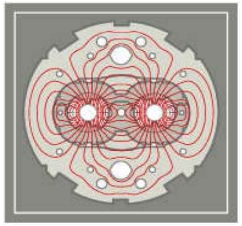

# Modeling of cable stability margin for transient perturbations

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Acknowledgments:

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# Outline

- *Beam Induced Quench*
- *Model Description*
- *Heat Transfer to helium*
- *Stability Margin*
- *Results*
  - *Impact of the Heat Transfer Model*
  - *Impact of the Cooling Surface*
  - *Systematic Calculation of the Stability Margins*
- *Conclusions*

# Beam Induced Quench

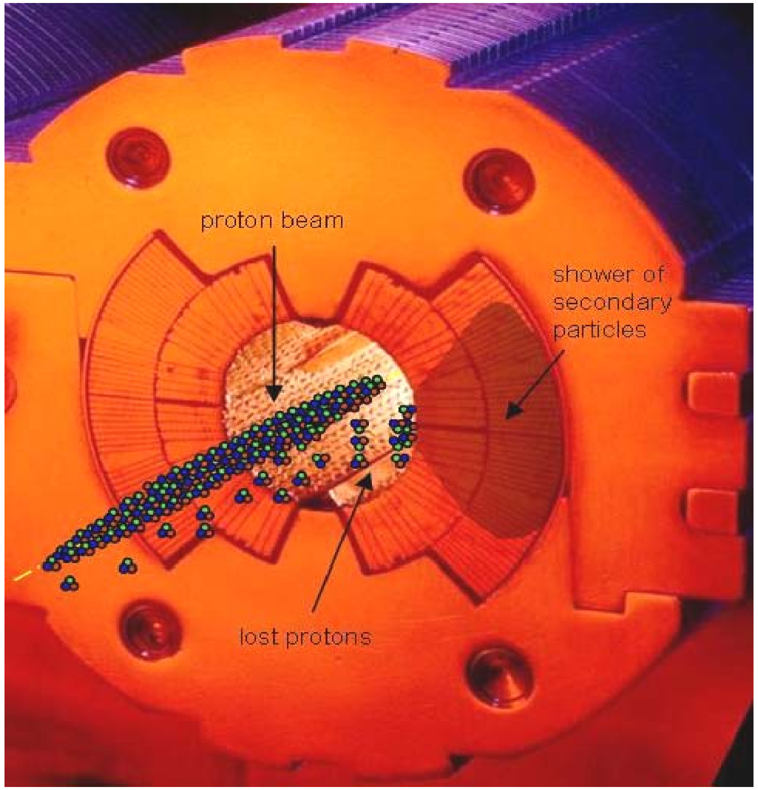
**Lost particles** from high energy and high intensity proton beams can induce <u>**quenches**</u> in the **superconducting** (SC) **magnets** of the **Large Hadron Collider**, thus significantly reducing its operation time.

⬇

A **protection system** (**Beam Loss Monitor**) predicting an imminent beam induced quench and dumping the beam before quenching the magnet has been developed.

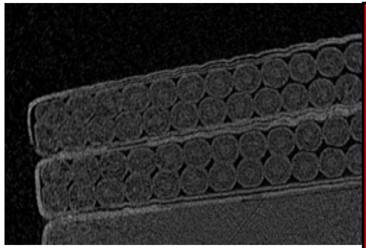
⬇

**Reaction thresholds for the BLM's** need to be set comparing the energy deposition of the hadronic shower in the coil with the <u>***expected stability of the SC cables***</u>.

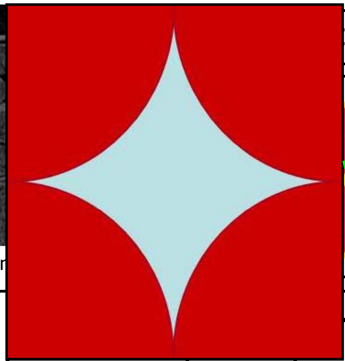


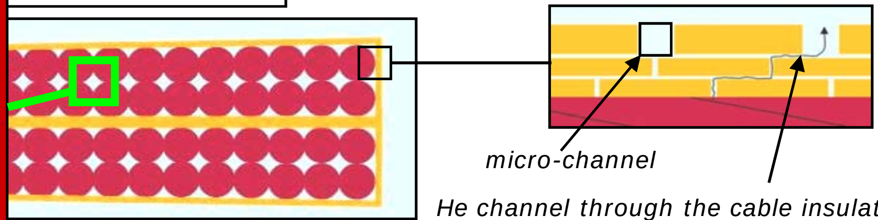

➡ The estimation of the stability against transient distributed disturbances is the aim of this work.

