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Stability modeling of the LHC Rutherford cables subjected to beam losses.

Chats-AS Workshop, Bologna, Italy
September 15th 2015

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Outline

- Model description
  - 1-D model with 1 strand
  - 1-D model with *N* strands
  - Heat exchange model for NbTi and Nb_3Sn cable
- Convergence studies
- Comparison between 1-strand and N-strand model
- Uniform vs non-uniform heat deposition
- Comparison between NbTi and Nb_3Sn cable results
- Conclusions

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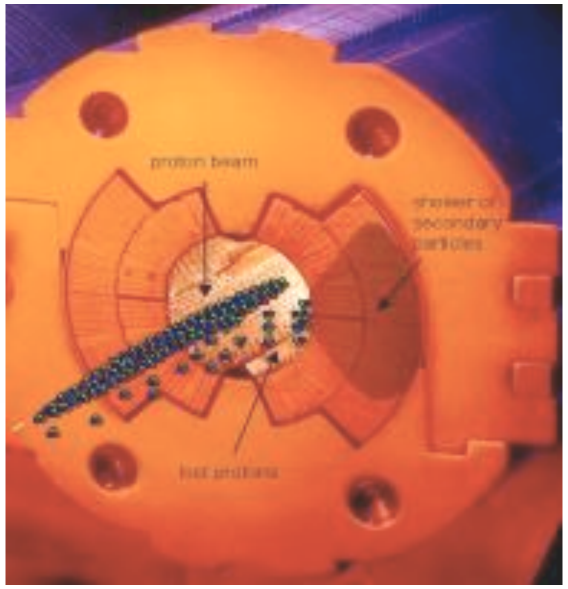
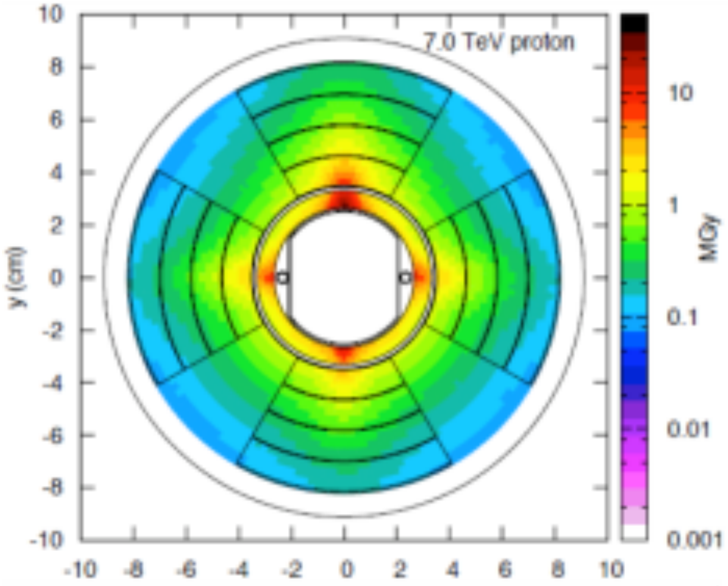
Stability of Rutherford cables vs beam loss disturbance

Beam loss

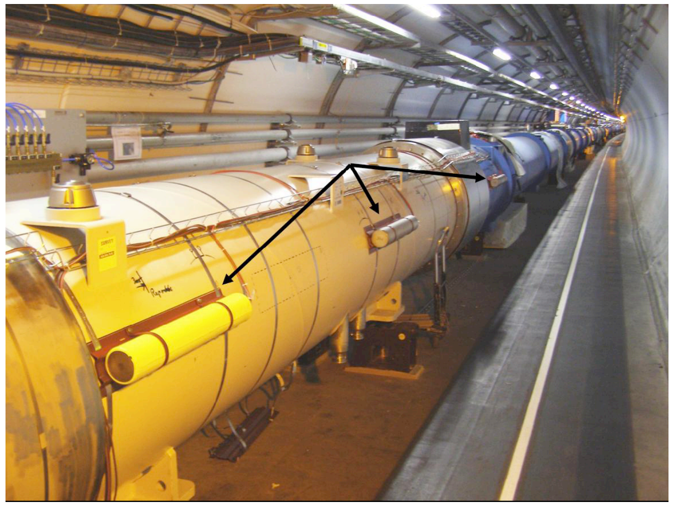


Heat deposit



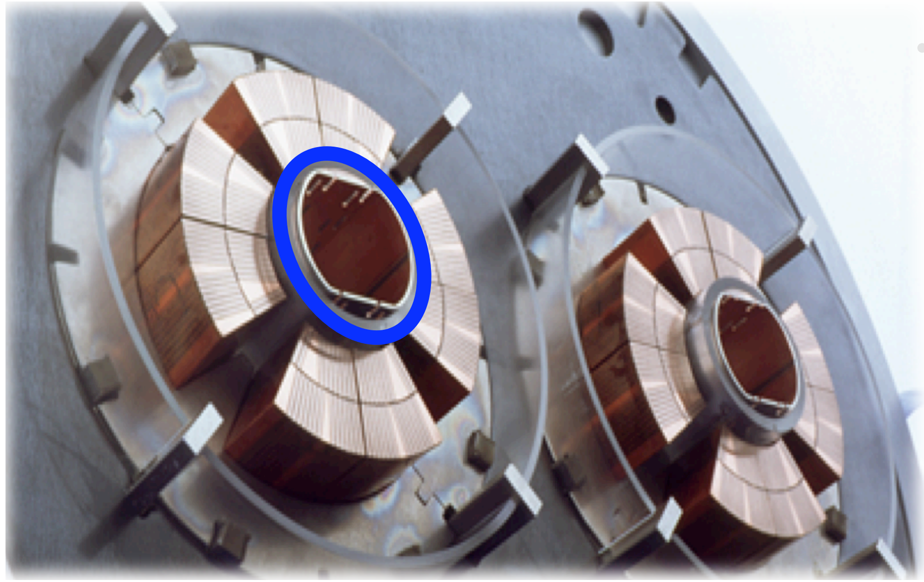
- Beam loss duration ranges from micro-seconds to hours
- Typical beam loss mechanisms:
  - Beam dump (1-100 μs)
  - Collision, collimator losses (steady-state)
- LHC operation in 2008-13 at ~ half the nominal energy: 17 beam induced quenches
- Operation at 7 TeV even more challenging

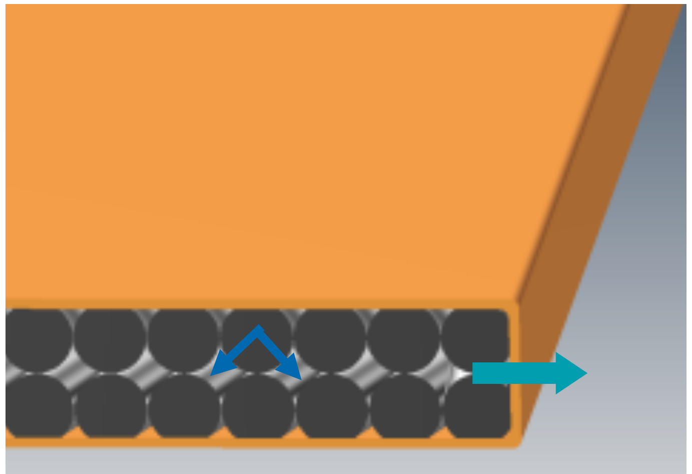
Beam loss monitors



Stability of Rutherford cables vs beam loss disturbance

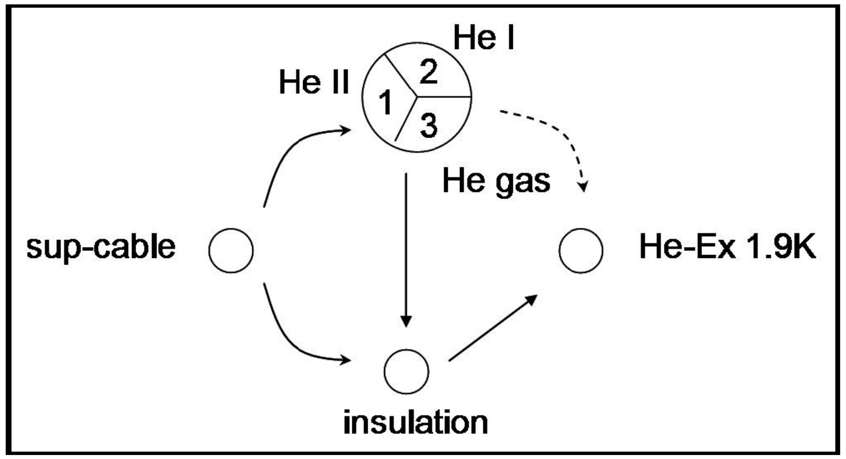
- Models of thermal stability of Rutherford cables subjected to the external heat disturbance from beam losses were developed
- The models were developed at increasing levels of complexity: 0-D, 1-D with a 1-strand model and 1-D with *N*-strand model





Drawings by D. Santandrea

- All models include strands, interstitial helium/glass epoxy and helium bath, connected to each other with a heat transfter coefficient



NbTi – Nb$_3$Sn: *Operating conditions*

NbTi
for LHC MQ quadrupole

- Total current = 11870 A, 36 strands
- Operating current density = 1820 A / mm^2
- Peak magnetic field = 6.85 T
- Temperature = 1.9 K
  - $T_{cs} - T_{op} = 2.89$ K
  - $T_c - T_{op} = 5.04$ K
  - $J_{op}/J_c = 0.465$

Nb$_3$Sn
for Hi-Lumi LHC MQXFv2 quadrupole

- Total current = 16470 A, 40 strands
- Operating current density = 1600 A / mm^2
- Peak magnetic field = 11.4 T
- Temperature = 1.9 K
  - $T_{cs} - T_{op} = 5.34$ K
  - $T_c - T_{op} = 10.94$ K
  - $J_{op}/J_c = 0.472$

