Stability Margin Calculations for the LHC Magnets

(*1st part*)

towards prediction of realistic quench levels
for the operation of the LHC with high energy proton beams

by M.Calvi

Acknowledgment:

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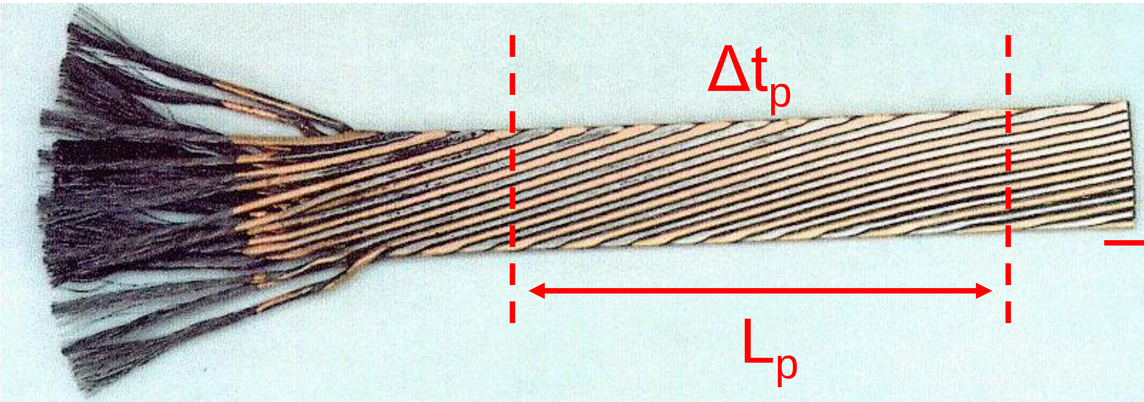
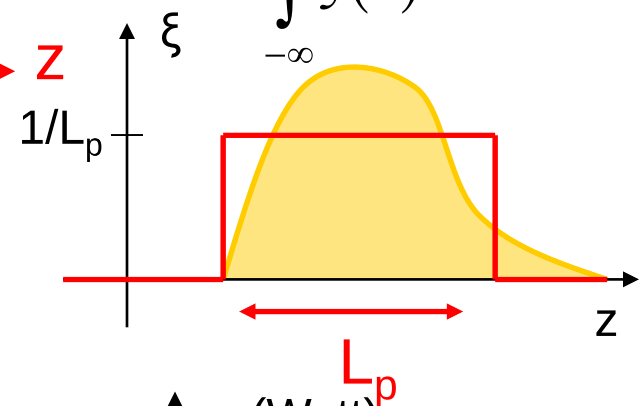
Overview

- Stability Margin
- Heat Transfer in He II (1.9K, 1bar)
  - Kapitza thermal resistance (dominant in He II)
  - BL formation and SS heat transfer in He I
  - Gas formation
- 0D Model:
  - Cable enthalpy & Joule heat
  - Heat exchange with helium
- 1D Model: Single strand coupled with helium channel
  - The heat conduction along the cable length
  - The helium counter flow
- M-1D Model: Multi-strands model
  - Thermal coupling among strands
  - Currents redistribution through distributed electrical contacts
- An example towards realistic beam loss simulation scenario
- Conclusions

Stability Margin



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

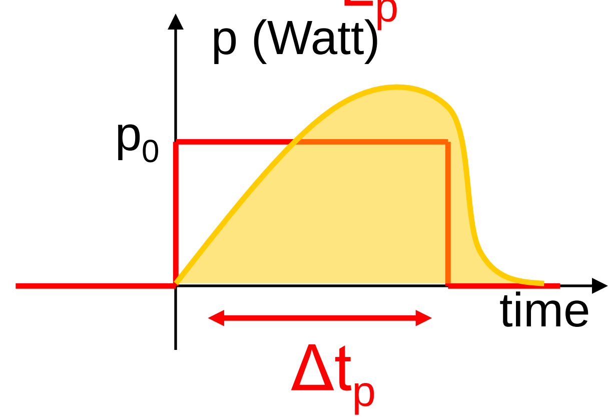


$$\dot{q} = \xi(z)\,p(t)$$

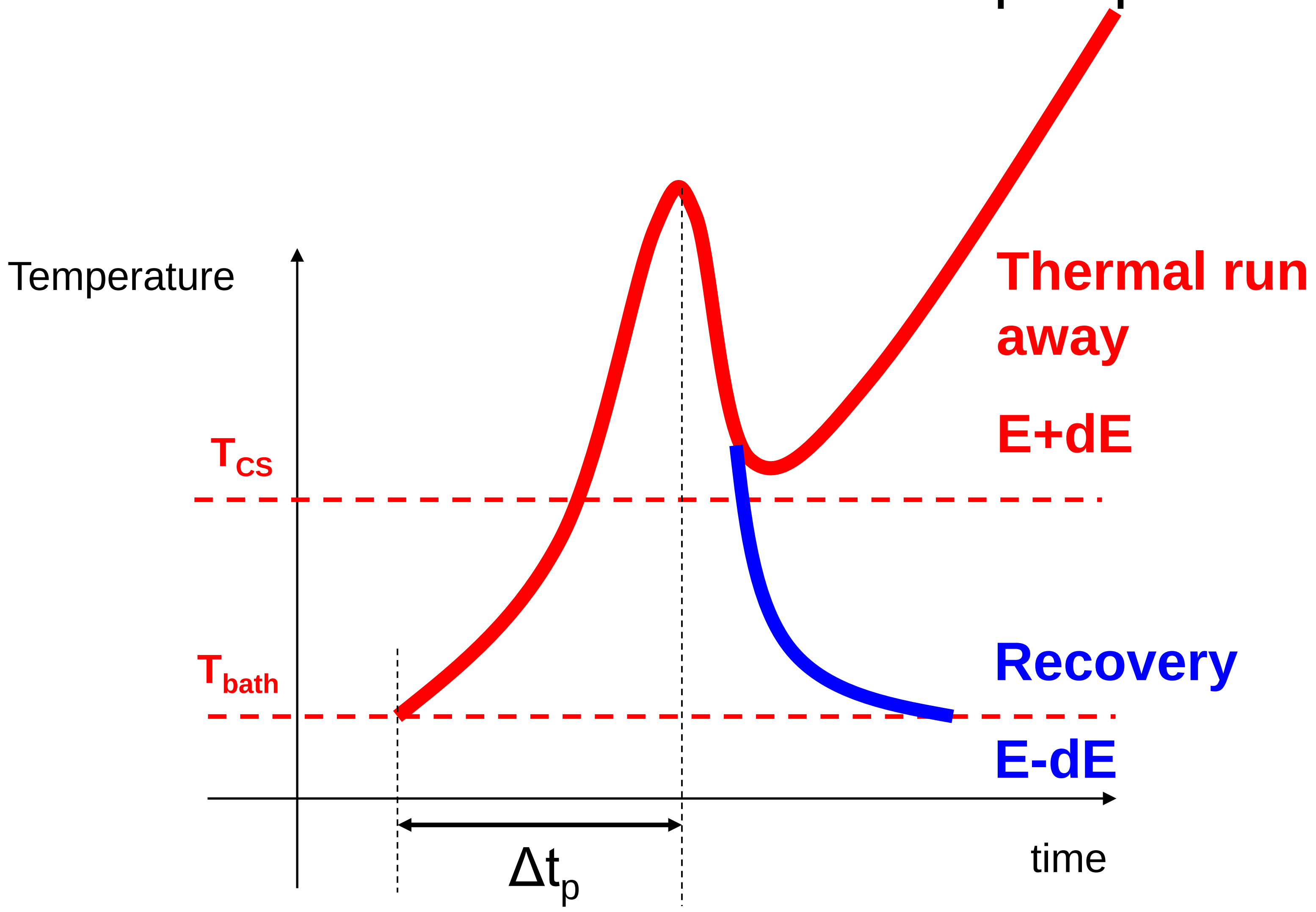
$$E = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \dot{q}(z,t)\,dz\,dt = \int_{-\infty}^{+\infty} p(t)\,dt$$

