DIPARTIMENTO
INGEGNERIA DELL'ENERGIA ELETTRICA
E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Heat transfer to liquid helium in the stability modeling of Rutherford cables.

Beam Induced Quench Workshop
CERN, Switzerland, September 16th 2014

M. Breschi[1], P. P. Granieri[3], A. Bevilacqua[1,2], L. Bottura[2]

[1]University of Bologna, Italy

[2]CERN, Geneva, Switzerland

[3]Karlsruhe Institute of Technology, Germany

Thanks to Eleonora Bergonzoni, Marco Massimini, Pietro Galassi

Outline

- Heat transfer to superfluid/liquid helium
  - Phases of heat transfer and transitions
- Stability of Rutherford cables vs beam loss disturbance
  - 0-D model
  - 1-D model with 1 strand
  - 1-D model with *N* strands
- Conclusions

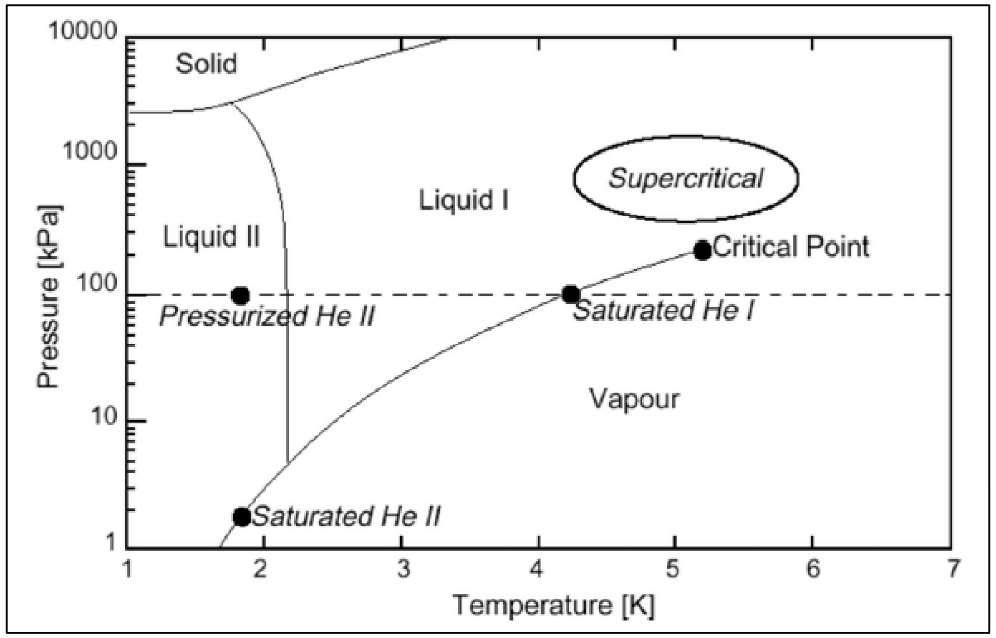
DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Outline

- Heat transfer to superfluid/liquid helium
  - Phases of heat transfer and transitions
- Stability of Rutherford cables vs beam loss disturbance
  - 0-D model
  - 1-D model with 1-strand
  - 1-D model with *N*-strand
- Conclusions

DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Phases of heat transfer to superfluid/ liquid helium



- Several phases are possible in the heat transfer to helium from He II to the gaseous state

1)	$T_h < T_\lambda$	Kapitza coefficient: h_k	**He II**
2)	$T_\lambda < T_h < T_{sat}$	Helium I heat transfer coefficient: h_{hel}	**He I**
3)	$T_h = T_{sat}$	Nucleate boiling He I: $h_{nucl.\ boil.}$	**He I/gas**
4)	$T_h = T_{sat}$	Film boiling He I: $h_{film.\ boil.}$	**He I/gas**
5)	$T_h > T_{sat}$	He gas/supercritical helium: h_{gas}/h_{sc}	**gas/supercr. He**

ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088
DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

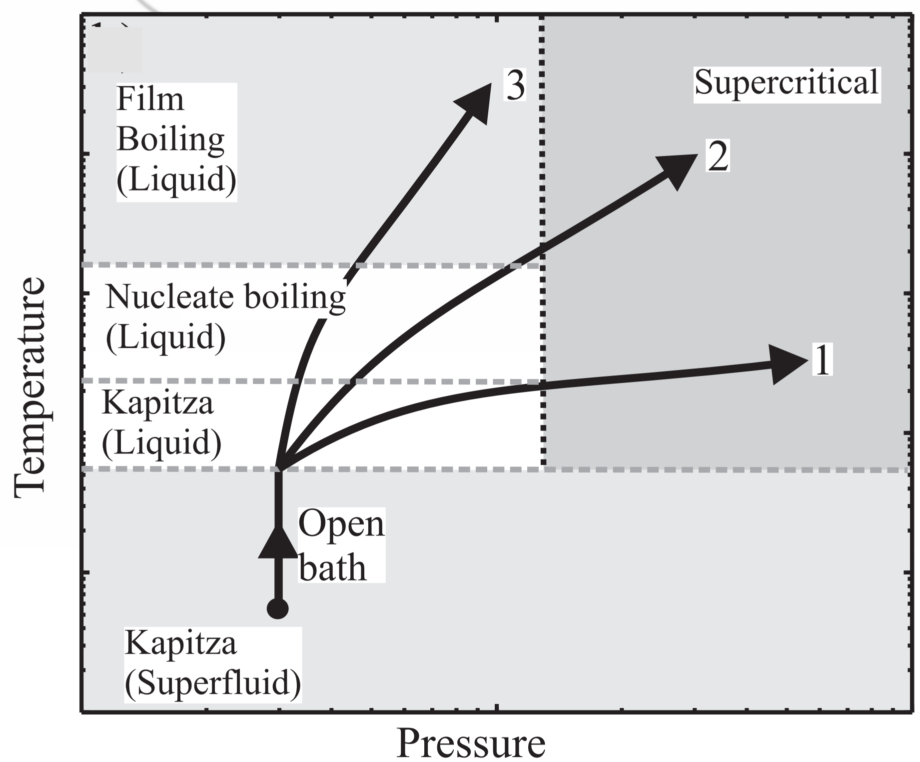
Phases of heat transfer to helium

- The various phases can be described as follows

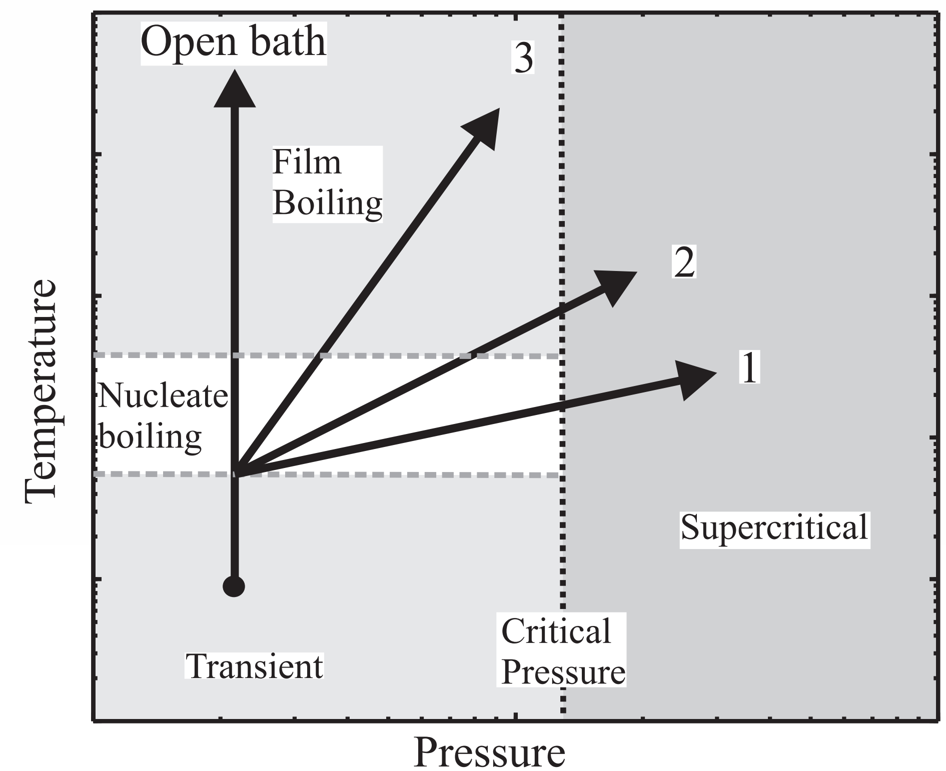
1) Kapitza resistance at the interface between solid surface and superfluid/liquid helium
2) At low heat flux in superfluid helium the second sound regime is dominant. At high heat flux onset of quantum turbulence and Gorter Mellink limit applies.
3) Nucleate boiling: vapor bubbles appear in the helium; the bubbles are separated from each other
4) Film boiling: an evaporated thin film is created at the cooled surface with a dramatic reduction of the heat exchange coefficient
5) Phase transition to supercritical helium in closed volumes

DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Cooling regimes for He II and He I



He II – high heat flux



He I

- The actual evolution of heat transfer phases depends on several parameters: V_{he}/A_{he}, heating power, open or closed bath
- For an open bath of superfluid helium, the two cooling regimes are the Kapitza regime and the superfluid film-boiling regime

- G. Willering "Stability of superconducting Rutherford cables for accelerator magnets", Ph. Dissertation, University of Twente, The Netherlands, 2009

DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

From Kapitza resistance to nucleate boiling

- The temperature rise from 1.9 K to T_λ requires the deposition of a minimal amount of energy about 236 kJ/m^3
- At the saturation temperature, after a given time required to reach ebullition, a transition to nucleate boiling occurs
- This time t_{eb} of transition to nucleate boiling is computed in [1] by solving the equation of transient conduction in helium I

$$t_{eb} = \frac{\pi}{4}\lambda c \rho \frac{\Delta T_{eb}^2}{q^2}$$

ΔT_{eb} is the superheat of the liquid at the onset of boiling at the wall

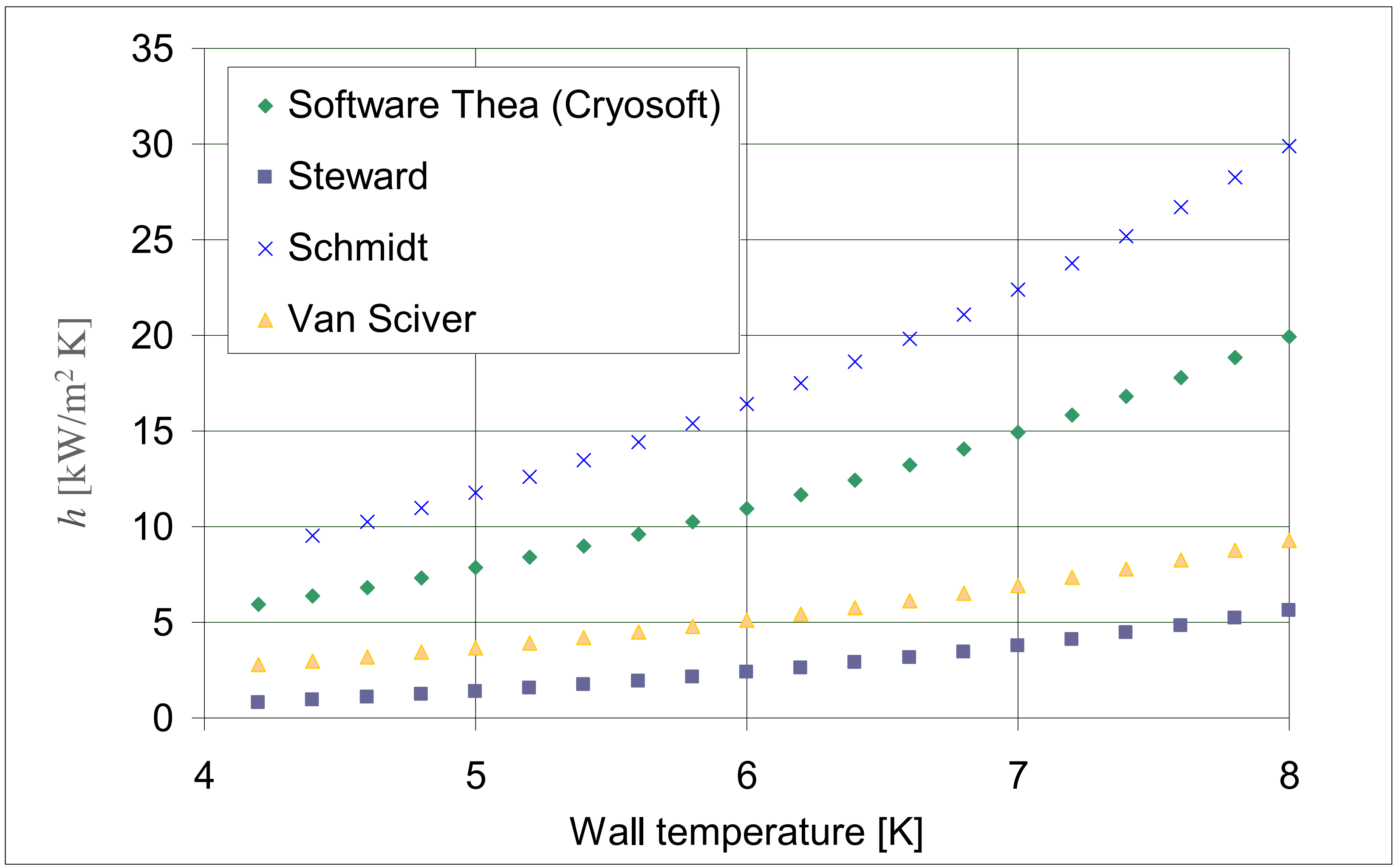
- In most stability models the Kapitza and the nucleate boiling regimes are represented as a single phase

- [1] V. I. Deev, et al, “Transient boiling crisis of cryogenic liquids”, Int. Journal of Heat and Mass Transfer, 47, 2004

DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

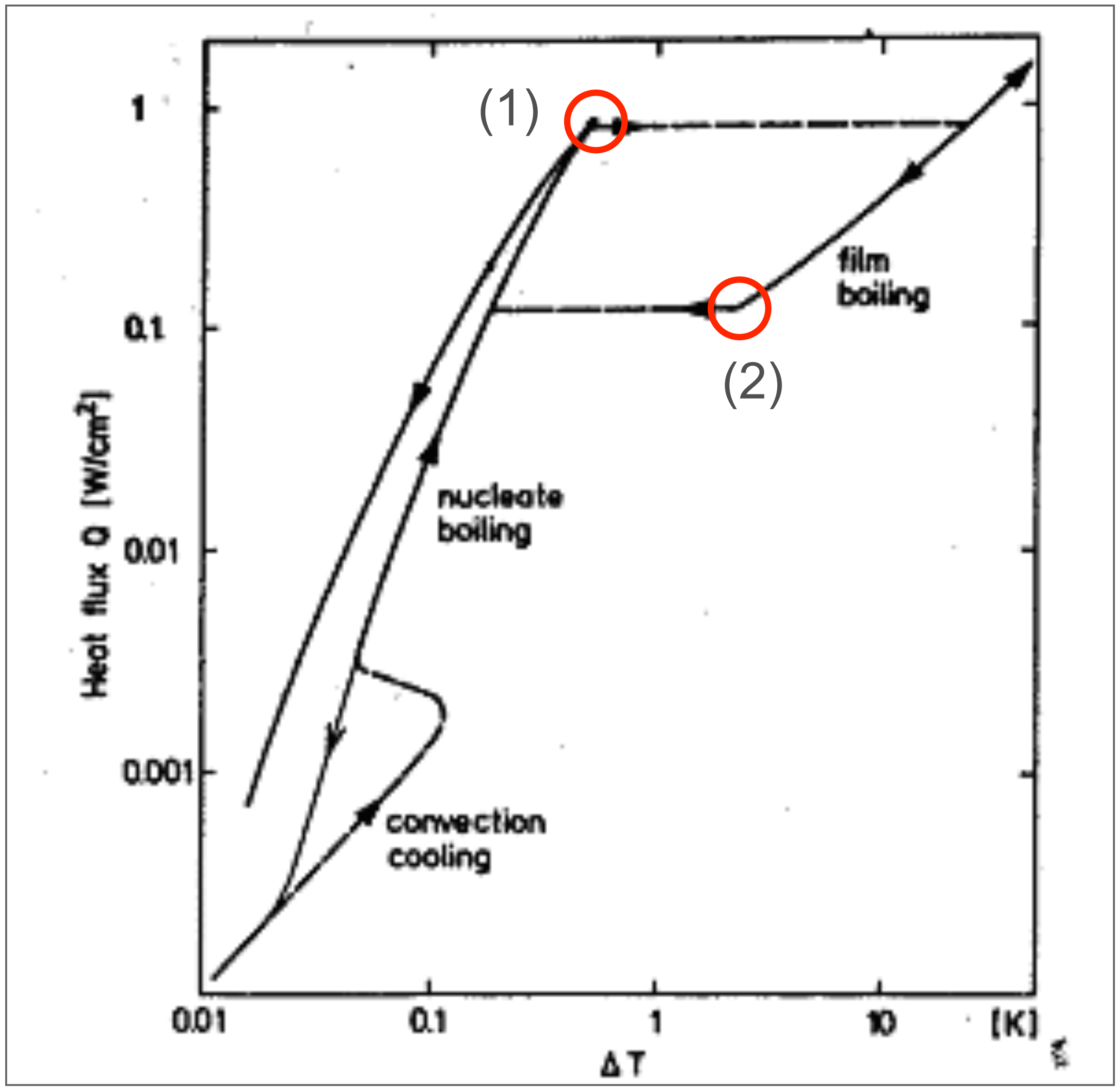
Transient nucleate boiling: models

- A comparison of various available models for the Kapitza-transient heat transfer at nucleate boiling is presented in the plot for helium I



- A typical expression for this phase is given by $Q = A\left(T_s^m - T_h^m\right)$

Transition from nucleate to film boiling: steady state



- The forward transition (1) from nucleate to film boiling occurs at a higher ΔT than the backwards transition (2) to nucleate boiling (hysteresis)
- This peculiar feature must be taken into account in stability modeling of recovery for long heat pulses

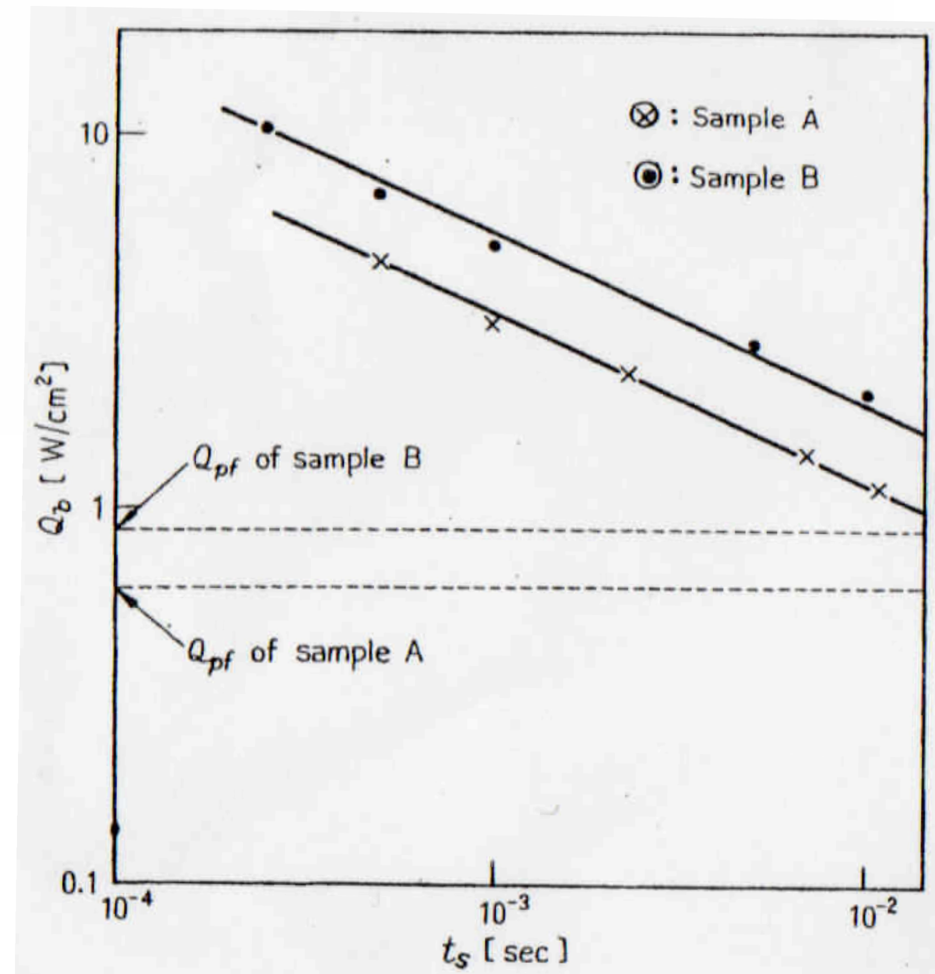
- C. Schmidt, “Review of steady state and transient heat transfer in pool boiling He–I”, Proceedings of the Saclay Workshop on Stability of Superconductors in He-I and He-II, International Institute of Refrigeration, Paris, 1982, pp. 17-31.

