Numerical analysis of propagation of thermal disturbances in REBCO tapes

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Outline

- Aim of the work and background
- Experimental setup and implications for modeling
- Model
- Simulation setup and rationale
- Model calibration
- Heat slug: experiments and simulations
- Quench tests: experiments and simulations
- Conclusions and perspective

Aim of the work

1. Analyzing the experimental data from tests performed @ KIT on a brass stabilized REBCO HTS tape (for current lead application)
    - heat slugs
    - quench propagation

2. Developing a 1D multilayer numerical model for the simulation of the tests

3. Calibrating/validating the model using/against experimental data

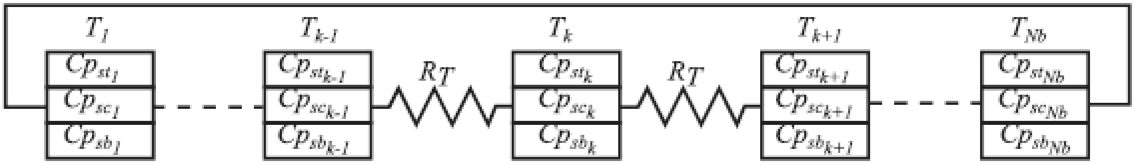
Background (I)

Adiabatic tests of HTS tape with ***Cu stabilizer*** (similar experimental setup, different stabilizer):

- X. Wang et al., Normal Zone Initiation and Propagation in Y-Ba-Cu-O Coated Conductors With Cu Stabilizer. [IEEE TAS, Vol 15, No. 2, June 2005]
  - $I_c(T)$, MQE, NZPV

Models

- D. Colangelo, et al., Analysis of the influence of the NZPV on the design of resistive FCL. [Supercond. Sci. Technol., Vol. 27, 2014]
  - 1D multilayer integral form electro-thermal model, applied to FCL
  - 1D approximation validated against a full 3D model



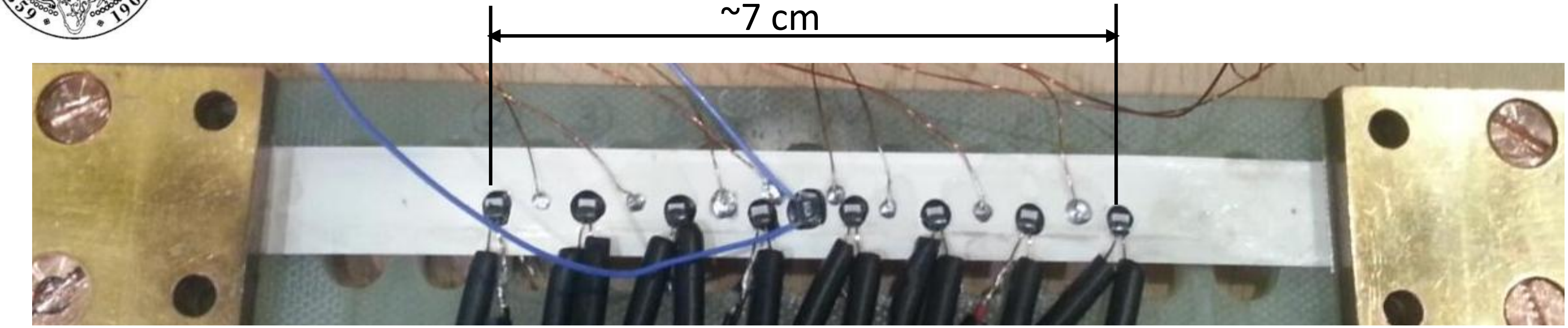
Background (II)

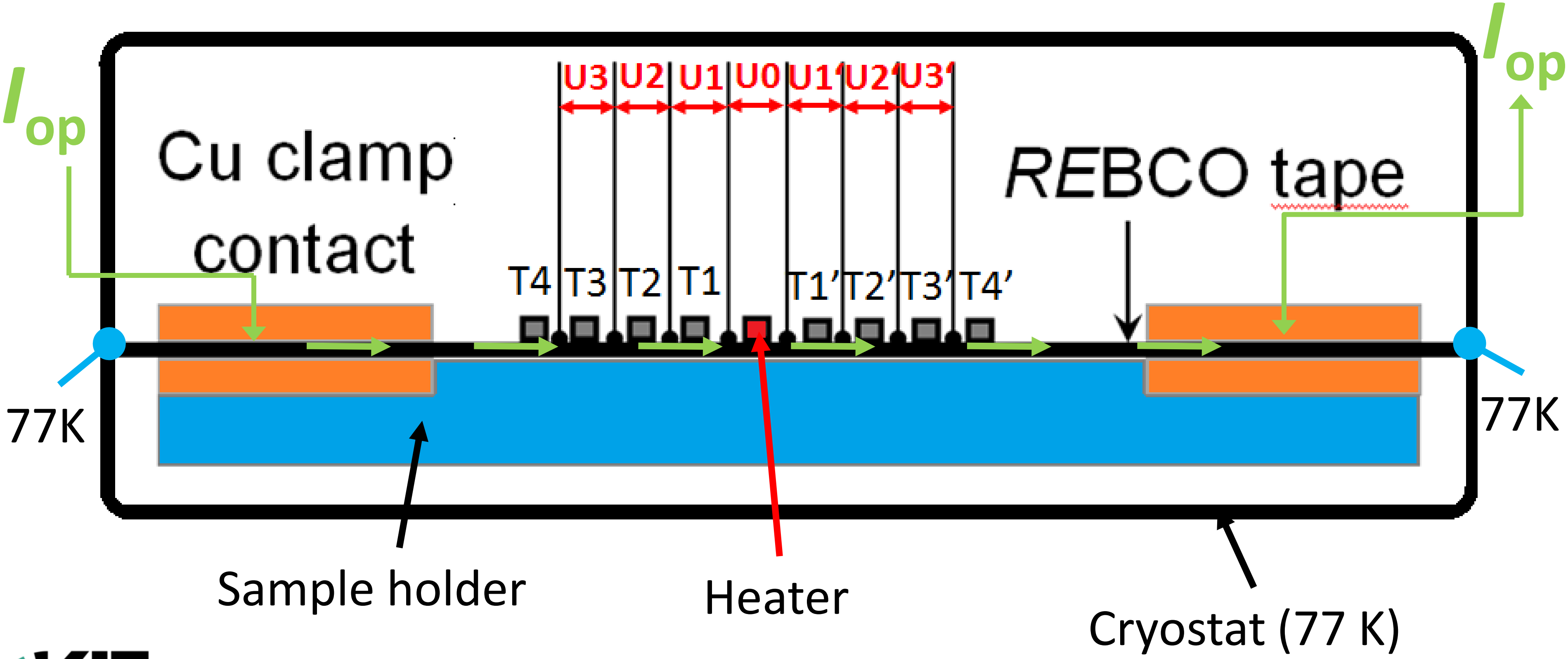
1D single layer models

- G. Celentano, et al., Hot Spot Stimulated Transition in YBCO Coated Conductors Experiments and Simulations. [IEEE TAS, Vol. 19, No. 3, June 2009]
  - MQE, NZPV
  - 1D single layer PDE applied to study quench propagation on 2G HTS: good approximation of V_{taps} far from the heater, but T overestimation