# Model Description



Courtesy of C. Schenerlein






It was demonstrated **ensional** model gives a good estimate of the stability for distributed energy depositions → **the longitudinal dimension is neglected**. The strands in the cable cross-section are lumped into a single thermal component characterized by uniform temperature and homogenized thermal properties:

$$\begin{cases} A_s\rho_s C_s \dfrac{\partial T_s}{\partial t} = \dot{q}'_{ext} + \dot{q}'_{Joule} - p_{s,He}h_{s,He}(T_s - T_{He}) - p_{s,i}h_{s,i}(T_s - T_i) \\ A_{He}\rho_{He}C_{He}\dfrac{\partial T_{He}}{\partial t} = p_{s,He}h_{s,He}(T_s - T_{He}) + p_{i,He}h_{i,He}(T_i - T_{He}) - (p_{i,He} + p_{s,i})Q_{HeII} \\ A_i\rho_i C_i \dfrac{\partial T_i}{\partial t} = -p_{i,He}h_{i,He}(T_i - T_{He}) - p_{s,i}h_{s,i}(T_i - T_s) - p_{i,b}h_{i,b}(T_i - T_b) \end{cases}$$

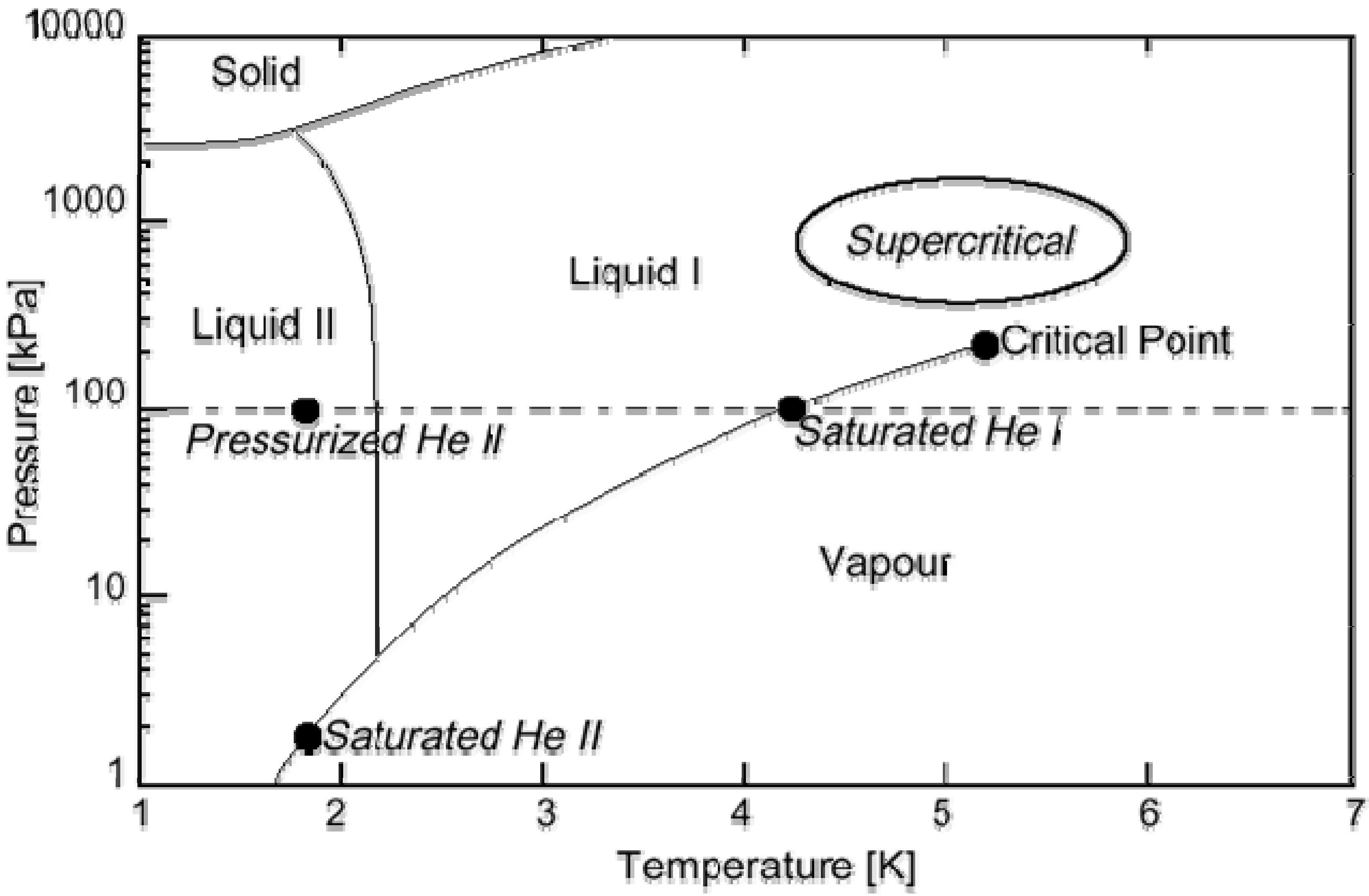
The subscripts refer to:
- s : strands
- He : He fraction in the cable
- i : insulation
- b : external He bath

*p* : contact (wetted) perimeter
*h* : heat transfer coefficient

$$Q_{HeII} = \frac{1}{A_i}\left(\frac{A}{L^{1/3}}\right)\left[\int_{T_b}^{T_h} f(T)\,dT\right]^{1/3}$$


L. Bottura, M. Calvi, A. Siemko, "Stability Analysis of the LHC cables", *Cryogenics*, 46 (2006) 481-493.
M. Breschi, P.P. Granieri, M. Calvi, M. Coccoli, L. Bottura, "Quench propagation and stability analysis of Rutherford resistive core cables", *Cryogenics*, 46 (2006) 606-614.
ZERODEE Software, CryoSoft, France, 2001.
B. Baudouy, et al., "He II heat transfer through superconducting cables electrical insulation", *Cryogenics*, 40 (2000) 127-136.

