Temperature Mapping of Niobium-coated 1.3 GHz Copper cavities

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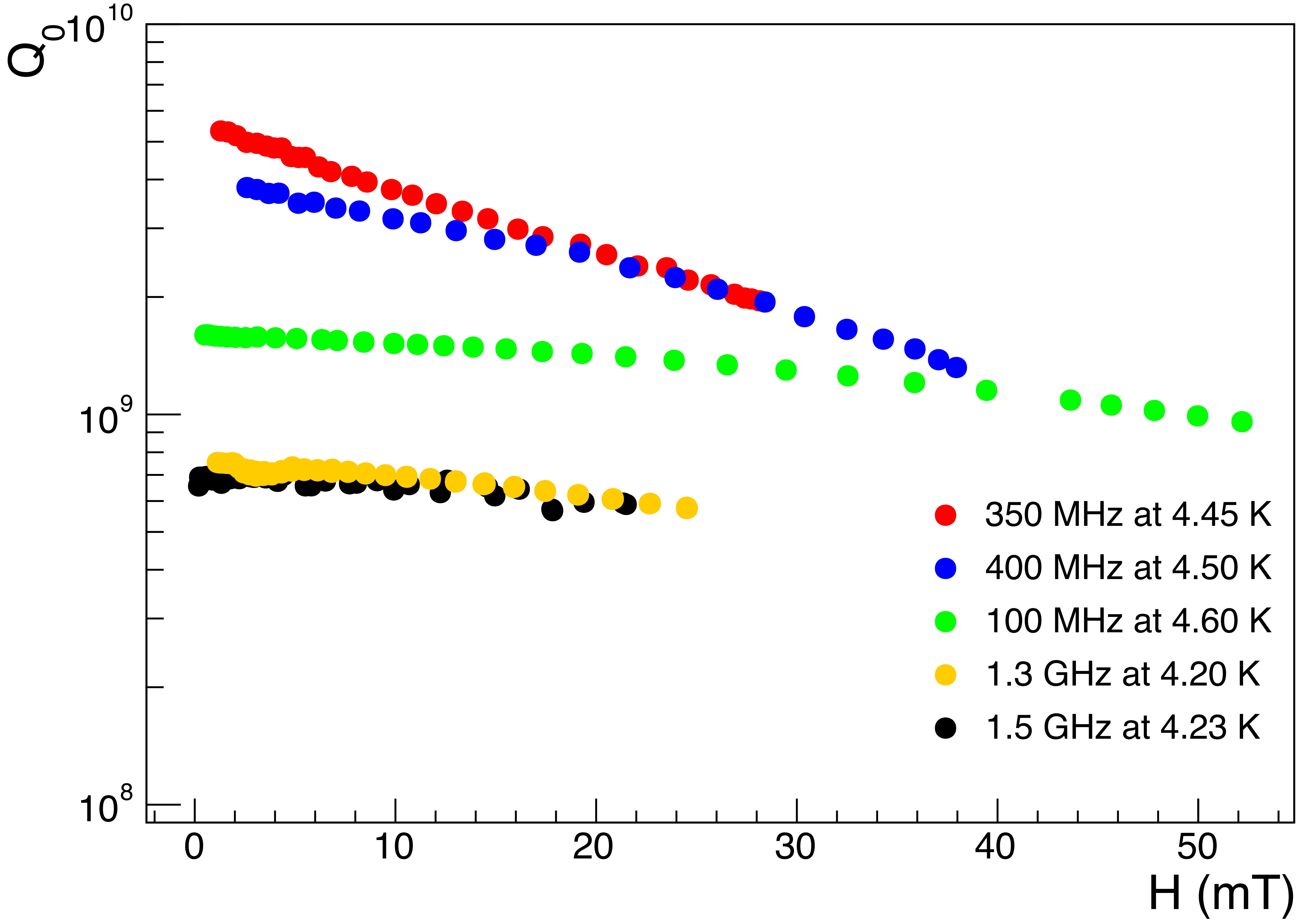
Outline

- Temperature mapping system for niobium-coated copper cavities at CERN
- Heat dissipation of Nb/Cu cavities in He-I
- Engineering copper surfaces for thin film cavities

R&D Studies of Thin Film Cavities at CERN

CERN has pioneered development of **thin film superconducting radio-frequency cavities** for particle accelerators. **This technology has been applied in LEP II, LHC and more recently in HIE-ISOLDE**.



Many efforts are put in place at CERN in view of the potential implementation of **Nb/Cu cavities in FCC machines**

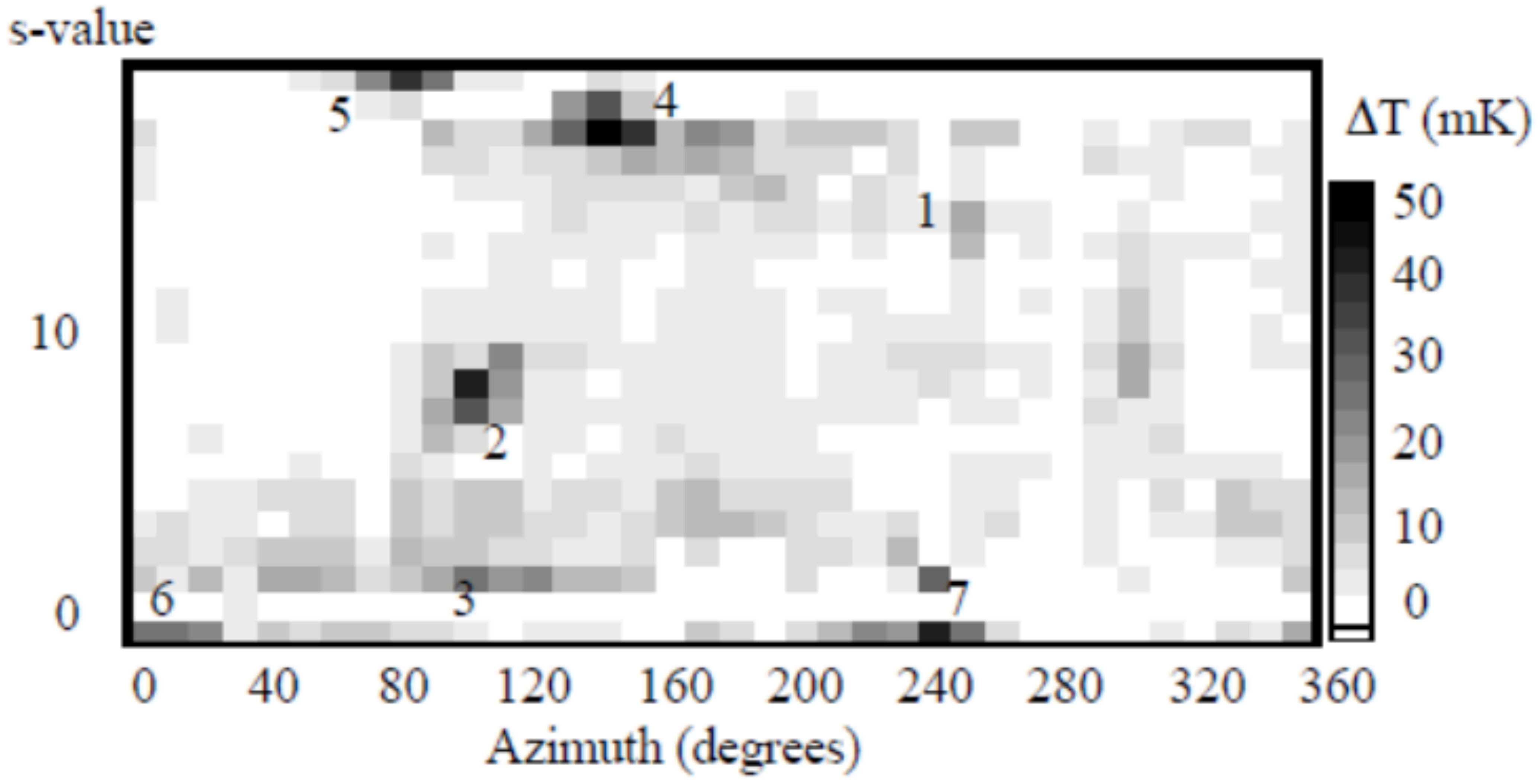
However, niobium **thin film cavities historically feature a progressive degradation of performance** by increasing the accelerating field

For more details:
Lorena's talk, *"Study of the influence of the manufacturing process and thermal cycling on the RF performance of 1.3 GHz Nb/Cu SRF cavities"*

Motivation of Temperature Mapping System

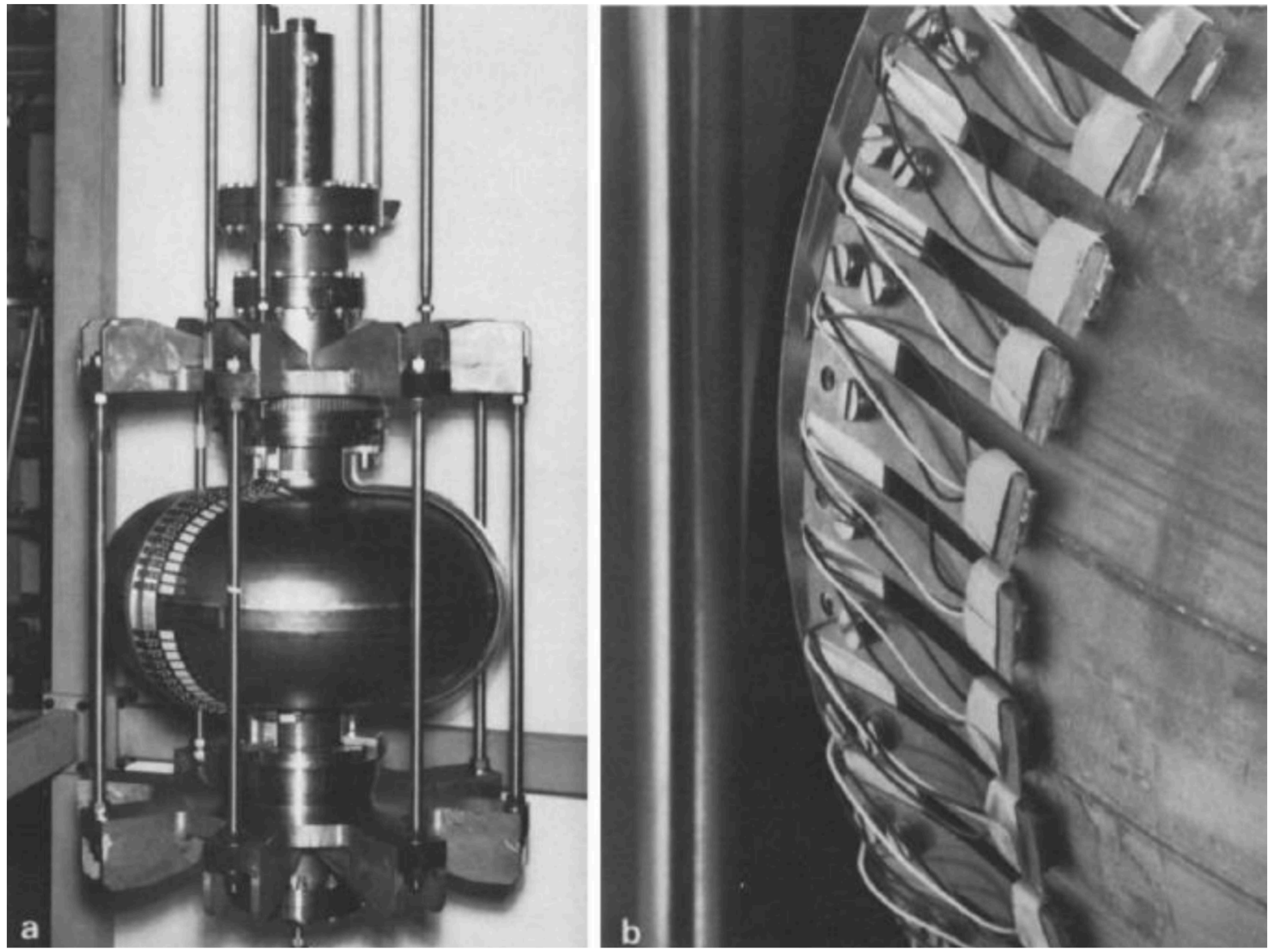
A dedicated study on heat dissipation of Nb/Cu cavities may help us understand the degradation of their performance and, as a consequence, improve them. **A temperature mapping system is needed for thermal studies on copper coated cavities.**

One of the first T-map on a bulk Nb cavity:



H. Padamsee, "History of gradient advances in SRF", arXiv: 2004.06720

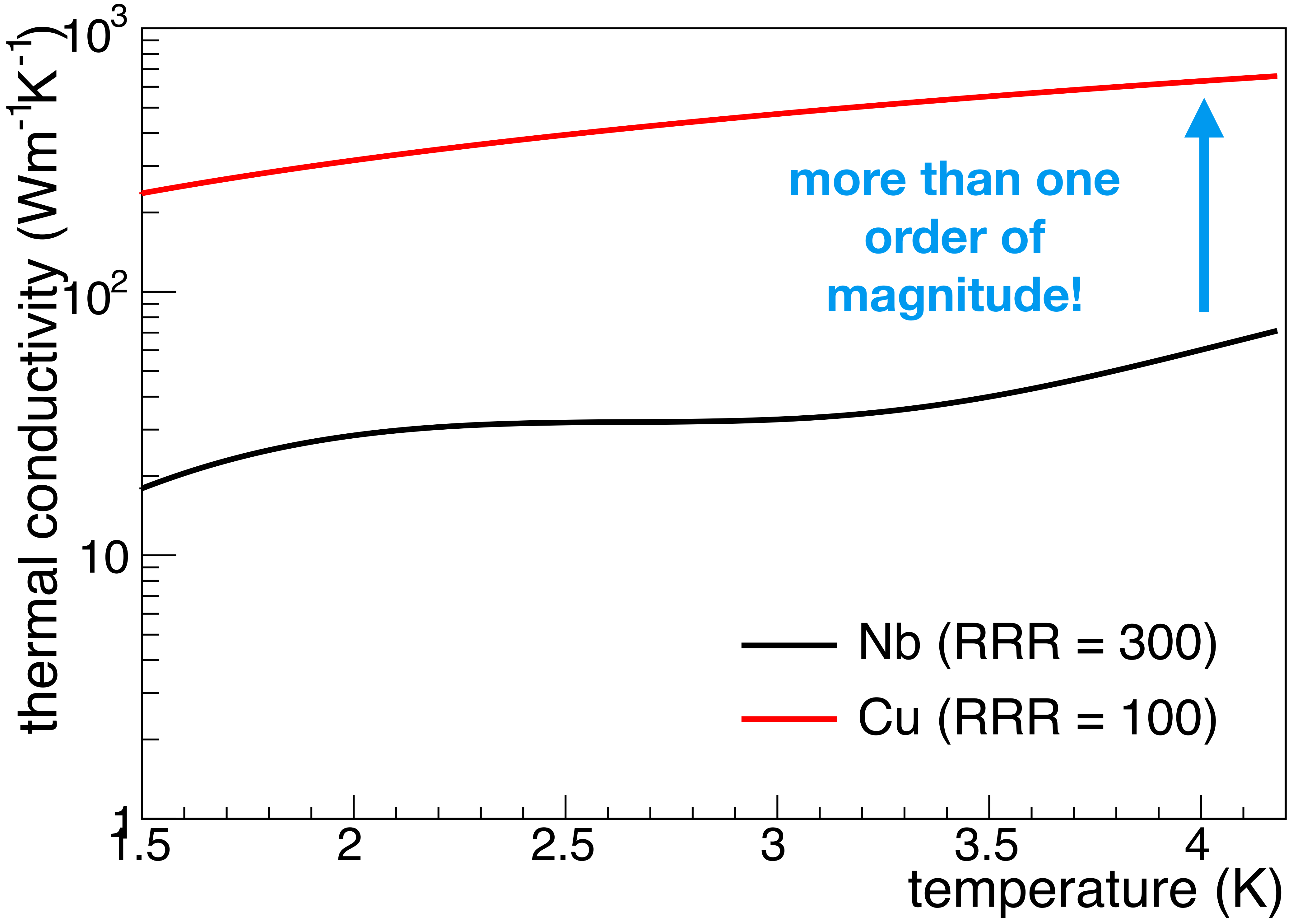
Rotating temperature mapping system at CERN in the 80s:



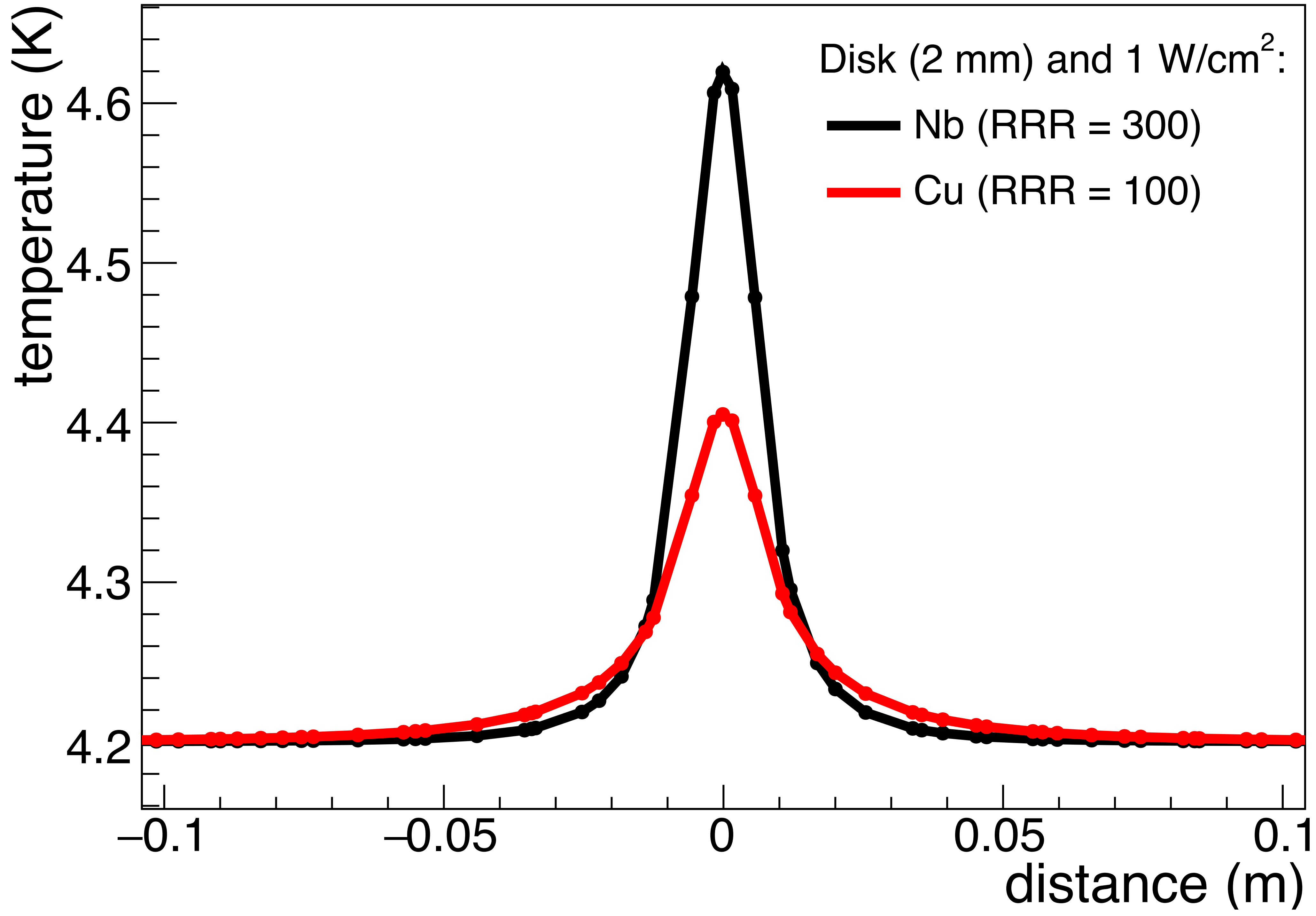
Ph. Bernard et al., NIM 190 (1981), report: CERN/EF/RF 80-2

Challenge

Development of a temperature mapping system, based on contact thermometry, to study thin film SRF cavities on copper. No T-map systems for Nb/Cu cavities are currently in operation.