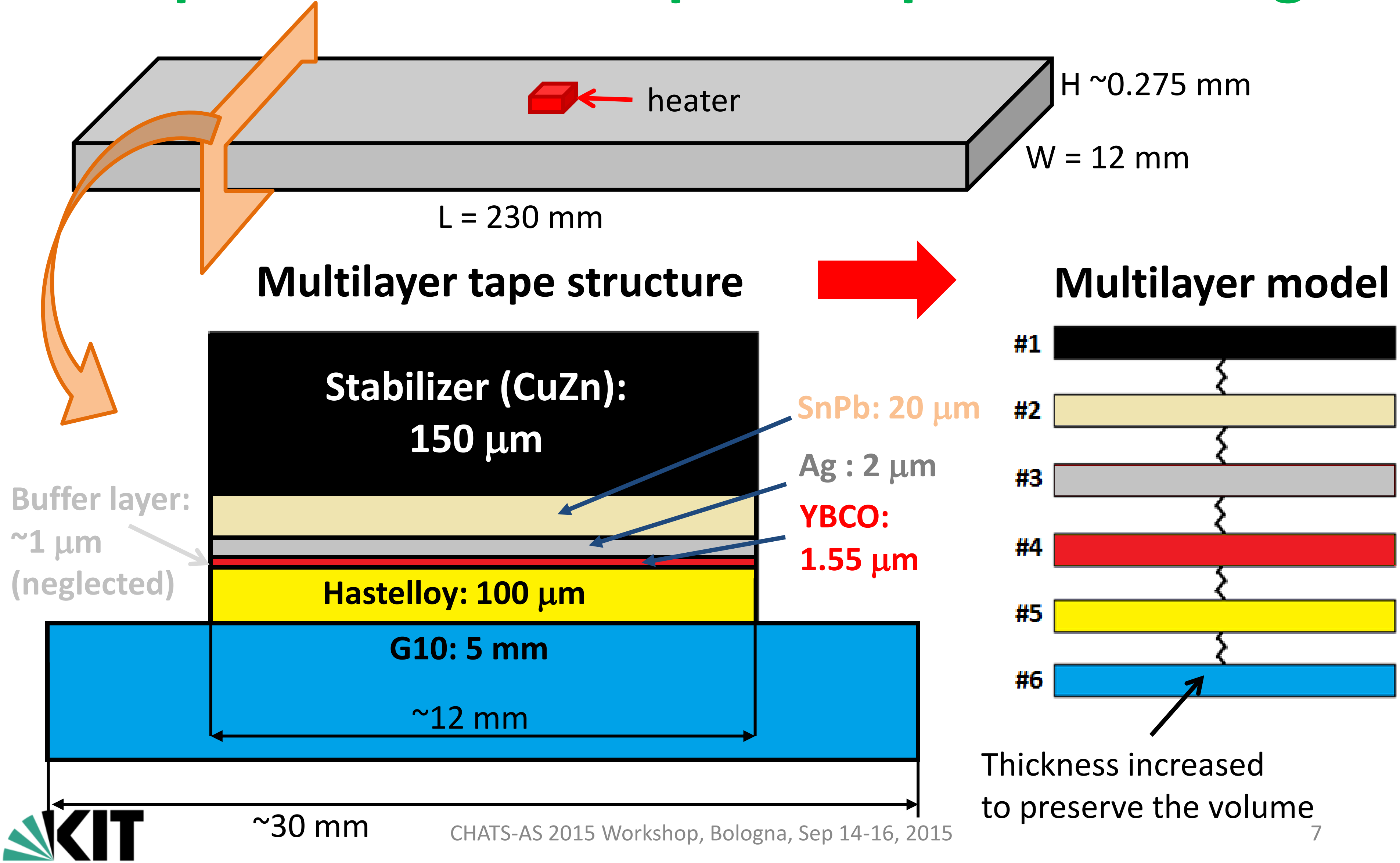
- J. Pelegrín, et al., Numerical and experimental analysis of normal zone propagation on 2G HTS wires. [IEEE TAS, Vol 21, No. 3, 2011]
  - 1D single layer solved with FEM to study quench propagation

Experimental setup





The tape: implications of sample setup to modeling



H ~0.275 mm

W = 12 mm

L = 230 mm

Multilayer tape structure

Multilayer model

Stabilizer (CuZn): 150 μm

SnPb: 20 μm

Ag : 2 μm

YBCO: 1.55 μm

Buffer layer: ~1 μm (neglected)

Hastelloy: 100 μm

G10: 5 mm

~12 mm

~30 mm

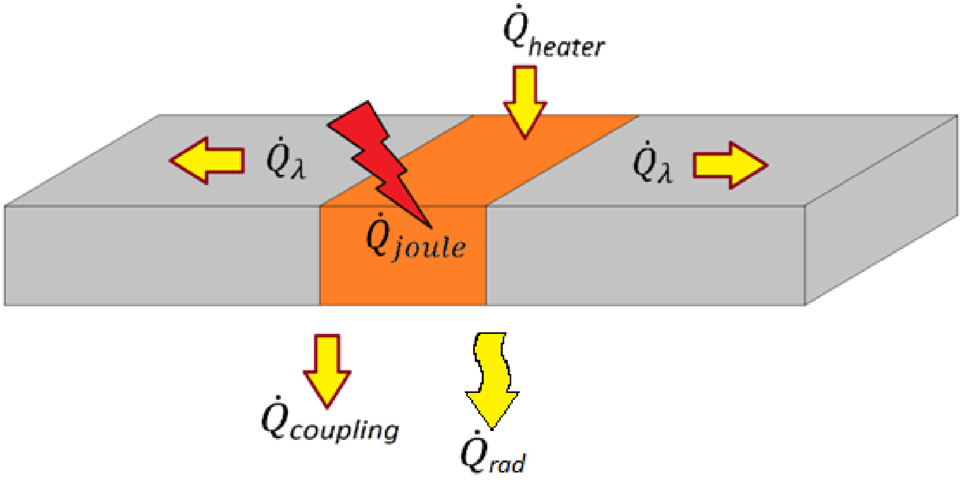
Thickness increased to preserve the volume

Model (I): Thermal

- 1D (along the tape) energy conservation law FOR EACH LAYER

$$c_p(T)\rho(T)\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)+Q_{joule}-Q_{rad}+Q_{heater}+Q_{coupling}^{in}-Q_{coupling}^{out}$$

Need calibration



- Finite differences and implicit time scheme
- Linearization (frozen coefficients)

Model (II): Electrical

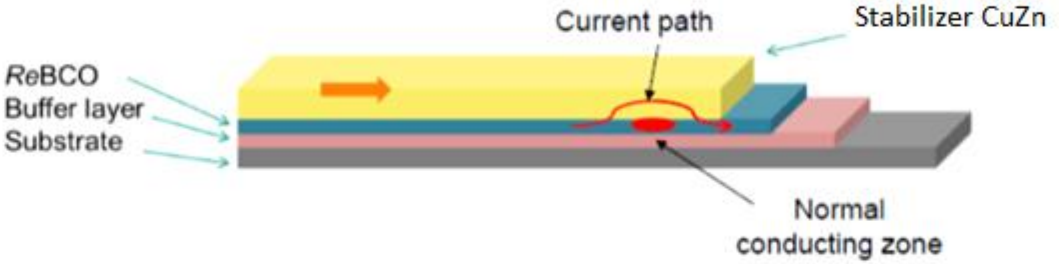
- To evaluate the J_C (and T_{cs}) use the linear approximation:

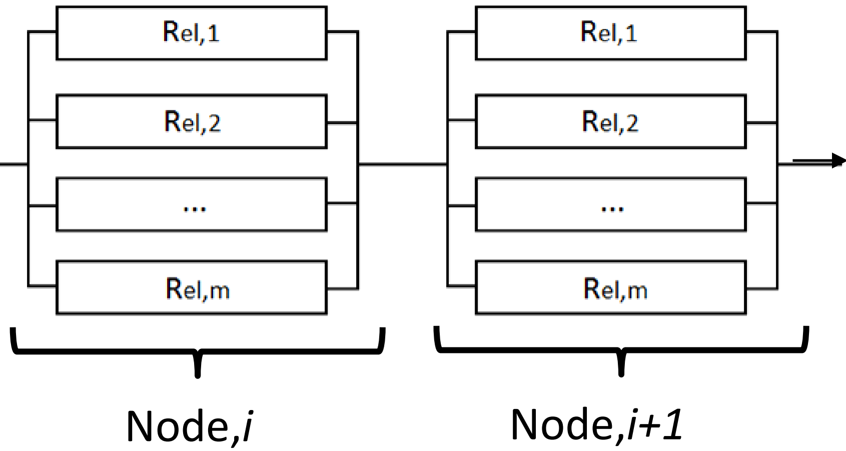
$$J_C(T) = J_{C,0}\frac{T_C - T}{T_C - T_0} \qquad T_{CS} = T_C - (T_C - T_0)\frac{J_{op}}{J_{C,0}}$$