$$E = p_0 \Delta t_p$$

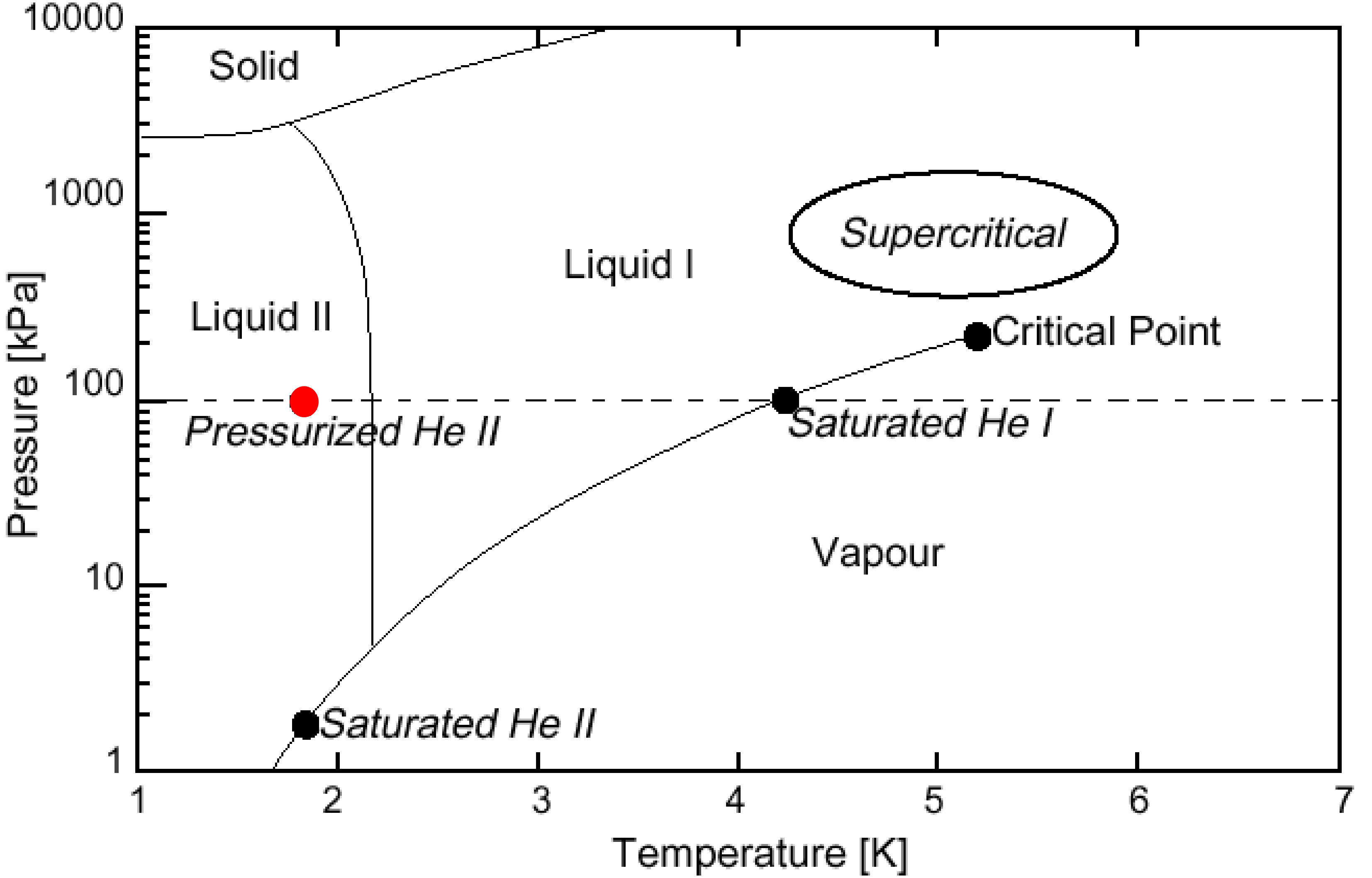
$$\frac{E}{\Delta V_p} = \frac{p_0 \Delta t_p}{A L_p}$$



Stability-Margin(Δt_p,L_p)

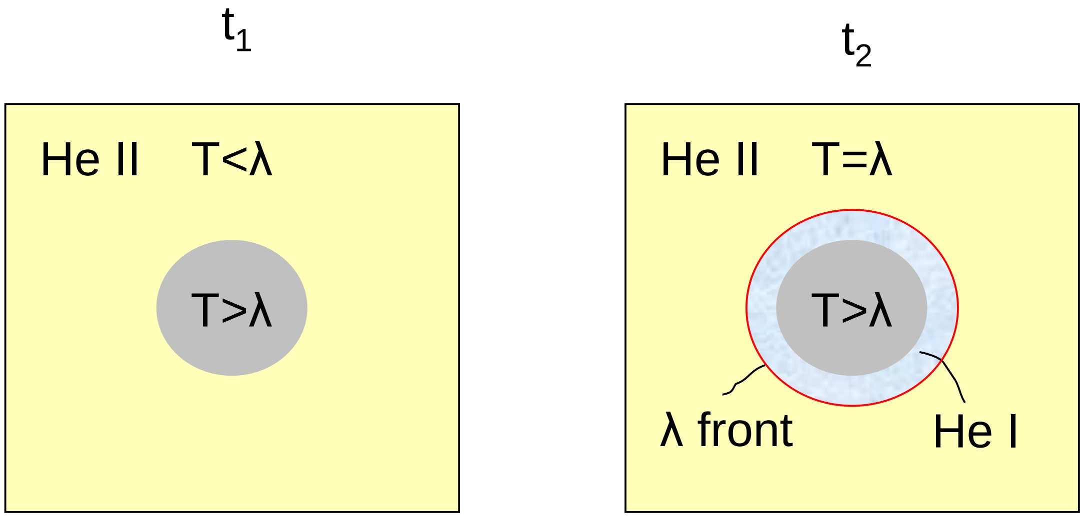


Helium (P,T)



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

Helium

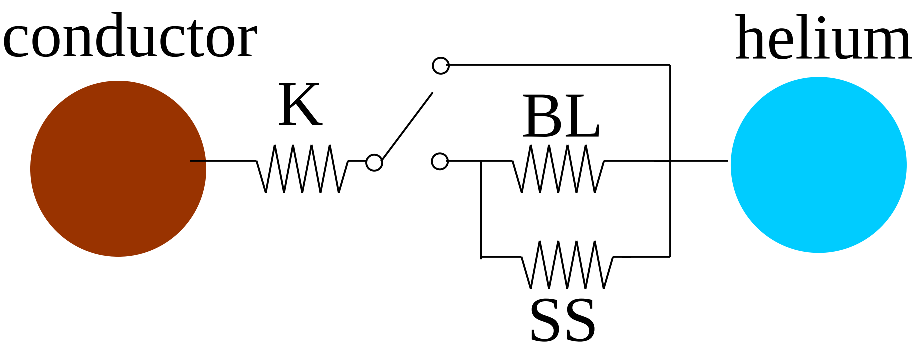


Transition HeII → HeI

$$T_{He} < T_{\lambda} \rightarrow h^{HeII}$$
$$T_{He} > T_{\lambda} \rightarrow h^{HeI}$$