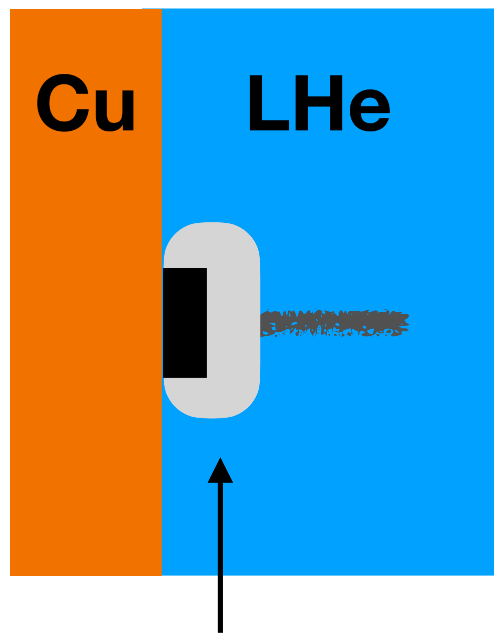
The thermal conductivity of copper is more than one order of magnitude higher than that of niobium

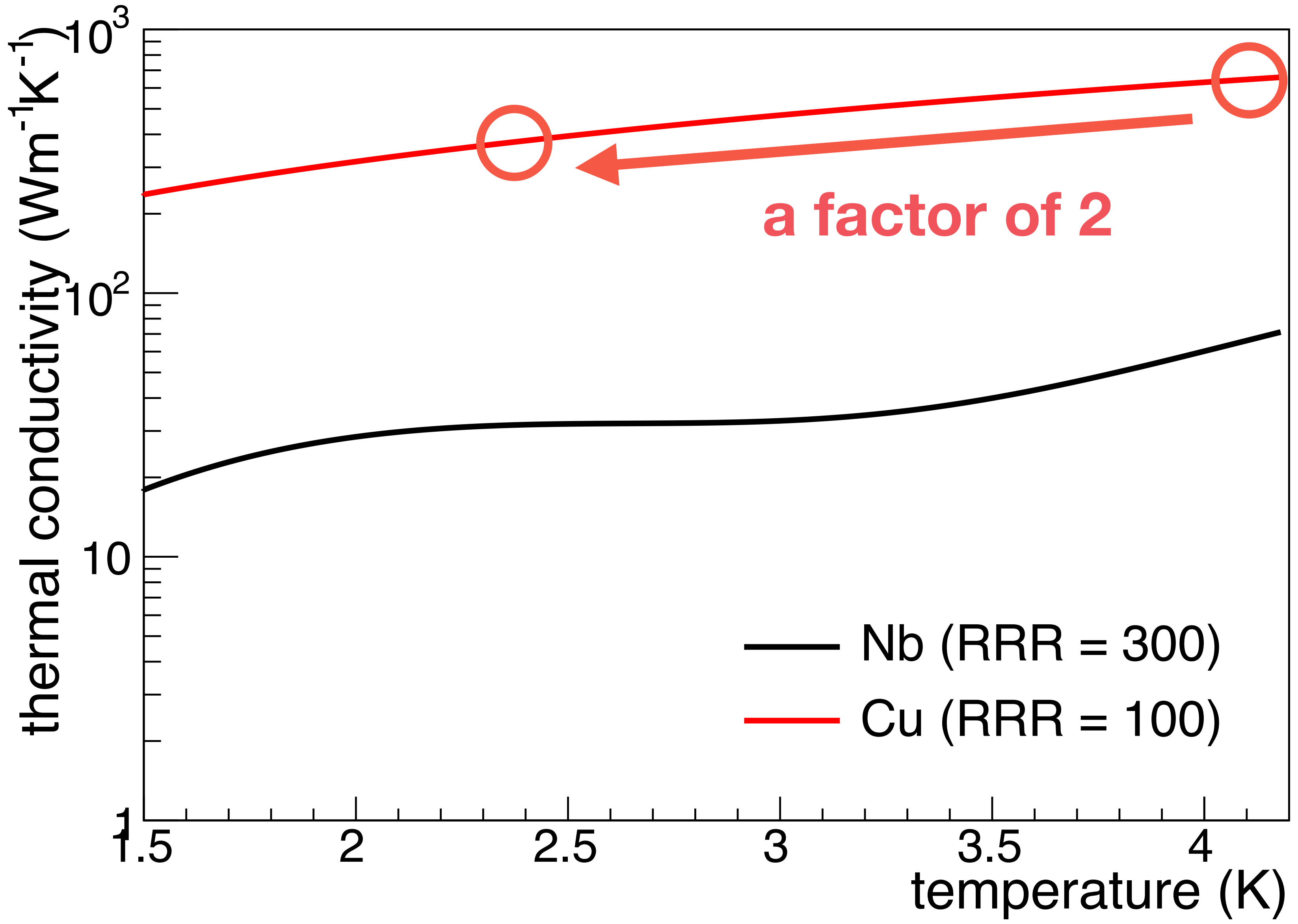


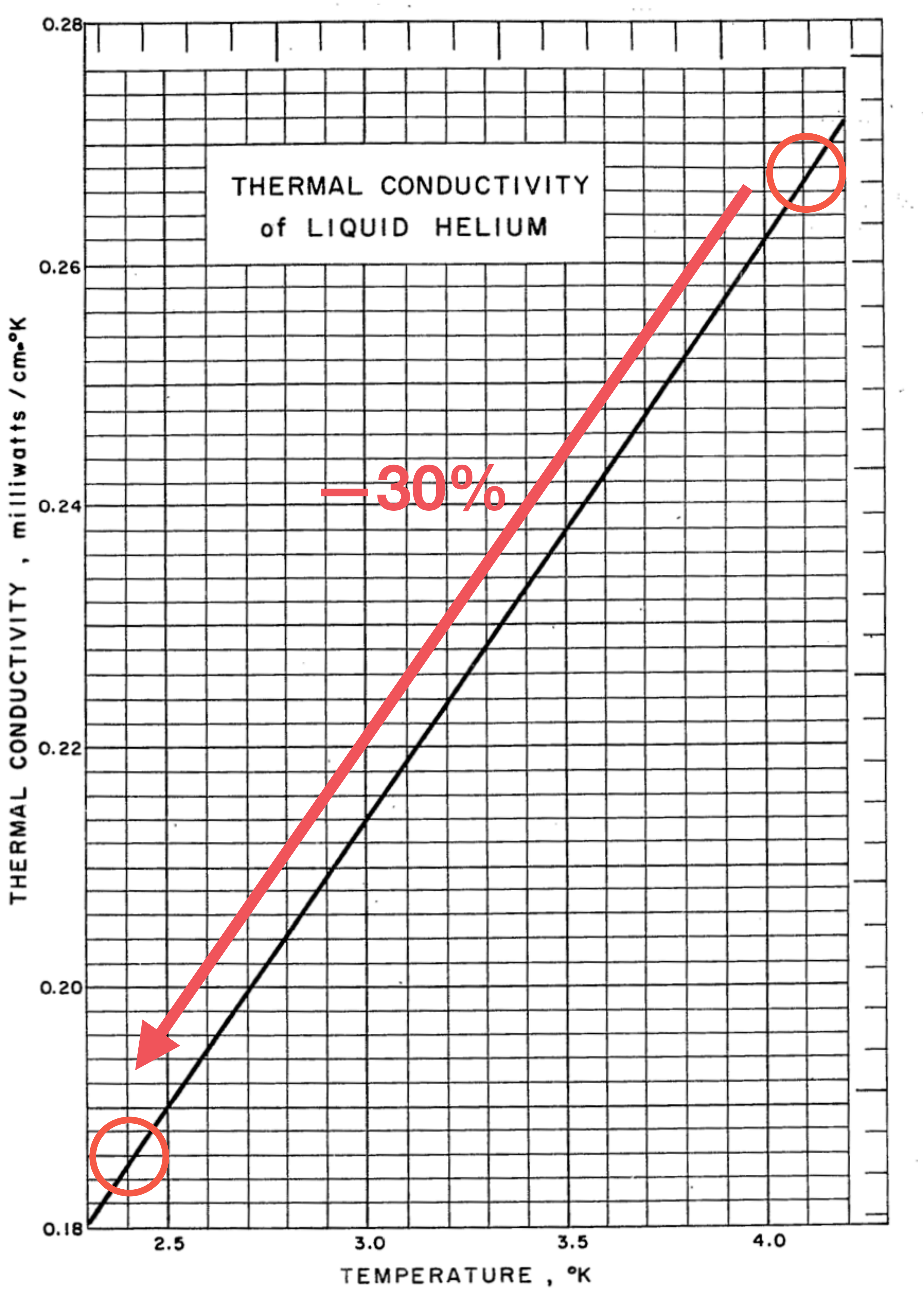
As a consequence, the temperature profile in copper surfaces turns out to be lower and slightly wider than than in niobium

Key Parameters

- **Environmental conditions for acquisition of T-maps on copper surfaces:**





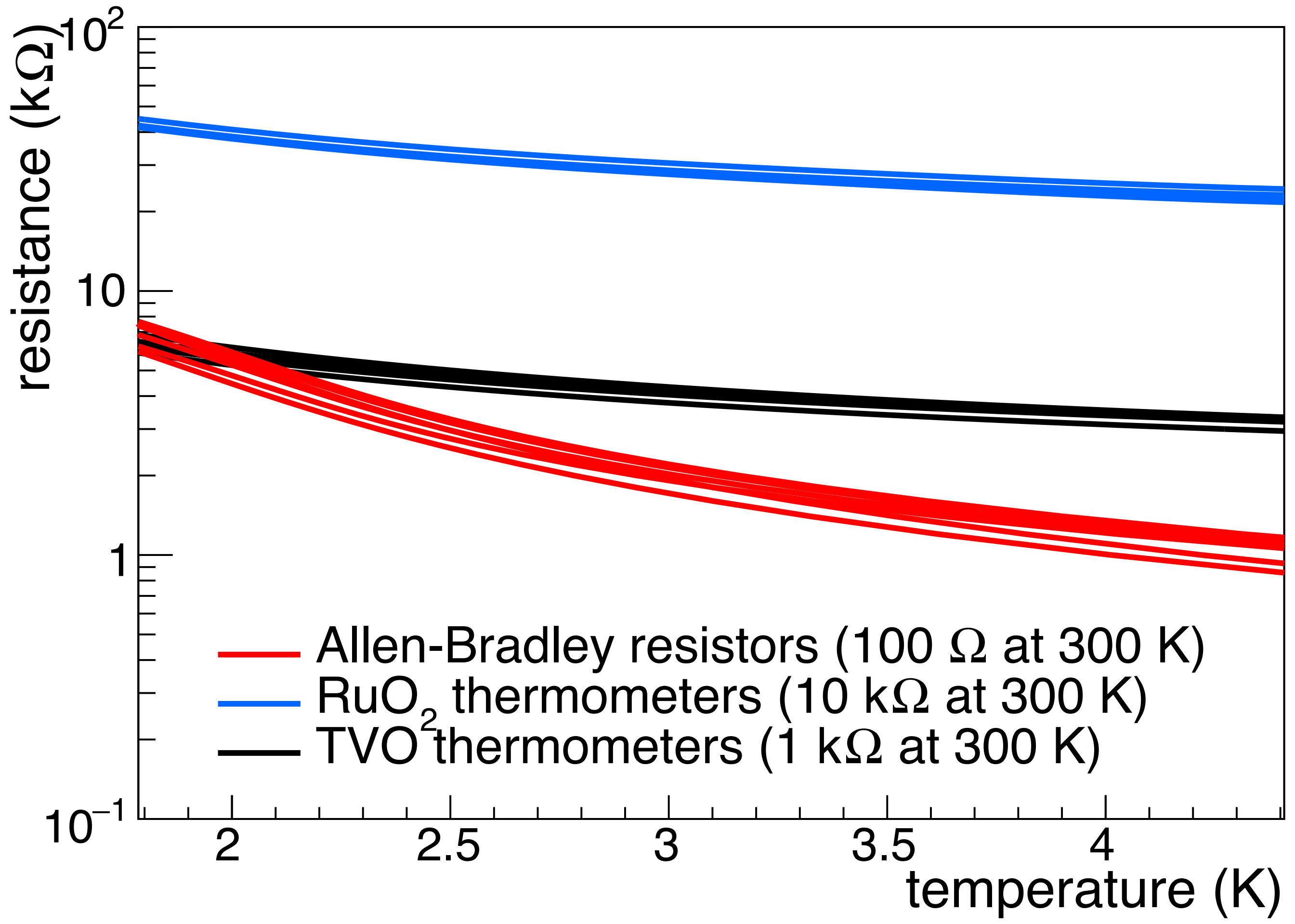


Cryogenic Data Notebook, report: BNL 10200-R

- **Sensitivity of thermometers:**

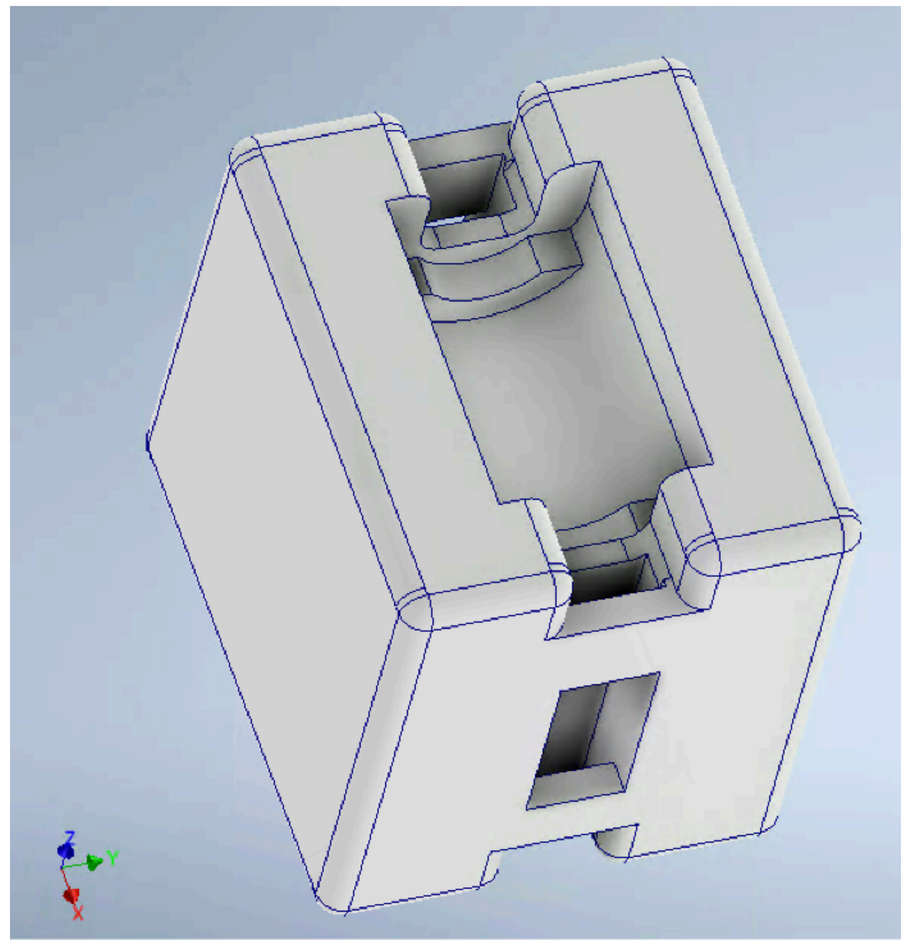
Thermometer	ΔR/R	Price per unit
RuO_2	~1.5	~1 CHF
Allen-Bradley	~7	~2-3 CHF
TVO	~1.5	~50 CHF

In the future, possibility to directly substitute Allen-Bradley thermometers with TVO thermometers



Key Parameters

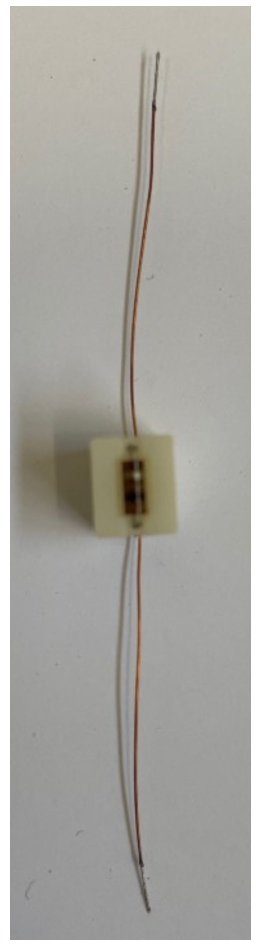
- **Thermal isolation of thermometers:**



Drawing by Marco Chiodini

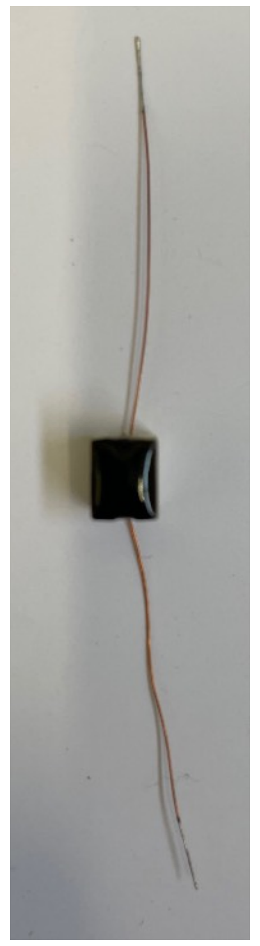
3D printed in Accura 25

suitable at cryogenic temperatures



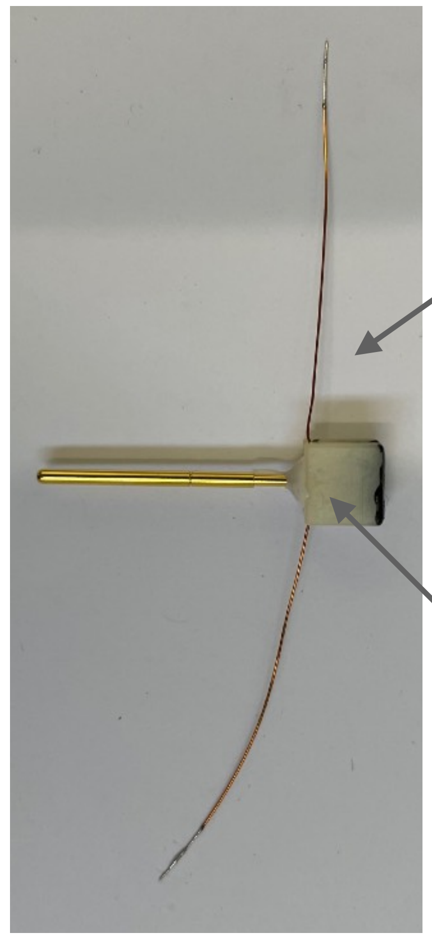
sealed with Stycast epoxy

high thermal conductivity and impervious to superfluid He



spring loaded pin in BeCu

elastic at cryogenic temperatures and non-magnetic



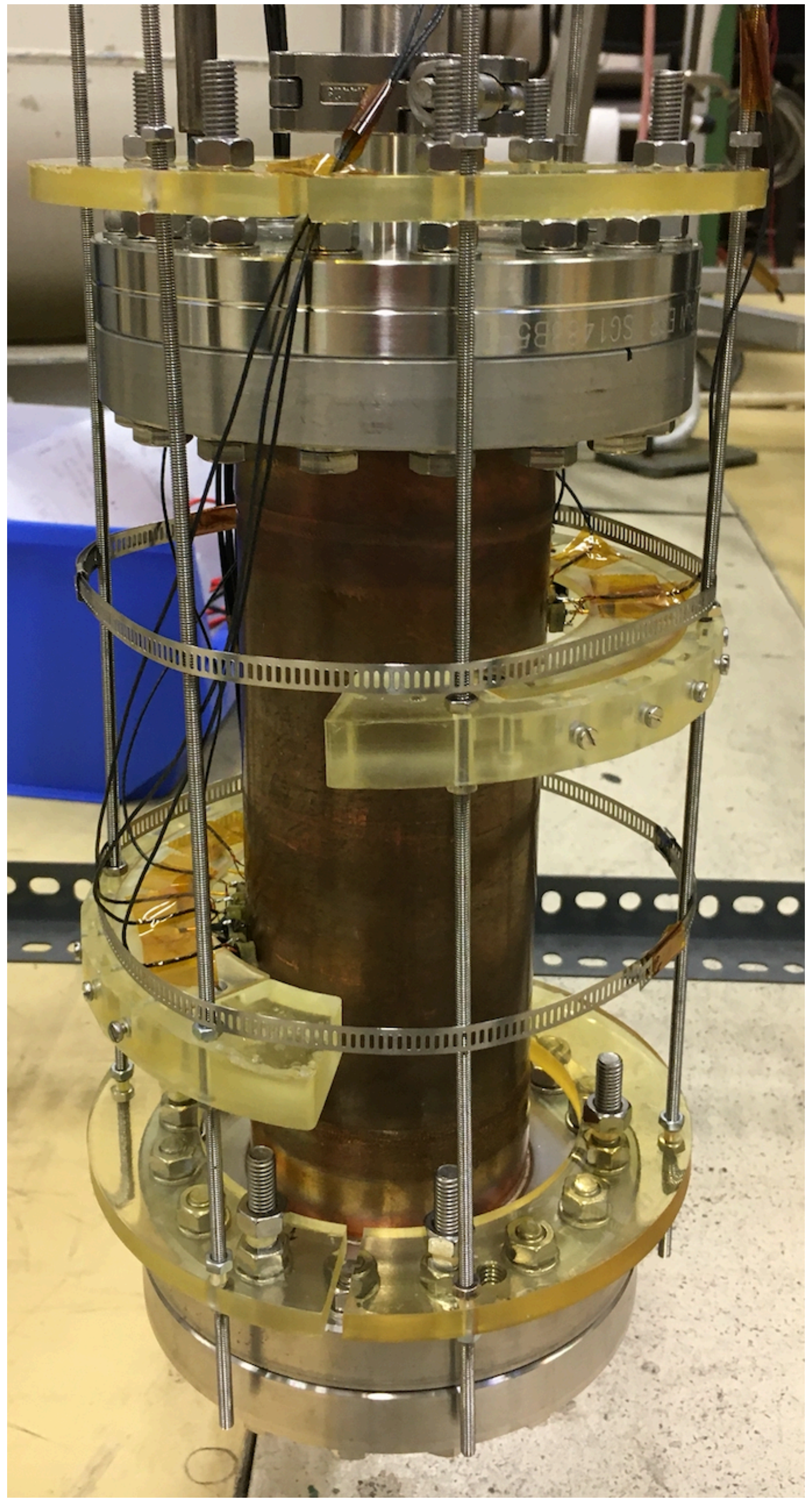
Manganin wire
(low thermal conductivity)

