Beam Induced Quenches in the LHC

Experimental Work on Short–timescale Heat Pulses Into He II in Confined Spaces

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Very overarching view of work

What?

- Investigate heat transfer from a heated metal (such as a LHC magnet cable) to the helium used to cool the metal
- Investigate the transport of this heat within the helium once it is there

Why?

- We know that during fast heating events, models used to predict metal-to-helium and intra-helium heat transfer substantially underestimate real world heat transport capability (the LHC survive UFO attacks at least three times larger than we expect)

How?

- Improve computer models by better understanding/better incorporation of theory
- Conduct experiments aimed at replicating LHC relevant conditions

This presentation

Looking at the experimental side:

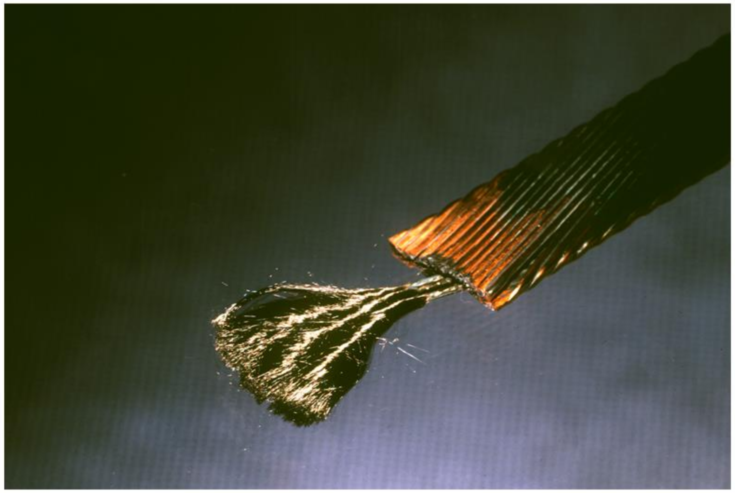
Experimental investigation means replicating some key conditions

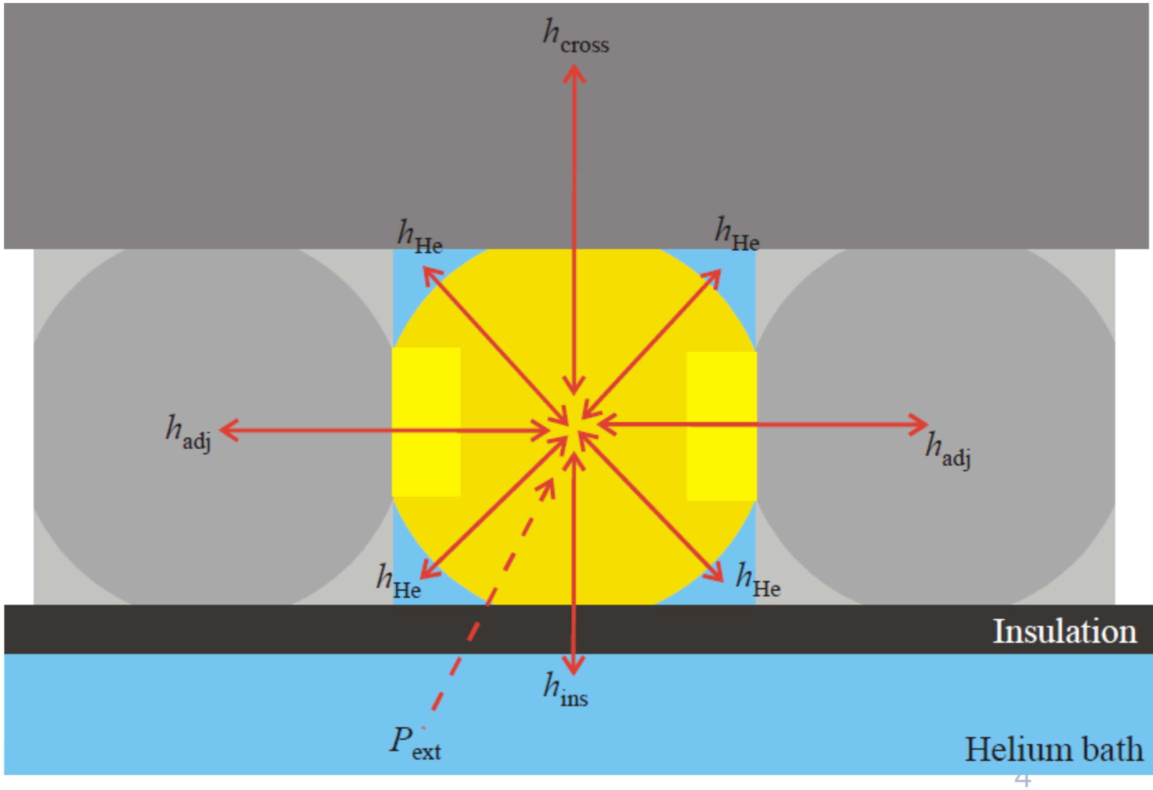
- Time scale and magnitude of relevant heating events
- Spatial scale of both heated metal and helium cooling volume

Spatial scale

- The strands in an LHC MB cable are about 1 mm in diameter
- Thus, the perimeter of the strand is about 3 mm

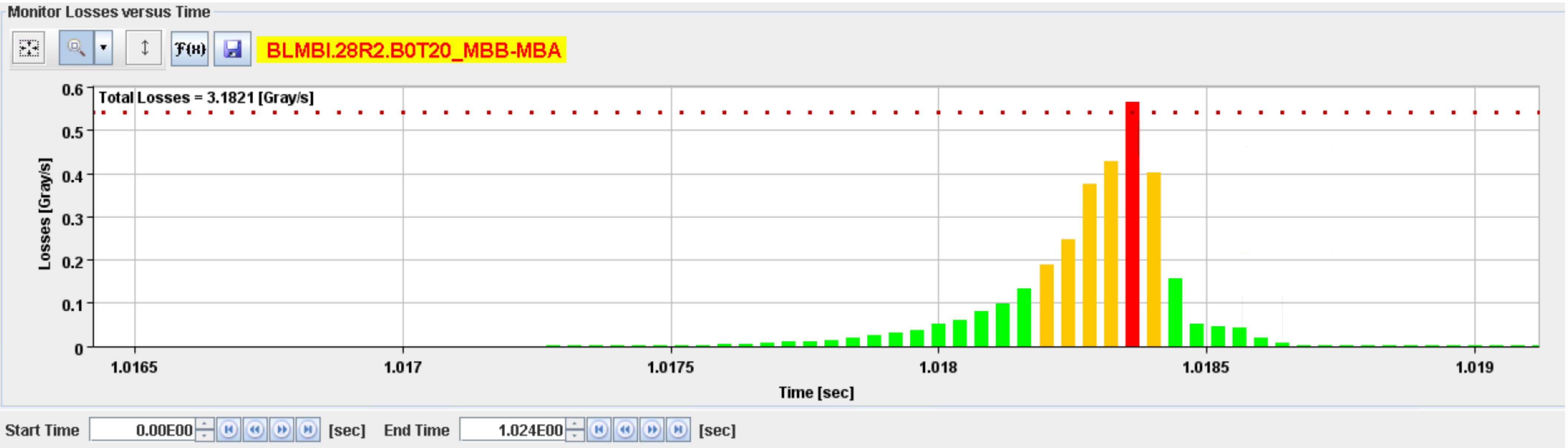
- «Unwrapping» the circular geometry leaves us with a rectangular helium volume about 3 mm wide, and 90 µm thick





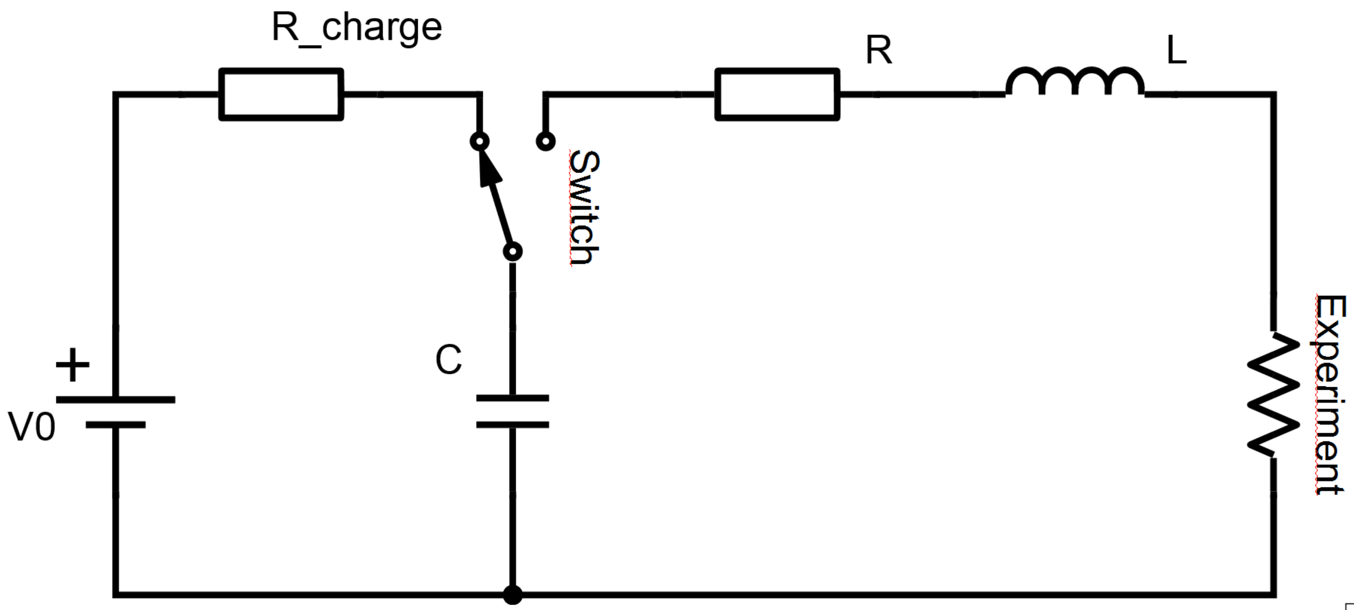
Time scale (1)