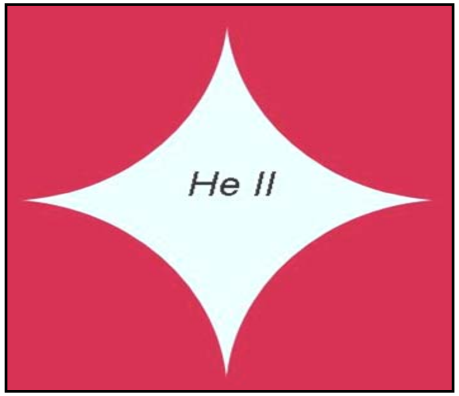
# Heat transfer to helium



# Heat transfer to helium

Superfluid helium

$T_{He} < T_{\lambda}$




At the beginning of the thermal transient the heat exchange with **He II** is limited by the **Kapitza resistance** at the interface between the helium and the strands. The corresponding heat transfer coefficient is:

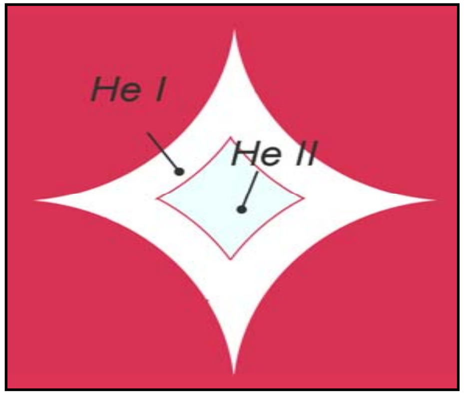
$$h_K = \sigma\left(T_s^2 + T_h^2\right)\left(T_s + T_h\right)$$

L. Bottura, M. Calvi, A. Siemko, "Stability Analysis of the LHC cables", *Cryogenics*, 46 (2006) 481-493.

# Heat transfer to helium

Normal helium

$T_\lambda < T_{He} < T_{Sat}$




When all the He reaches the $T_\lambda$, the **He I** phase starts growing and temperature gradients are established in the He bulk. A thermal **boundary layer** forms at the strands-He interface, where a heat diffusion process takes place:

$$h_{BL} = \frac{1}{2}\sqrt{\frac{K_h \rho_h c_h}{\pi \Delta t}}$$

After the boundary layer is fully developed, the heat transfer mechanism is driven by a steady state heat transfer coefficient is $h_{ss}$ = 50 W/m²K. The transition is approximated in the following way:

$$h_{HeI} = \max\left\{\frac{h_K h_{BL}}{h_K + h_{BL}}; h_{ss}\right\}$$

This expression of $h_{BL}$ gives an estimation of the heat transfer coefficient for constant heat flux, which is not the case during the evolution of the system. Further corrections are going on to generalize this approach for problems concerning arbitrary heat flux evolution at the surface.

L. Bottura, M. Calvi, A. Siemko, "Stability Analysis of the LHC cables", *Cryogenics*, 46 (2006) 481-493.

V.D. Arp, "Stability and thermal quenches in forced-cooled superconducting cables", *Proceeding of 1980 superconducting MHD magnet design conference*, Cambridge (MA): MIT, 1980, pp. 142-157.

# Heat transfer to helium

Nucleate boiling

$T_{He} = T_{Sat}$

Once the saturation temperature is reached, the He enters the **nucleate boiling** phase. The formation of bubbles separated from each other occurs in cavities on the strands surface. The transient heat exchange during this phase is very effective:

