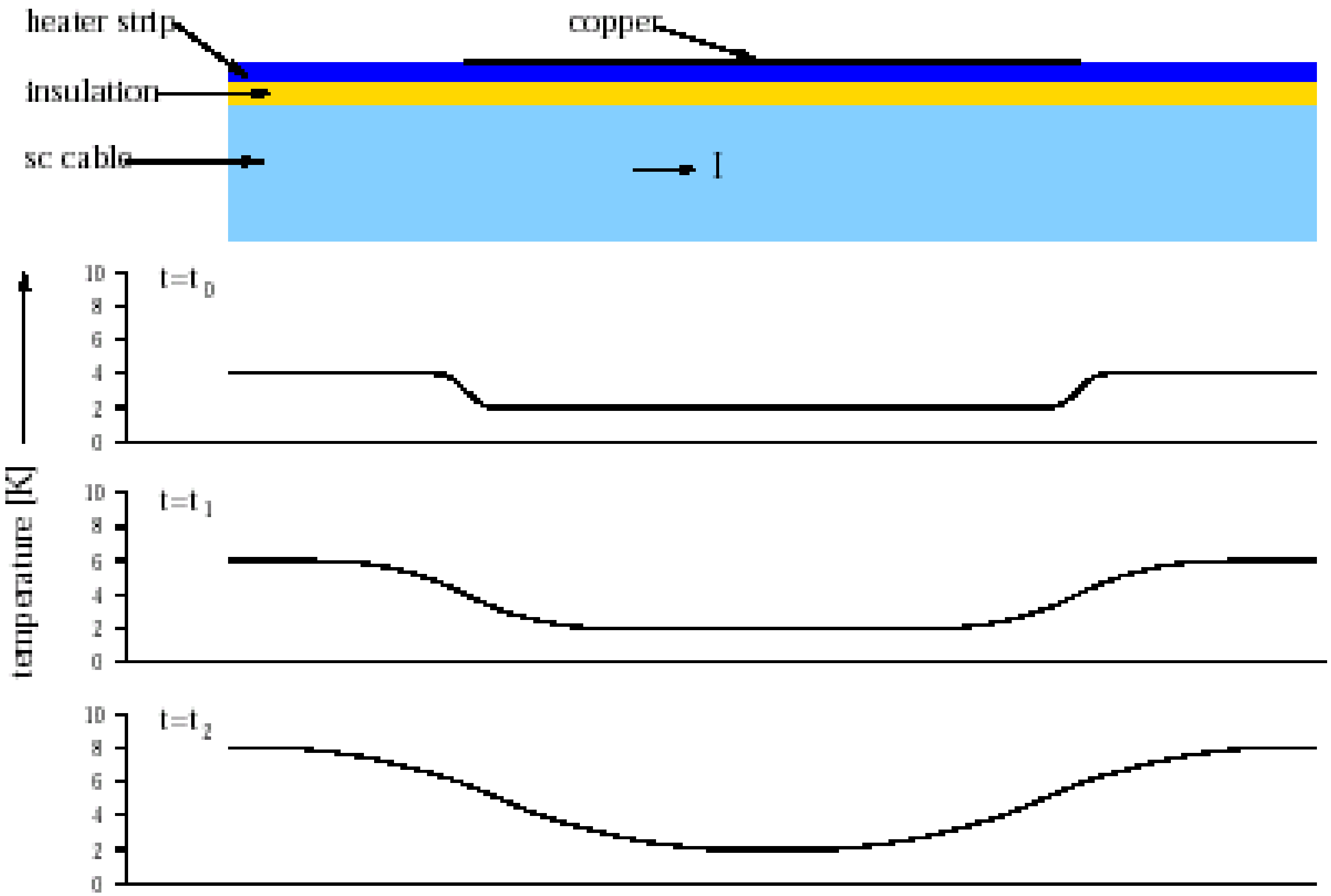
Numerical Modeling & Stability Analysis of the LHC Superconducting Cables

the experience with
SPQR and THEA codes

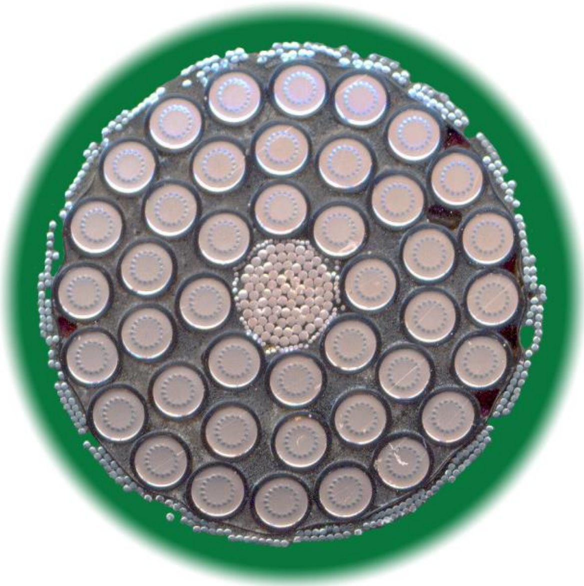
Overview

- Short history of SPQR and THEA codes
- Stability margin
- The models
- Simulations examples and comparison between the two codes
- Work in progress
- Conclusions

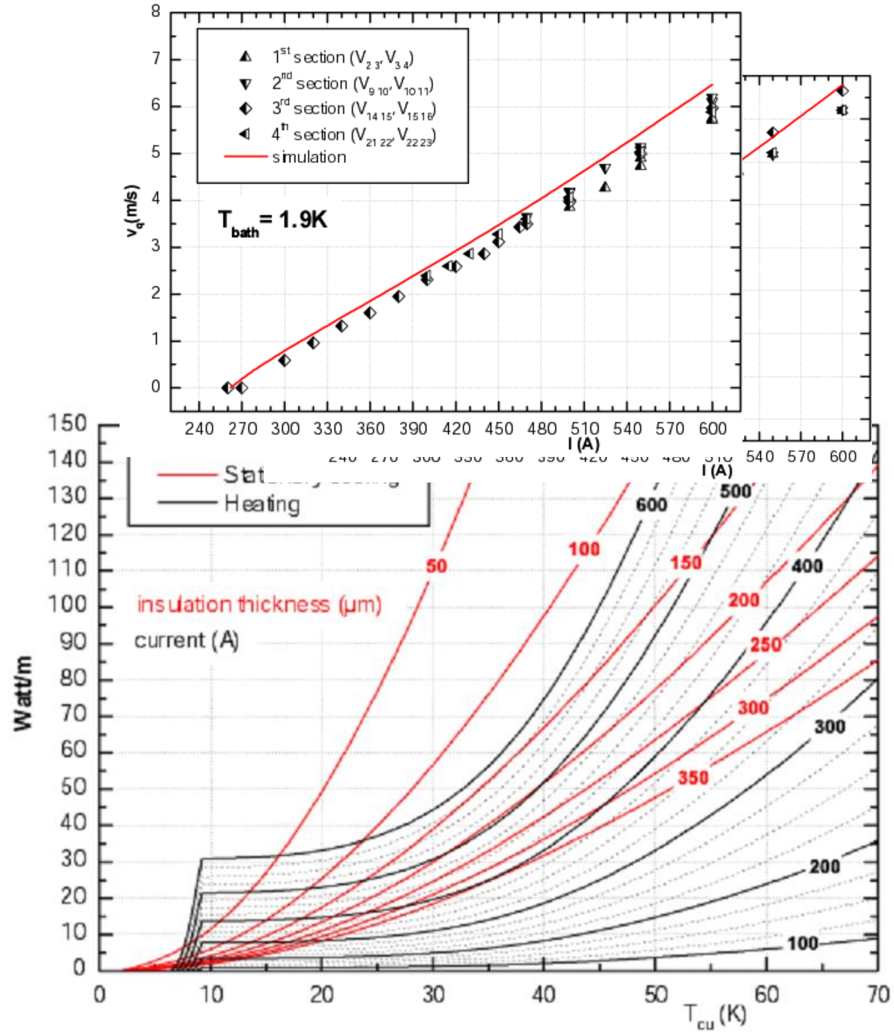
SPQR History - 1/5



SPQR History - 2/5

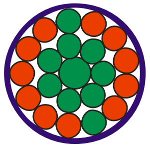


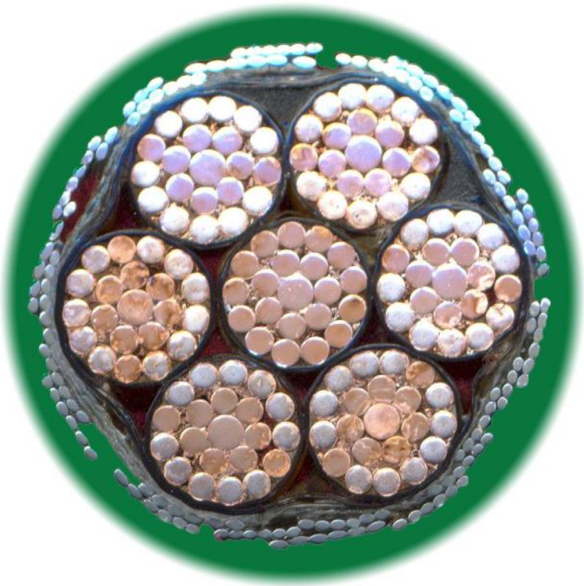
600 A auxiliary busbars
powering the LHC
corrector magnets
42 conductors
A_{cu}=1.8 mm^2
A_{NbTi}=0.2mm^2