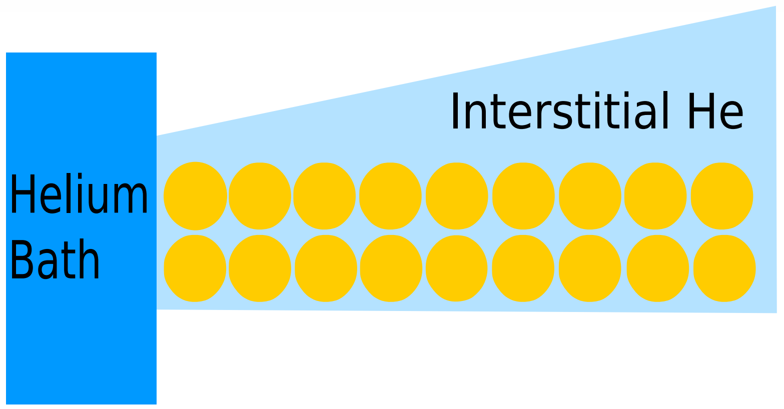
NbTi vs Nb_3Sn: *Heat Transfer Model*

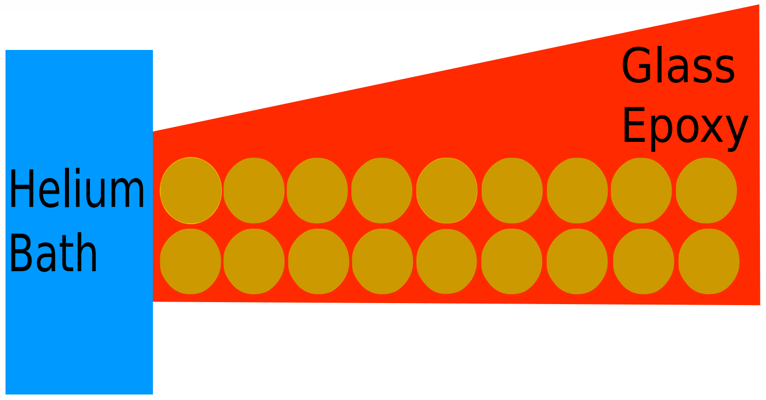
NbTi

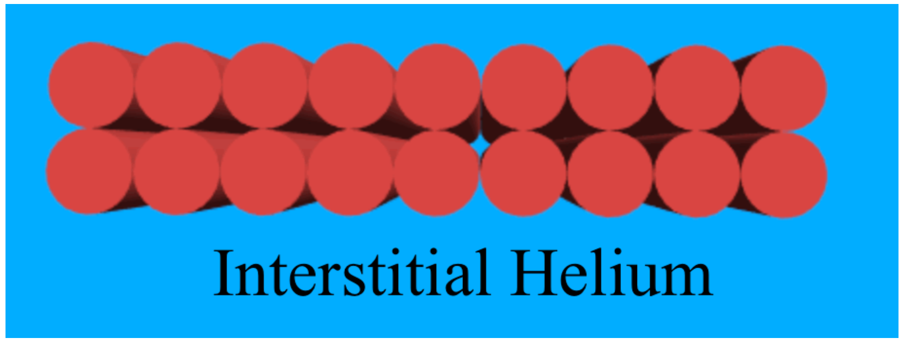
- He II is in direct contact with the strands

Nb_3Sn

- No He II reaches the strands
- Heat transfer occurs due to solid conduction through the epoxy, then to He bath





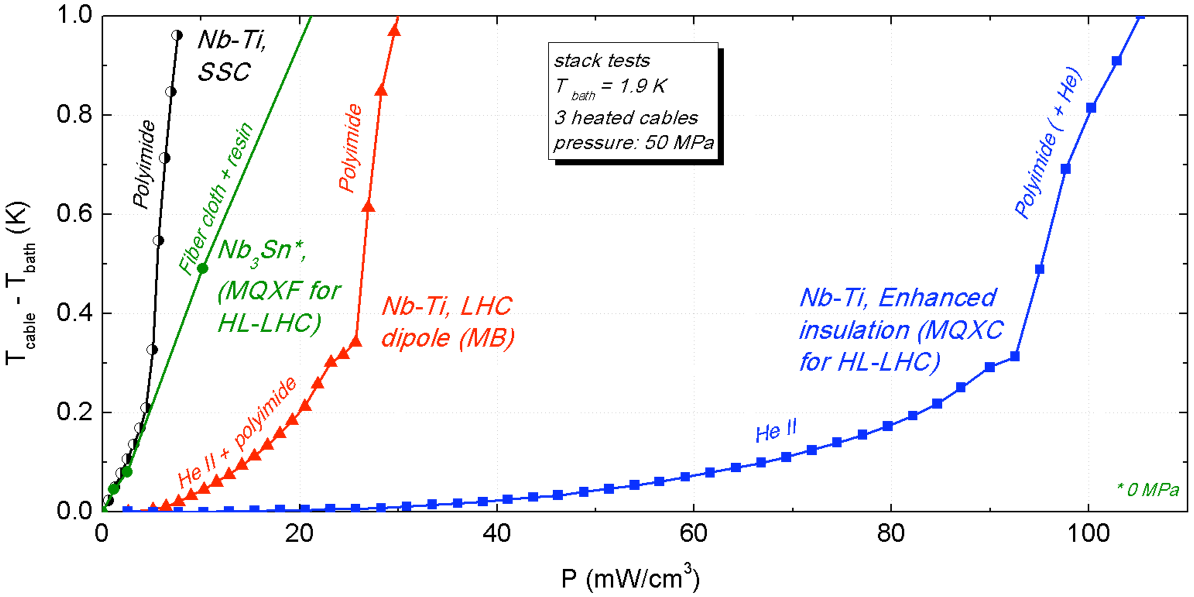


Heat transfer models with helium

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

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

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

$$\boxed{h_{HeI} = \max\left\{\frac{h_K h_{BL}}{h_K + h_{BL}}; h_{ss}\right\}} \quad \boxed{h_{BL} = \sqrt{\frac{K_h \rho_h c_h}{\pi \Delta t}}}$$

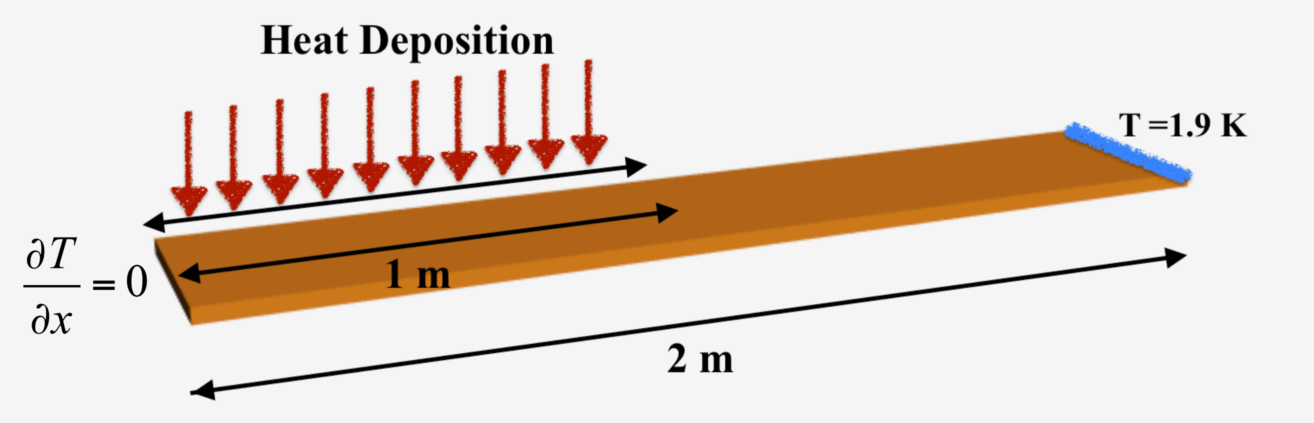
$$\boxed{h_{nucl.boiling} = \frac{\beta(T_s^m - T_h^m)}{T_s - T_h}}$$

$$\boxed{h_{film\ boiling} = 250\ W/m^2K}$$

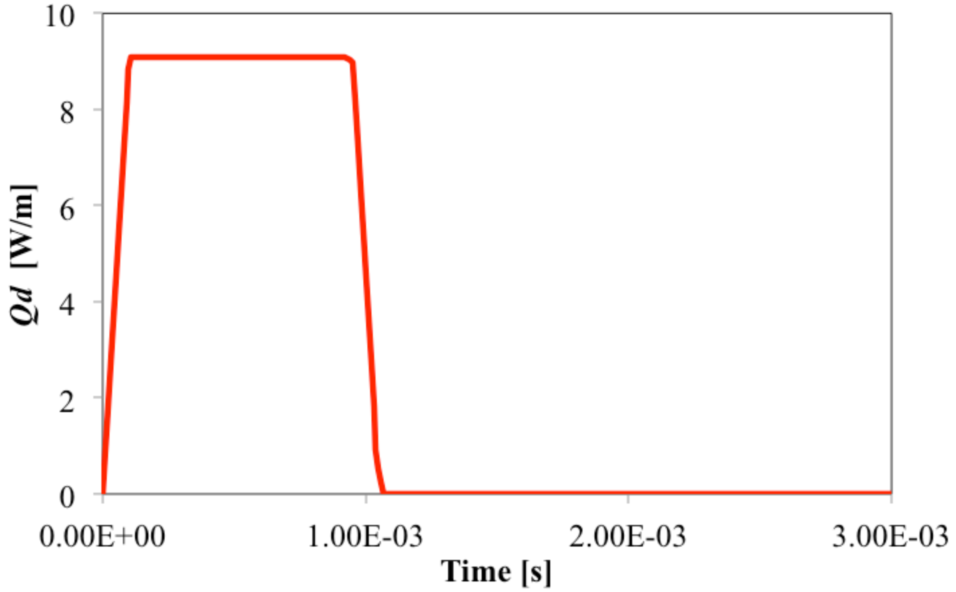
$$\boxed{h_{gas} = 70\ W/m^2K}$$

- The coefficients are taken from experimental results on each helium phase

1-D quench simulation: case study



Heat pulse



Model elements

- THERMAL: N_{strand} *(SC + Cu)* and → He II for *NbTi* / → Glass-Epoxy for Nb_3Sn
- HYDRAULIC: Helium Bath
- ELECTRIC: N_{strand} *(SC + Cu)*