Equivalent heat transfer coefficient

$$Q = h \cdot (T - T_{He})$$

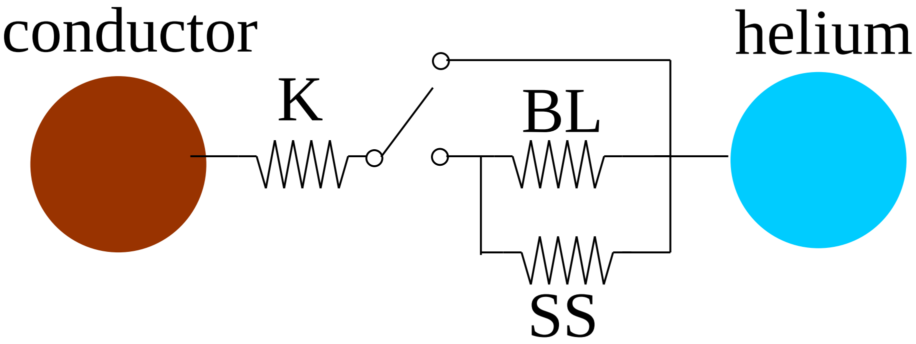


$$h^{HeII} = h_K$$
$$h^{HeI} = \tilde{h}_{BL} + \tilde{h}_{SS}$$

$$\tilde{h}_{SS} = \frac{h_{SS} h_K}{h_{SS} + h_K} \approx h_{SS}$$

$$\tilde{h}_{BL} = \frac{h_{BL} h_K}{h_{BL} + h_K} \approx h_{BL}$$

0D Model



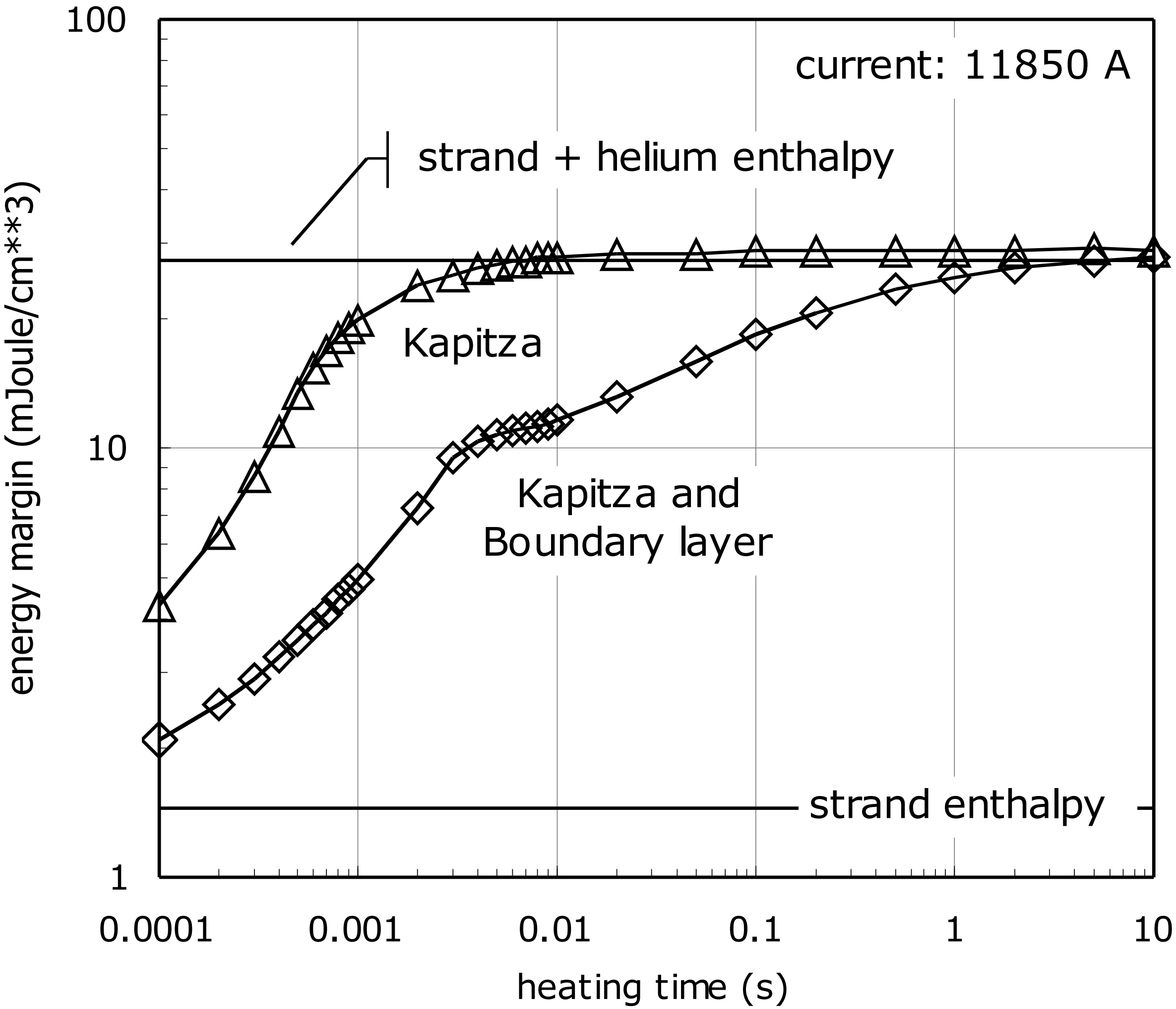
$$A_s \rho_s C_s \frac{\partial T_s}{\partial t} = \dot{q}' + \dot{q}'_{Joule} + h\left(T_h - T_s\right)$$

$$A_h \rho_h C_h \frac{\partial T_h}{\partial t} = h\left(T_s - T_h\right)$$

$$\rho_h = \rho\left(p_h, T_h\right)$$

$$p_h = p_0$$

0D Model *for different Tp*

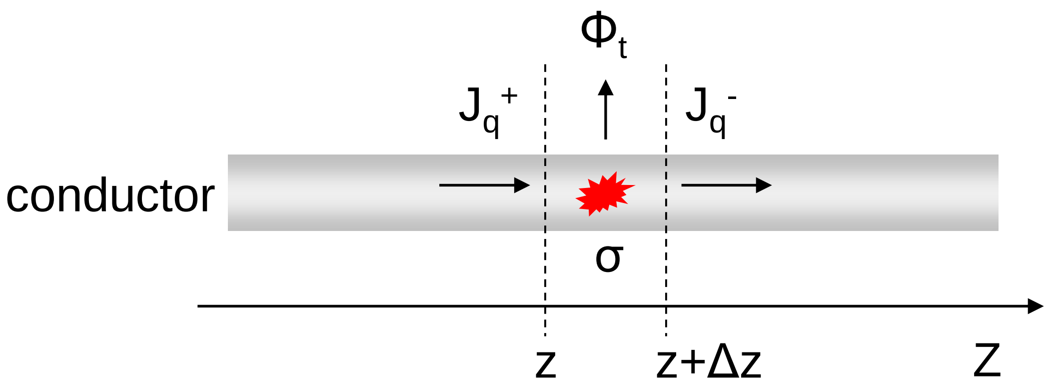


Energy margin as from the 0D model at nominal operating conditions, as a function of the time for the deposition of the heating perturbation.

Two different cooling models were considered: a simplified heat transfer based on the Kapitza resistance, and a more appropriate model that includes the Kapitza resistance as well as the transition to helium I and the formation of a boundary layer around the strand.

Also reported the enthalpy of the cable components, either excluding or including the helium fraction in the cable