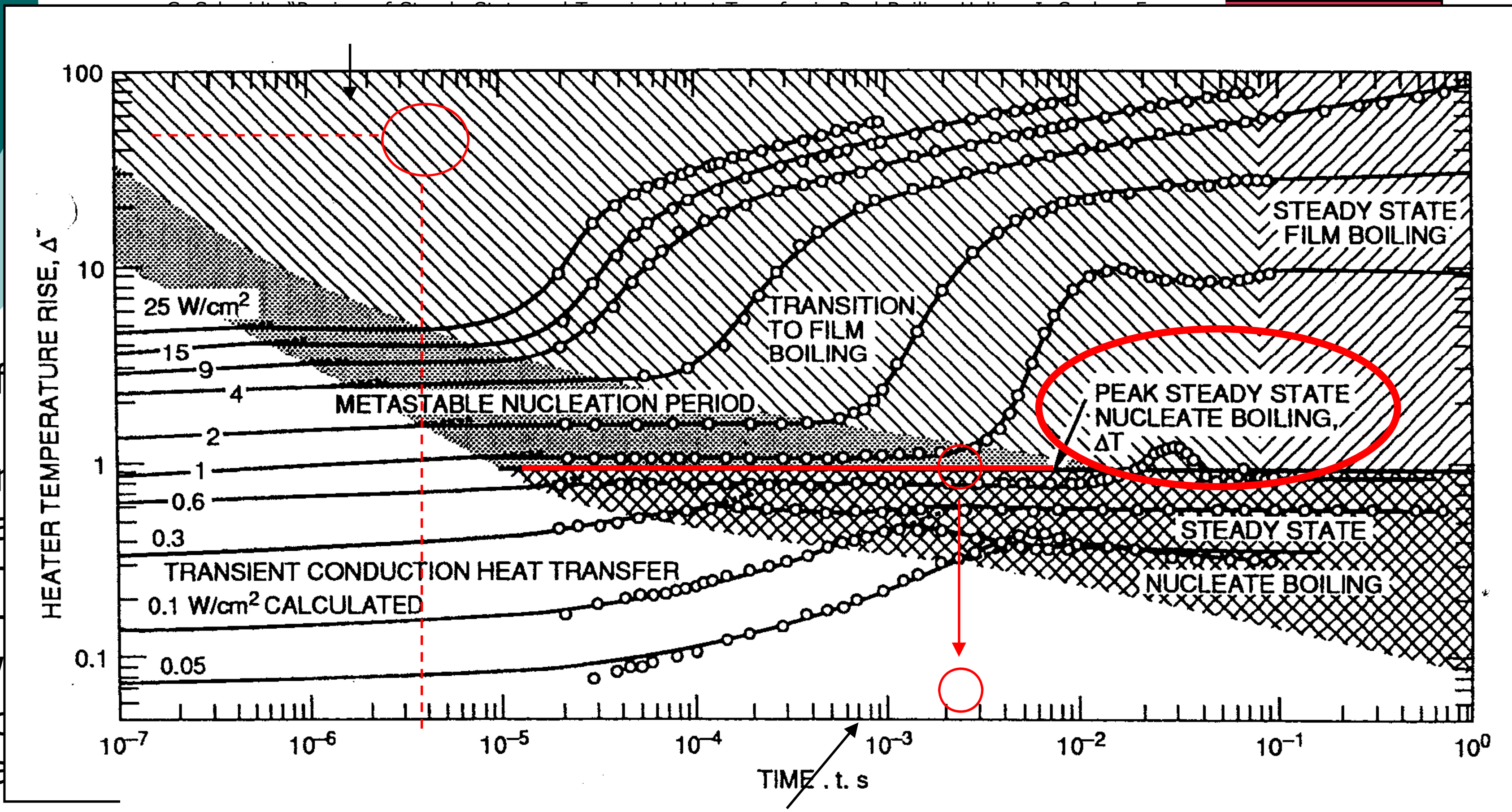
⇓

$$h_{nucl.boiling} = \frac{\beta(T_s^m - T_h^m)}{T_s - T_h}$$

C. Schmidt, "Review of Steady State and Transient Heat Transfer in Pool Boiling He I, Saclay, France: Int.l Inst. of Refrigeration: Comm. A1/2-Saclay, 1981, pp. 17-31.

M. Breschi et al. "Minimum quench energy and early quench development in NbTi superconducting strands", *IEEE Trans. Appl. Sup.*, vol. 17(2), pp. 2702-2705, 2007.

# Heat transfer to helium




M. Nishi et al., "Boiling heat transfer characteristics in narrow cooling channels", IEEE Trans on Magnetics, Vol. Mag-19, No 3, May 1983

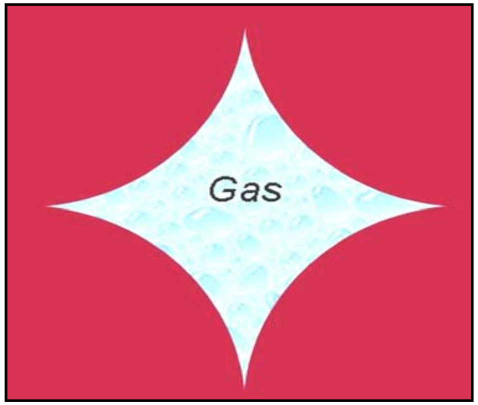
W.G. S

M. Breschi et al. "Minimum quench energy and early quench development in NbTi superconducting strands", *IEEE Trans. Appl. Sup.*, vol. 17(2), pp. 2702-2705, 2007.

# Heat transfer to helium

Gas

Energy deposited into the channel = Elat




The heat transfer model implemented in this study is *irreversible* (no recovery to a previous He phase is allowed).

This choice is conservative, but the impact of a more realistic *reversible* model is being investigated.

The film thickness increases with the strands temperature. Since the whole He in the channel is vaporised (film thickness equal to the channel width), the worsening of the heat transfer observed in experimental works is taken into account allowing transition to a **totally gaseous phase**. This is described by a constant heat transfer coefficient extrapolated from experiments:

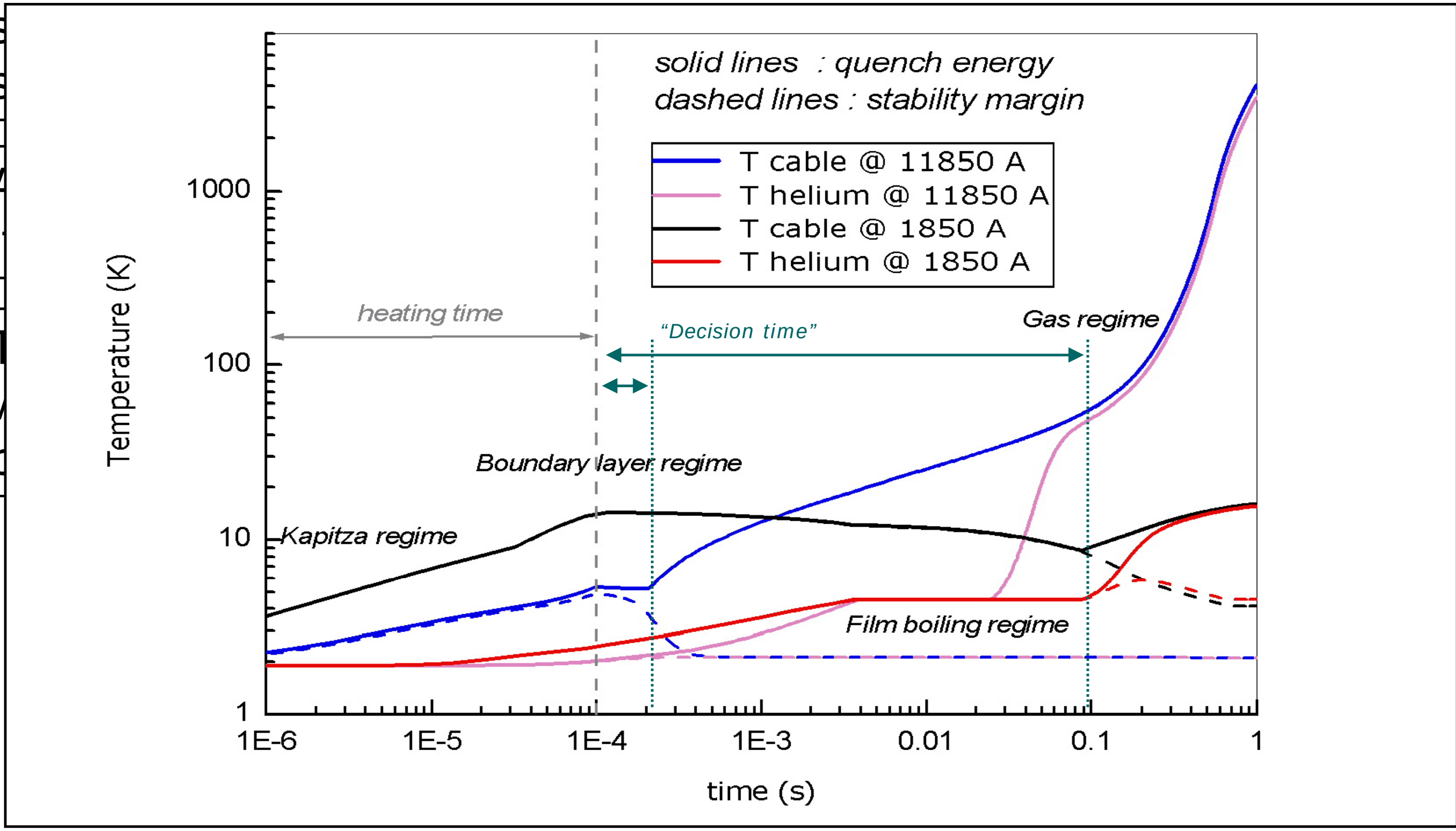
$$h_{gas} = 70\ W/m^2K$$

Y. Iwasa and B.A. Apgar, "Transient heat transfer to liquid He from bare copper surfaces to liquid He in a vertical orientation – I: Film boiling regime", *Cryogenics*, 18 (1978) 267-275.
M. Nishi, et al., "Boiling heat transfer characteristics in narrow cooling channel", *IEEE Trans. Magn.*, vol. 19, no. 3, pp. 390–393, 1983.
Z. Chen and S.W. Van Sciver, "Channel heat transfer in He II – steady state orientation dependence", *Cryogenics*, 27 (1987) 635-640.

# Stability Margin

The ***stability margin*** is the maximum energy per unit volume of cable that can be tolerated still leading to a recovery in the

The ***"decision time"*** (time the system waits before *"deciding"* to quench or not) is noticeably longer at low current regimes.



# Impact of the Heat Transfer Model

- **Different heat transfer models** have been considered:
  - *I. an unrealistic one only using the Kapitza heat transfer coefficient;*
  - *II. the full model as previously described;*
  - *III. the full model without the external reservoir and without boiling phases.*

- The Kapitza regime dominates up to 400 μs time scale;
- For longer pulses the lambda transition is reached and the limitations in the heat transfer due to the presence of He I (and/or gas phases) become important;
- After ~ 5 s pulse duration, the heat transfer through the insulation becomes effective and the models I and II give again the same results.