Boundary conditions

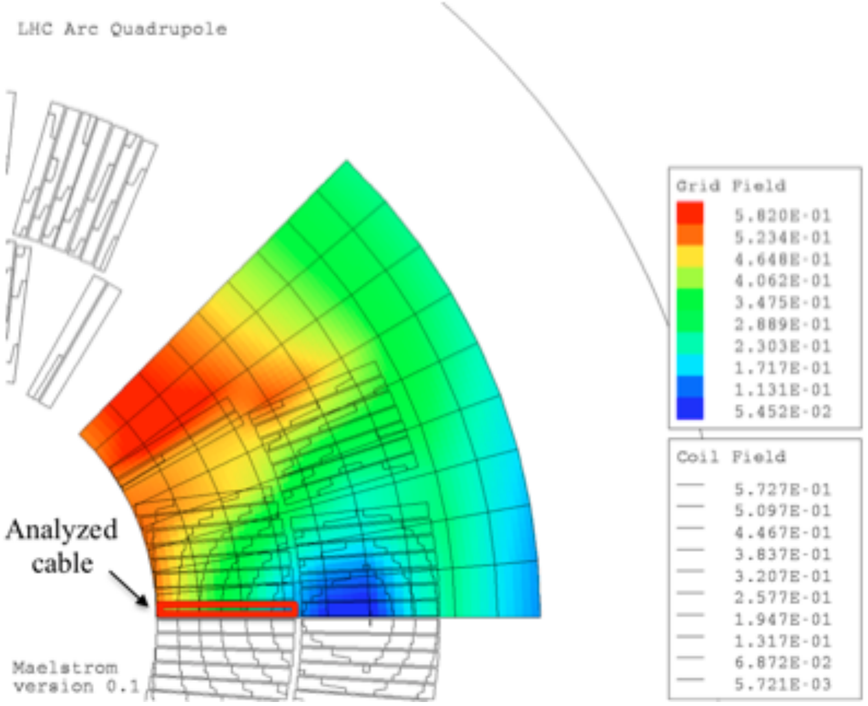
- $x = 0$ **m**: $\Delta V=0$; $\frac{\partial T}{\partial x} = 0$
- $x = 2$ **m**: $\Delta V=0$; $T = 1.9$ K

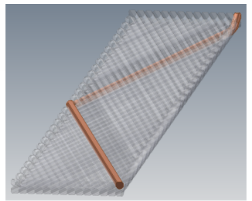
Initial conditions

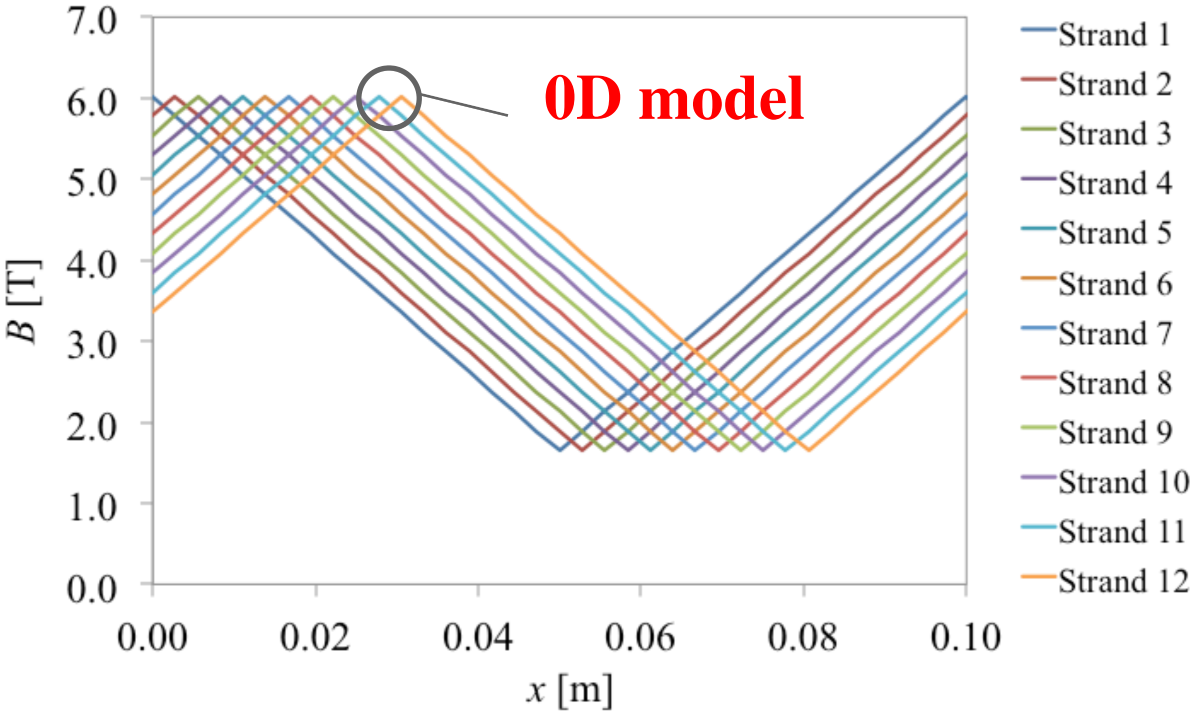
- $T = 1.9$ K everywhere
- $I_j = I_{op}/N_{strand}$ $j = 1, N_{strand}$

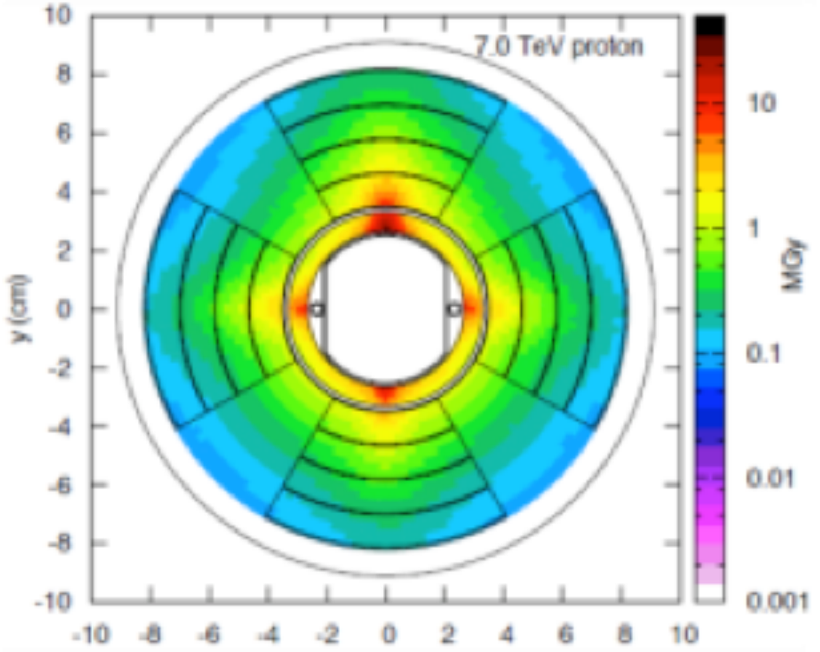
[1] L. Bottura, C. Rosso, M. Breschi, "A General Model for Thermal, Hydraulic and Electric Analysis of Superconducting Cables", Cryogenics, Vol. 40, pp. 617 – 626, 2000

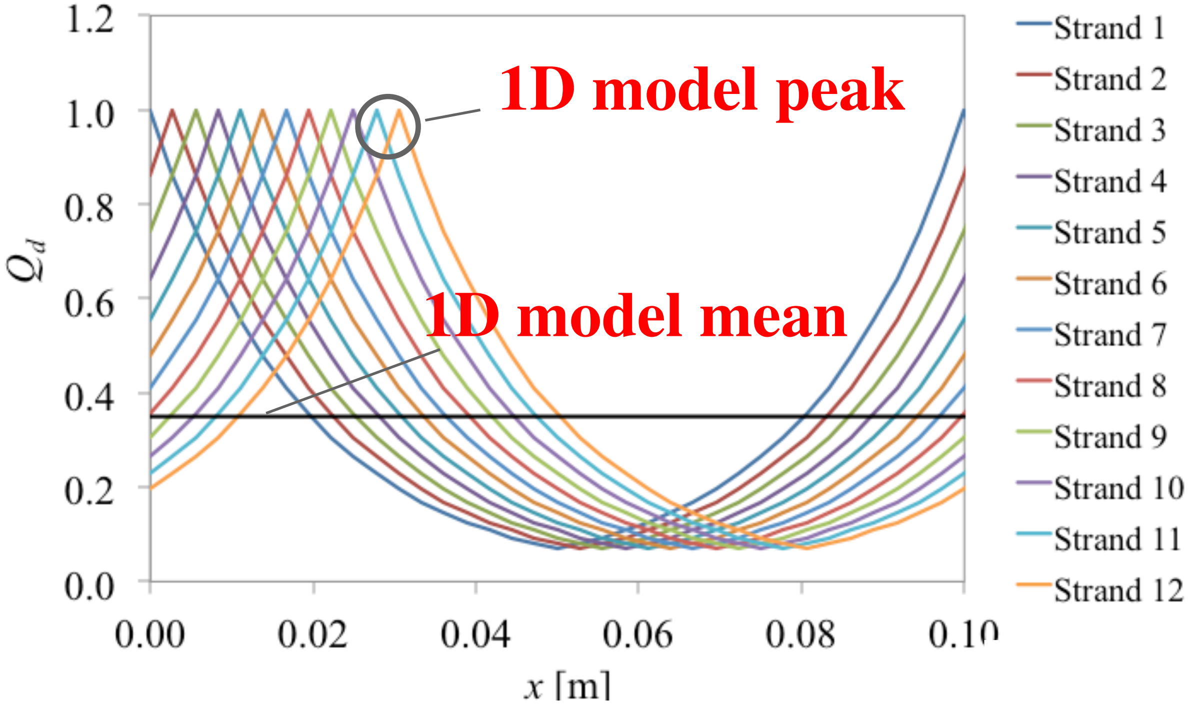
1-D model: non uniform magnetic field and heat deposit









