Analysis of the Stability Margin of Nb_3Sn QXF cable for the Hi-Lumi LHC project

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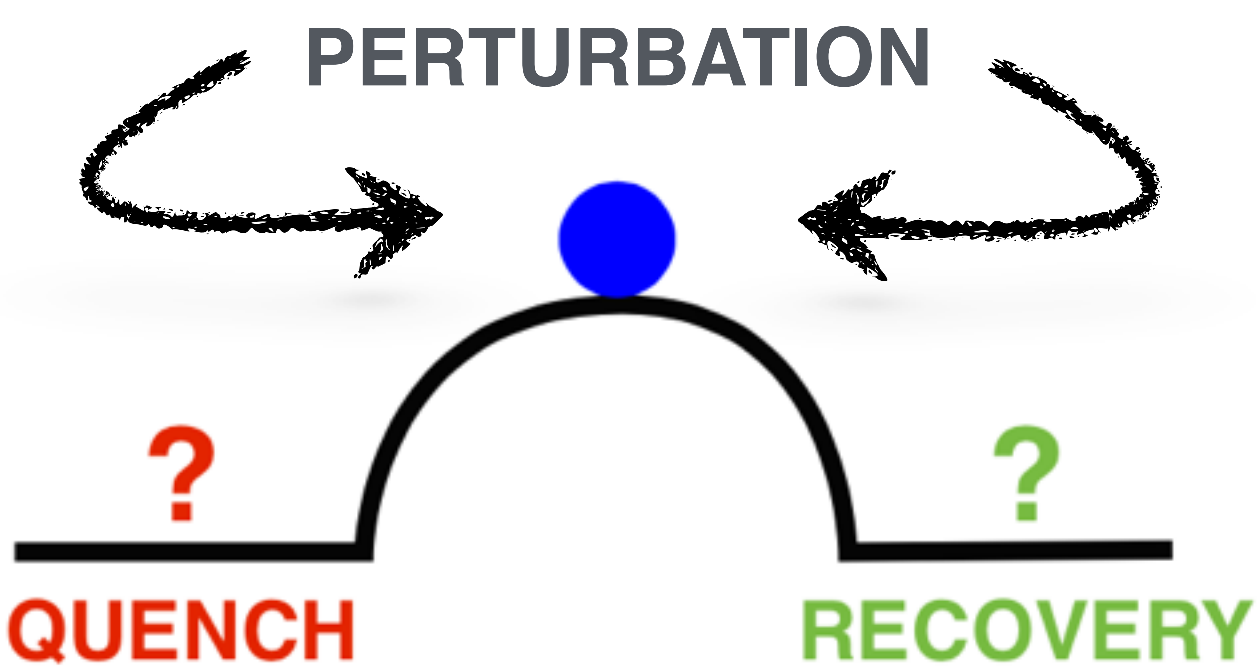
CERN, October 2015

Outline

- Stability of accelerator superconducting cables
- Zero dimensional approach
- One dimensional approach
- Convergence studies
- Results with Nb_3Sn cable
    - Single-strand model
    - Multi-strand model
- Comparison with NbTi cable
- Summary

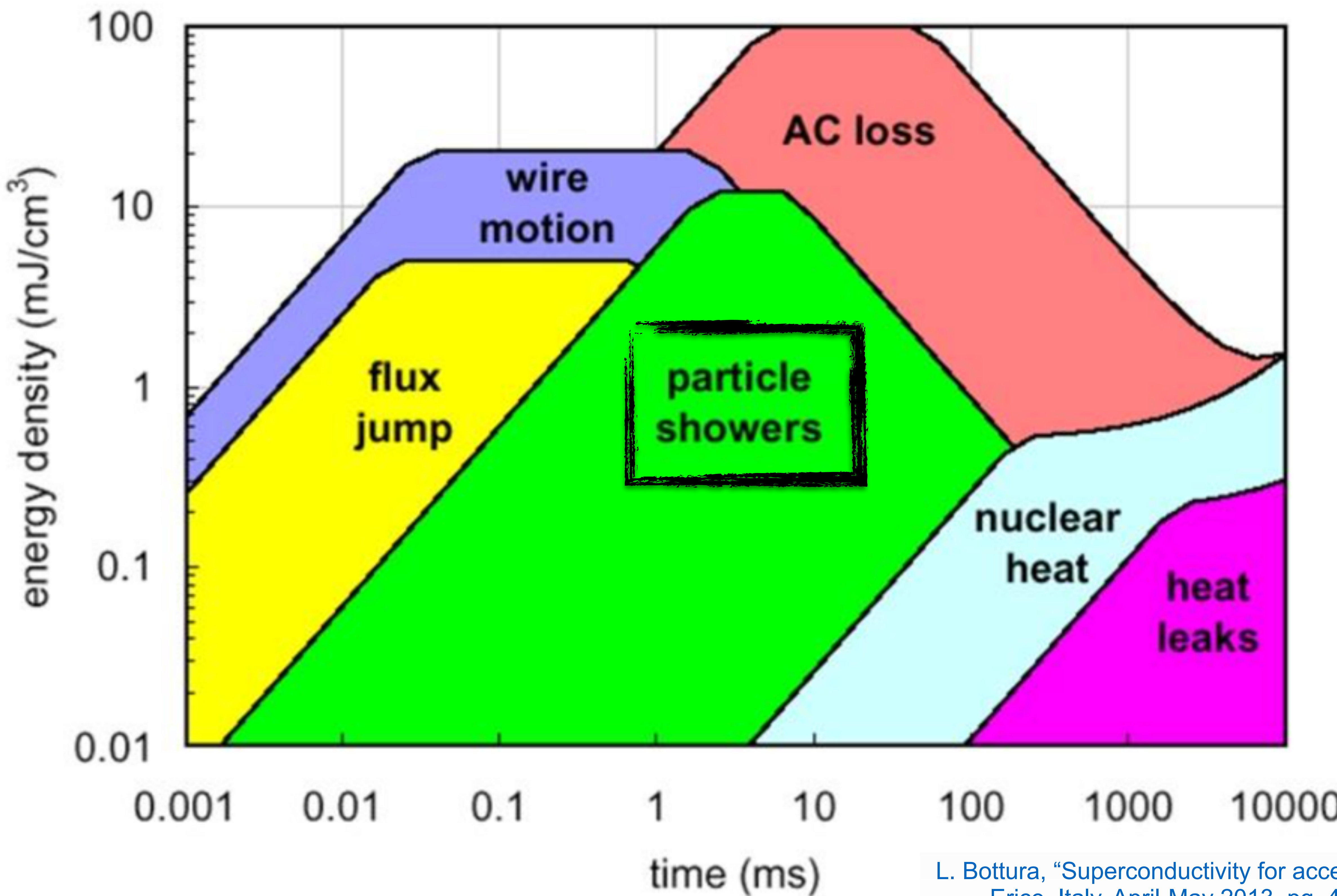
Stability margin

Stability margin:
the minimum energy density that an external source need to provide to cause a thermal runaway



L. Bottura, "Superconductivity for accelerators", Erice, Italy, April-May 2013, pg. 401-451

Stability margin



L. Bottura, "Superconductivity for accelerators", Erice, Italy, April-May 2013, pg. 401-451

Quench or Recovery?

How to determine the status of the system:

- Wait a lot after the disturbance and check the temperature
  [easy, obvious, high time consuming] ⟹ **0-D Model**

- Check the integrated Joule power along the whole cable for each strand
  [smart, fast, low time consuming] ⟹ **1-D Model**

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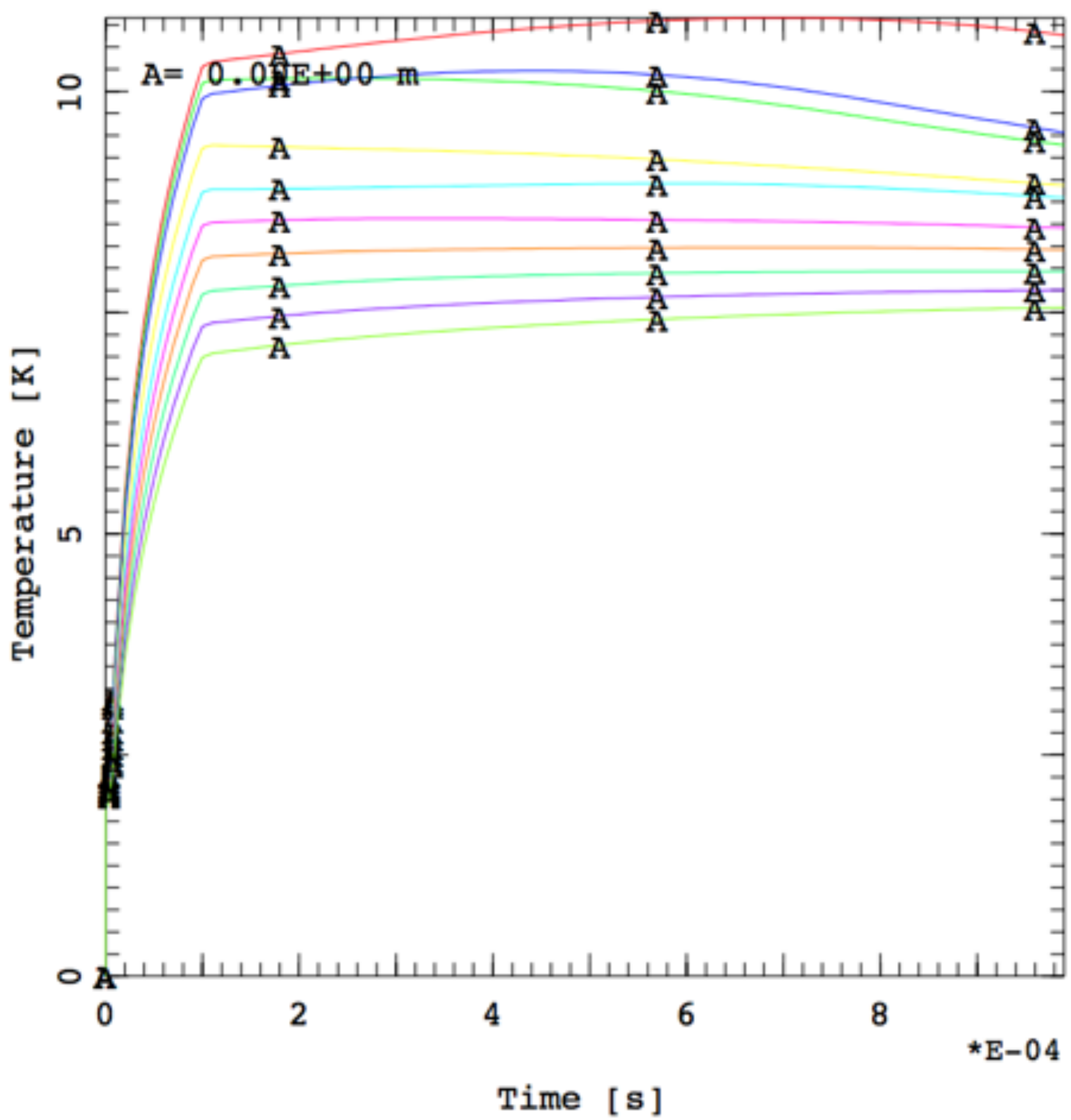
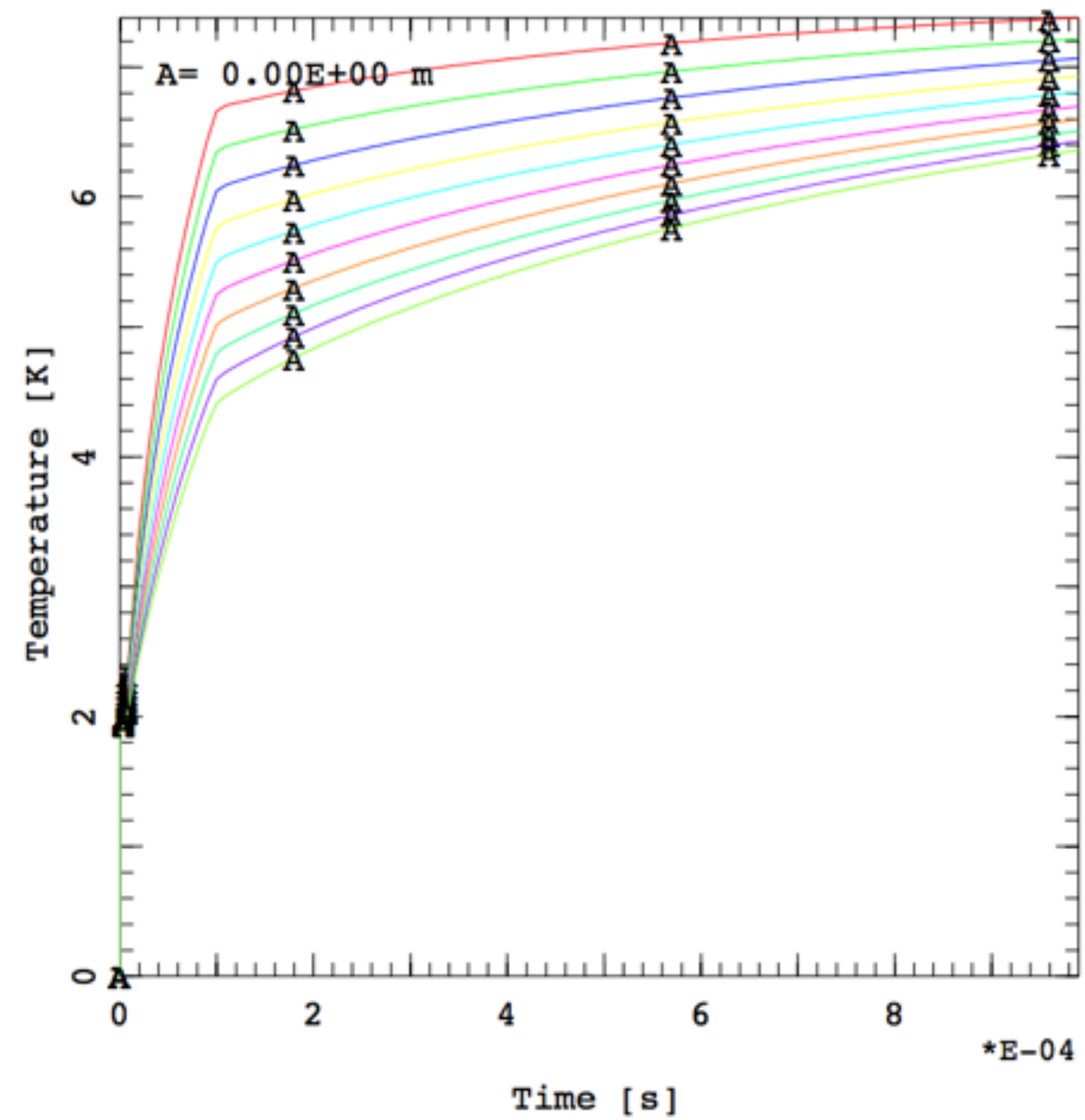
Recovery ?

The trends of the temperatures are not enough:





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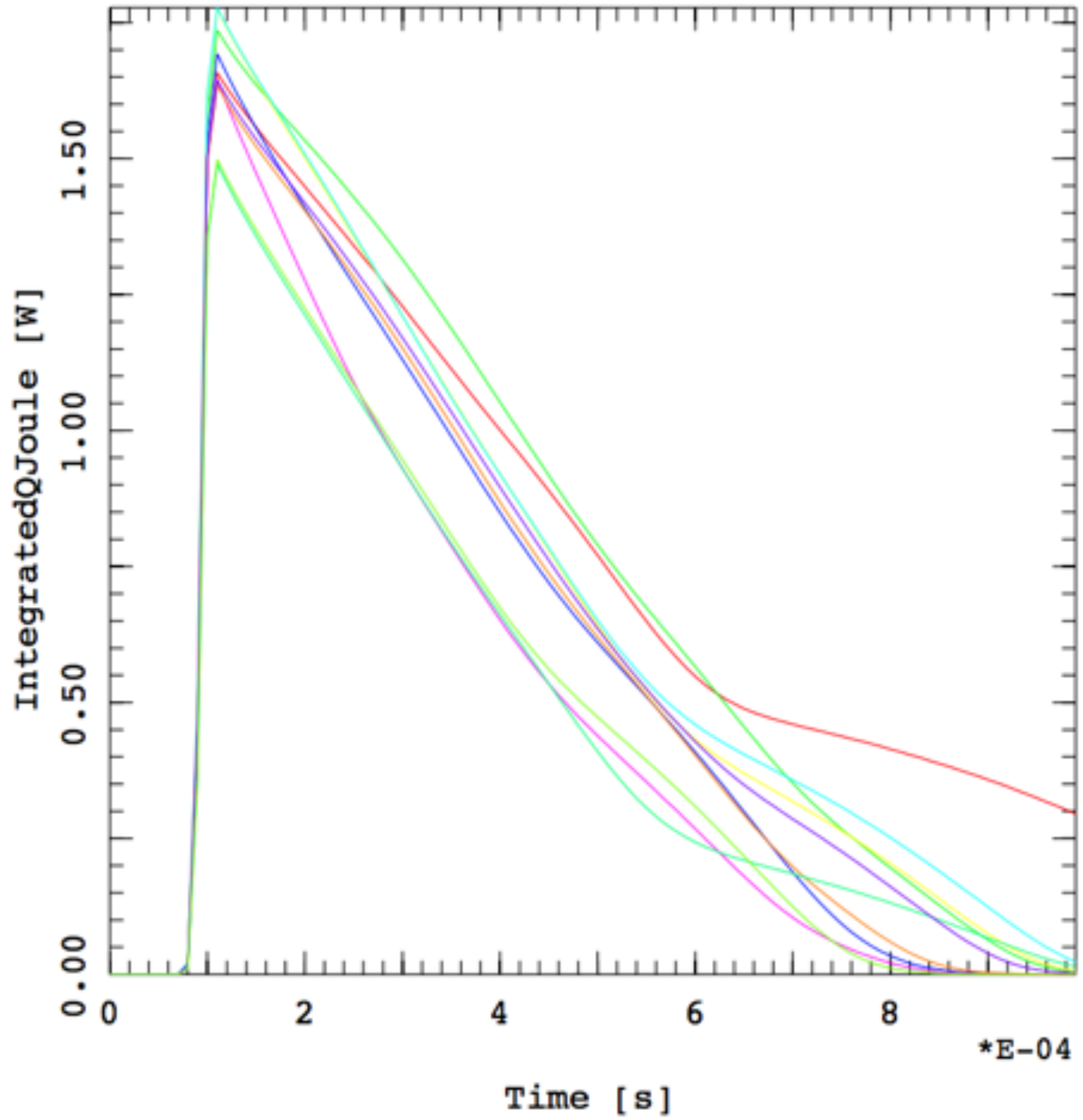
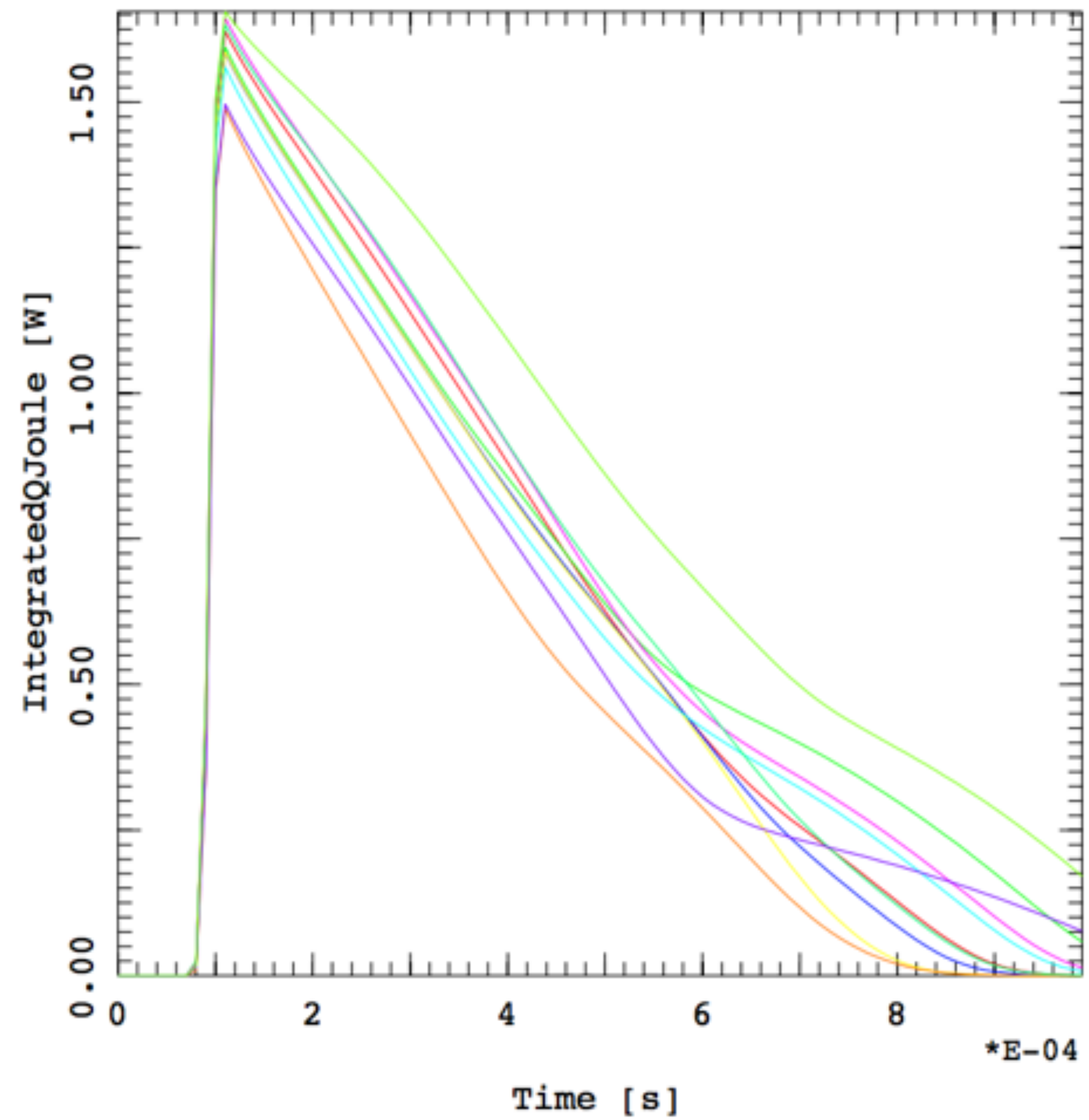
Heat disturbance: 10 μs

Recovery !