[Y. Iwasa, Case Studies in Superconducting Magnets Design and Operational Issues, 2nd Edition Springer 2009]
[G.A. Levin, et al., Stability and Normal Zone Propagation Speed in YBCO Coated Conductors With Increased Interfacial Resistance, IEEE TASC, Vol 19, No. 3, 2009]

- For $T(x) > T_{CS}$, apply repartition law for parallel resistances (for $I = I_{op} - I_c(x)$):

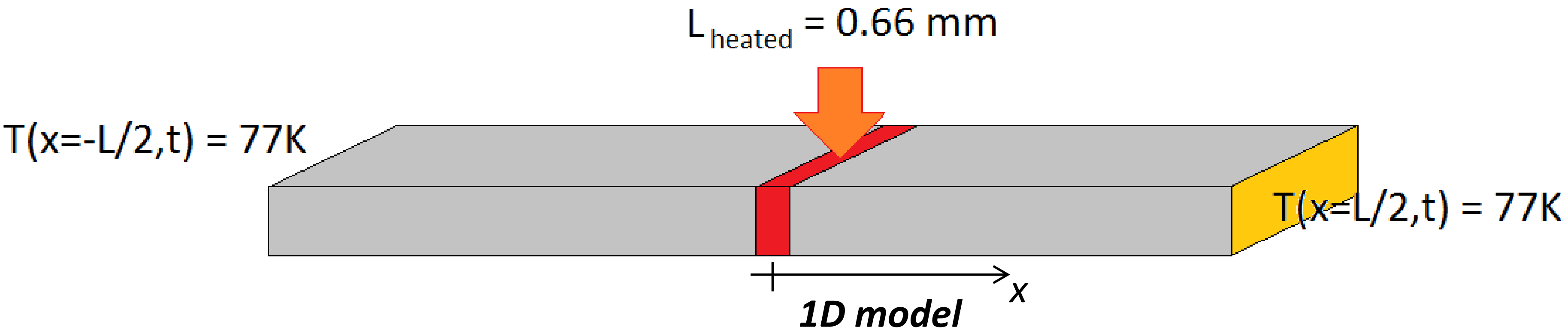
$$I_k = \frac{1/R_{el,k}}{\sum_i 1/R_{el,i}} I_{tot}$$





Simulation setup and rationale

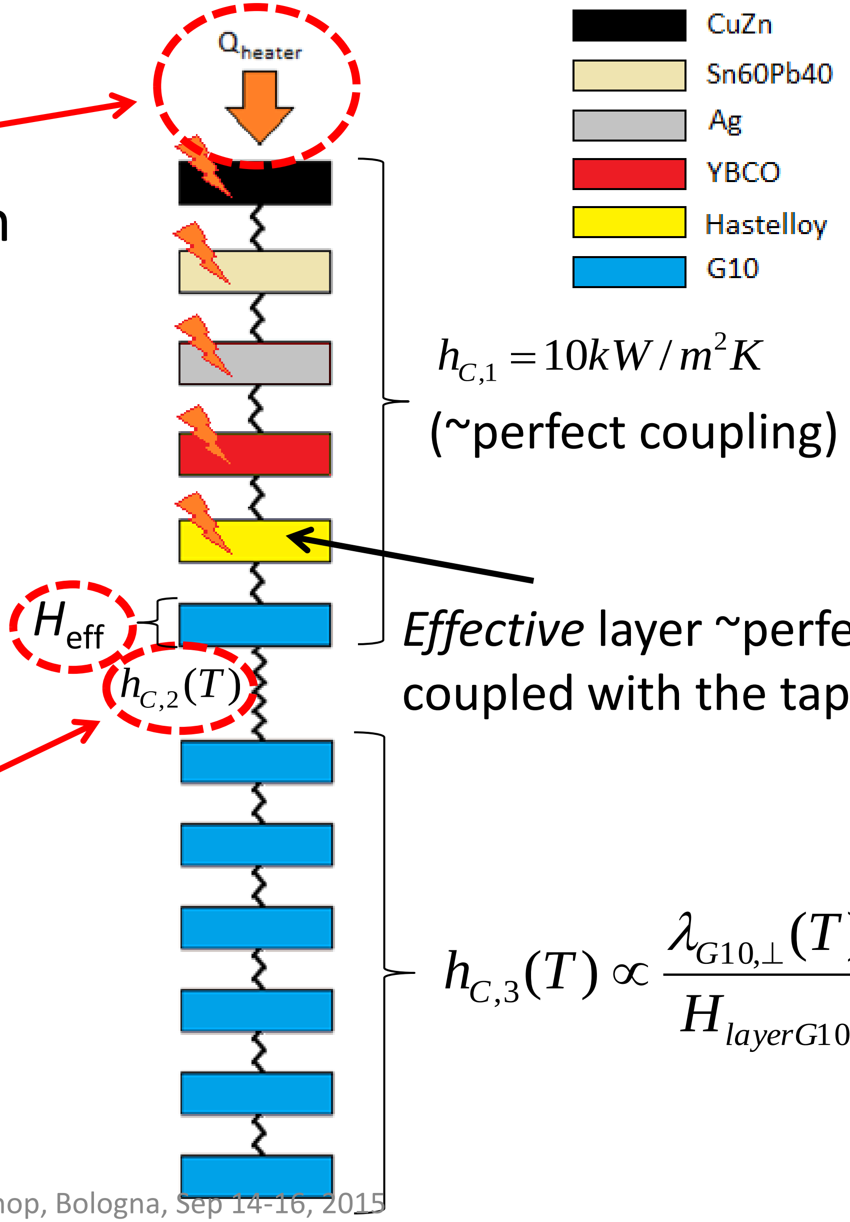
- Initial condition: $T(x, t=0) = 77$ K
- Boundary conditions: $T(x=\pm L/2, t) = 77$ K
- At t=0: switch on the heater for 0.1 s



- Calibrate model parameters on 1 heat slug out of 5
- Validate the model (freezing the calibrated parameters) against
  - other 4 heat slug tests
  - quench (I_{op} = 160 A)

Calibration of the model

- Radiative losses, conduction through wires, glue → calibration of the heater efficiency
- Uncertainty in the manual clamping of the tape to the holder → calibration of
  - *effective* layer thickness (guarantees correct diffusivity)
  - coupling between *effective* layer and the rest of the G10 (thermal losses)



$$h_{C,1} = 10kW/m^2K$$

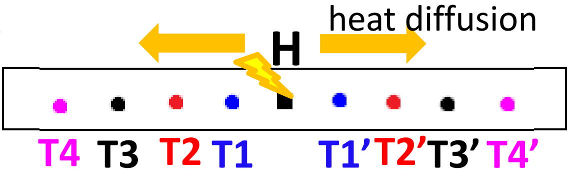
(~perfect coupling)