- This is a bit more convoluted, but for the very fastest heating, measurements made in the LHC indicate typical shapes as



- Asymmetric Gaussian pulse, lasting about 500 to 1000 µs
- A reasonably simple approximation to this is the kind of pulse one gets when discharging a capacitor in a circuit with a resistance and an inductance

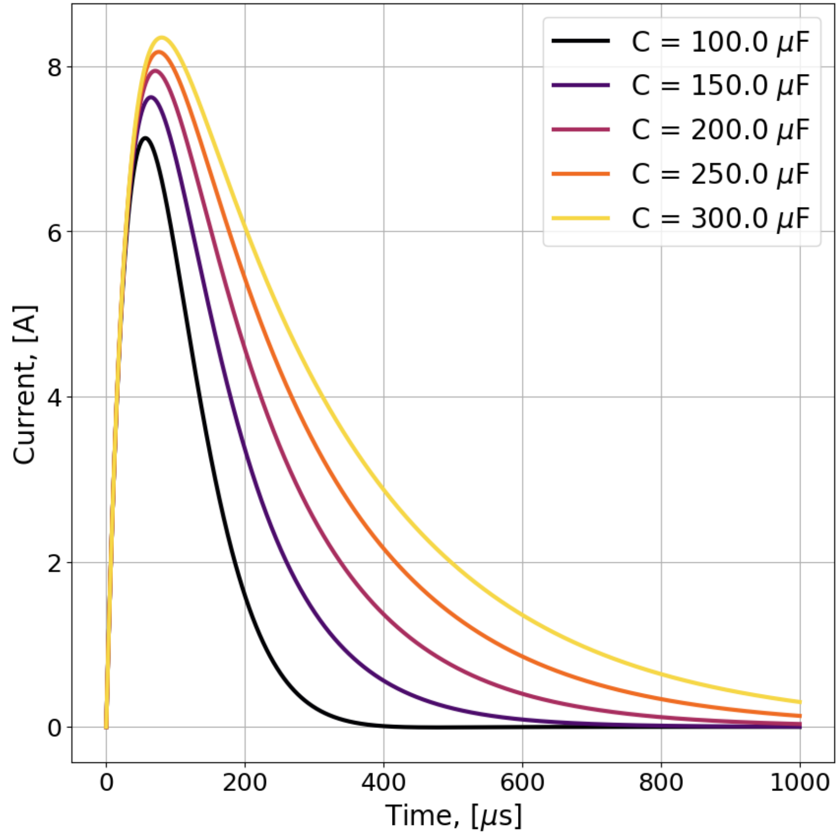
Time scale (2)



Simple enough to get sub millisecond pulse

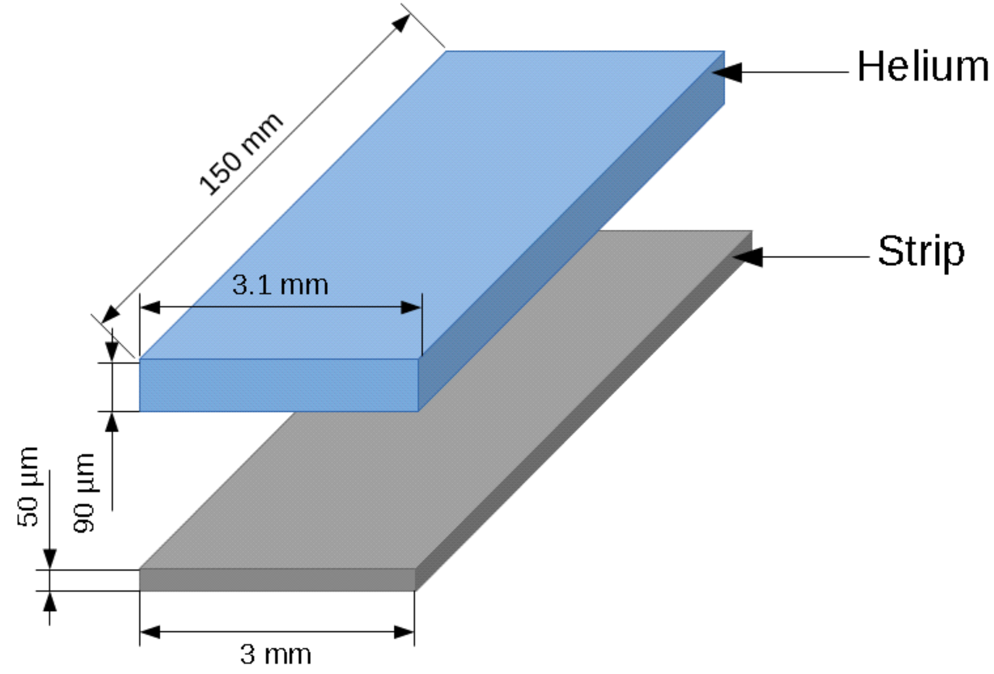
We also want slower pulses, on the order of 100 ms and 500 ms.

These choices are made to approximate heat pulses occurring during magnet protection events, using a simplified 0D heat transfer model to determine circuit parameters (these selection criteria are a bit complicated, and not so interesting, but feel free to ask about it off-line – key: based on heater surface temperature)