Transition from nucleate to film boiling: steady state vs. transient

- Two main differences can be observed when comparing the steady state and the transient heat transfer

1) In transient, heat fluxes higher than the peak steady state limit can be transferred to helium, improving stability at short pulse durations

2) The transition to film boiling can occur at heat fluxes lower than the peak steady state limit, when a limiting energy is reached, thus decreasing stability at low heat fluxes



- O. Tsukamoto, S. Kobayashi, “Transient heat transfer characterisctics of liquid helium”, Jour. Appl. Physics, 46, 1975

Transition from nucleate to film boiling: models of energy limit

- Models to determine the onset of film boiling are often based on the calculation of the energy required to vaporize a thin layer of helium close to the heated surface [1]
- From the thickness of the diffusion layer, the time and energy of the film boiling onset are derived:

$$x = \gamma \left(\frac{k}{C} t \right)^{\frac{1}{2}} \Rightarrow E_f = Q t_f = x L \Rightarrow t_f = \gamma^2 \frac{k}{c} \left(\frac{L}{Q} \right)^2 = 6.9\,10^5 Q^{-2}$$

γ factor accounting for phase transformation from liquid to gas

- A model of film boiling onset in He I was developed in [2], computing the time required for the bubbles to coalesce and create the film:

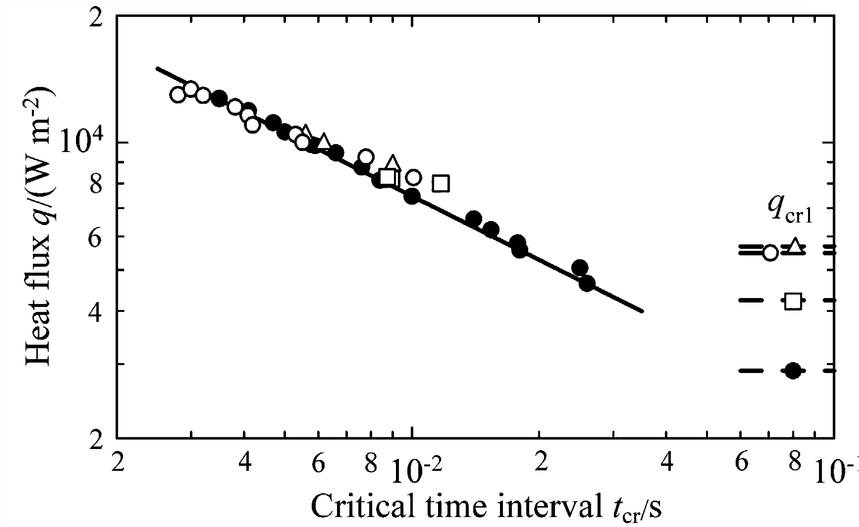
$$R(t) = f(Ja)\sqrt{a(t - t_1)}, n(t) = \int_0^t P_0 \left[1 - s_v(t_1) \right] \Rightarrow \quad t_f = CQ^{-2}$$

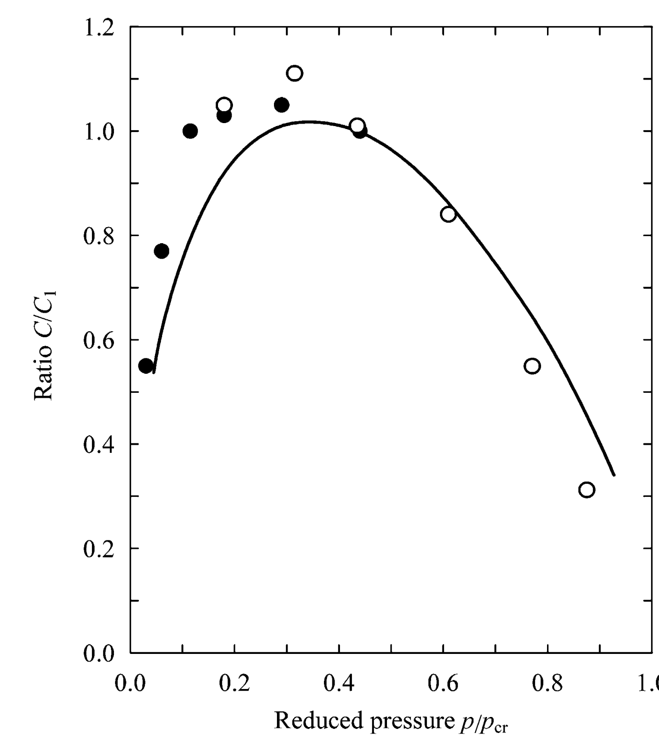
[1] G. Willering "Stability of superconducting Rutherford cables for accelerator magnets", Ph. Dissertation, University of Twente, The Netherlands, 2009

[2] V. I. Deev, et al, "Transient boiling crisis of cryogenic liquids", Int. Journal of Heat and Mass Transfer, 47, 2004

Transition from nucleate to film boiling: models of energy limit

- $E_f = Q\, t_f = Q\, C\, Q^{-2} = C\, Q^{-1}$ for helium I
- The energy transferred before the onset of film boiling decreases with increasing heat flux. A decrease of heat flow (thin insulation layer) may in some cases be advantageous for stability as it prolongs the duration of the nucleate boiling regime
- At film boiling $Q = h\,\Delta T$ with *h* in the range from 100 to 2000 W/m^2 K
- Are the time and energy limits of the transition to film boiling in transient conditions known for the strands in the LHC cables ?



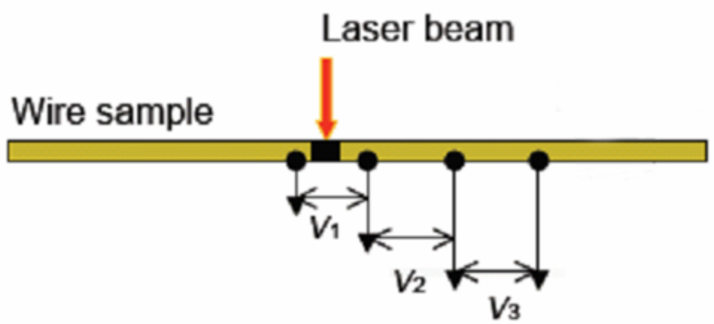


- C. Schmidt, International Institute of Refrigeration, Paris, pp. 17-31, 1982.
- V. I. Deev, et al, "Transient boiling crisis of cryogenic liquids", Int. Journal of Heat and Mass Transfer, 47, 2004

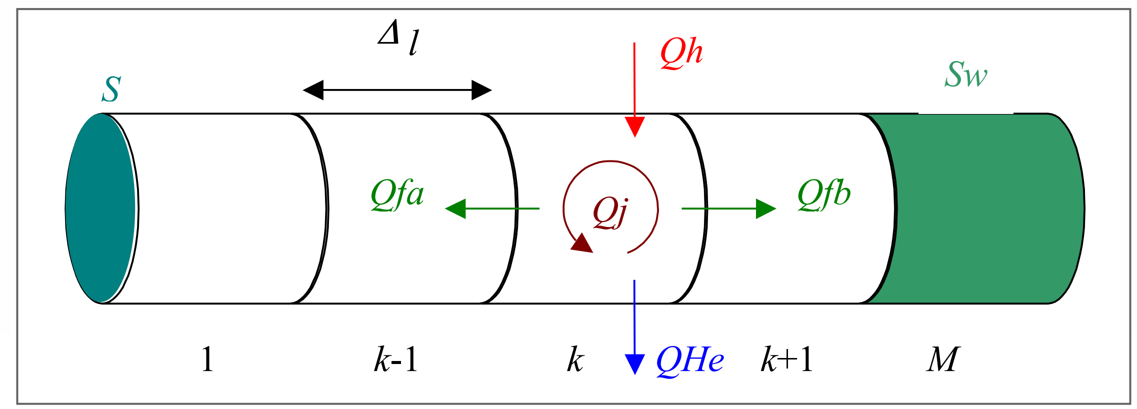
DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

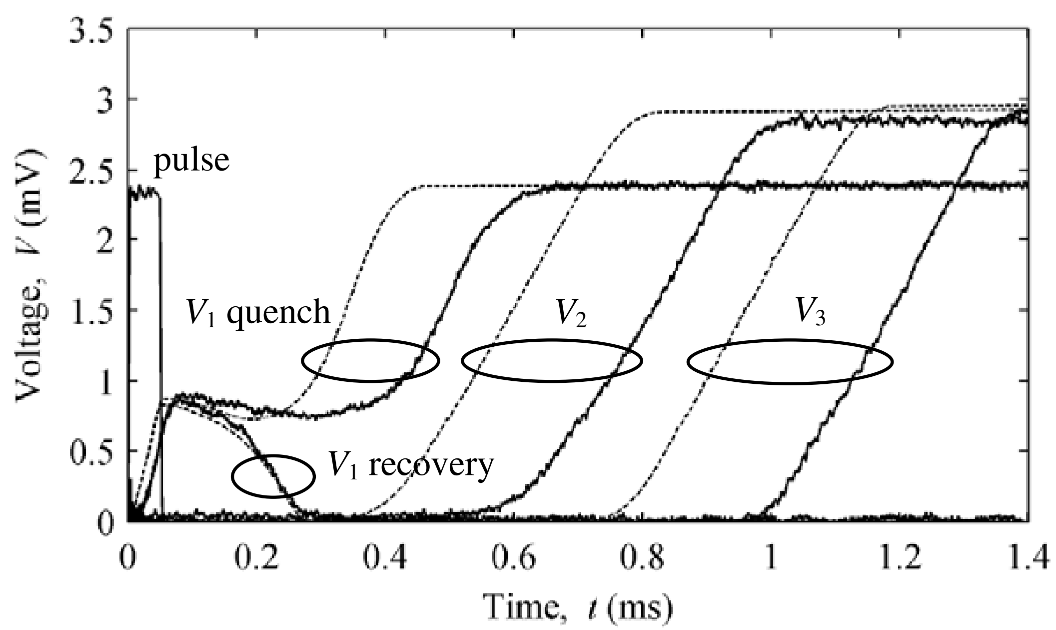
Transition from nucleate to film boiling: a collective phenomenon

- Voltage traces in quench experiments on NbTi and Nb_3Sn wires in pool boiling liquid helium revealed the need to account for spatial effects