Looking at the integrated Joule power, it is evident that it *will be* a recovery





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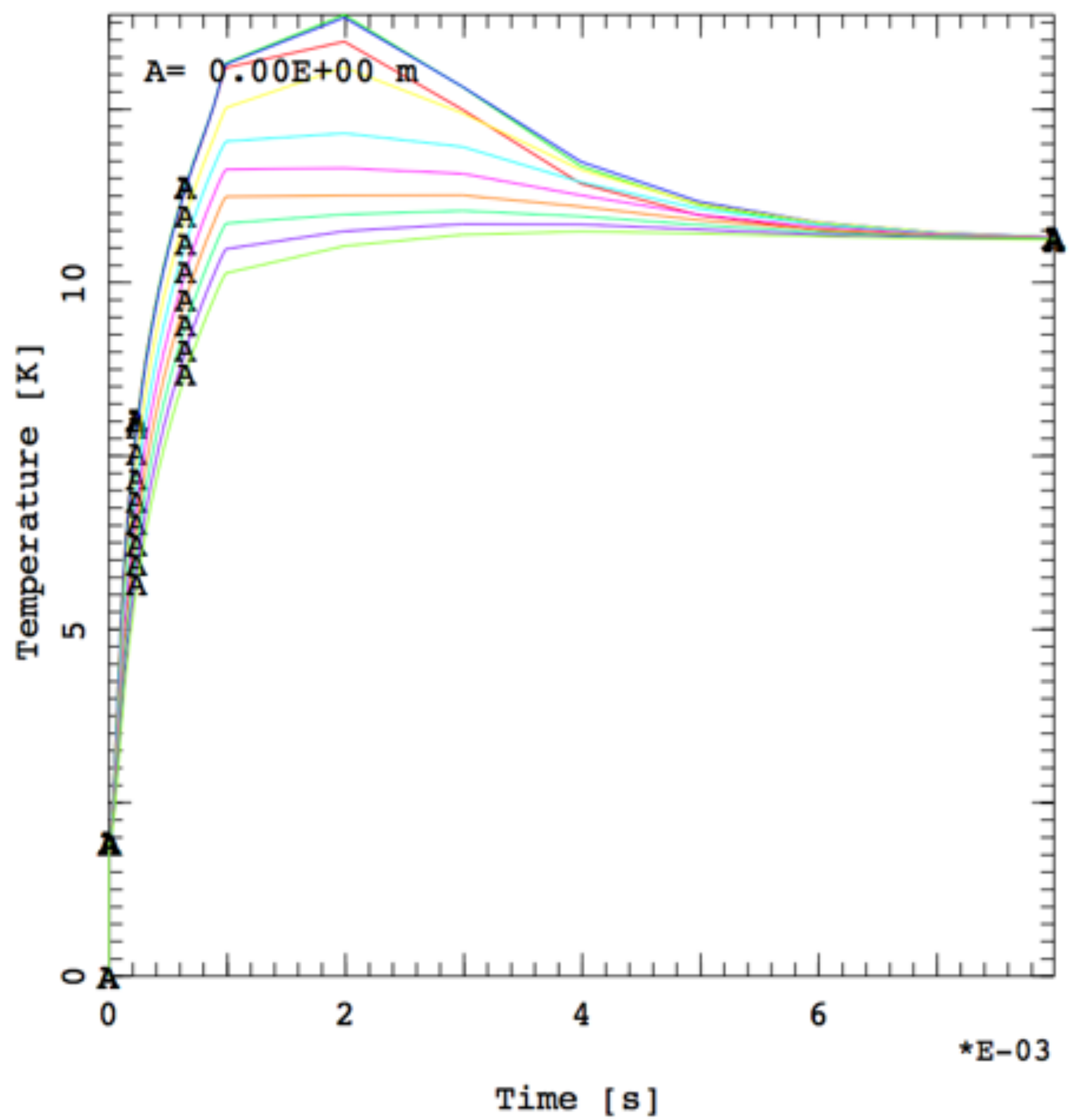
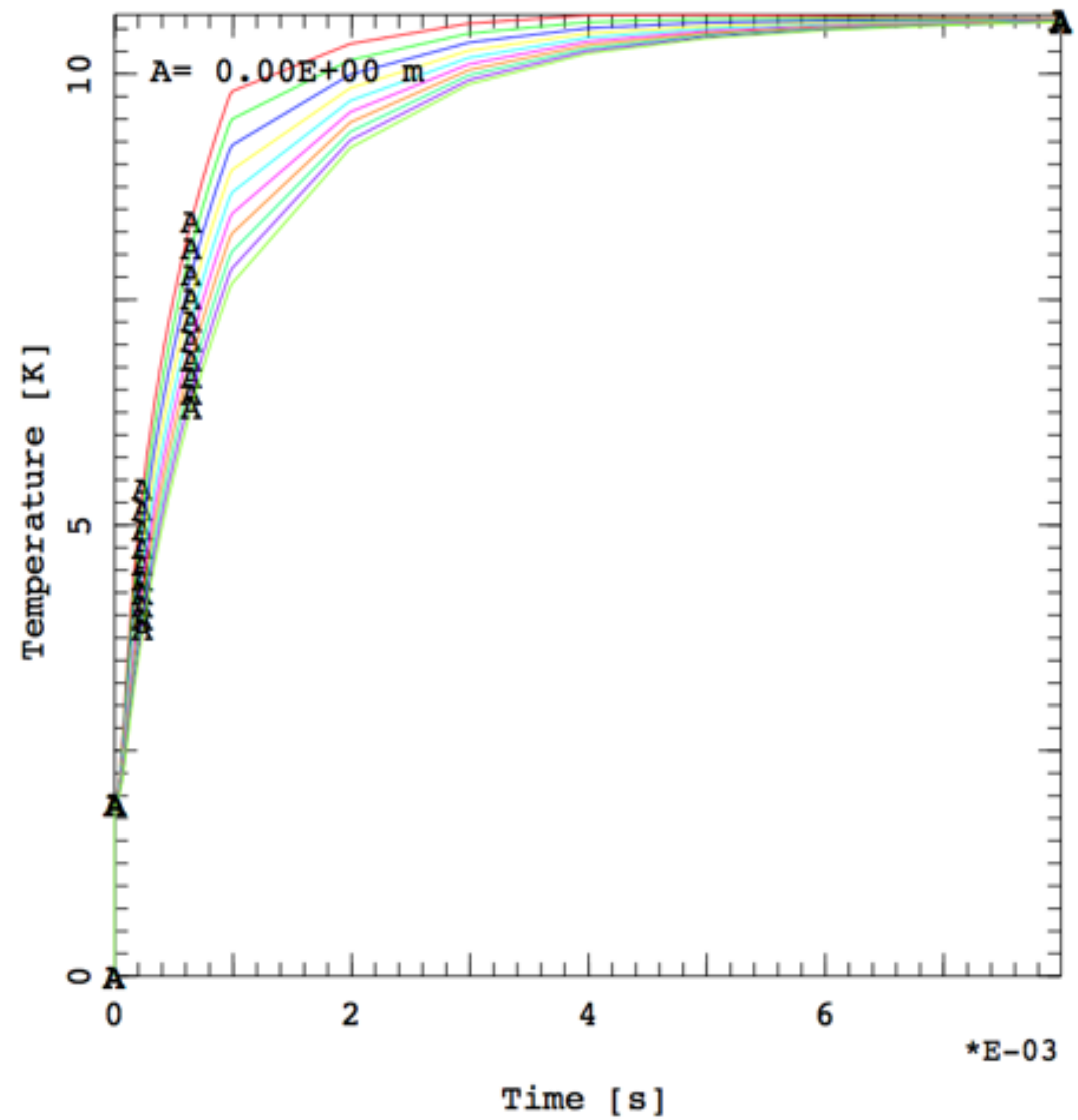
Heat disturbance: 10 μs

Quench ?

The trends of the temperatures are not enough:





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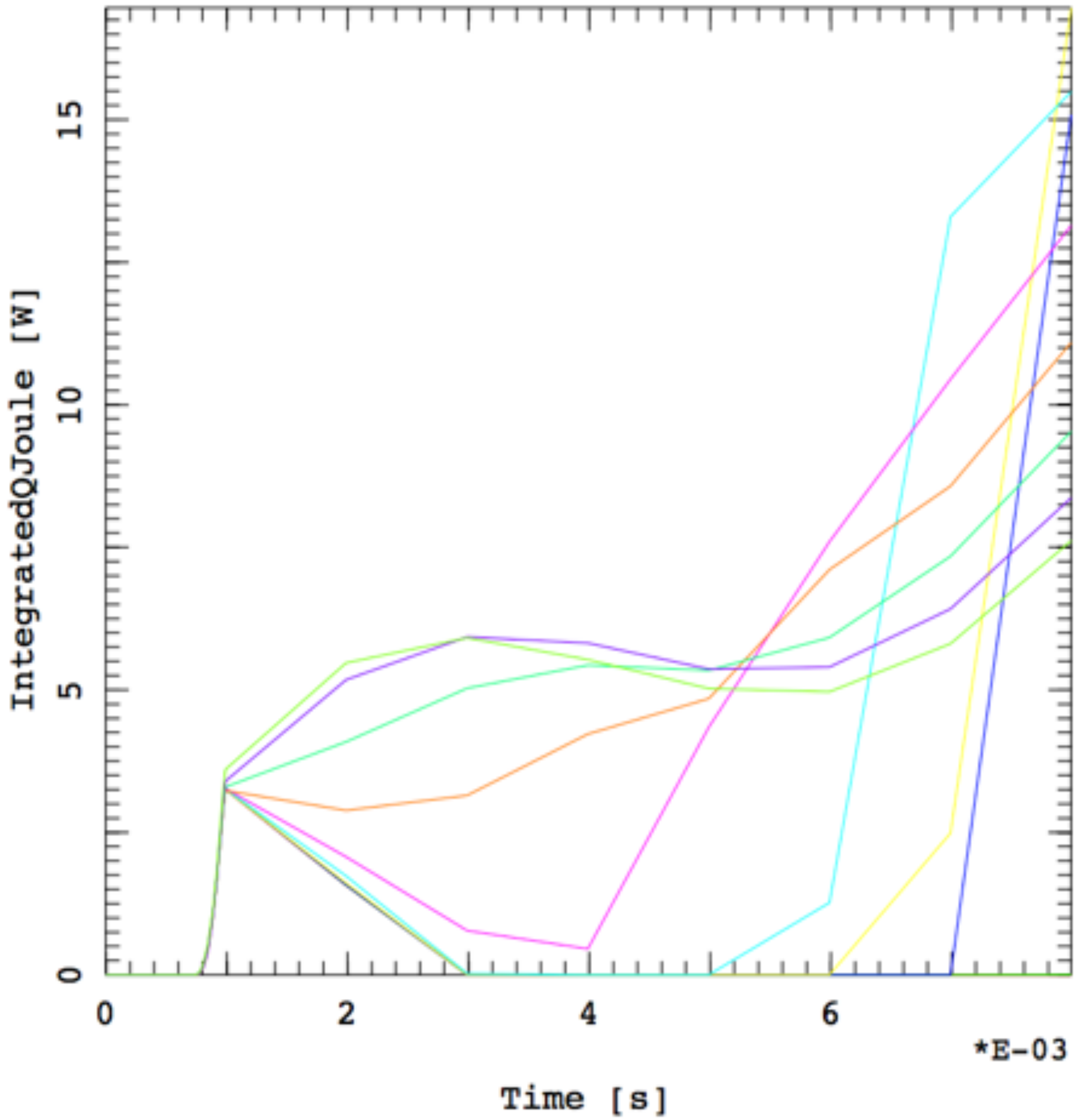
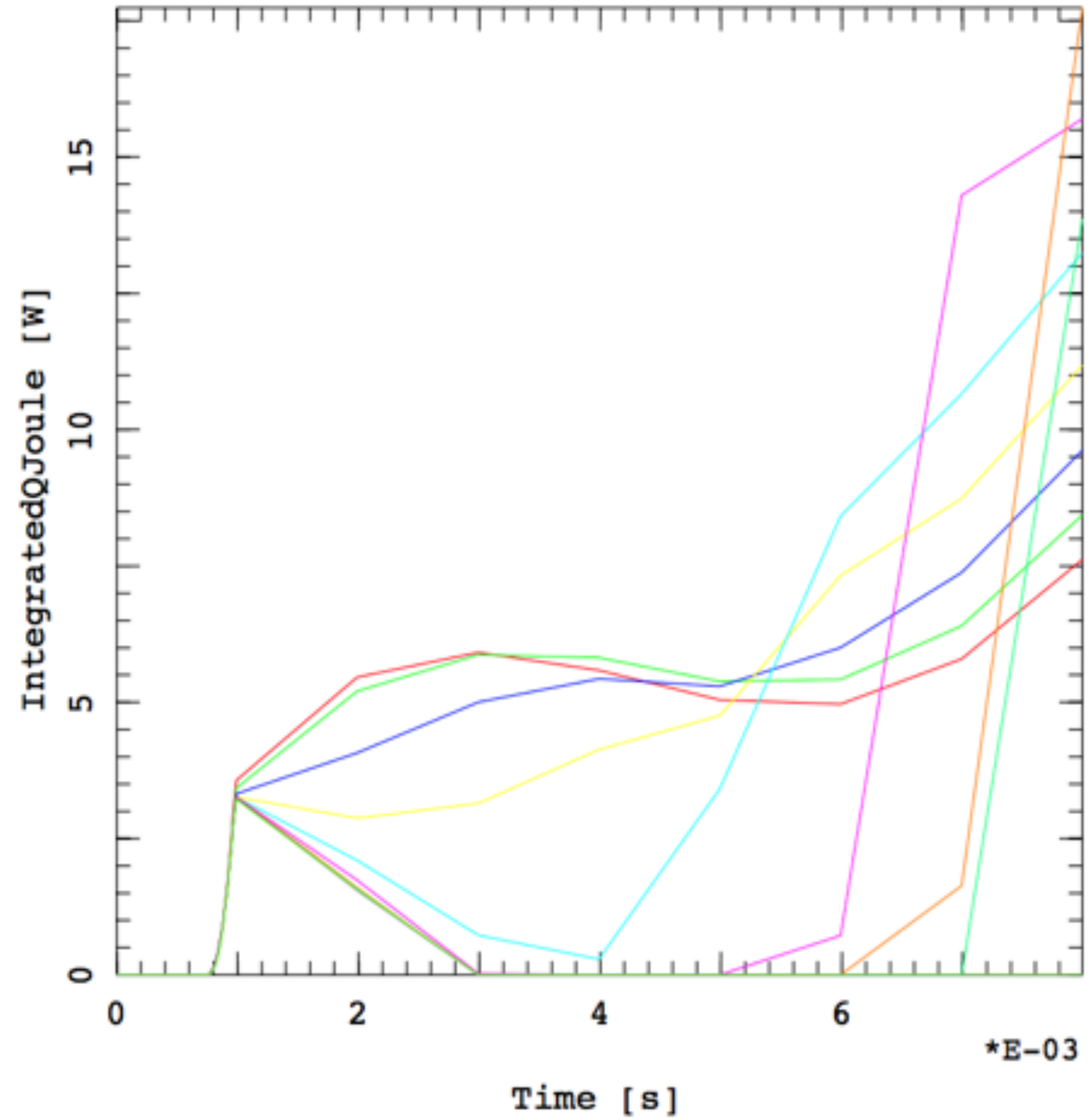
Heat disturbance: 100 μs

Quench !

Looking at the integrated Joule power, it is evident that it *will be* a quench





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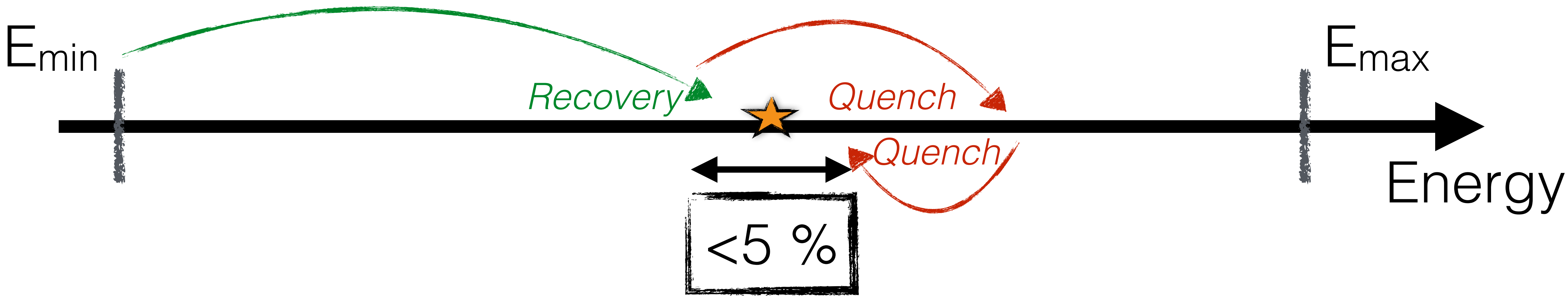
Heat disturbance: 100 μs

Stability Margin

- A bisection method with a convergence criterion of 5% is implemented for the calculation of the Stability Margin



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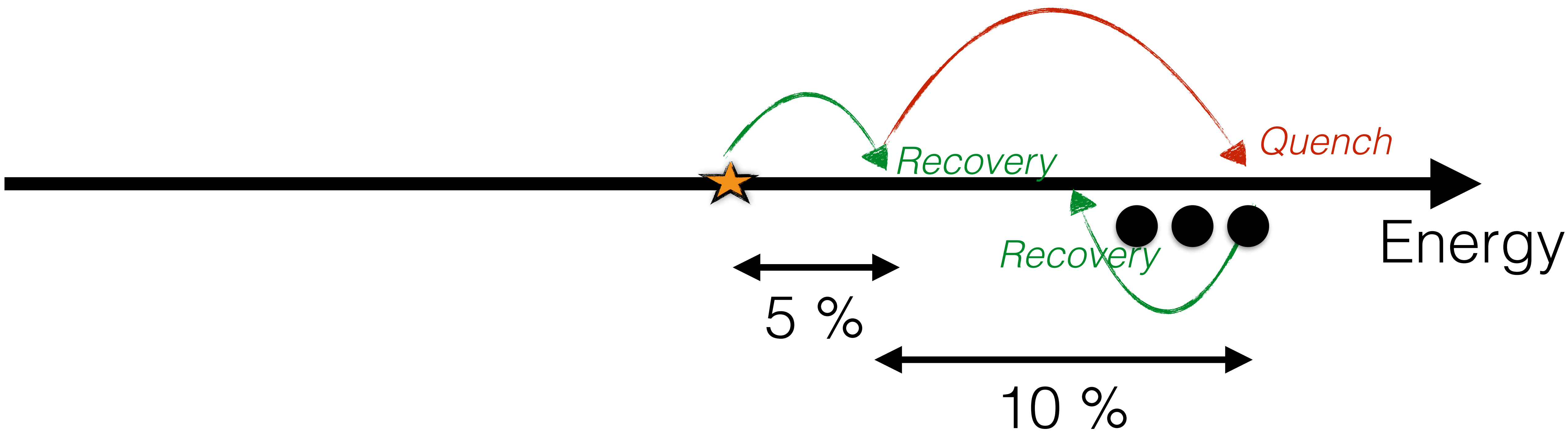
Stability Margin

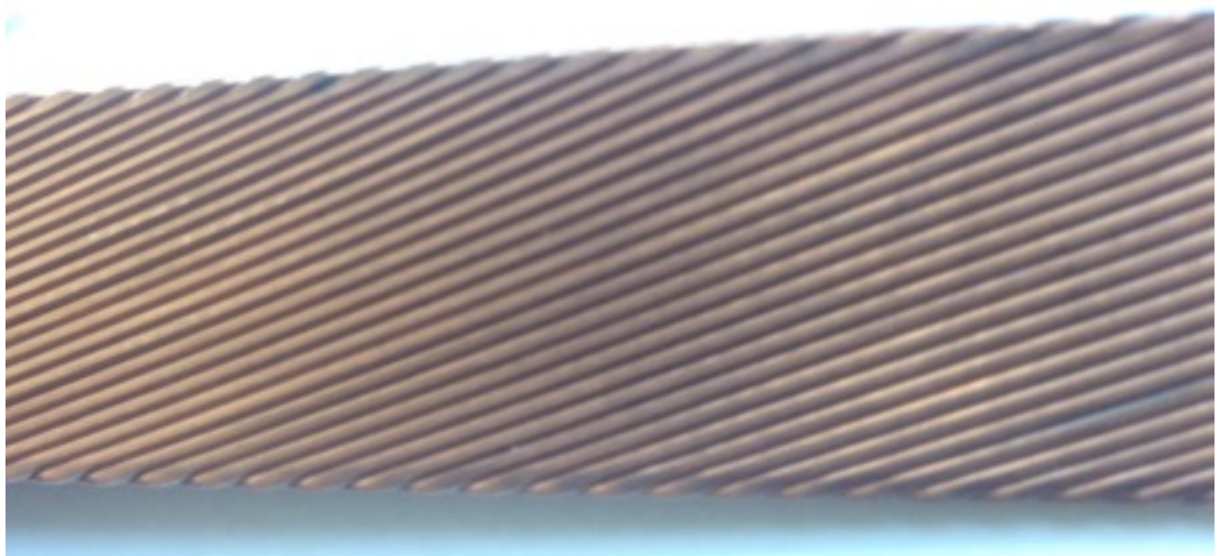
- Starting from the old results, the algorithm looks for the solution for the next value of Heating time