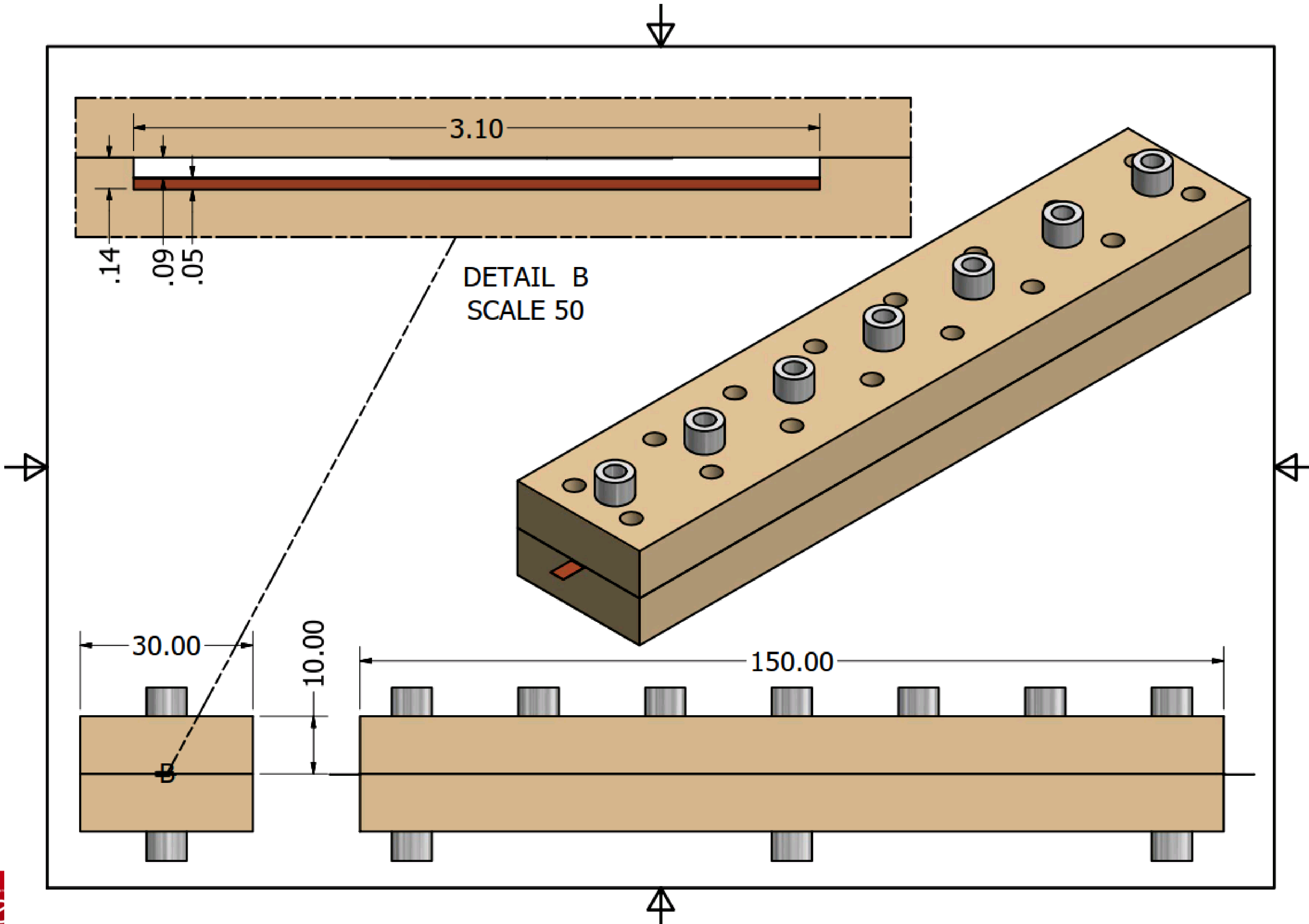


Summary of experimental setup

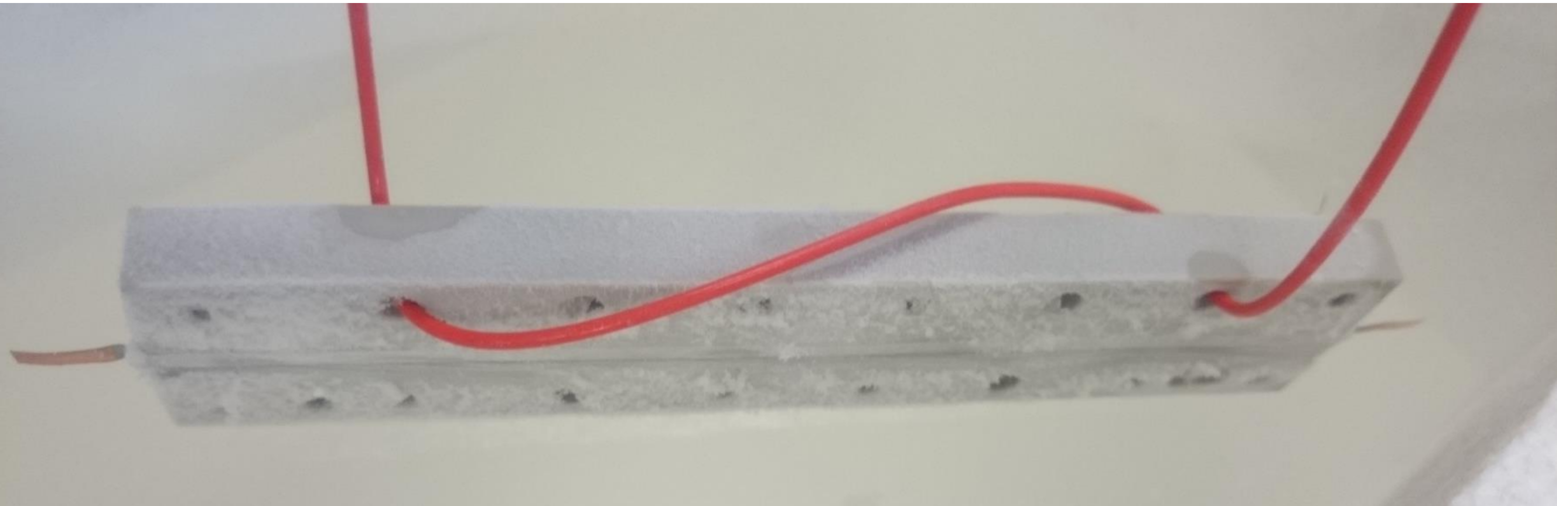
- RLC circuit used to deliver heat by resistive heating of metal → heater strip and helium channel
- Strip is stainless steel, 3 mm wide, 50 µm thick, 150 mm long
- Channel is 3.1 mm wide, 90 µm deep/thick, 150 mm long
- With gravity as reference direction, the helium is on top of the strip, **in direct contact**



Heater and helium “in something”

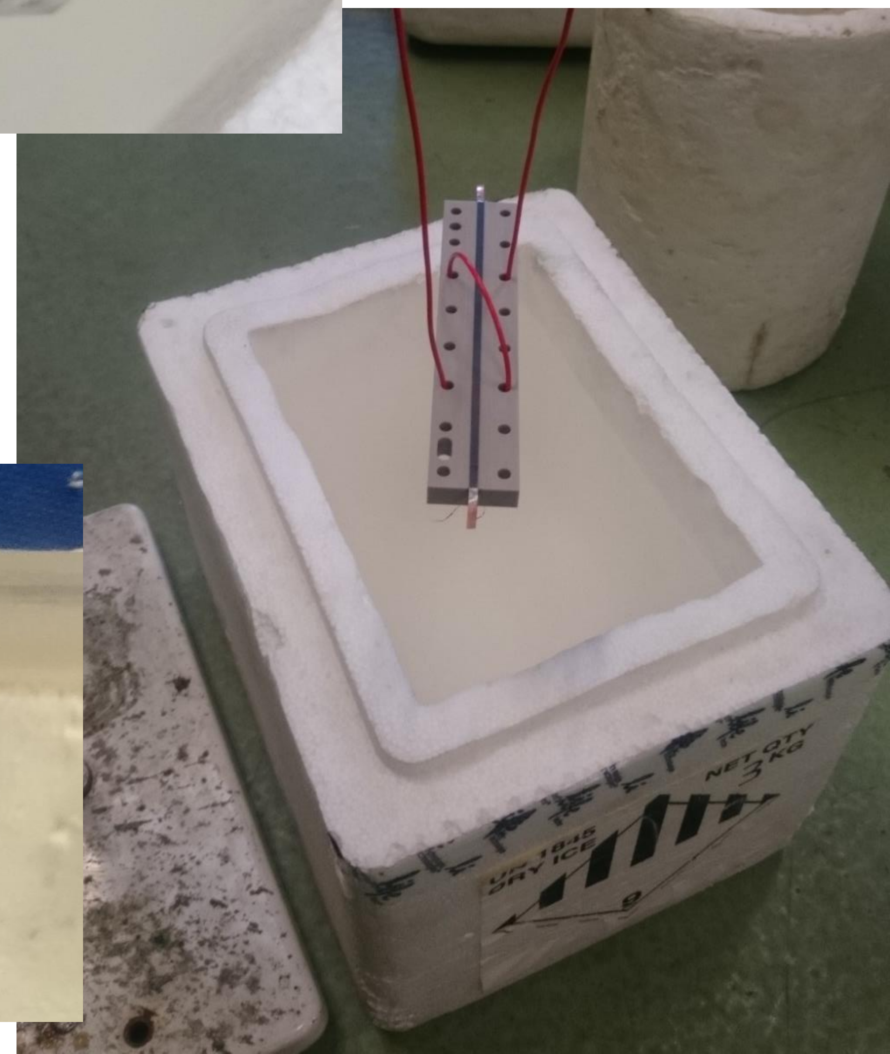


Real thing – “Bottom plate”



Slot for heater strip is machined into PEEK

Fiberglass reinforced PEEK is chosen due to thermal contraction being similar to stainless steel



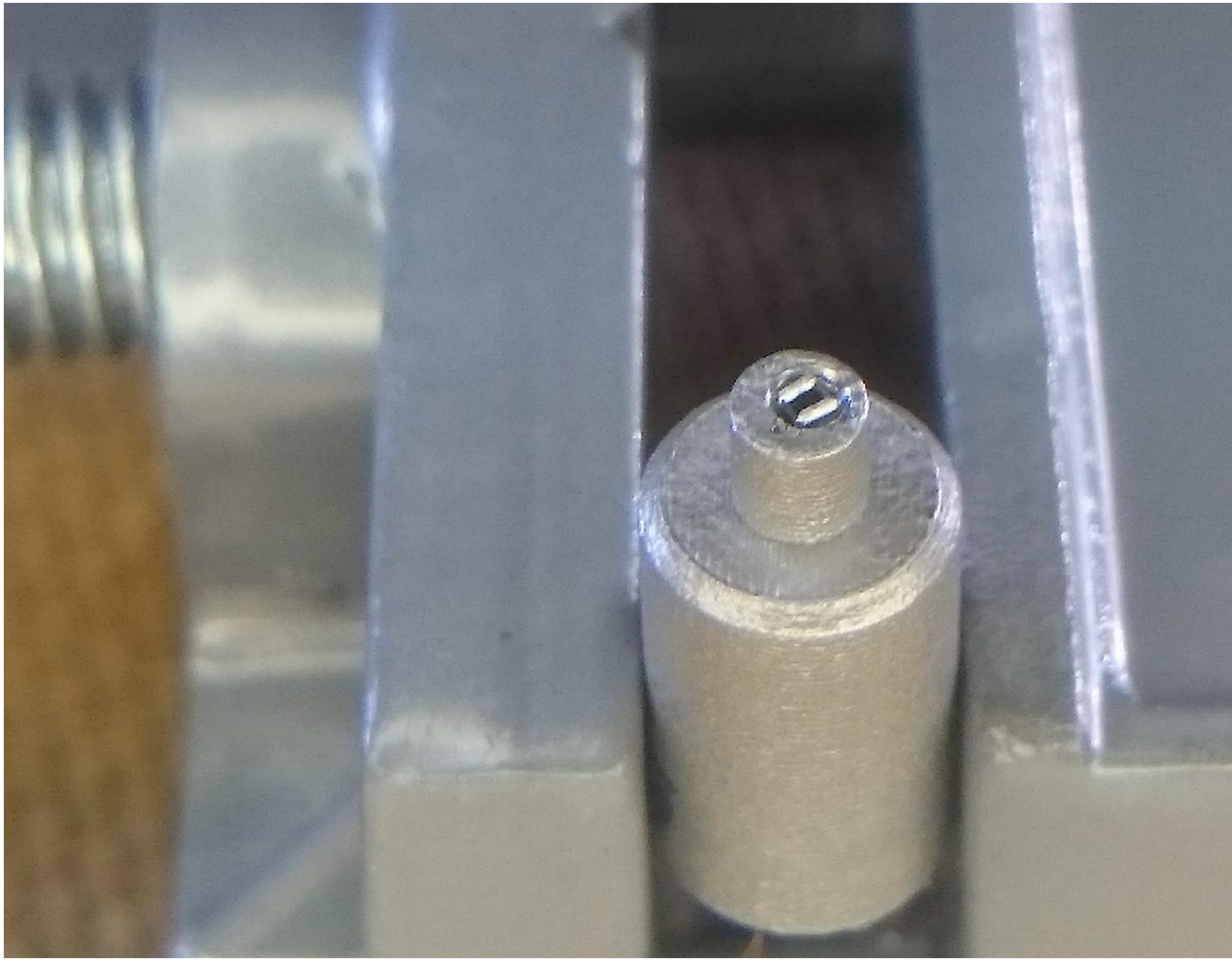
Real thing – “Sensor holders”