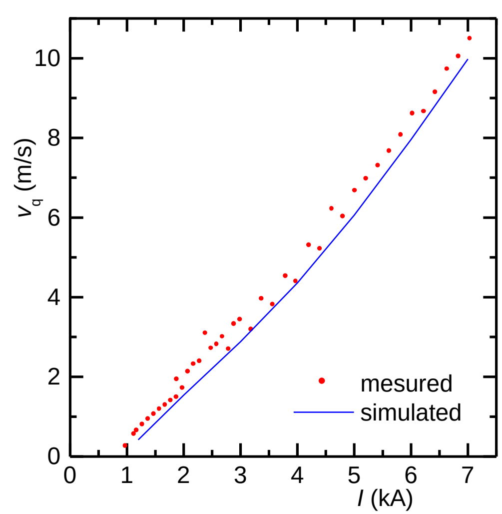
R.Herzog, M.Calvi, F.Sonnemann and J.M.Pelegrin, “Quench Propagation in the Superconducting 6 kA Flexible Busbars of the LHC”
Presented at the 2001 CEC/ICMC 2001, 16-20 July 2001, Madison, Wisconsin, USA

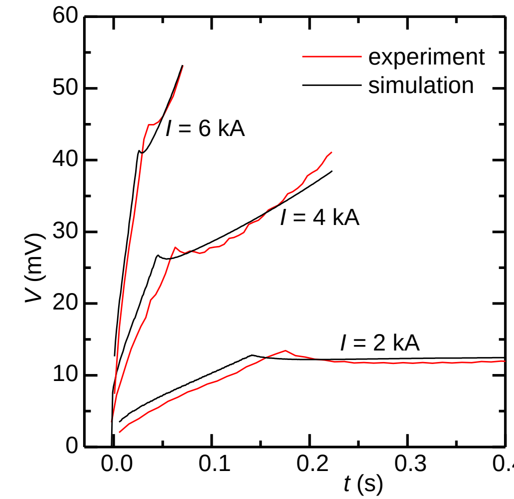
SPQR History - 3/5

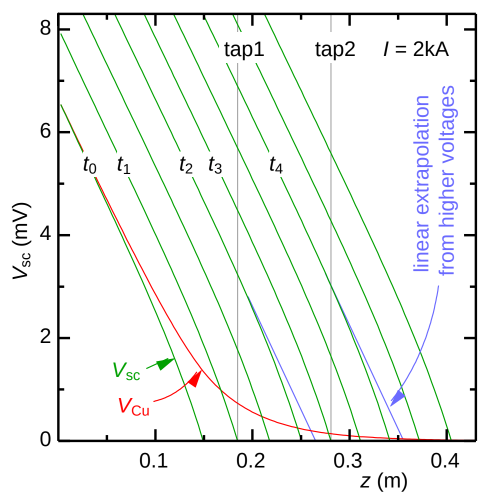


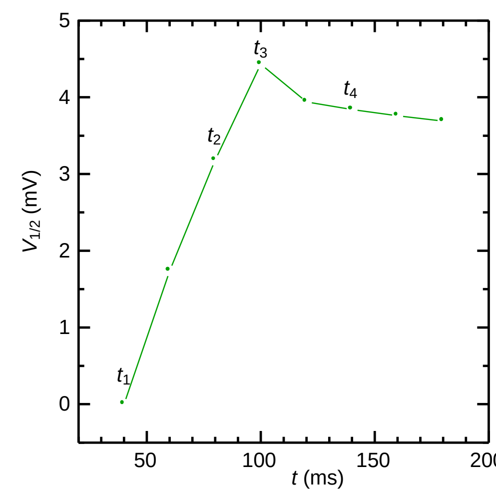


6 kA busbars
powering magnets
individually in the insertion
regions of the LHC
6 conductors
A_{cu}=8.7 mm^2
A_{NbTi}=2.6mm^2