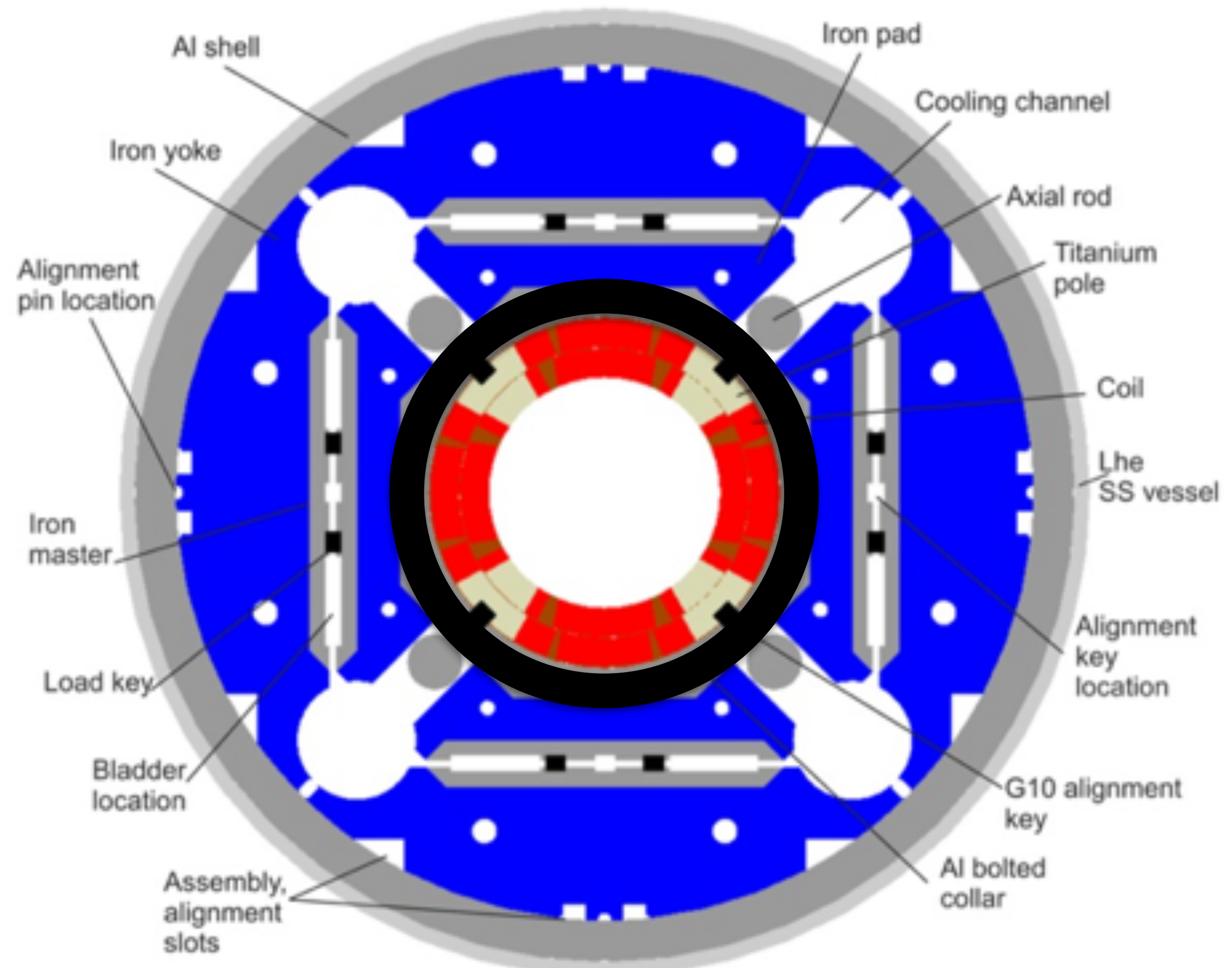
MQXF v2 Cable

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



MQXF cross section



Nb_3Sn Rutherford cable

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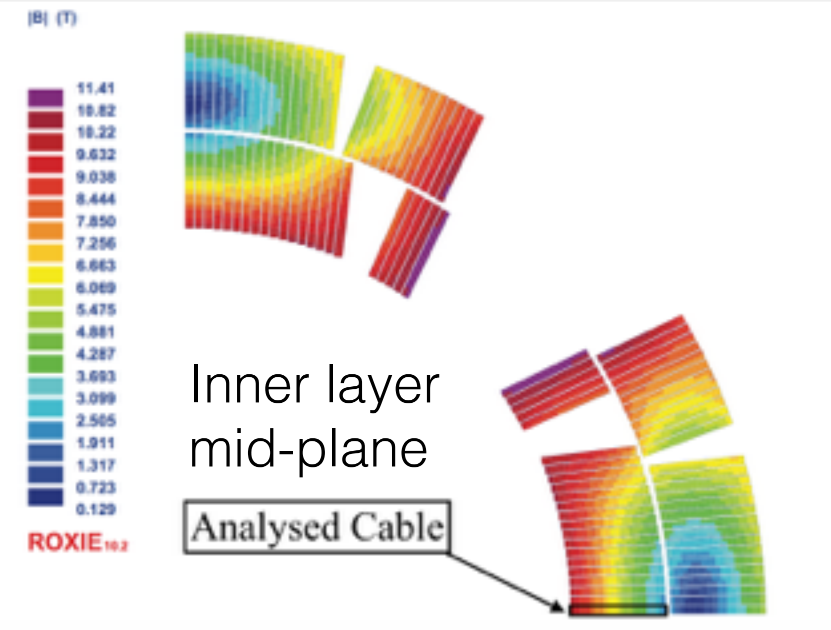
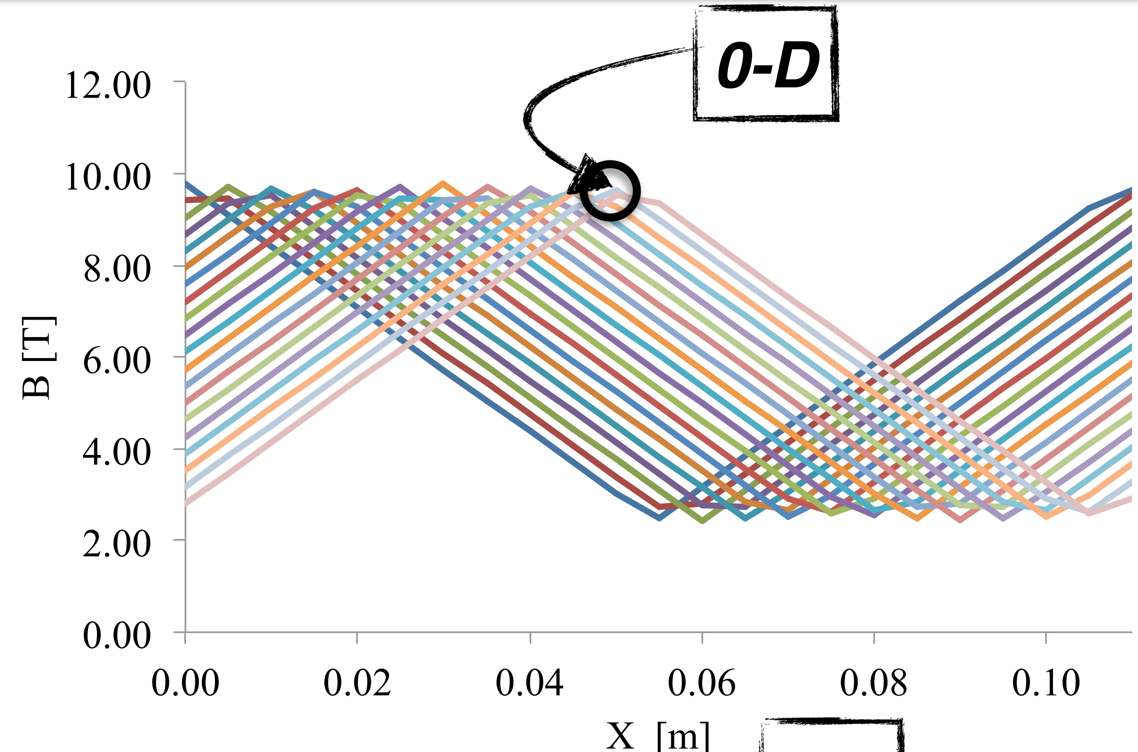
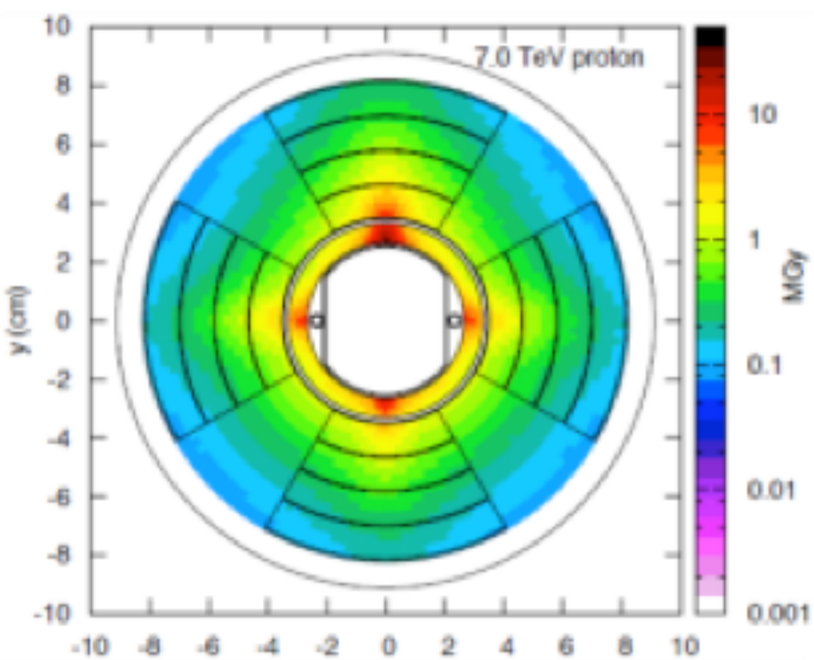
Model description

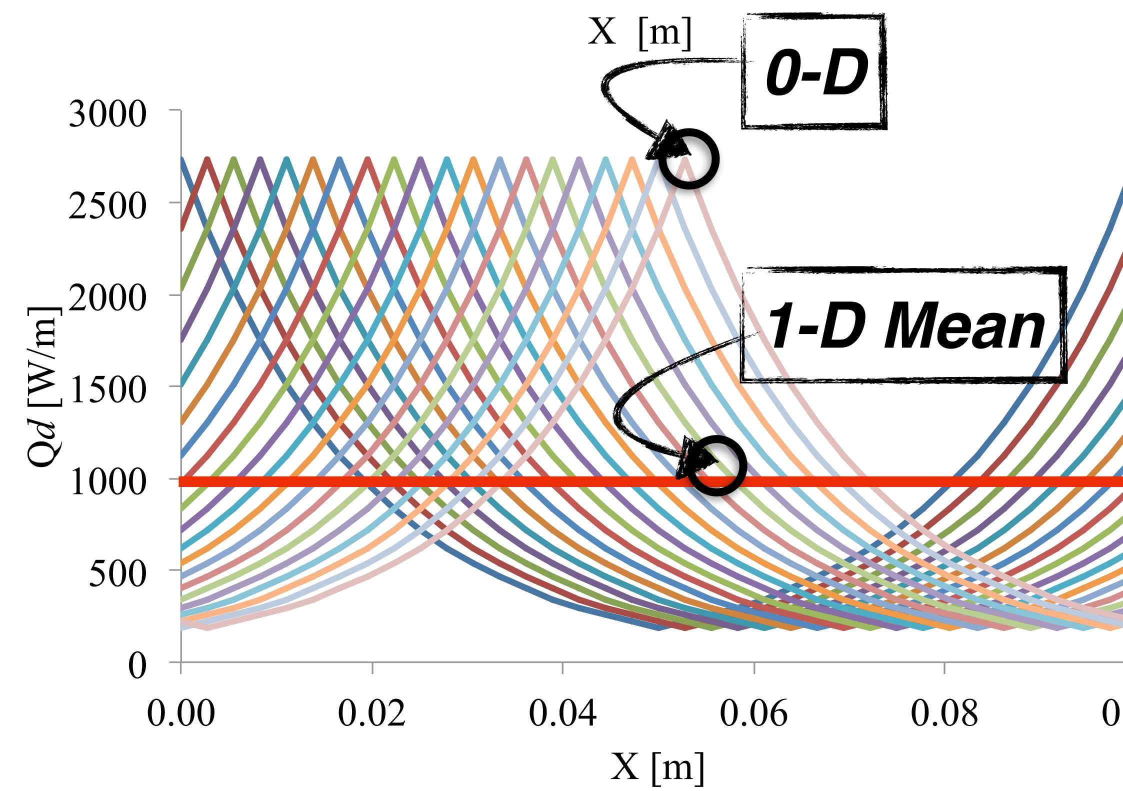


Cavanna et al, “Design of the NB3SN Inner Triplet”, 04 September 2015





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



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

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0-D[1] model description

- All strands are lumped into one single thermal and electric element, with uniform temperature
- The non-uniformity of the magnetic field and the heat deposition are not taken into account

$$A_{St}C_{St}\frac{dT_{St}}{dt} = \dot{q}'_{St} + \dot{q}'_{Joule} - p_{St,He}h_{St,He}(T_{St} - T_{He}) - p_{St,Ja}h_{St,Ja}(T_{st} - T_{Ja})$$

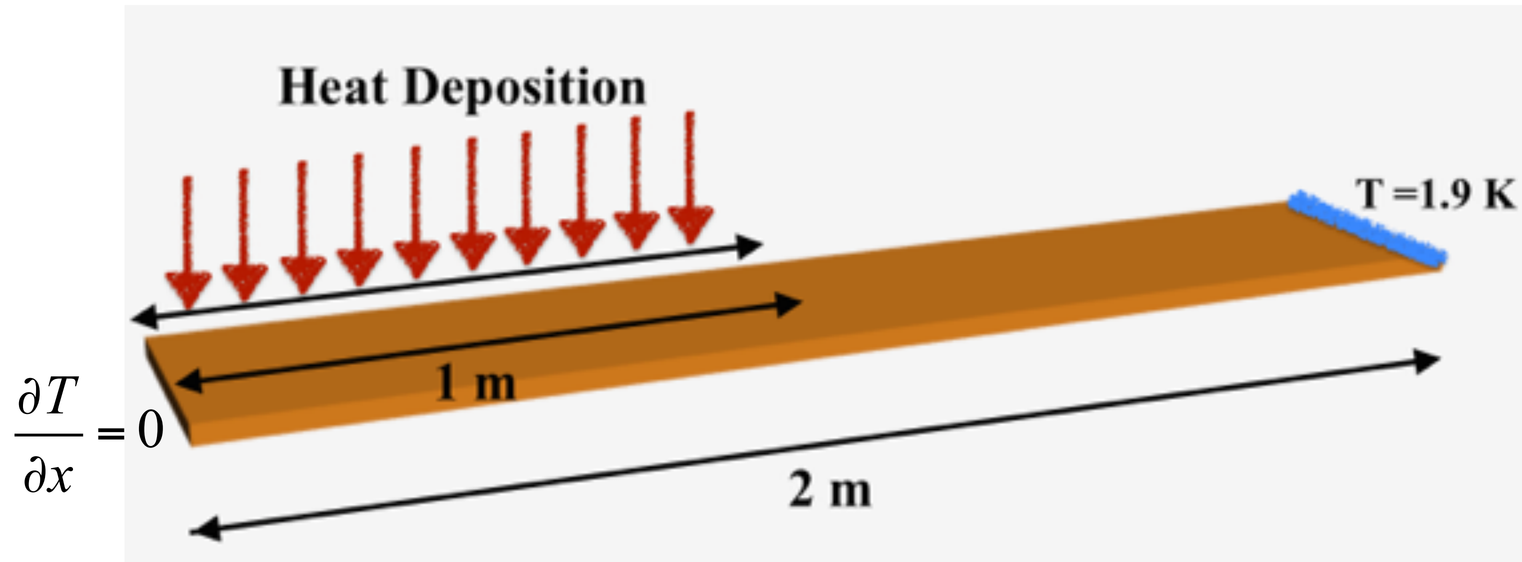
$$A_{Ja}C_{Ja}\frac{dT_{Ja}}{dt} = -p_{Ja,He}h_{Ja,He}(T_{Ja} - T_{He}) - p_{St,Ja}h_{St,Ja}(T_{Ja} - T_{St})$$

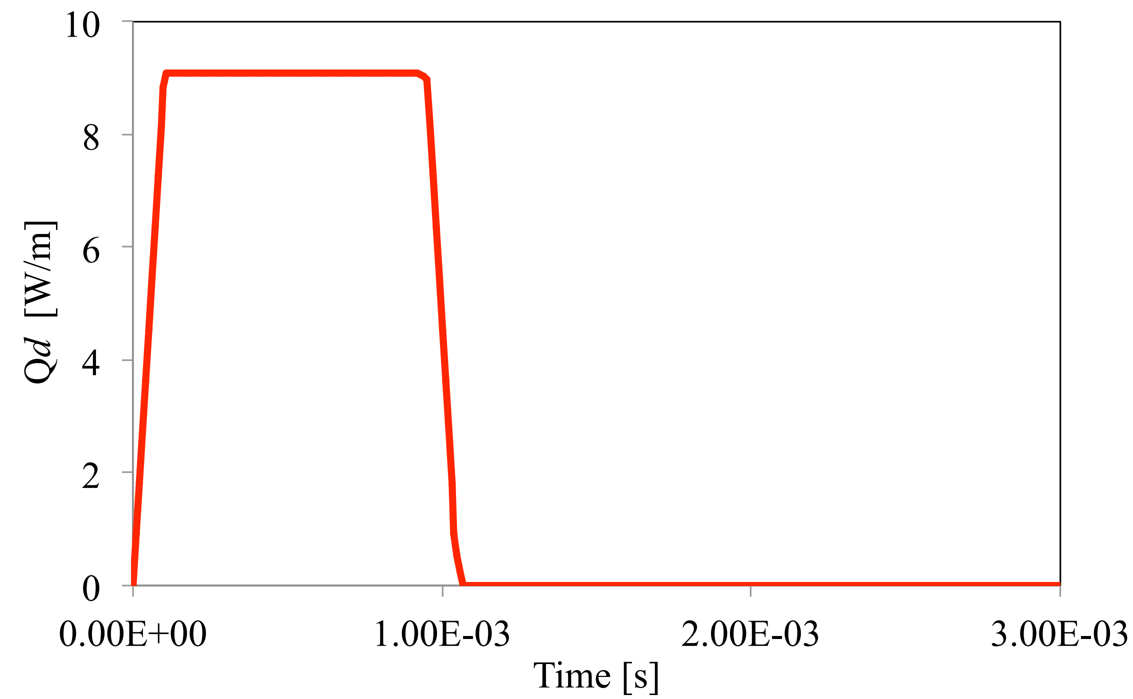
$$A_{Ja}C_{Ja}\frac{dT_{He}}{dt} = \dot{q}'_{Ja} - p_{St,He}h_{St,He}(T_{St} - T_{He}) - p_{Ja,He}h_{Ja,He}(T_{Ja} - T_{He})$$

[1] L. Bottura, “CryoSoft code **ZeroDee** v. 1.3”, January 2001

1-D[1] model description

Heat Pulse





Model Elements

- THERMAL: $\mathbf{N}_{strand}$ (Nb_3Sn + Cu) + Glass Epoxy
- HYDRAULIC: Helium Bath
- ELECTRIC: $\mathbf{N}_{strand}$ (Nb_3Sn + Cu)

[1] L. Bottura, "CryoSoft code **THEA** v. 2.2", December 2013

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1-D: Thermal Model

Heat transfer equation:

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

Heat exchange occurs between:

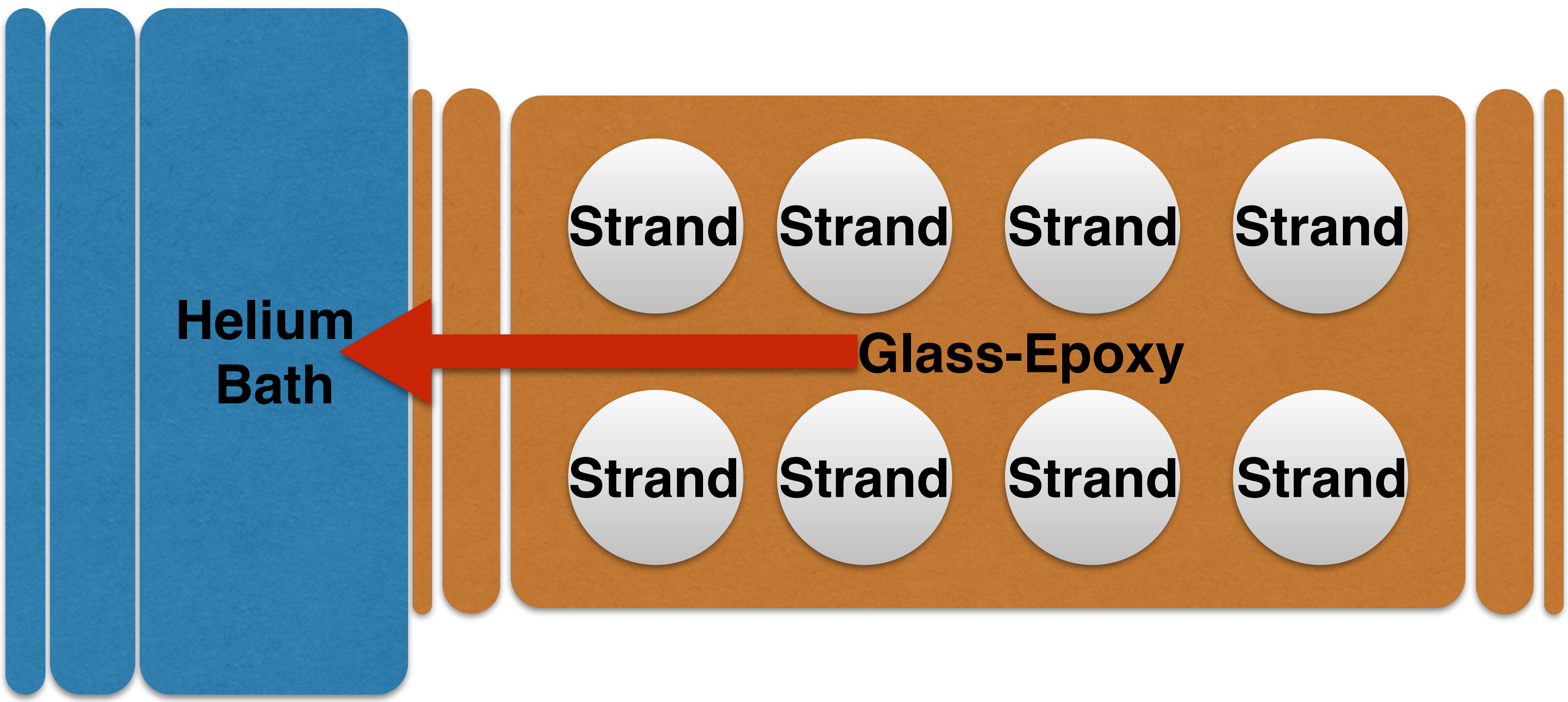
- adjacent and non-adjacent strands through thermal resistance [1]
- strands and Glass-Epoxy through solid conduction
- Glass-Epoxy and Helium bath [Hydraulic element] with a stationary heat transfer model, obtained by a fitting of experimental results [2]
  {We are still waiting for experimental results of Nb_3Sn from CryoLab}

There is NO contact between the strands and the Helium bath

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

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

1-D: Thermal Model



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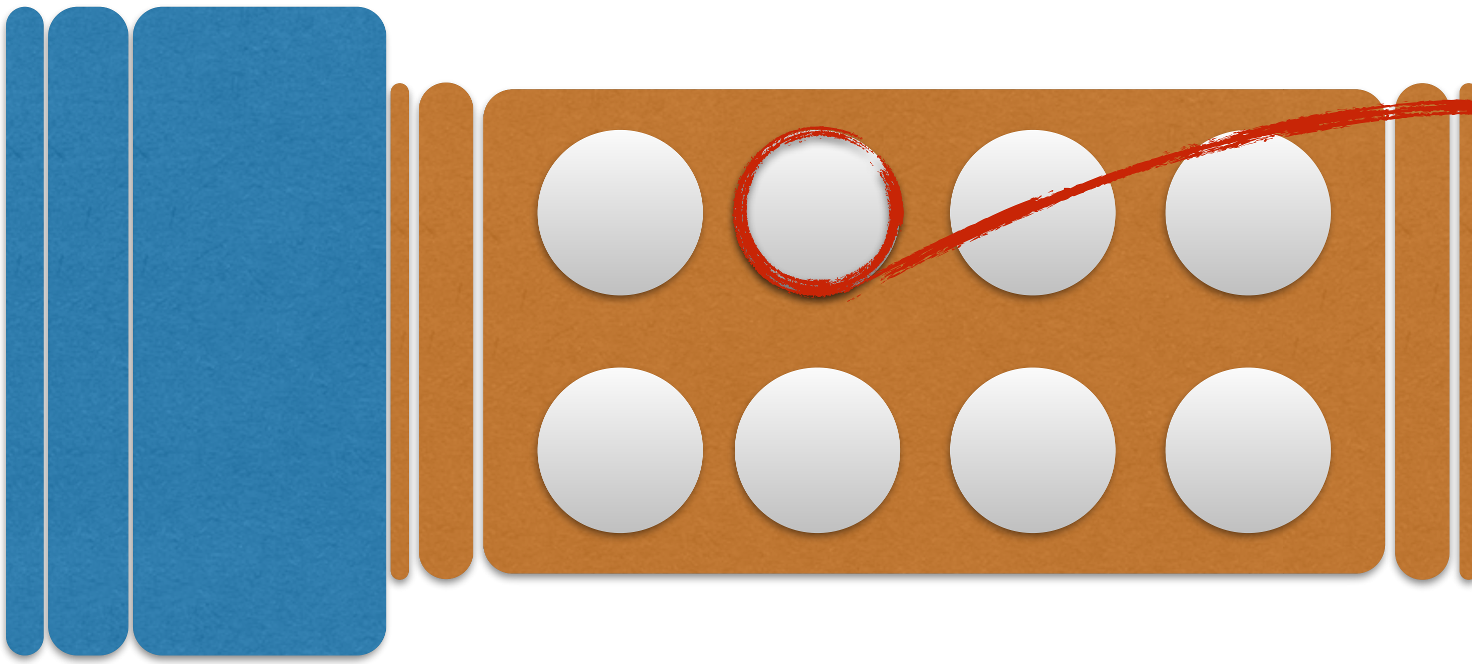
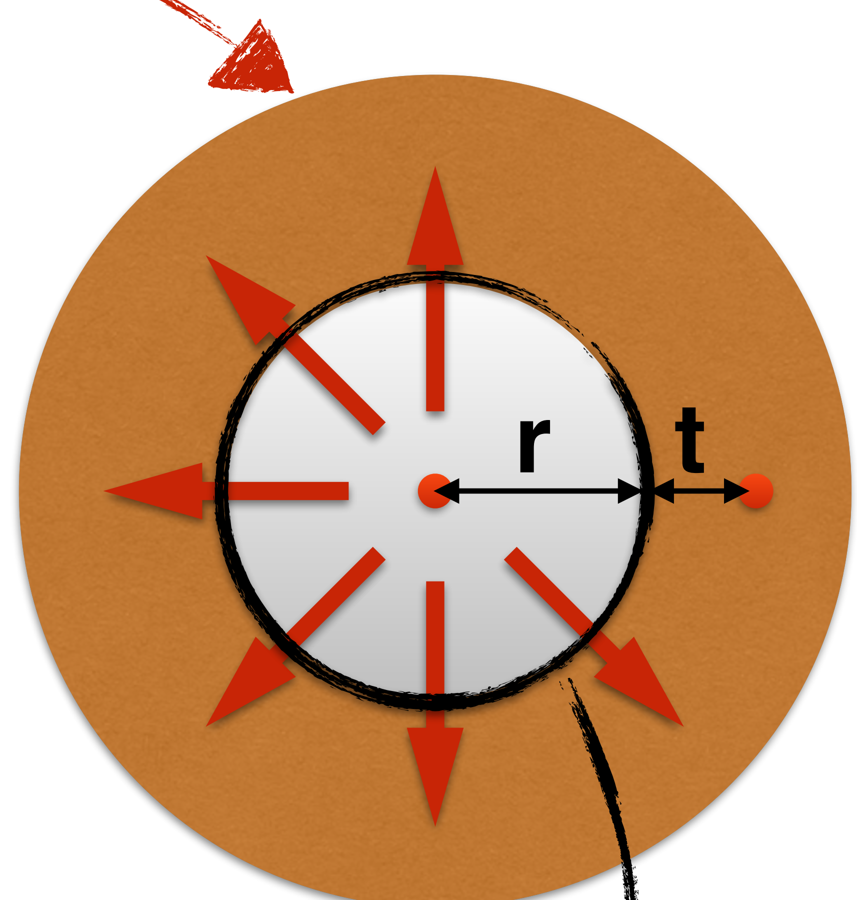
1-D: Thermal Model