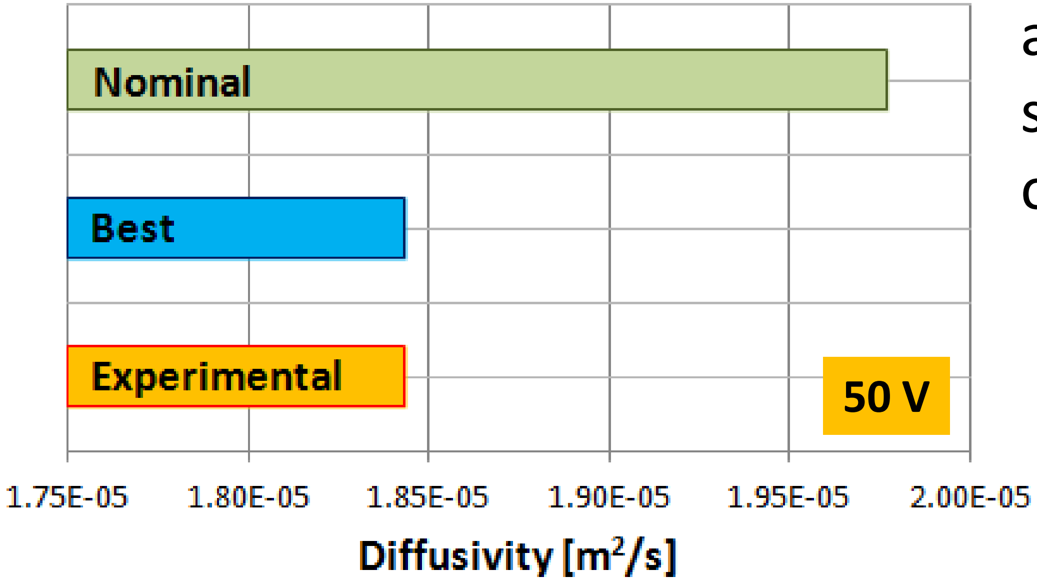
Effective layer ~perfectly coupled with the tape

$$h_{C,3}(T) \propto \frac{\lambda_{G10,\perp}(T)}{H_{layerG10}}$$

Calibration of the H_{eff}

Nominal tape diffusivity (from thermophysical properties) ≠ *experimental* (from T_{peak} propagation)





→ Calibrate the *effective* thickness of layer H_{eff} of G10 plastic to guarantee correct average tape diffusivity starting from exp behavior of T1' sensor

$$\alpha = \frac{\Delta x^2}{t_{peak,1}}$$

H_{eff}

Calibration on 50 V shot (slug with the highest energy)

Calibration of heater efficiency

The energy deposited in the tape is obtained through *calorimetric* estimation of internal energy → *T* profile is required

Gaussian fitting for the temperature measurements at peak times

$$\Delta T_{gauss} = a \cdot \exp(-bx^2)$$

- Internal energy:

$$E_{tape} = \left(\overline{\rho c_p}\right) W H \int_{-L/2}^{L/2} \Delta T_{gauss}(x)\,dx$$

W and *H* are the width and height of the tape respectively.

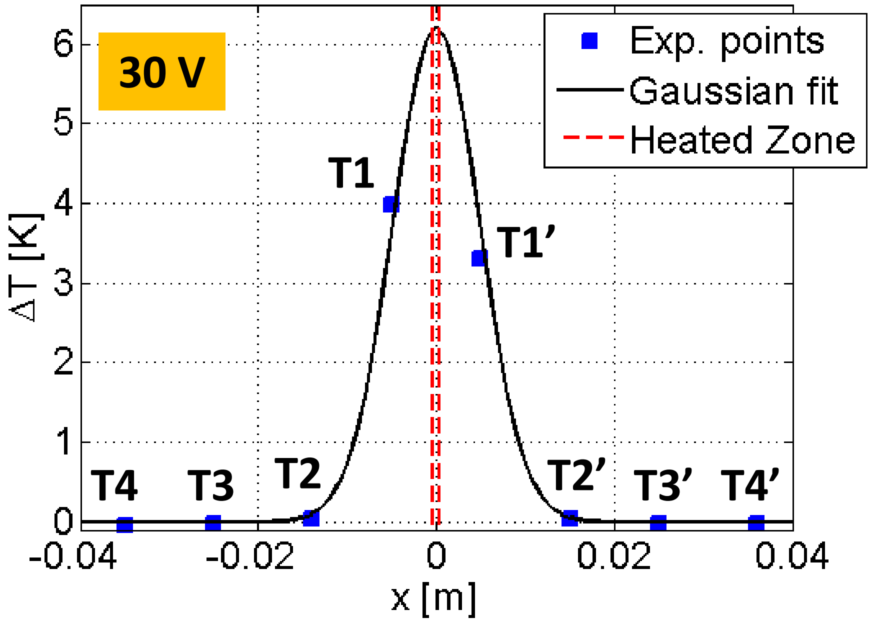
- Energy in the heater:

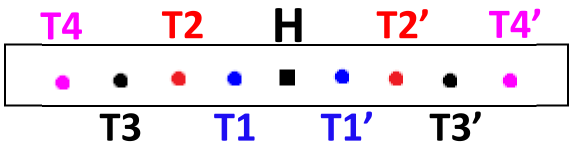
$$E_{nom} = \int_0^{t_{heater}} V_{heater}(t) I_{heater}(t)\,dt$$

Performed for all the cases → mean efficiency:

$$\boxed{\eta = \frac{E_{tape}}{E_{nom}}} \rightarrow \boxed{<\eta_{heater}>\tilde{=}\ 0.7 \pm 0.035}$$

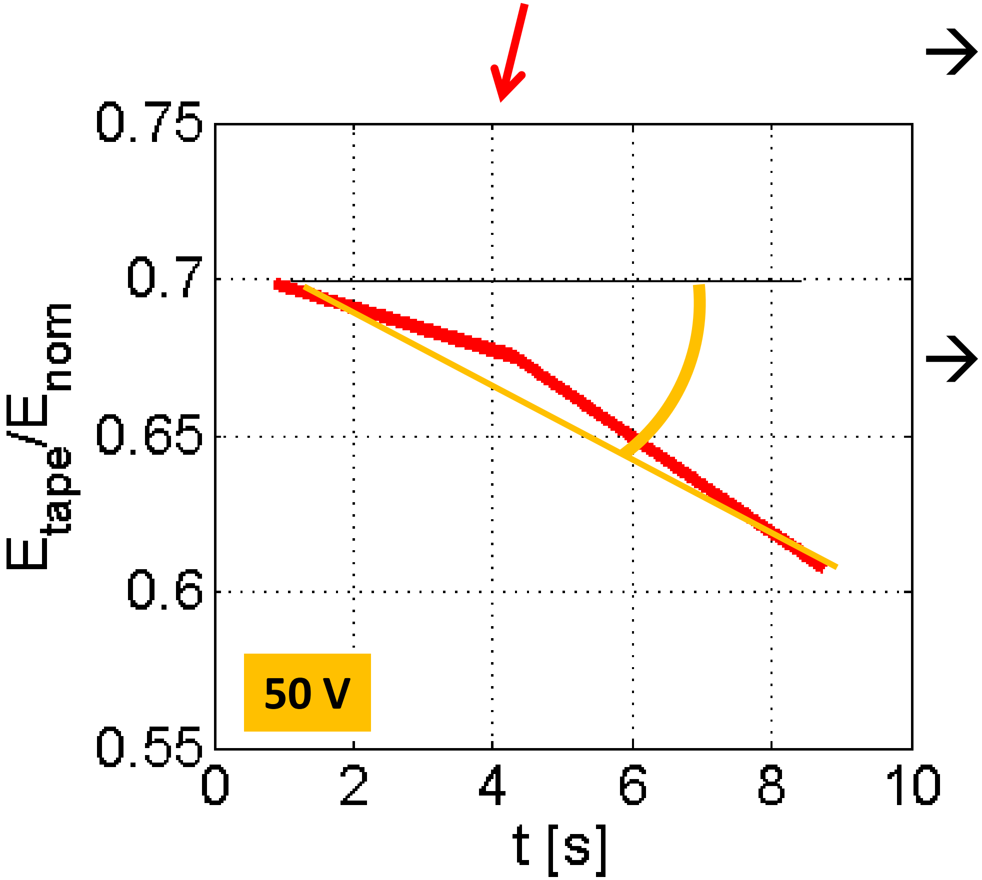
Gaussian fitting at T1' peak time





Calibration of the thermal losses

Analysis of experimental data → energy in the tape decreases in time → thermal losses to the sample holder