Challenging to mount sensors in their holders

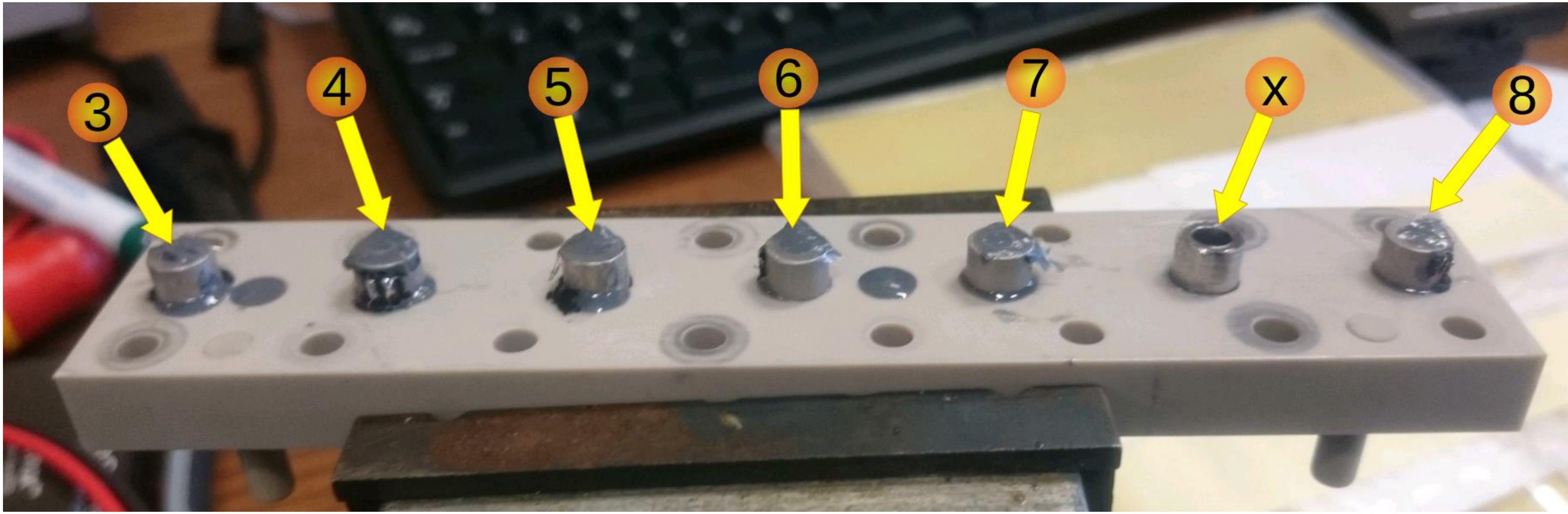
Sensor dimensions: 0.7 x 0.8 mm. 0.2 mm thick, plus poorly defined thickness of solder for leads

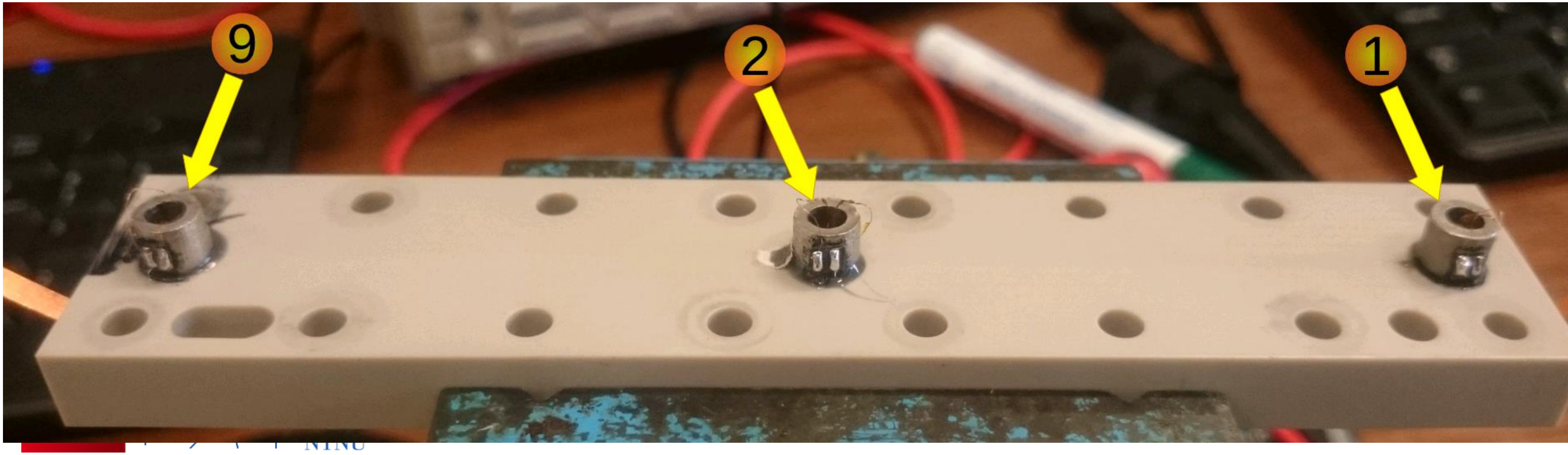
Sensor leads come uninsulated, and they are only 25 µm thick – very fragile

Approximately 1/3 mounting attempts fail (with subequent loss of sensor)