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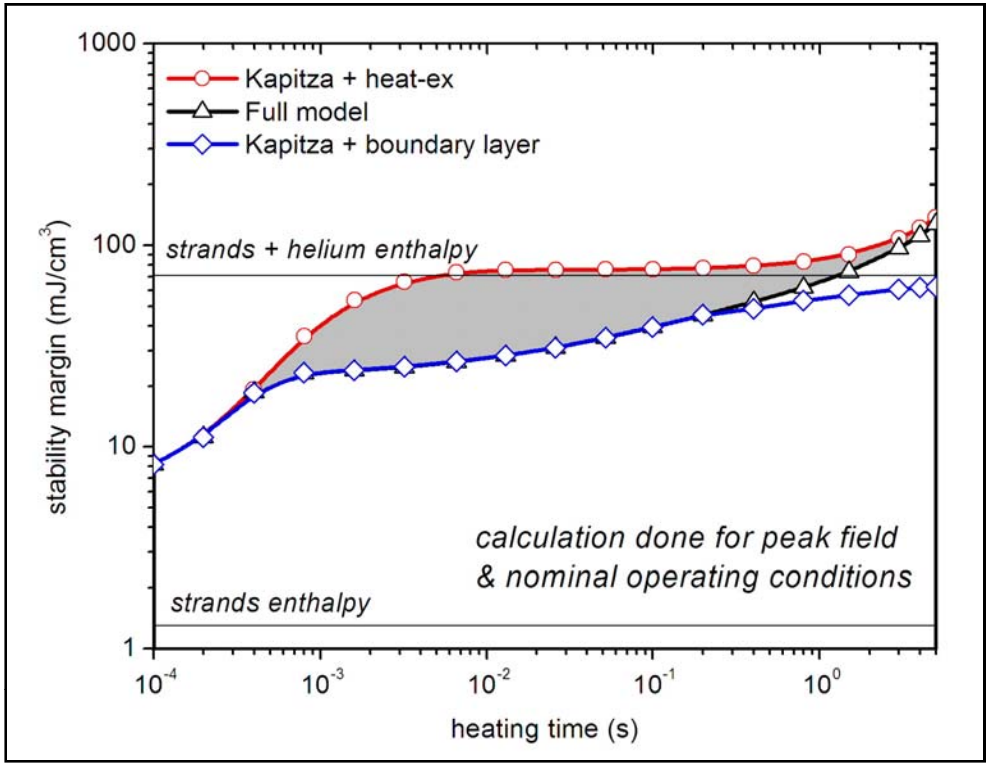
- The enthalpy reserve (between $T_{bath}$ and $T_{cs}$) of the dry cable gives the lower limit of the stability margin;
- The enthalpy reserve of the wet cable is not an upper limit for the system, because of the presence of an external reservoir. It represents an upper limit for the model III.

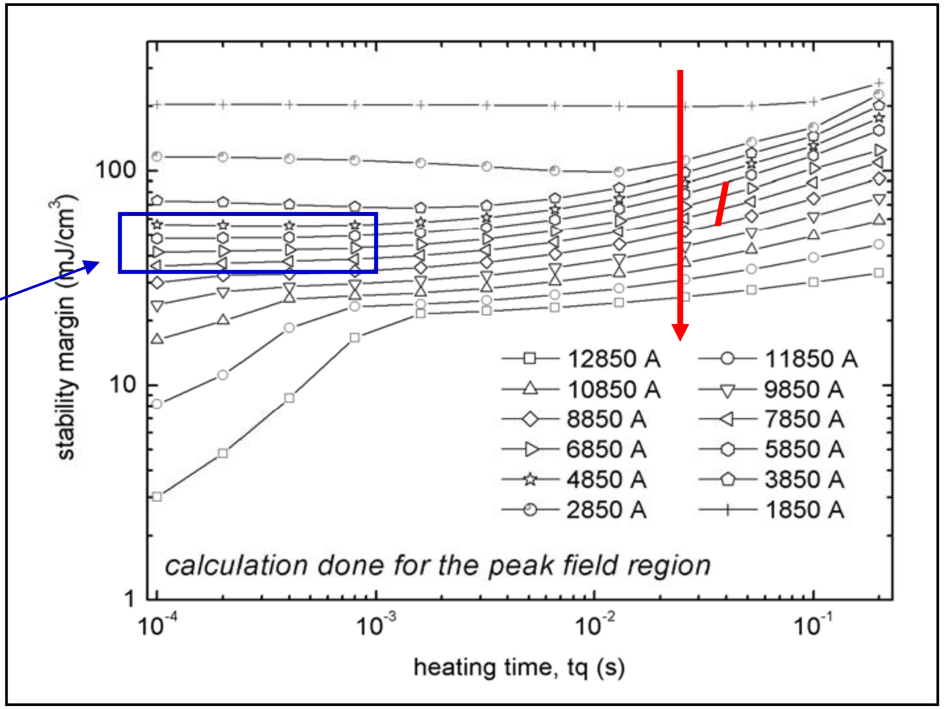
- The stability margin is greater than the strands enthalpy, even for short perturbation time of 0.1 ms.
- This is related to the time constant associated with the *"decision time"*.



# Systematic Calculation of the Stability Margins

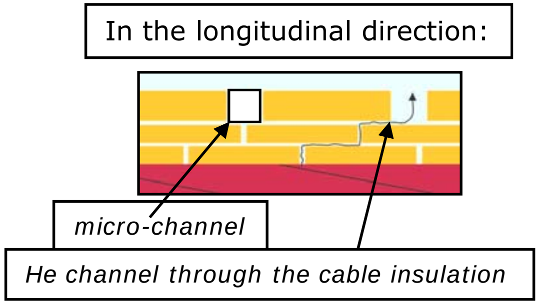
Stability margins of cable 1 (inner layer of the main dipoles) as a function of heating time and for different current levels:

- Slower is the process, higher is the impact of helium;
- For low currents and short heating times the stability margin curve gets flat, since the *"decision time"* is much greater than the heating time.
- The wide range of heating times is a source of numerical problems.