→ linear interpolation of energy value of the tape in time (calibration performed <u>on 50 V shot</u>)

→ angular coefficient = q_{loss}

$$q_{loss} = \frac{dE}{dt} = h_{c,2} W H \int_{-L/2}^{L/2} \Delta T(x)\,dx$$

$$\Rightarrow h_{c,2}$$

Heat transfer coefficient

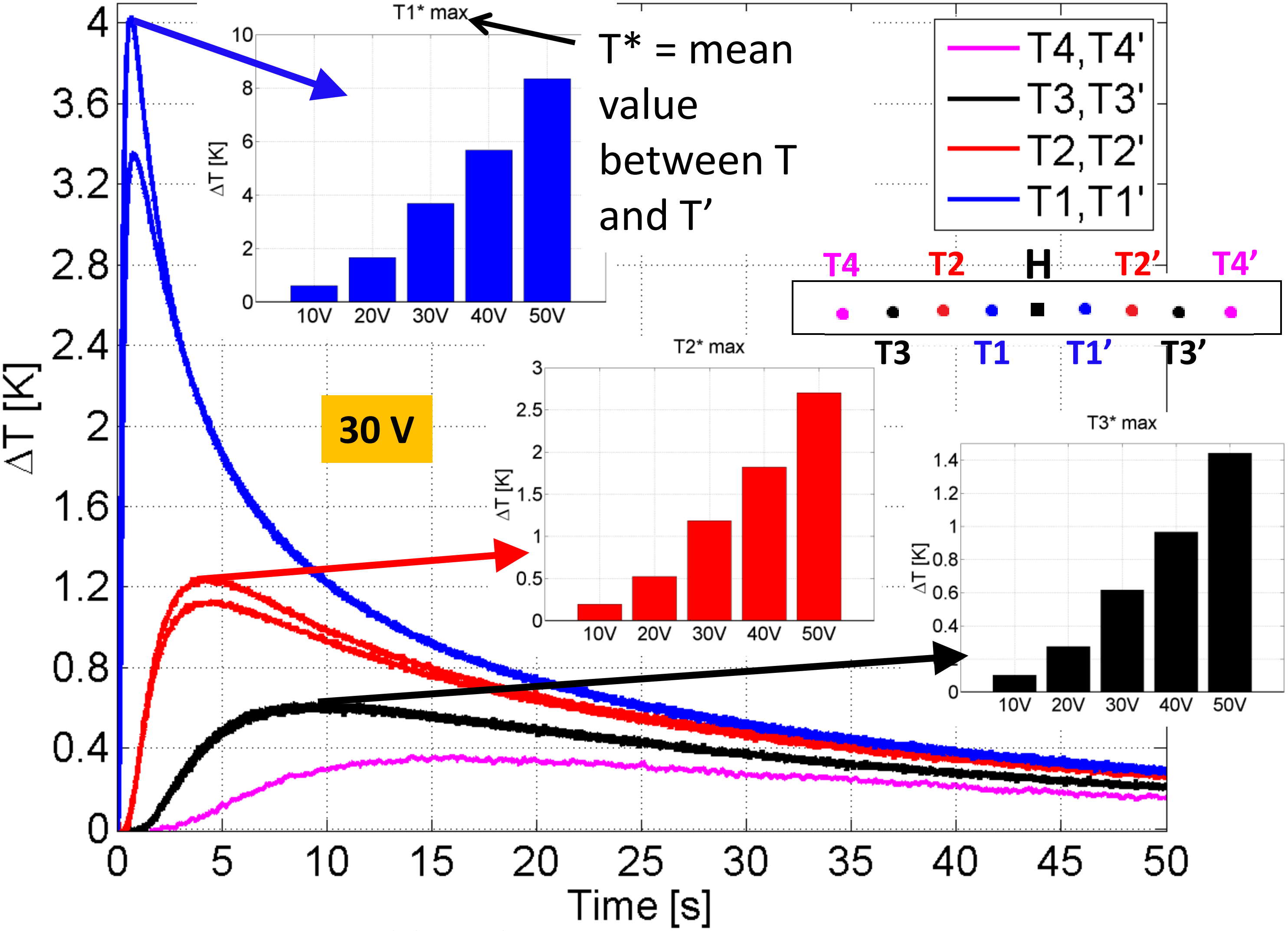
scaled according to $\frac{\lambda_{G10,\perp}(T)}{\lambda_{G10,\perp}(T_0)}$

Heat slug tests: experiment

5 heat slugs @ different power.

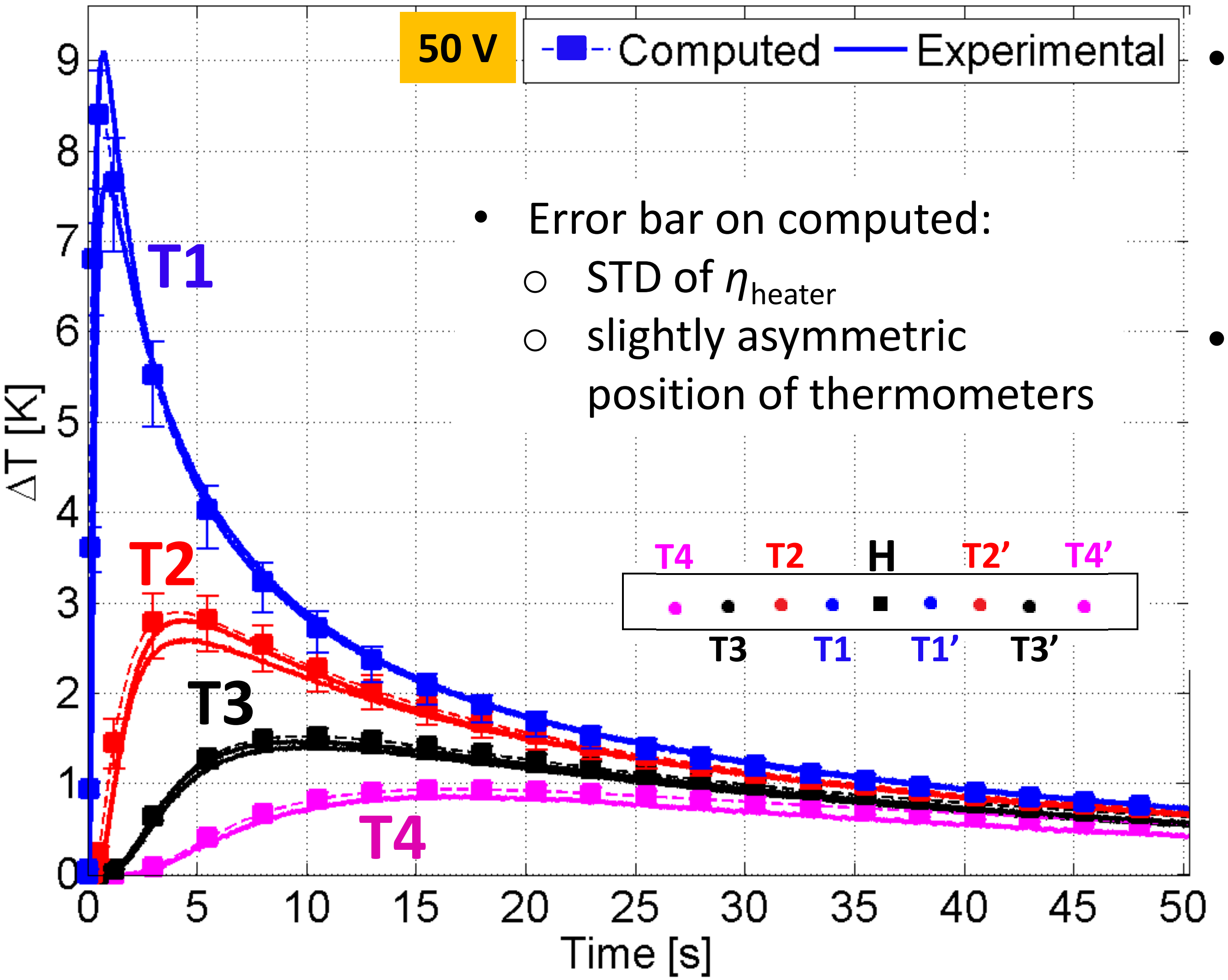
T ≠ T’ due to
- not symmetric positions wrt the heater
- different mass of glue used to stick the sensors