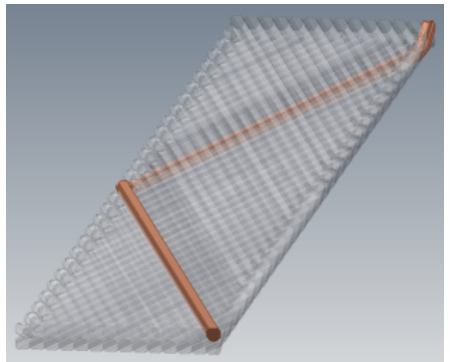


- Example of heat deposit calculation for the MQXA magnet (courtesy of L. Esposito, CERN)

Battistoni et al., "The FLUKA code: Description and bench- marking," in Proc. AIP Conf. Hadronic Shower Simul. Workshop, 2007, vol. 896, pp. 31–49

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 / glass epoxy and helium bath, not with the other strands



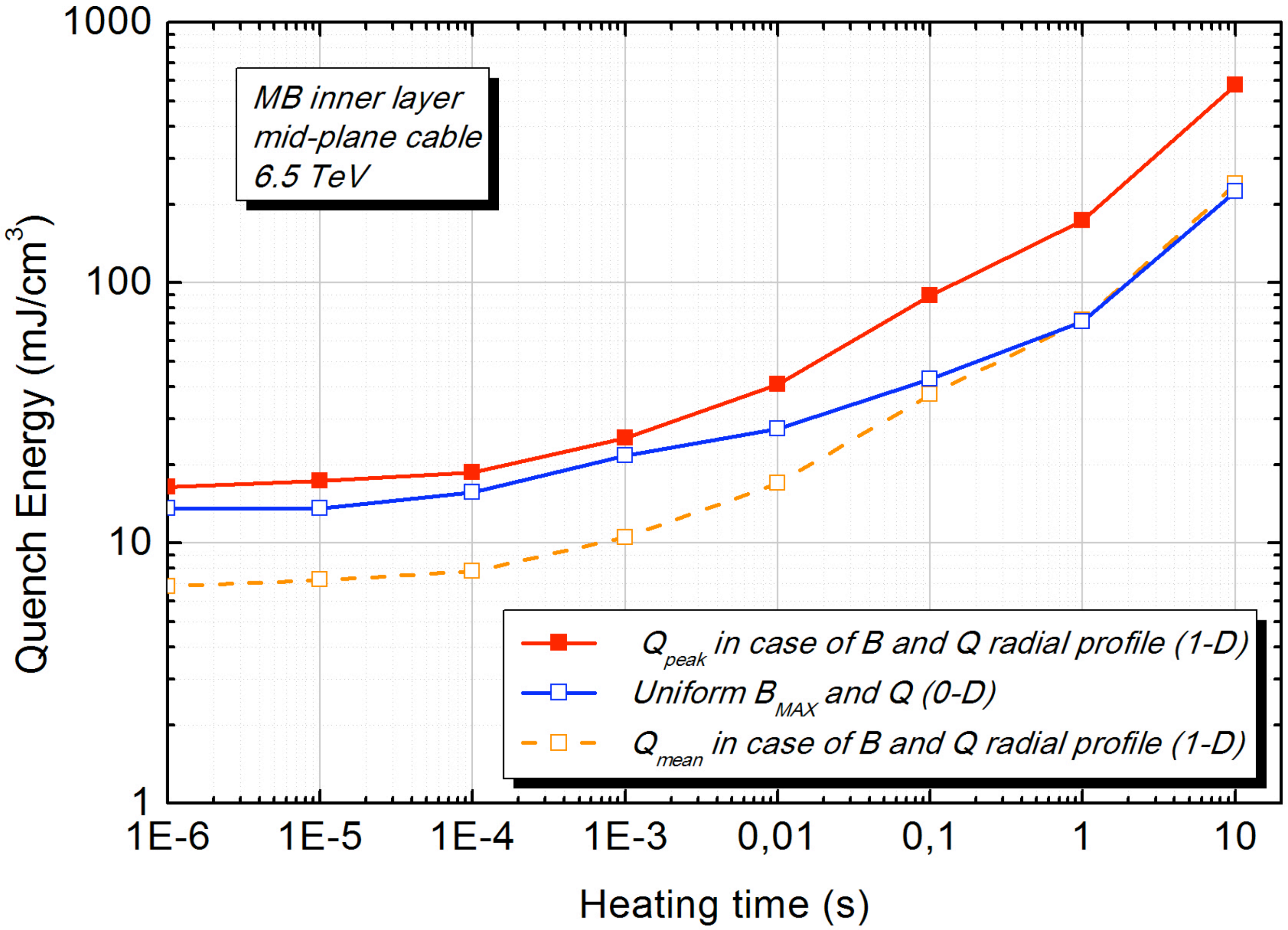
Drawing by D. Santandrea

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

THEA code

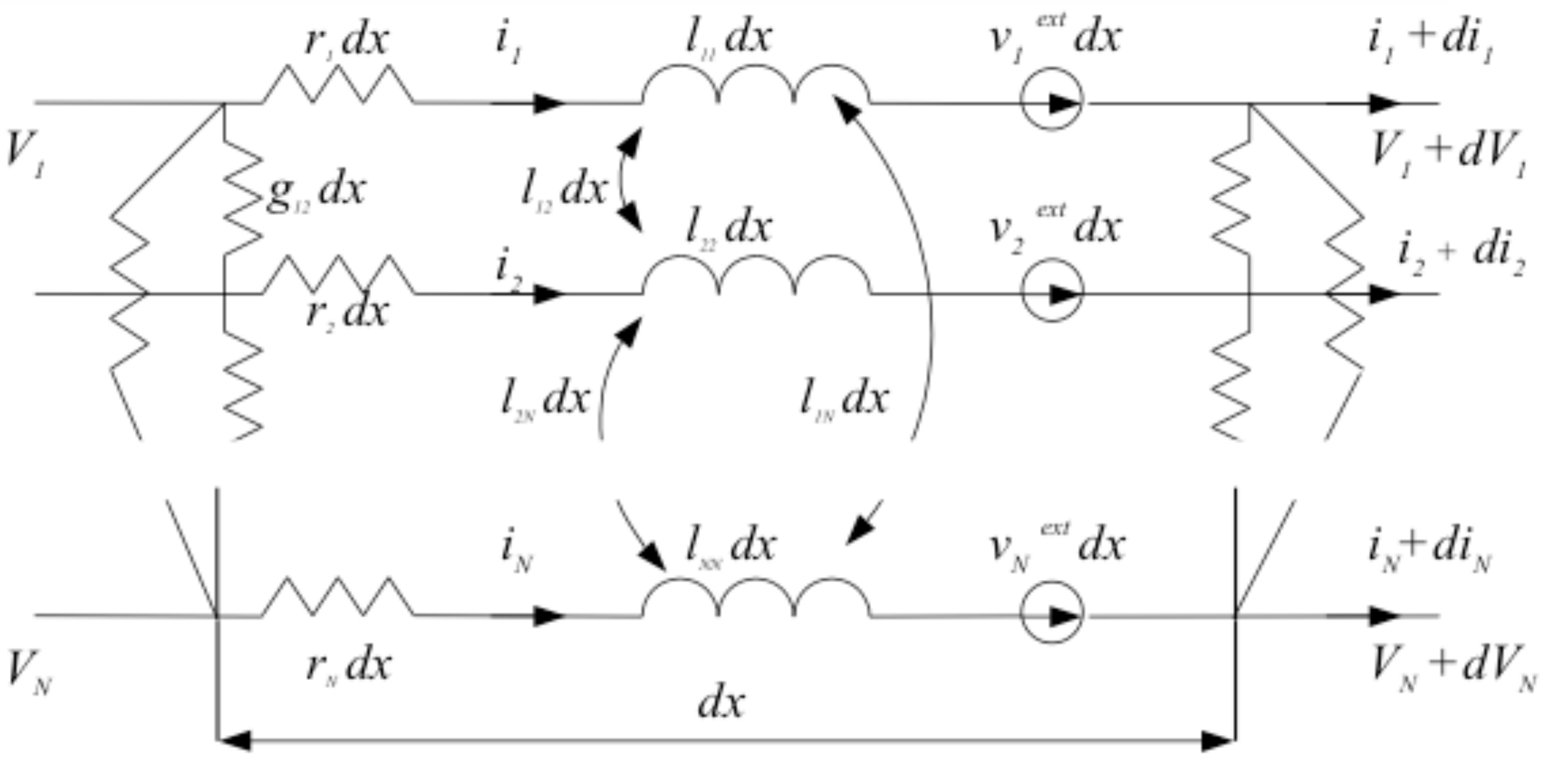
- At low pulse durations the 0D model results are close to the 1D model with QE = $Q_{peak}\, t_{pulse}$ (local effects relevant)