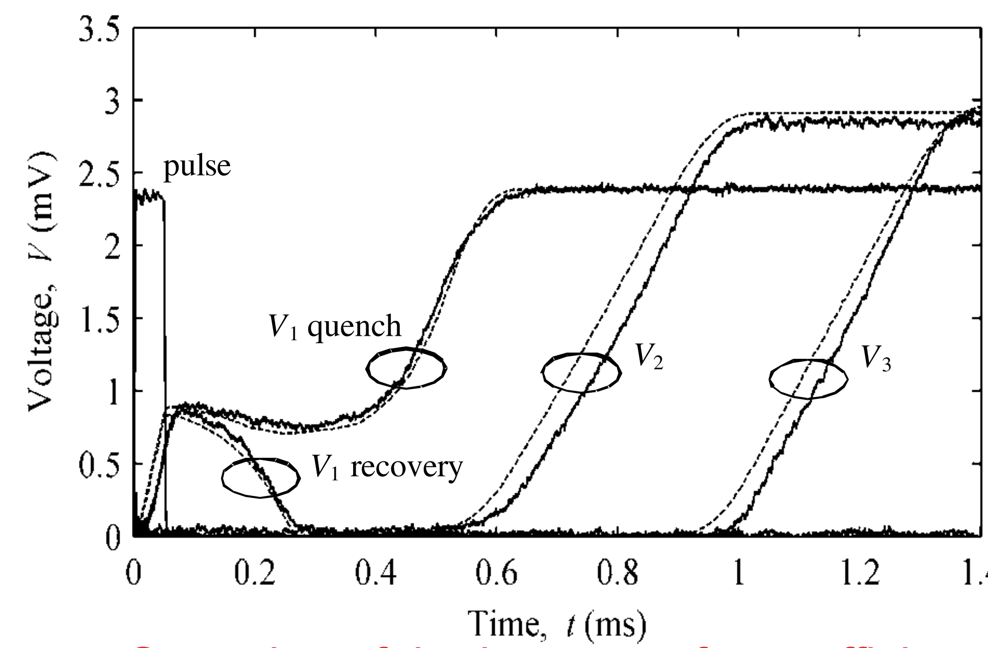


Measurements by F. Trillaud, CEA Saclay, France





No smearing of the heat transfer coefficient



Smearing of the heat transfer coefficient

- M. Breschi, et al., "Comparing the thermal stability of NbTi and Nb_3Sn wires", Superconductor Science and Technology, Vol. 22, 2008.

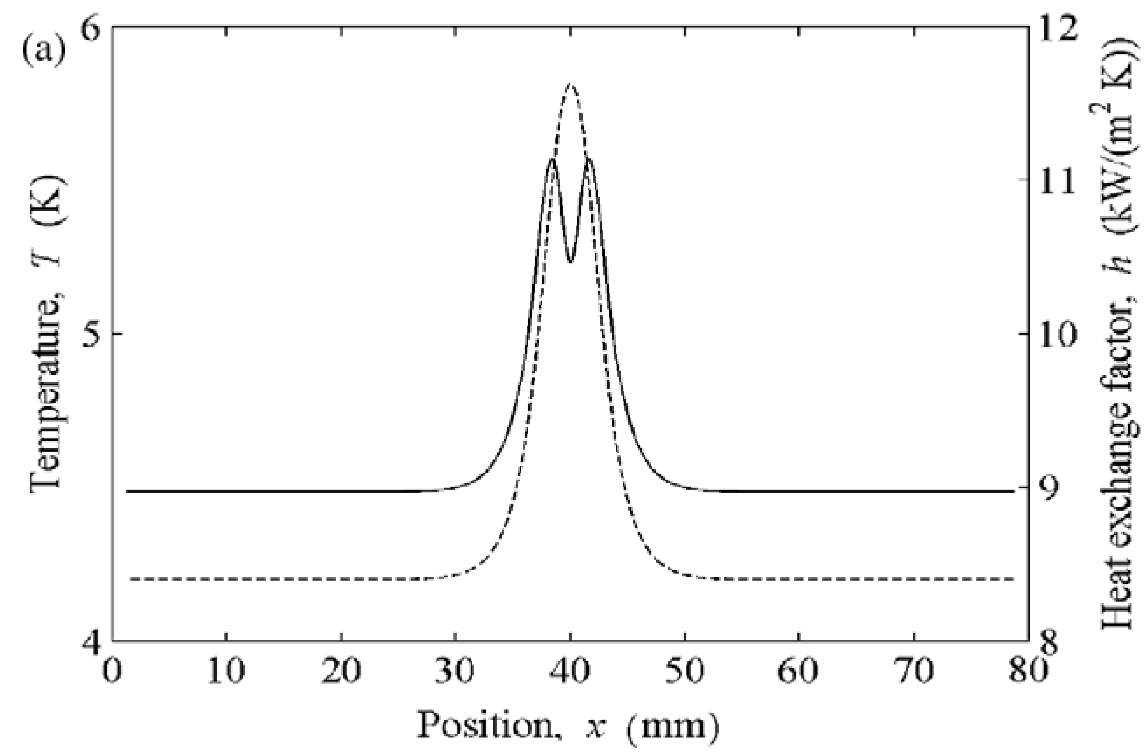
Transition from nucleate to film boiling: model of spatial smearing

- The transition to film boiling is a collective phenomenon rather than a local transition. The heat transfer coefficients calculated for each sector are smeared along the sample length

$$H_{check}(i) = 0 \quad \text{for nucleate boiling}$$
$$H_{check}(i) = 1 \quad \text{for film boiling}$$

$$w(i,j) = \frac{1}{\sqrt{2\pi}\,\sigma} \int_{x_l(j)}^{x_r(j)} \exp\left\{-\frac{[x_m(i)-x]^2}{2\sigma^2}\right\} dx$$

$$h_i = [1 - H_{smeared}(i)]\,h_{nucl} + H_{smeared}(i)\,h_{film}$$



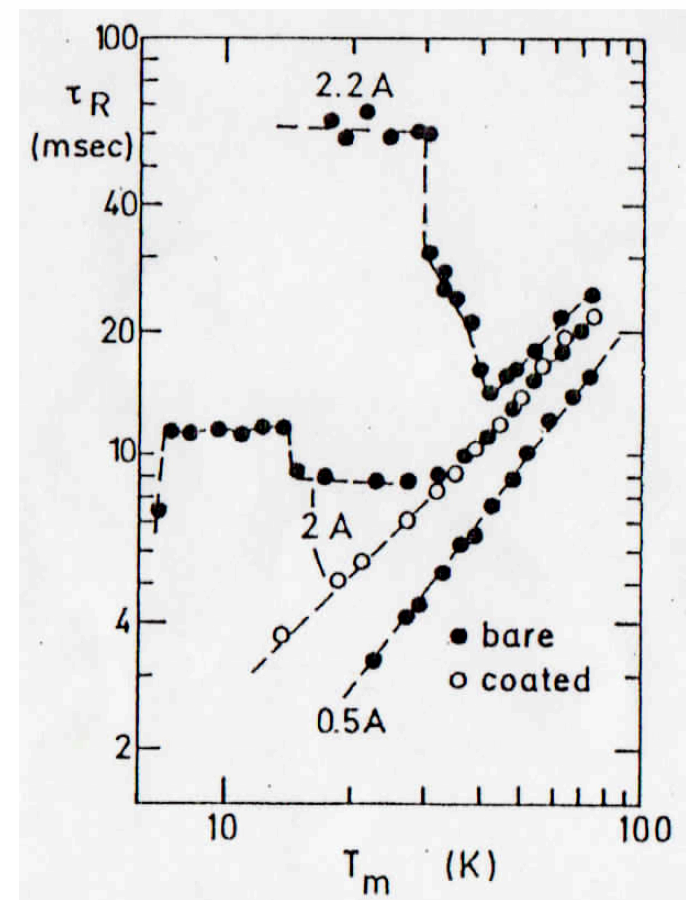
- In a wire length less than σ, the transition to film boiling is not allowed even if the critical energy E_f is reached (σ = 1 mm, r_b = 0.35 mm)

- M. Breschi, et al., "Comparing the thermal stability of NbTi and Nb_3Sn wires", Superconductor Science and Technology, Vol. 22, 2008.

DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Backward transition from film boiling to nucleate boiling: recovery

- The knowledge of the heat transfer for the backwards transition to nucleate boiling is essential for recovery analysis
- Most heat transfer experiments were performed with increasing heat fluxes but few data are available for decreasing heat fluxes
- The heat transfer in recovery processes at decreasing temperatures is lower than in the steady state mode
- In presence of repeated heat pulses, the heat transfer will also depend on the hystory of the pulsed heating
- Is the heat transfer at decreasing fluxes, for short, long and repeated pulsed disturbances, known for the LHC strands ?



- C. Schmidt, International Institute of Refrigeration, Paris, pp. 17-31, 1982.
- Recovery time vs temperature reached in the pulse

DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

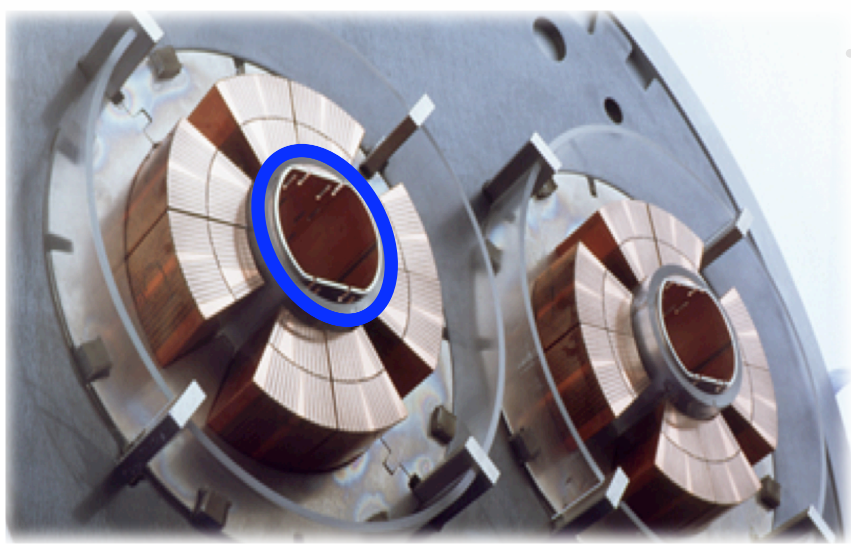
Outline

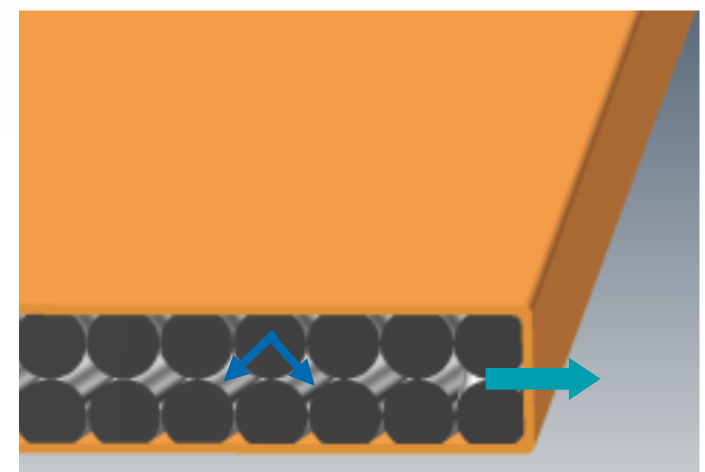
- Heat transfer to superfluid/liquid helium
  - Phases of heat transfer and transitions
- Stability of Rutherford cables vs beam loss disturbance
  - 0-D model
  - 1-D model with 1-strand
  - 1-D model with *N*-strand
- Conclusions