1D Model



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

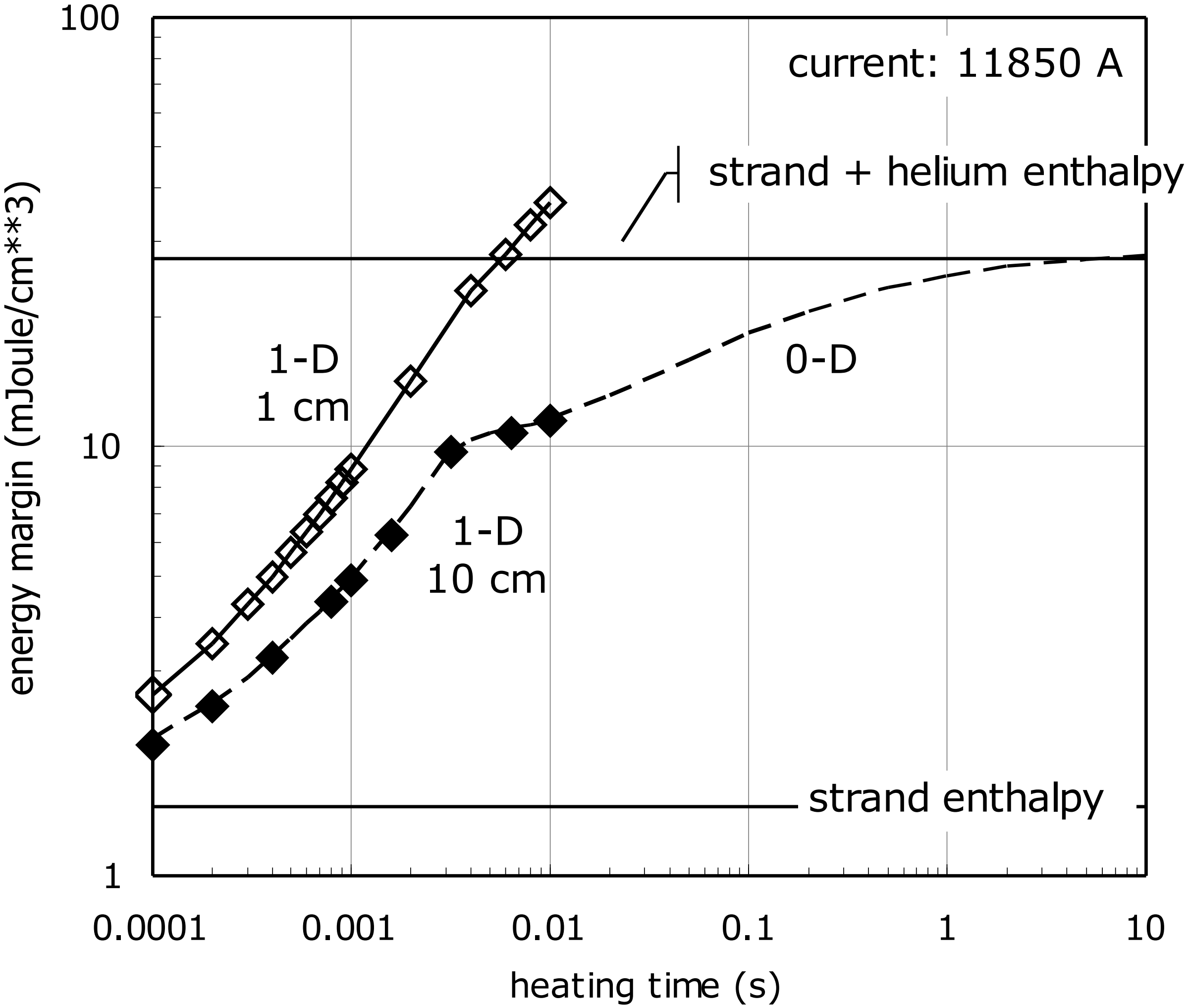
$$A\rho C \frac{\partial T}{\partial t} = \dot{q} + \dot{q}_{Joule} + \frac{\partial}{\partial z}\left(Ak \frac{\partial T}{\partial z} \right) - p_w h\left(T - T_H\right)$$

Who is *really* interesting to the model used for helium counter flow is kindly invited to read one of the following reference papers:

L. Bottura, C. Rosso, M. Breschi. *A General Model for Thermal, Hydraulic and Electric Analysis of Superconducting Cables.* Cryogenics, 2000; 40: 617.

L. Bottura, M.Calvi. A.Siemko. *Stability of the LHC Cables*. Very soon available on Cryogenics.

1D Model *for different Tp*

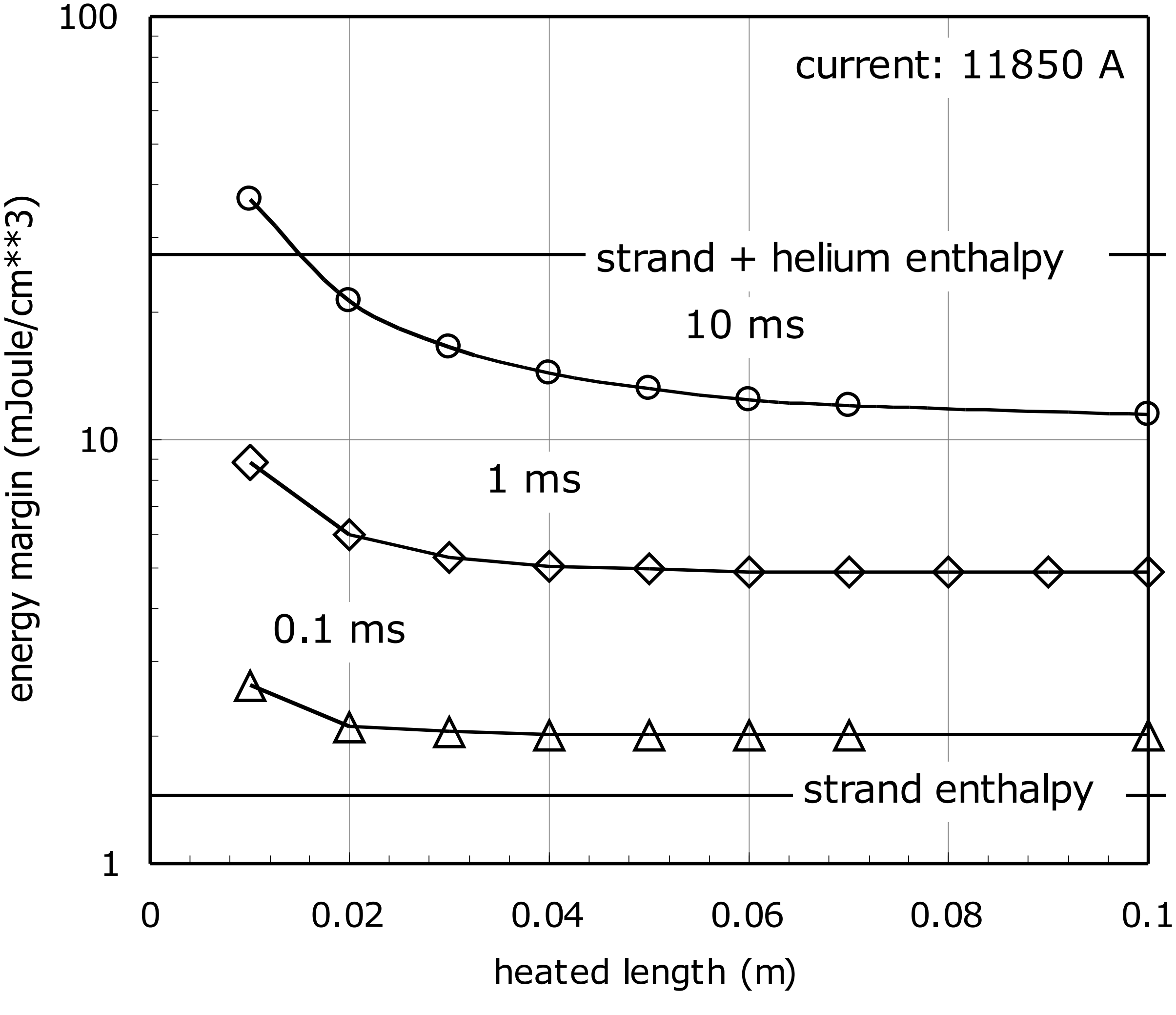


Energy margin as from the 1D model at nominal operating conditions, as a function of the perturbation time.

The simulations have been performed for two different heated lengths as indicated.