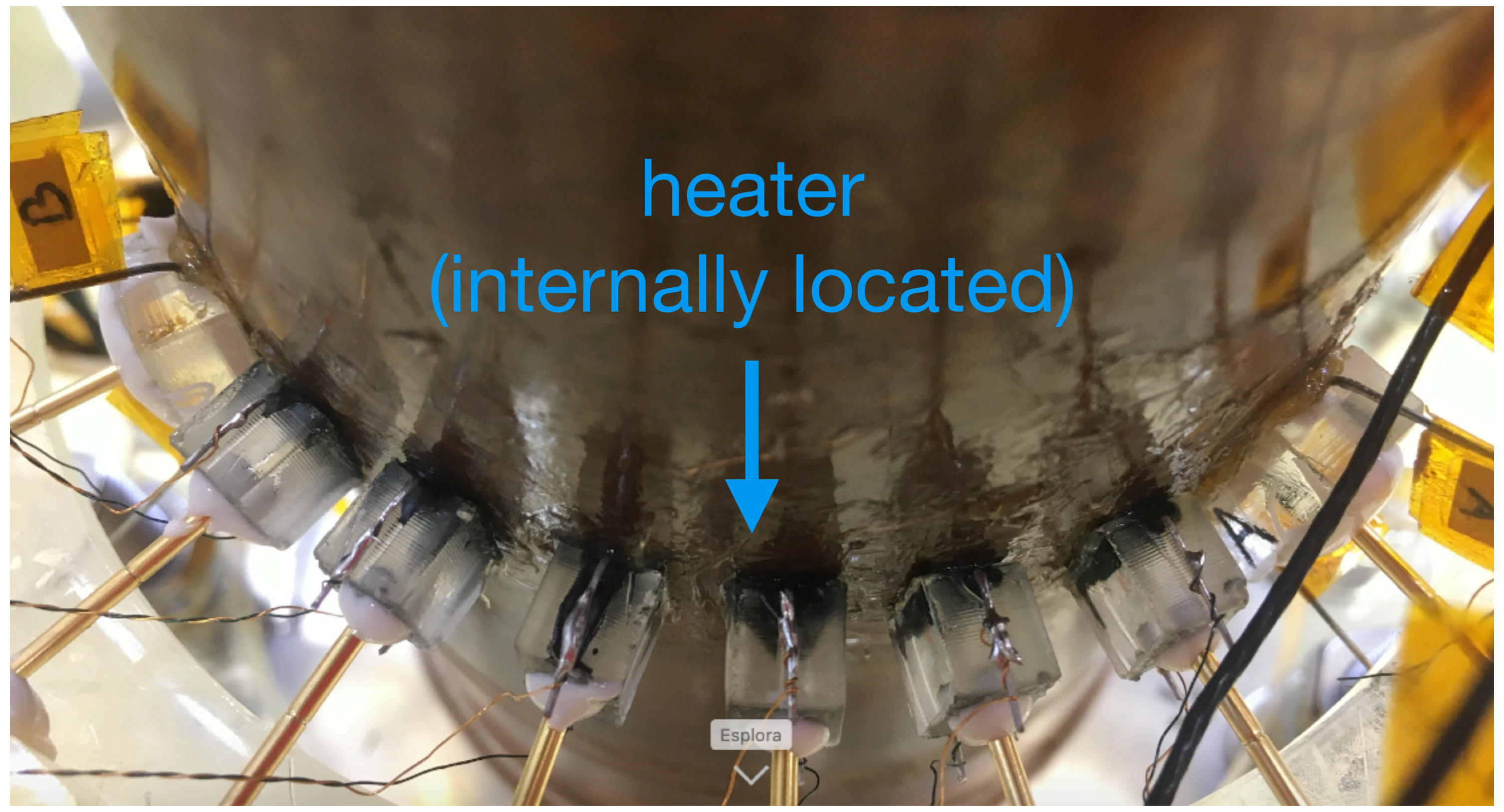
Silicone rubber CAF4
(for cryogenic temperatures)

- **Analog digital converters (ADC) with high resolution and sampling rate:**

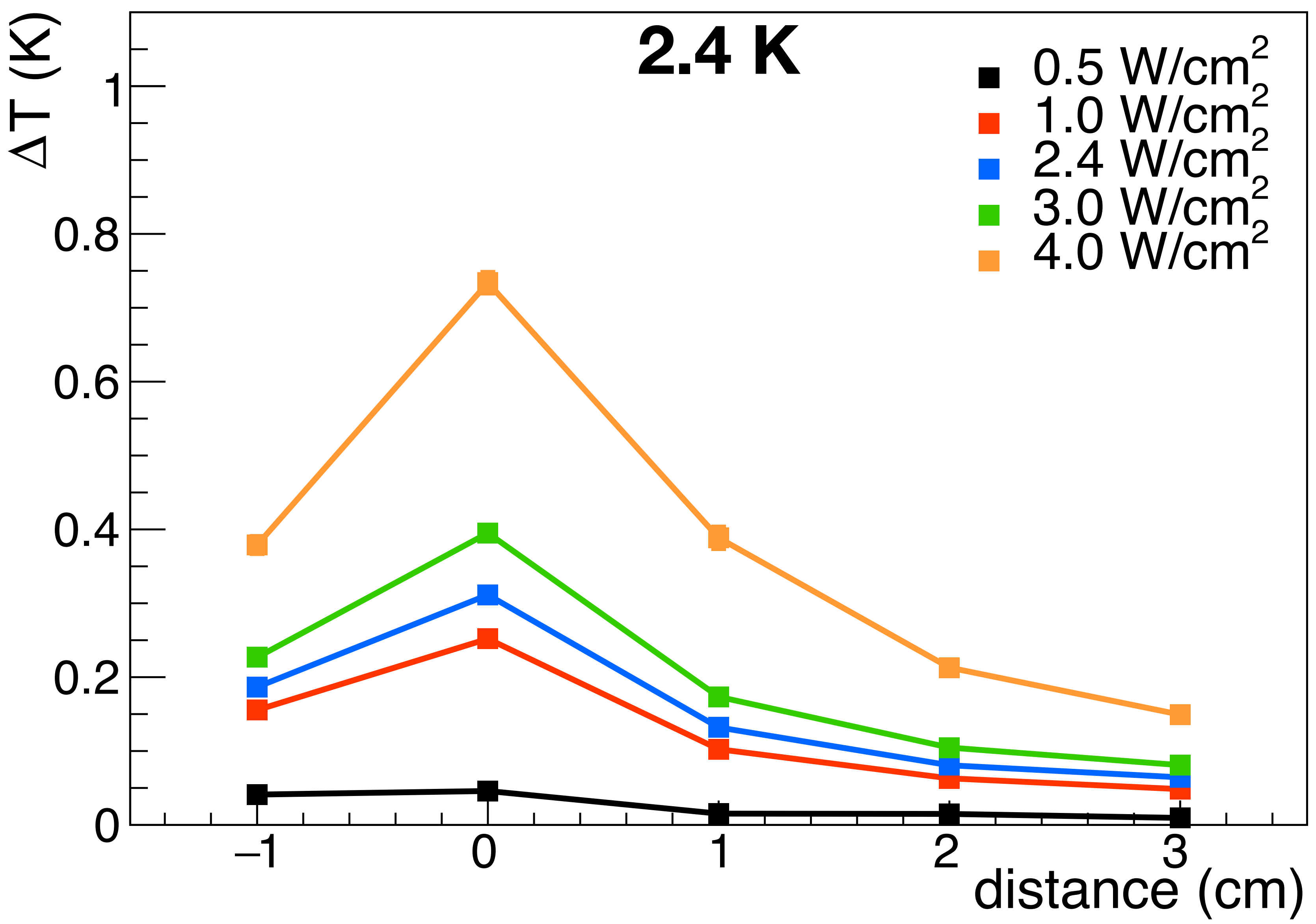
- 24-bit analog input in ±3 V (high resolution)
- miniXLR cables (low noise)
- 2-wire differential acquisition (better precision)
- sampling rate up to 100 kS/s (high speed temperature mapping)

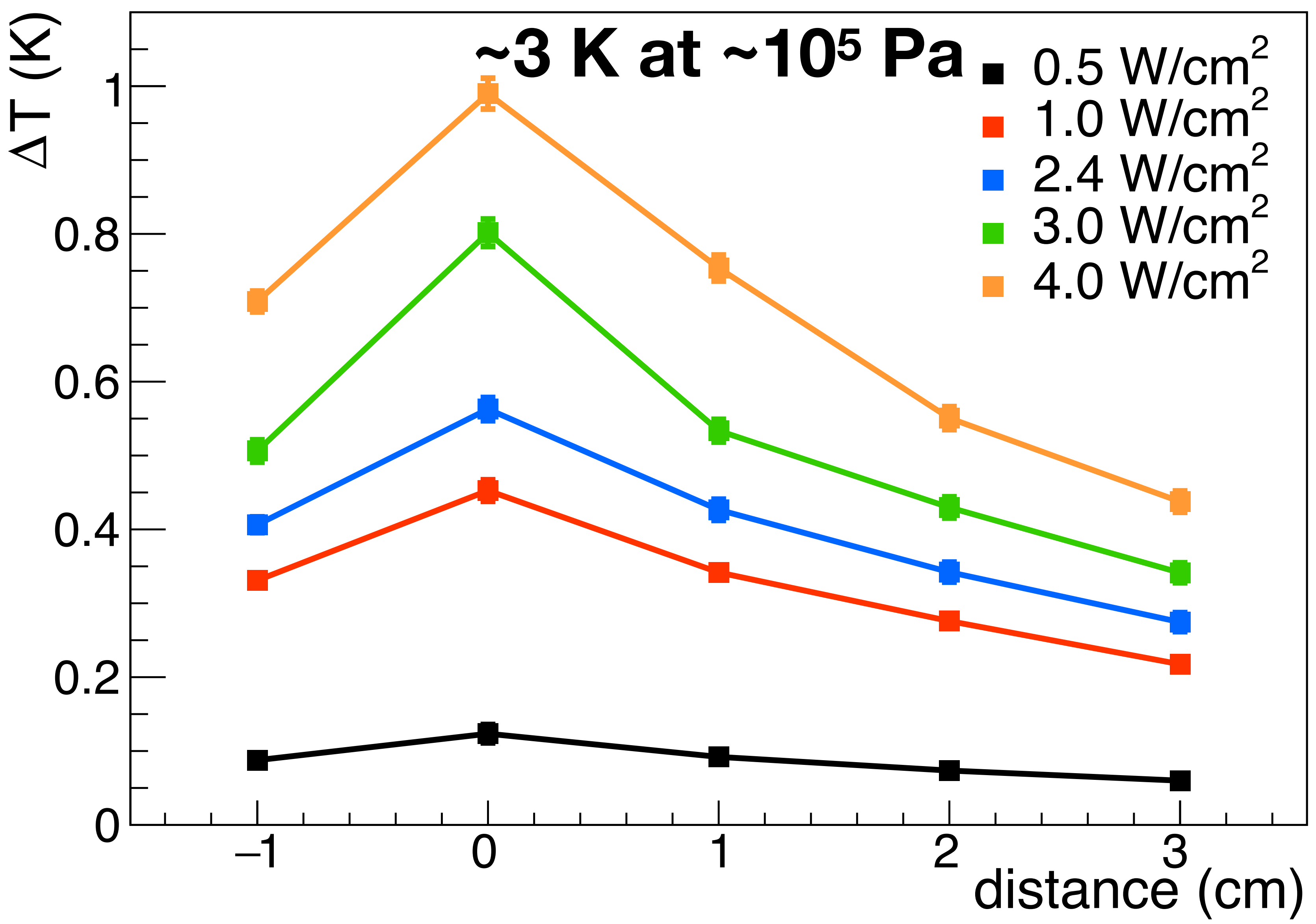
Thermal Studies on Copper Surfaces





Goal: characterization of thermometers and their thermal contacts with copper surfaces thanks to a dummy cylindrical cavity

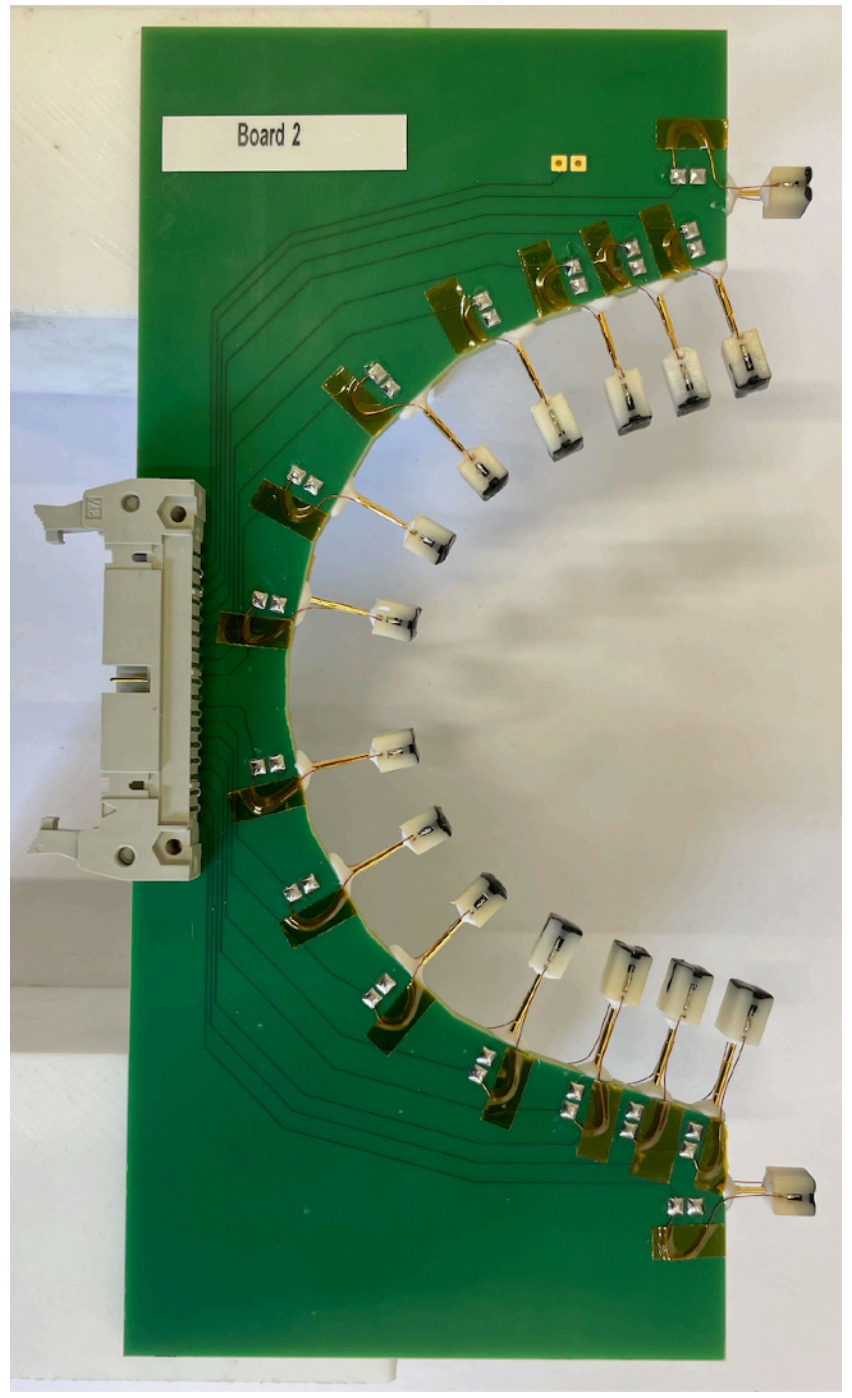


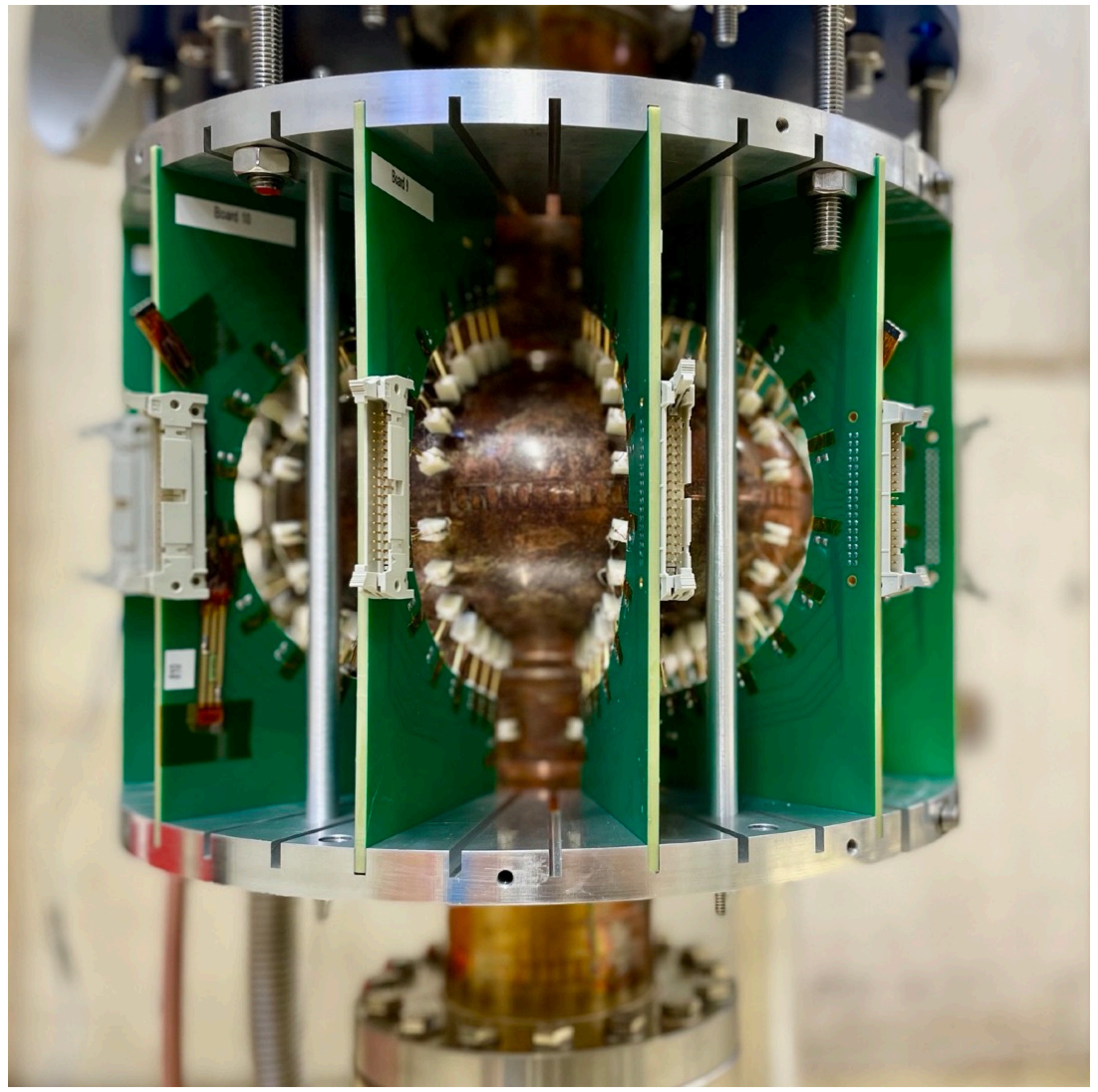


A. Bianchi et al., "Thermal Mapping Studies on Nb/Su SRF Cavities", 2021, THPCAV007

Temperature Mapping System for Nb/Cu cavities

Twelve boards (~200 thermometers):

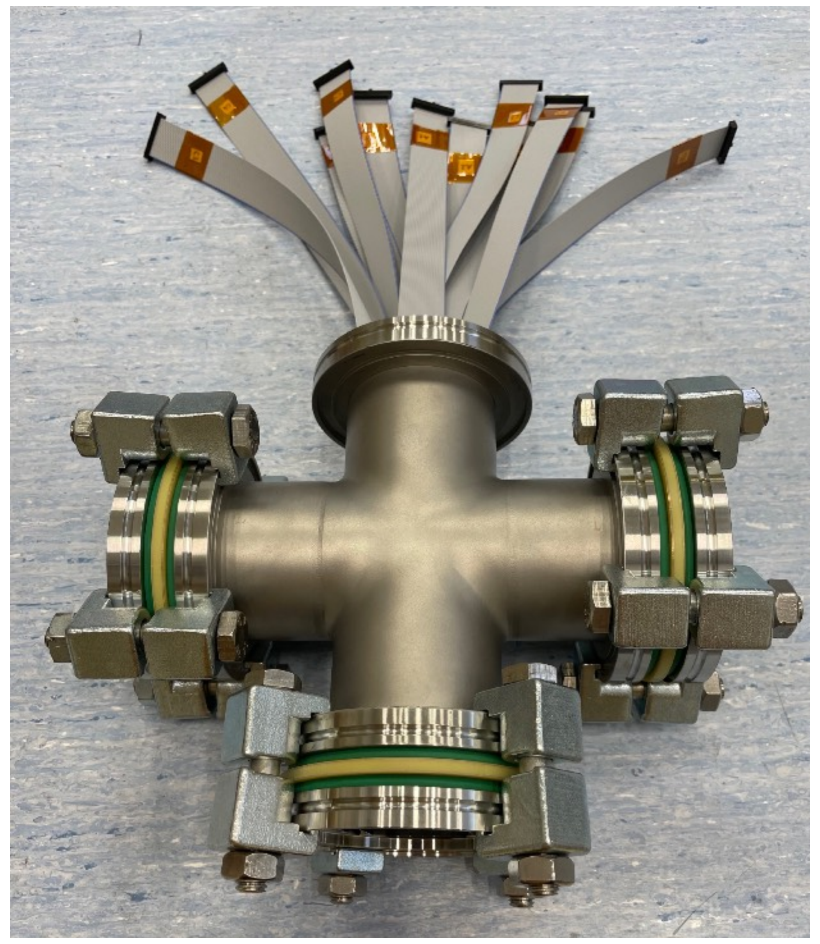


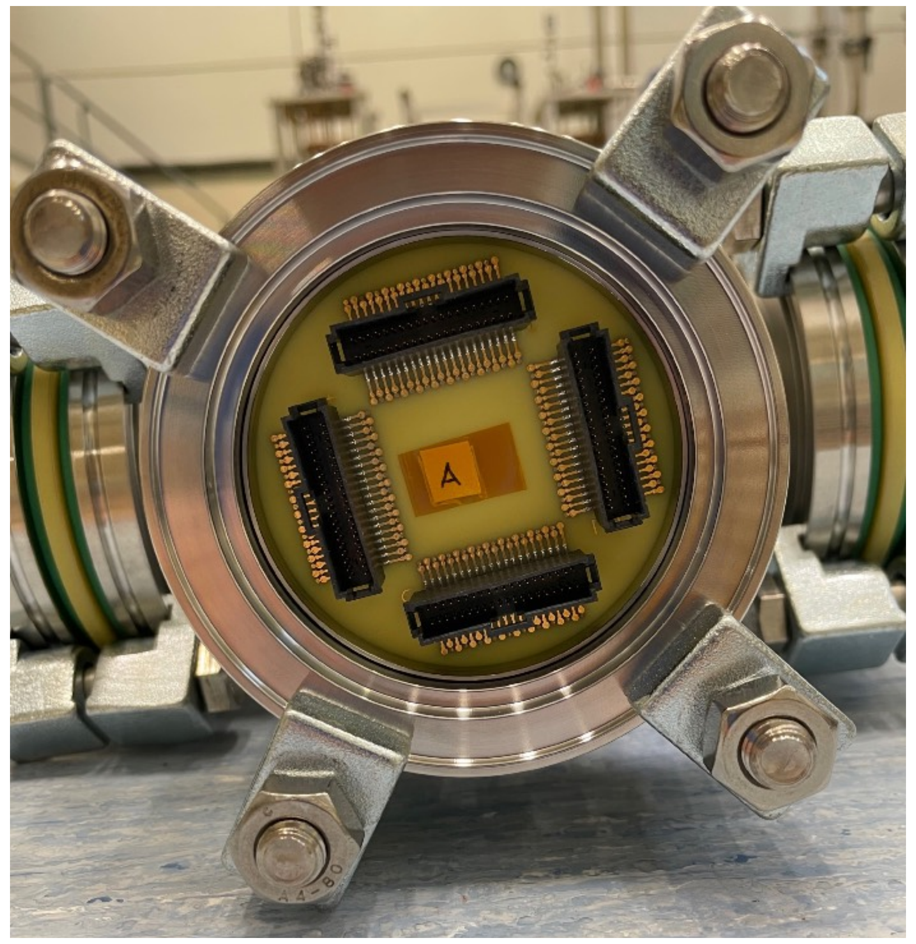


- **~200 thermometers**
- **~500 feedthroughs** in 3 SMT/SMD PCBs
- **6 multiplexers**
- **12 ADC channels** (maximum sampling rate: 100 kS/s)