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



1-D approximation: *N*-strand model

- The *N* cable strands are modeled with a 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

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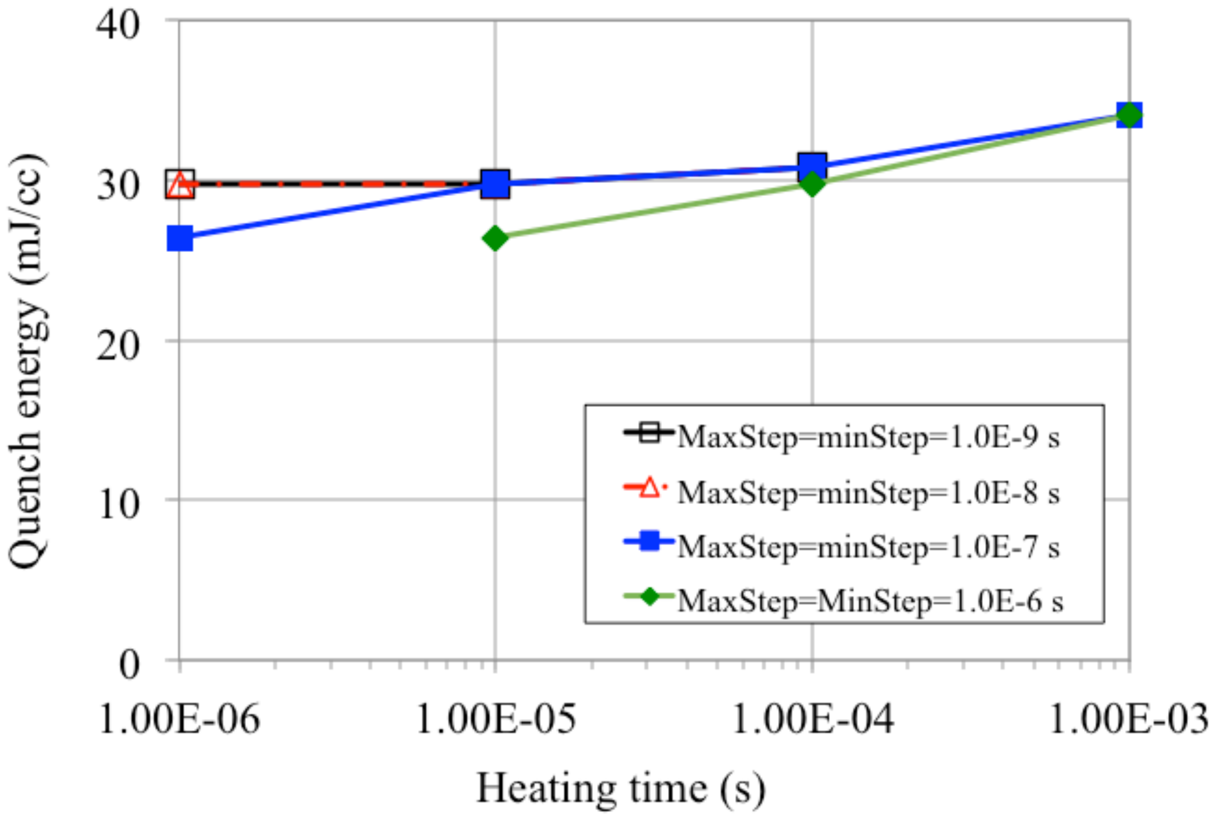
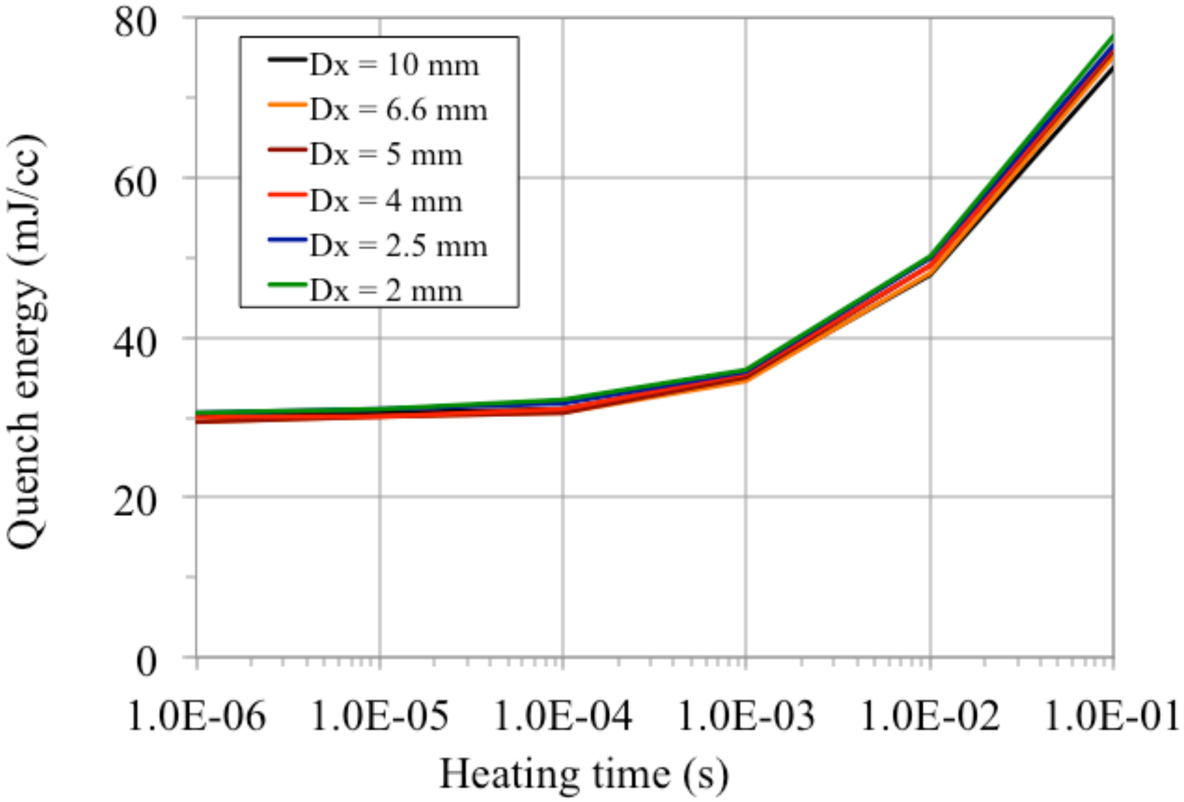
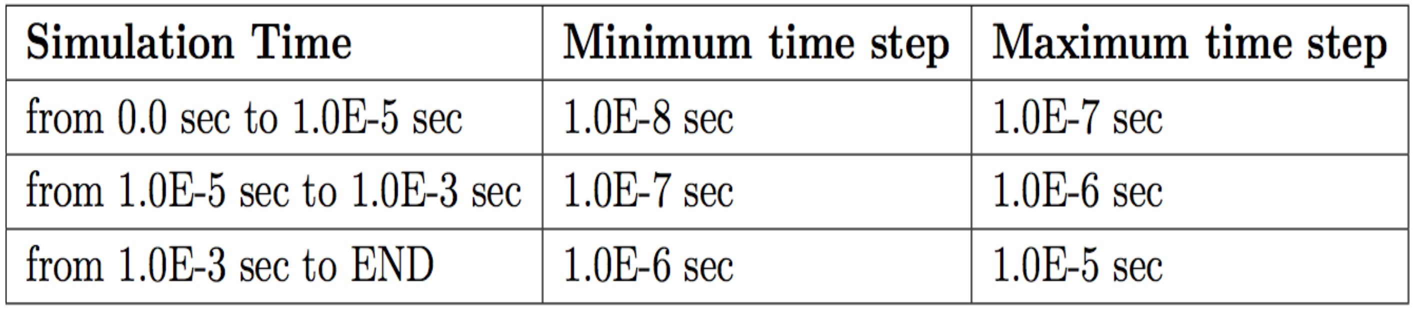
Convergence studies

- Convergence is reached with integration time steps of 10^{-8} s for short disturbances (1 μs)

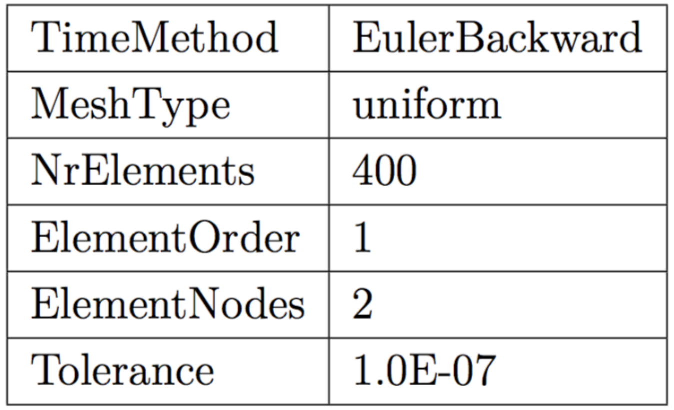
- Convergence within 3 % is reached with a mesh element size about 5 mm







Simulation Time	Minimum time step	Maximum time step
from 0.0 sec to 1.0E-5 sec	1.0E-8 sec	1.0E-7 sec
from 1.0E-5 sec to 1.0E-3 sec	1.0E-7 sec	1.0E-6 sec
from 1.0E-3 sec to END	1.0E-6 sec	1.0E-5 sec