The results of the 0-D model are reported for comparison

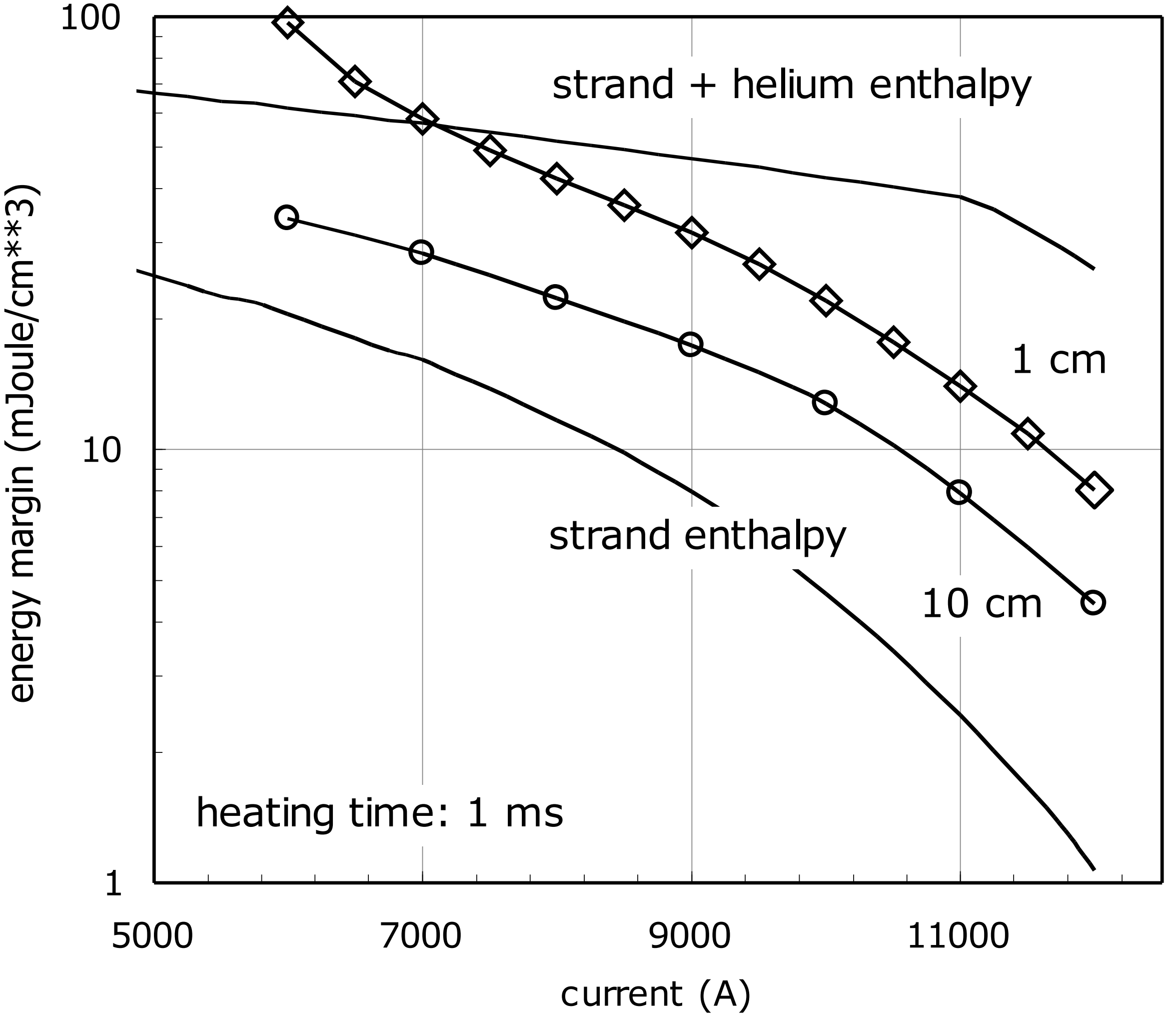
1D Model *for different Lp & Tp*



Energy margin as from the 1D model at nominal operating conditions, as a function of the length of the heated zone.

The simulations have been performed for different heating times as indicated.

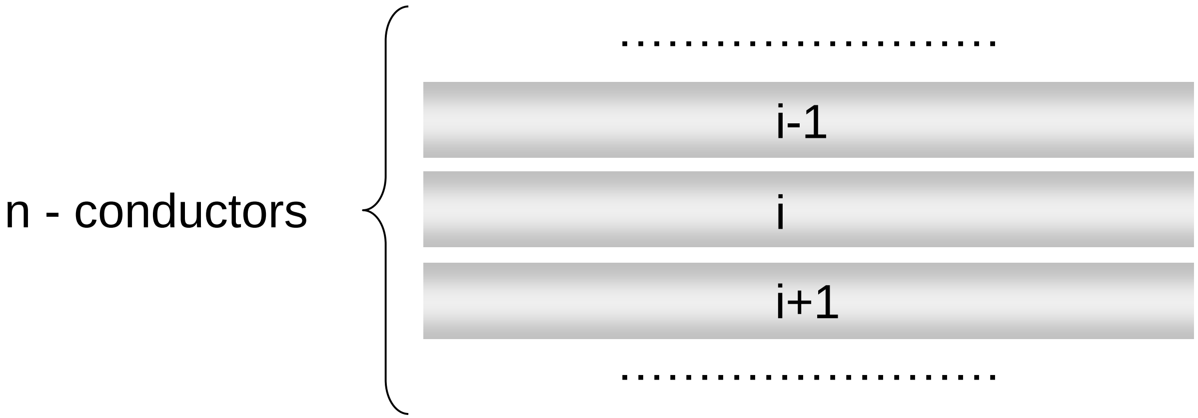
1D Model *for different I and Lp*



Energy margin as from the 1D model as a function of the cable operating current.

The simulations have been performed for two different heating lengths, as indicated.

Multi-1D Model



Thermal equation:

$$A_i \rho_i C_i \dot{T}_i = \dot{q}_i + \dot{q}_{Joule,i} + \frac{\partial}{\partial z}\left(A_i k_i \frac{\partial T_i}{\partial z} \right) + \sum_{\substack{i=1 \\ i \neq j}}^{N} G_{ij}^{th}\left(T_j - T_i\right) + \sum_{h=1}^{H} p_{w,i} h_{ih}\left(T_i - T_h\right)$$

Electrical equations:

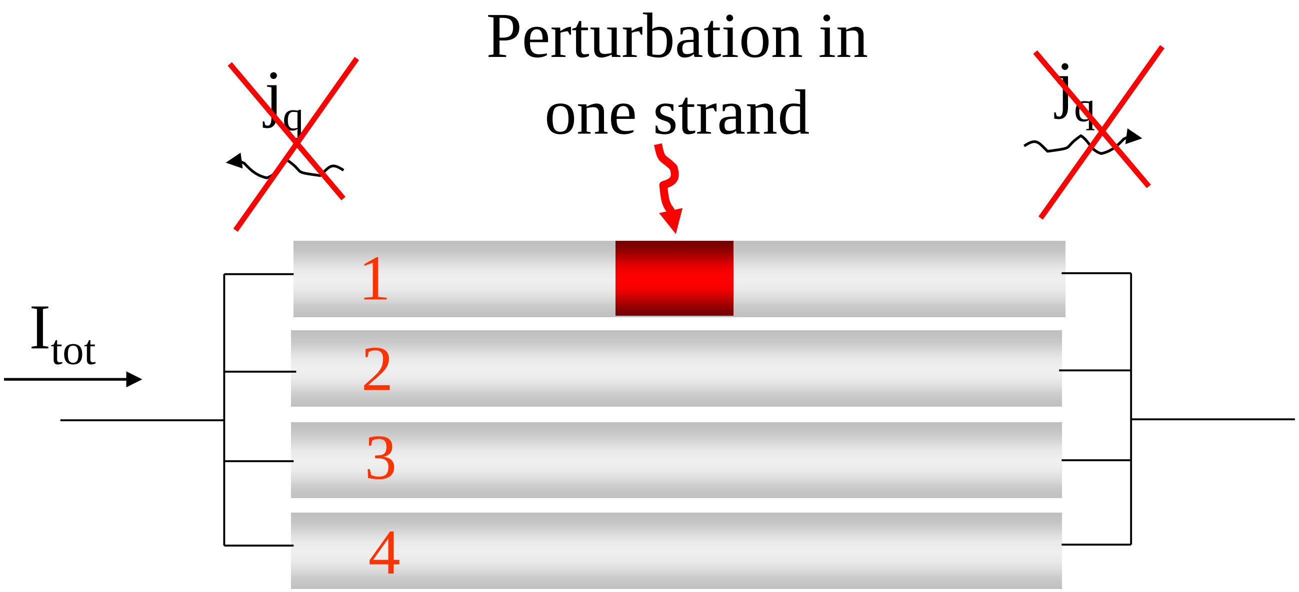
$$\mathbf{l}\frac{\partial \mathbf{I}}{\partial t} + \mathbf{r}\mathbf{I} - \frac{\partial}{\partial z}\left(G_{el} \frac{\partial \mathbf{I}}{\partial z} \right) = \Delta \mathbf{V}^{ext}$$