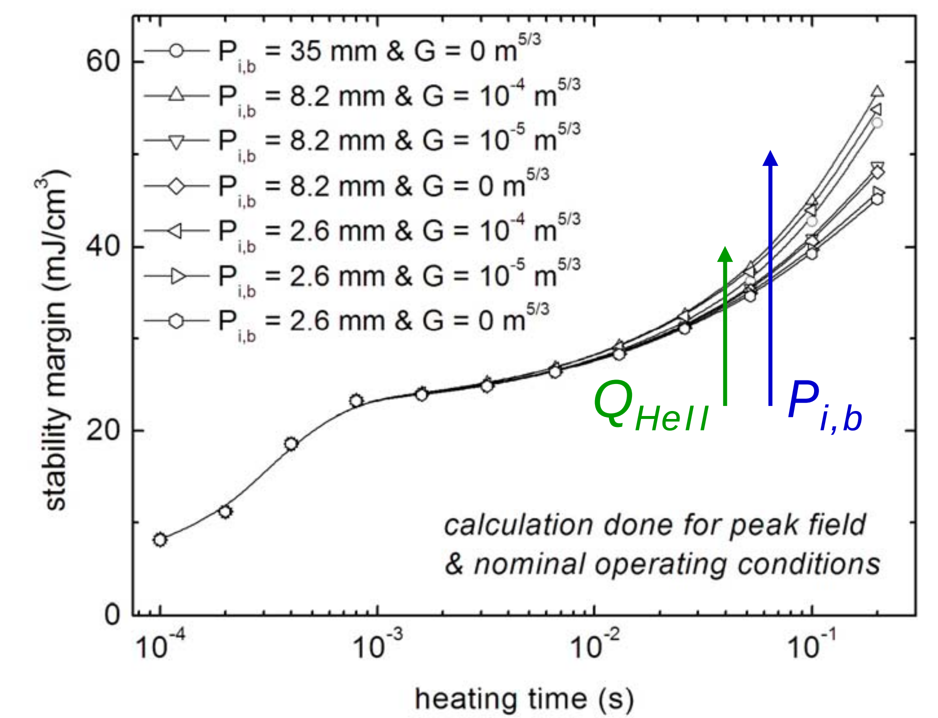


# Impact of the Cooling Surface

The influence of the He **micro-channels** located **between the cables** in the coil and of the **He channels network through the cable insulation** is unknown. This parametric study allows to investigate the effectiveness of these heat transfer mechanisms.



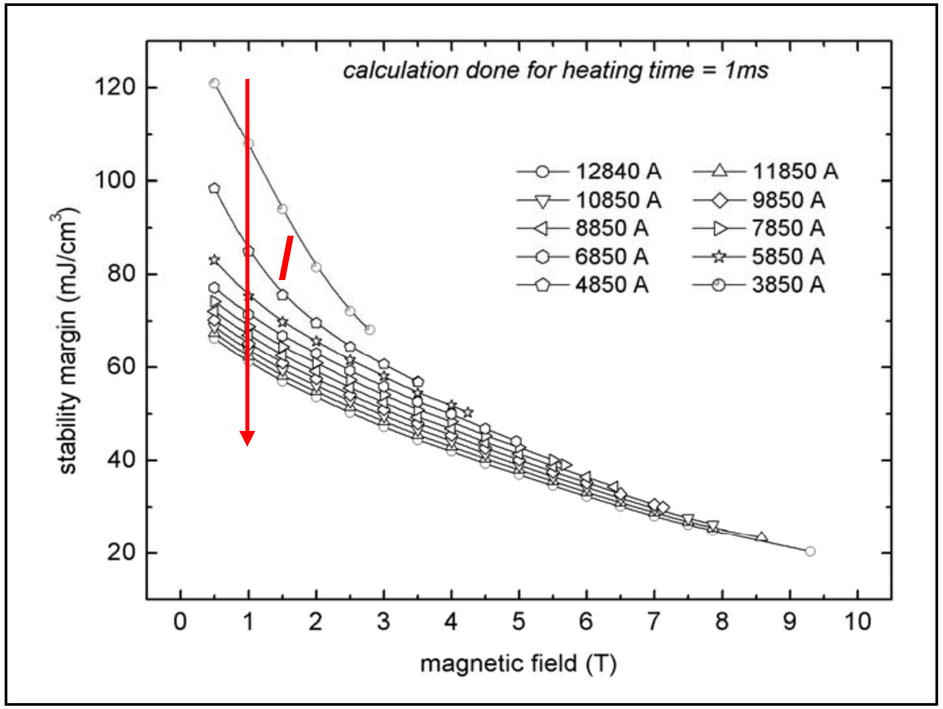

- In the following calculations a conservative case has been considered, where $p_{i,b}$ = *2.6 mm* and $G$ = *0* $m^{5/3}$.



# Systematic Calculation of the Stability Margins

Stability margins of cable 1 as a function of magnetic field (ranging from 0.5 T to the peak field for a given current) and for several current levels:

- The stability margin for a given cable has been estimated as a function of the heating time, current and magnetic field. This allows interpolating the results at any field for any cable in the magnet cross section.