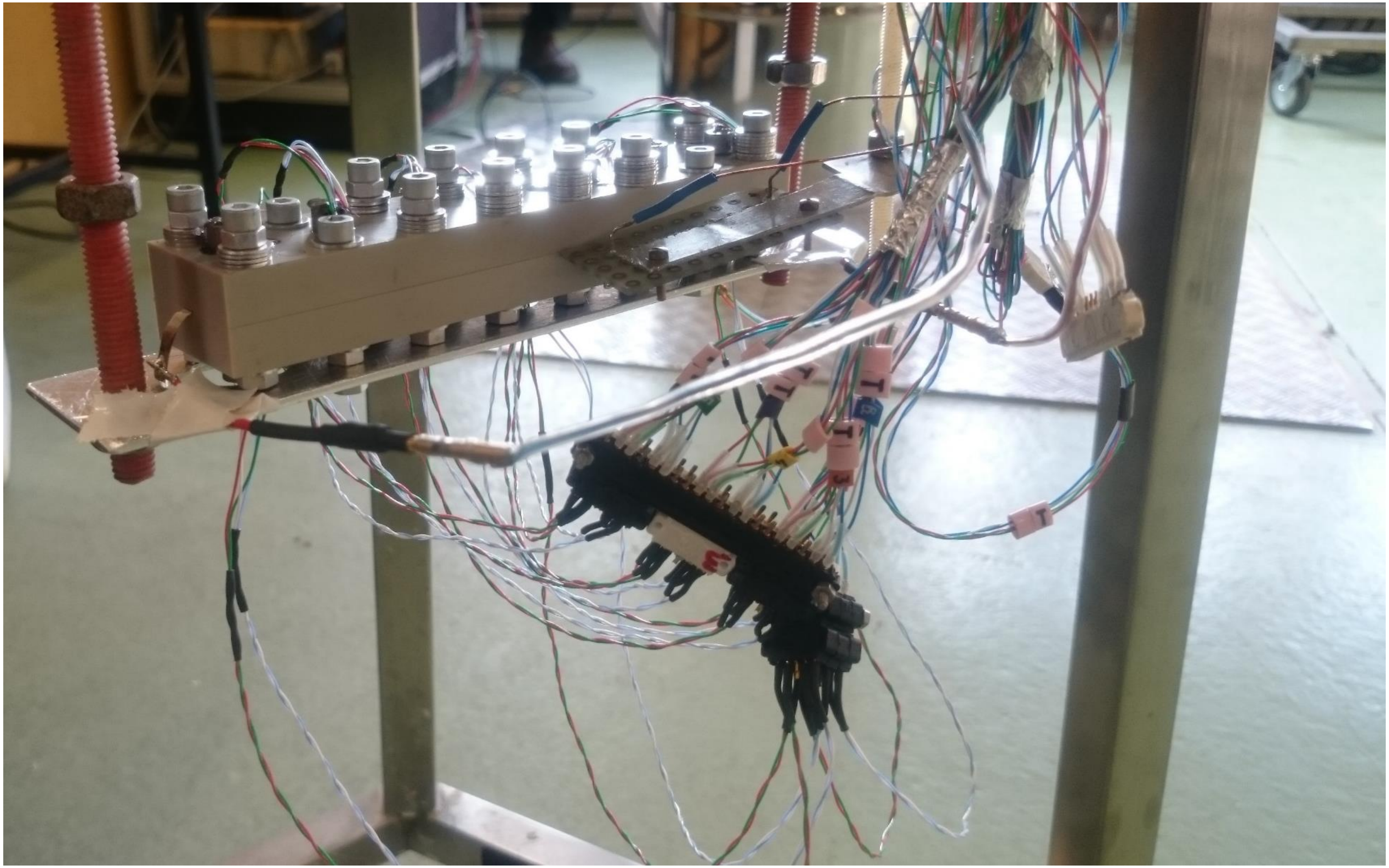


Real thing – All sensors

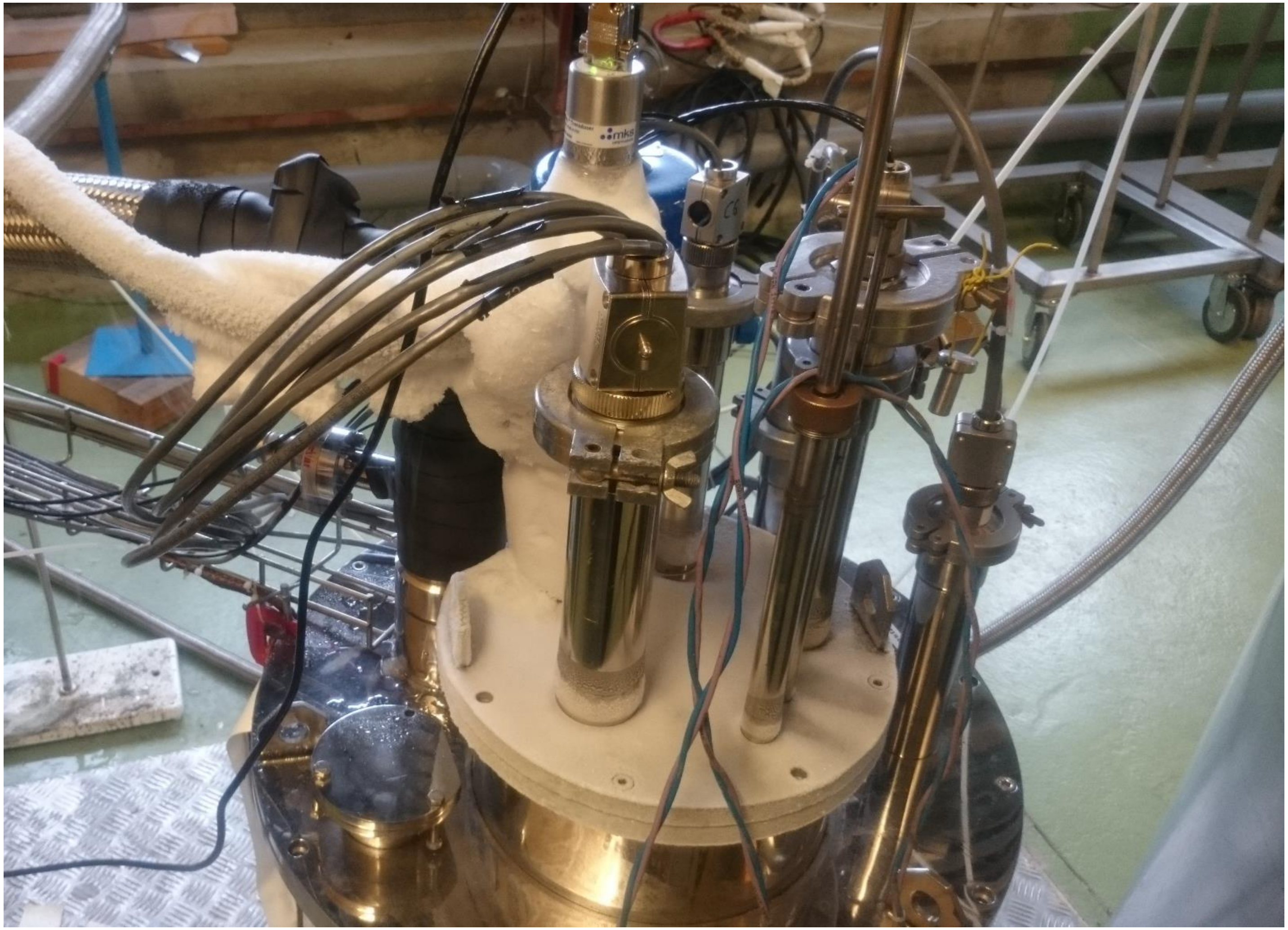




Real thing – Wired up



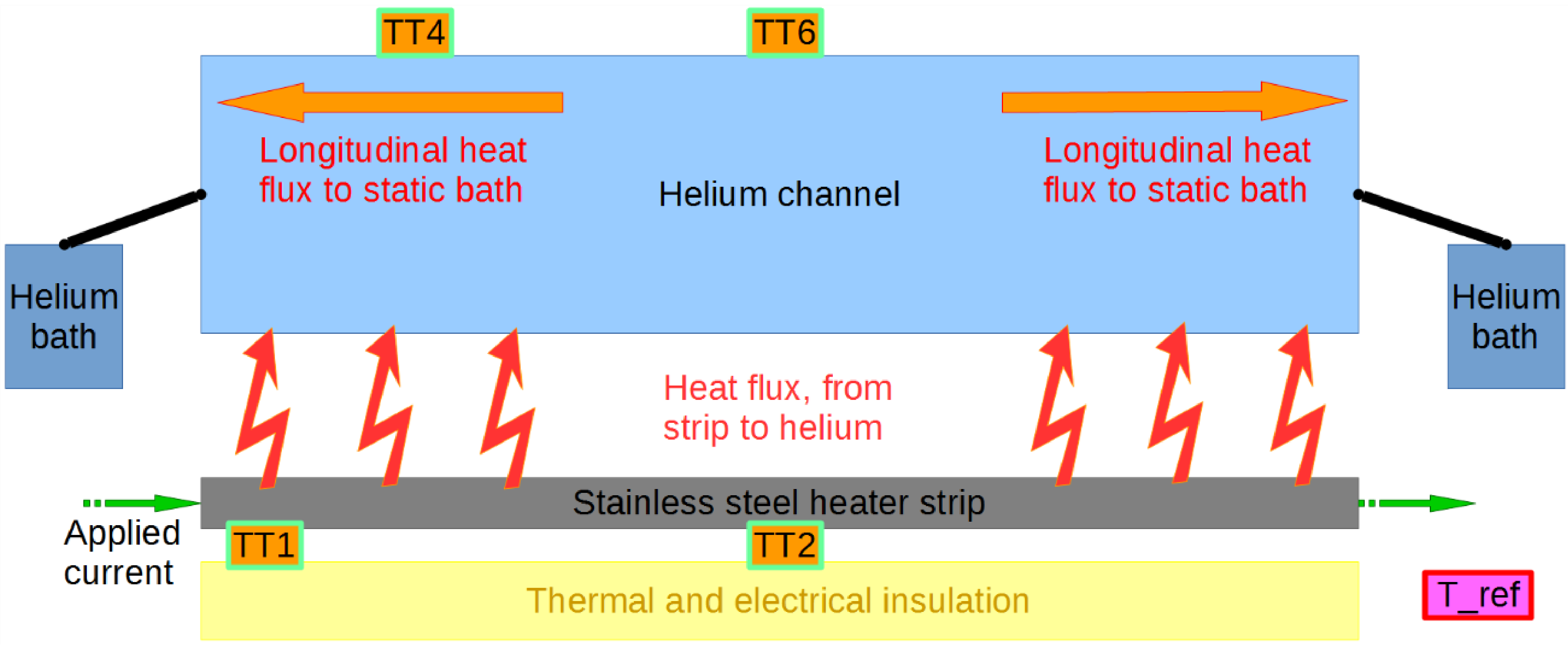
Real thing – Into cryostat



Bitter reality

Four of the eight working sensors broke during cooldown

Suspected cause: thermal contraction putting sensor leads under strain in the glue, combined with poor design for sensor holders that left leads exposed to sharp edges or bends



Test campaign

Four main time scales

- Steady state
- Slow pulse (RLC pulse of about 500 ms)
- Intermediate pulse (RLC pulse of about 100 ms)
- Fast pulse (RLC pulse of about 1 ms)

Within the different RLC pulse regimes, some additional variations were possible, apart from varying the charging voltage;

- Particularly the fast pulse was flexible, with various parallel and series connections of capacitors (for the other pulses the number of physical components with which to play were limited)

Steady state measurements (1)