No external sources of voltage

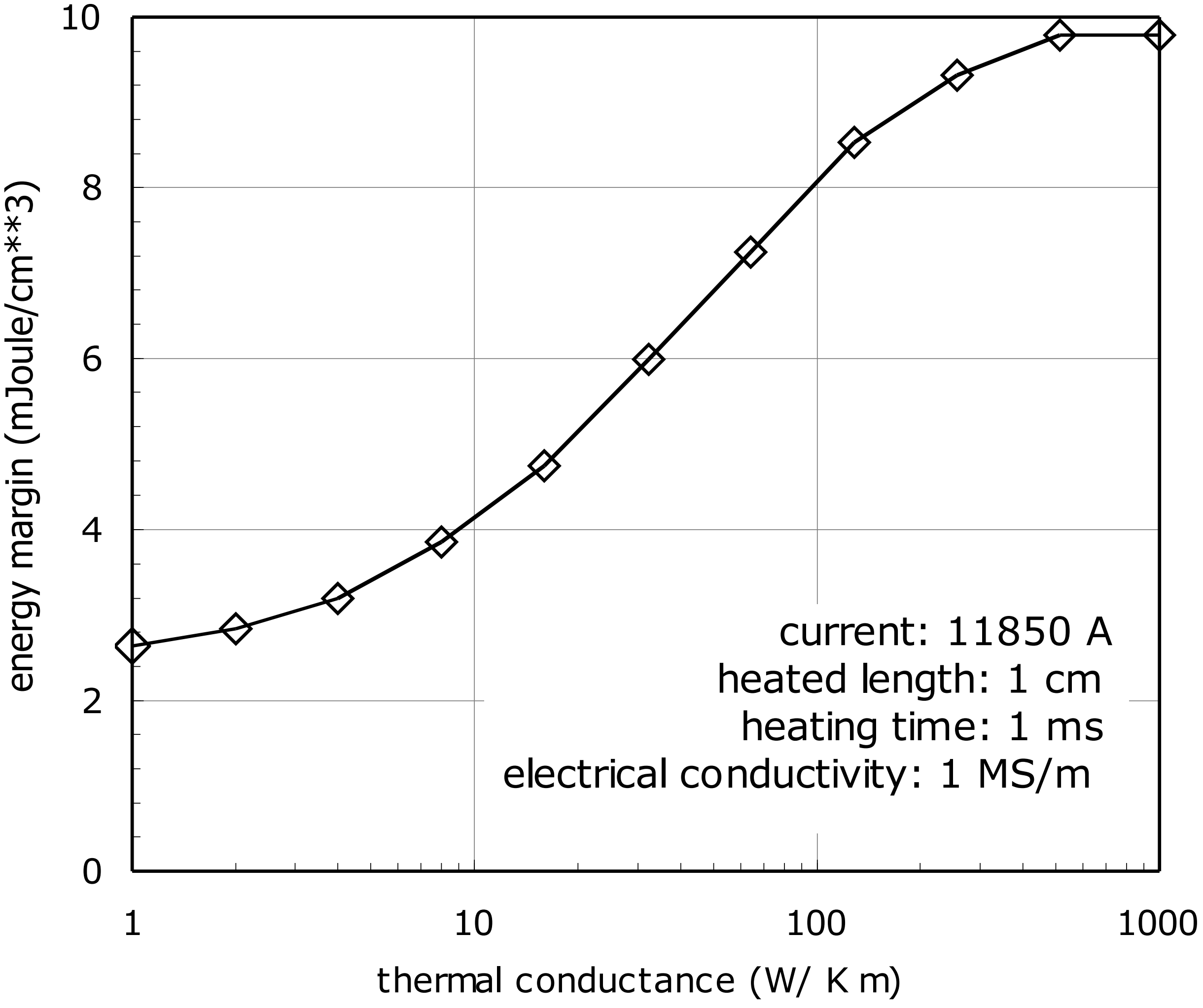
Uniform initial conditions $I_i = I_{tot}/n$

Strands are ideally shorted at the boundary

M-1D Simulations



M – 1D Model *for different G_{th}*

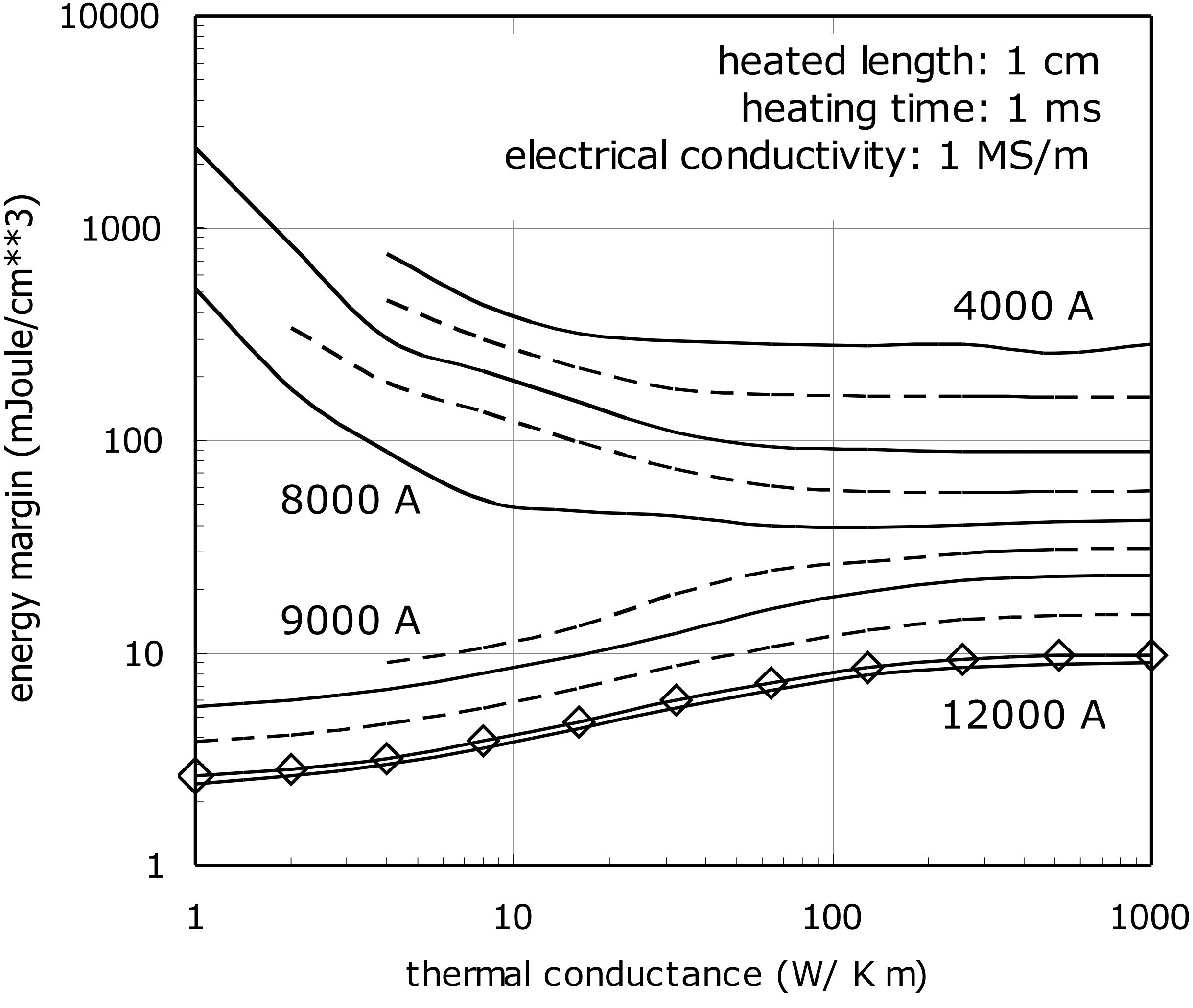


Energy margin computed using the 1-D model for a 4 super-strands cable at nominal operating conditions, of which one is heated for a heating time of 1ms and over a heated length of 1cm.

The 4 super-strands are electrically coupled by a inter-strand conductance of 1 MS/m.

The analysis has been performed parametrically varying the inter-strand thermal conductance.

