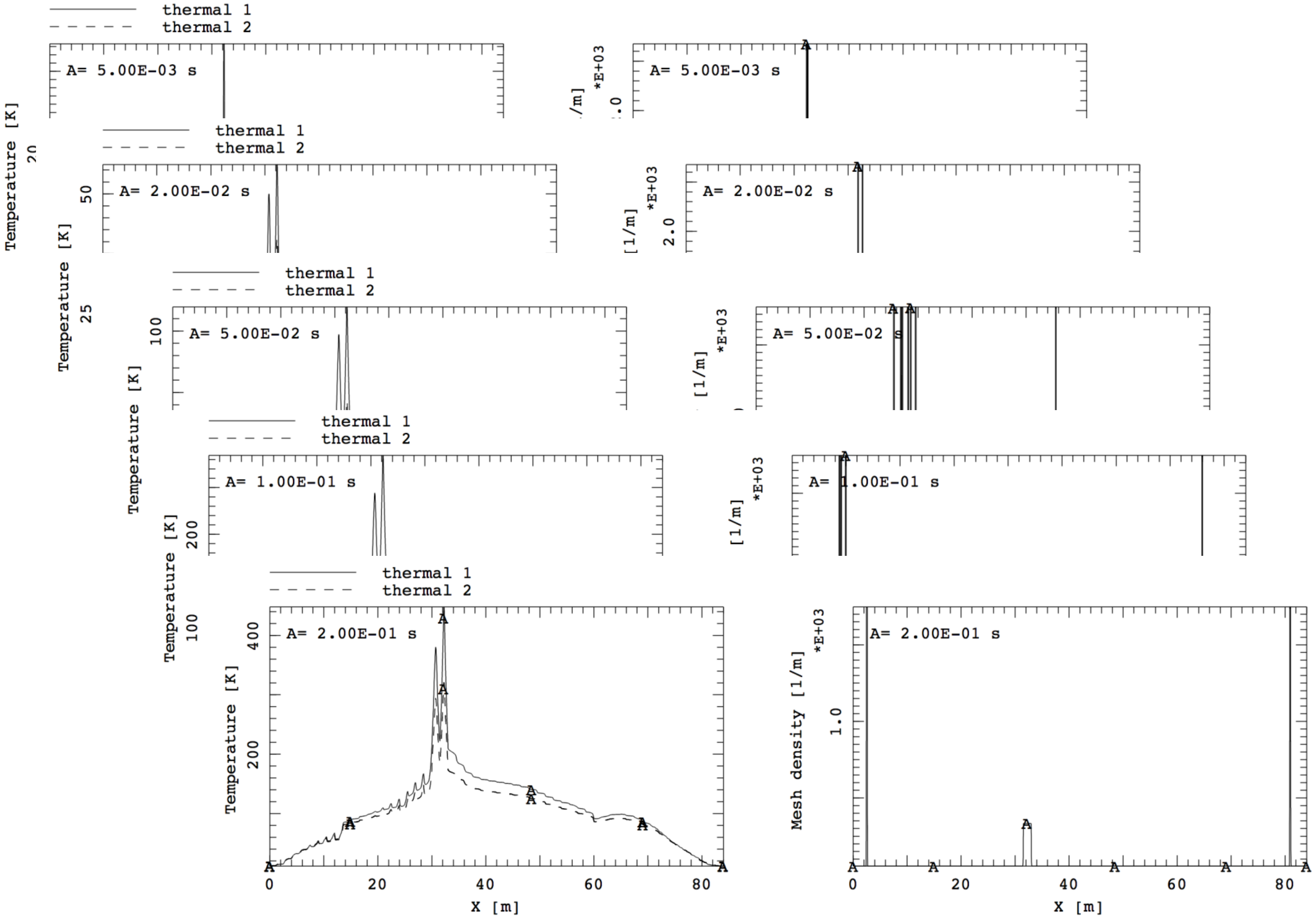
- New accelerator magnets based on Nb_3Sn are pushing the boundary of protection
- Accurate simulation of quench transients in these magnets is crucial to the design choices, definition of priority R&D and to prove that the magnets are fit for operation
- We have today large uncertainties in the simulation 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 !!!