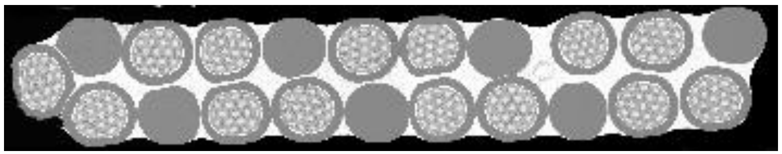




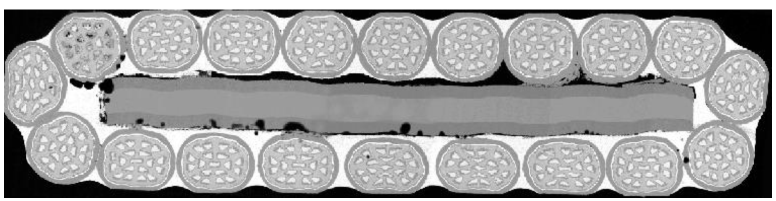




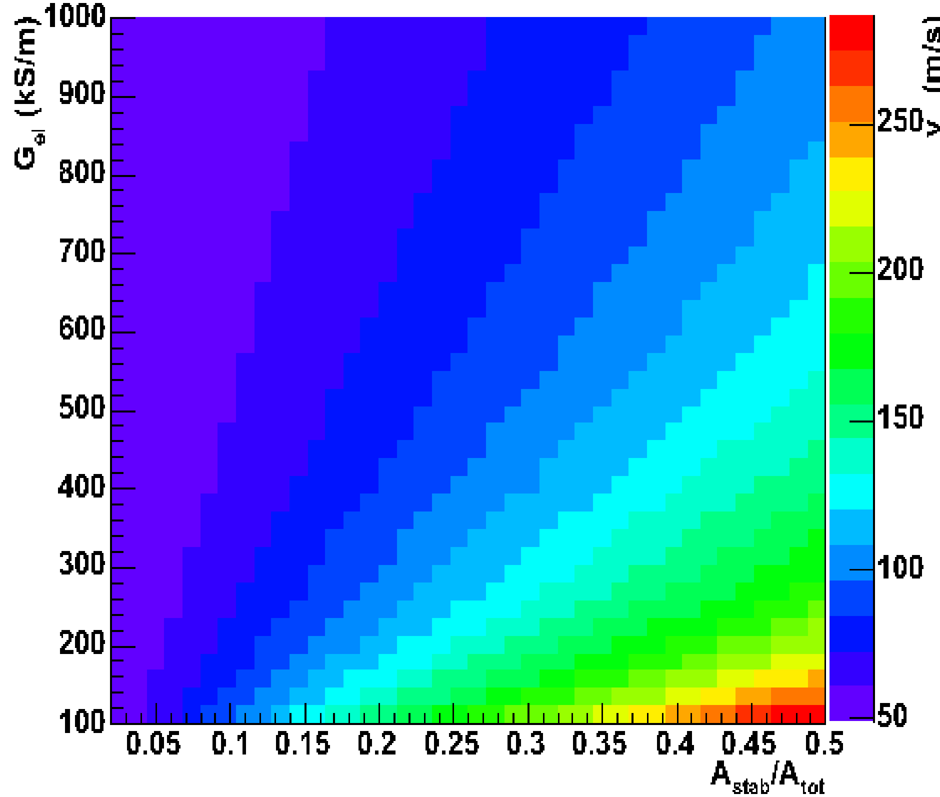
SPQR History – 4/5



Mixed Strand Cables
14 Sc strands
7 Cu strands

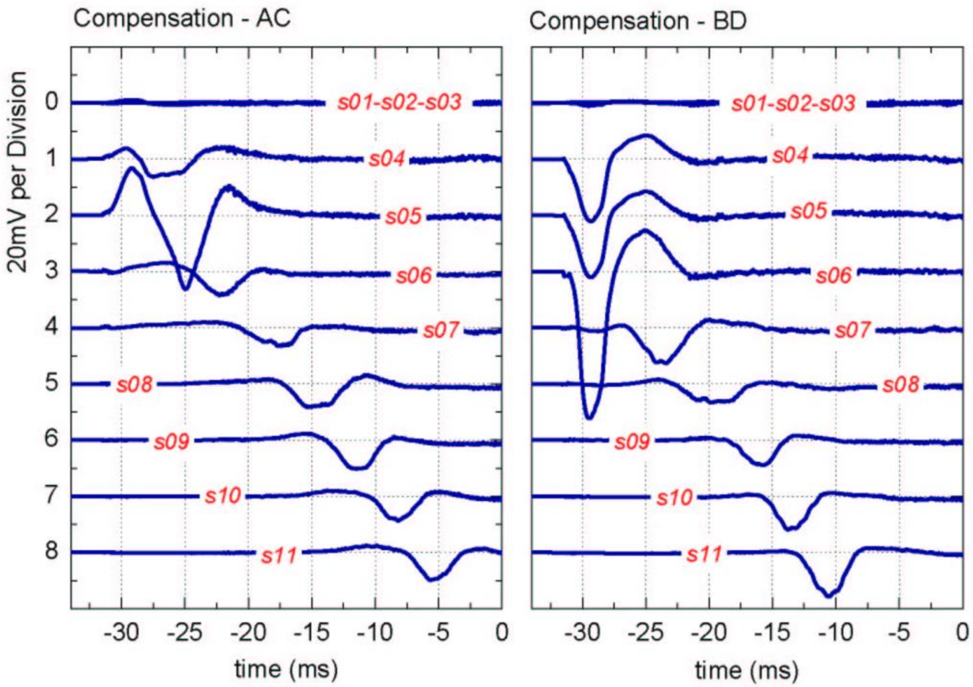


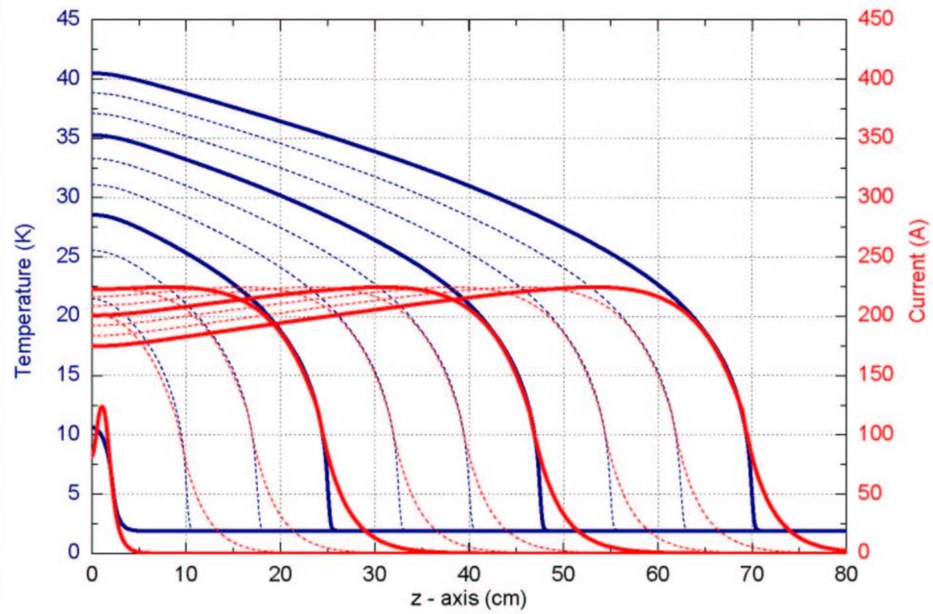
Mixed Strand Cables
20 Sc strands
Cu core
(Courtesy of M.Coccoli)



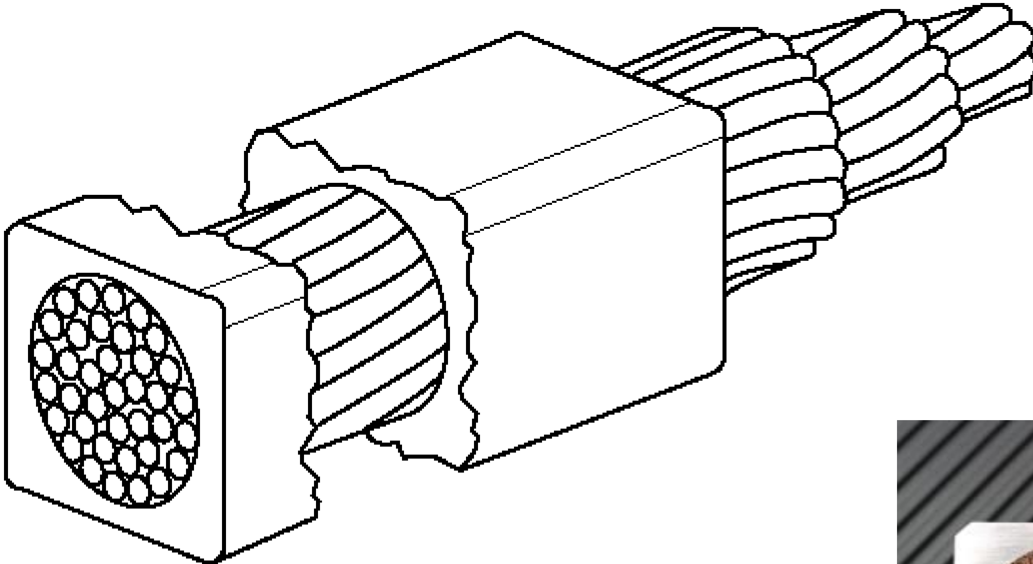
SPQR History – 5/5

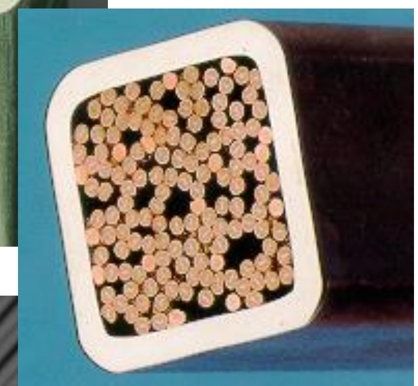
The Local Quench Antenna





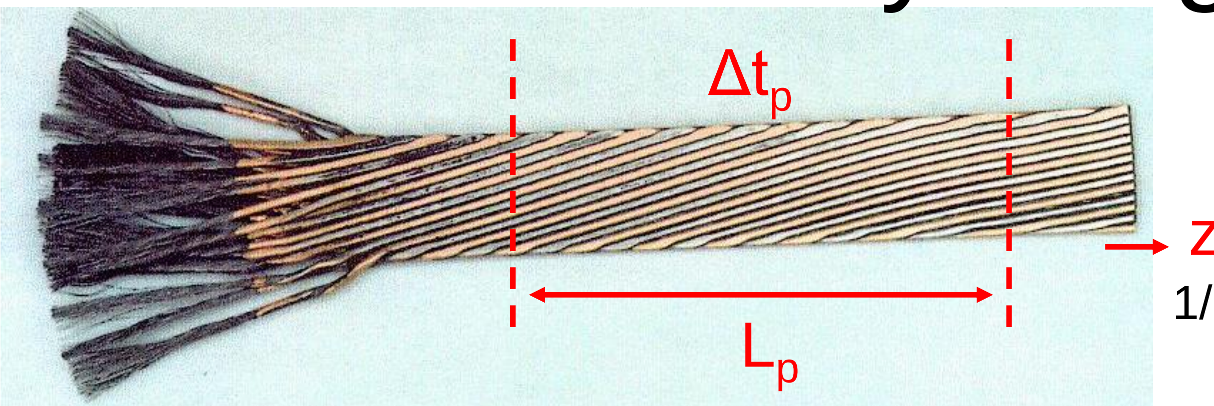
THEA – code (Luca’s history)