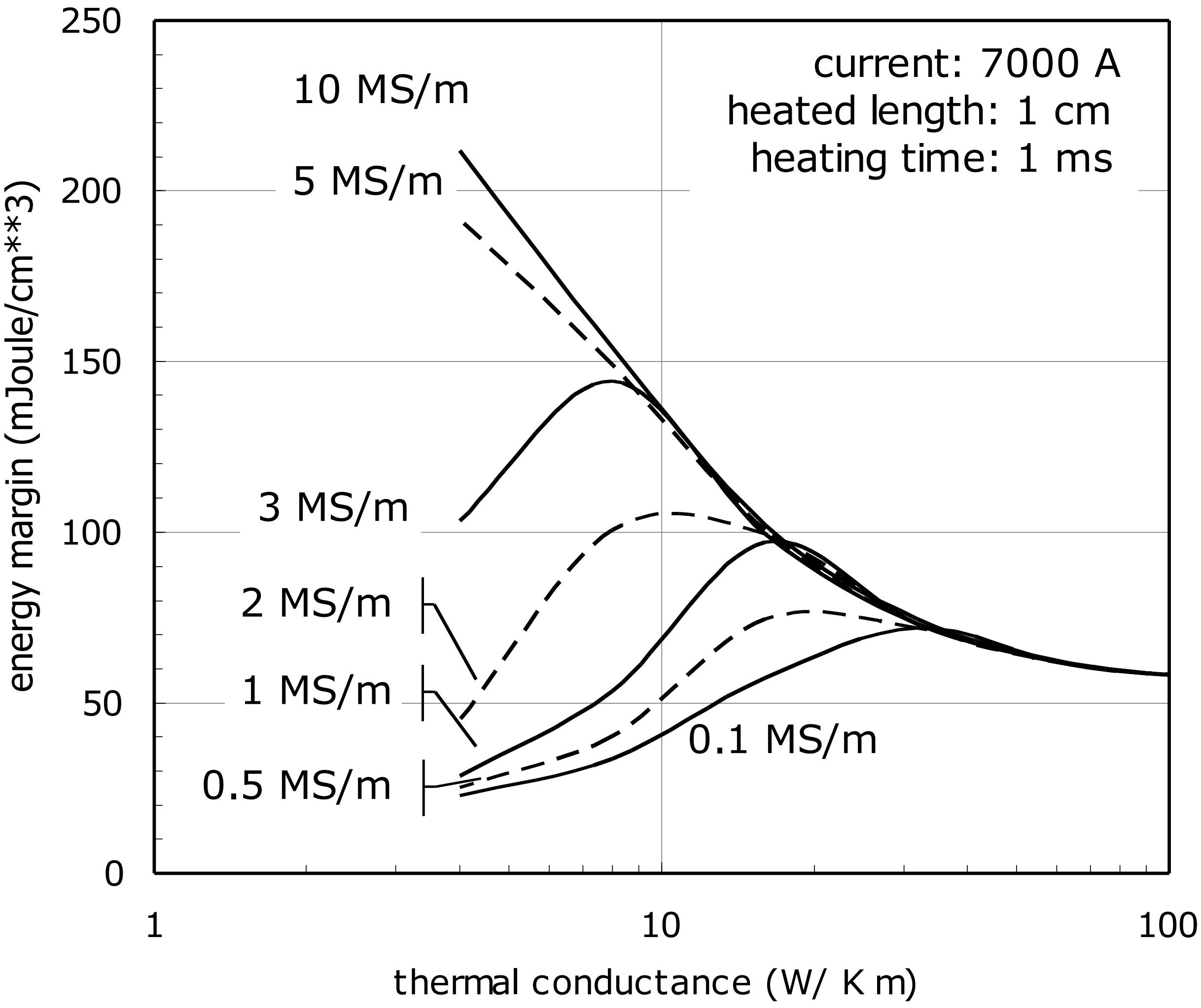
M-1D Model *for different G_{th} & I*



Energy margin for a 4 superstrands cable as a function of the interstrand thermal conductance at several operating currents between 4kA and 12 kA.

Each curve is spaced by 1 kA, and the curve at nominal operating conditions, 11850 A, is marked by symbols.

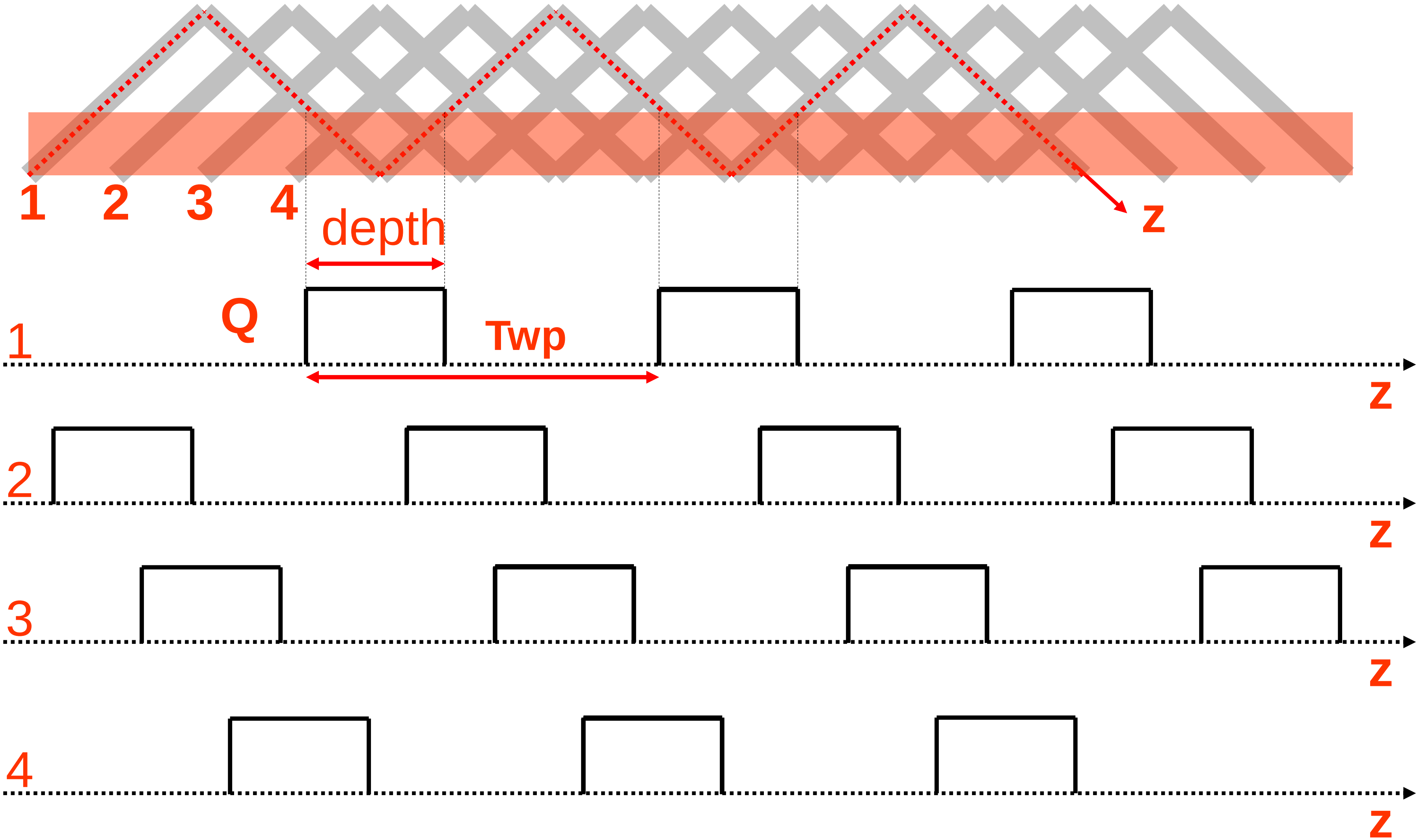
MD Model *for different G_{th} & G_{el}*