The T_{peak} is proportional to the input power



T* = mean value between T and T’

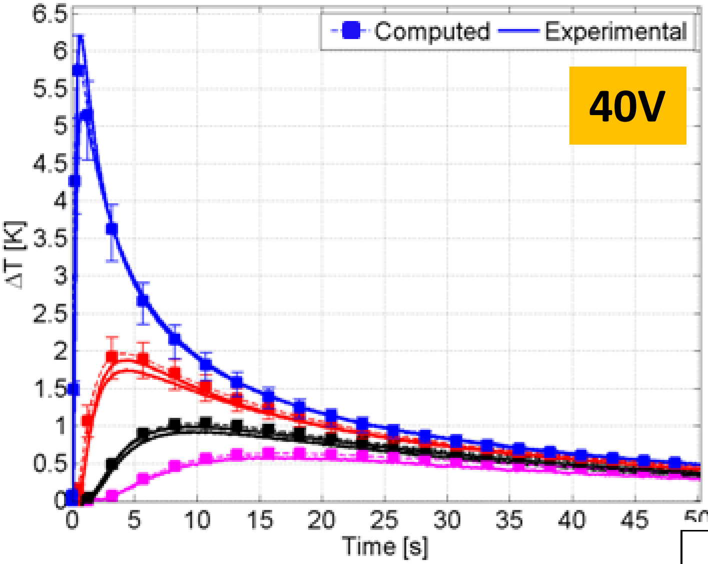
Heat slug tests: simulation results



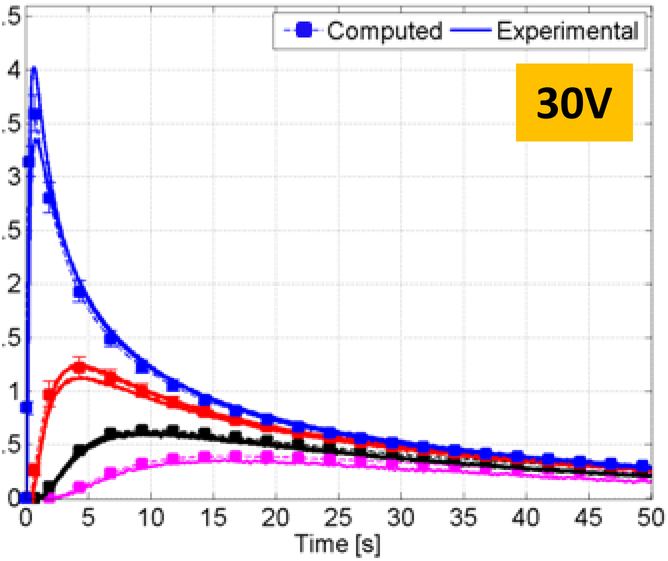
- Error bar on computed:
  - STD of η_{heater}
  - slightly asymmetric position of thermometers

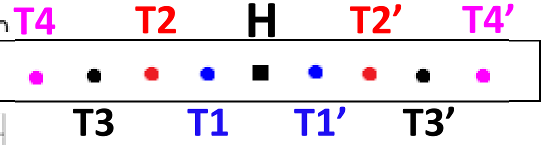
- Computed *T*: mean value in the respective opposite position
- Computed *T* evolution compares very well with the experimental data

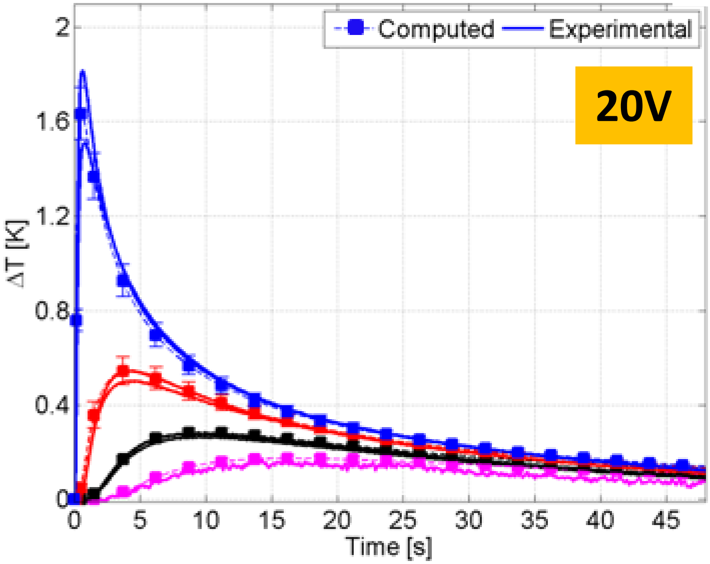
Heat slug tests: model validation



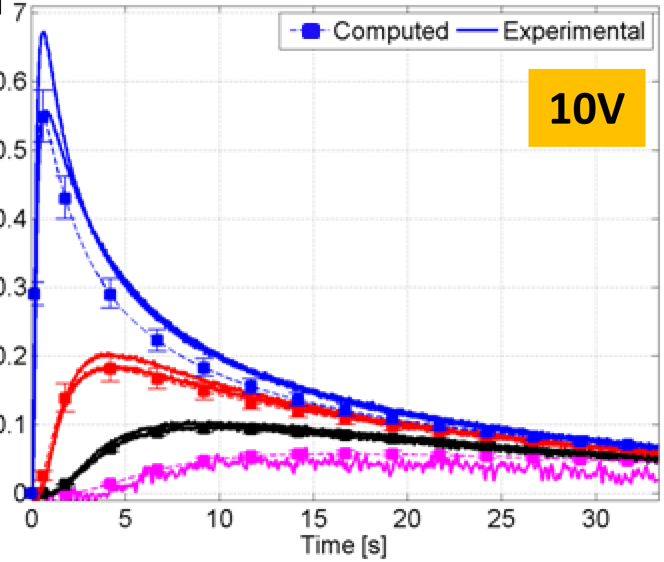
Computed *T* evolution always within the experimental uncertainty or very close to experimental measurements