TimeMethod	EulerBackward
MeshType	uniform
NrElements	400
ElementOrder	1
ElementNodes	2
Tolerance	1.0E-07

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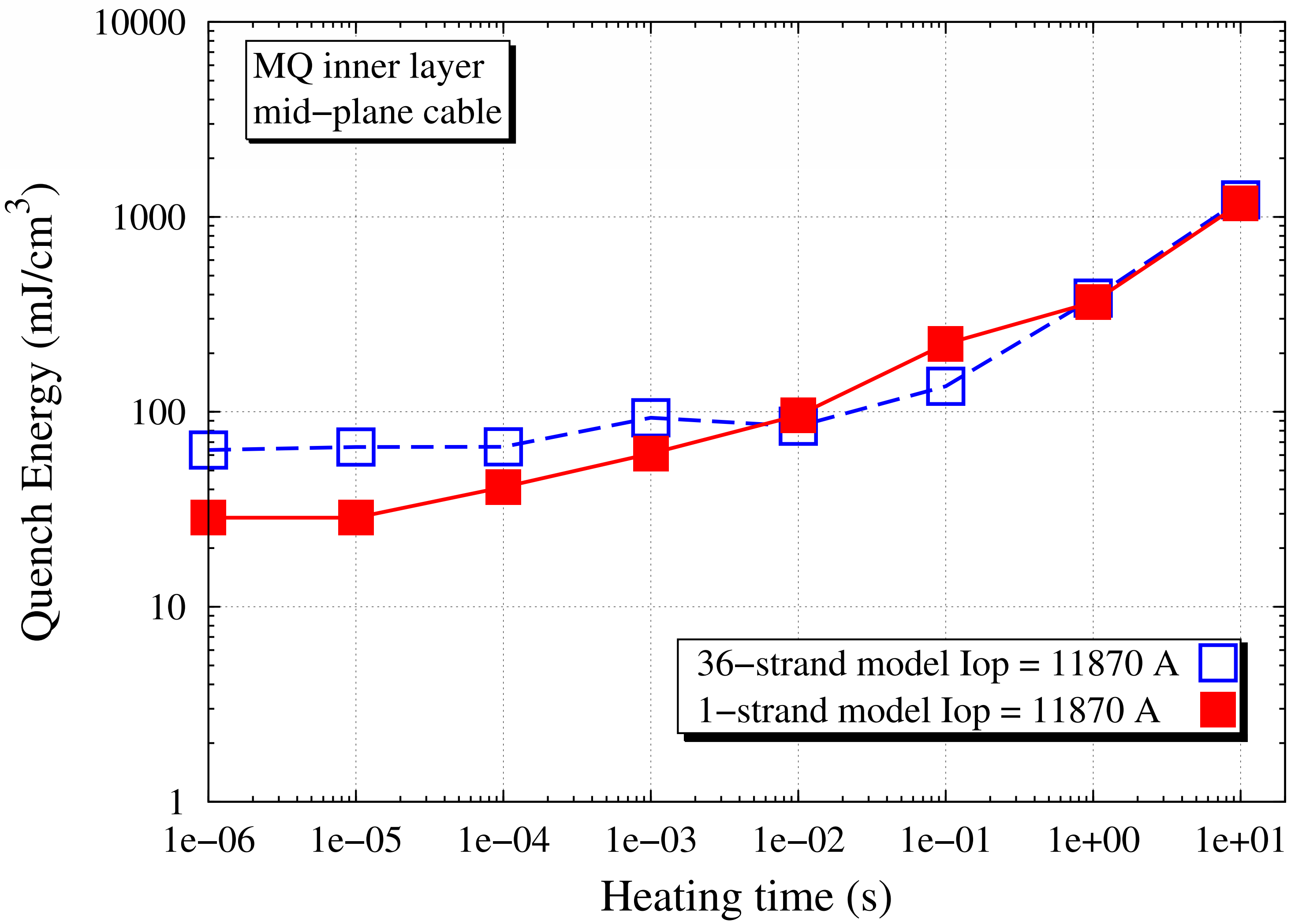
Comparison between 1-strand and *N*-strand model (MQ-mid plane): NbTi

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

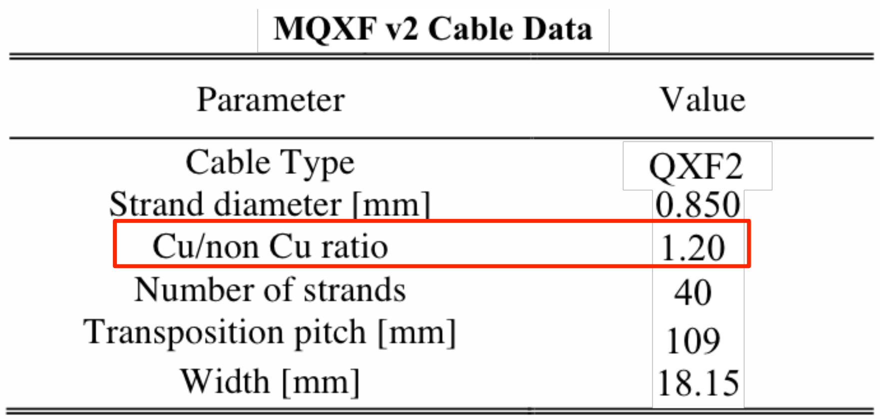
- The model is applied to analyse the MQ inner layer cable



- 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", IEEE Trans. Appl. Supercond., vol. 25, 4700405, 2015.

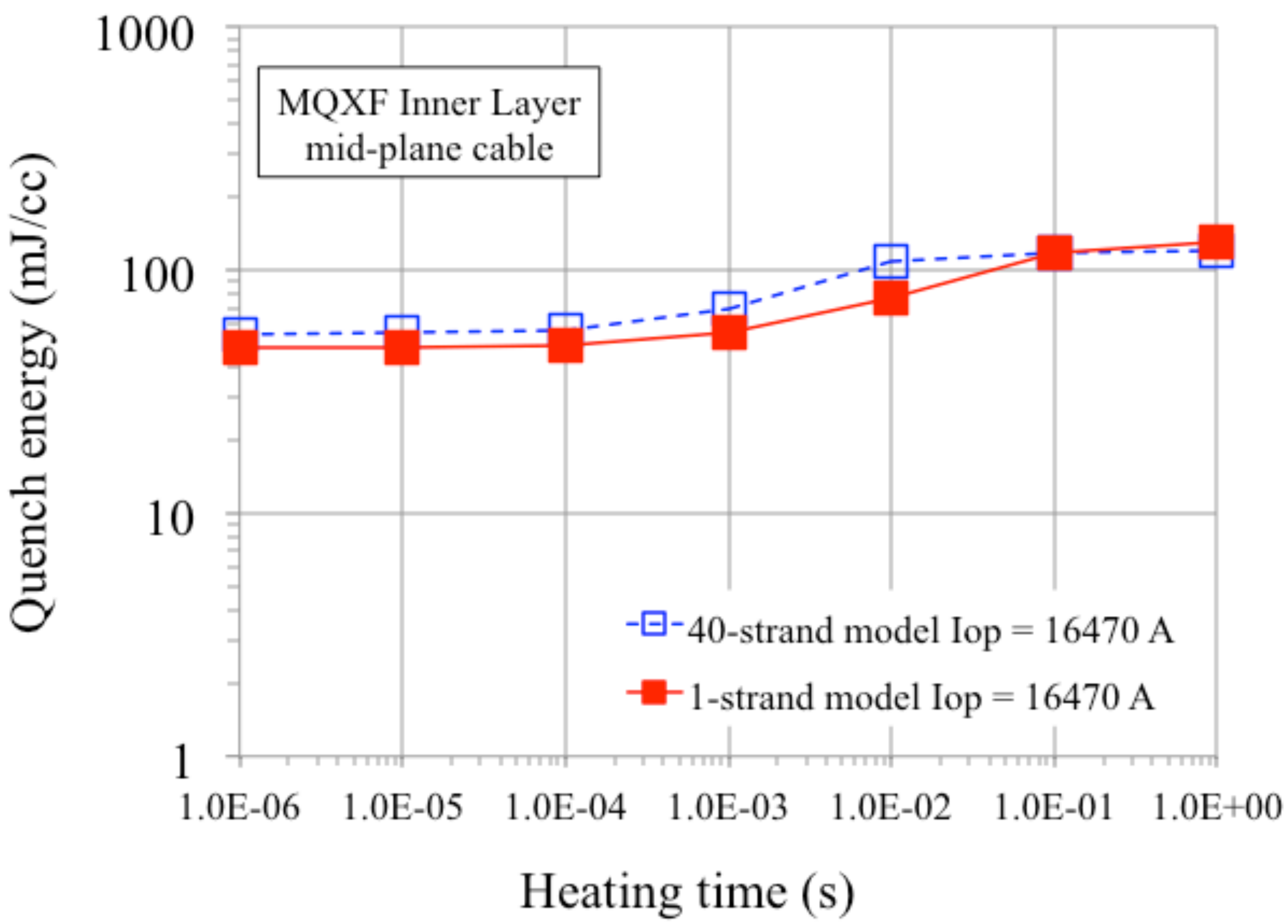
Comparison between 1-strand and *N*-strand model (MQXF-mid plane): Nb_3Sn



MQXF v2 Cable Data

Parameter	Value
Cable Type	QXF2
Strand diameter [mm]	0.850
Cu/non Cu ratio	1.20
Number of strands	40
Transposition pitch [mm]	109
Width [mm]	18.15