Initially, analysis concentrates on steady state measurements

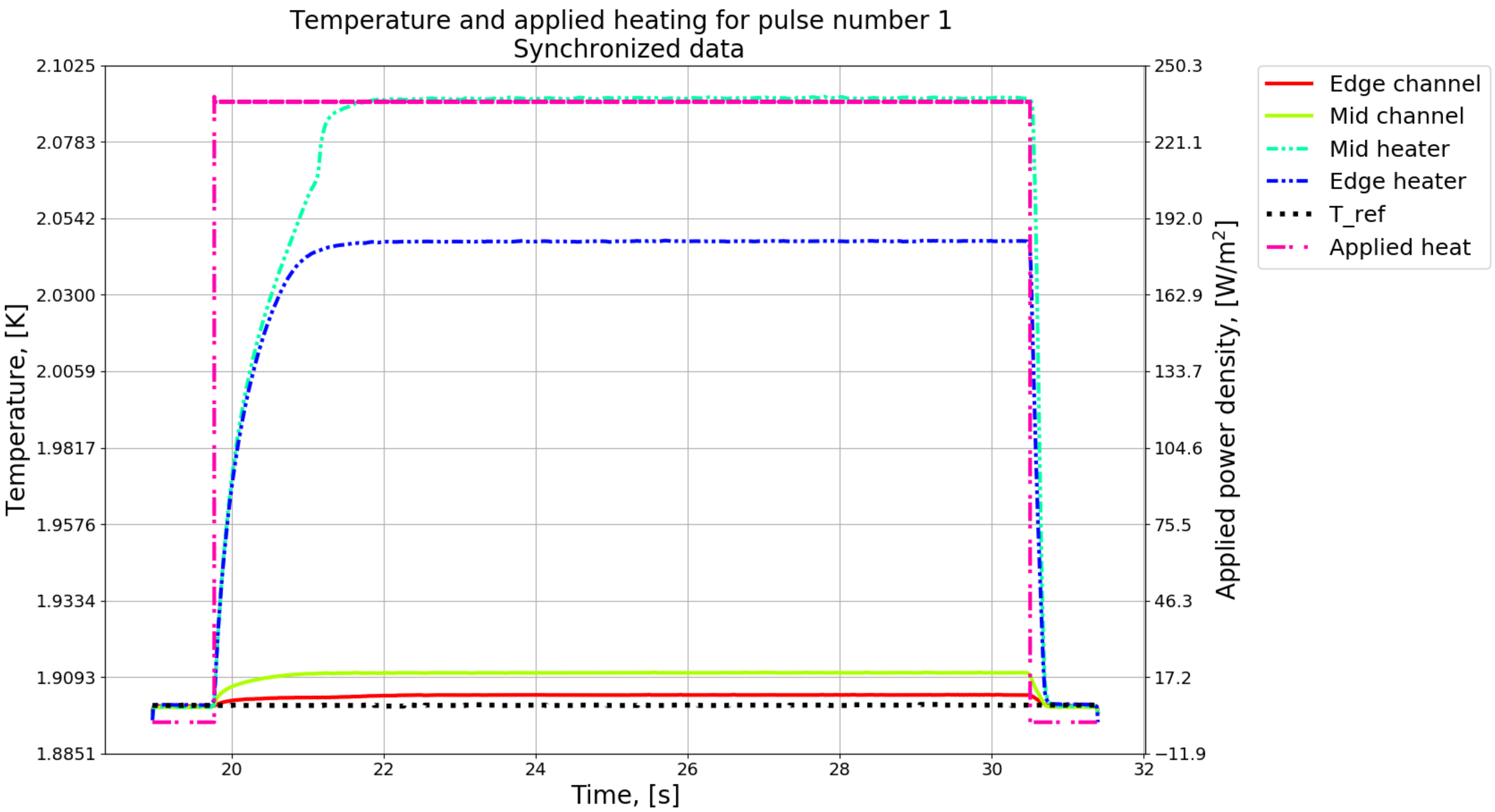
- The RLC circuit from before is replaced by a current source
- The current source is set to feed some set current to the experiment
- The current passes through the stainless steel strip, heating it, and in turn heating the helium

The applied heat is expressed in terms of W/m^2, by squaring the voltage measured across the heater strip, dividing by the strip resistance, and dividing again by the width and length of the strip.

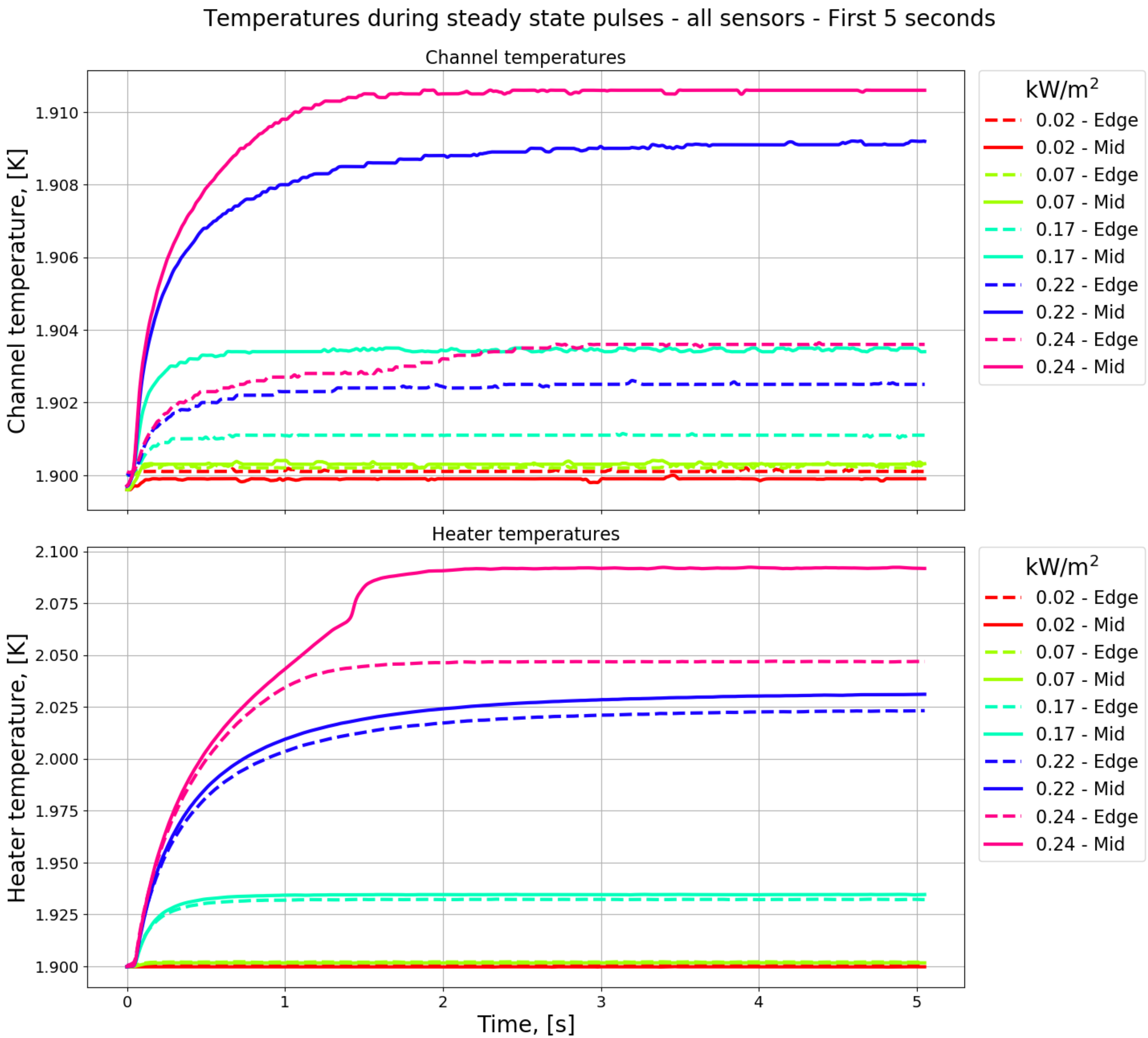
Once all temperatures have stabilized, this power density is equal to what is transported from the heater strip into the helium

This same heat is also transported out of the channel (though at the different density, since the cross section of the helium channel is significantly smaller than the area of heater strip to helium)

Steady state measurements (1)



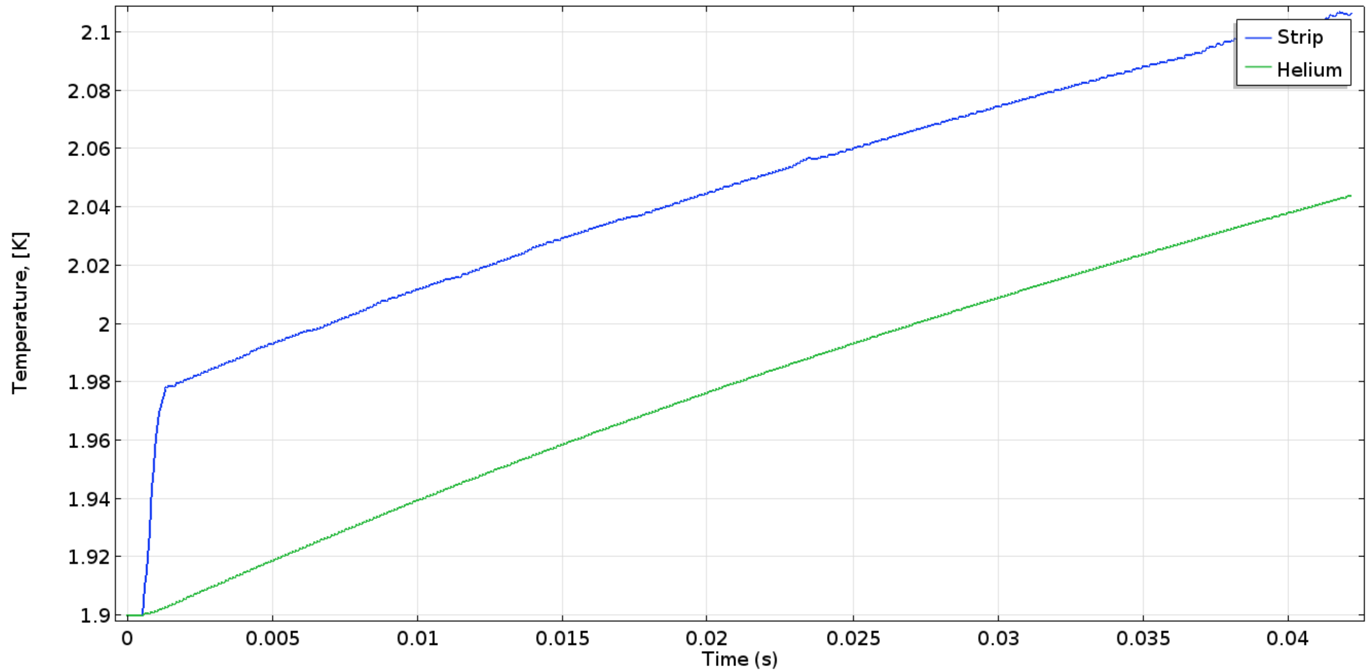
Steady state measurements (2)



Steady state measurements (3)