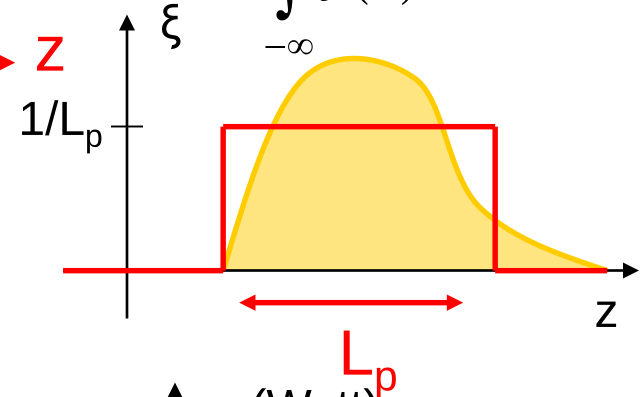


ROUND BUNDLE WITH 37 STRANDS ENCLOSED IN R
CONDUIT - SHOWING TRANSPOSITION OF ST

Stability Margin



$$\int_{-\infty}^{+\infty} \xi(z)\,dz = 1$$

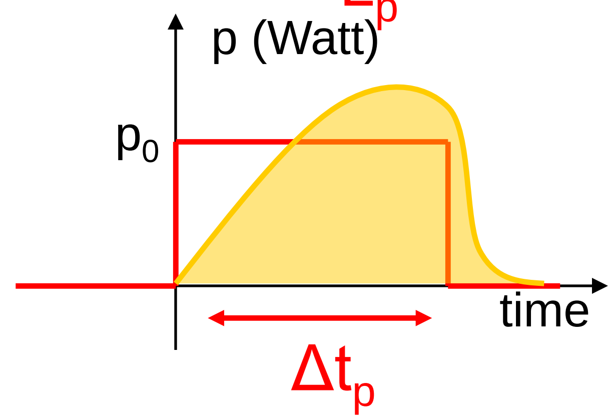


$$\dot{q} = \xi(z)\,p(t)$$

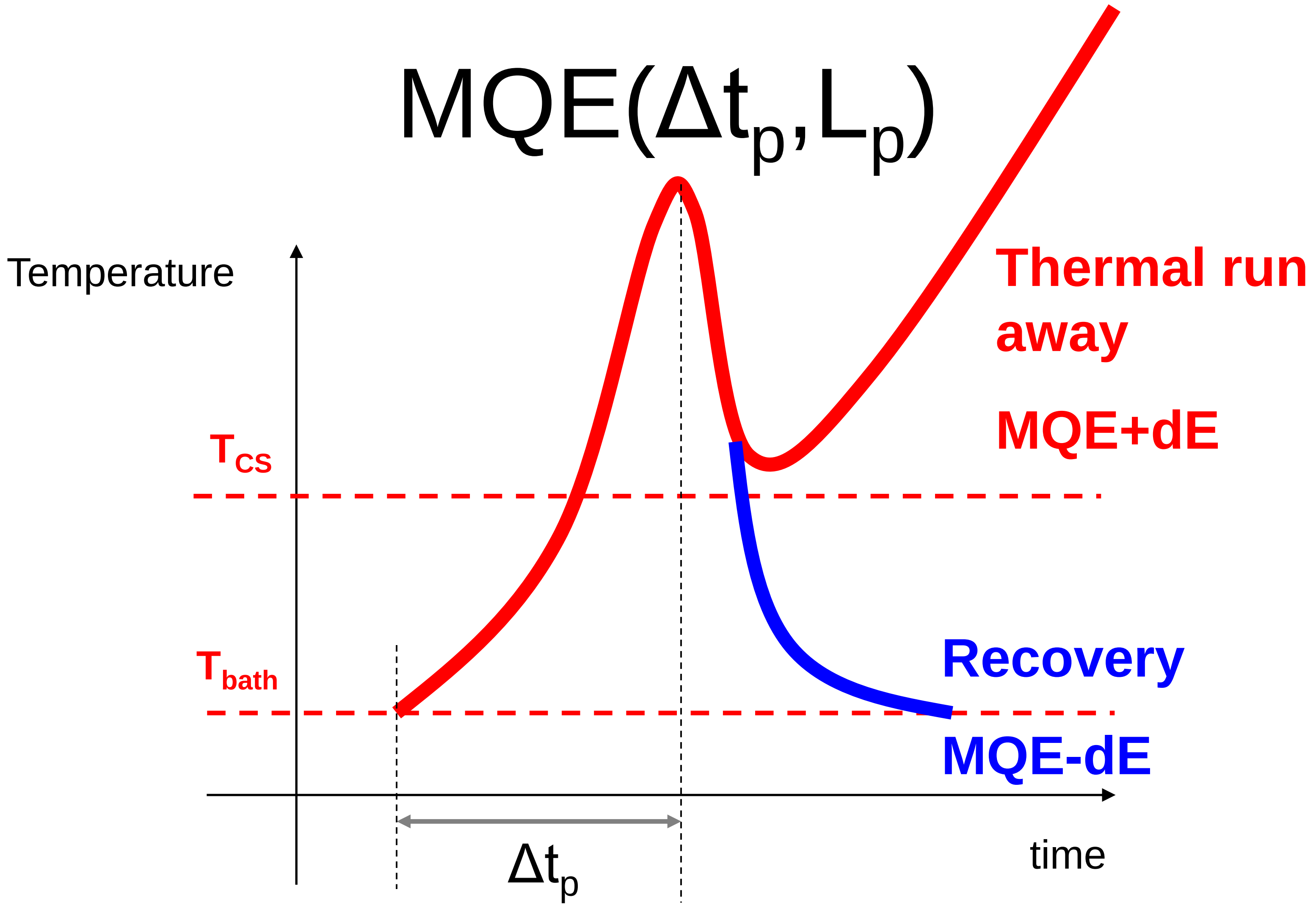
$$E = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \dot{q}(z,t)\,dz\,dt = \int_{-\infty}^{+\infty} p(t)\,dt$$

$$E = p_0 \Delta t_p$$

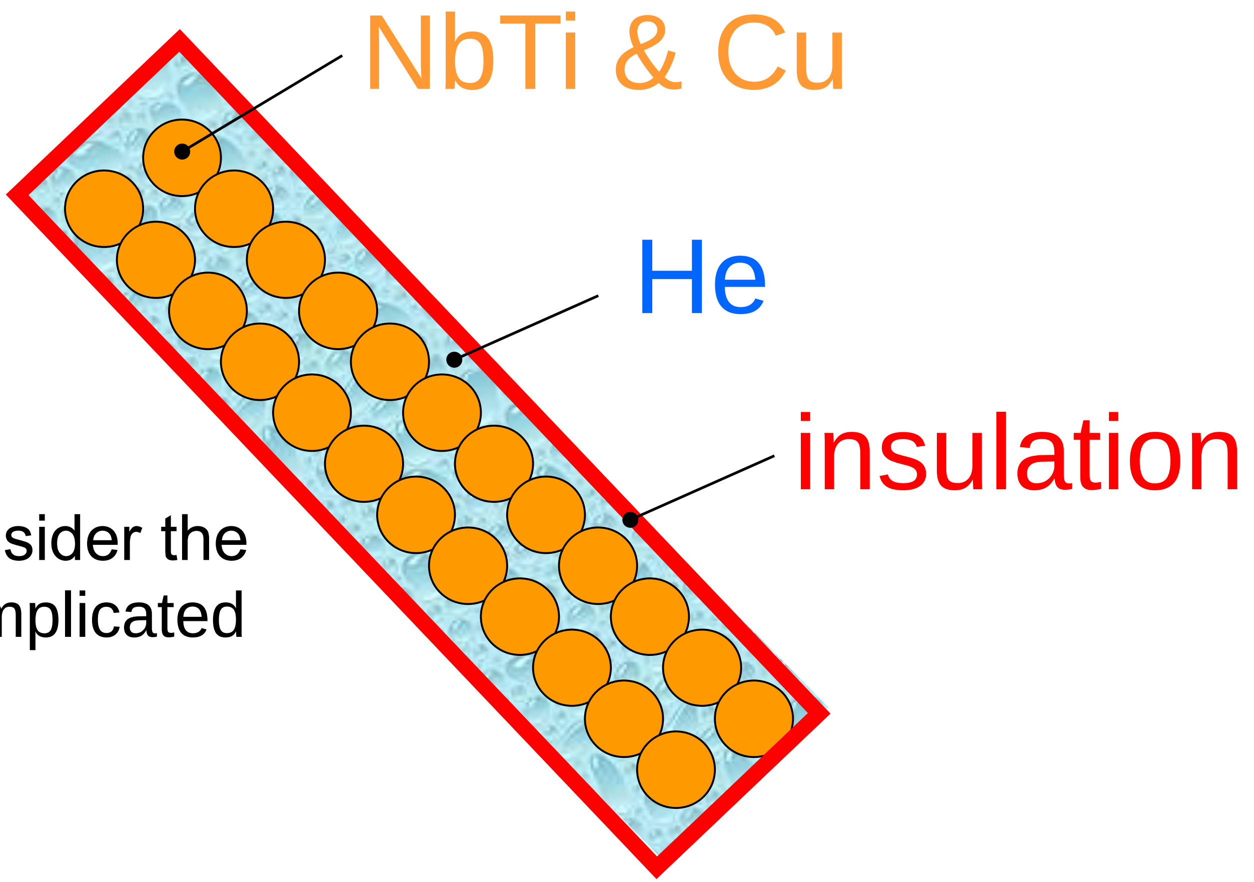
$$\frac{E}{\Delta V_p} = \frac{p_0 \Delta t_p}{A L_p}$$