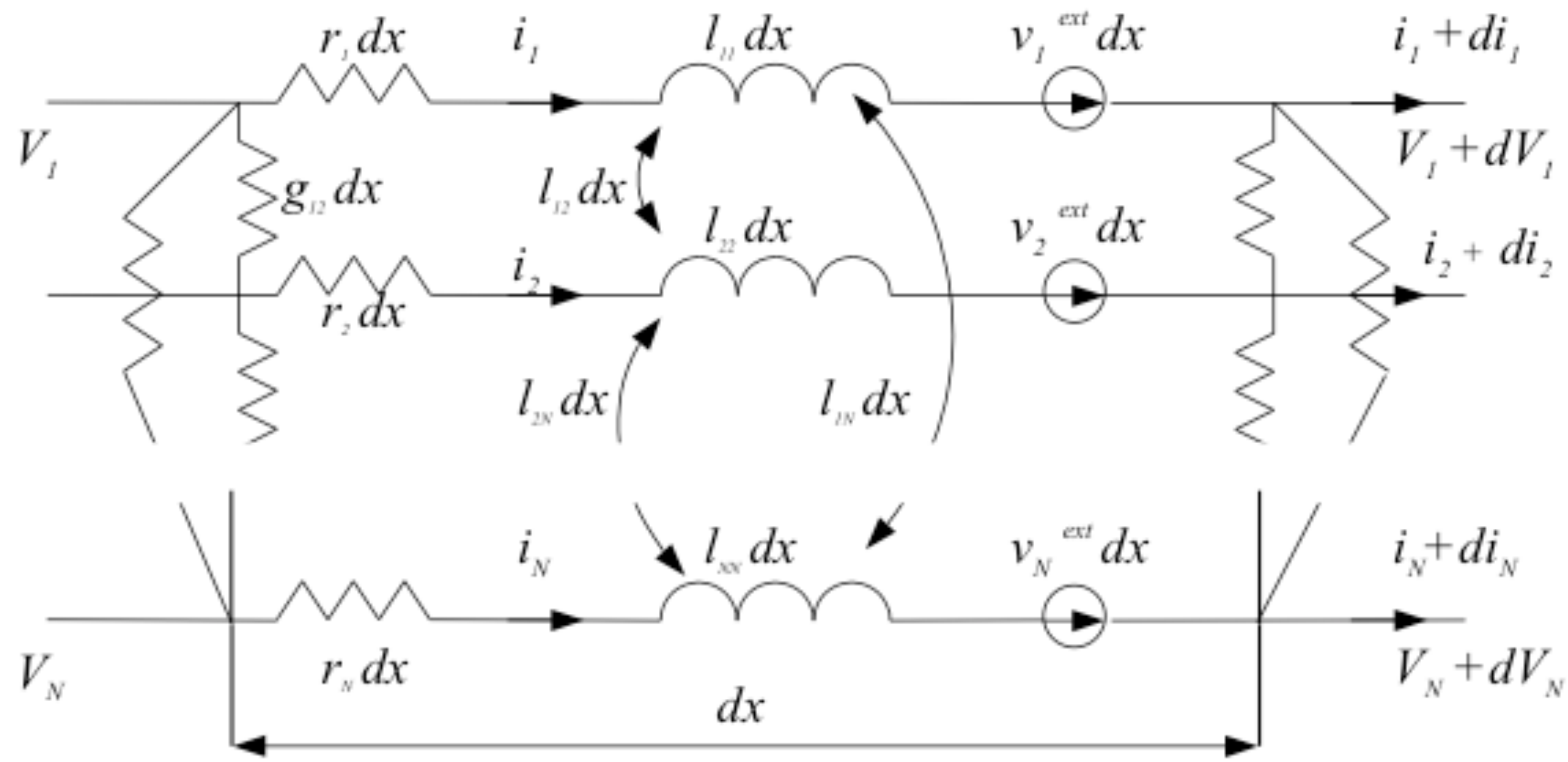
$$h_{St-GE} = \frac{1}{\frac{r}{K_{St}} + \frac{t}{K_{GE}}}$$



The contact thermal resistance between the strand and the Glass-Epoxy is not taken into account

1-D: Electrical Model

- The strands are modelled with a distributed parameter circuit model [1]
- The strands are connected through conductances and mutual inductance [2]



$$\mathbf{L}\frac{\partial \mathbf{T}}{\partial t} + \mathbf{R}\mathbf{I} - \frac{\partial}{\partial x}(\mathbf{C}^{-1}\frac{\partial \mathbf{I}}{\partial x}) = \Delta \mathbf{V}^{ext}$$

[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”, PhD. Dissertation, University of Twente, The Netherlands, 2009

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Operating condition

Nb_3Sn for Hi-Lumi LHC MQXFv2 quadrupole

- Total current = 16470 A
- Operating current density = 1600 A / mm²
- Peak magnetic field = 11.4 T
- Temperature = 1.9 K

Tcs – Top = 5.34 K
Tc – Top = 10.94 K
Jop/Jc = 0.472

Boundary condition

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

Initial condition

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

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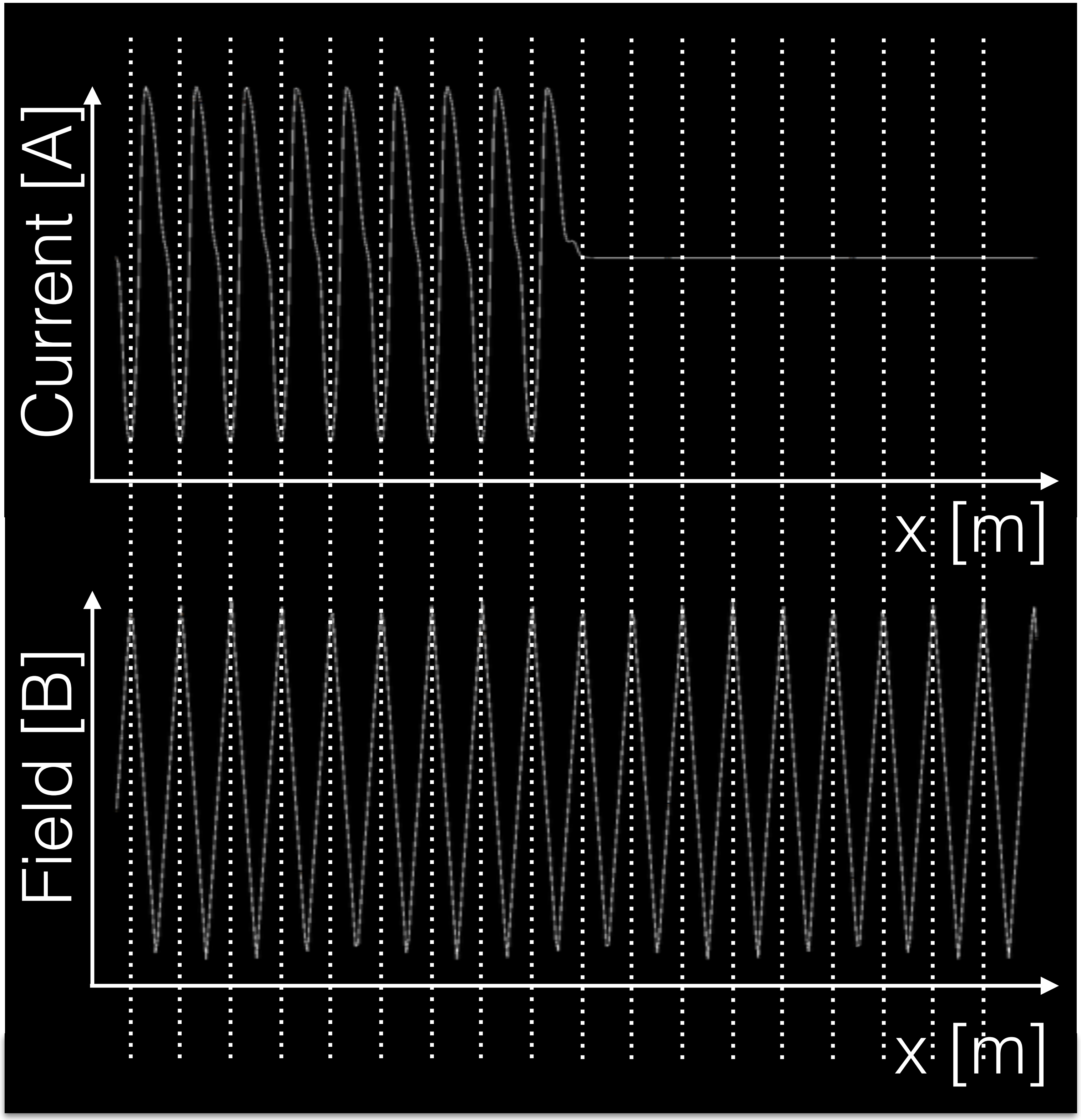
Strands currents distribution

- The current distribution follows the trend of the magnetic field: **the current is minimum where the field is maximum** and viceversa



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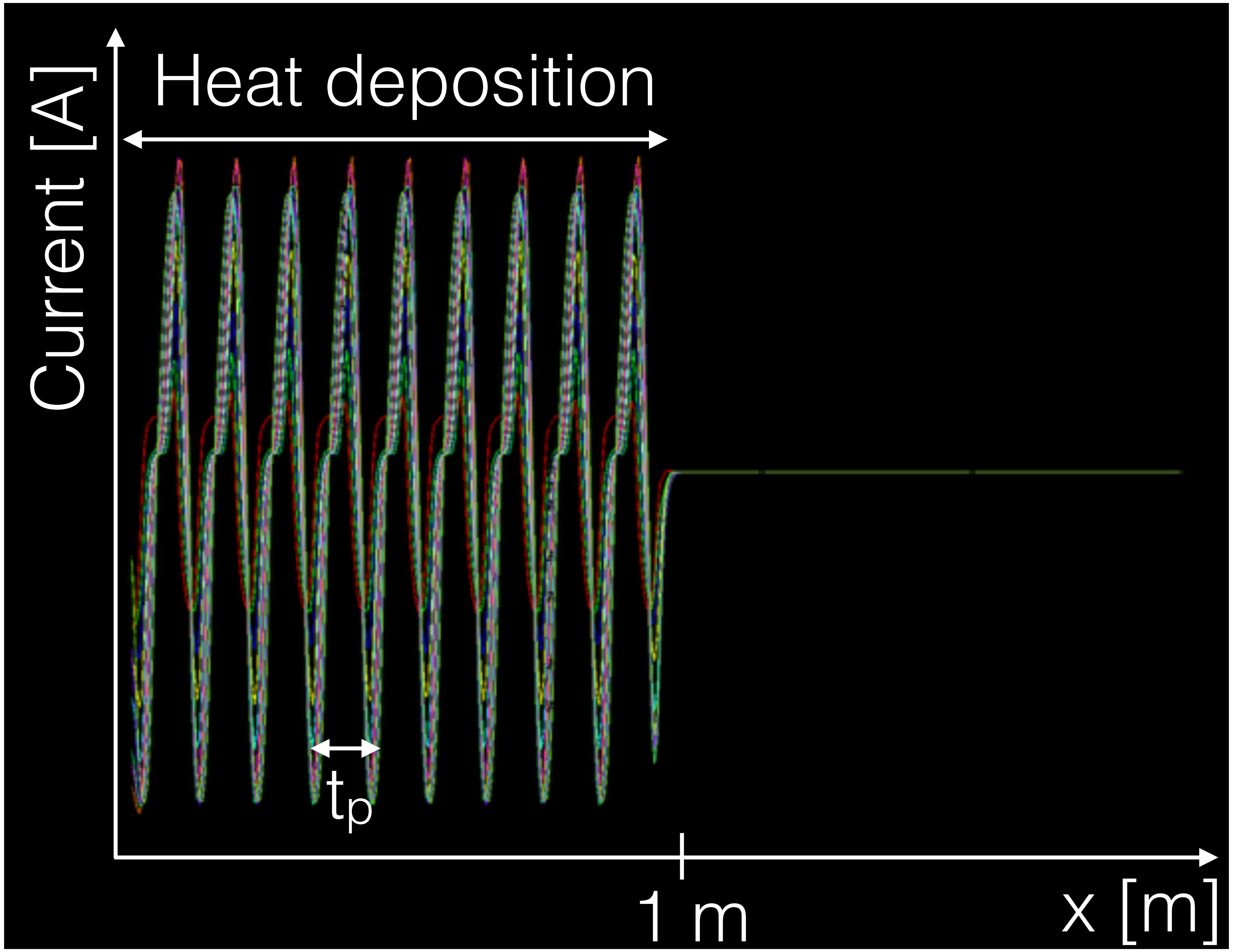
Strands currents distribution

- **The propagation of the normal zone can be observed** [video]
- While the zone is subjected to the transition from superconducting to normal state, the currents try to "escape", looking for a less demanding condition
- After the quench all the current is flowing in the copper and we can observe a stable behaviour



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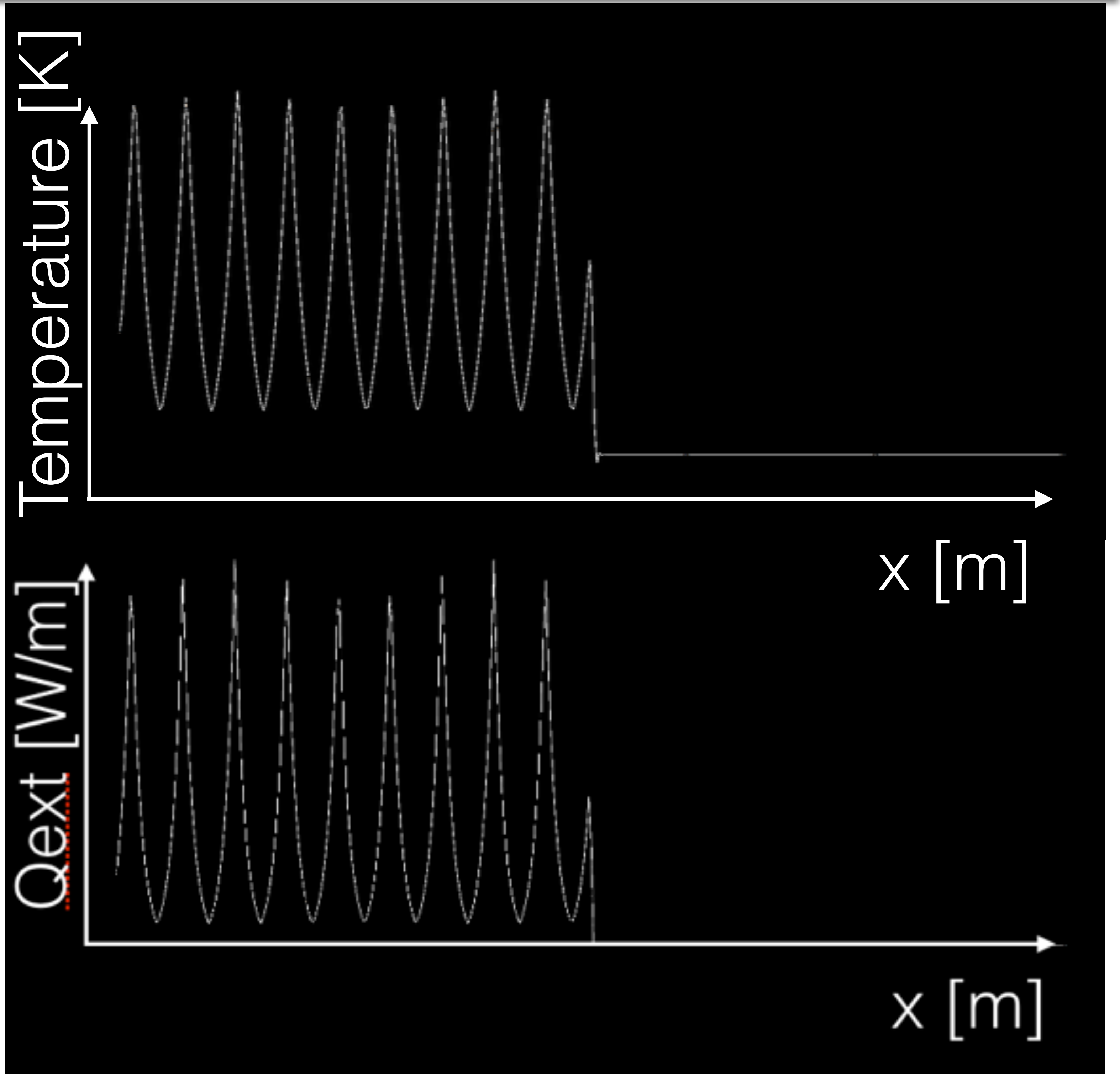
Strand Temperature

- The distribution of the temperature follows the trend of the heat deposition



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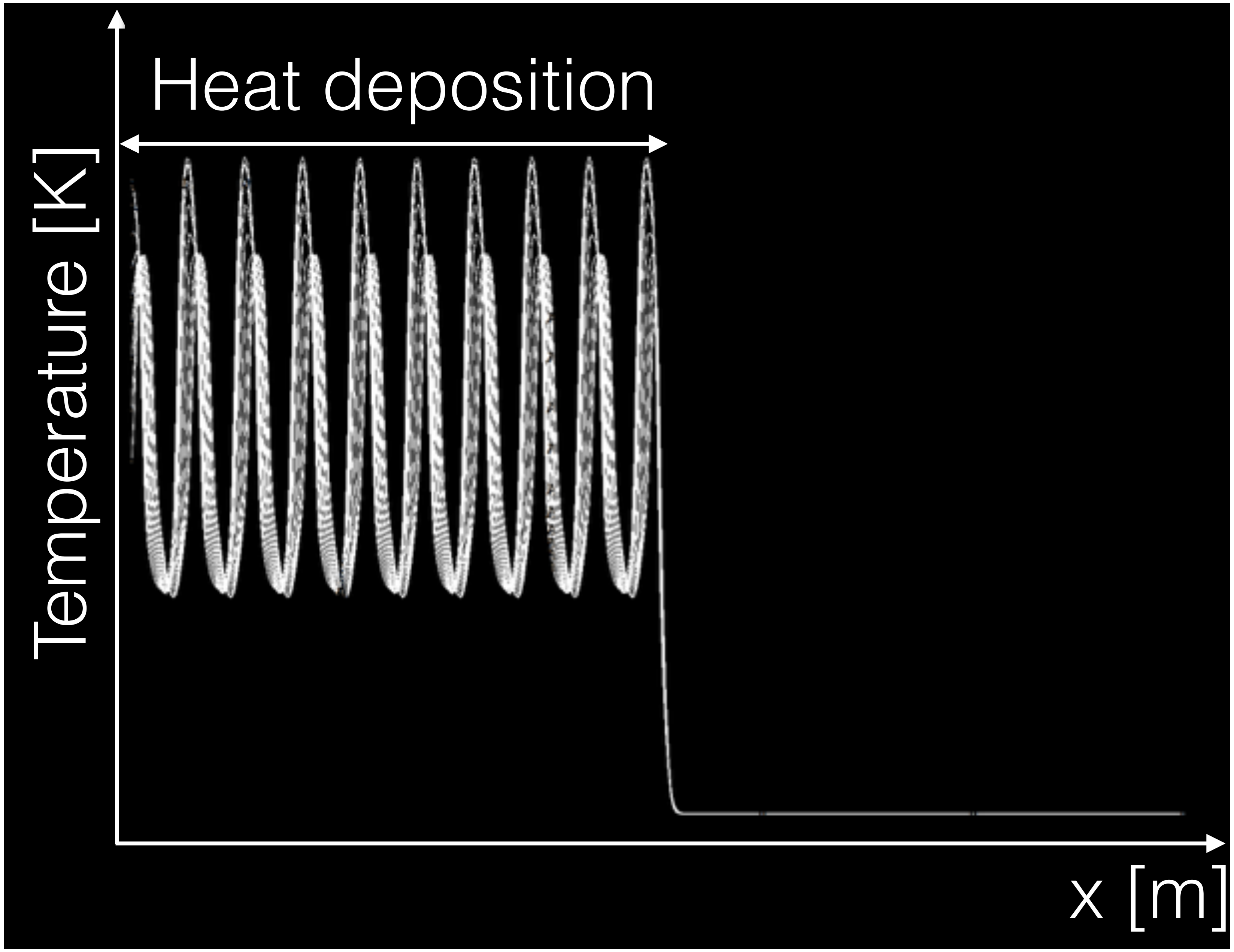
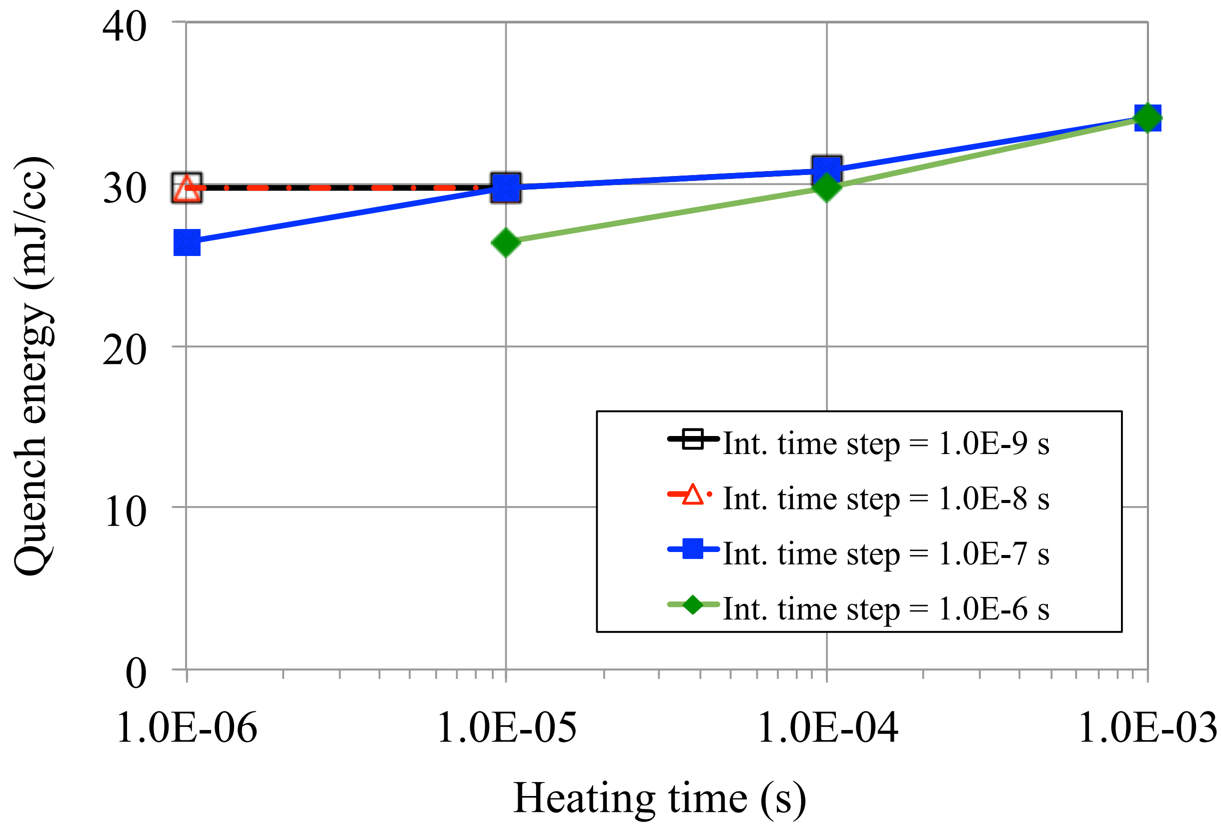
Strands Temperature

- We can observe the **propagation on the normal zone** along the cable length [video]