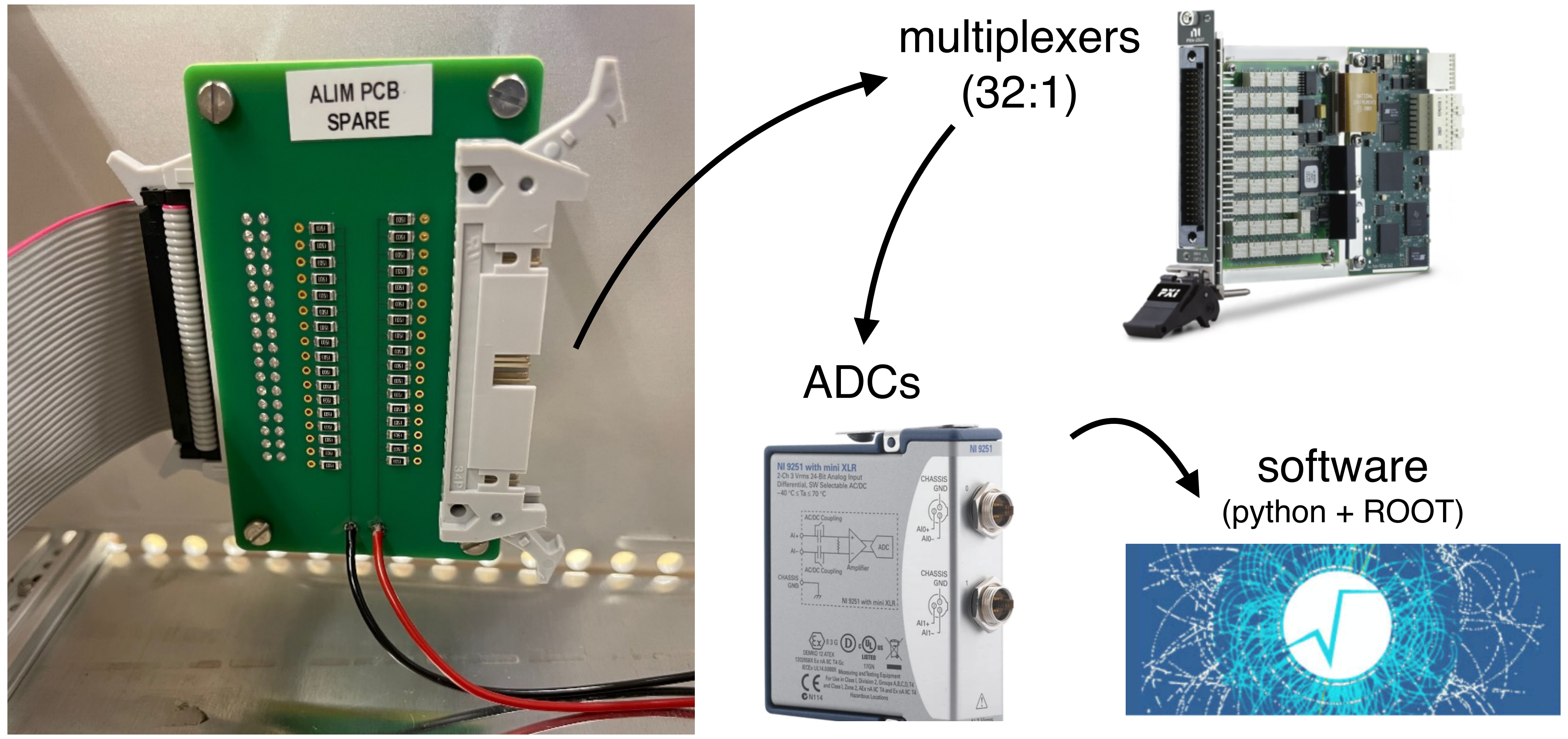
  → possibility of **high-speed temperature mapping**

Five hundreds feedthroughs in three SMT/SMD PCBs:

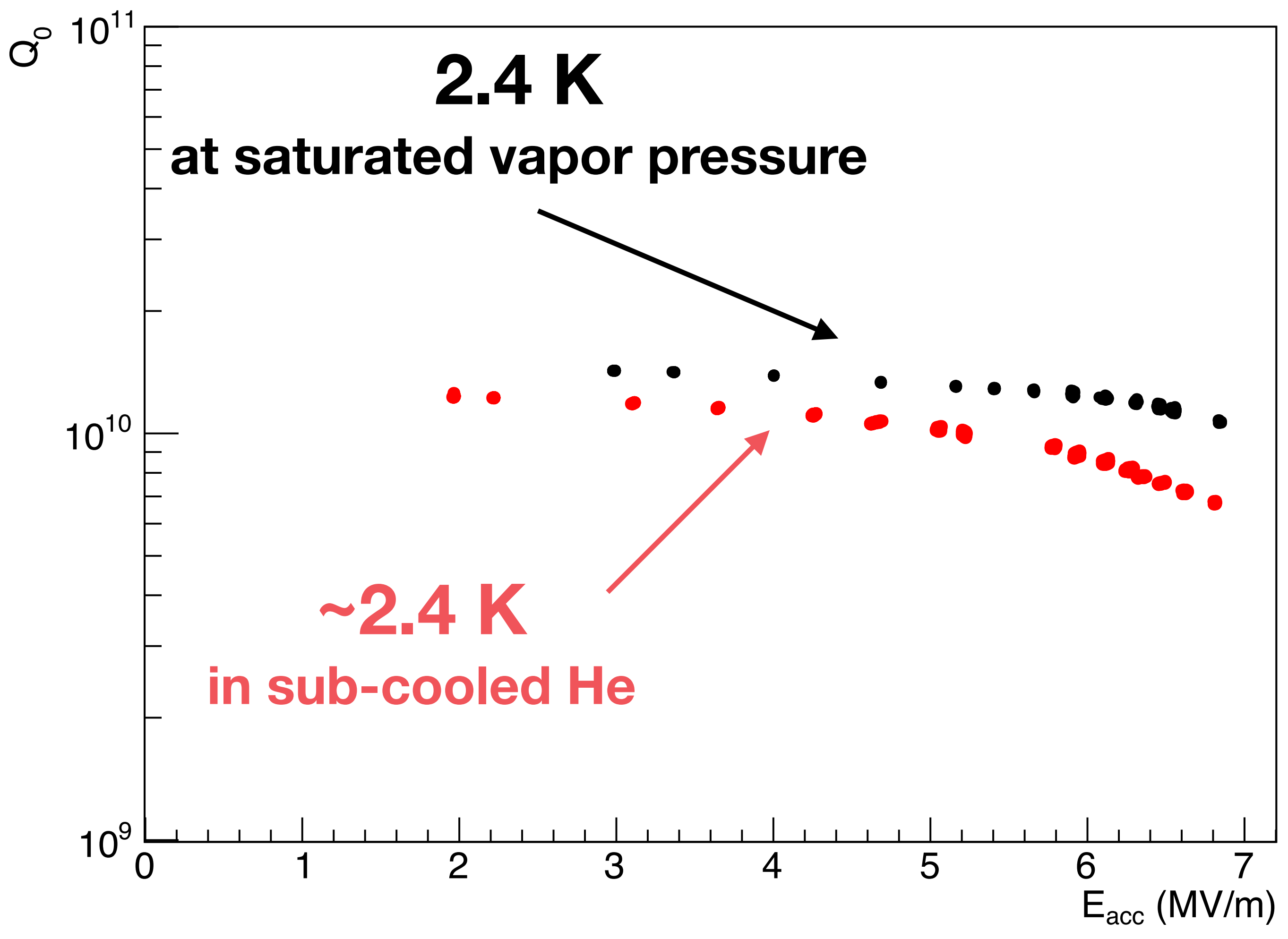


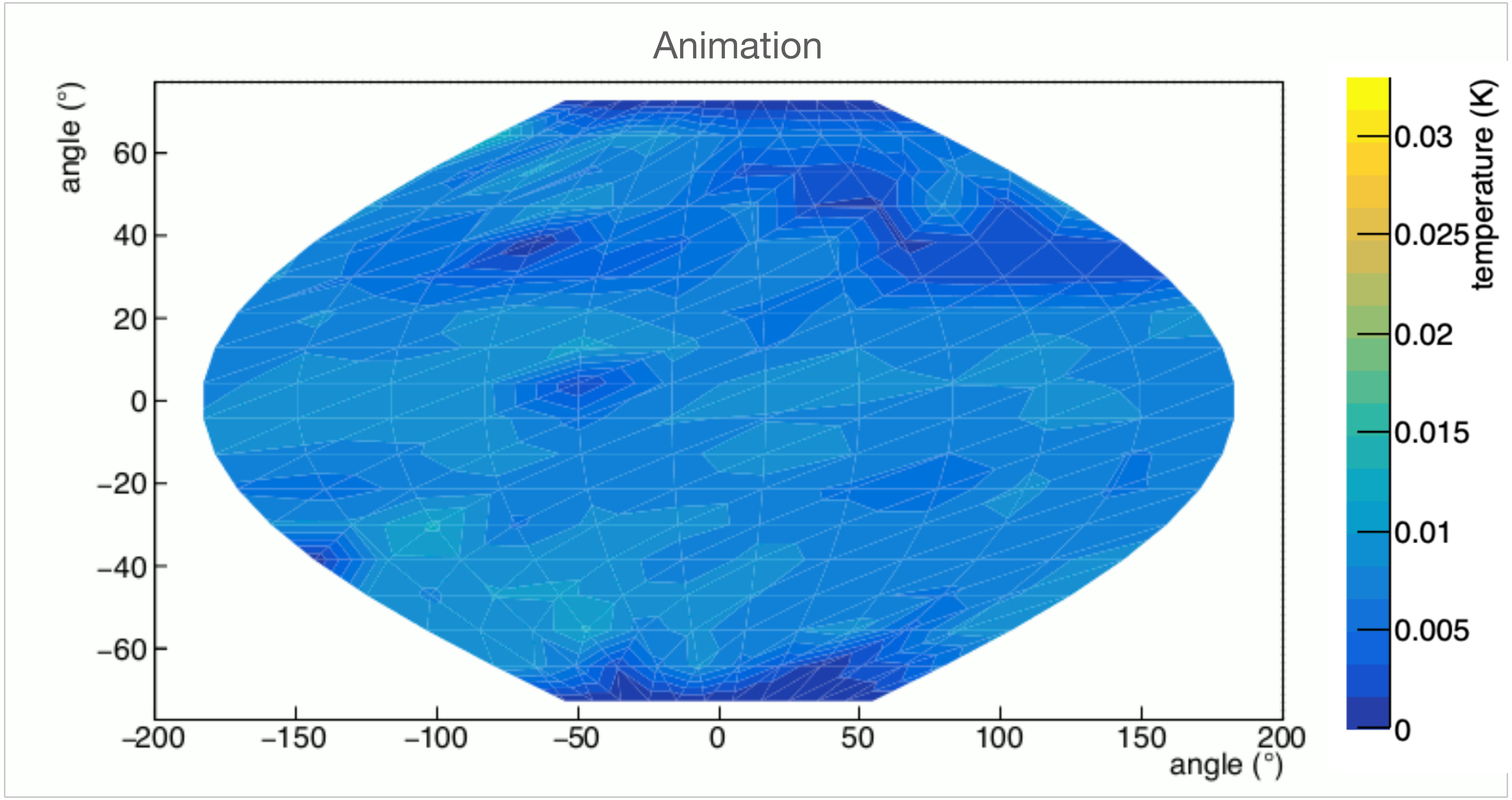


Twelve PCBs for electrical circuit:



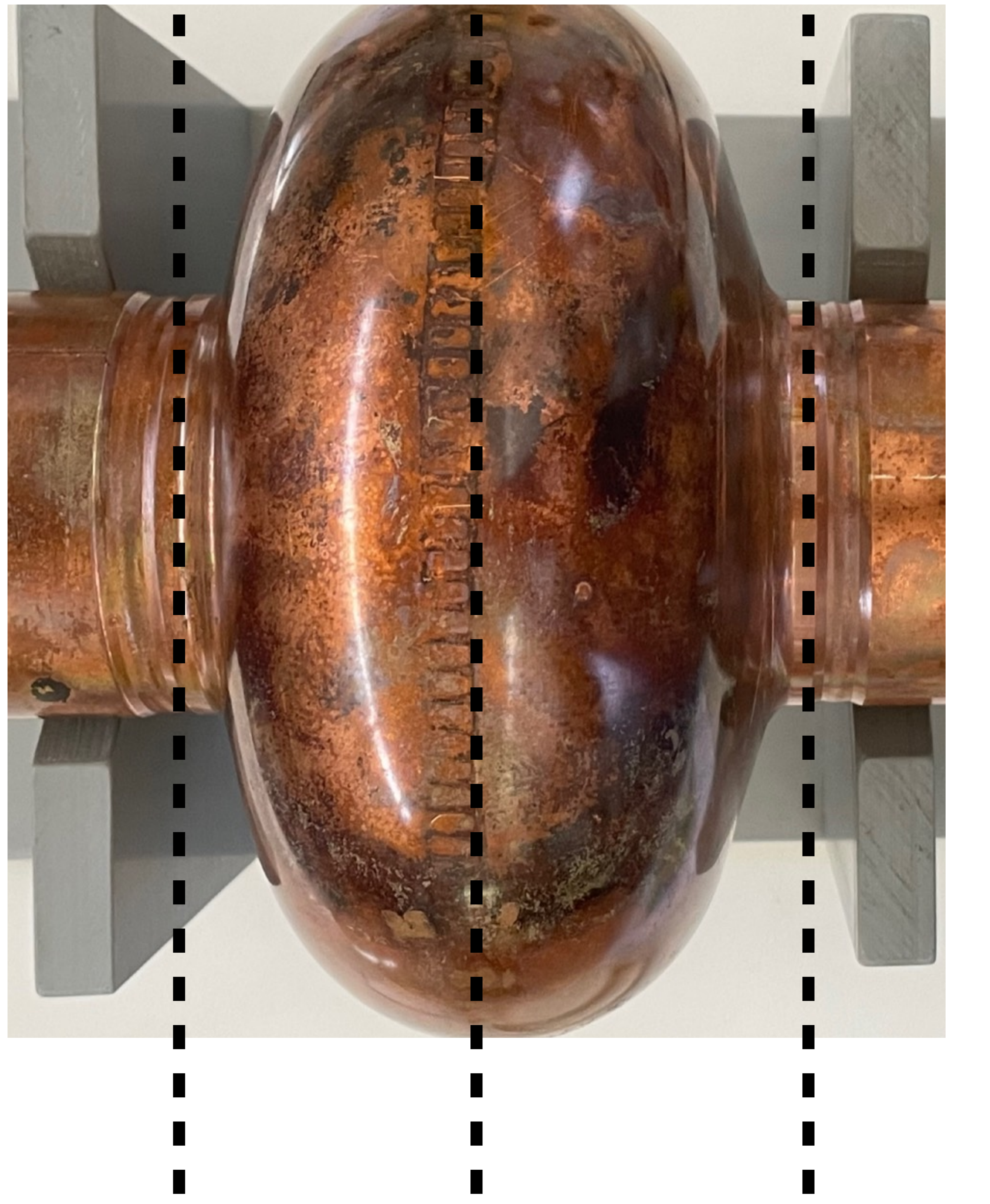
Temperature Maps at 2.4 K

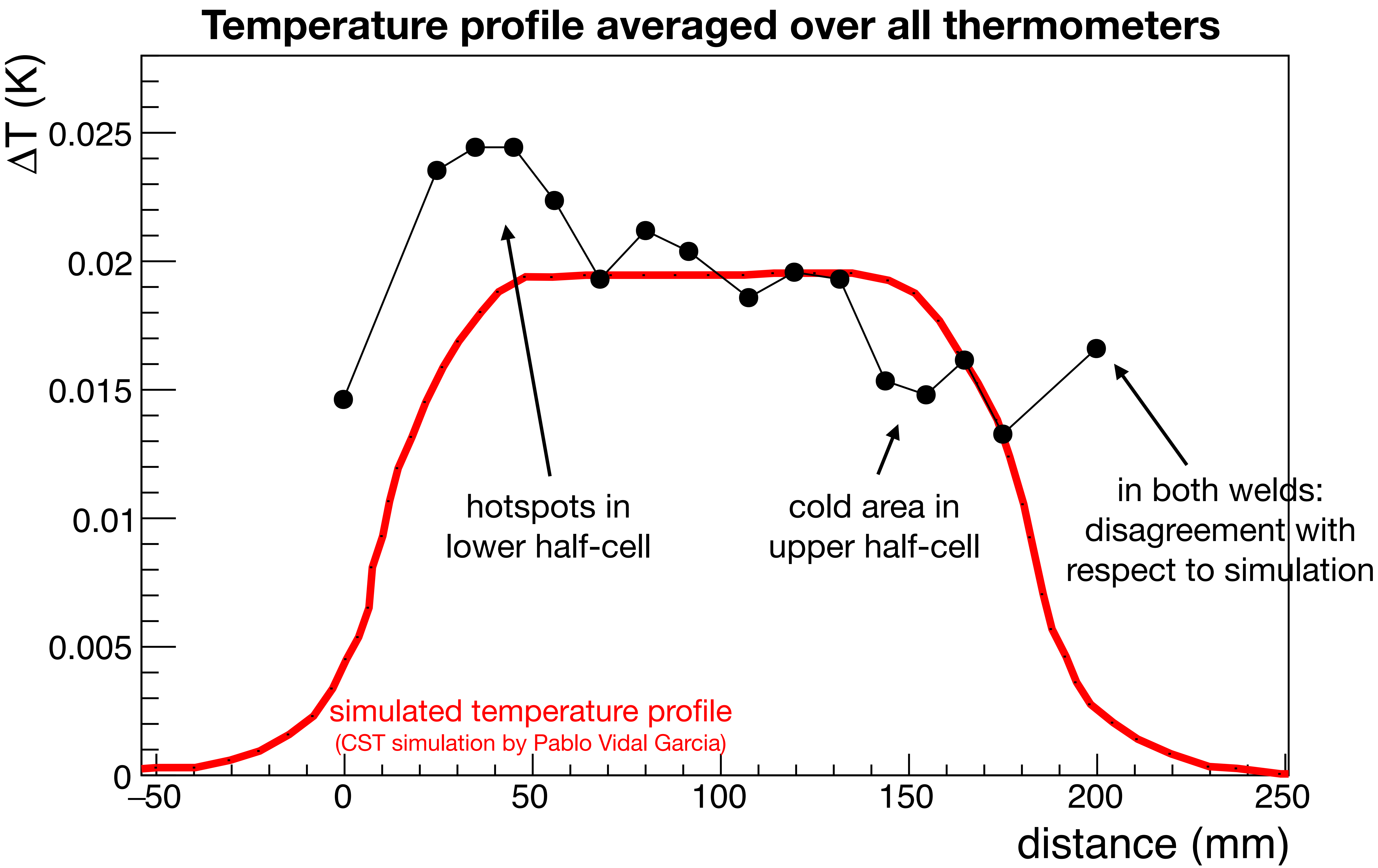




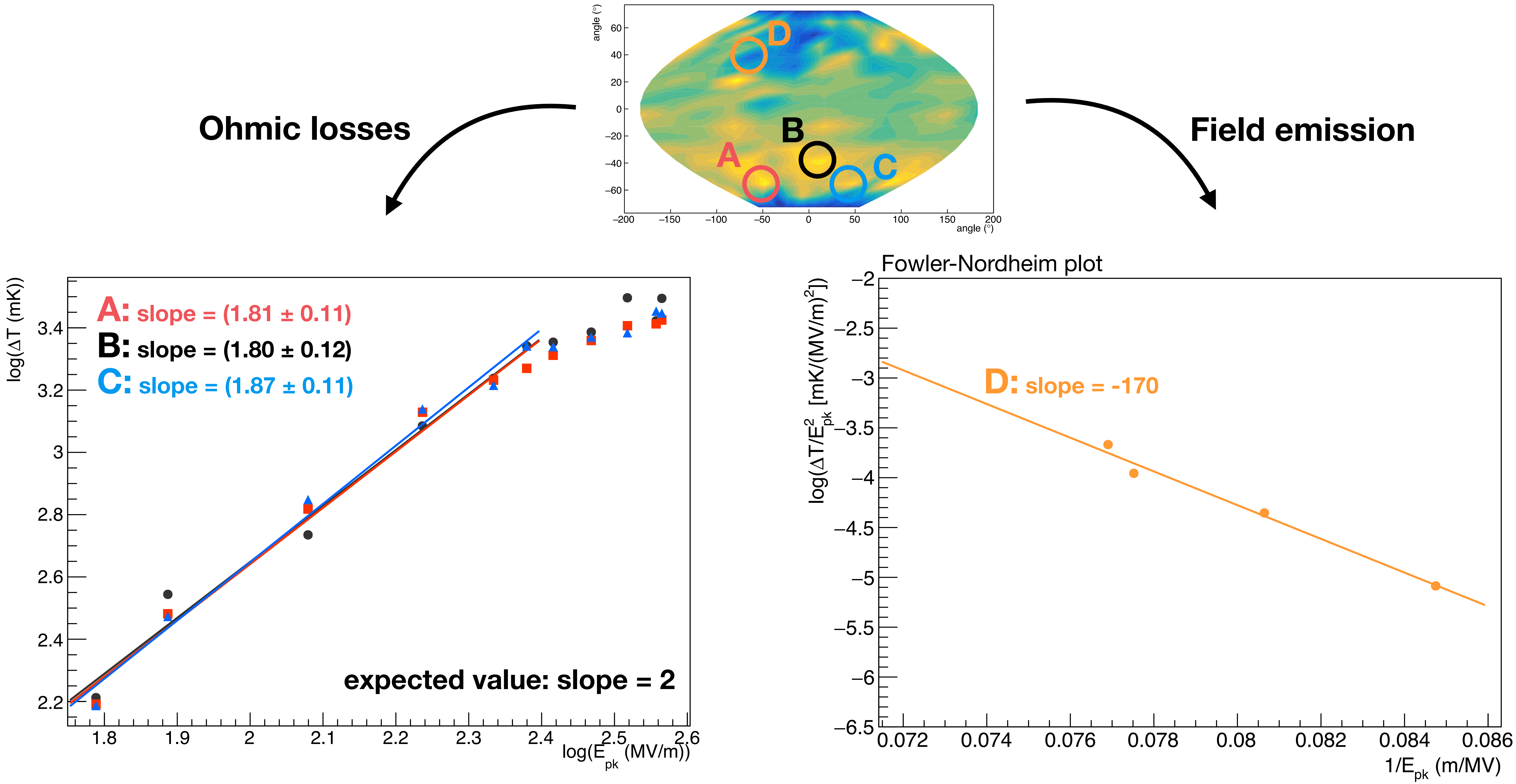
Presence of some hotspots but also, surprisingly, one cold area!

Temperature Profile at 2.4 K



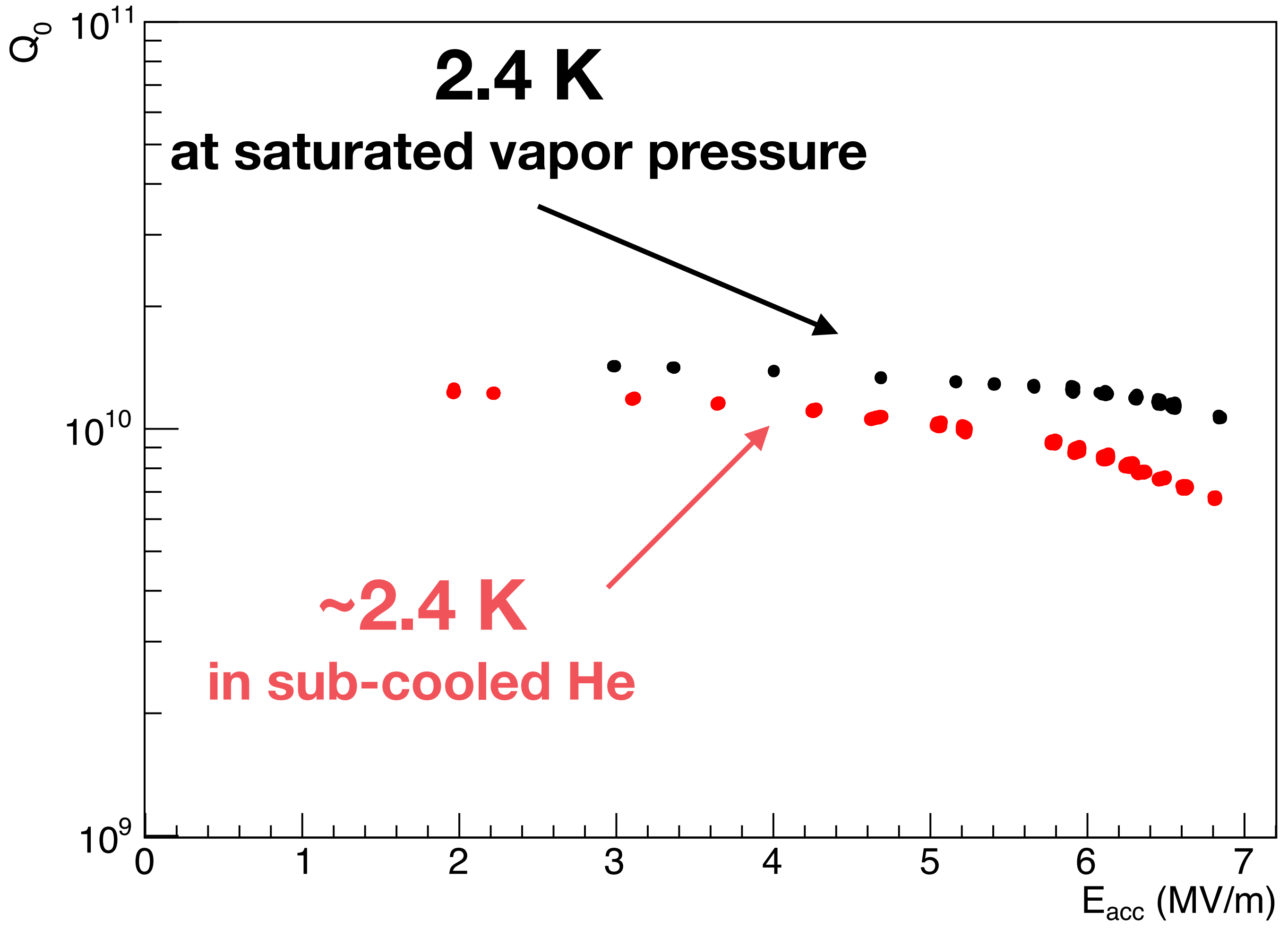


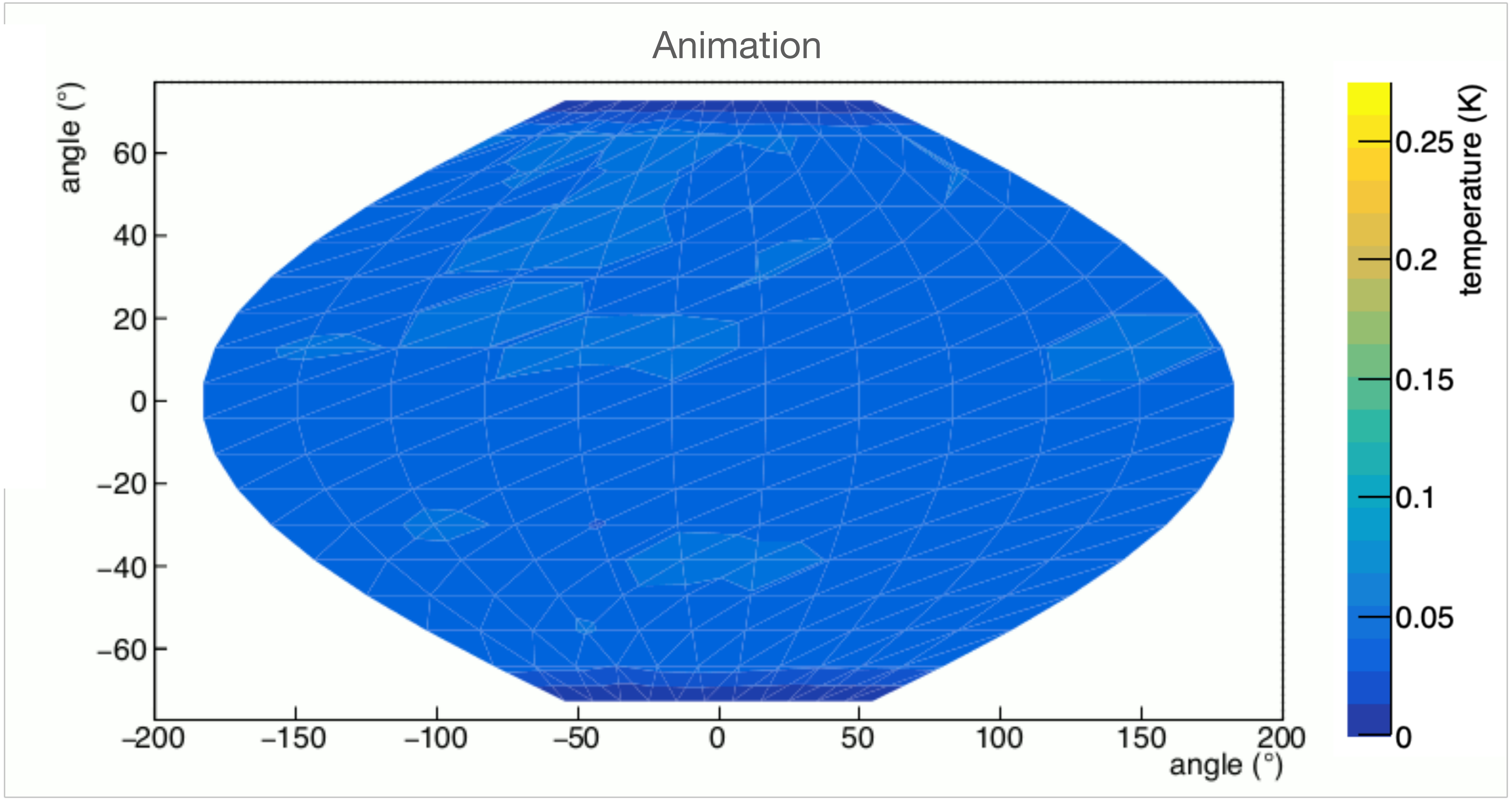
Heat losses



angle (°)
D
A
B
C
Ohmic losses
Field emission
A: slope = (1.81 ± 0.11)
B: slope = (1.80 ± 0.12)
C: slope = (1.87 ± 0.11)
expected value: slope = 2
log(ΔT (mK))
log(E_pk (MV/m))
Fowler-Nordheim plot
D: slope = -170
log(ΔT/E_pk^2 [mK/(MV/m)^2])
1/E_pk (m/MV)

Temperature Maps at 2.4 K in sub-cooled He

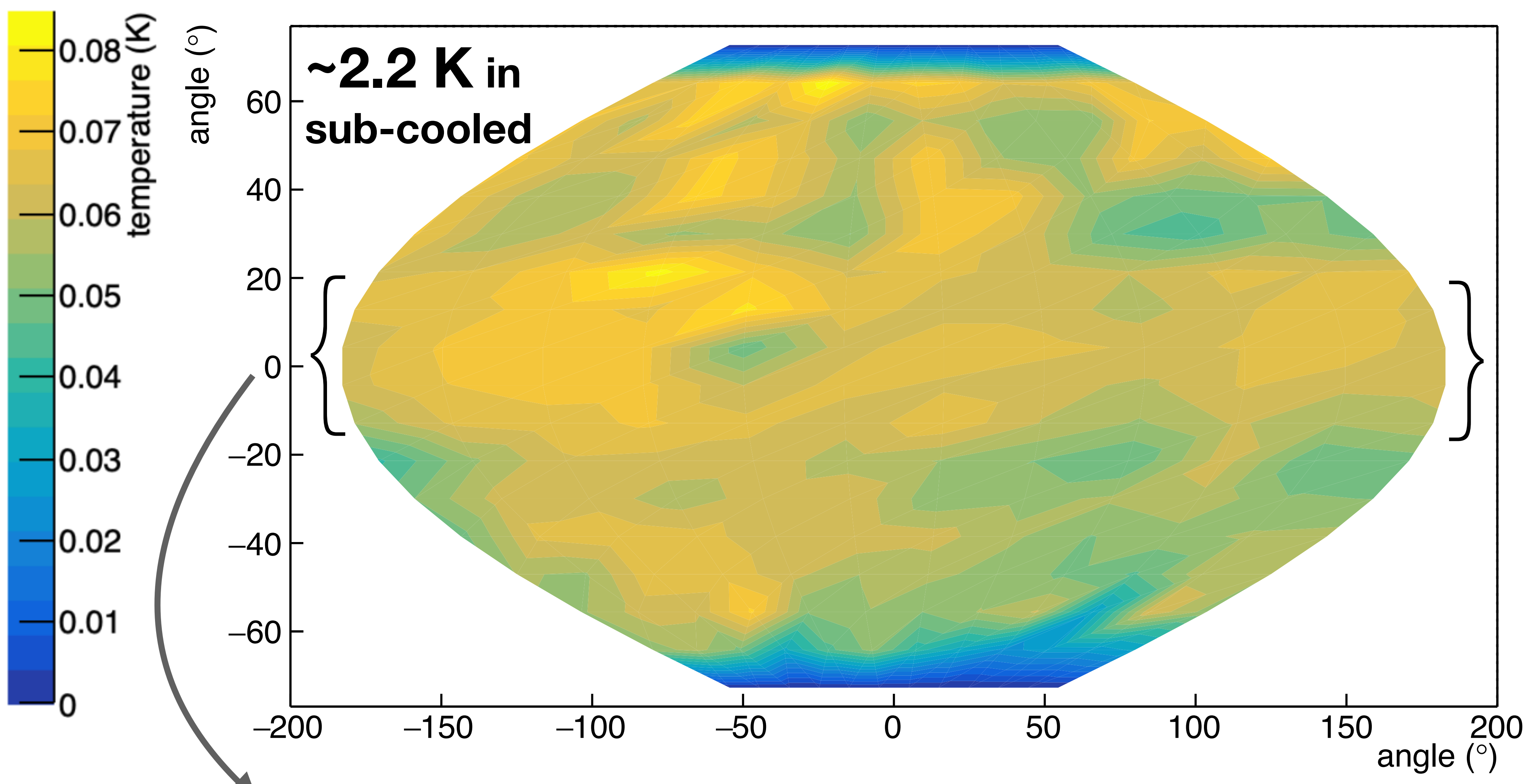


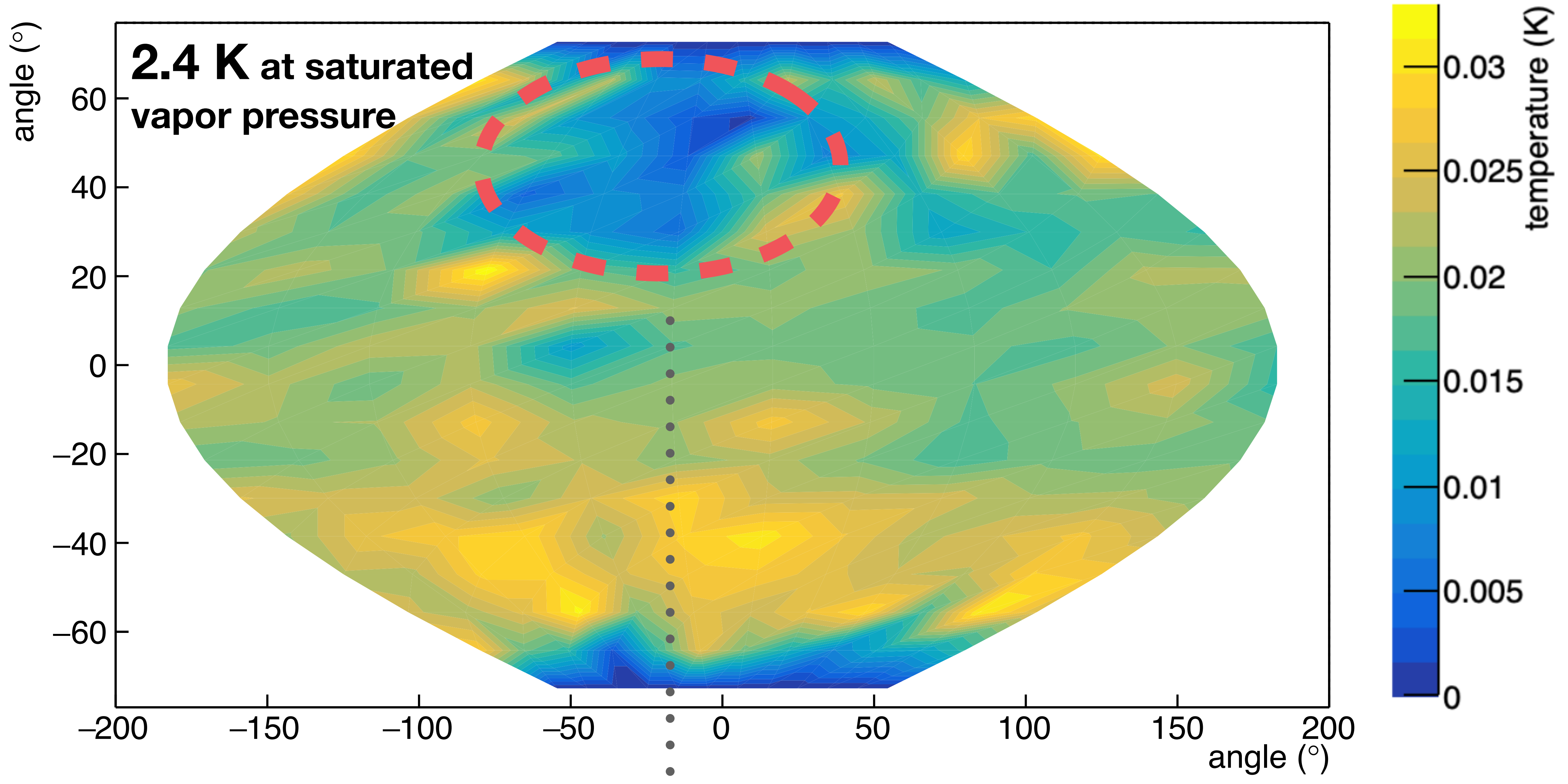


In sub-cooled He, no cold area is detected

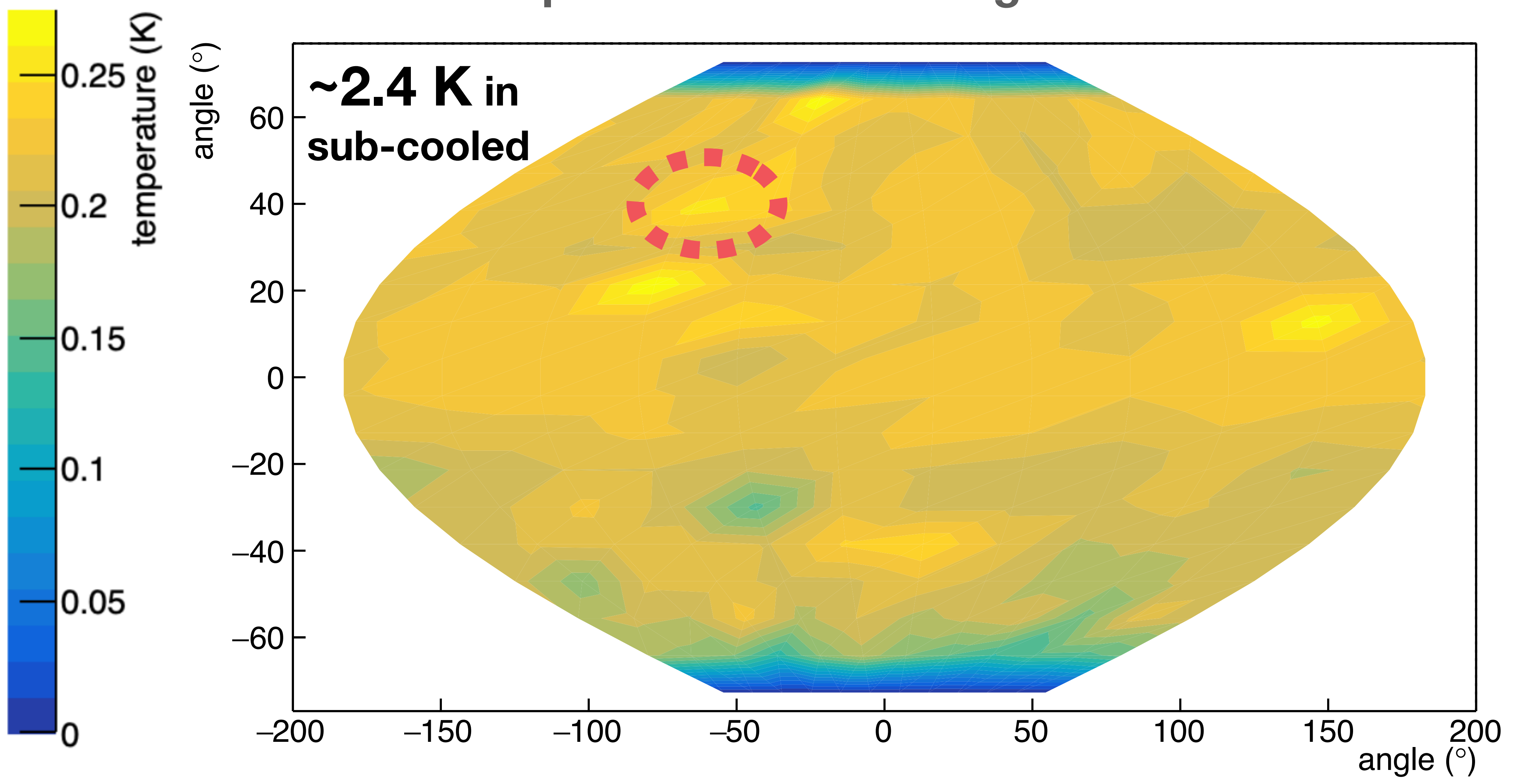
In this condition, the overpressure on the liquid He bath impedes the formation of gaseous He bubbles