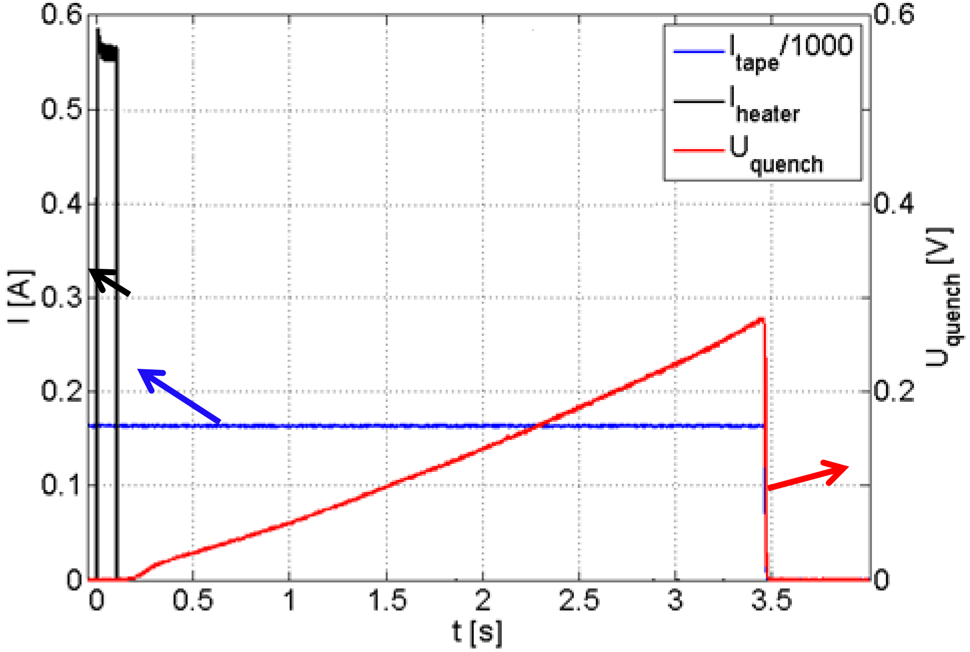




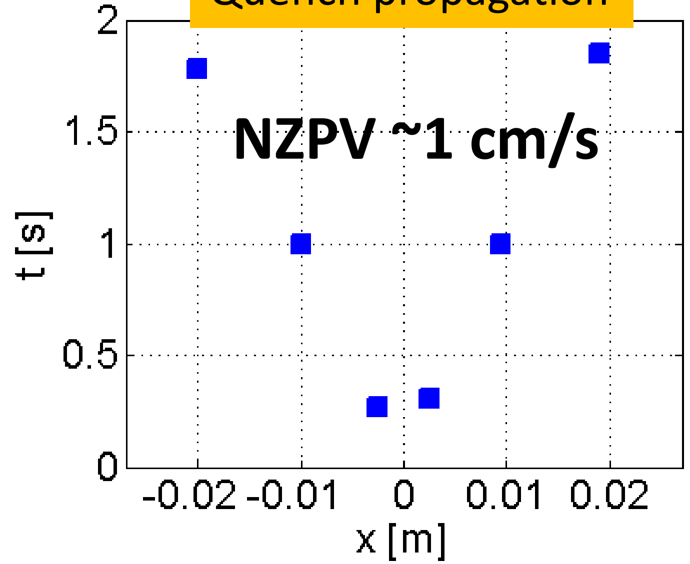
The model is successfully validated against heat slug data not used for the calibration



Quench test: experiment



Quench propagation



I_{op} = 160 A

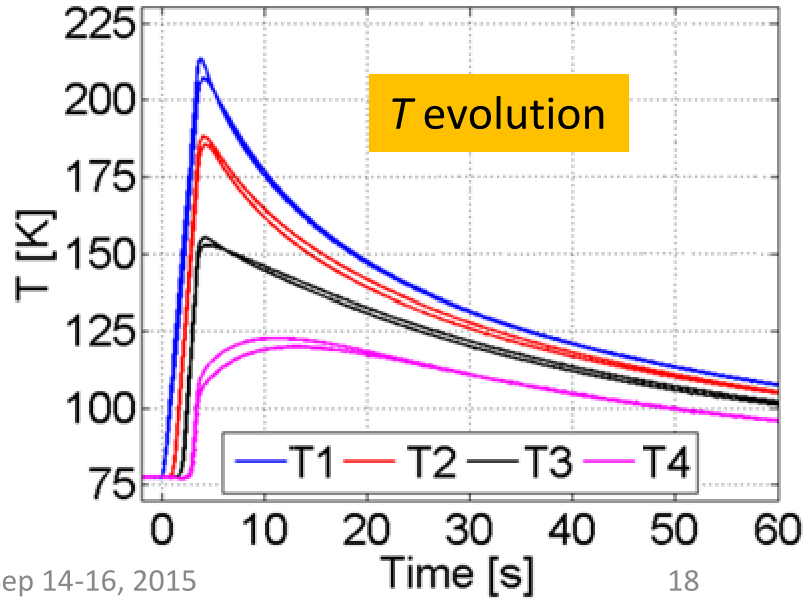
U_{quench} detection threshold = 30 mV

t_{delay} = 3 s

ΔT_{max} = ~130 K

$U_{quench,max}$ = ~0.3 V

T evolution

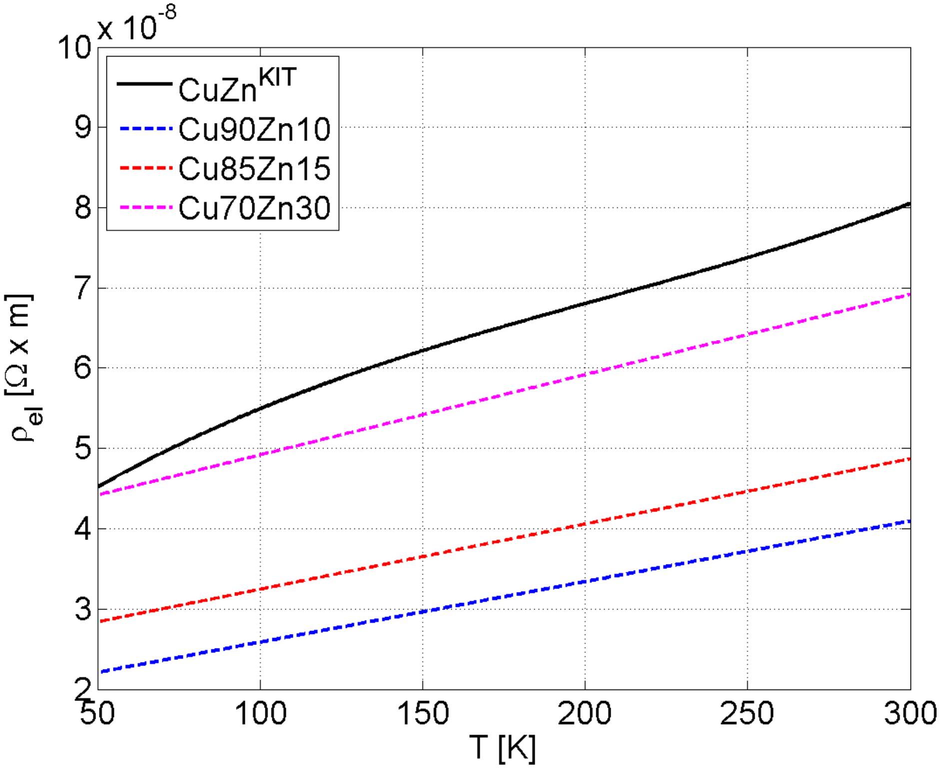


Quench propagation: issues

Two sources of uncertainty:

- Brass thermo-physical/electrical properties measured including some residual solder: use data for Cu70Zn30 and Cu90Zn10

[A.F. Clark, G.E. Childs and G.H. Wallace, Cryogenics, v10, p295, August (1970)]