DIPARTIMENTO
INGEGNERIA DELL'ENERGIA ELETTRICA
E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Stability of Rutherford cables vs beam loss disturbance

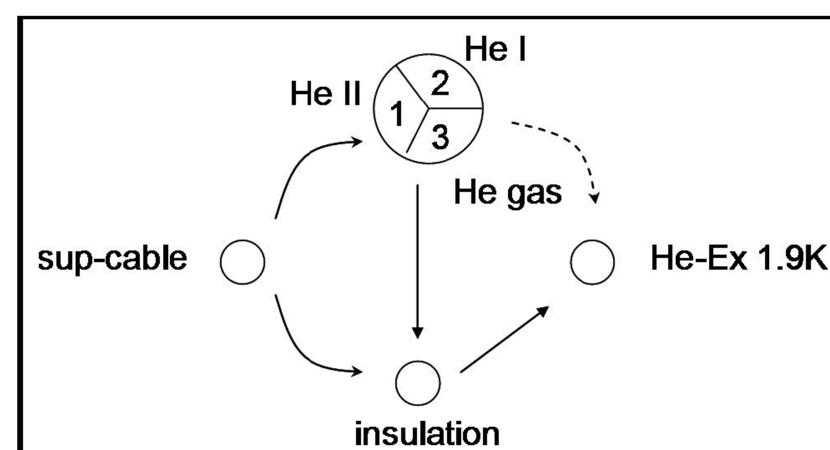
- Models for the thermal stability of the Rutherford subjected to the external heat disturbance from beam losses were developed
- The model was developed at increasing levels of complexity: 0-D, 1-D with a 1-strand model and 1-D with *N*-strand model





Drawings by D. Santandrea

- The model includes strands, interstitial helium and helium bath, connected to each other with a heat transftер coefficient



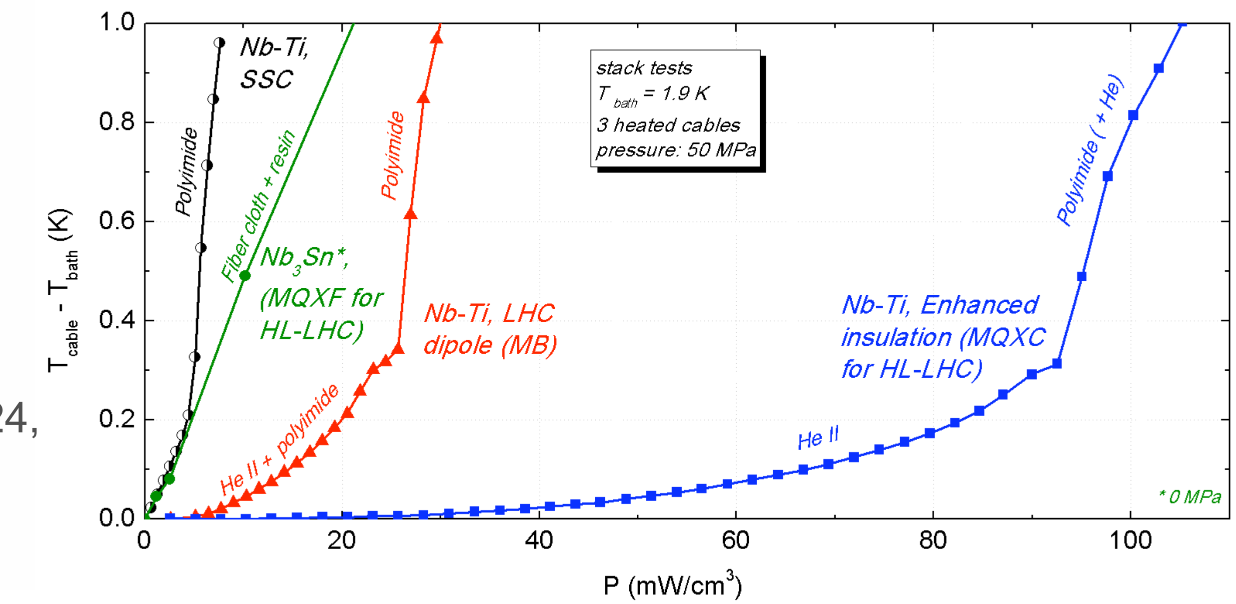
DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Heat transfer models

Heat transfer to helium bath

- Model based on stationary heat transfer, with a fitting of experimental results [1]

[1] P. P. Granieri, et al., IEEE Trans. Appl. Supercond., vol.24, 4802806, 2014



Heat transfer to interstitial helium

- The heat transfer towards the interstitial helium is based on a transient heat transfer model, including several phases

$$h_{s,h} = \begin{cases} h_K & \text{He II} & T_h \le T_\lambda \\ h_{HeI} & \text{He I} & T_\lambda < T_h < T_{Sat} \\ h_{nucl.boil.} & \text{Nucleate Boiling} & T_h = T_{Sat} \\ h_{film} & \text{Film Boiling} & E_{film} = E_{\lim} \\ h_{gas} & \text{Gas} & E_{gas} = E_{lat} \end{cases}$$

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

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

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

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

$h_{film\ boiling}$ = 250 W/m²K

h_{gas} = 70 W/m²K

- The coefficients are taken from experimental results on each helium phase, but the whole process should be validated experimentally