MQE(Δt_p,L_p)

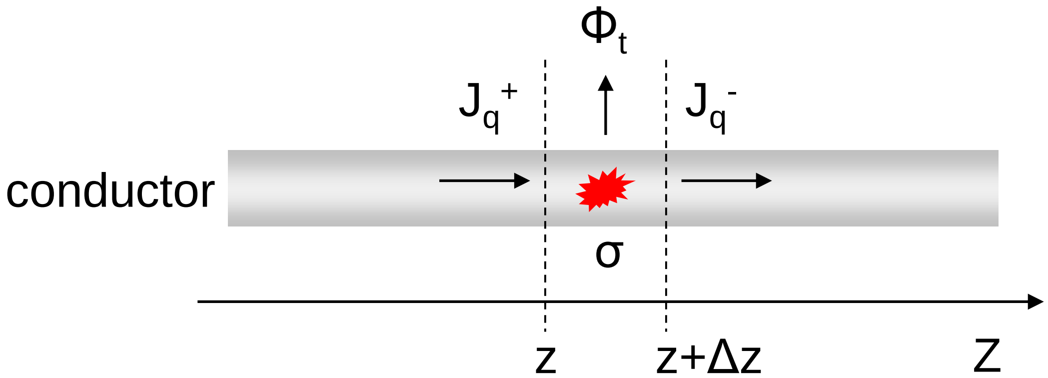


The physical system



Let's consider the most complicated cable

Thermal 1/2



The internal energy balance can be expressed as: $\dot{u} = -\mathrm{div}\cdot j_q + \sigma - \Phi_t$

$$\dot{u} = Ac(T)\,\dot{T}$$

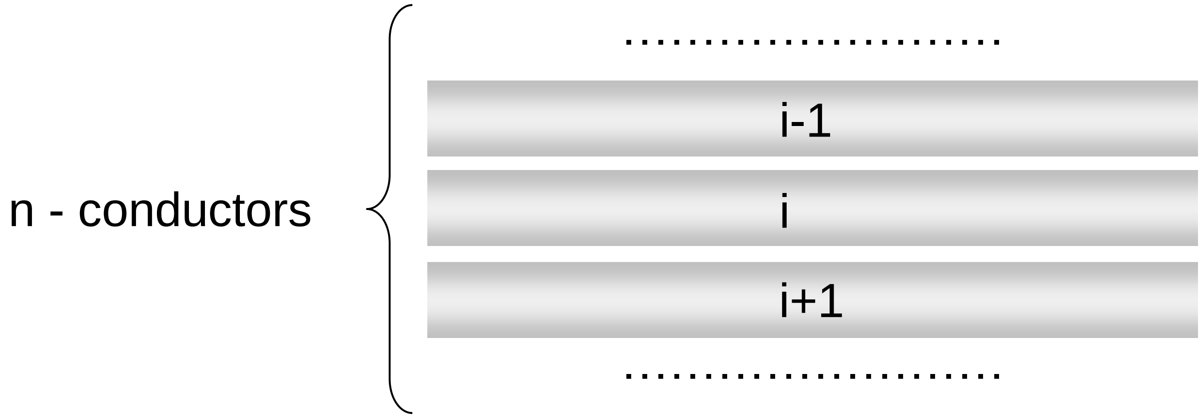
$$j_q = -Ak(T)\,\frac{\partial T}{\partial z}$$

$$\sigma = RI^2$$

$$R = \rho(T, B)/A$$

$$Ac(T)\,\dot{T} = A\,\frac{\partial}{\partial z}\left(k(T)\frac{\partial T}{\partial z}\right) + RI^2 - \Phi_t(T, T_b \ldots ?)$$

Thermal [2/2]



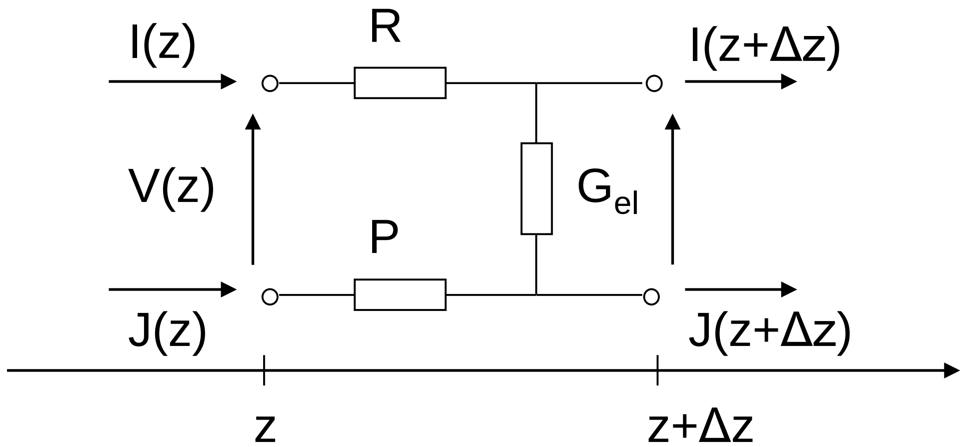
$$A_i c_i(T_i)\dot{T}_i = A_i \frac{\partial}{\partial z}\left(k(T_i)\frac{\partial T_i}{\partial z}\right) + \sum_j \beta_{ij}(T_j - T_i) + R_i I_i^2 + \sigma^{extra}$$