Channel of real dimensions, including illdefined longitudinal heat transfer

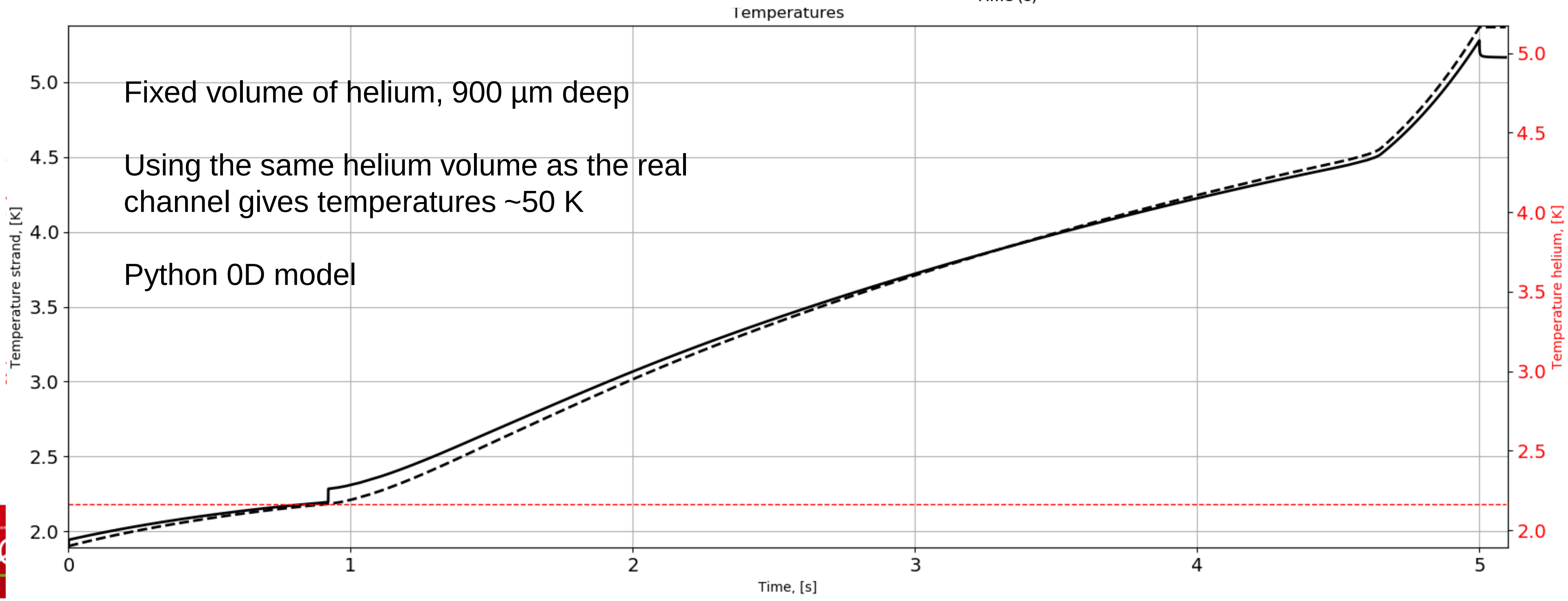
COMSOL 1D model



Fixed volume of helium, 900 µm deep

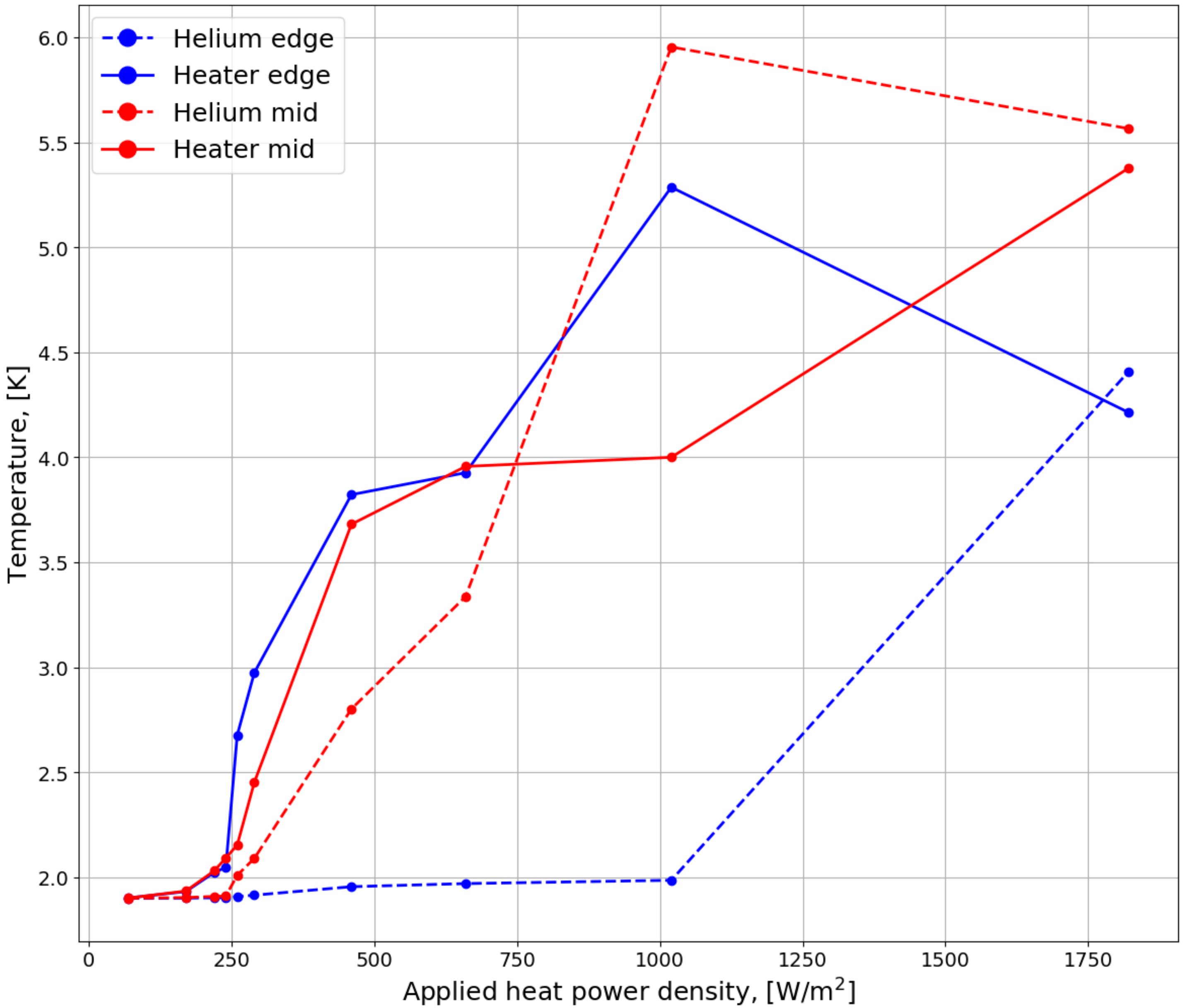
Using the same helium volume as the real channel gives temperatures ~50 K

Python 0D model



Steady state measurements (4)

Summary of measured steady state temperatures reached for all steady state pulses



Comparison with theory (1)

Two main expressions exist to describe the heat transfer in the Kapitza regime

For small temperature difference:

$$Q = a\,T^3 \Delta T$$
$$\Delta T = (T_{Heater} - T_{Helium})$$

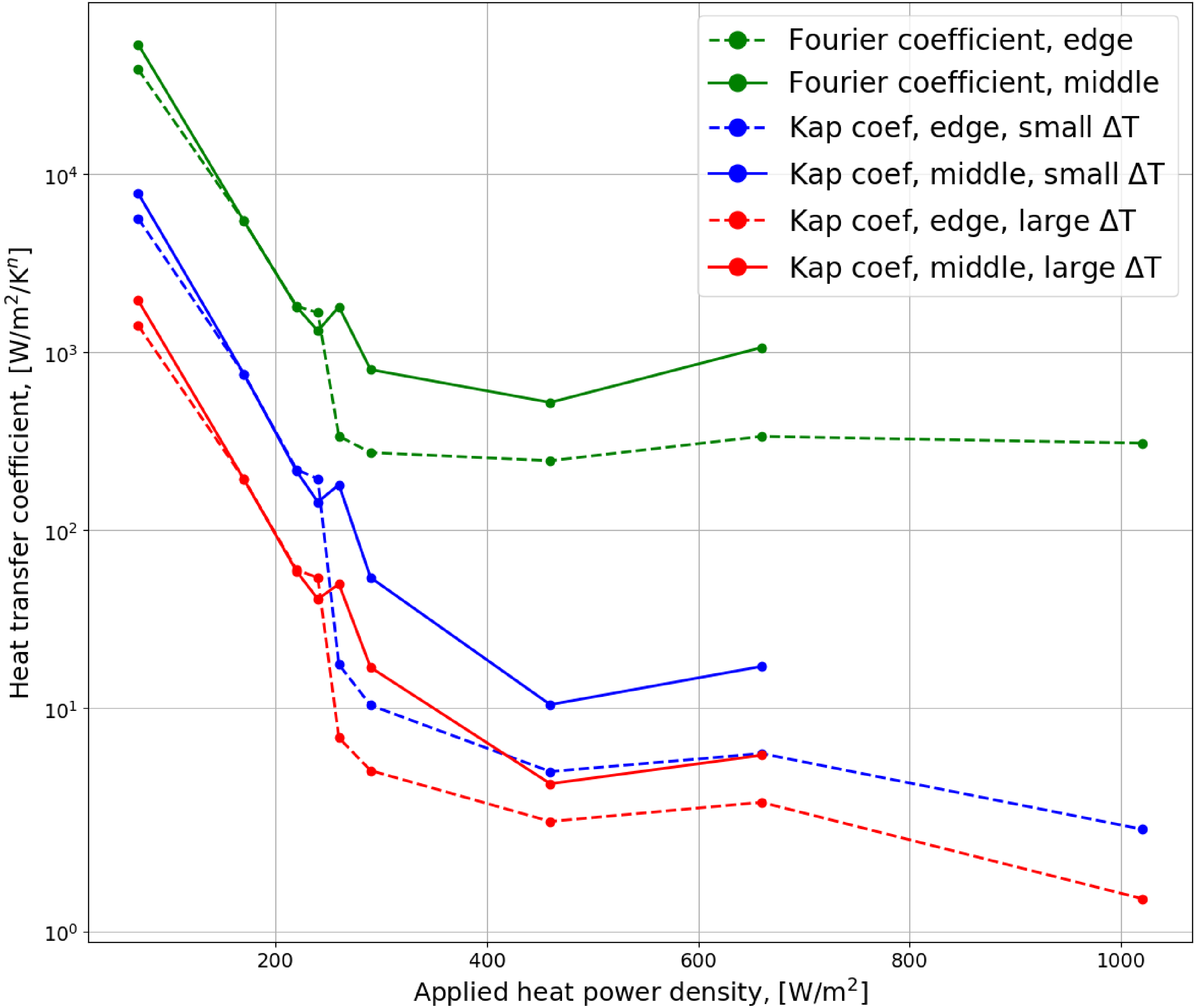
a = heat transfer coefficient of units [W/m^2/K^4]