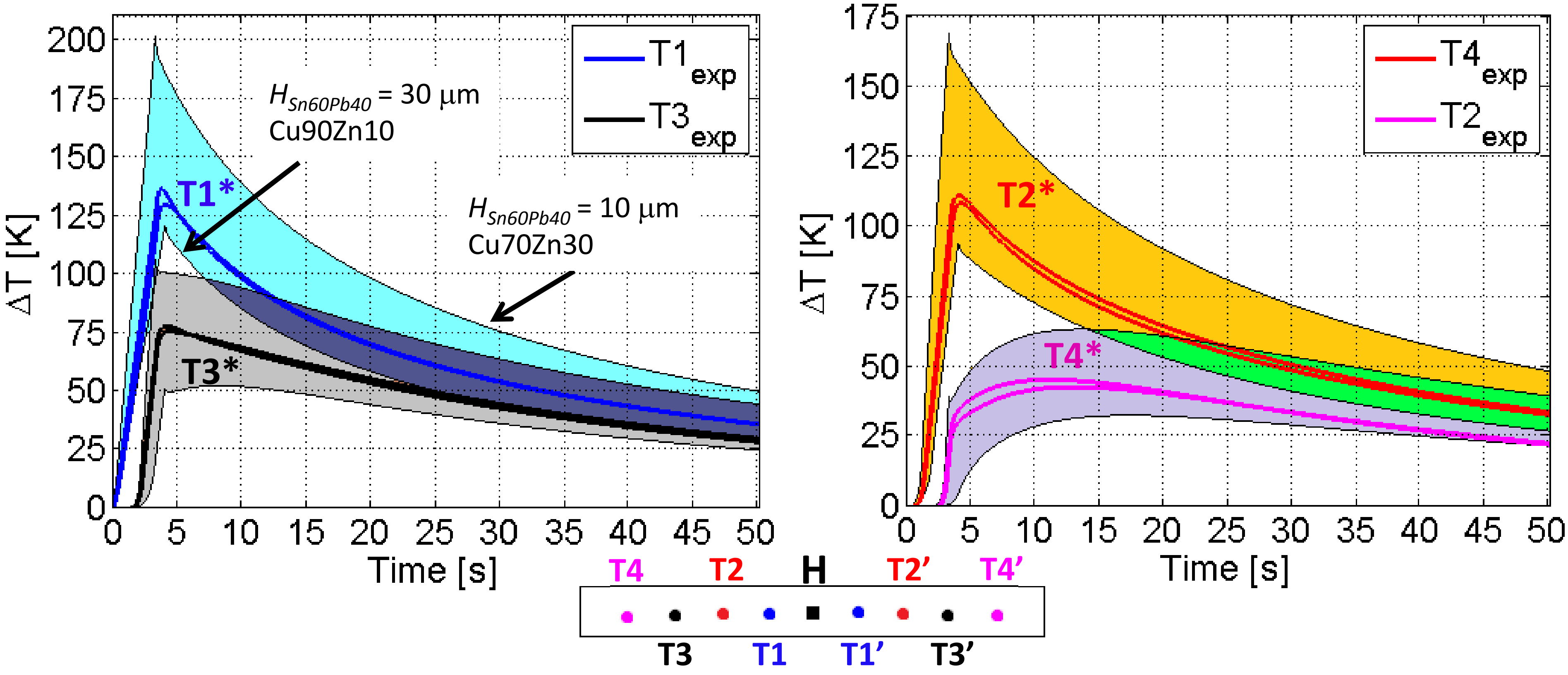


- Solder thickness (10-30μm)

→ perform two sensitivity studies

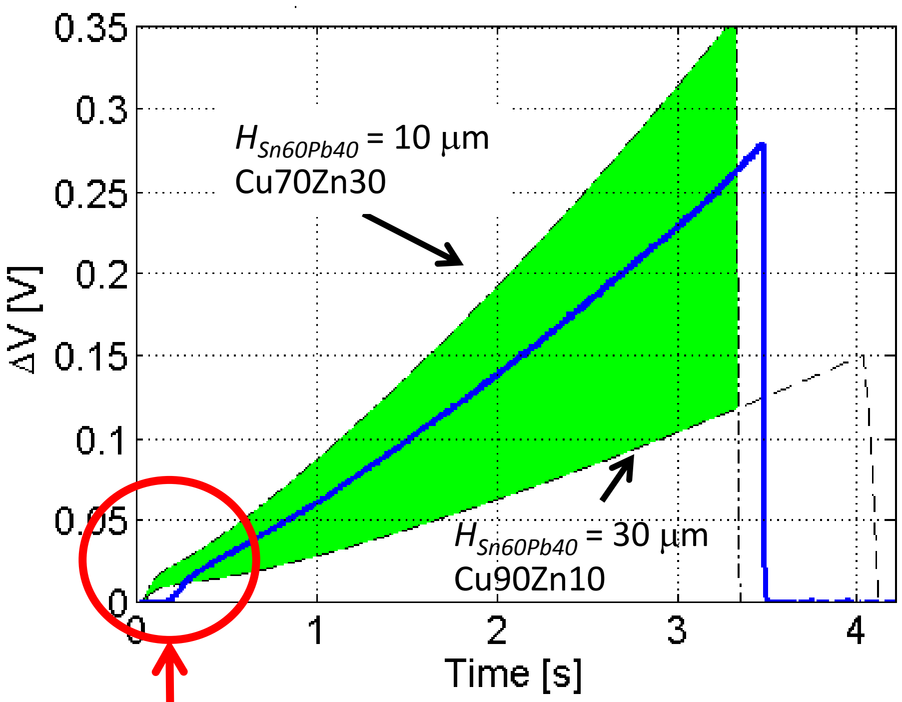
ρ_{el} for other layers obtained from literature

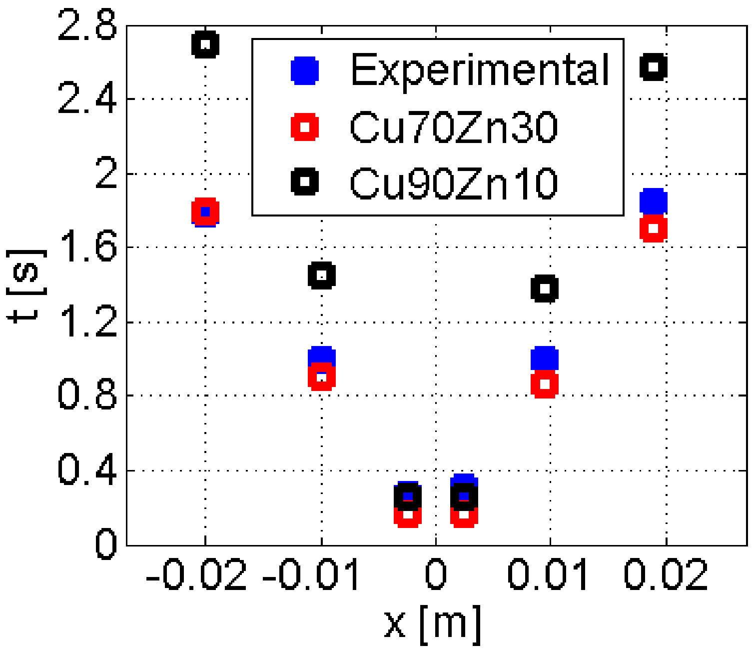
Quench test: model validation (I)



Considering different types of commercial brass and solder thickness, the experimental data are bracketed by computed results

Quench test: model validation (II)





$NZPV_{exp}$ ≈ 1.11 ± 0.12cm/s

$NZPV_{Cu70Zn30}$ ≈ 1.07 cm/s

$NZPV_{Cu90Zn10}$ ≈ 0.71 cm/s

- Exp. global Δ*V* is bracketed by comp results
- Computed take off anticipates the measured one possibly due to
  - local current redistribution in the tape below the heater (less wide than the tape) not accounted for in the 1D model
  - J_c linear approximation

Conclusions and perspective

- Experimental tests performed at KIT on a brass - stabilized REBCO HTS tape analyzed
- 1D multilayer numerical model developed
- Model successfully validated against experimental measurements
  - heat slugs
  - quench, within uncertainty on ρ_{el} stabilizer and the solder thickness
- In perspective, conclude the analysis/validation on non-stabilized tape

THANK YOU