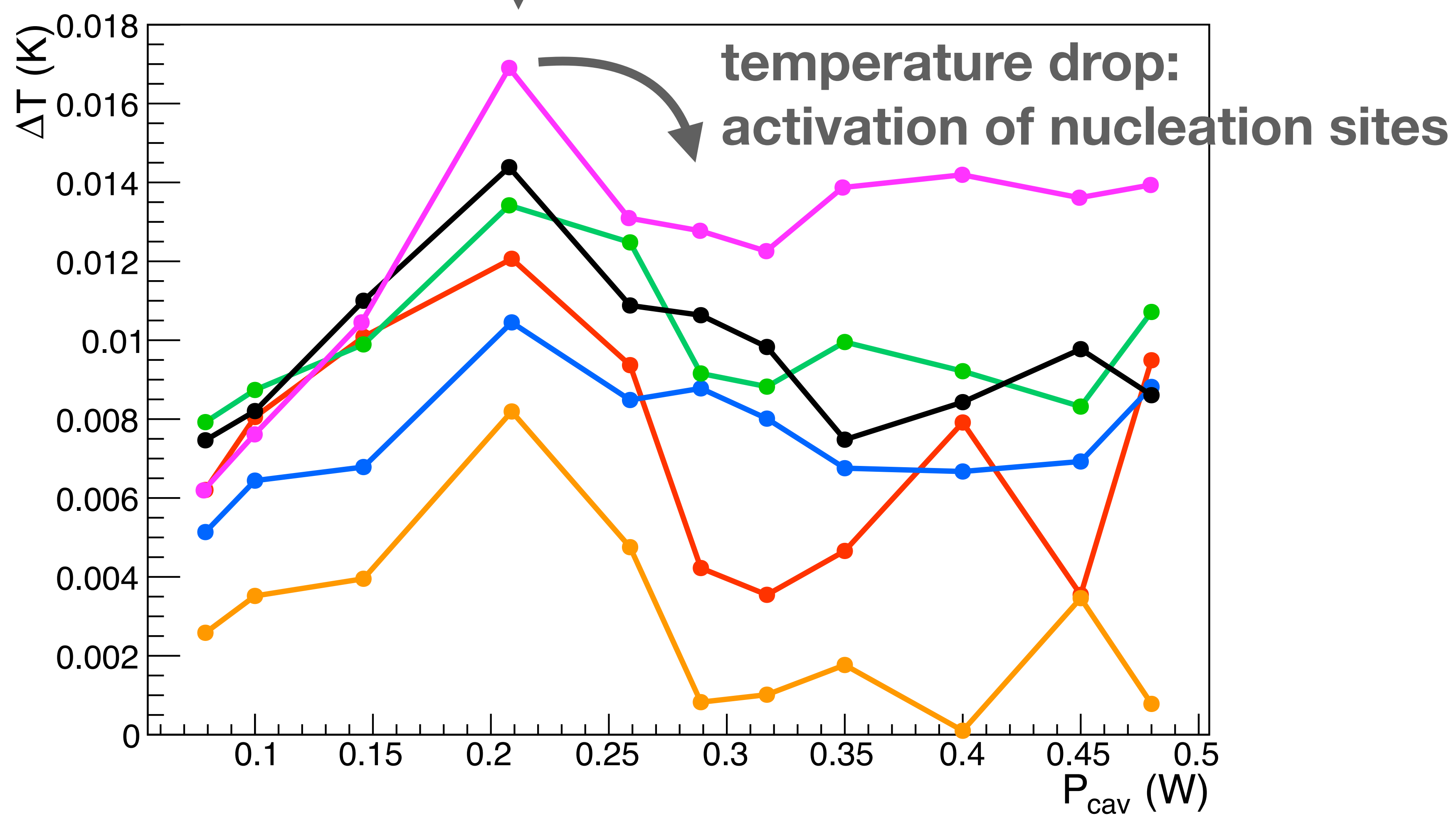
Nucleate Boiling Regime



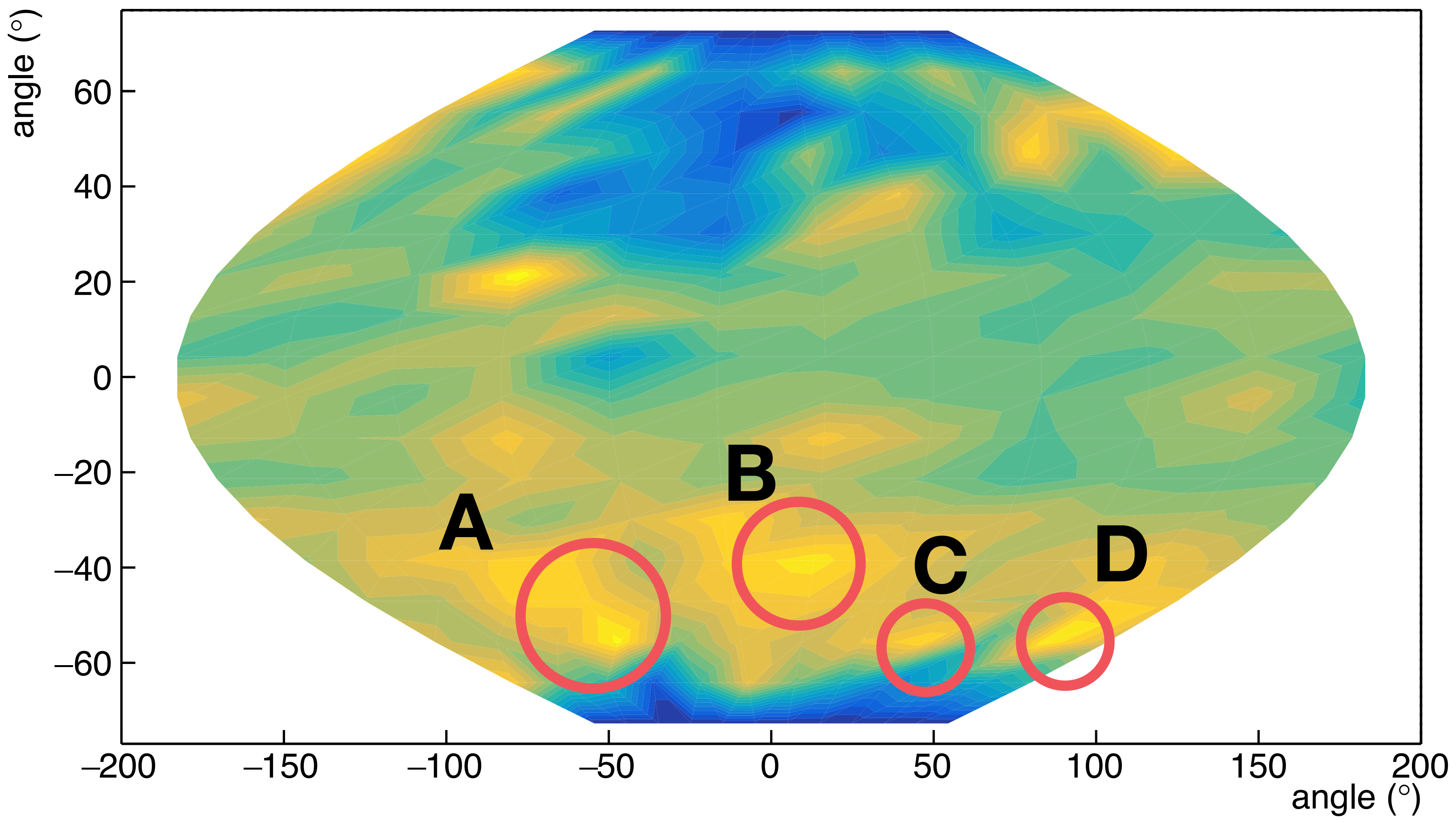


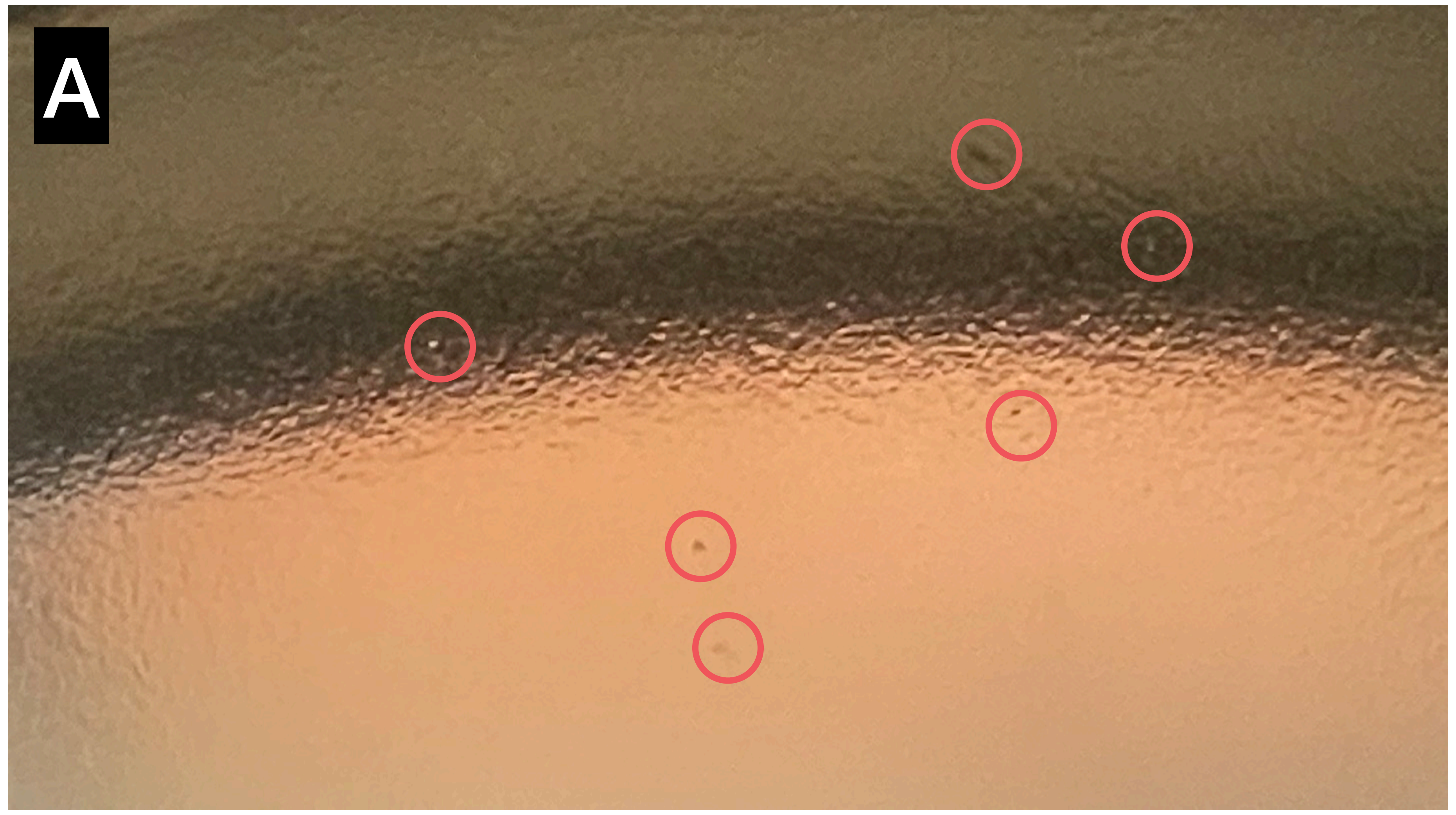
The temperature along the axis of the cell is maximum close to the equator where the magnetic field is maximum.