For large temperature difference:

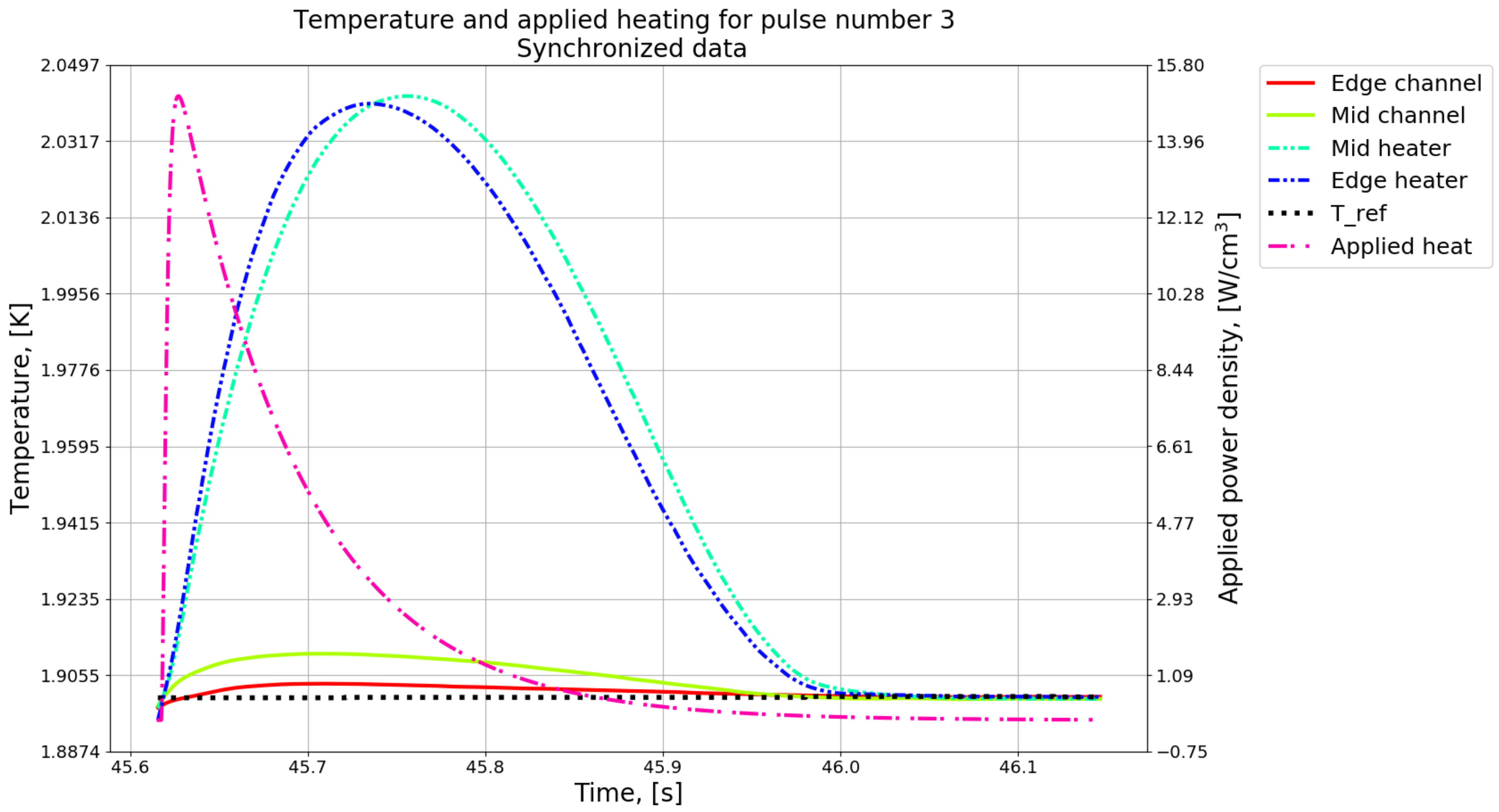
$$Q = a\,(T_{Heater}^4 - T_{Helium}^4)$$

a = heat transfer coefficient of units [W/m^2/K^4]

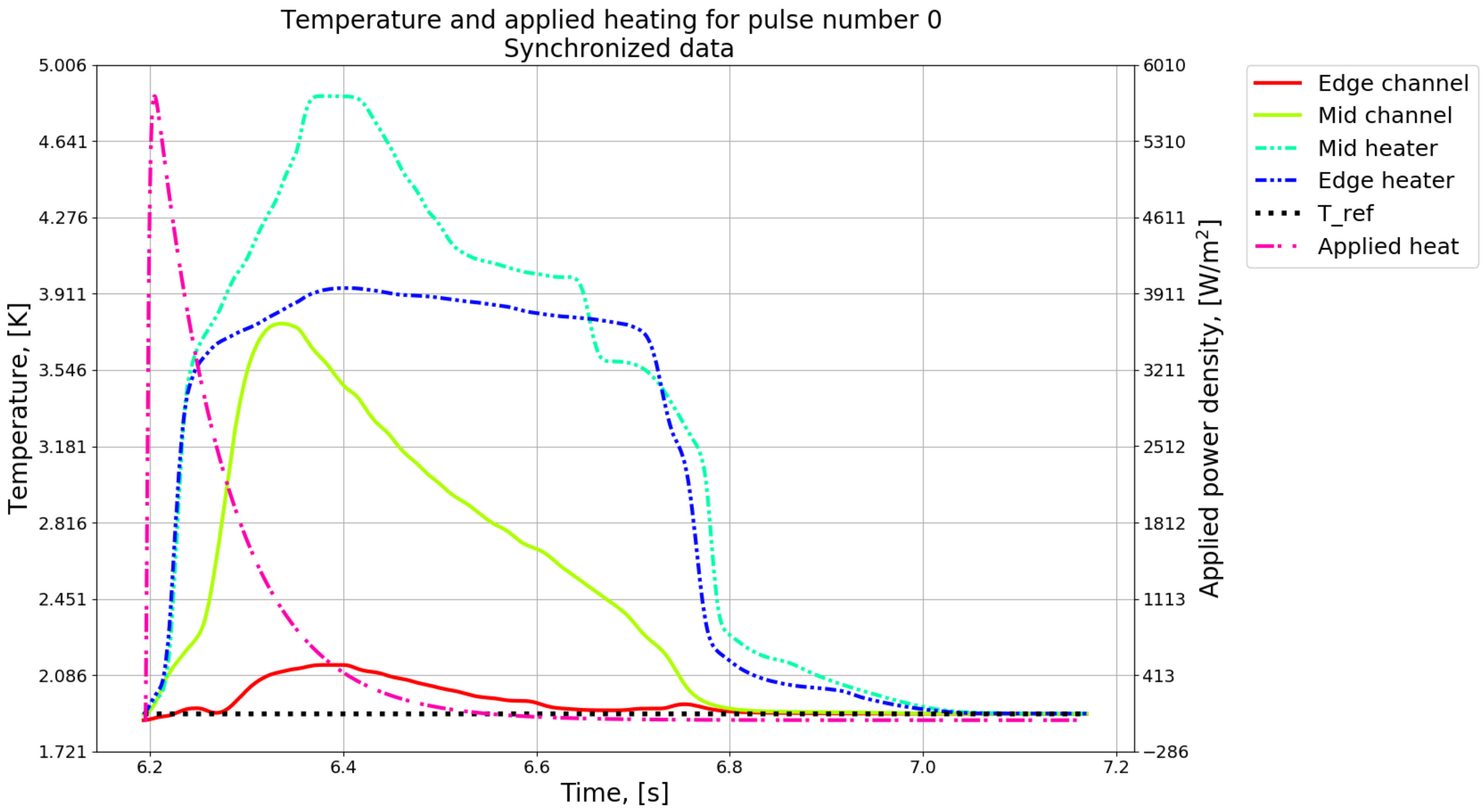
Comparison with theory (2)



Example of pulse data (1)



Example of pulse data (2)



Some conclusions

- Having done the experiment with open ended channel is, not so surprisingly, a problem for the analysis

Solution: redo experiment with ends closed

- Always starting from 1.9 K means that we miss out on targeted helium regime conditions

Solution: by starting at different temperatures, for example 2.1 K, or 4 K, etc, we can more directly study the different regimes, without having to move through lower regimes first

- Simulations are very far away from what experiments indicate

Solution: for now, it is not possible to substantially improve simulations, but they can be tuned to give better upper and lower bounds for expected temperatures