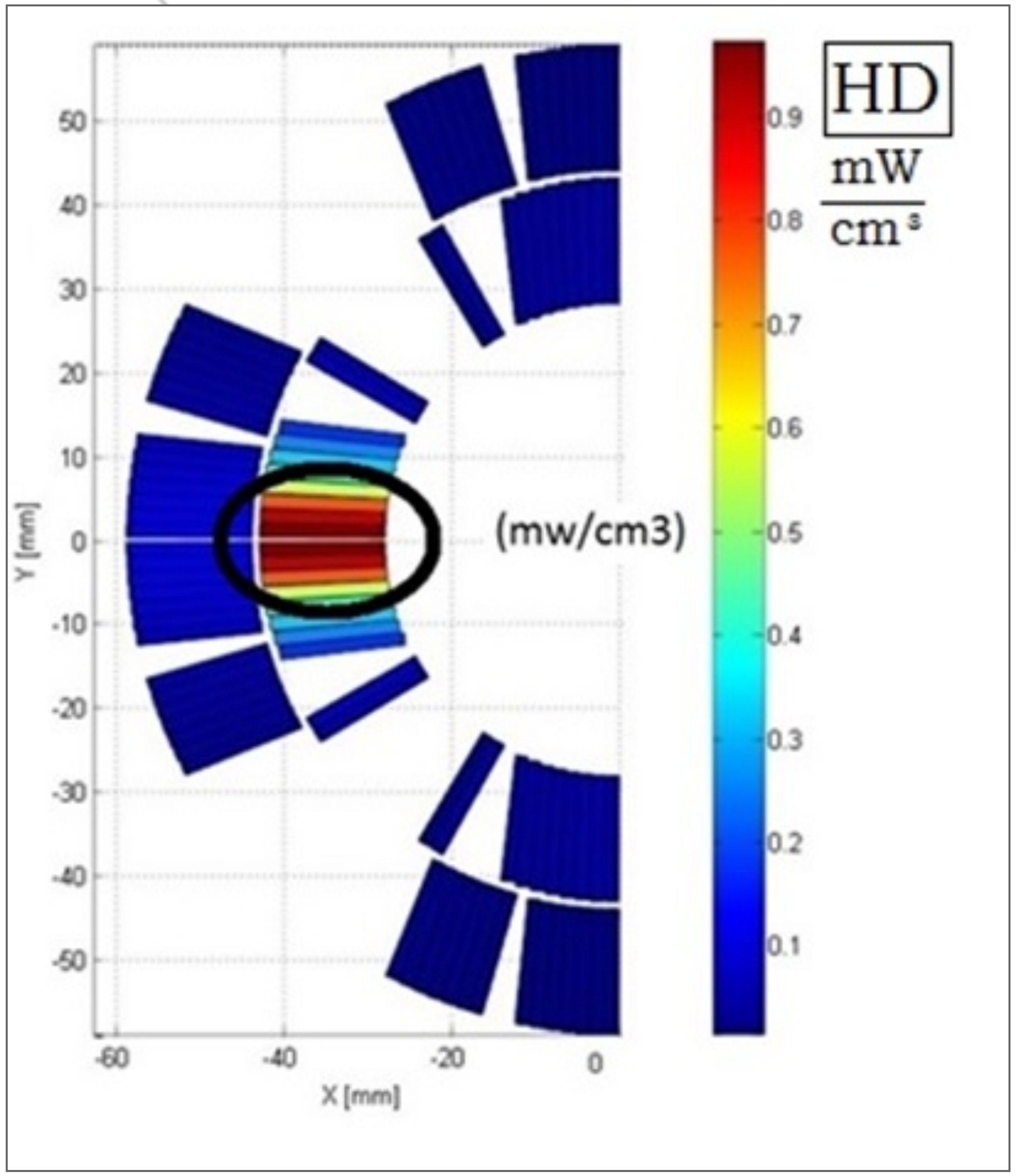
Stability models: 0-D model

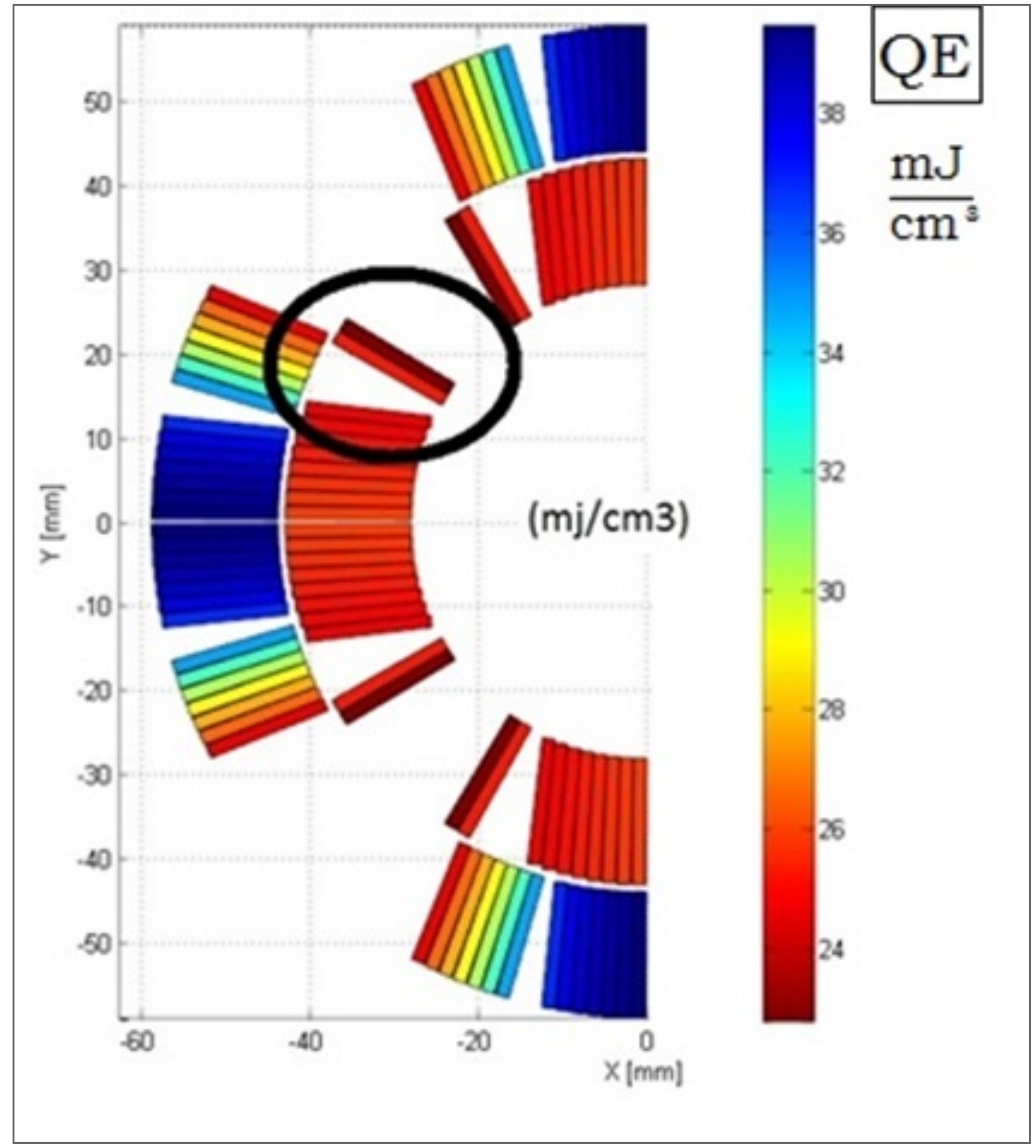
- In the 0-D model the equations account for the enthalpy of the strands, interstitial helium and electrical insulation

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

- All strands are lumped into one single thermal and electrical element, with uniform temperature
- The non-uniformity of magnetic field, cooling and heat deposit over the cable width are not taken into account
- The maximal value of magnetic field on the cable is considered

Results of the 0-D model: HD vs QE





- The highest heat deposit is on the mid-plane cable

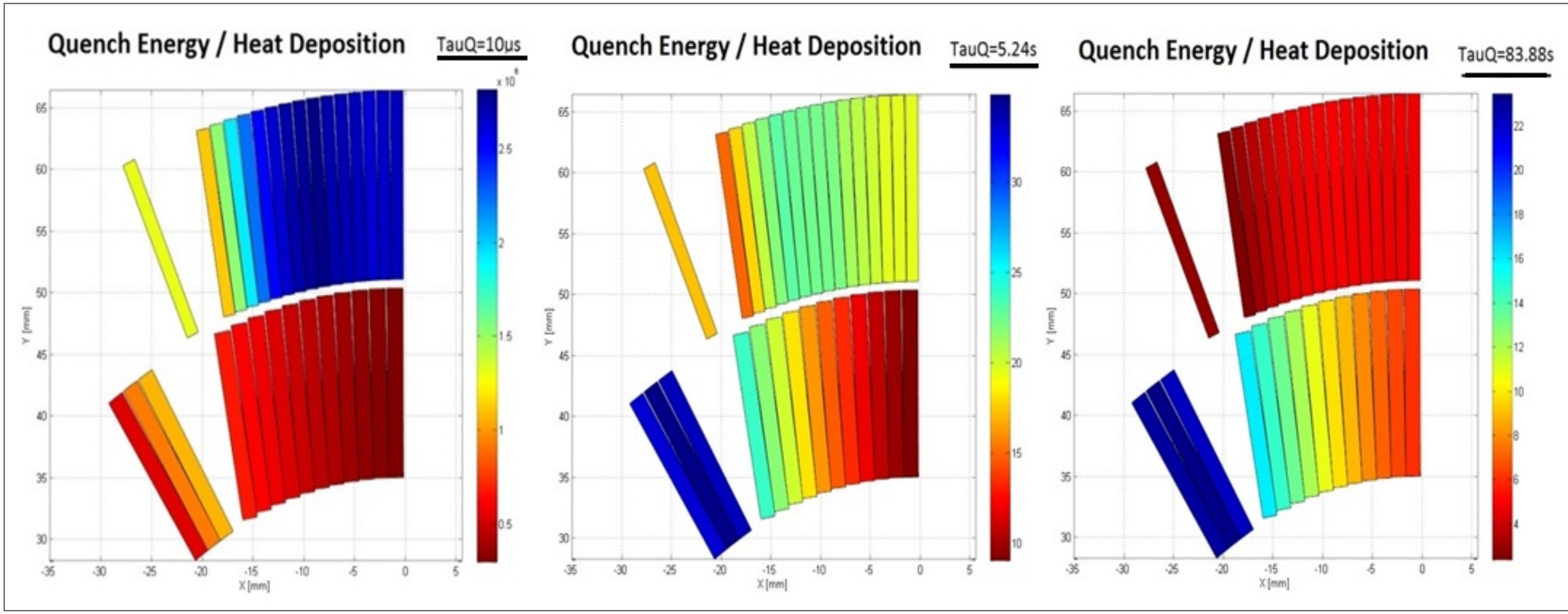
MQ

- The lowest quench energy is at the pole position

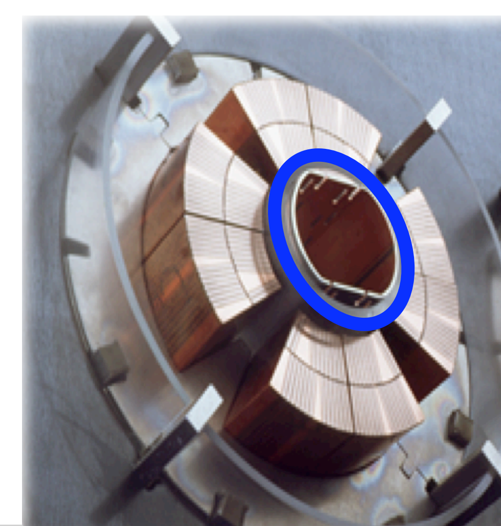
- P. P. Granieri, et al., "0-D and 1-D approaches to investigate the thermal stability of superconducting cables", presented at CHATS-AS, Boston, 2013.

DIPARTIMENTO
INGEGNERIA DELL'ENERGIA ELETTRICA
E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

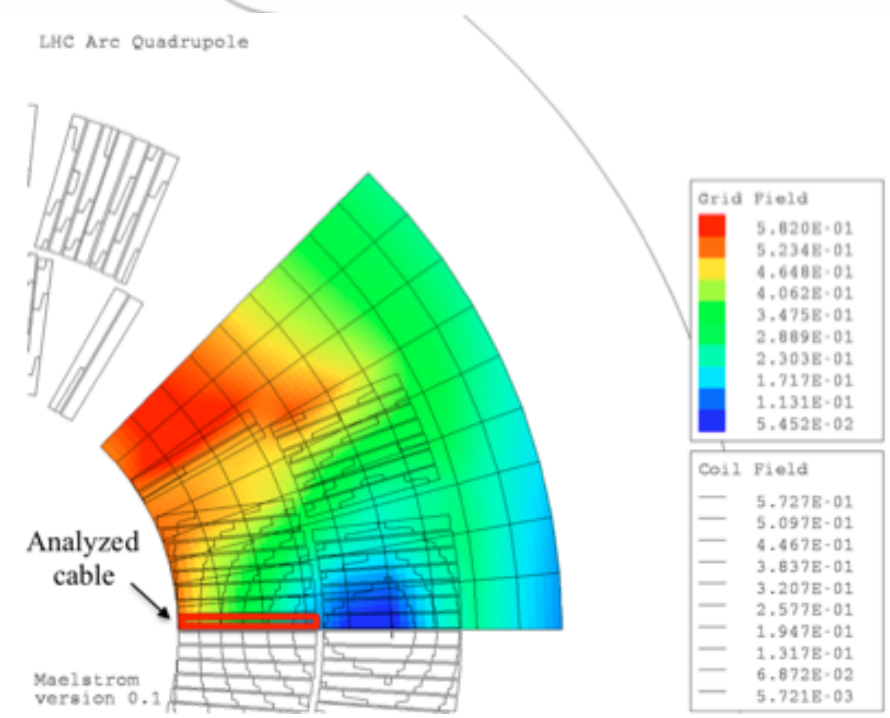
Results of the 0-D model: impact of cooling