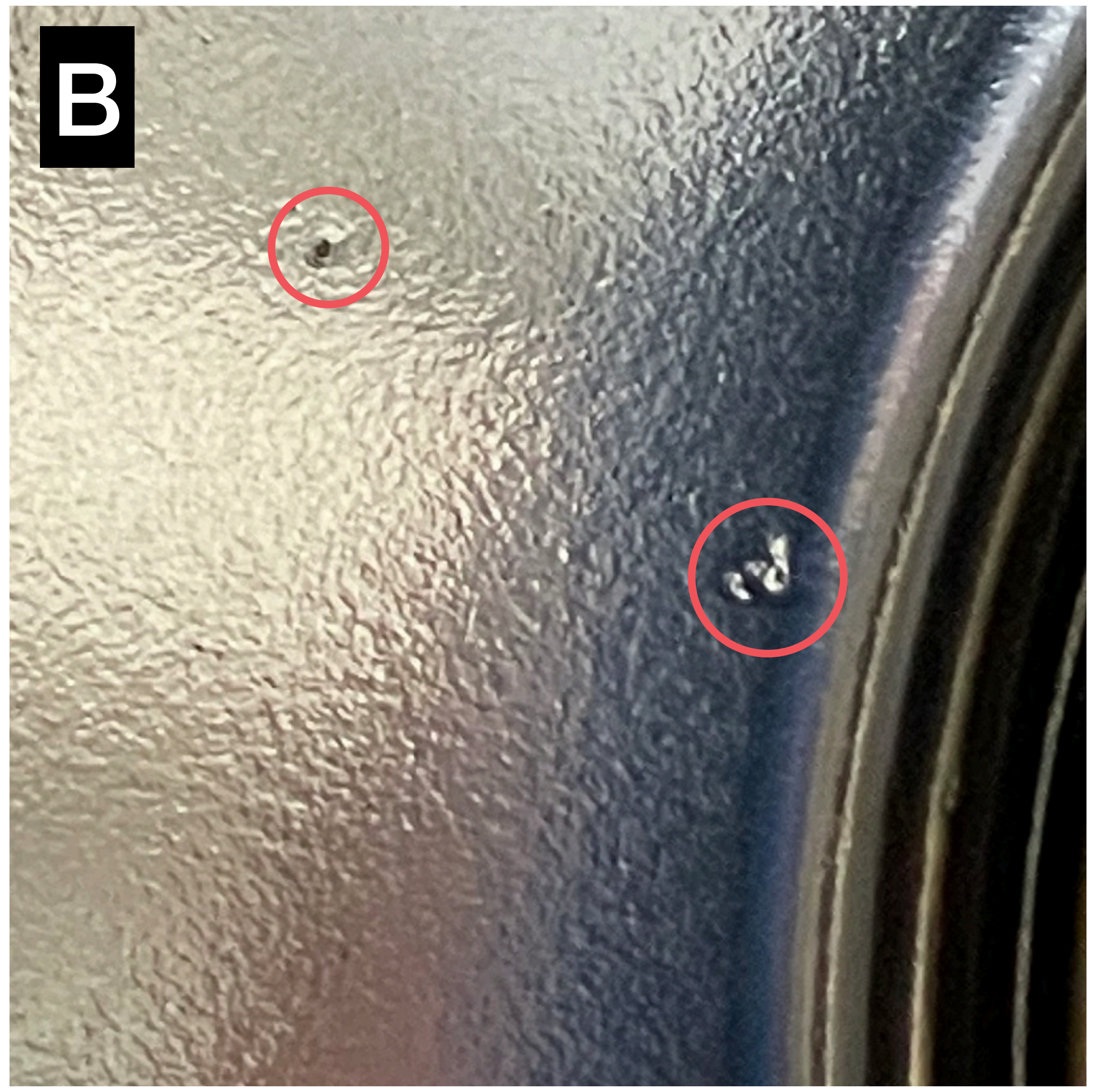




Optical Inspection







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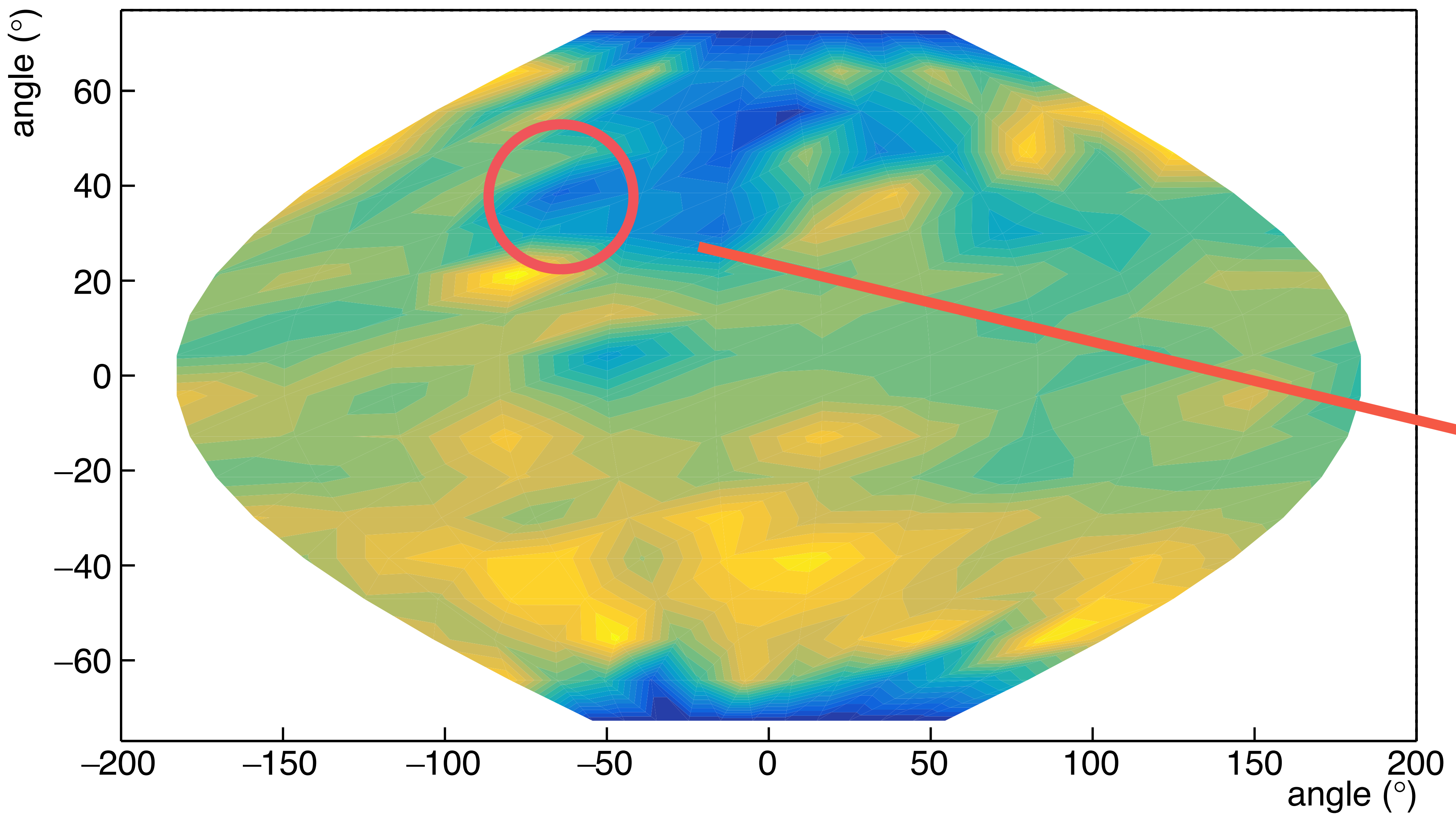
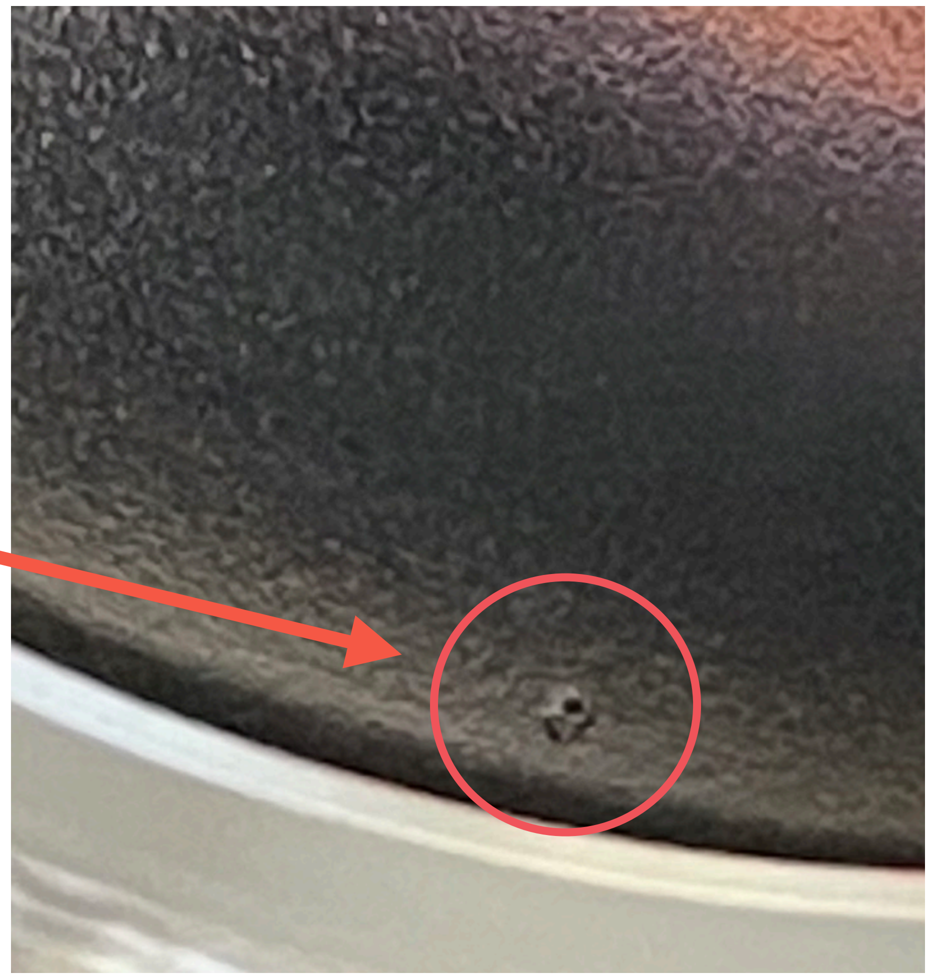
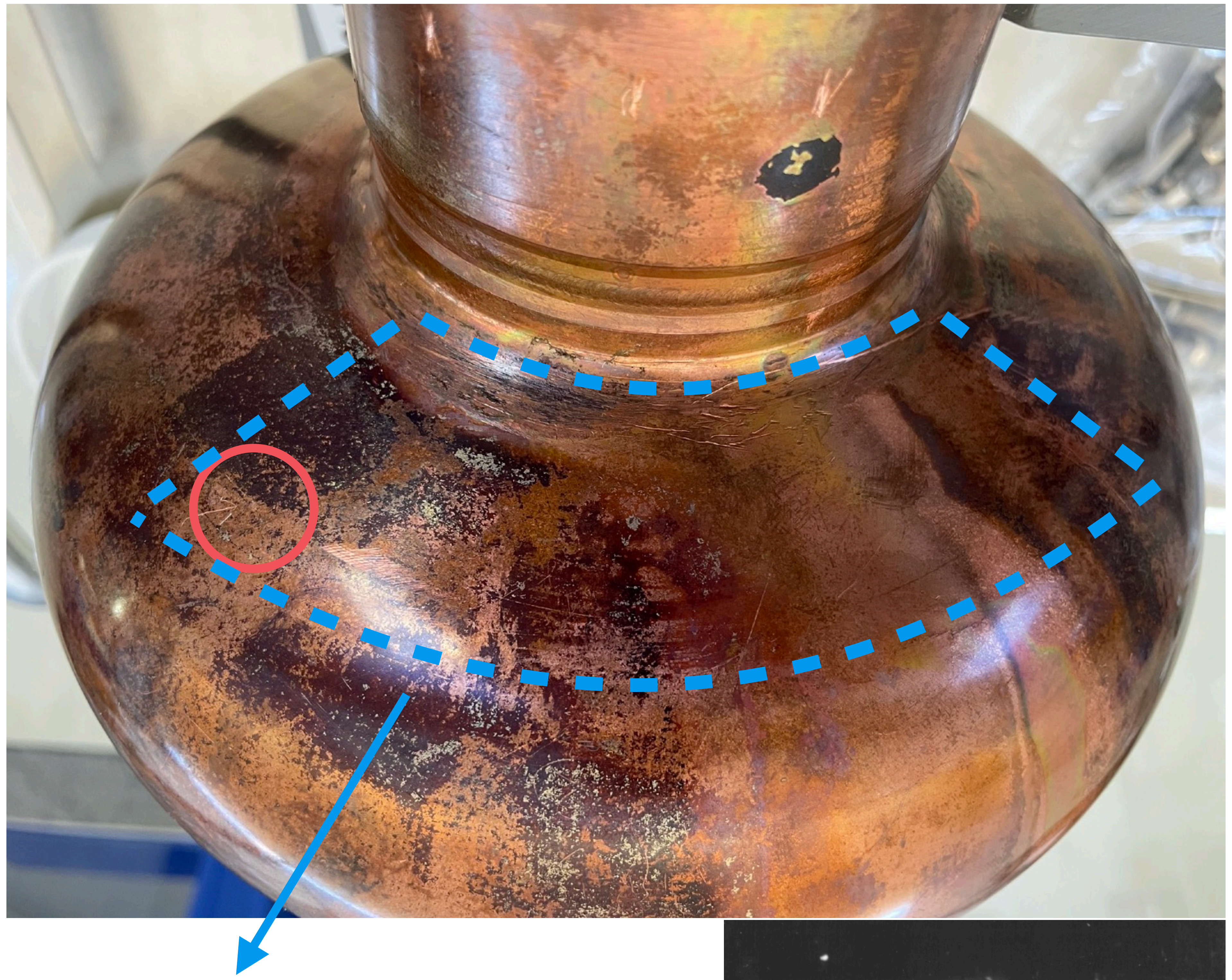
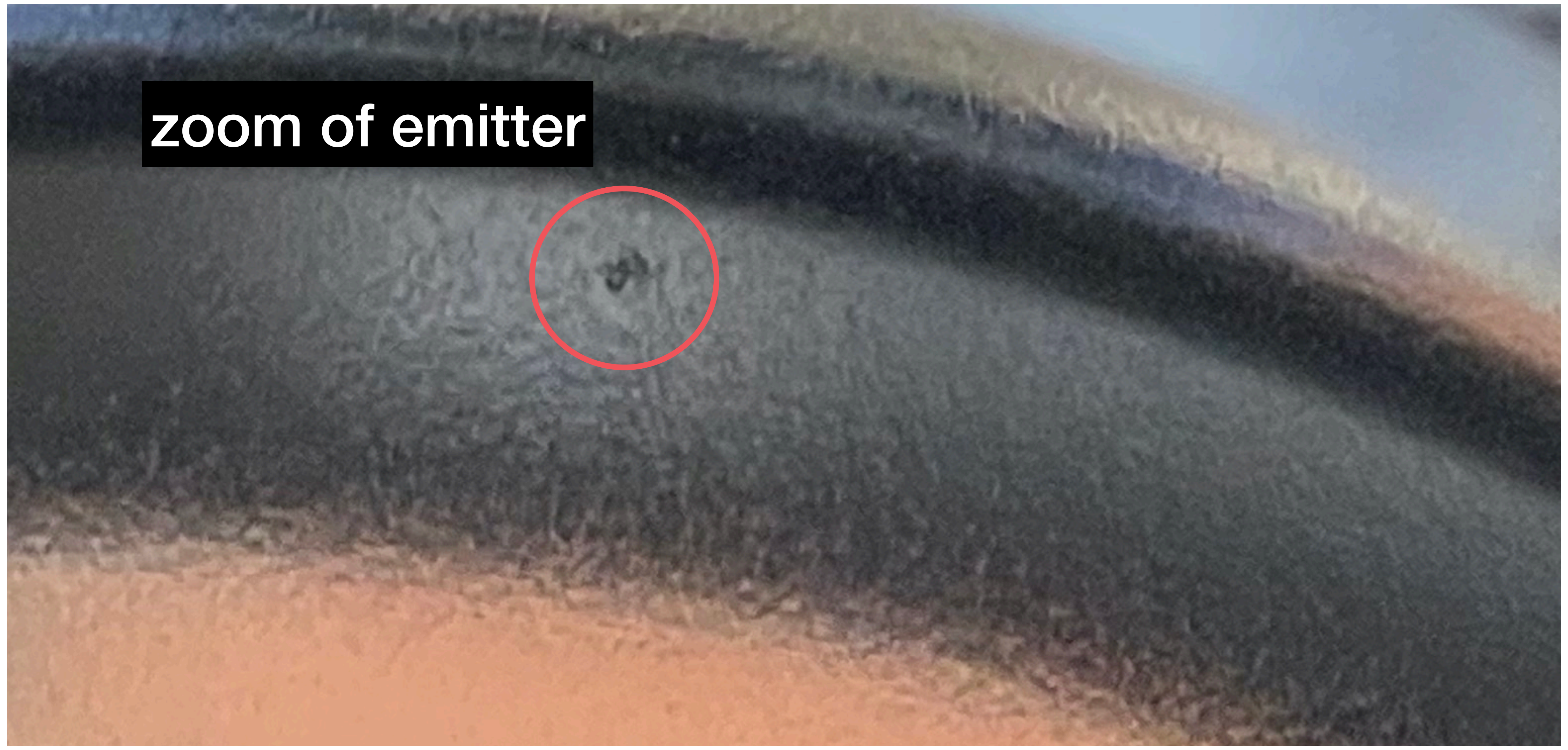
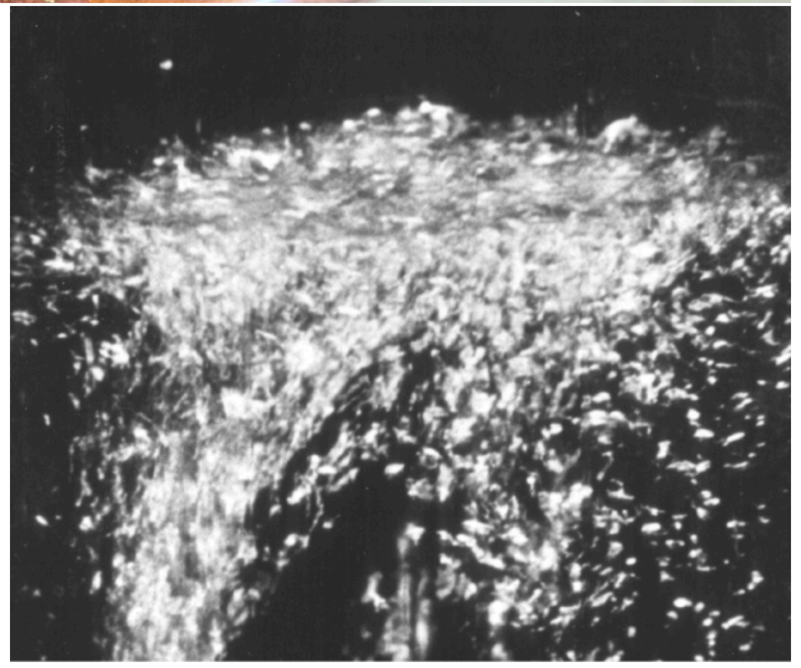






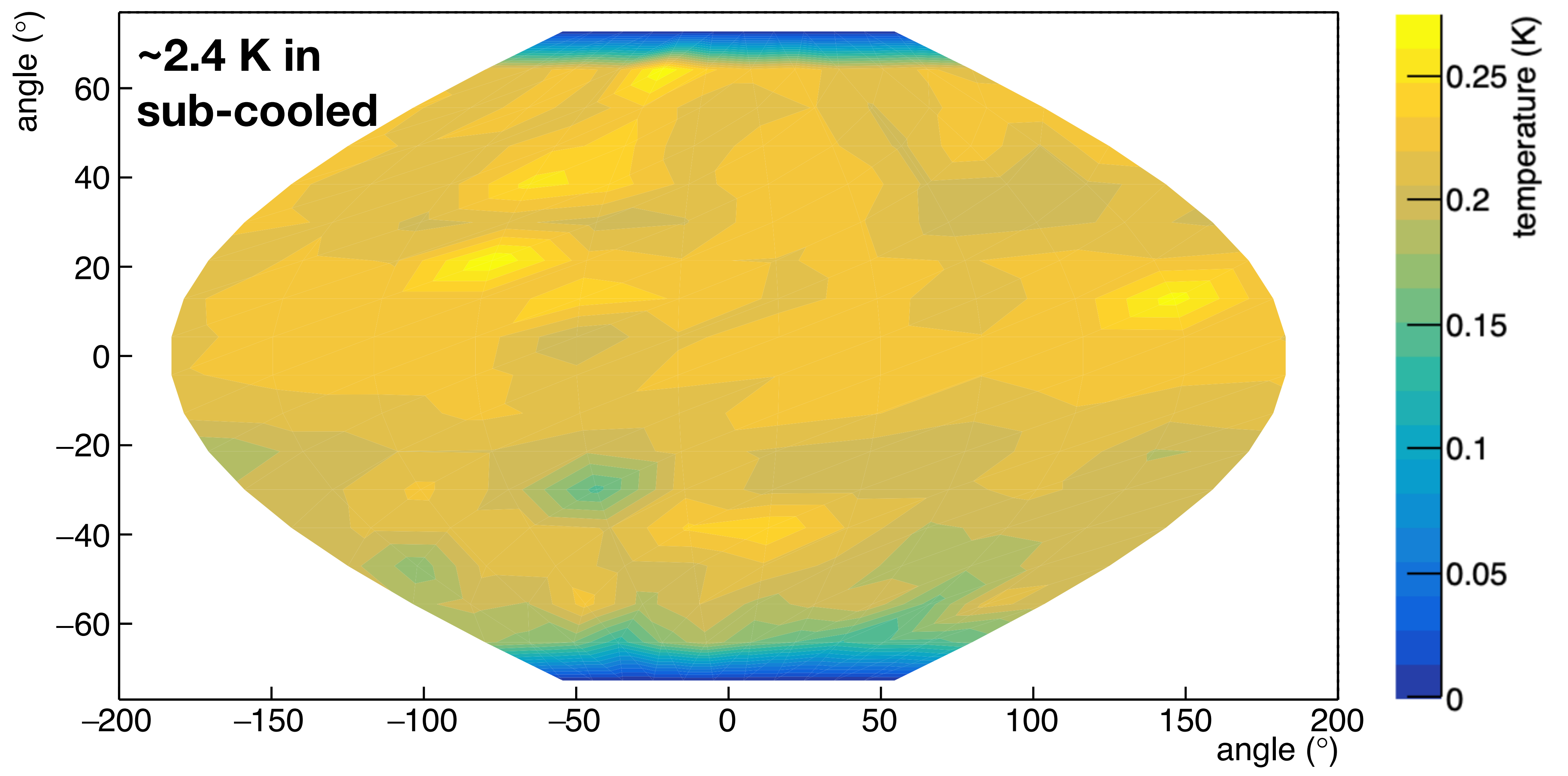


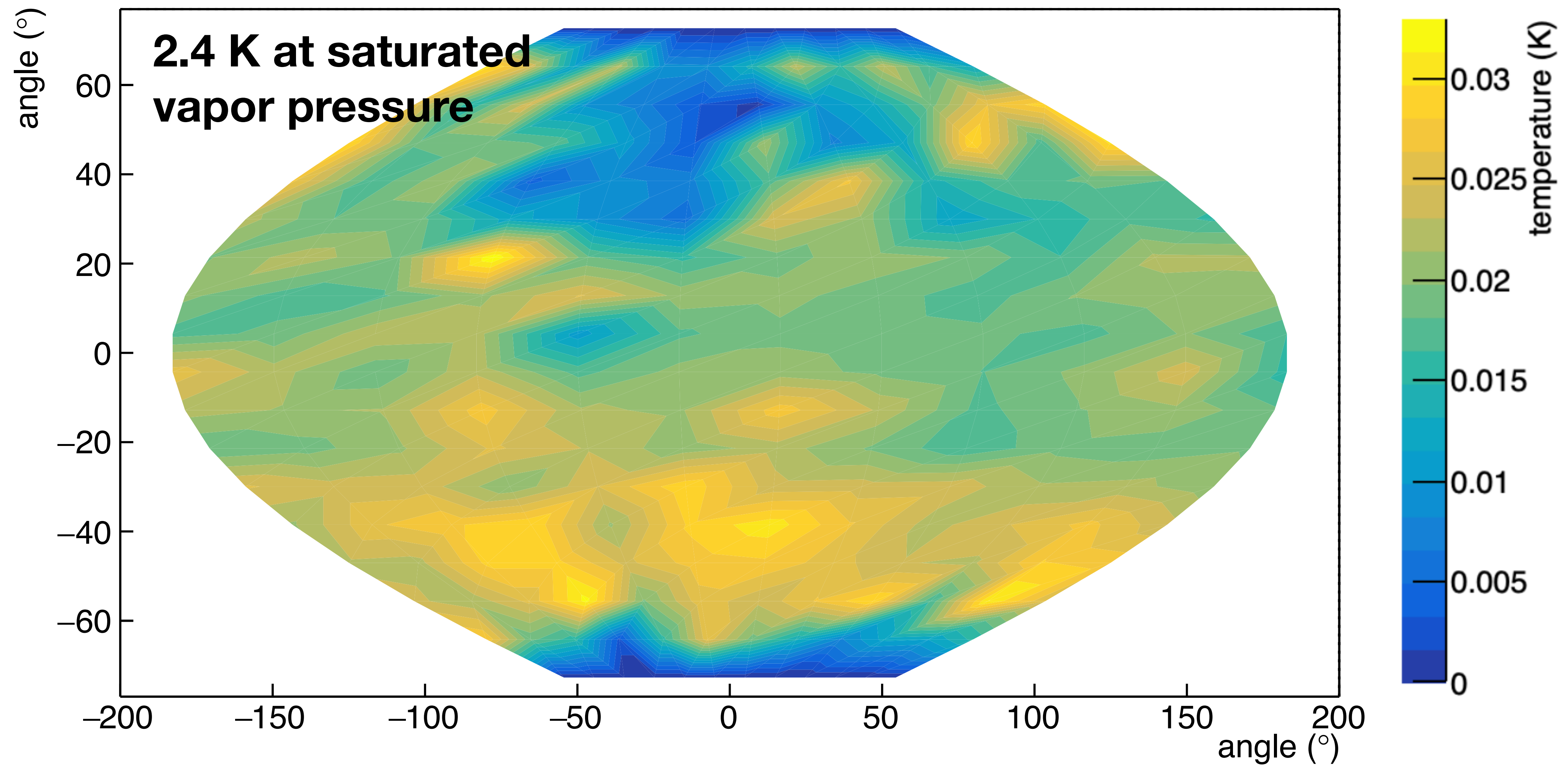
Extent of cold area: several hints suggest that this area is in nucleate boiling regime



“Liquid Helium”, Wikipedia (2022)