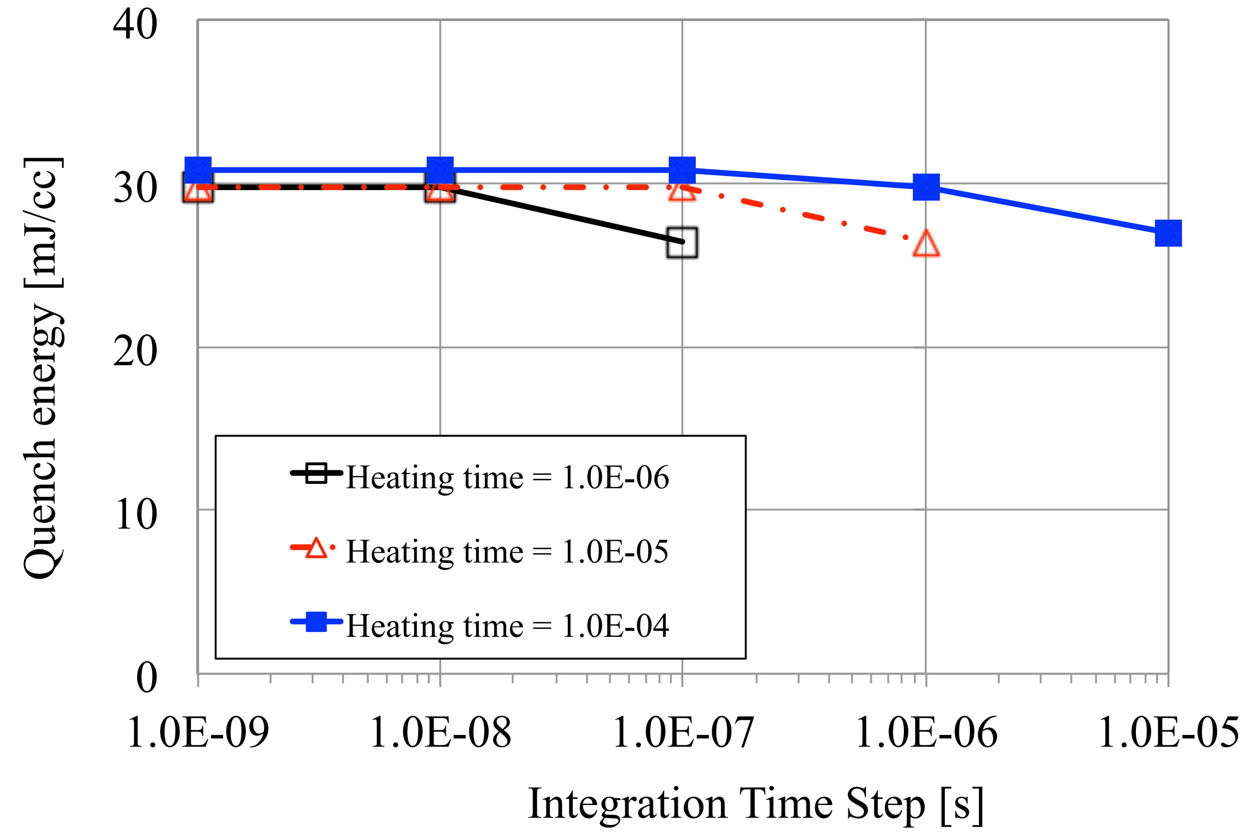


Convergence studies

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



- Depending on the heating time, the proper integration time step has to be chosen



Suggested time steps:

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

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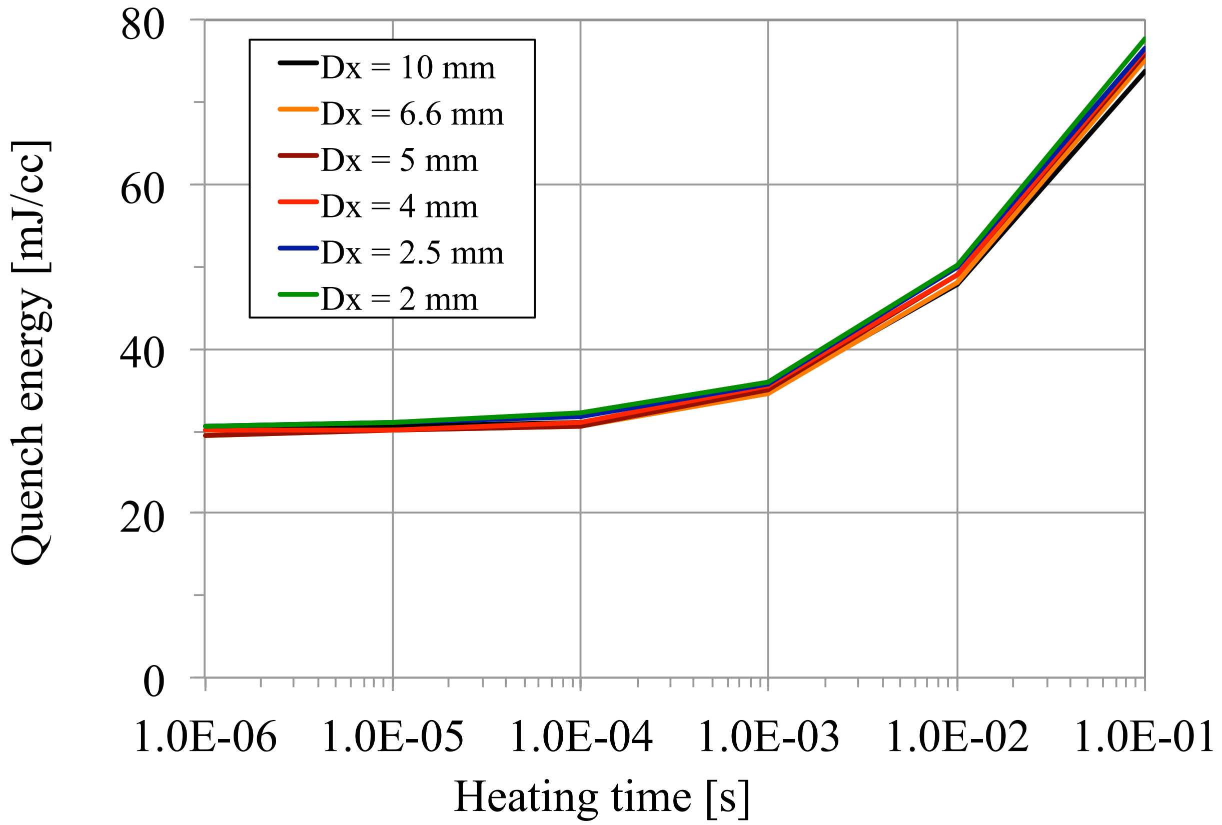
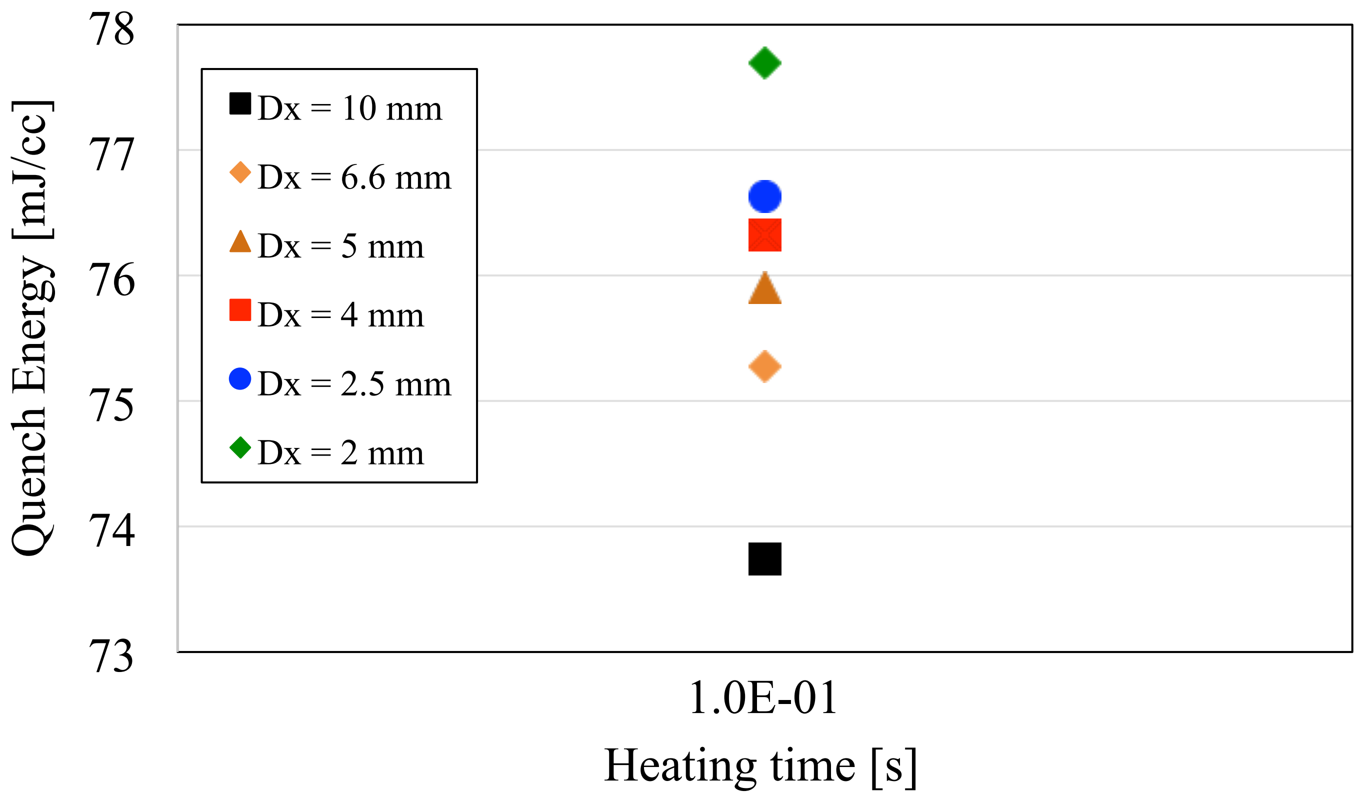
Convergence studies

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



- Reducing the mesh dimension entails a strong increasing of computational time



Simulation parameters:

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

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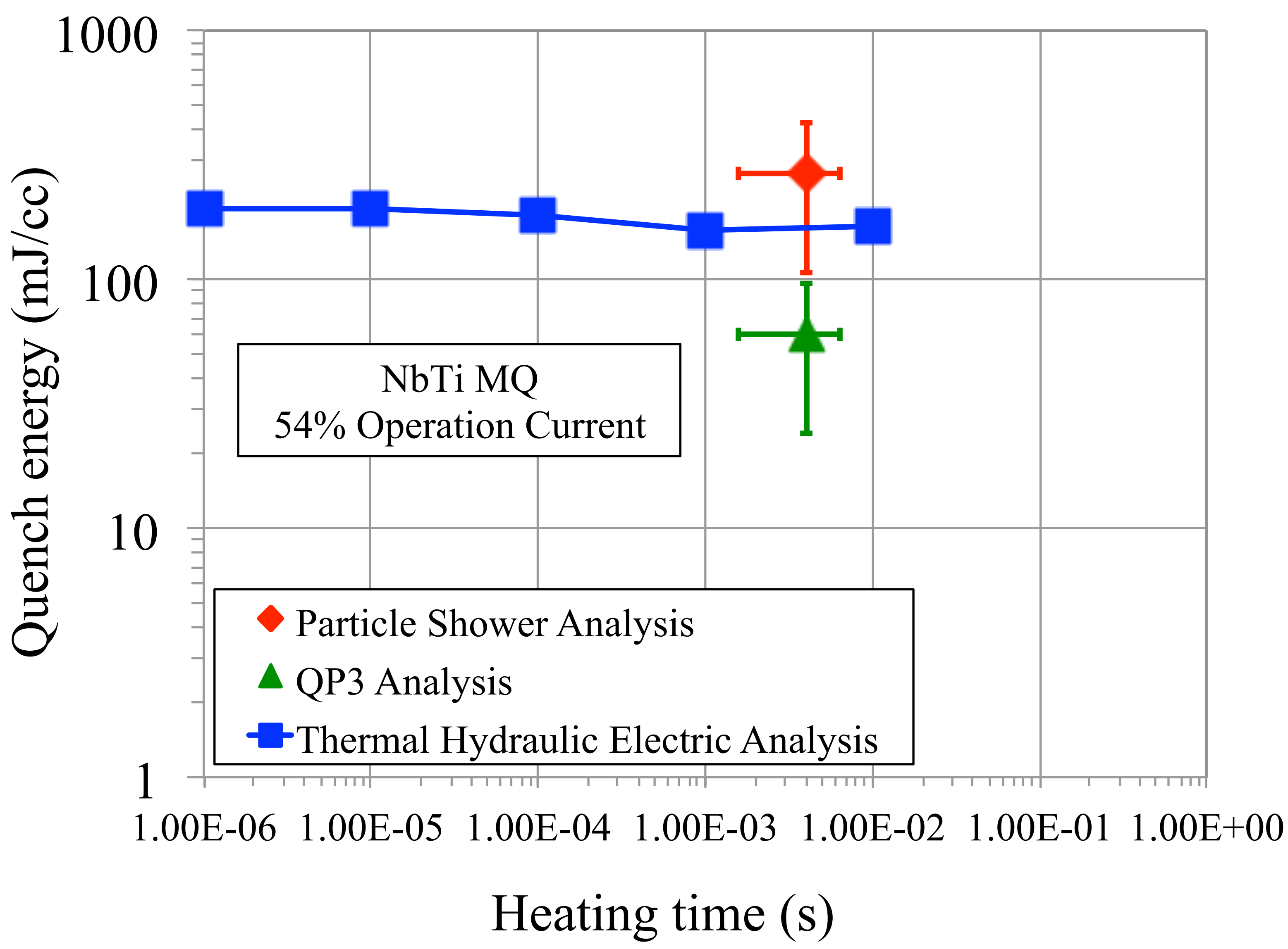
Model validation

NbTi
for LHC MQ
quadrupole

- THEA simulations are coherent with the *pseudo-experimental* results presented in [1], based on the reconstruction of the energy introduced in the magnet at quench by means of the Beam Loss Monitors and FLUKA simulations [2]



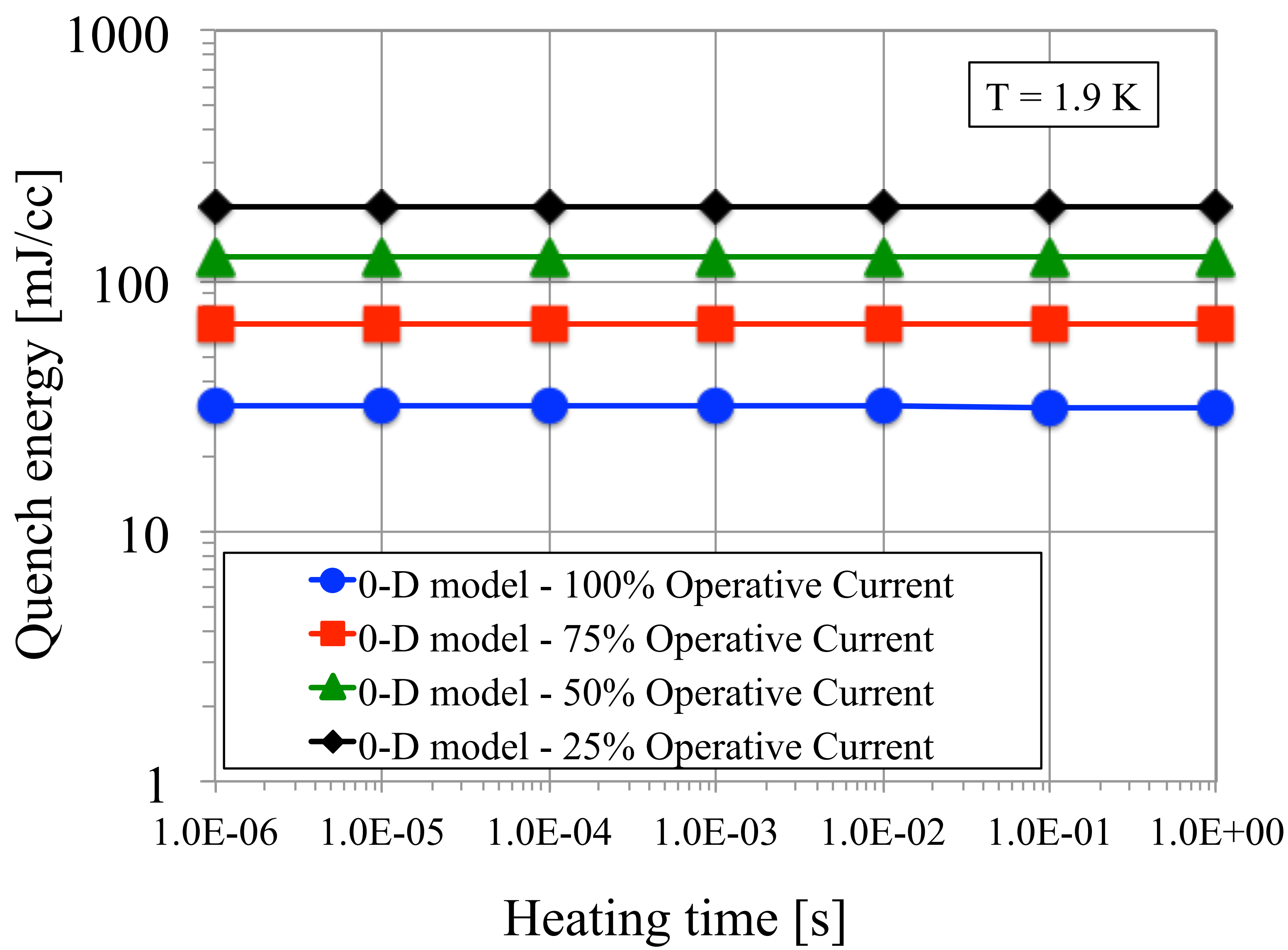
[1] B. Auchmann et al. "Testing Beam-Induced Quench Levels of LHC Superconducting Magnets in Run 1", Phys. Rev. ST Accel. Beams 18, 061002, 2015.

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

0-D model

UNIFORM Heat Deposition
UNIFORM Magnetic Field

- **Lower values of current** determine **higher QEs**
- No significant variation of QEs can be observed with the raising of the heating time



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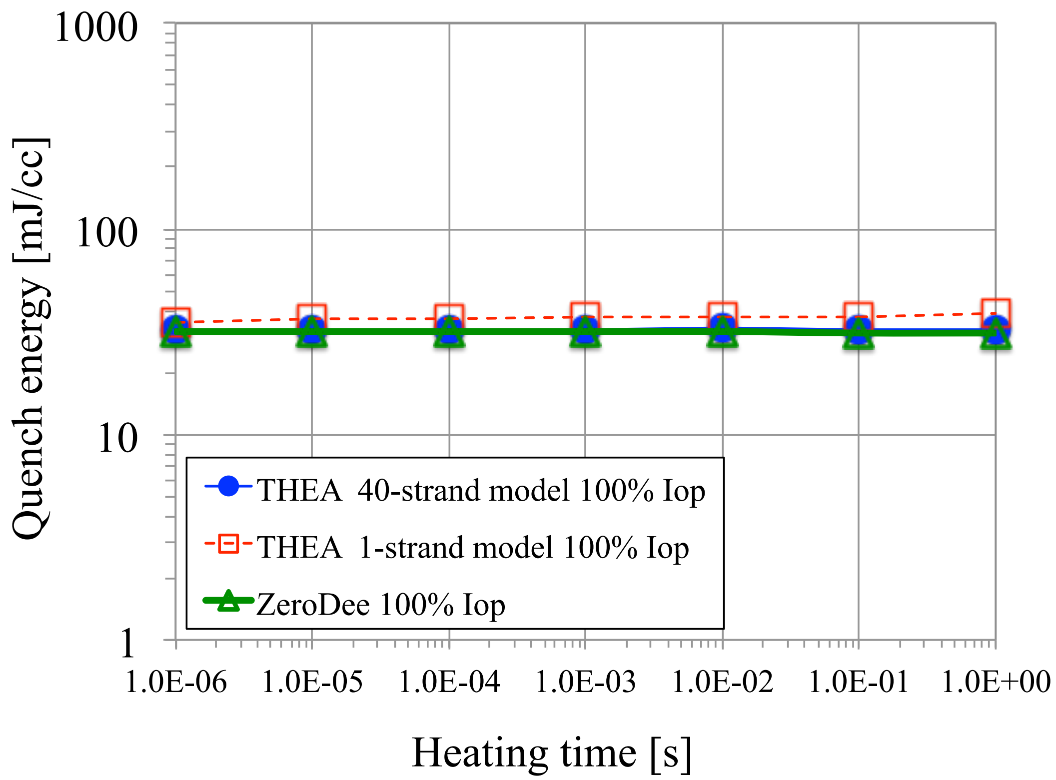
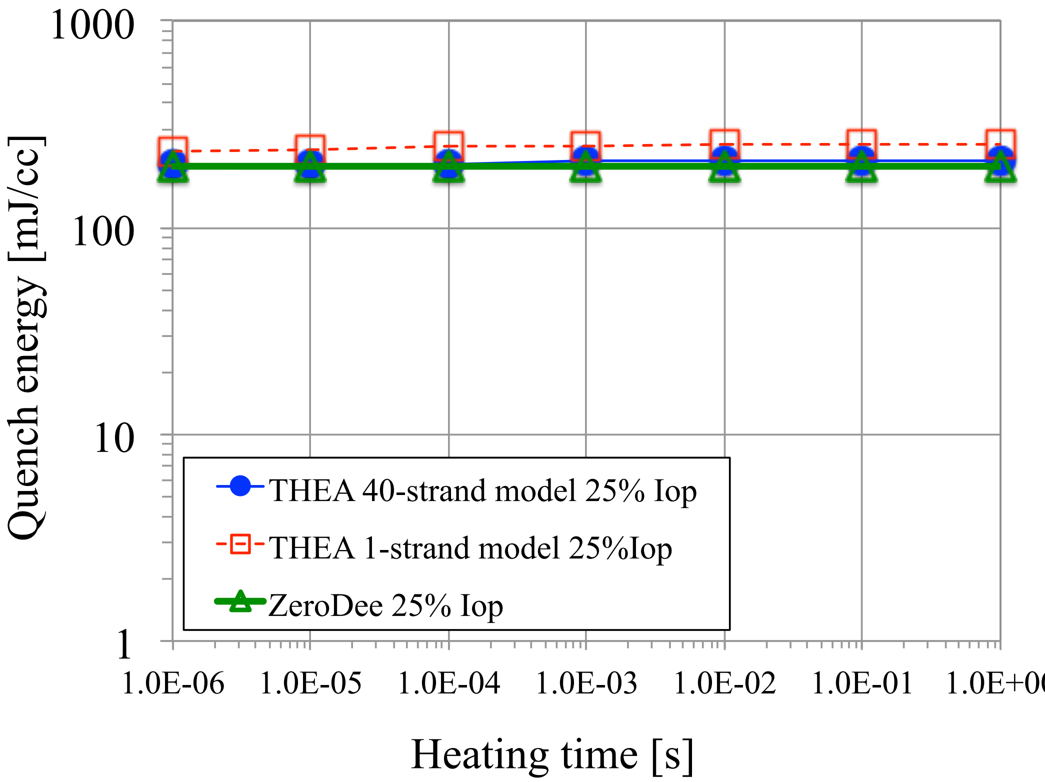
0-D and 1-D models