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



- The 40-strand model gives Quench Energies very close to the 1-strand model (only 10% increase with 10^{-6} s pulse)

- The absence of interstitial He does not allow a significant increase of QEs with increasing the pulse duration

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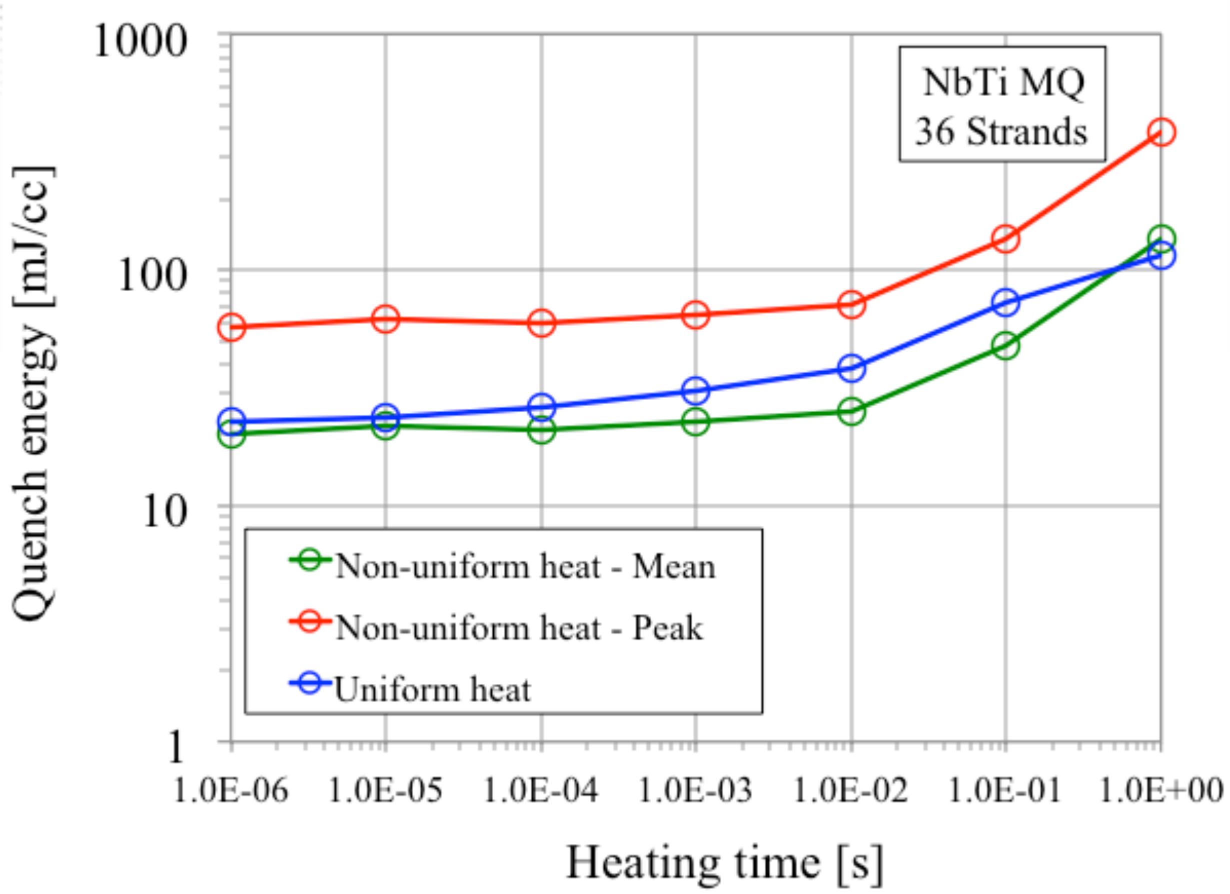
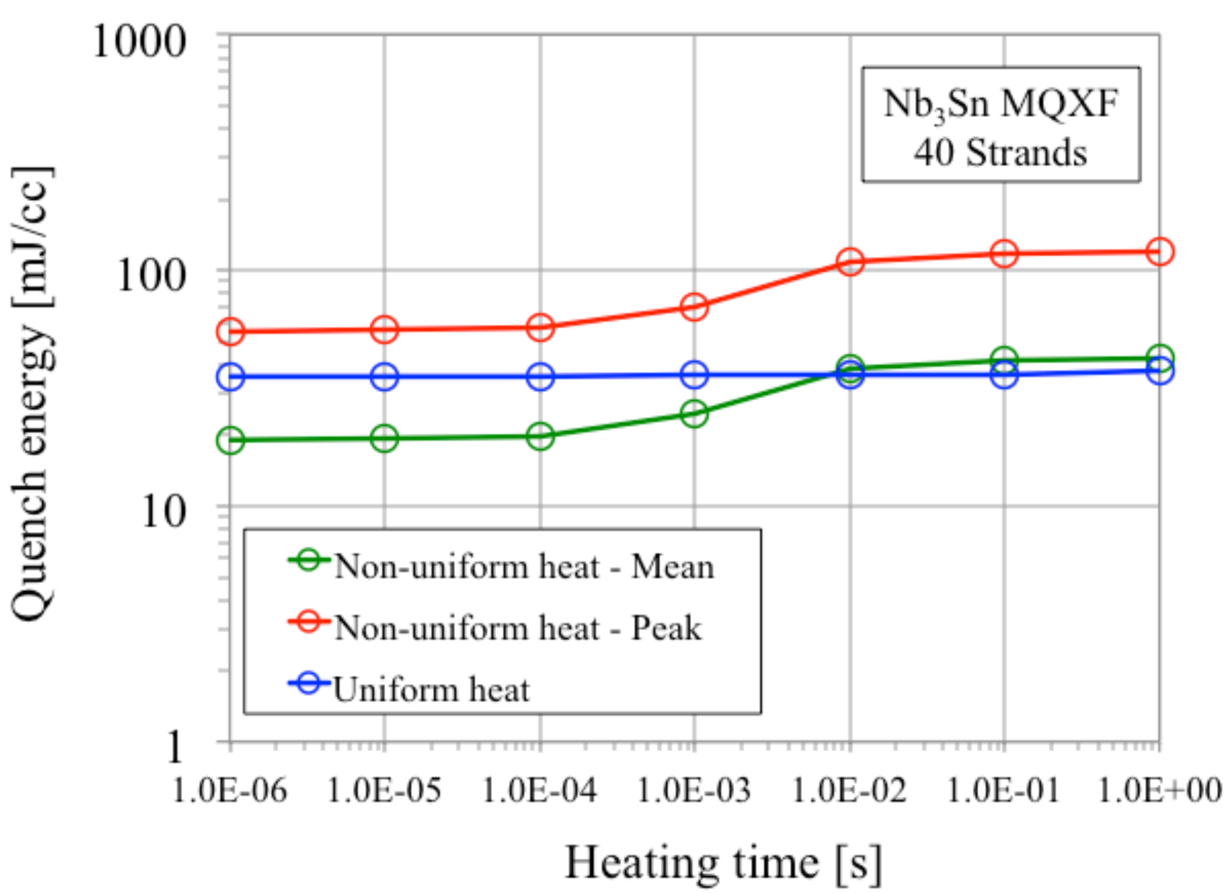
QE dependence on the heat deposition model: uniform vs non-uniform

- 36-strand model



NbTi

- 40-strand model



Nb$_3$Sn

- A higher impact of the heat distribution non-uniformity is found for the Nb$_3$Sn, especially at low pulse durations