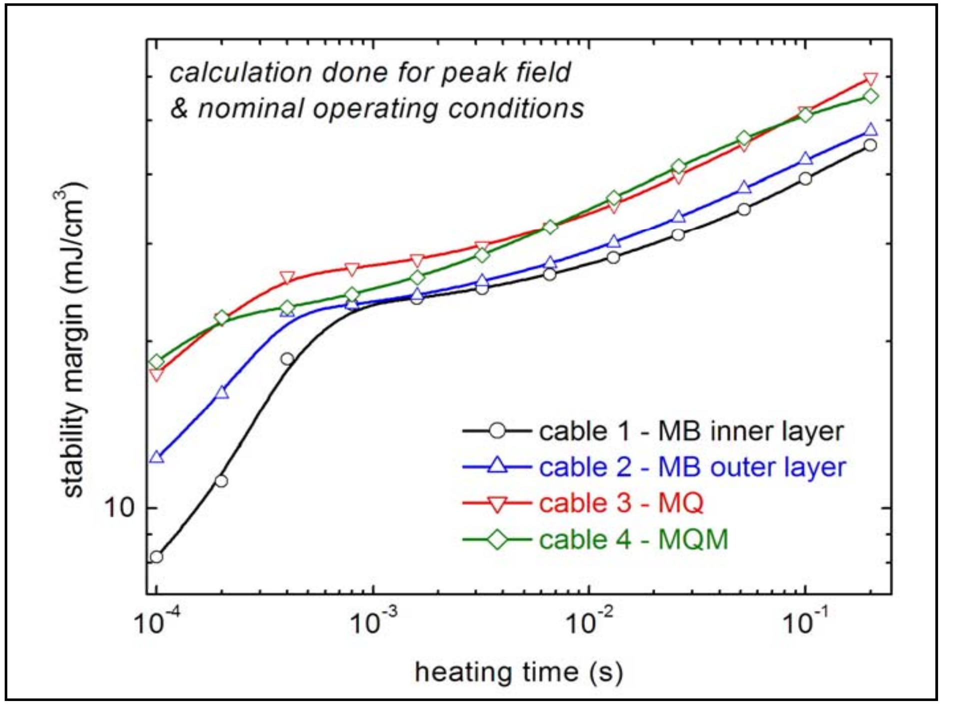


# Systematic Calculation of the Stability Margins

Stability margins of all the CERN LHC cables working at 1.9 K as a function of heating time:

- The stability of all the CERN LHC superconducting cables working at an operational temperature of 1.9 K has been numerically computed with respect to the actual range of beam loss perturbation times.

- Calculations on the CERN cables working at 4.5 K and on all the non-CERN cables are in progress, to finally provide a systematic scan of the stability margin of all types of LHC cables.

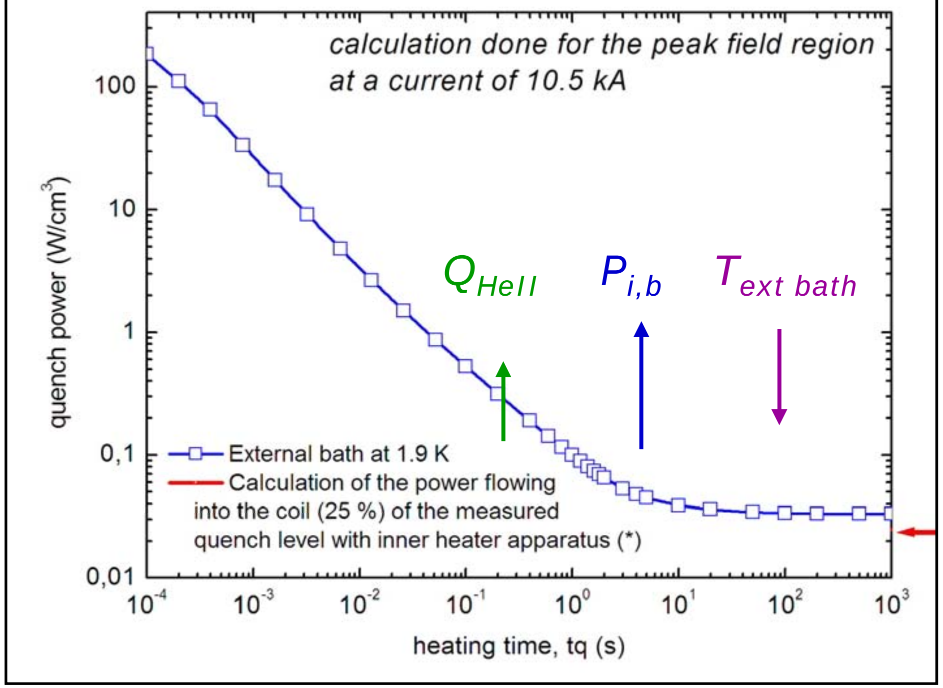


# Systematic Calculation of the Stability Margins

The stability margin and the quench power needed to quench the cable are estimated for different heating times up to the steady-state value:

- The model developed links the transient to the steady state regime:

  for long heating times the power needed to quench the cable decreases and reaches asymptotically the steady state value.




(*) D. Bocian, "Modeling of quench levels induced by steady state heat deposition ", previous talk.

D. Bocian, B. Dehning, A. Siemko, "Modelling of quench limit for steady state heat deposits in LHC magnets", to be published on *IEEE Trans. Appl. Sup.*.

# Conclusions

- A 0-D thermal model has been used to study the stability of the LHC SC magnets, taking into account all relevant helium phases discussed in the literature and introducing a new way to deal with the gaseous phase in narrow channels;
- The concept of "*decision time*" has been introduced to explain the behavior of a cable against transient disturbances. Further research is going on;
- A complete scan of the stability margins of the LHC cables has been obtained, with respect to several parameters;
- Improvements of the heat transfer model are ongoing, together with the increase of the complexity of the 0-D approach. Indeed, a more accurate multi-strand approach with periodical boundary conditions would better describe the internal structure of the cable and the predicted shape of a beam loss energy deposit;

- **A dedicated stability experiment would allow a validation of the model and a tuning of its parameters, thus allowing to obtain a reliable tool:**

→ **to set the BLM system, thus being able to predict beam induced quenches with accuracy;**

→ **for design of cables for accelerators SC magnets.**