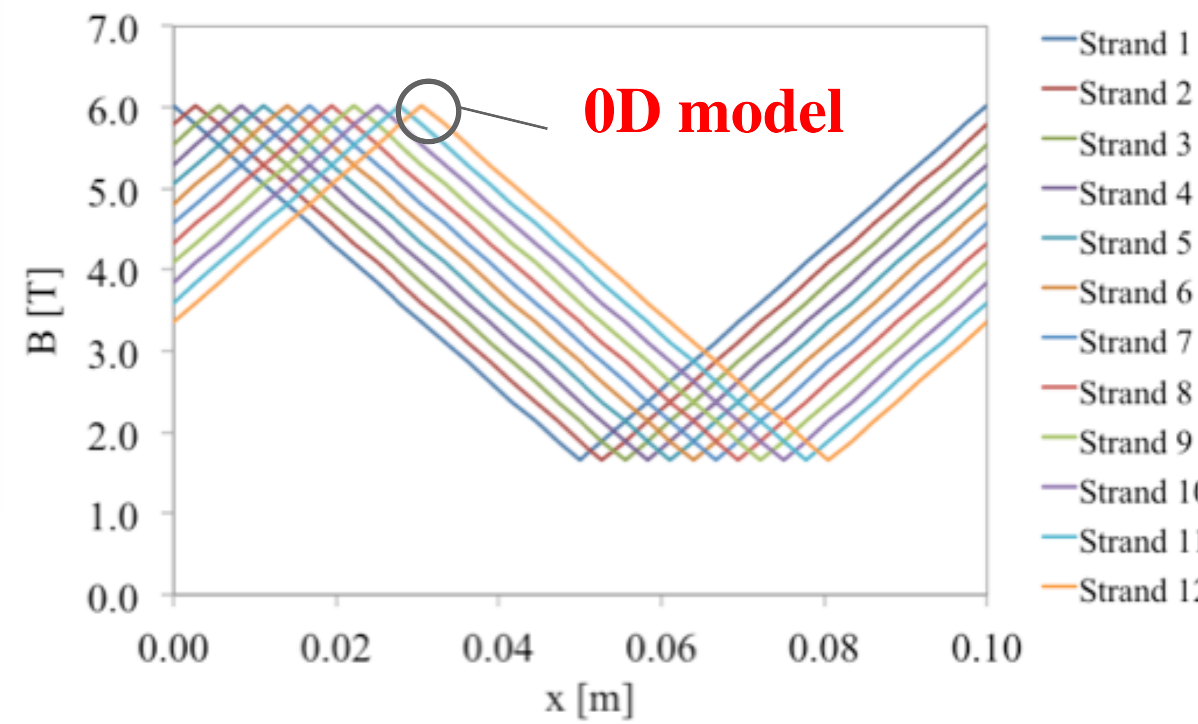


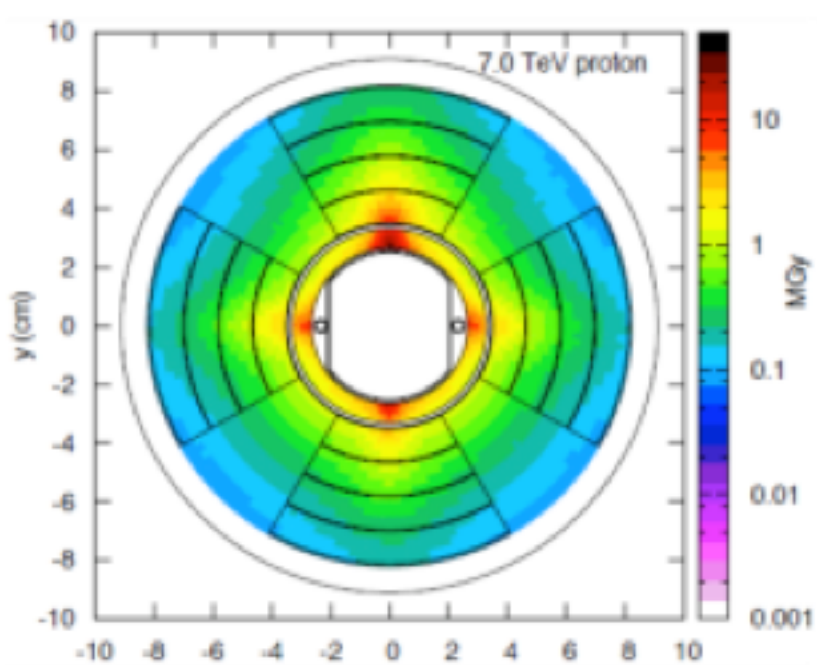
- The role of the helium bath becomes relevant at $t > 0.1$ s
- At short pulse durations the inner layer cables are the most solicited
- At long pulse durations, since the helium bath is closer to the inner layer, the outer layer cables become the most critical

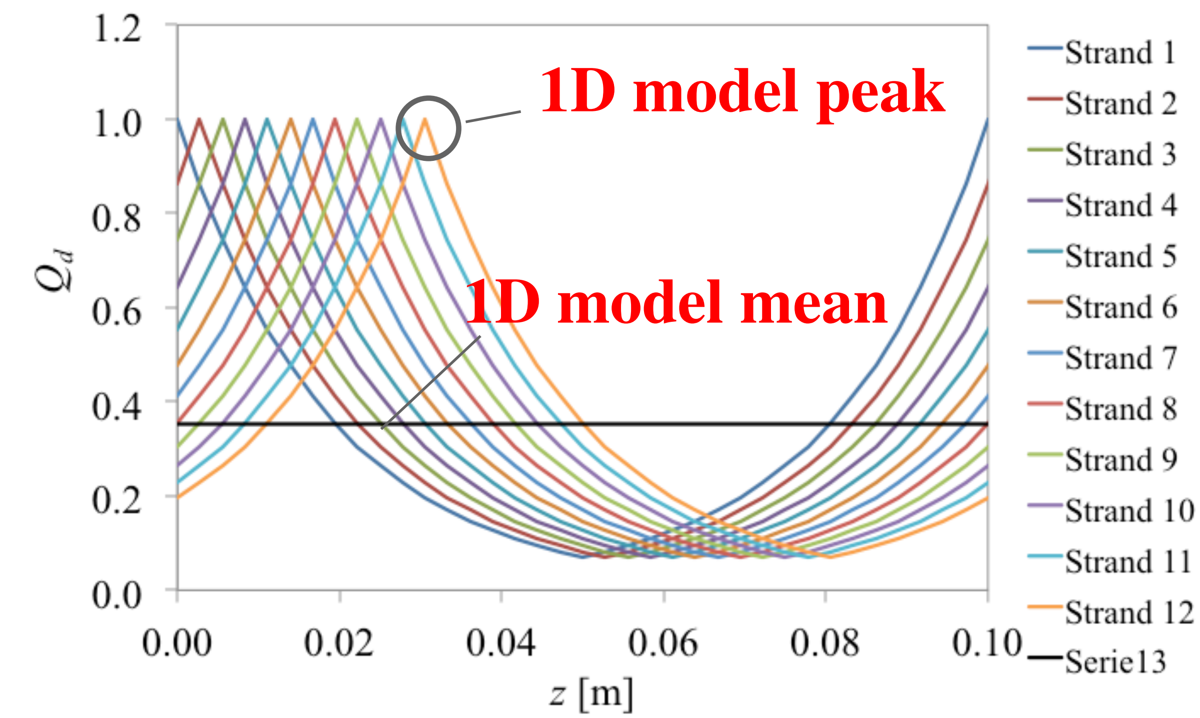


1-D model: non uniform magnetic field and heat deposit





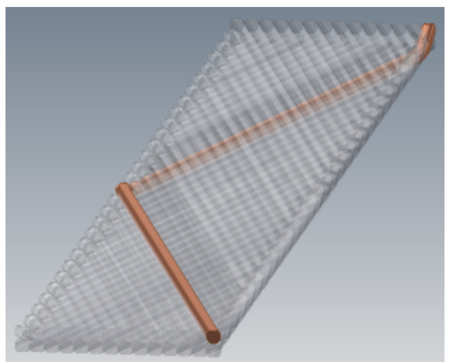




- Example of heat deposit calculation for the MQXA magnet (courtesy of L. Esposito, CERN)

1-D approximation: 1-strand model

- In a first approach only one strand is considered in the simulations, able to exchange heat with interstitial helium and helium bath, not with the other strands

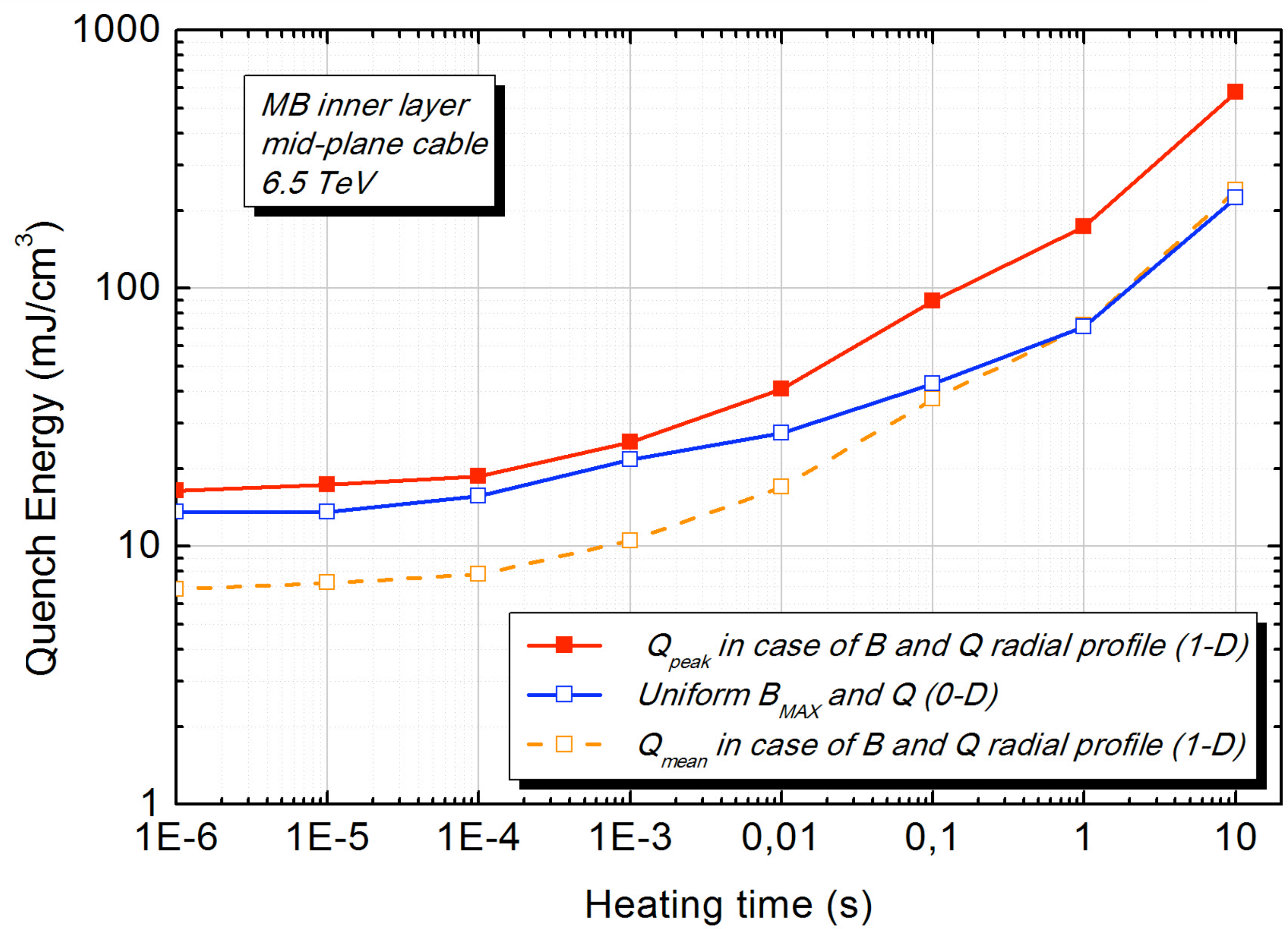


Drawing by D. Santandrea

$$A_i\rho_i C_i \frac{\partial T_i}{\partial t} - \frac{\partial}{\partial x}\left(A_i k_i \frac{\partial T_i}{\partial x}\right) = q_i' + q_{Joule,i}' + \sum_{j=1, j\neq i}^{N} \frac{(T_j - T_i)}{H_{ij}} + \sum_{h=1}^{N} p_{ih} h_{ih}(T_h - T_i)$$