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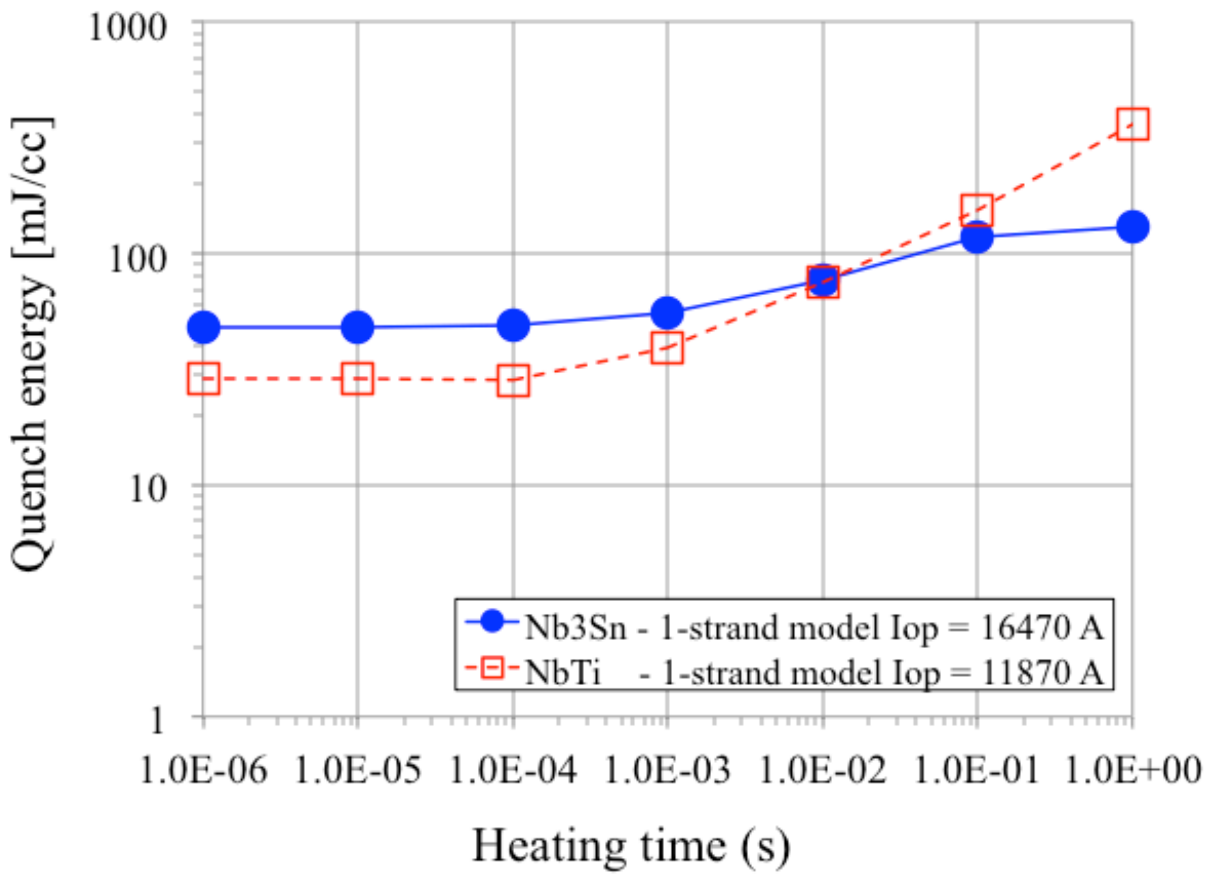
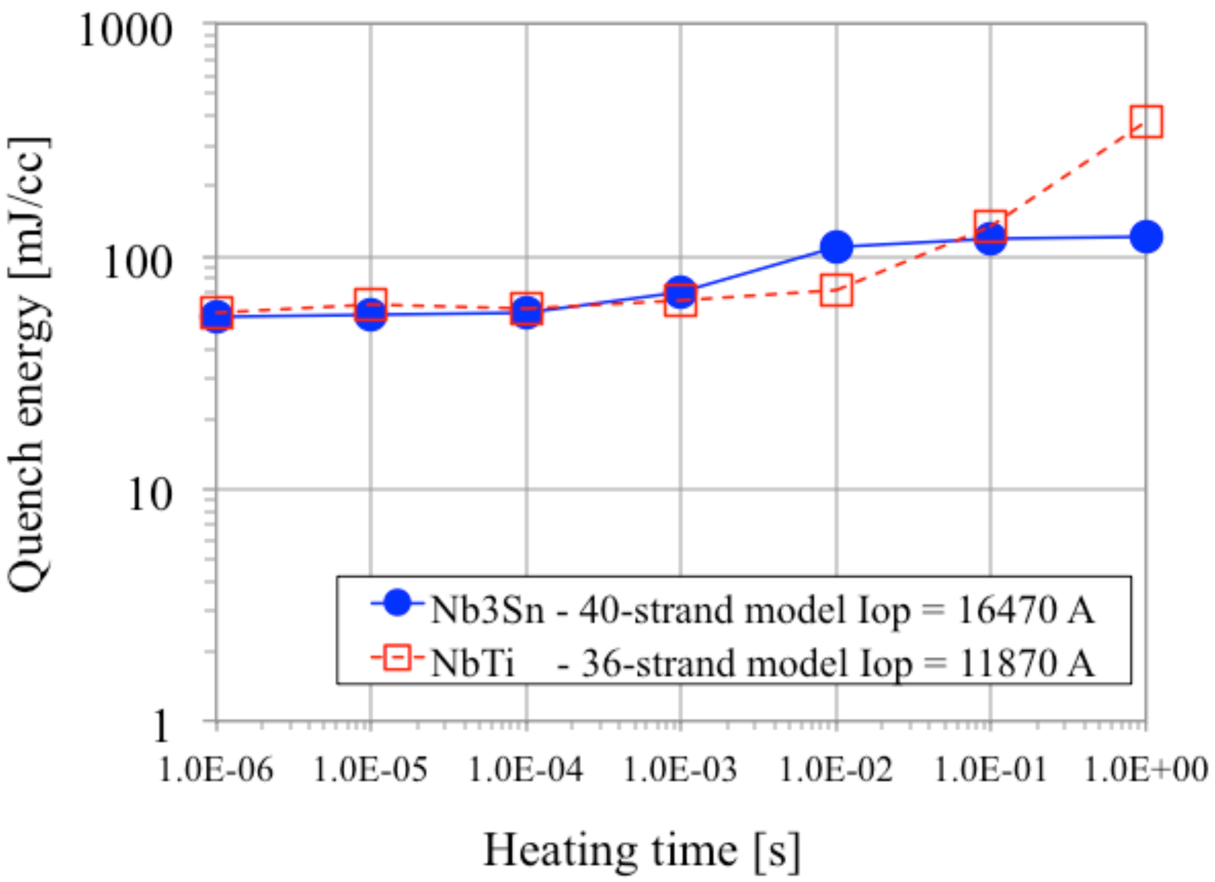
Comparison between NbTi and Nb_3Sn

- 1-strand model



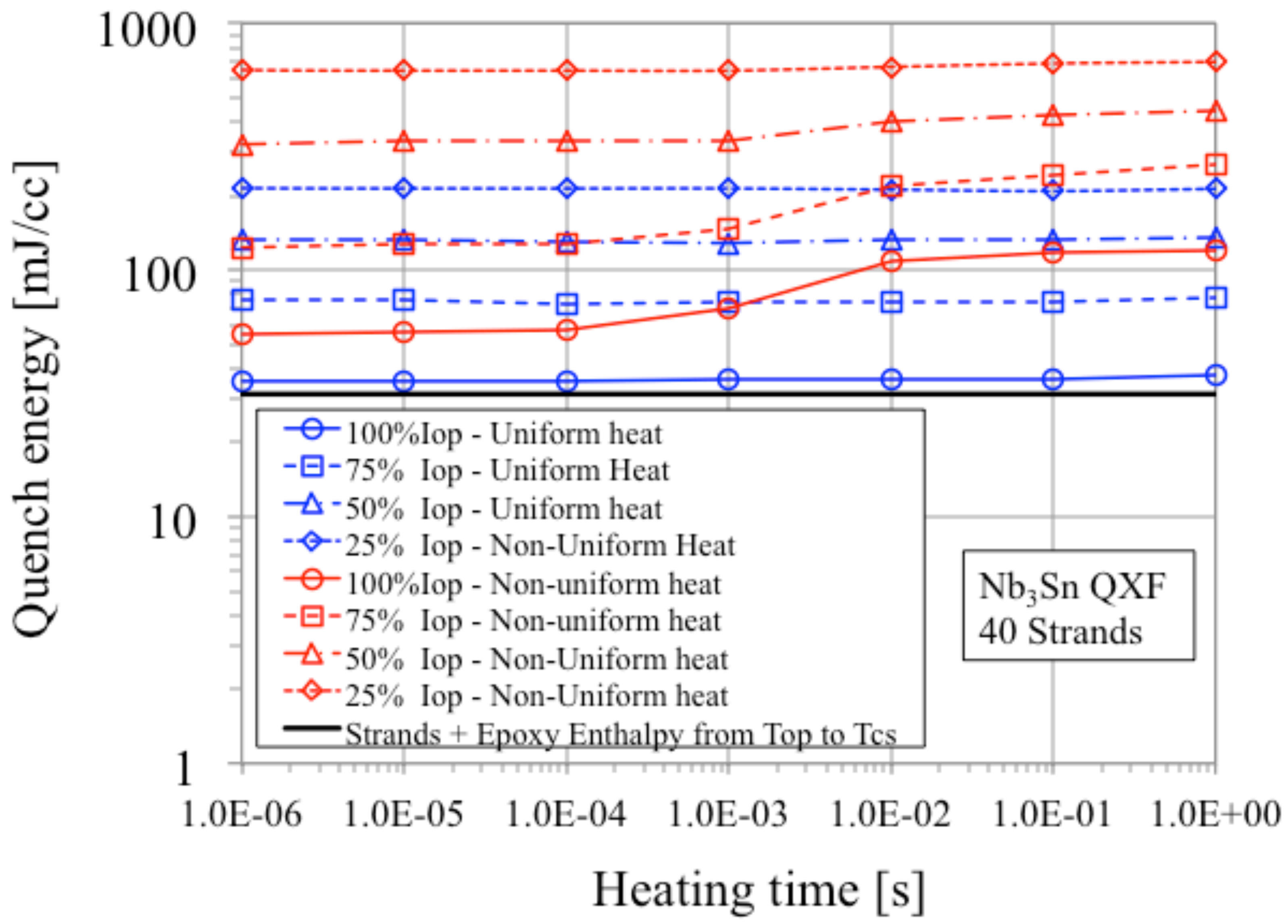
- *N*-strand model



- Nb_3Sn has a double temperature margin with respect to NbTi
- The QE of NbTi increases significantly with increasing the heating times
- NbTi exhibits a greater QE increase than Nb_3Sn in the *N*-strand model
- The NbTi and Nb_3Sn cables exhibit comparable values of QEs at low pulse durations

Nb_3Sn: QE dependence on the operation current

- 40-strand model



- Lower values of operation current determine higher QE
- For uniform heat depositions the QEs increase slightly with heating time
- For non-uniform heat depositions, the QEs increase with heating time, especially at high operation currents

Conclusions

- The QEs of a NbTi cable for the LHC and of a Nb_3Sn cable for the Hi-Lumi LHC have been analyzed by means of a coupled electro-thermal model
- At short pulse durations, the *N*-strand model gives values of QE a factor 2 higher than the 1-strand model for the NbTi cable, but no significant differences are found for the Nb_3Sn cable
- Although the operating conditions of the NbTi and Nb_3Sn cable differ significantly, the QEs of the two conductors at low pulse durations are very similar
- The details of the non-uniformity of the heat disturbance due to beam losses affect the QEs at short and intermediate pulse durations, especially for the Nb_3Sn conductor

Thank you for your attention

M. Breschi