UNIFORM Heat Deposition
UNIFORM Magnetic Field

100 % Operating current

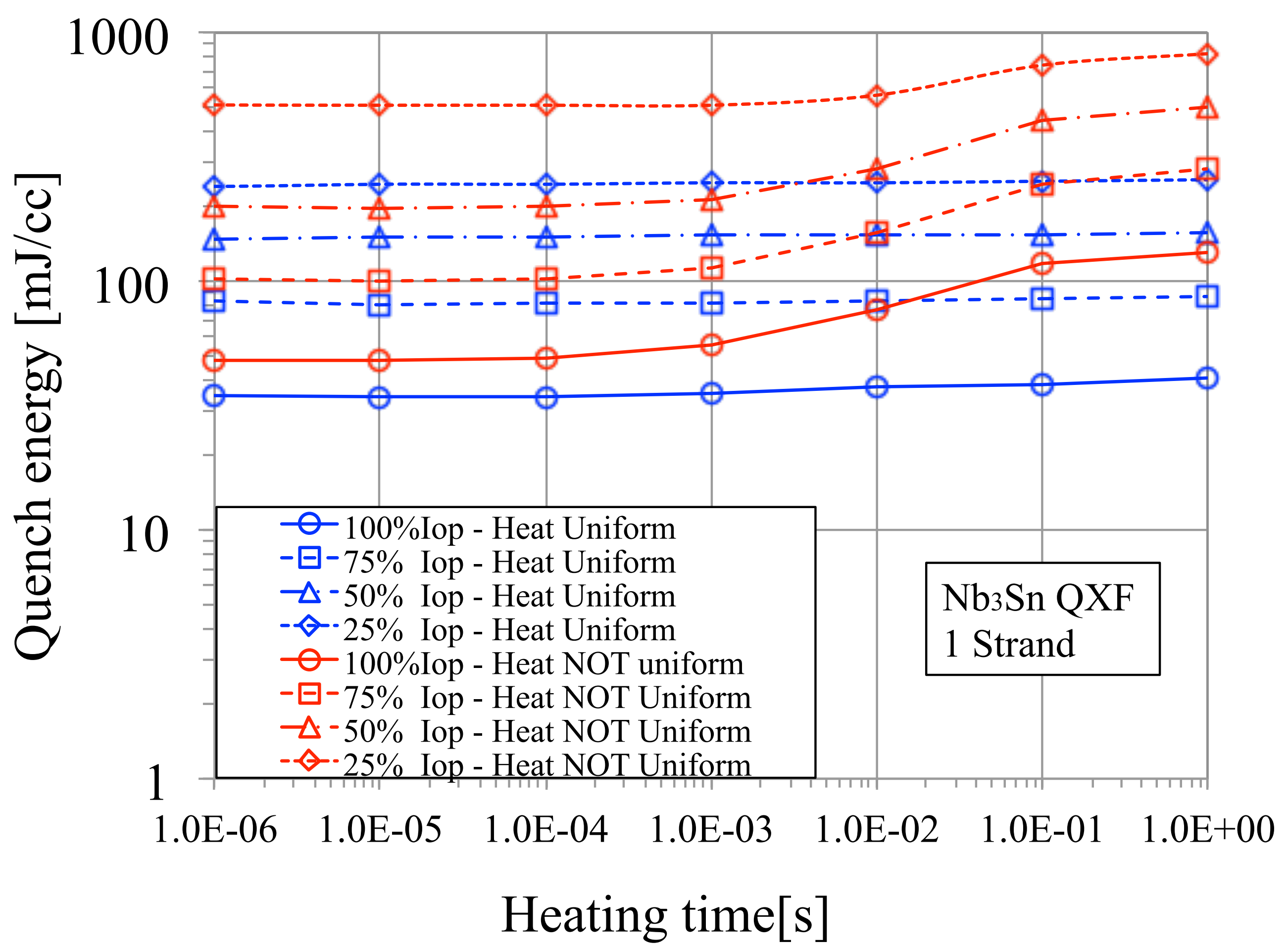


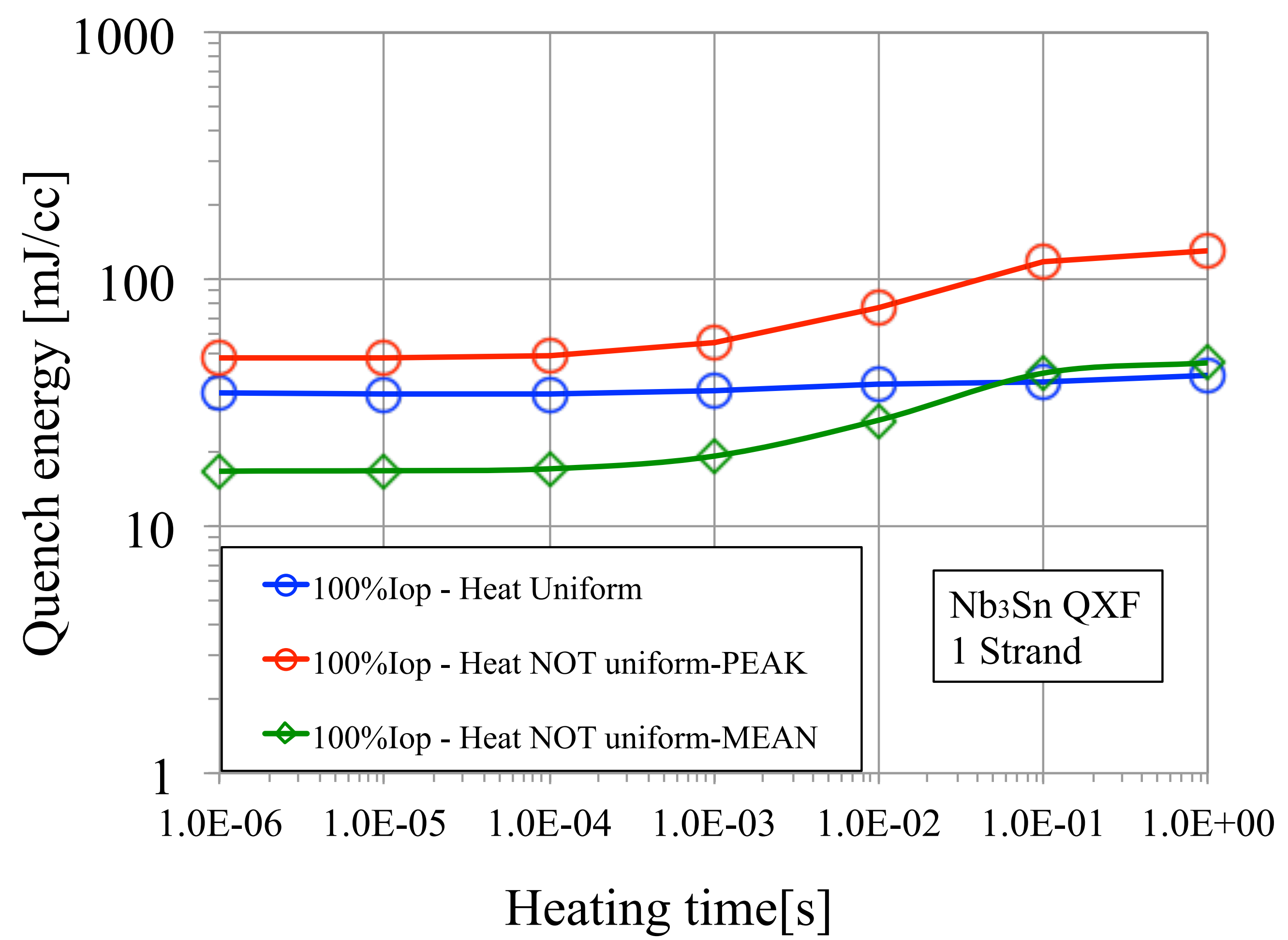
25 % Operating current



- The **0-D and 1-D models are in a good agreement**, both for high and low currents

1-D: one-strand model





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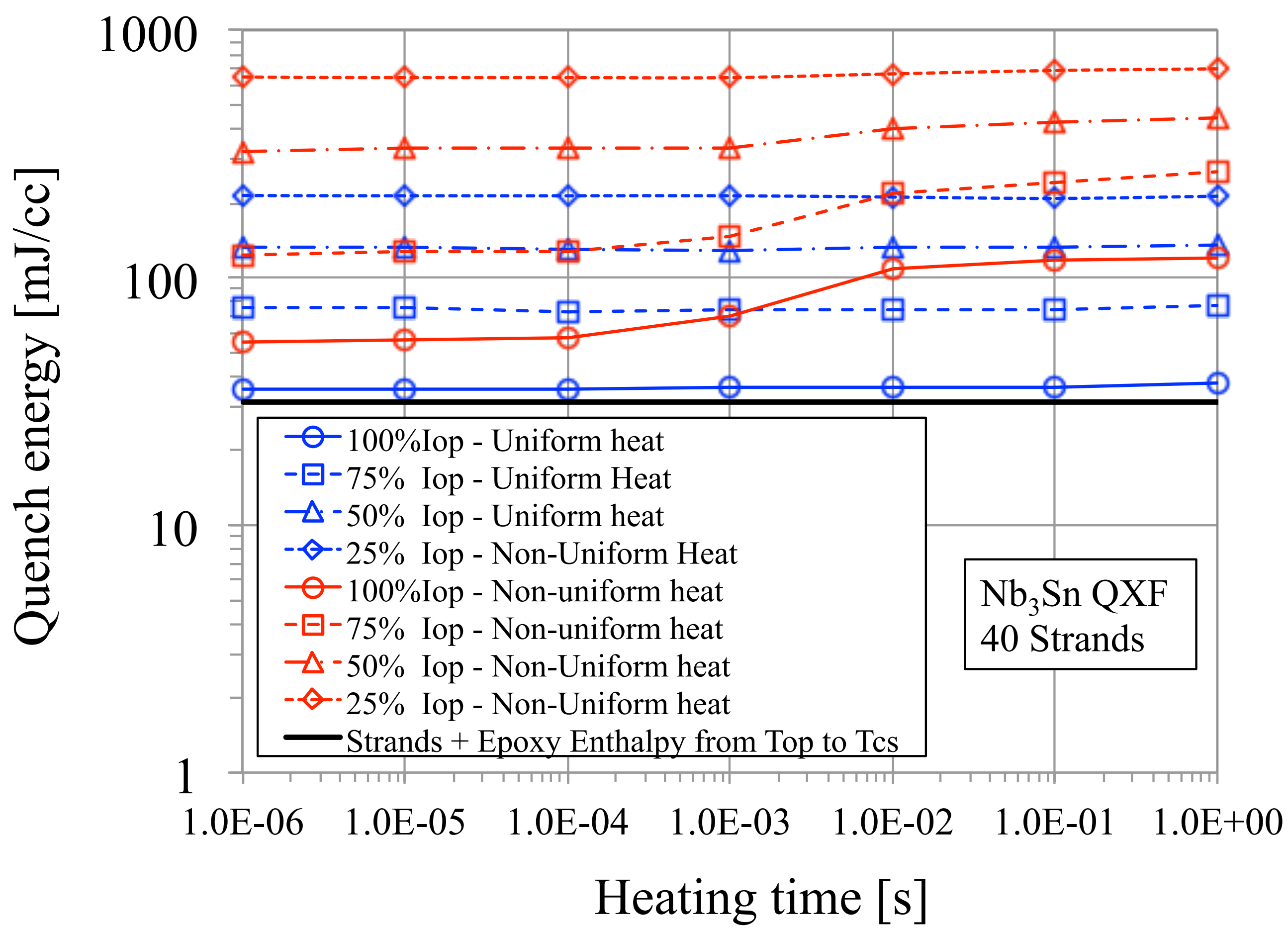
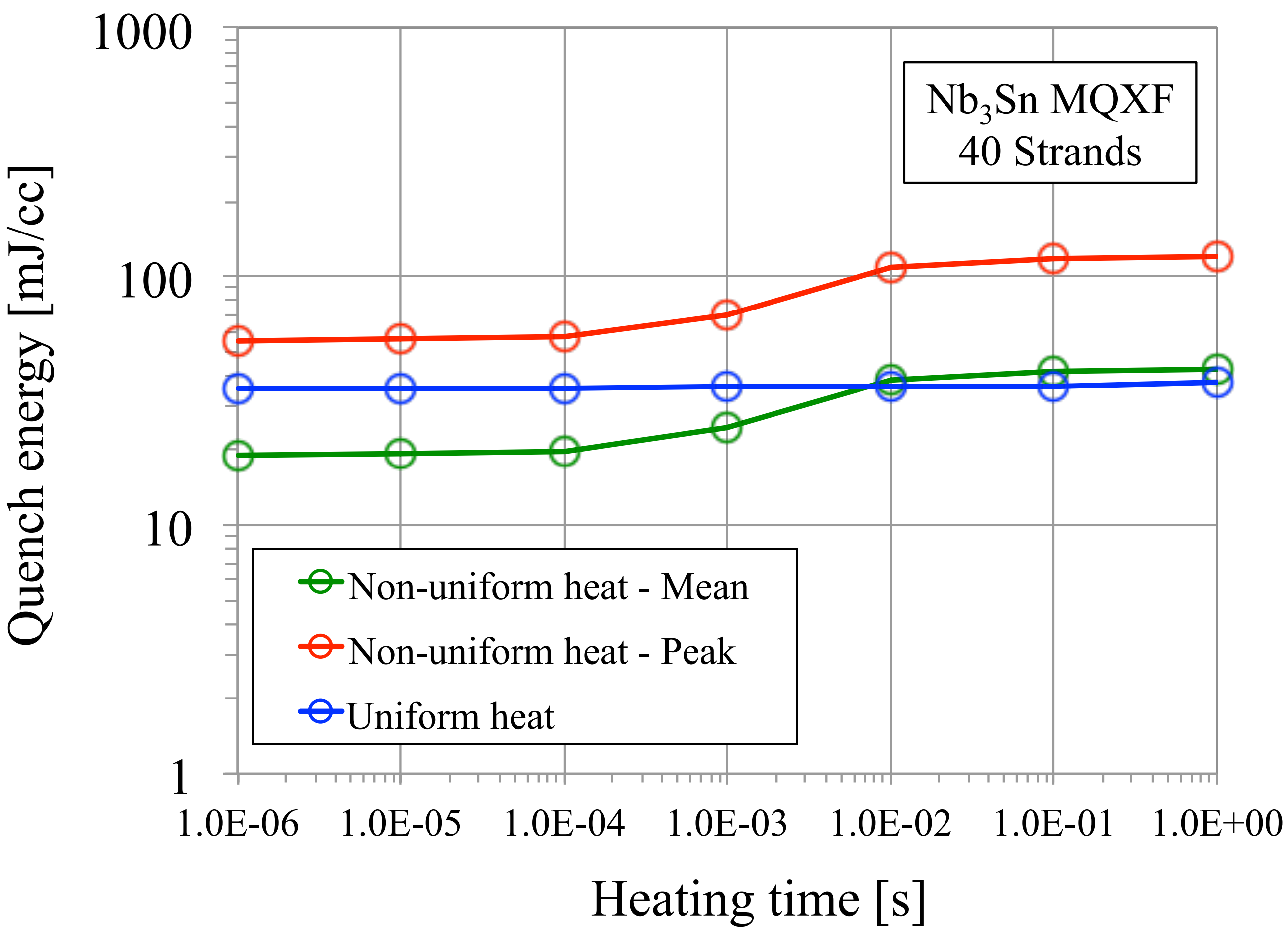
1-D: multi-strand model





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1-D: multi-strand model

- For uniform heat deposition the QEs increase only slightly with the heating time
- For **non-uniform heat deposition**, the **QEs increase with the heating time**, especially at high operation current
- The QEs calculated for the uniform heat deposition at operating current are coincident with Enthalpy of the cable
- Uniform heat deposition implies a better stability of the cable, because **at fast time scale we can observe a local behaviour** and the peaks of the heat deposition are responsible for the quench

1-D: Nb_3Sn vs NbTi

Nb_3Sn for Hi-Lumi LHC MQXFv2 quadrupole

- Total current = 16470 A
- Operating current density = 1600 A / mm²
- Peak magnetic field = 11.4 T
- Temperature = 1.9 K

$Tcs - Top = 5.34$ K
$Tc - Top = 10.94$ K
$Jop/Jc = 0.472$

NbTi for LHC MQ quadrupole

- Total current = 11870 A
- Operating current density = 1820 A / mm²
- Peak magnetic field = 6.85 T
- Temperature = 1.9 K

$Tcs - Top = 2.89$ K
$Tc - Top = 5.04$ K
$Jop/Jc = 0.465$

Nb_3Sn has a double temperature margin with respect to NbTi

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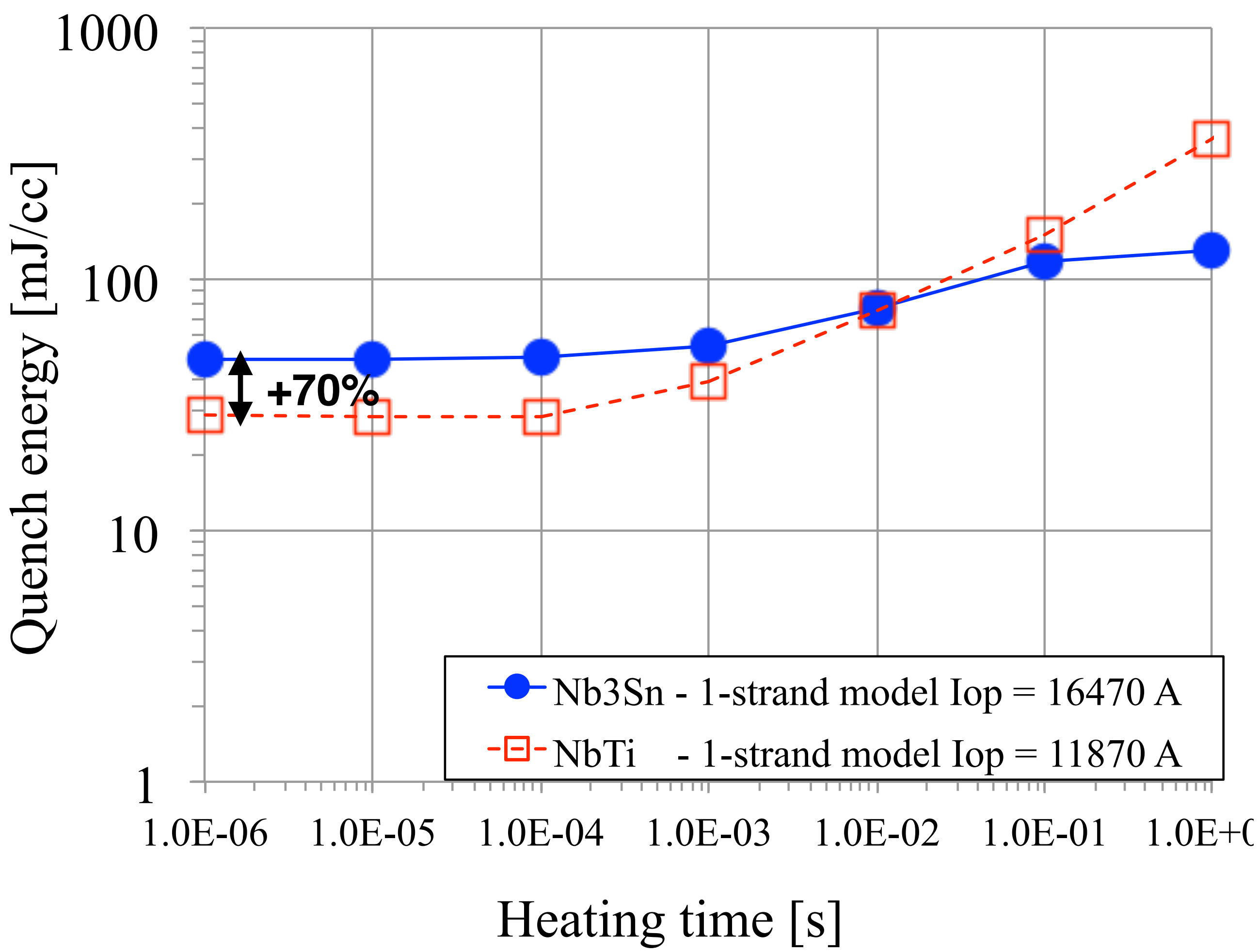
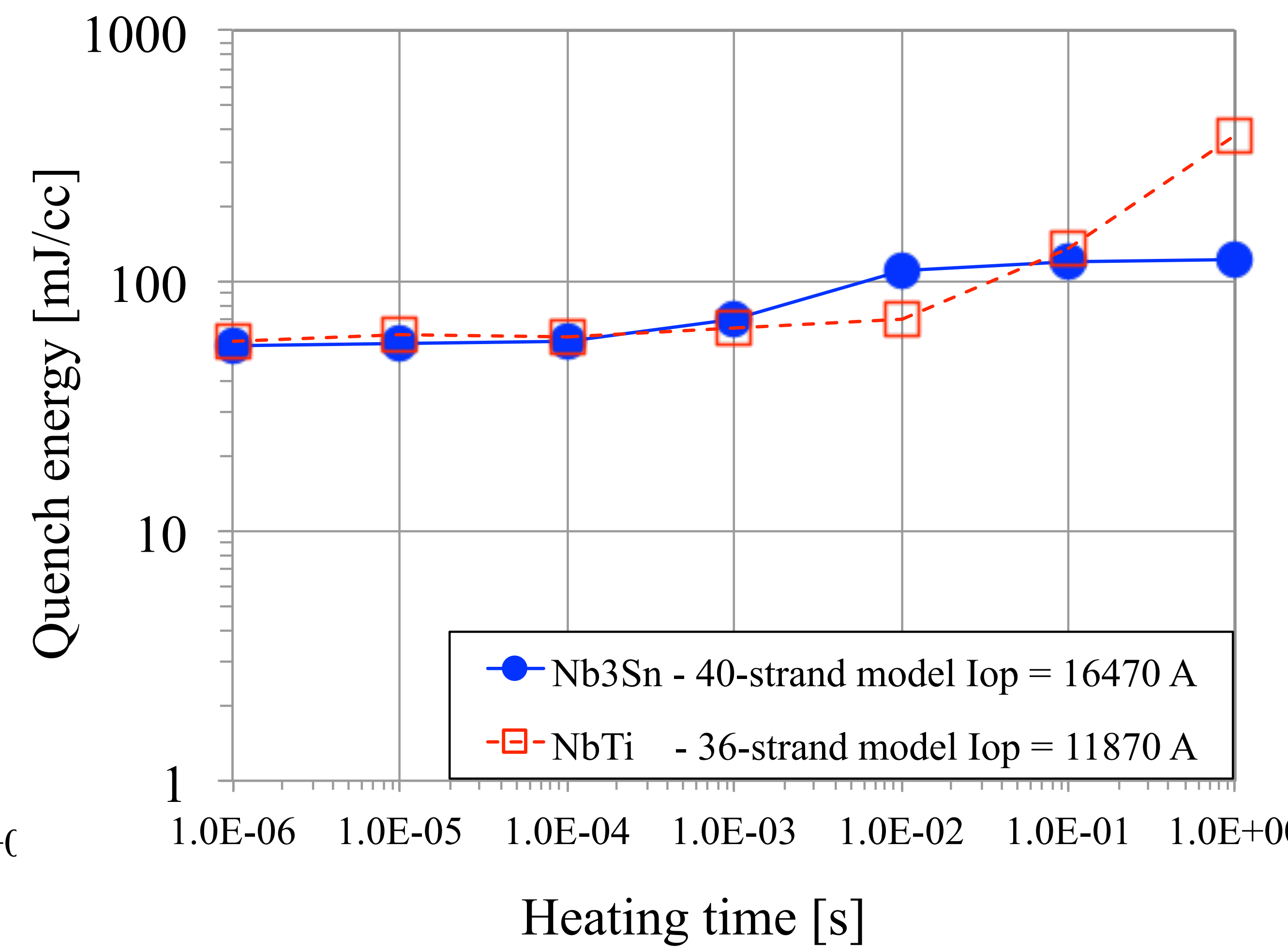
1-D: Nb_3Sn vs NbTi [1]

one-strand model



multi-strand model



- **NbTi exhibits a greater increase** of QEs than Nb3Sn **in the multi-strand model**
- The **NbTi and Nb3Sn cables exhibit comparable values of QEs** at low pulse durations