THEA code

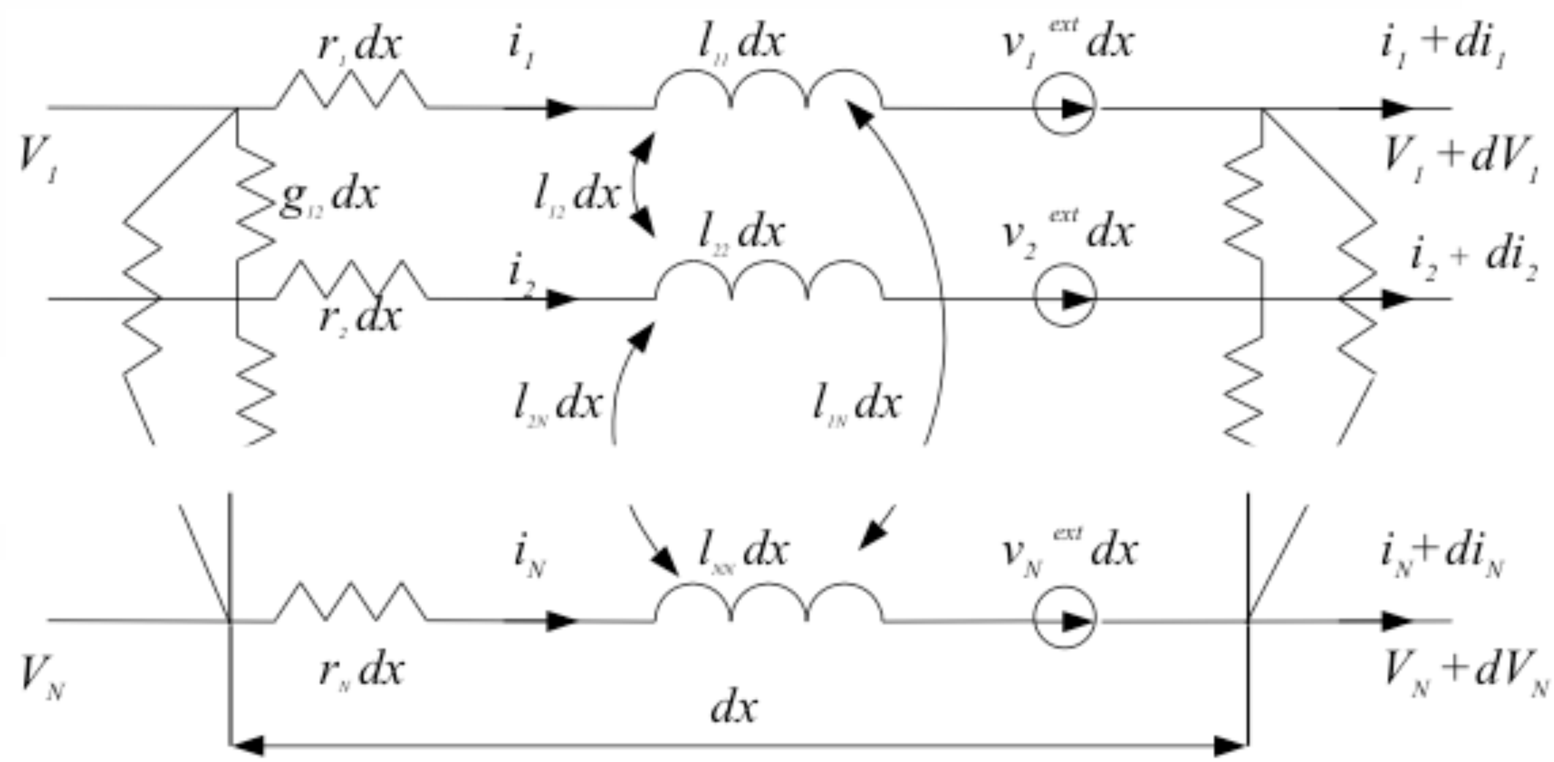
- At low pulse durations the 0D model results are close to the 1D model with QE = $Q_{peak}\, t_{pulse}$ (local effects relevant)
- At high pulse durations the 0D model results coincide with the 1D model with QE = $Q_{mean}\, t_{pulse}$ (global effects predominant)



[1] L. Bottura, C. Rosso, M. Breschi, "A General Model for Thermal, Hydraulic and Electric Analysis of Superconducting Cables", Cryogenics, Vol. 40, pp. 617 – 626, 2000

1-D approximation: N-strand model

- The *N* cable strands are modeled distributed parameter circuit model [1]
- The strands are connected through conductances and mutal inductances in the electric model, and thermal resistances in the thermal model



$$A_i \rho_i c_i \frac{\partial T_i}{\partial t} - \frac{\partial}{\partial x}\left(A_i k_i \frac{\partial T_i}{\partial x}\right) = q_i' + q'_{Joule} + \sum_{j=1, j\neq i}^{N} \frac{\left(T_j - T_i\right)}{H_{ij}} + \sum_{h=1}^{N} p_{ih} h_{ih}\left(T_h - T_i\right)$$

- The values of interstrand electrical and thermal resistances are taken from [1] and [2]

[1] M. Breschi, "Current distribution in multistrand superconducting cables", Ph.D. dissertation, University of Bologna, Italy, 2001

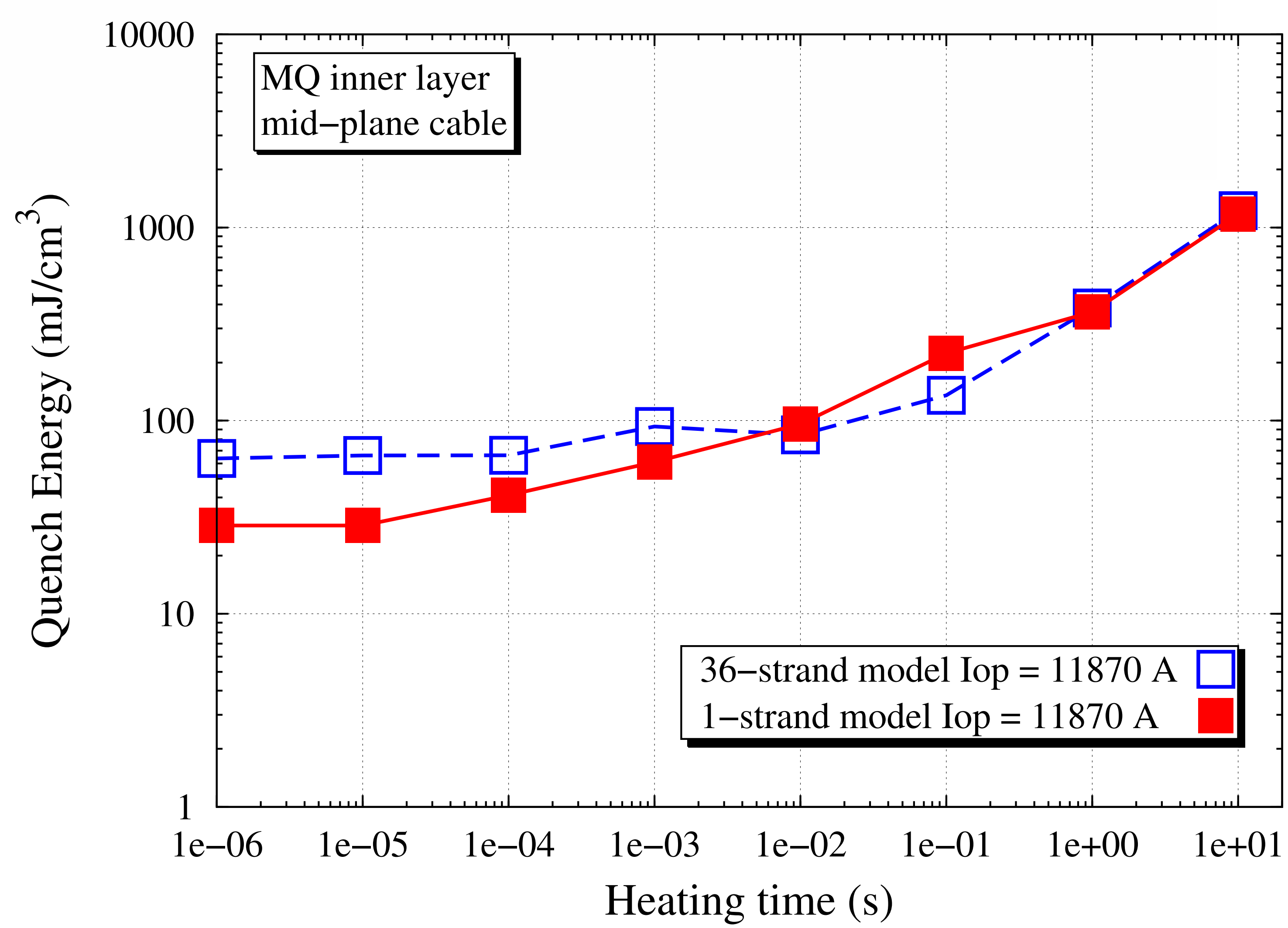
[2] G. Willering, "Stability of superconducting Rutherford cables for accelerator magnets", Ph. Dissertation, University of Twente, The Netherlands, 2009

Comparison between 1-strand and N-strand model (MQ-mid plane)

MQ CABLE DATA

Parameter	Value
Cable Type	LHC2
Strand diameter [mm]	0.825
Cu/non Cu ratio	1.95
Number of strands	36
Transposition pitch [mm]	100
Width [mm]	15.1

- The model is applied to analyse the MQ inner layer cable



- The 36-strand model gives QEs a factor 2 higher than that of the 1- strand model at short pulse durations
- The QEs are coincident for long pulses
- For pulse durations from 10^{-2} to 10^{-1} s, the 36-strand model QE is less than the 1-strand model

- M. Breschi, A. Bevilacqua, L. Bottura, P. P. Granieri, “Quench energy analysis of LHC superconducting cables using a multi-strand, 1D model”, presented at ASC 2014, Charlotte, US, 2014.

DIPARTIMENTO INGEGNERIA DELL'ENERGIA ELETTRICA E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

DIPARTIMENTO
INGEGNERIA DELL'ENERGIA ELETTRICA
E DELL'INFORMAZIONE "GUGLIELMO MARCONI" - DEI

Summary

- The main data on heat transfer that are crucial for stability analyses are the Kapitza conductance, nucleate boiling heat exchange,the time, spatial range, and energy/heat flux of the film boiling onset
- The knowledge of pressure evolution during a quench is relevant to determine whether or not the helium reaches supercritical conditions
- The temperature, heat flux and time required for backwards transition from film boiling is important for recovery analysis
- The details of the non-uniform distribution of the heat disturbance due to beam losses and of the magnetic field over the cable volume are relevant especially for short and intermediate pulse durations
- At short pulse durations, the *N*-strand model gives values of QE a factor 2 higher than the 1-strand model

Thank you for your attention

M. Breschi