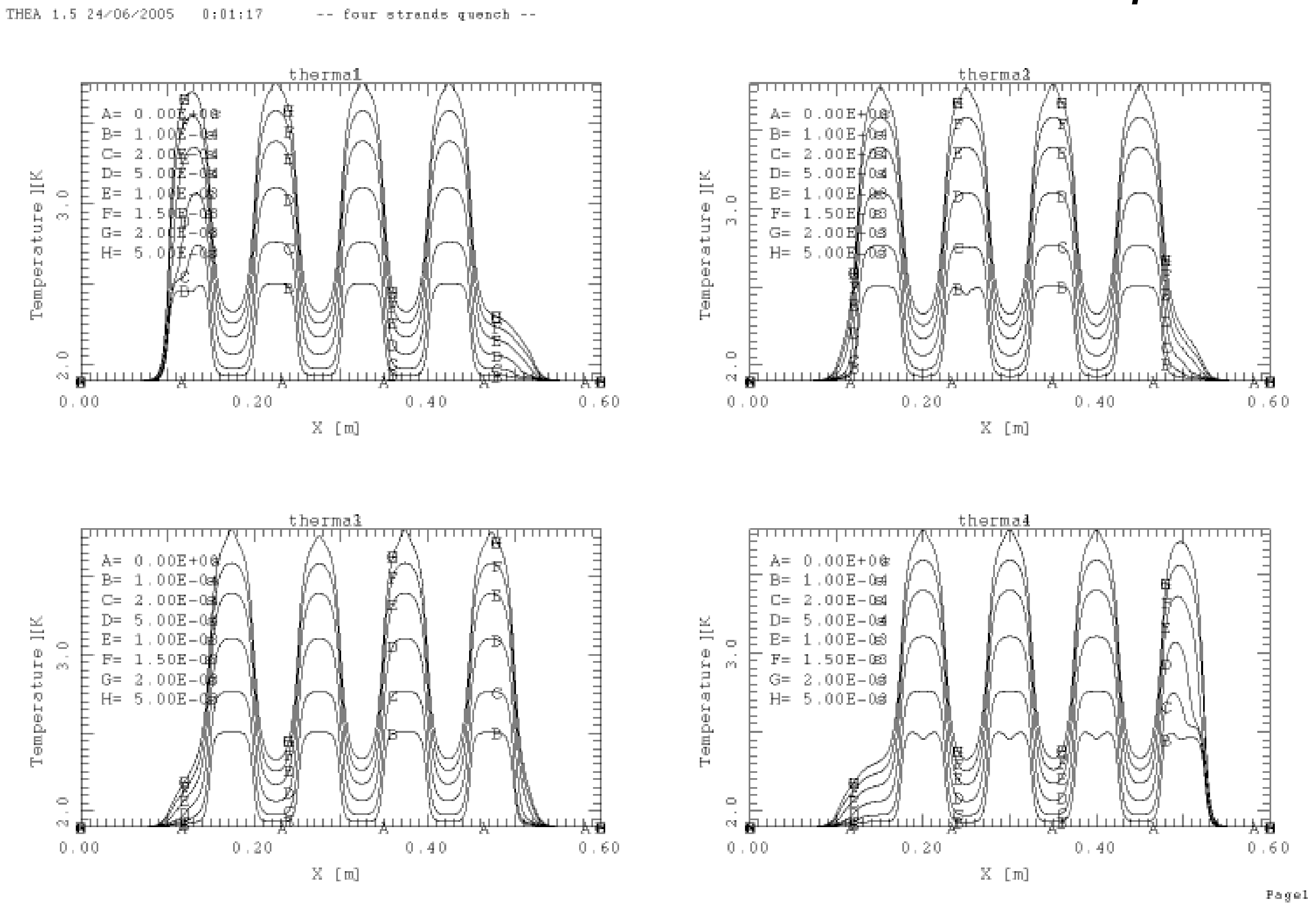
Energy margin for a 4 super-strands cable as a function of the inter-strand thermal conductance at several inter-strand electrical conductances, as marked in the plot.

Operating current is 7 kA.

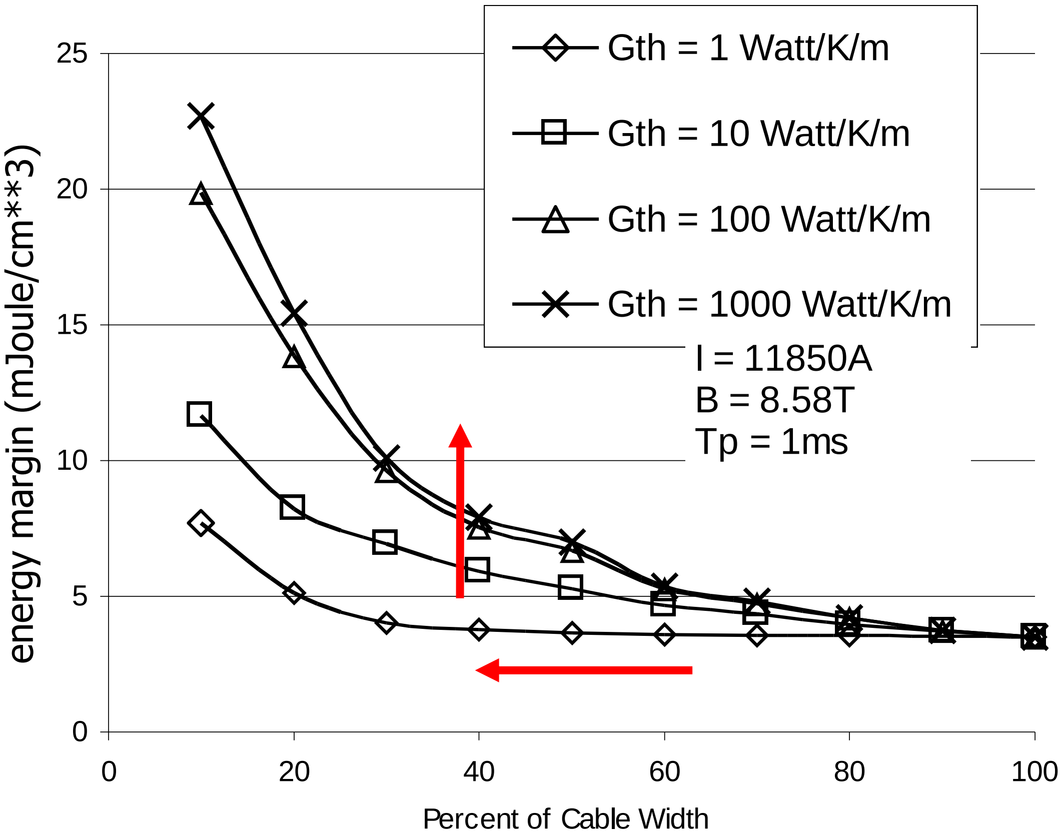
“Beam Loss” *like Scenario*

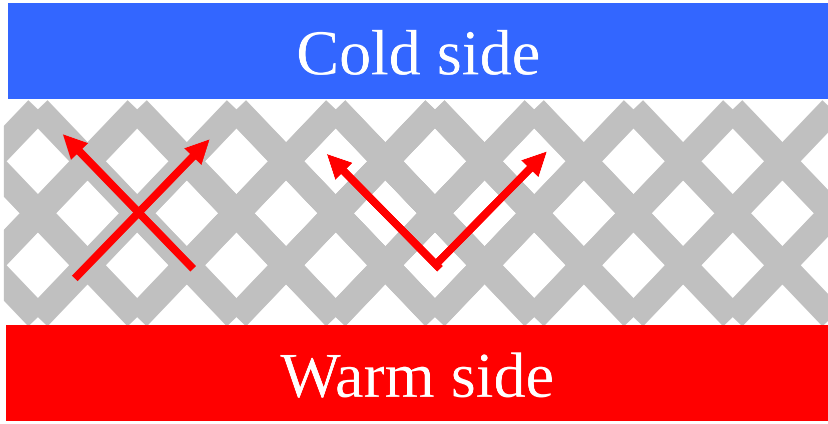


"Beam Loss" *simulation example*



"Beam Loss" *Simulation results*





Resume

- Slower is the process higher is the impact of helium
- Slower is the process larger is the length of the perturbation for which the conduction in metal does still play a role
- At high currents a good thermal coupling among the strands improves the stability
- At low current and with an efficient cooling the stability of a weak thermally coupled multi-stands cable can be higher than a fully coupled system
- Knowing the shape of the expected perturbation (I.e. beam loss) may improve the accuracy of the stability margin calculations

Conclusions and Outlook

- Heat exchange coefficient between strands and helium is the parameter with greatest relevance on the actual energy margin
- At high current regime the electrical conductance does not play an important role
- The thermal coupling among strand is a key parameter which should be correctly estimated
- Experiments are expected to validate the model:
  - Stability experiments in fresca facility (A.Verwej)
  - Heat transfer measurements into helium in operating like conditions (to be planned)
- Defining scaling laws to extrapolate the experimental results to real operating conditions is one of the expected outcome of this study