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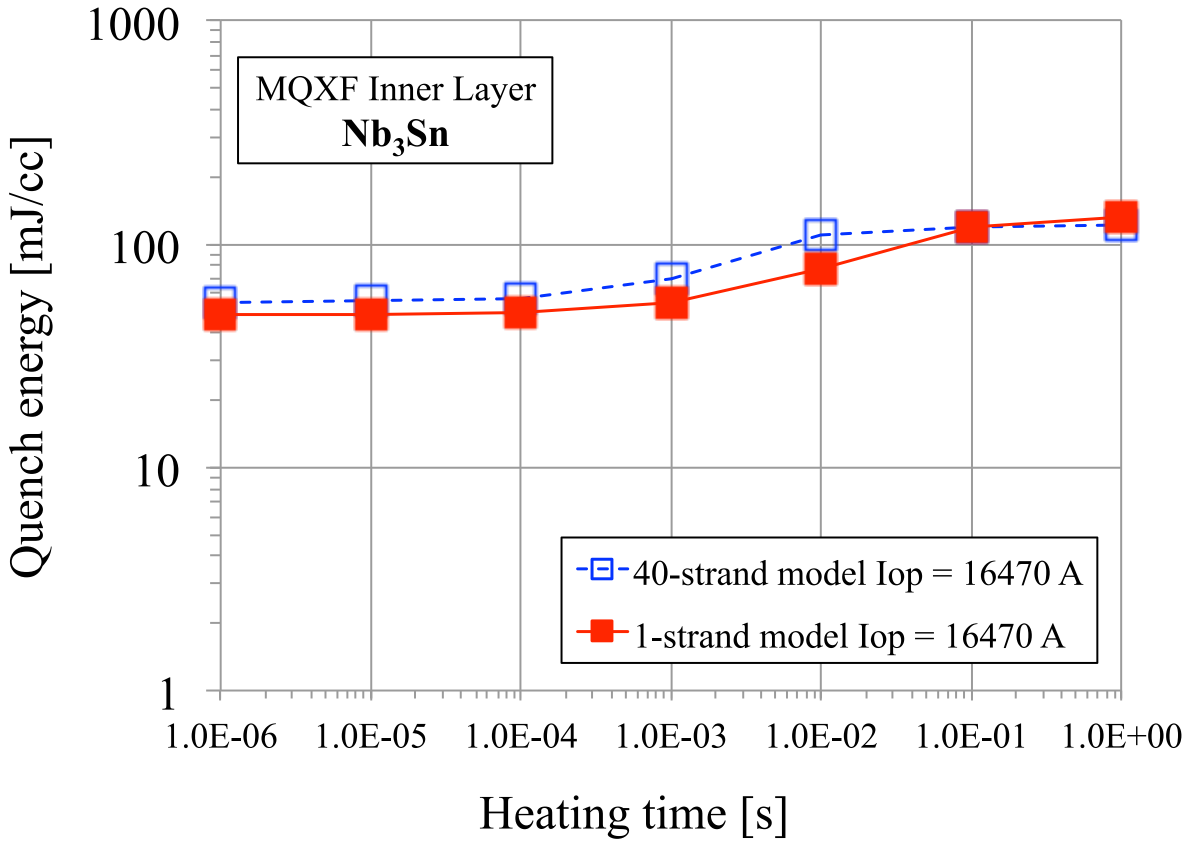
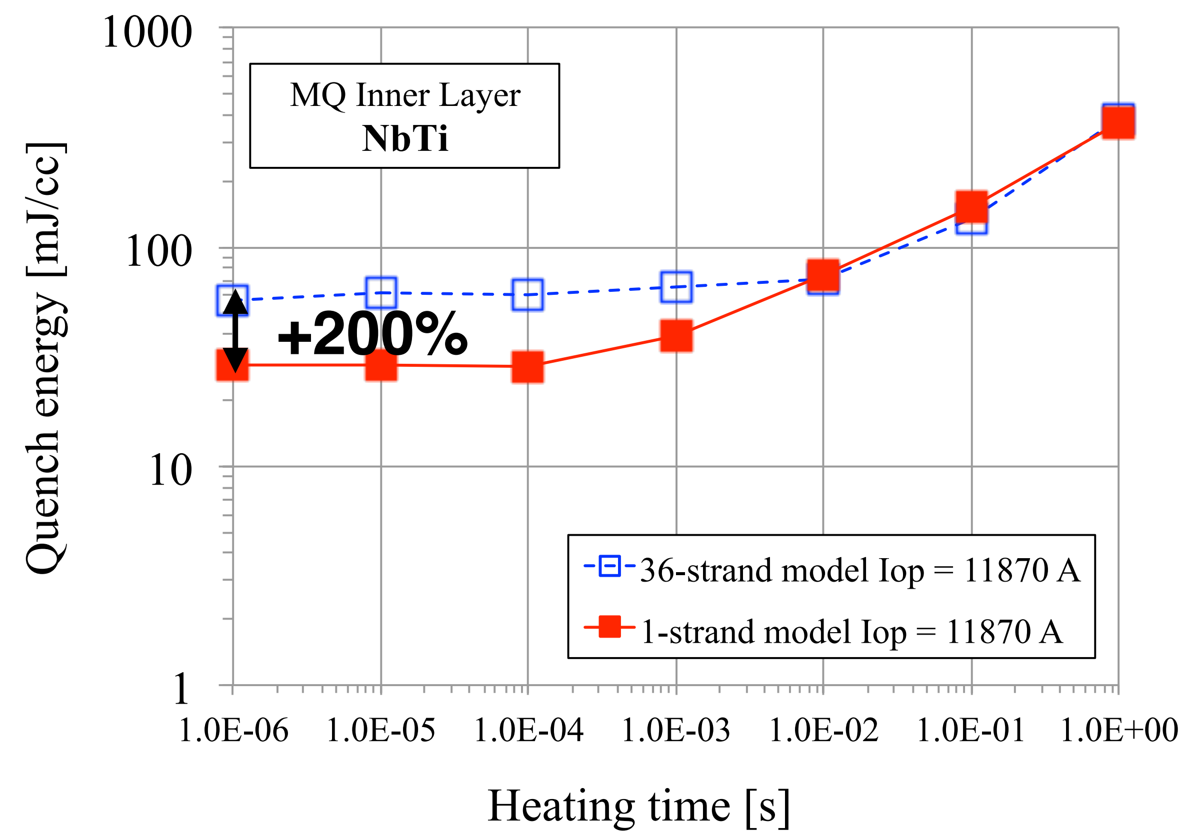
"Quench energy analysis of LHC superconducting cables using a multi-strand, 1D model", IEEE Trans. Appl. Supercond., vol. 25, 4700405, 2015.

1-D: Nb_3Sn vs NbTi [1]





Nb3Sn 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

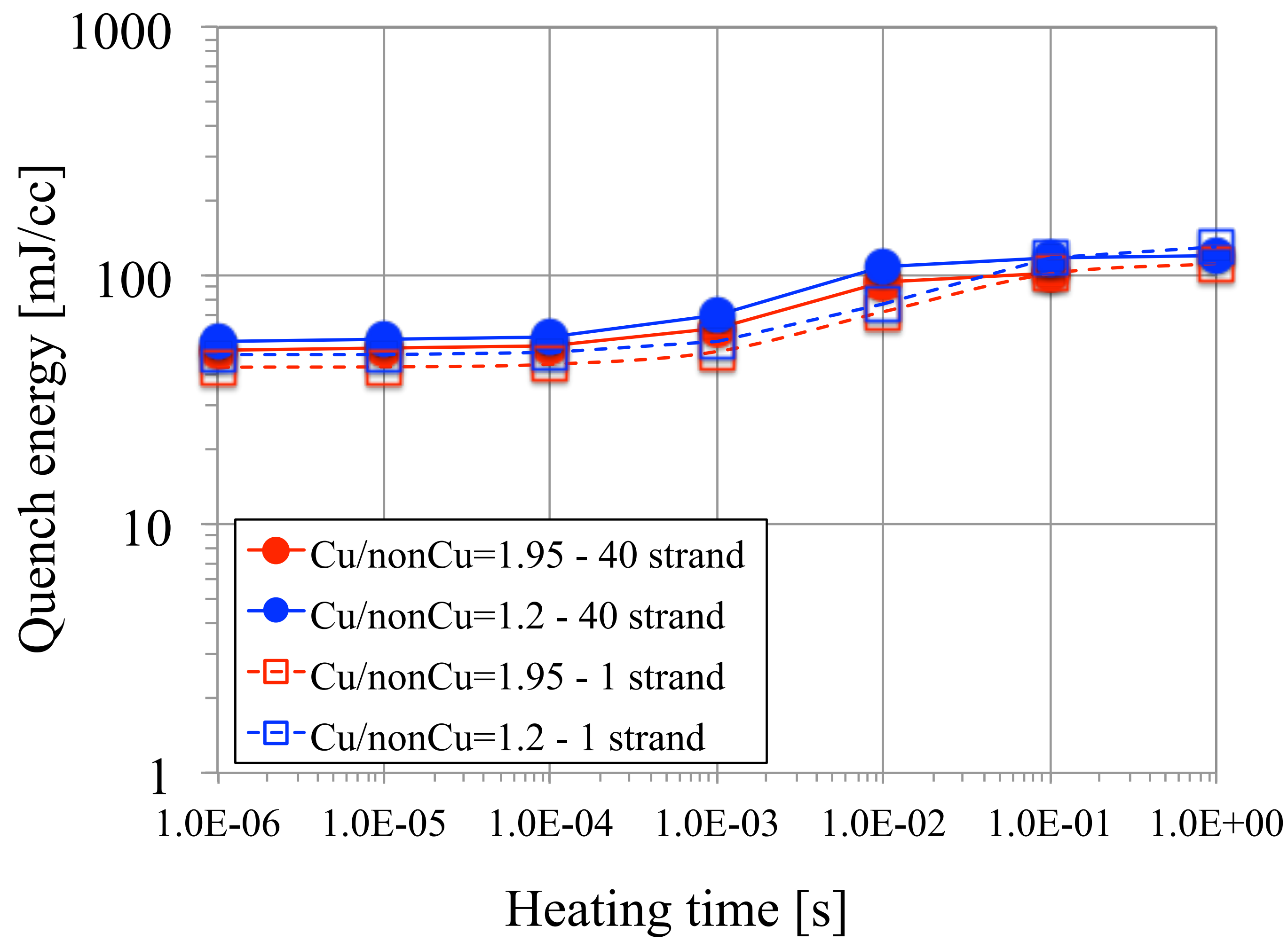
NbTi MQ Cable Data

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

[1] 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.

The Cu/nonCu ratio

- The **thermal conductivity of the copper is much greater** than the one of the superconductors
- We cannot observe a relevant increase of QEs from the one-strand to multi-strand model, due to the different Cu/nonCu ratio



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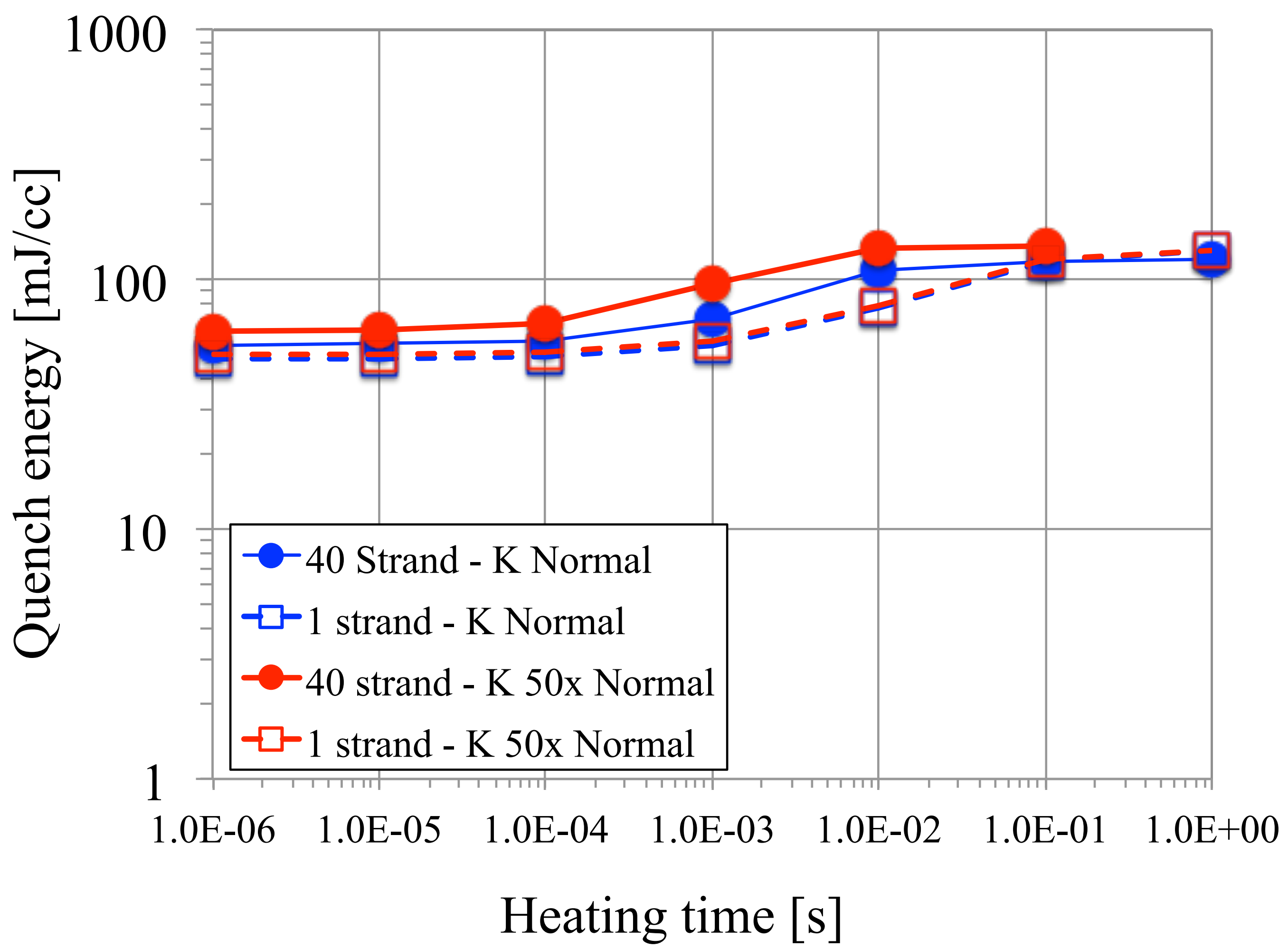
Nb_3Sn thermal conductivity

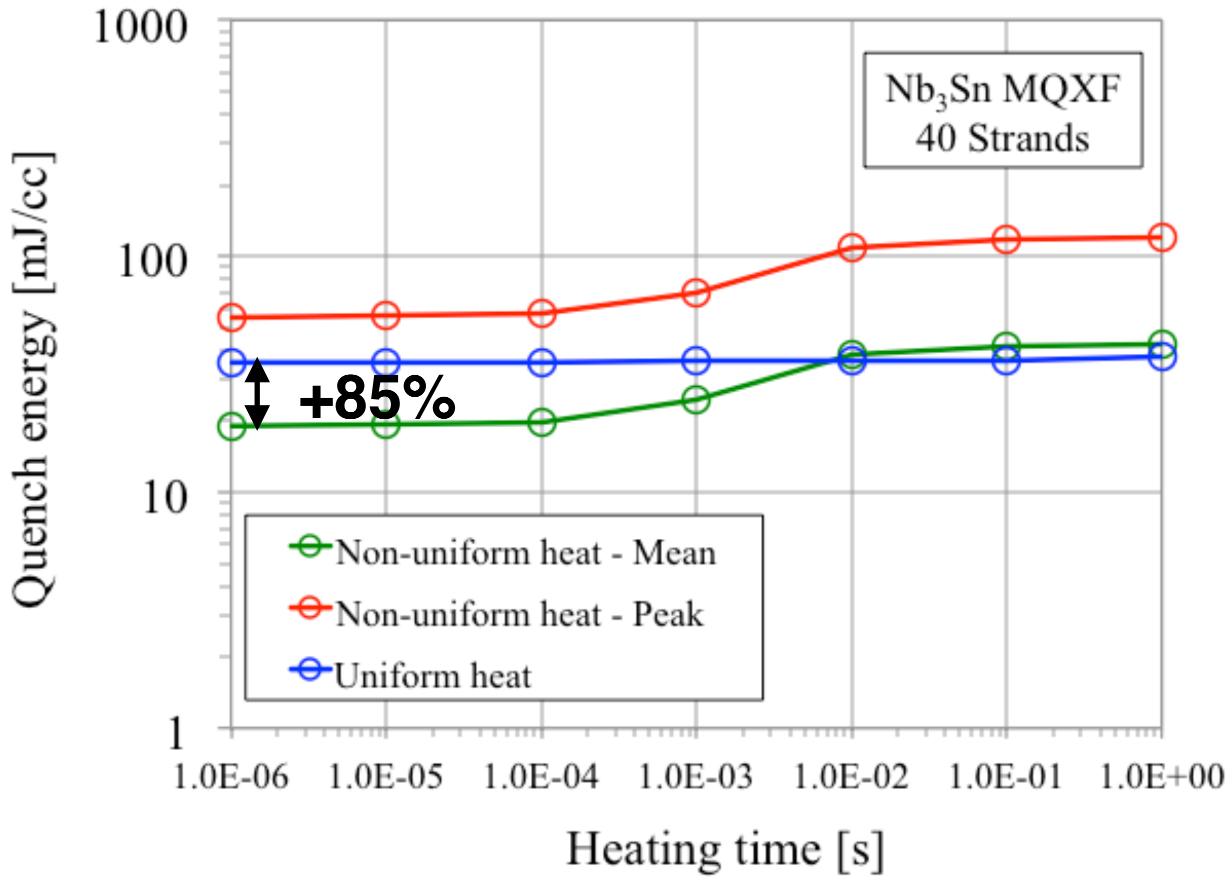
- **Nb_3Sn has a thermal conductivity** one/two orders of magnitude **lower** then the **NbTi** one

- Using comparable thermal conductivity a **strong increase of QEs** from the one-strand to the multi-strand model **is not achievable**

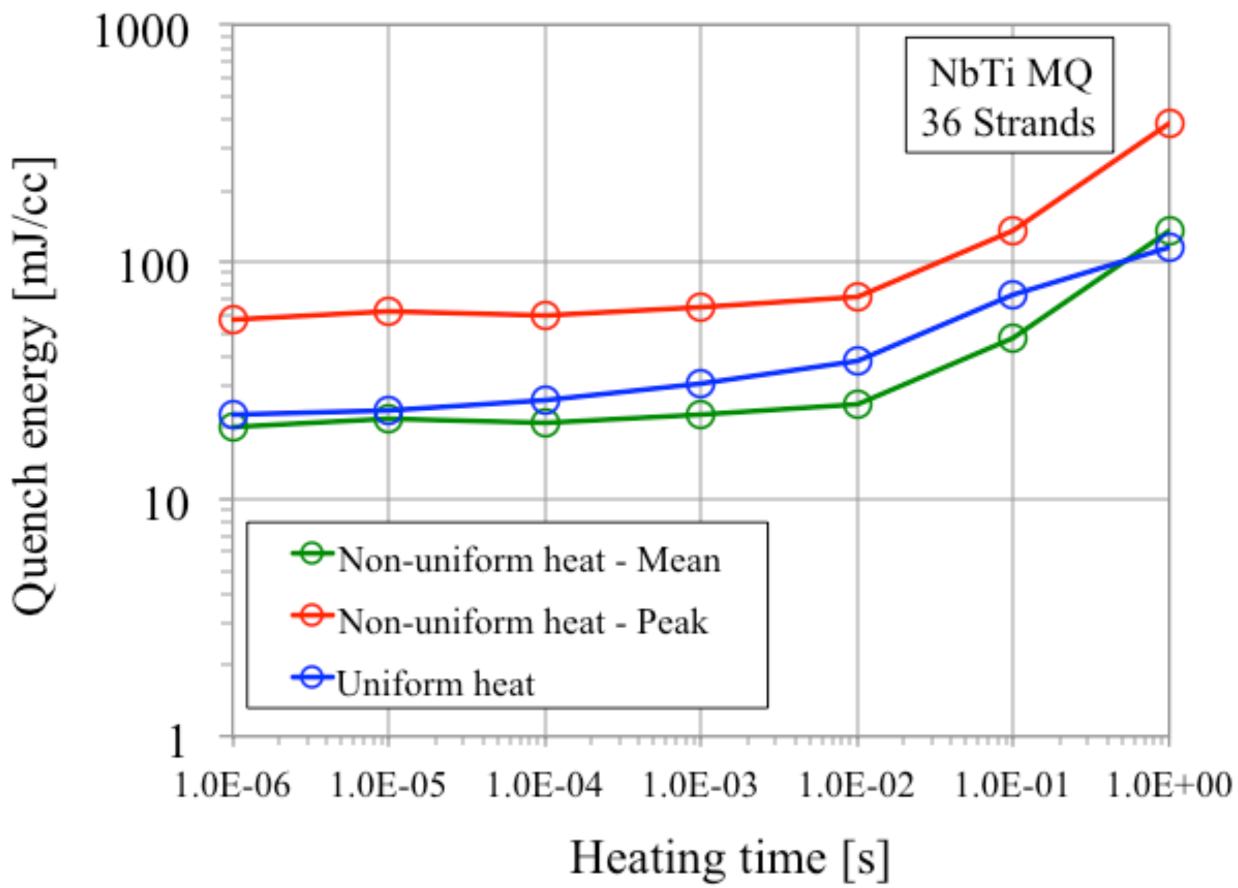


1-D: Nb_3Sn vs NbTi [1]

Nb_3Sn multi -strand model



NbTi multi -strand model



- The **non-uniformity** of the heat deposition has a very **strong impact on the Nb_3Sn**
- The **Nb_3Sn cables are more sensitive to the details** of the non-uniform distribution **of the heat deposition** than the NbTi cables