Does the term of heat generation change too? Of course…

But it does depend on the actual electrical network

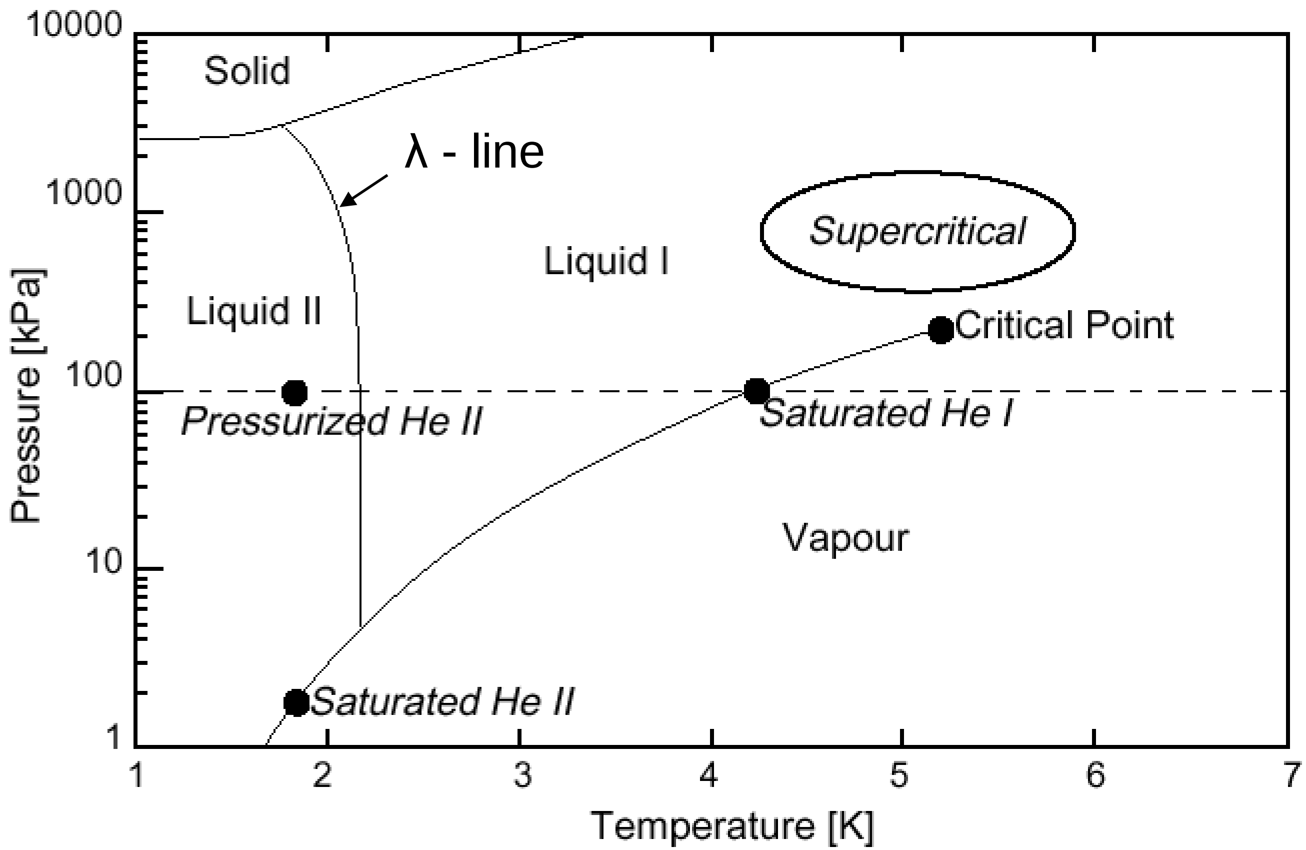
➔

Electrical



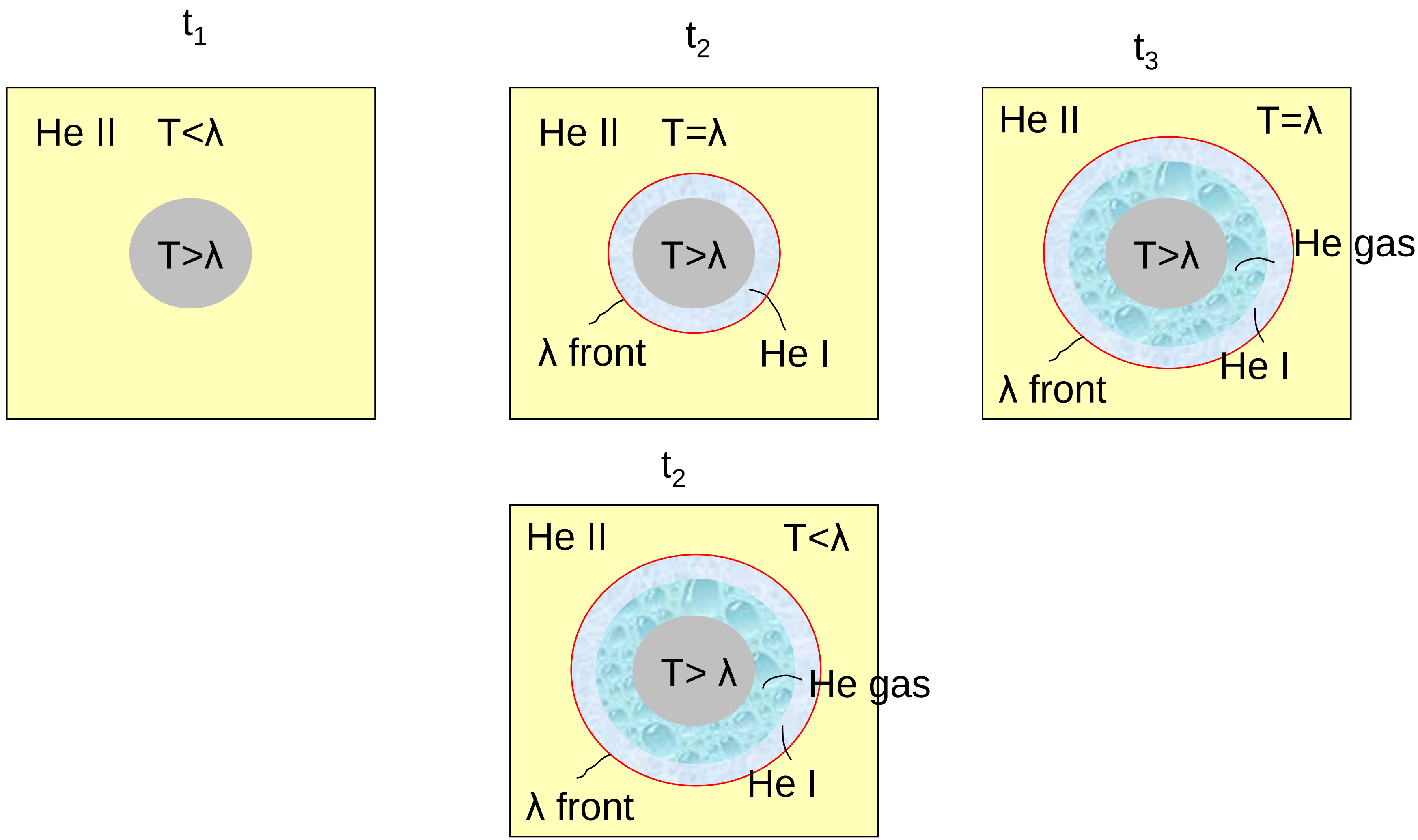
$$L_{eq}\dot{I} + \frac{1}{G_{el}}\frac{d^2 I}{dz^2} + \left(P(z) + R(z)\right)\cdot I = R(z)\cdot I_{tot}$$

Helium (1/2)



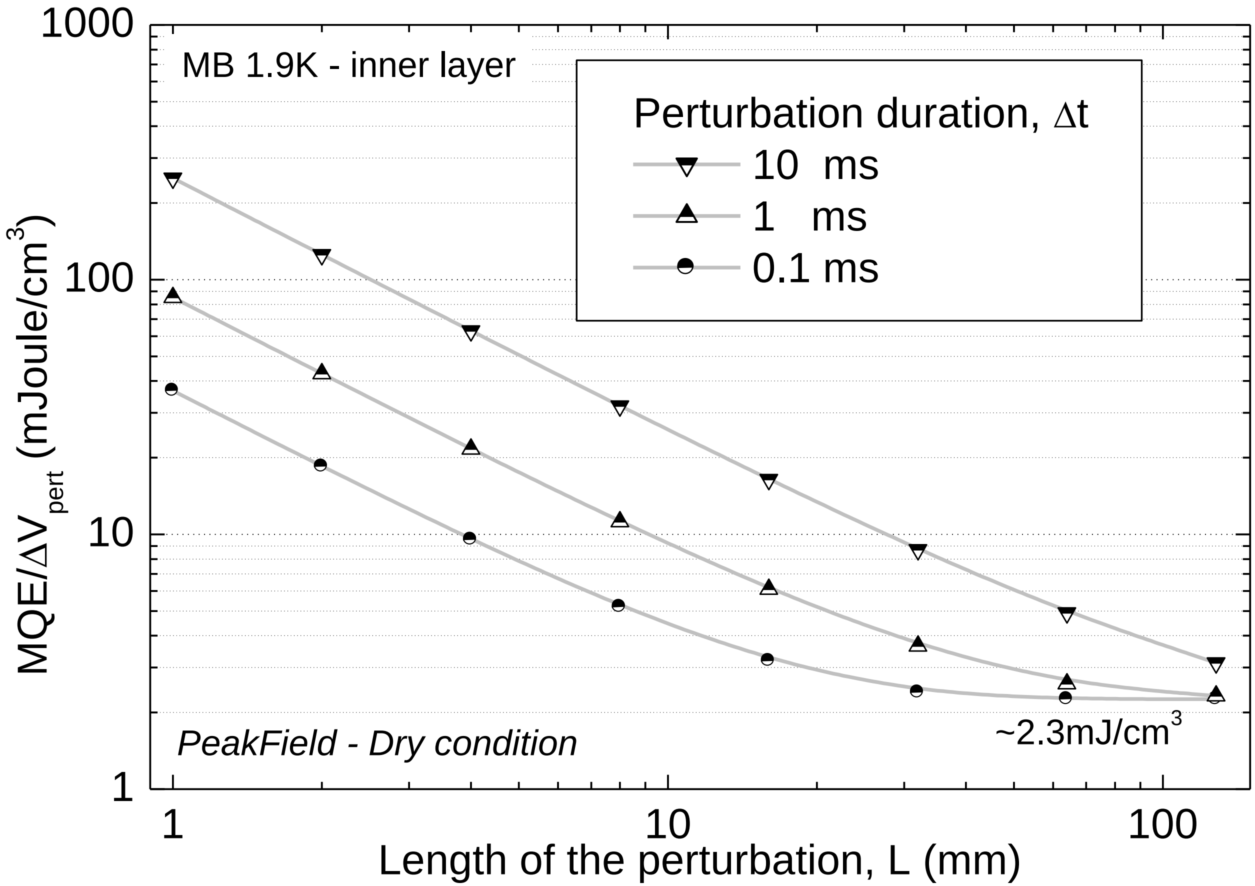
10000
1000
100
10
1
Solid
λ - line
Liquid I
Supercritical
Liquid II
Critical Point
Pressurized He II
Saturated He I
Vapour
Saturated He II
Pressure [kPa]
1
2
3
4
5
6
7
Temperature [K]