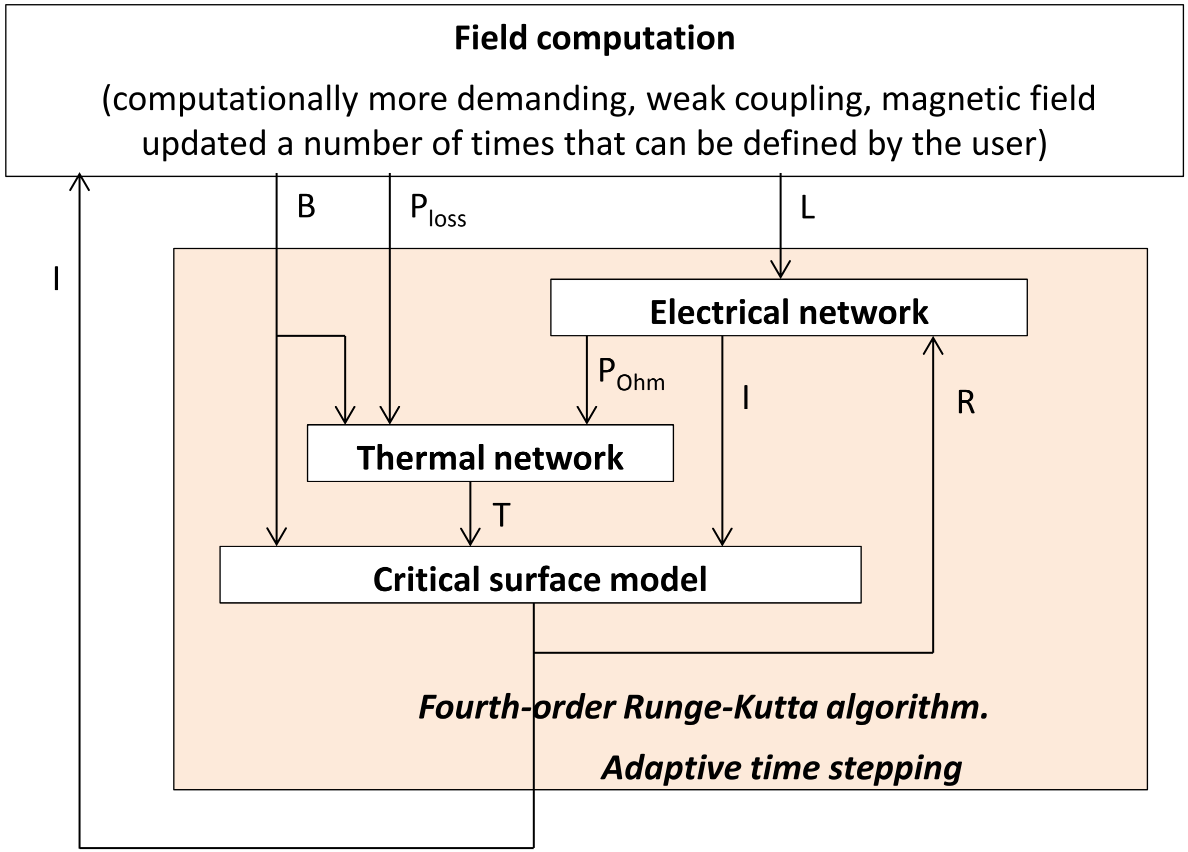
Typical quench sequence (case 4)



Typical quench sequence (case 4)



ROXIE Quench Module



Explicit Runge-Kutta solver: Conditionally stable
Adaptive time stepping: Necessary, high non-linear problem
Static mesh: computationally "expensive"

Simulation : Test bench conditions

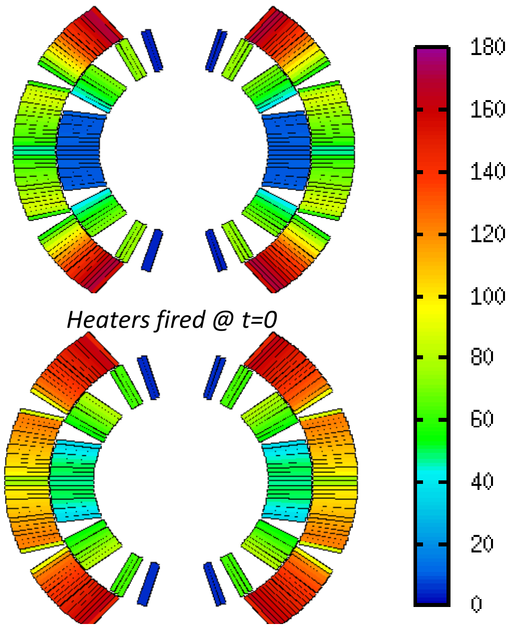
Manual trips with the two operating protection heaters

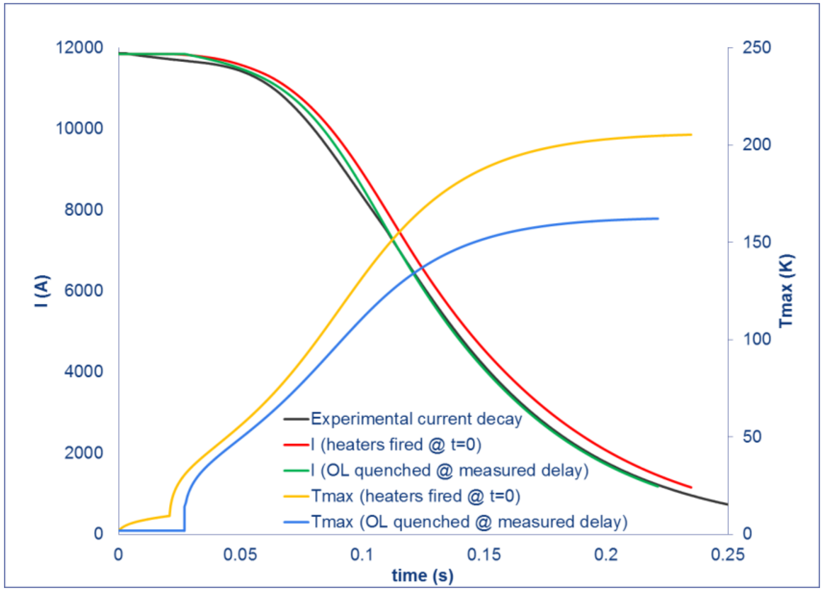
Dump delay 1000 ms → Self-dump (non-linear inductance and resistance)

I_0 = 11850 A, T_{bath} = 1.9 K

	MIITs after heater effective [MA²s]	MIITs from heater fired until effective [MA²s]	OL-IL delay [ms]	PH delay [ms]
Experimental data	10.9	3.4	13.4	≈27
CASE1: OL heaters fired @ t=0 (computed heat transfer from heater to coil)	12.3	2.9	42.5	21
CASE2: OL quenched @ PH measured delay (OL fully quenched at PH measured delay)	11.4	3.8	33.8	27

Max. Temperature [K]





Heaters delay