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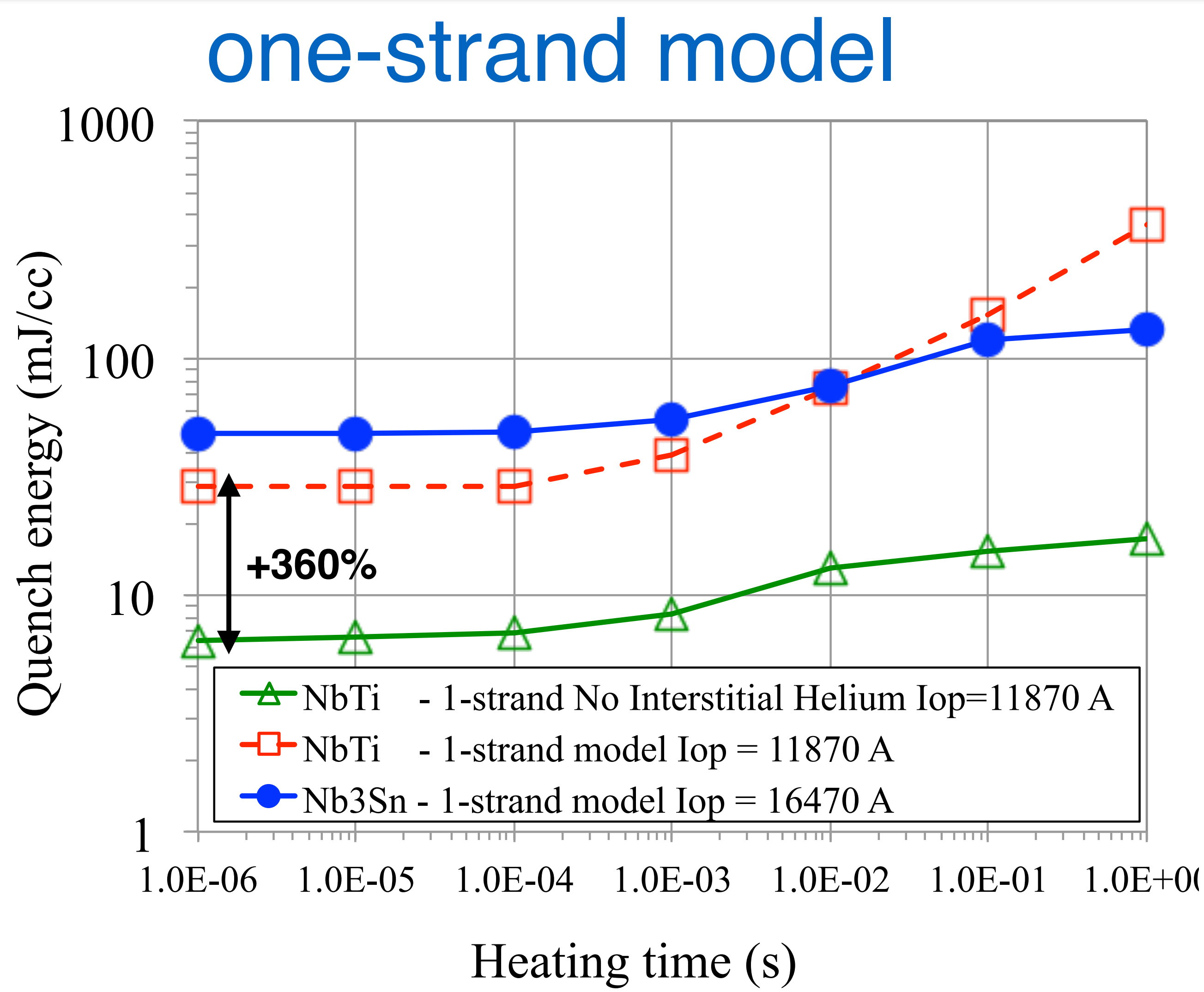
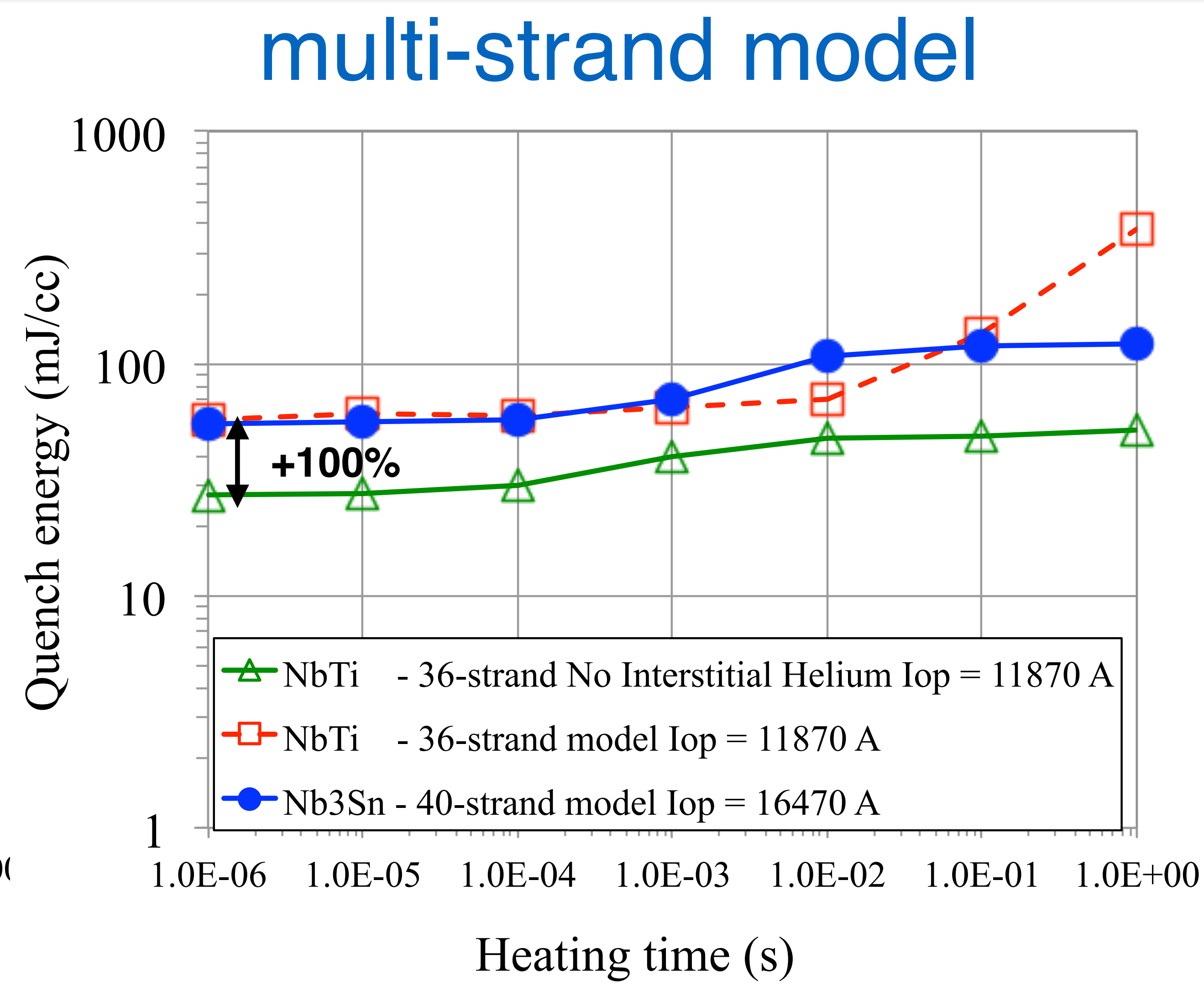
[1] Breschi, A. Bevilacqua, L. Bottura, P. P. Granieri, “Quench energy analysis of LHC superconducting cables using a multi-strand, 1D model”, IEEE Trans. Appl. Supercond., vol. 25, 4700405, 2015.

NbTi with Glass Epoxy





- **A strong decrease of QEs is observed**: a factor 4 for the one-strand model and a factor 2 for the multi-strand model
- The **NbTi interstitial He** gives a strong contribution to the stability margin for long heating times
- The presence of Glass-Epoxy induce the **same trend in Nb_3Sn and NbTi**

CERN High Luminosity LHC

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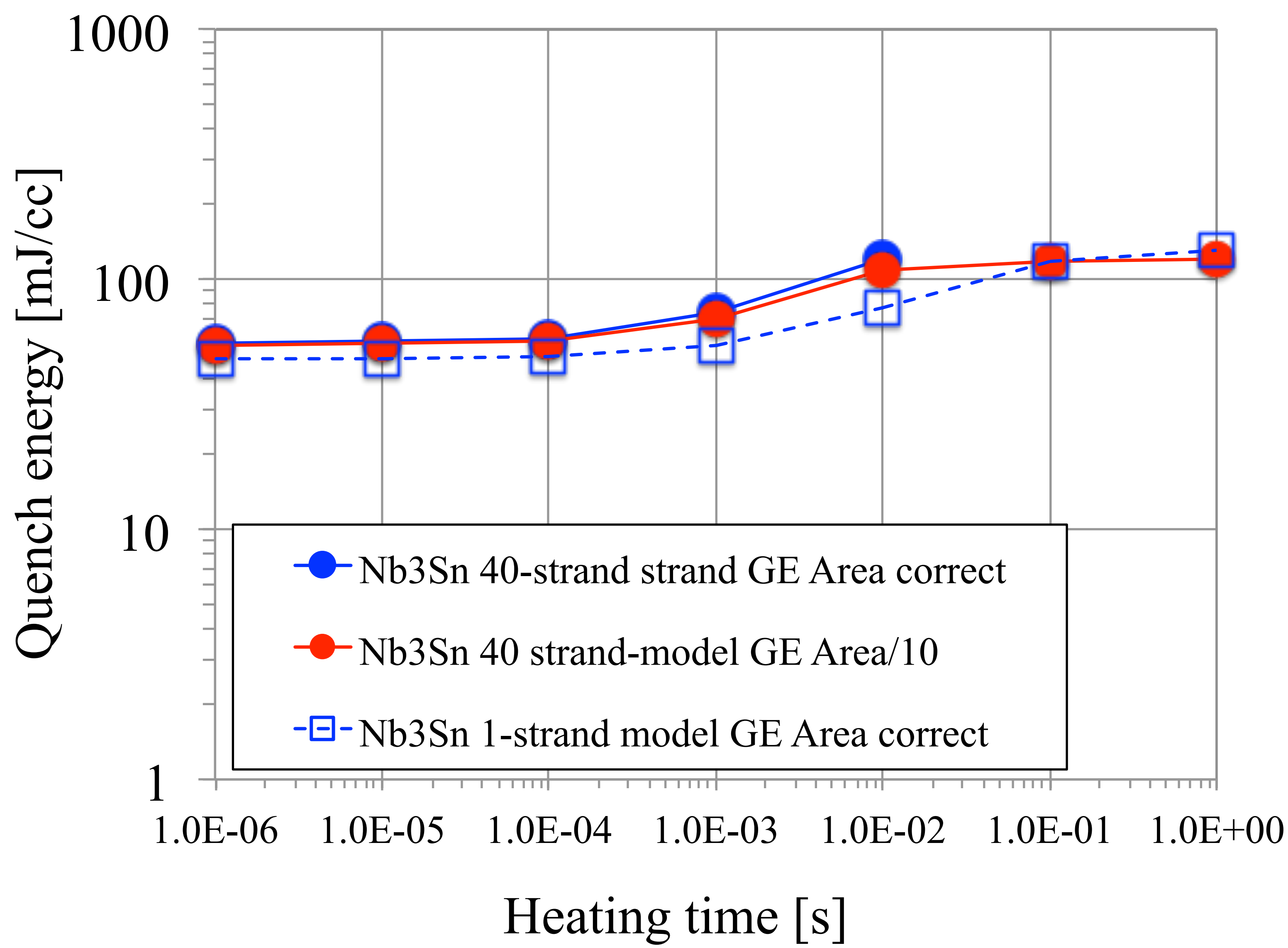
The role of Glass-Epoxy



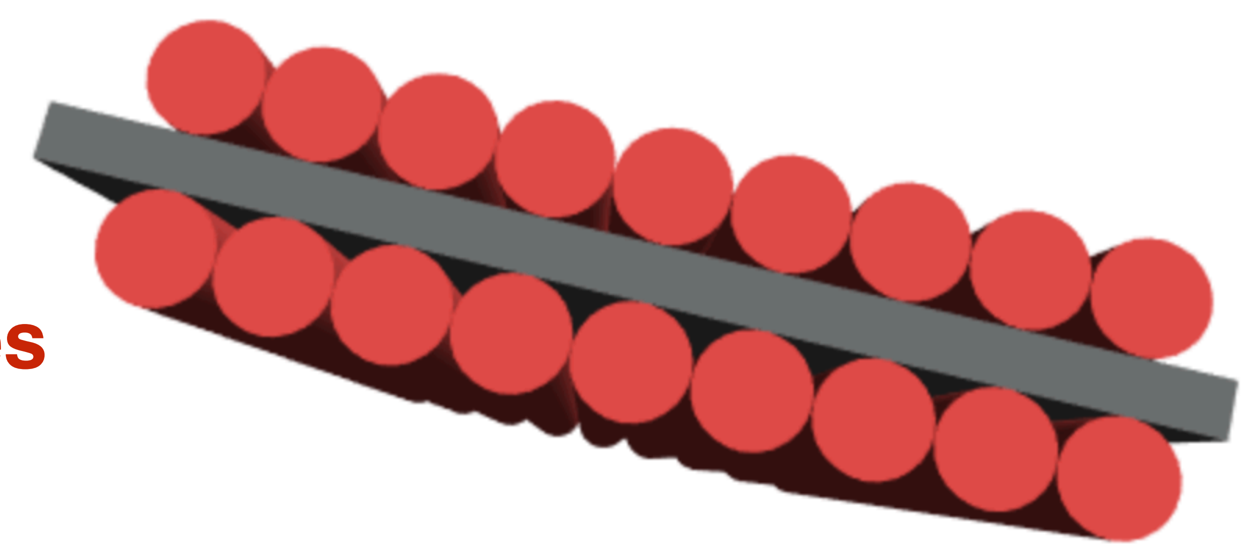
- The **Glass-Epoxy gives a very weak contribution to the stability** of the cable

Nb_3Sn Cored Cable

- **The core** is introduced as a **new thermal element** and represent a thermal “bridge” between all the strands
- **The current is assumed not to flow in the core** in longitudinal direction, due to its high resistance
- Introducing the core means to **increase significantly the electrical and thermal resistances between non-adjacent strands**

CORE

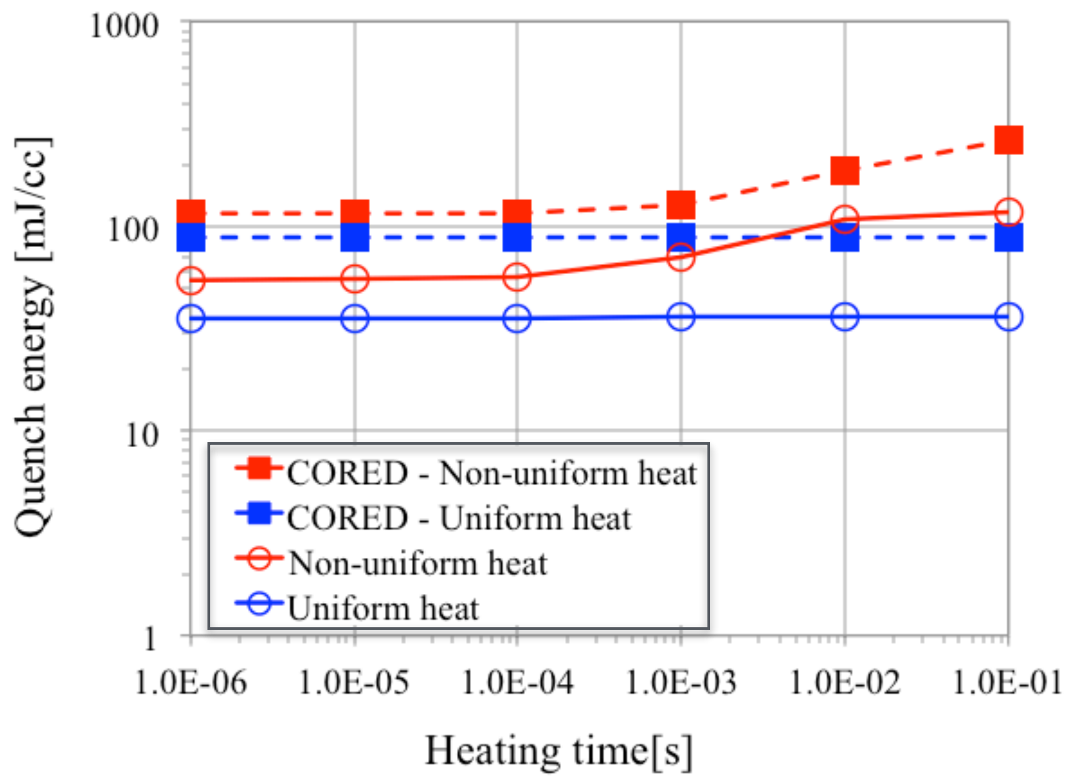
- Stainless steel
- Width: 12 mm
- Thickness: 25 μm



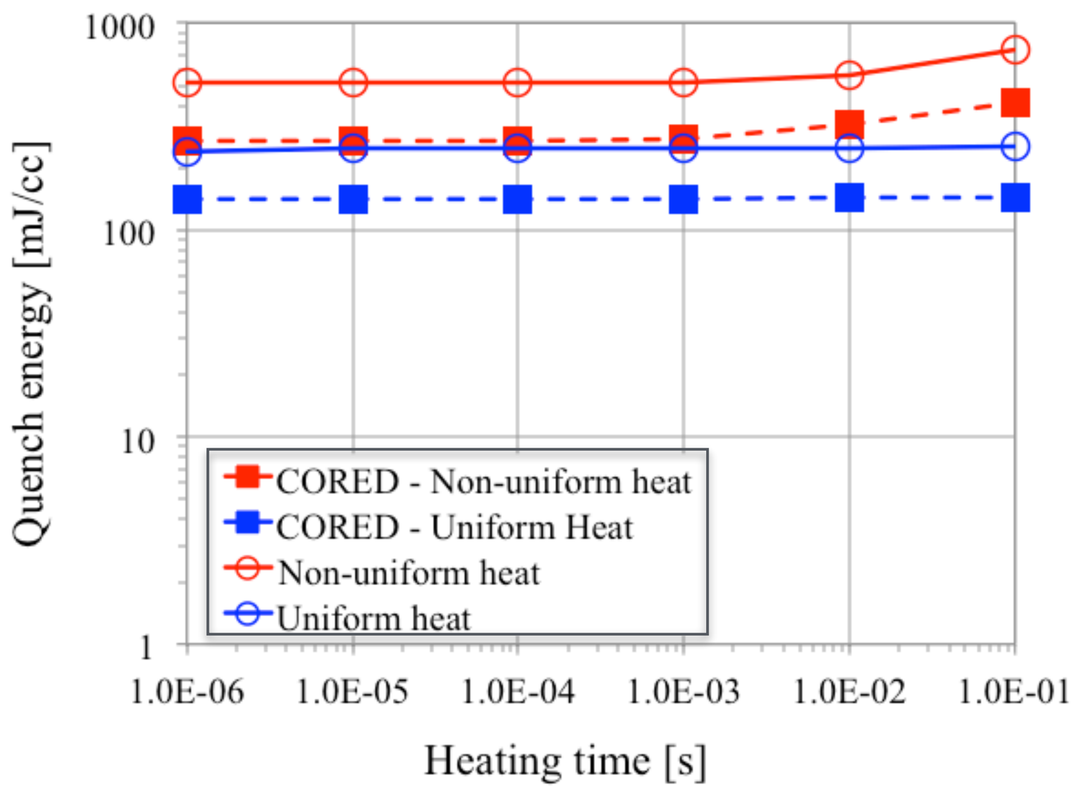
[2] G. Willering, “Stability of superconducting Rutherford cables for accelerator magnets”, Ph. Dissertation, University of Twente, The Netherlands, 2009

Nb_3Sn Cored Cable

100% Operating Current



25% Operating Current



- As expected, a lower stability of the cored cable is obtained at the 25% of the operating current
- Surprisingly, at full current, the cored cable exhibits higher QEs than the cable without core

- The **core represent a thermal link between the strands**: at **100% of** operating **current it is a bridge**, while **at 25% it is a wall**.

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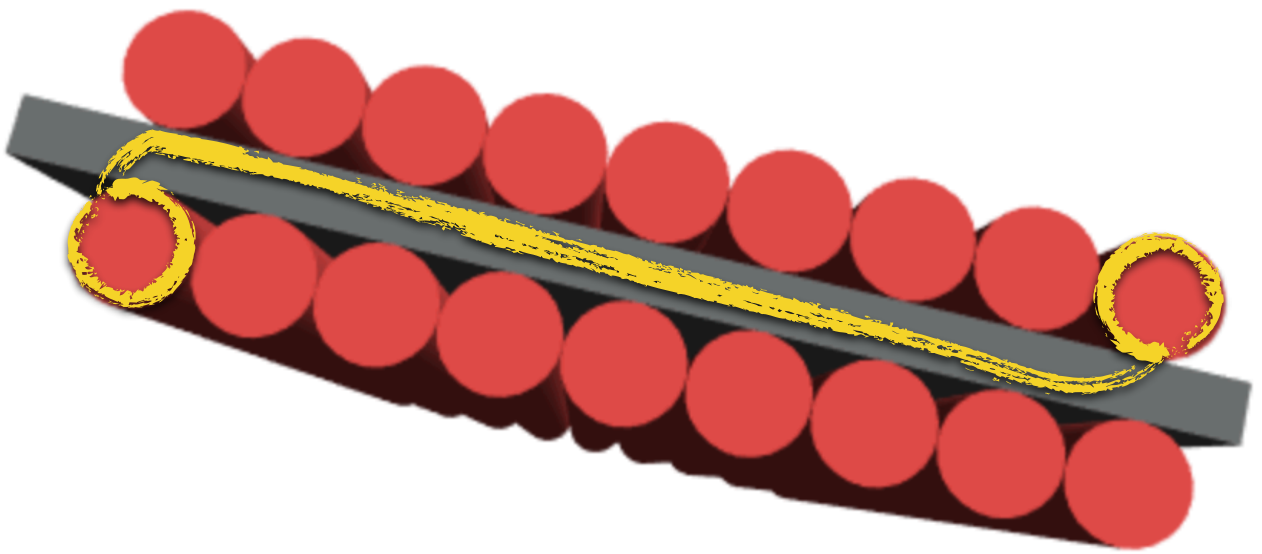
Nb_3Sn Cored Cable

Core as Thermal Element:

- Each non-adjacent strand can **exchange heat only through the core**
- Each strand is using the **whole heat capacity of the core**



Core is **NOT** Thermal Element:

- The **heat capacity of core is not considered anymore**
- The only effect of the core is to **increase the thermal and the electric resistances** between non-adjacent strands

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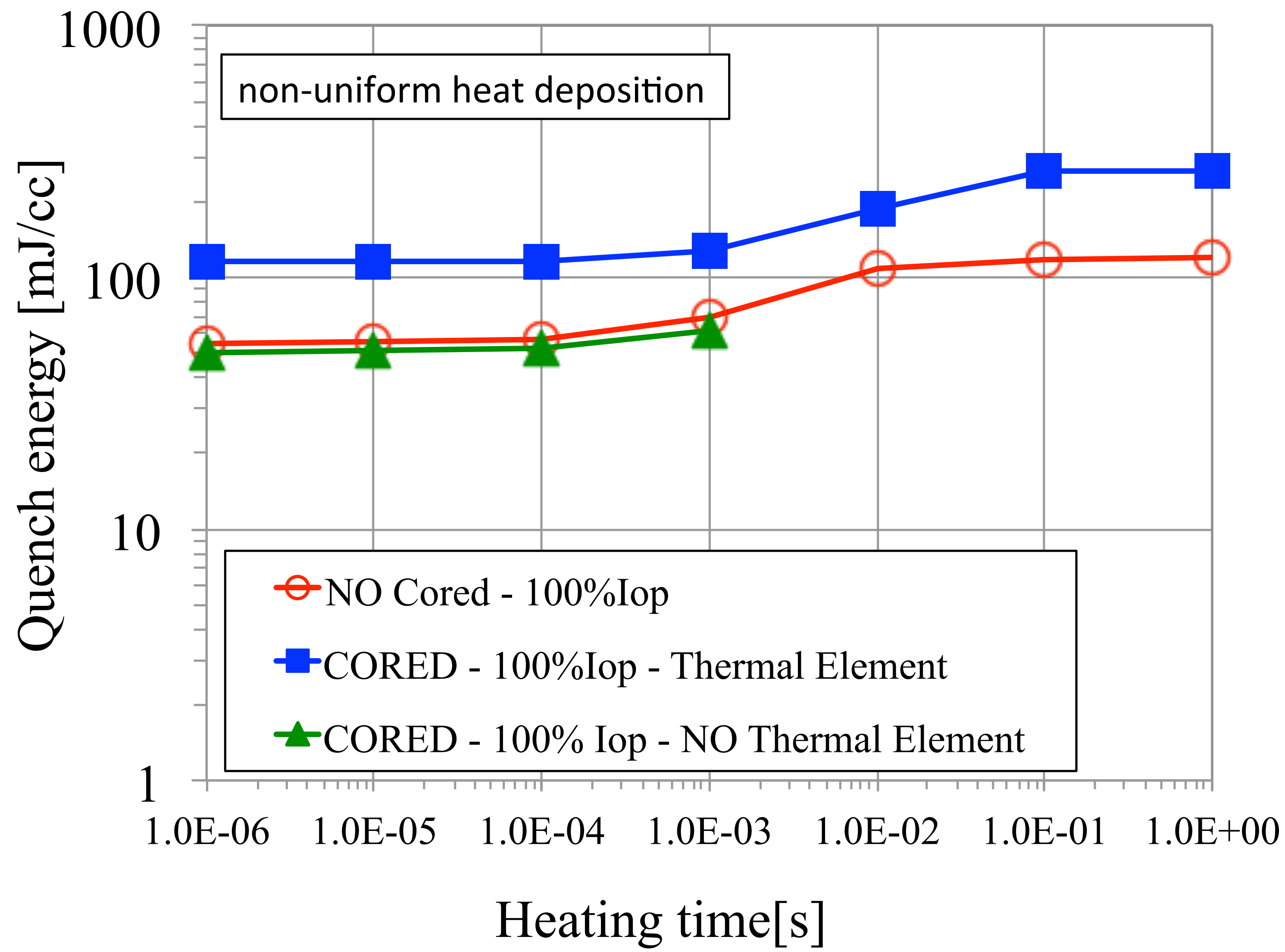
Nb_3Sn Cored Cable

- **If the core is not considered as a thermal element** (NO heat capacity) we cannot observe any variation of the QEs



The **core should be split in several thermal elements**, each one linked with the neighbouring strands

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Summary

- The **stability of the Nb_3Sn cable for Hi-Lumi LHC** has been analysed by means of zero and one-dimensional models

- **The absence of interstitial liquid helium** does not allow significant enhancement of the QE with the duration of the heat disturbance

- **Nb_3Sn** exhibits a **local behaviour** at **fast time scale**, and a **global behaviour** at **slow time scale**

- The areas of the **insulator and stabiliser** do **not seem to affect** significantly the values of **QEs for Nb_3Sn**

- Although the operating conditions are more demanding, **the Nb_3Sn QEs at fast time scale are very close to the NbTi ones**

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Future work

- Introduce the **experimental value for the H**eat **T**ransfert **C**oefficient between the Helium bath and the Nb_3Sn, both **stationary and transient** model

- Implement a **more realistic geometry and parameters** of the strands, of the Glass epoxy and of the core

Compare these results with experimental values

Thank you for your attention

E. Felcini