Helium (2/2)

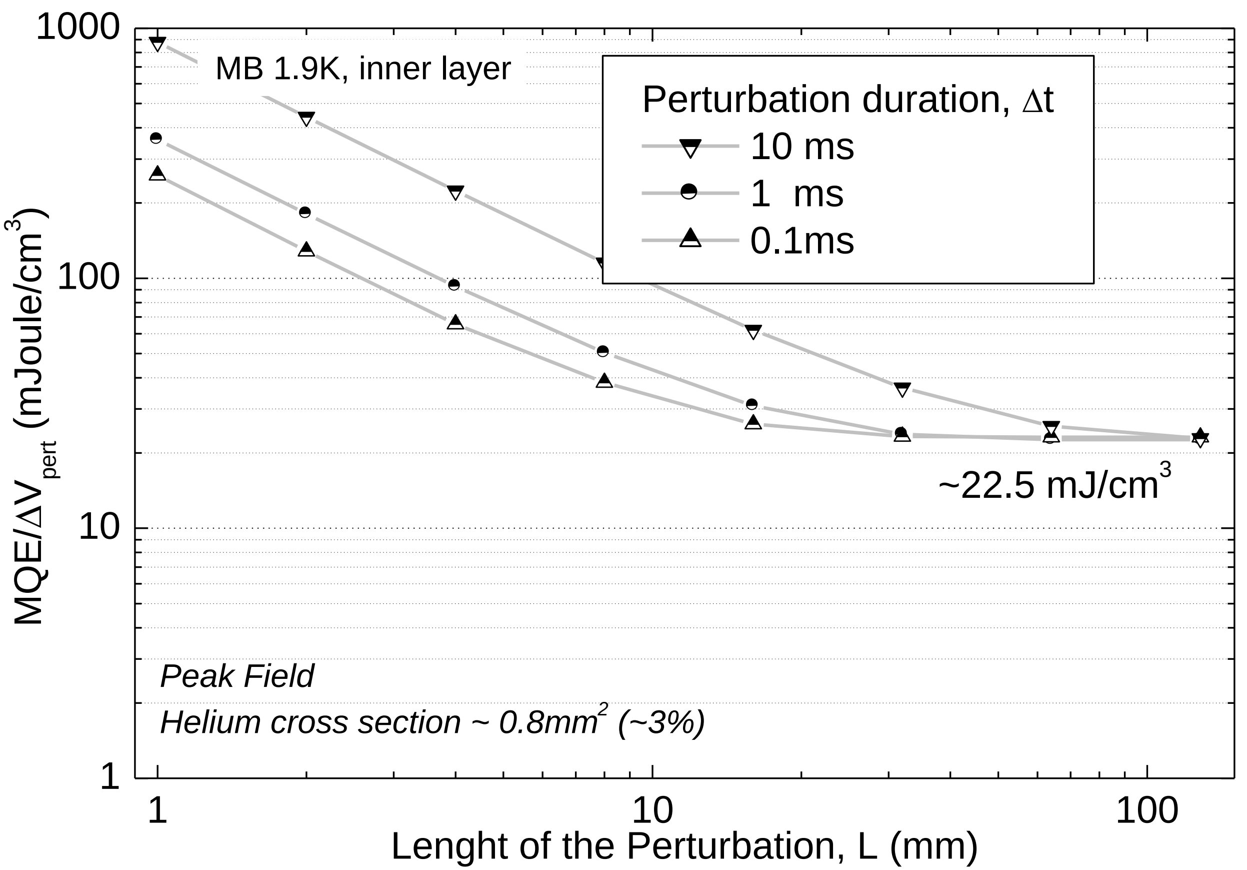


t1
He II
T<λ
T>λ
t2
He II
T=λ
T>λ
λ front
He I
t3
He II
T=λ
T>λ
He gas
He I
λ front
t2
He II
T<λ
T> λ
He gas
He I
λ front

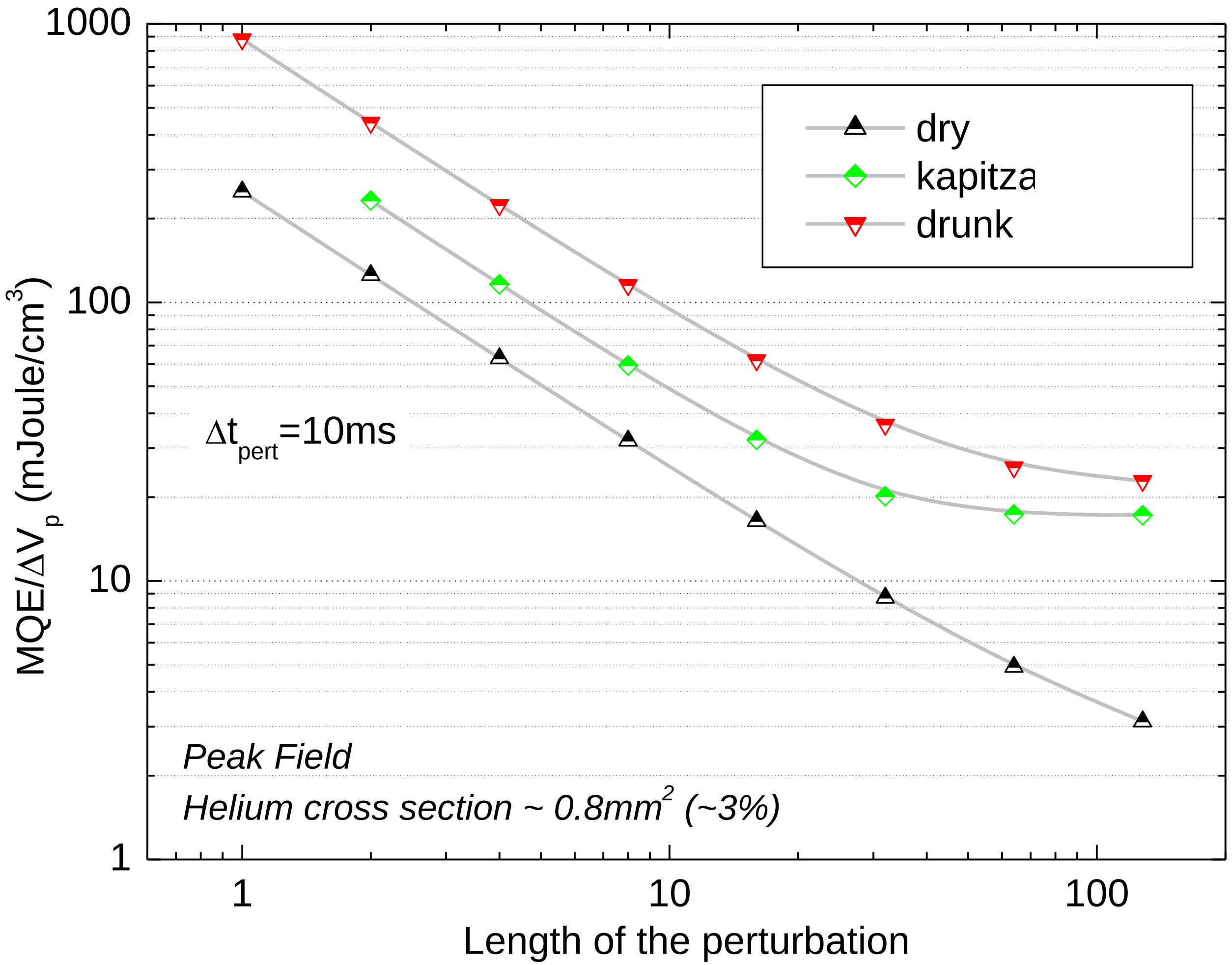
Space & Time Perturbation (1/3)



Space & Time Perturbation (2/3)

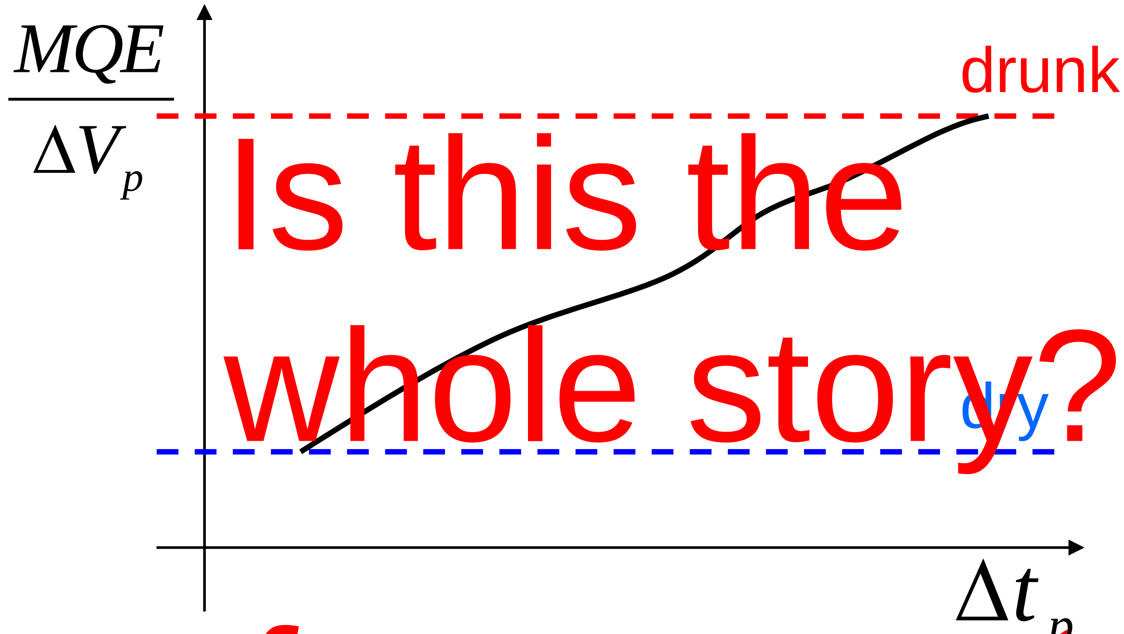


Space & Time Perturbation (3/3)



Resume 1

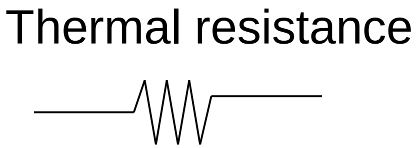
For length of perturbation larger than tens of centimeters the heat conductivity in the metallic part does not play a role



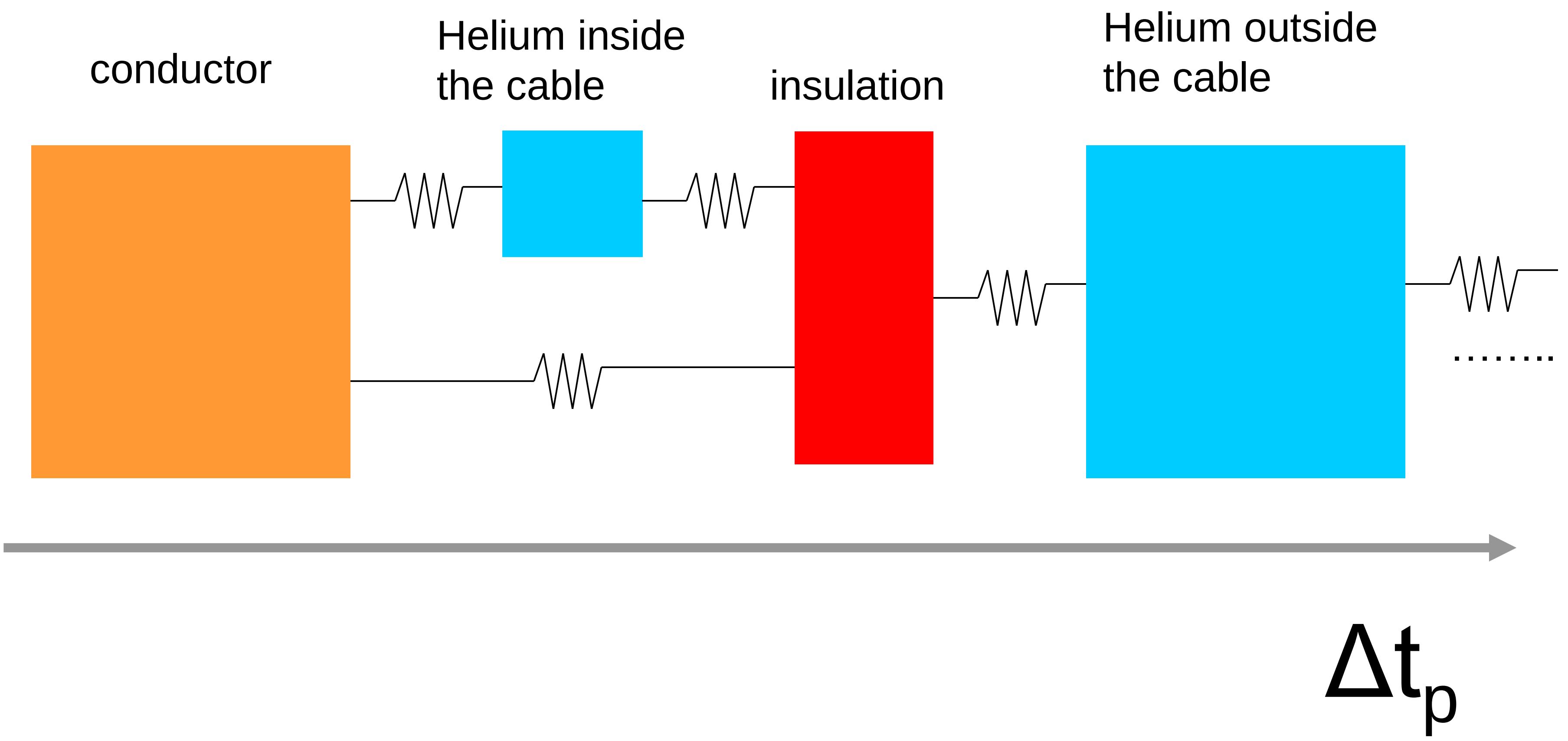
Is this the whole story?

Slower is the perturbation process higher is the margin of the stability, up to the limit of the enthalpy of the cable

… of course not


Thermal resistance

Resume 2


conductor
Helium inside the cable
insulation
Helium outside the cable
……..
Δt_p

Conclusions

- The two codes predict quantitatively the same behaviors
- A first estimation of the stability margin for all LHC superconducting magnets have been already carried out and it will be available in few days (end of next week)
- Work is still in progress to correctly model helium
- Target for the end of the year:
    - stability margin as a function of the perturbation duration
    - better understanding of helium heat correlations
- Preliminary results will be available in one month