Heat dissipation of Nb/Cu cavities

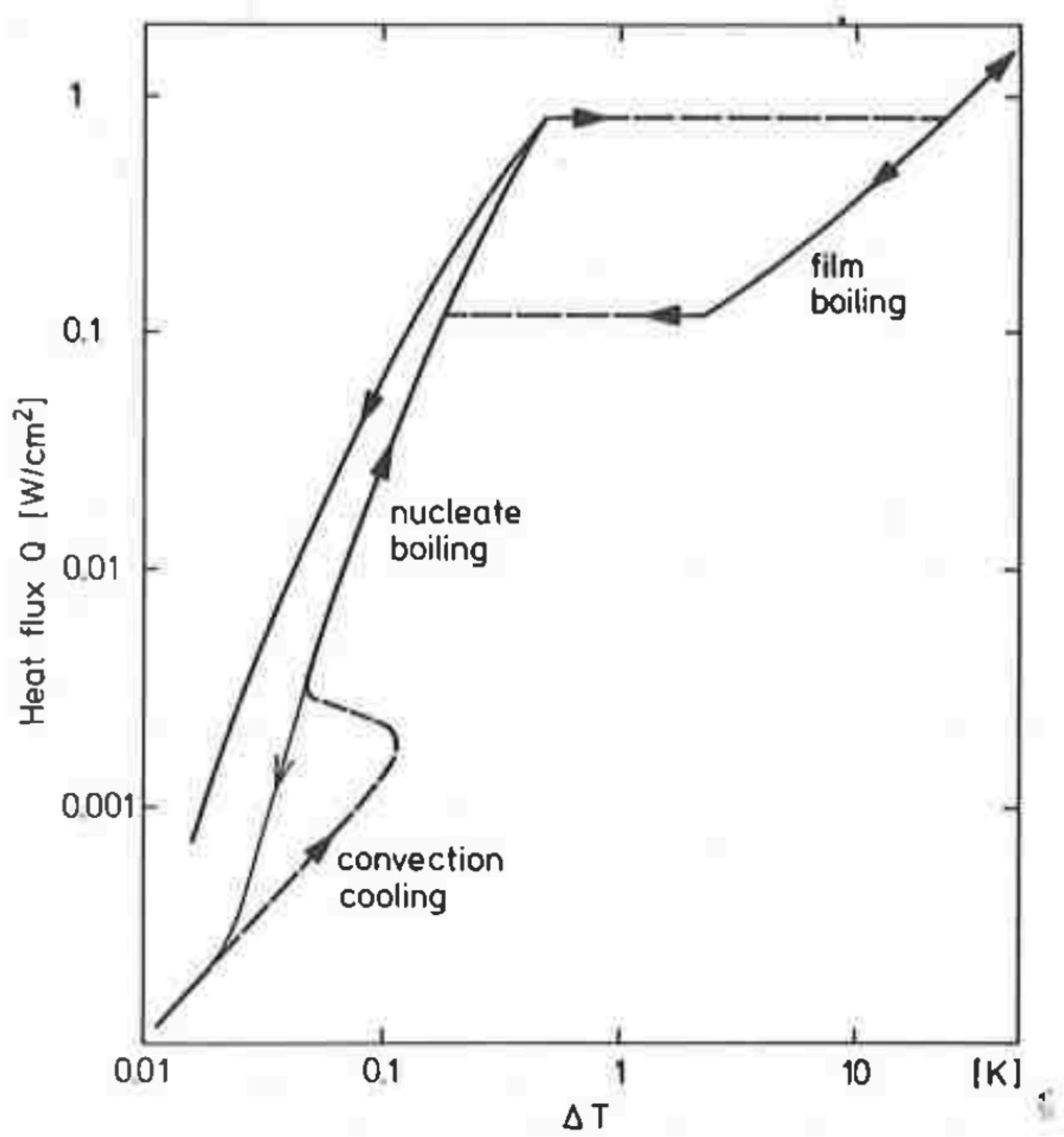




Heat dissipation of Nb/Cu cavities at operating conditions is not uniform

↓

the heat transfer by nucleate boiling is more effective than that by convection



C. Schmidt, *Review of steady state and transient heat transfer in pool boiling helium I*, 1981

Engineering the Surface of Copper Cavities

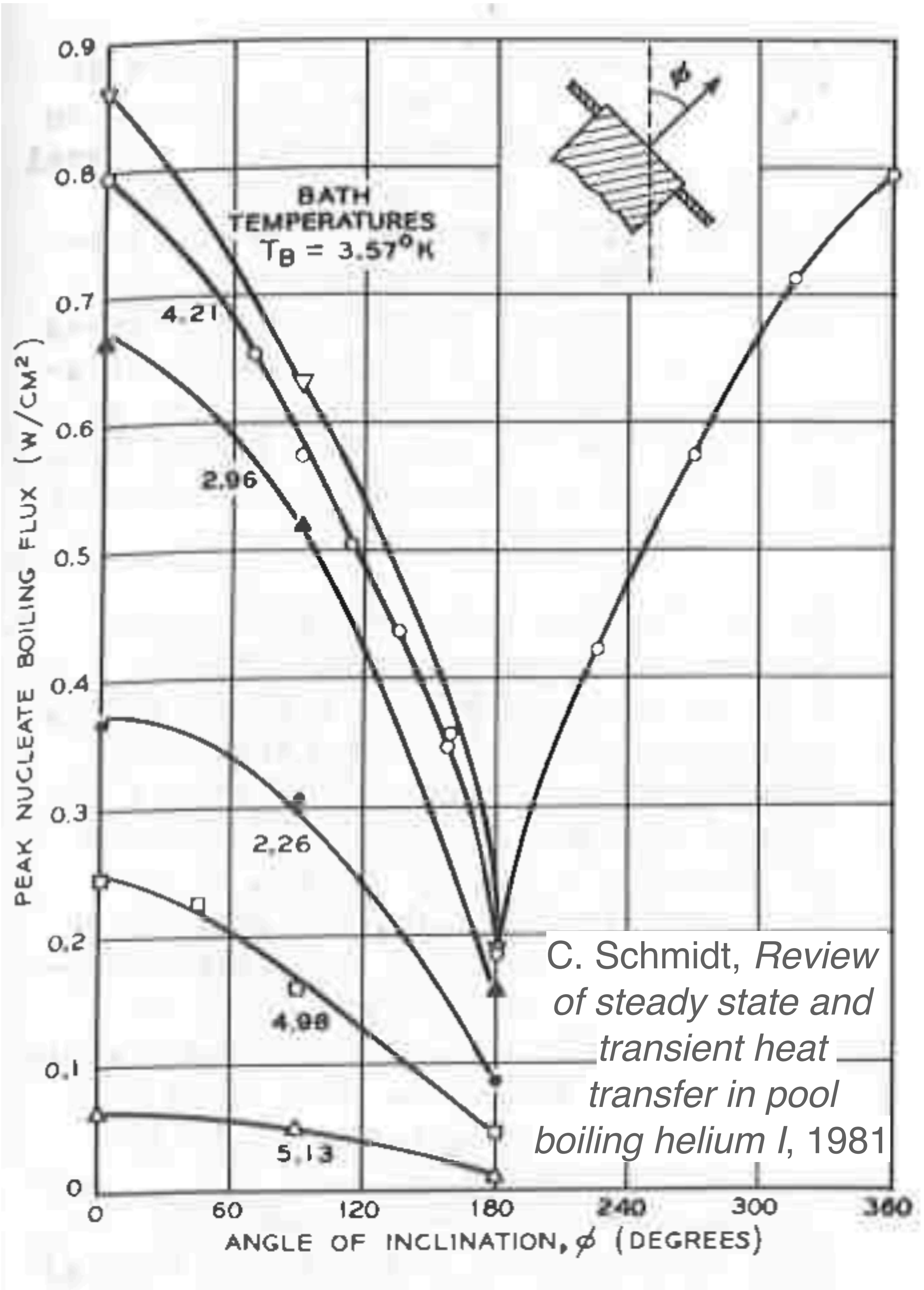
Might we induce heat dissipation by nucleate boiling in the outer surface of Nb/Cu cavities?

The heat dissipation between Cu cavities and He-I depends on several parameters. For example:

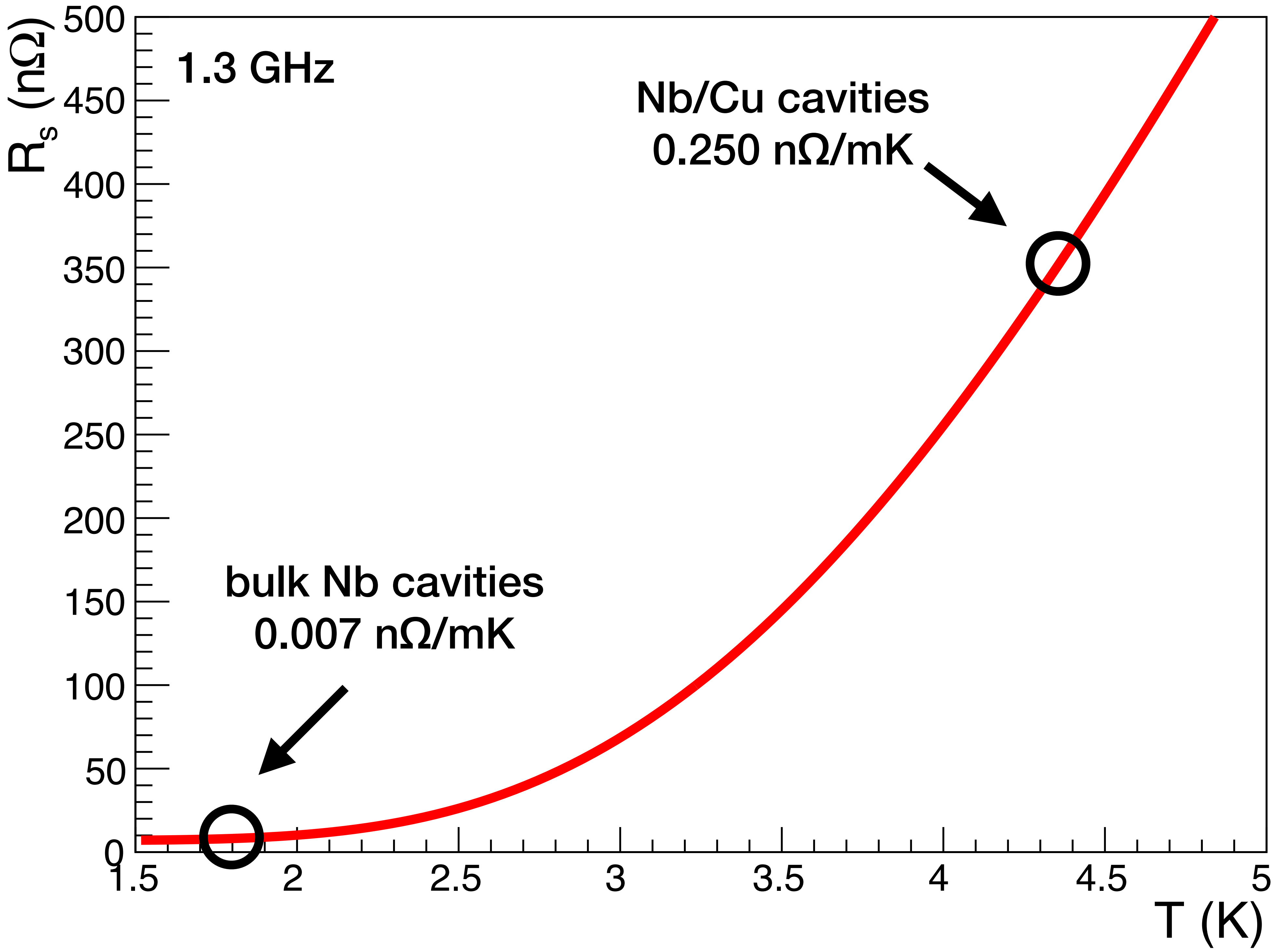
- surface orientation
- thickness of substrate
- external oxidation of substrate
- thermal conductivity of copper substrate
- etc

↓

many constraints to be considered…



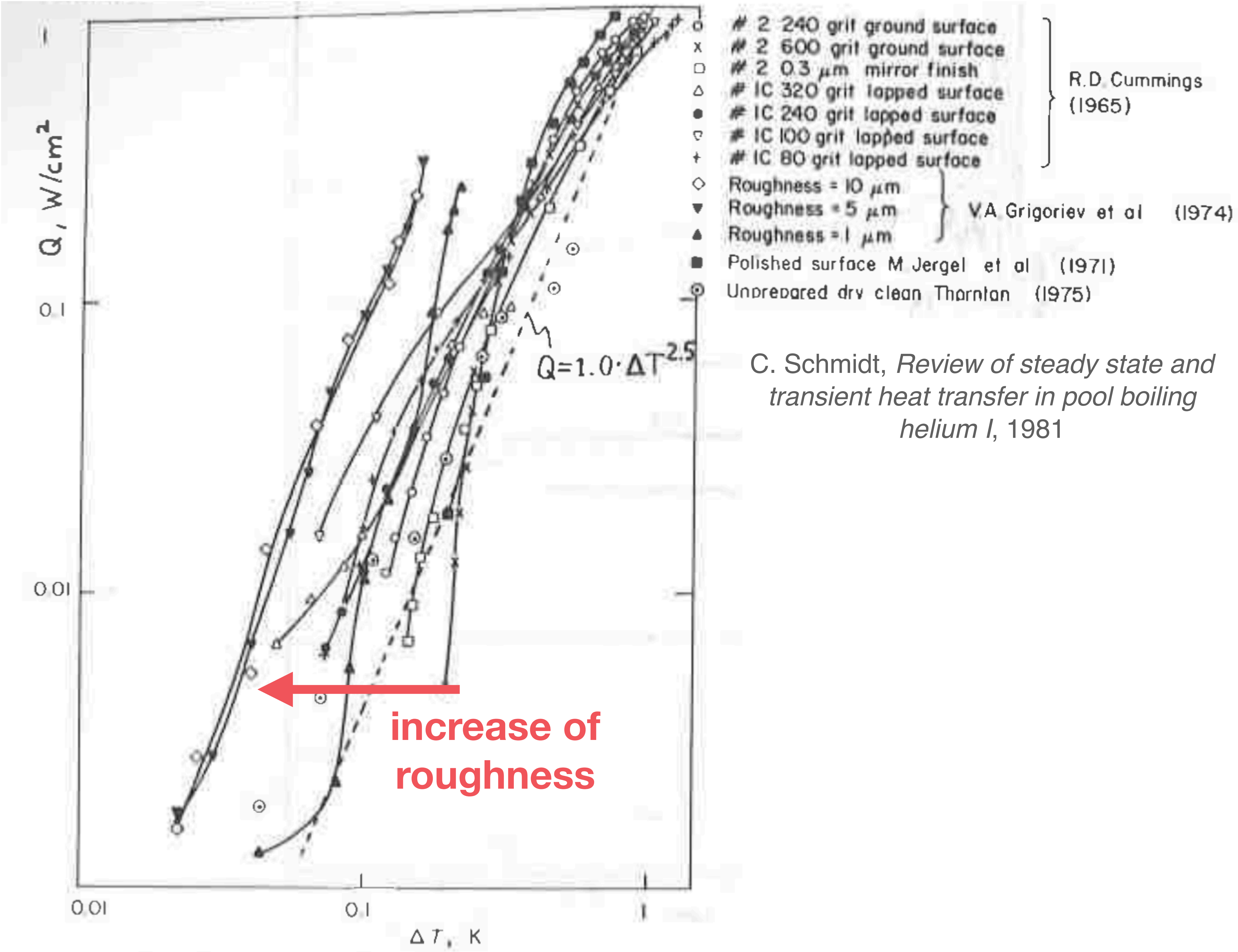
C. Schmidt, *Review of steady state and transient heat transfer in pool boiling helium I*, 1981



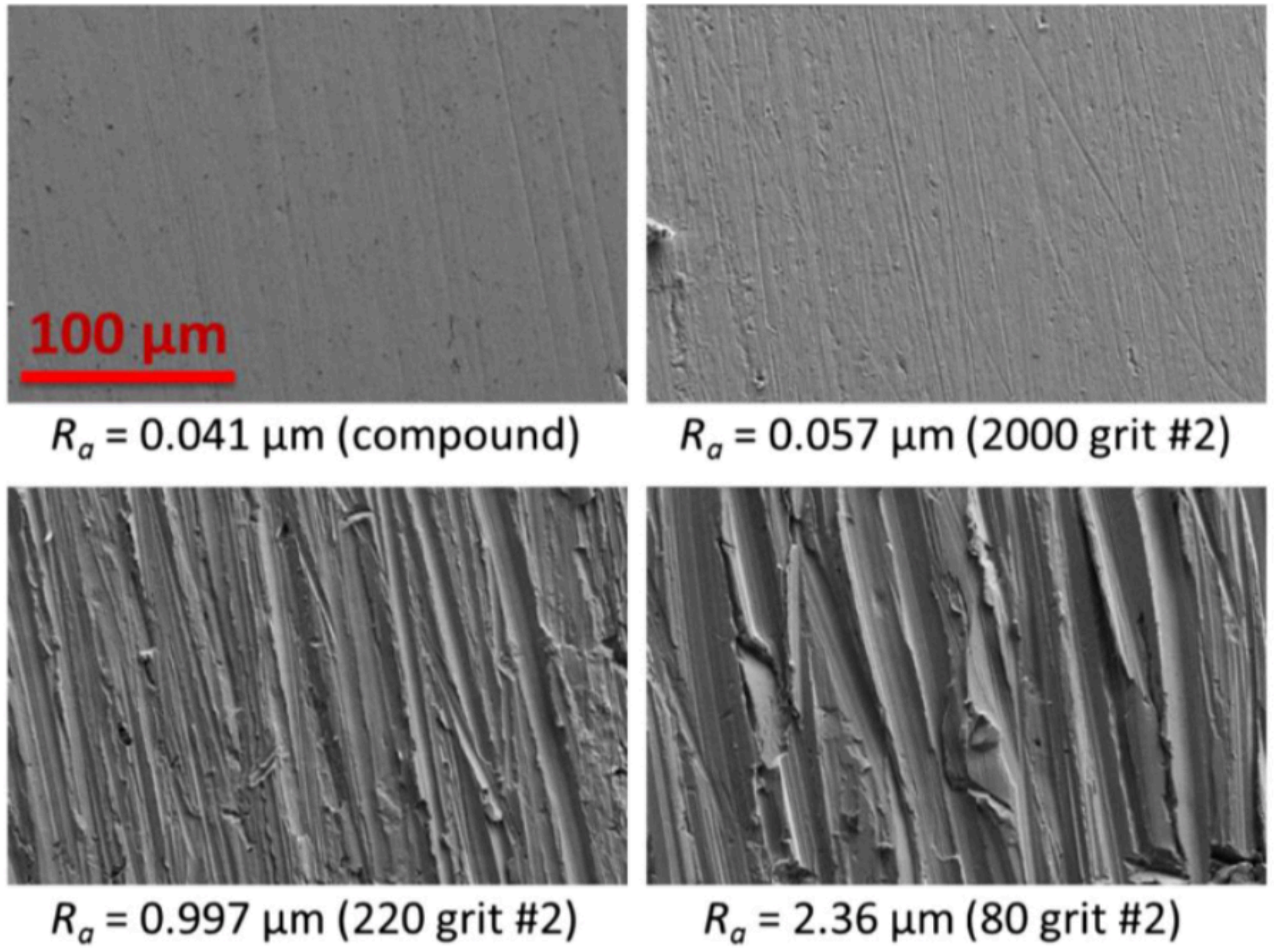
A small variation in the temperature of the film at 4.2 K (He-I) implies a high increase of surface resistance.

Roughness of Copper Cavities

The **roughness of the outer surface of cavities** does not play an important role in bulk Nb cavities that operate in He-II, where the Kapitza resistance is relevant. However, this parameter **might improve the performance of Nb/Cu cavities that mainly operate in He-I.**



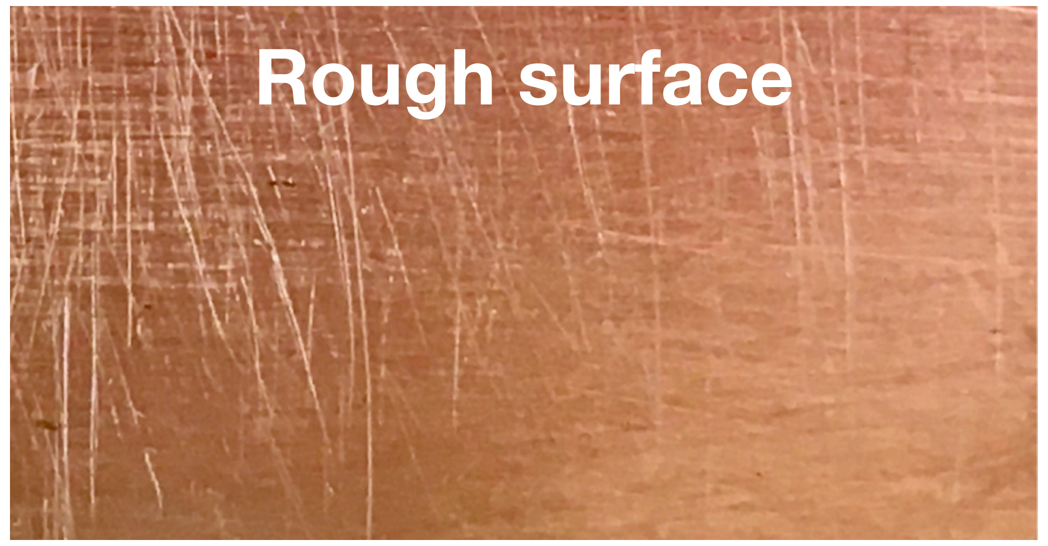
C. Schmidt, *Review of steady state and transient heat transfer in pool boiling helium I*, 1981

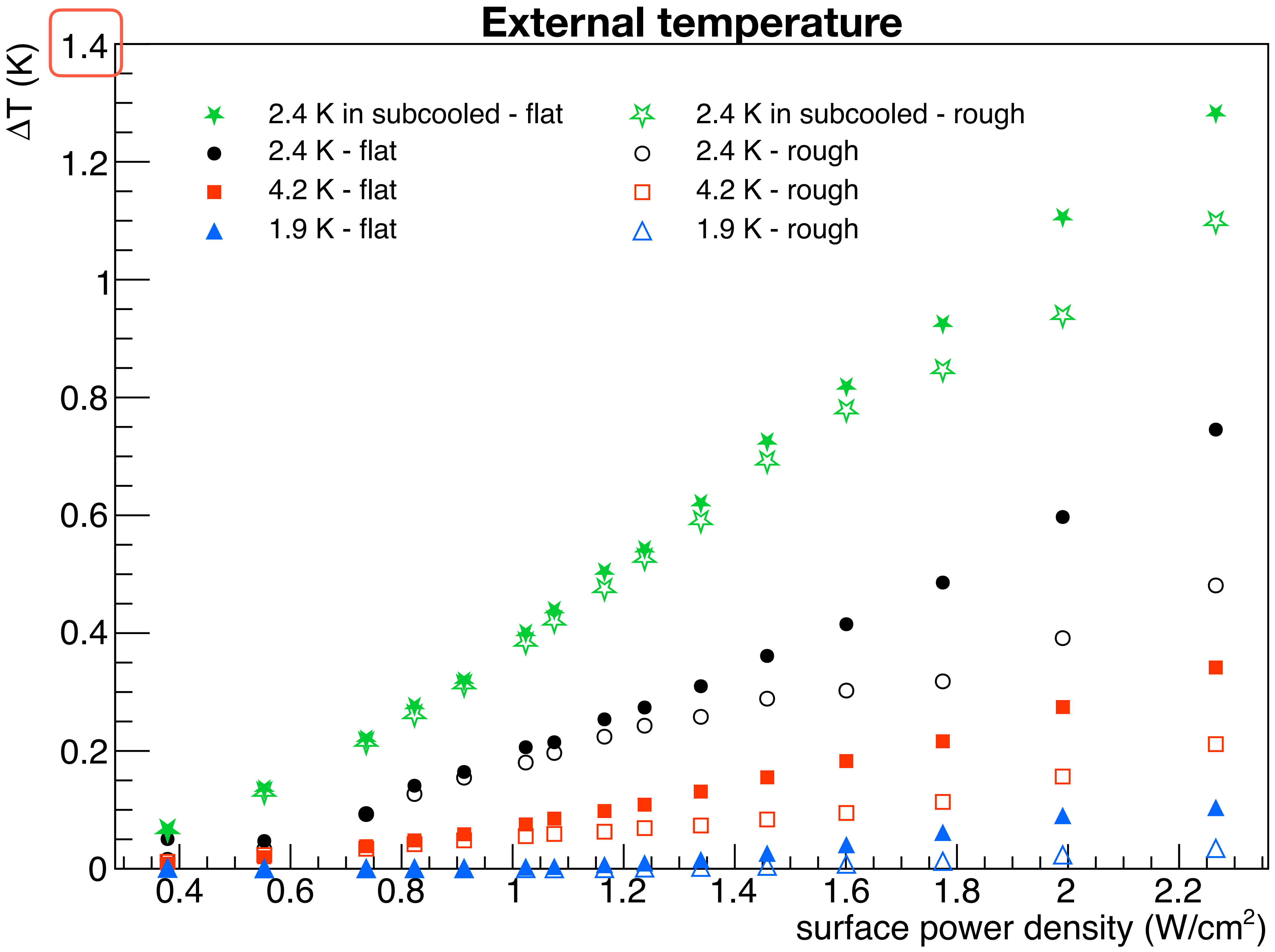


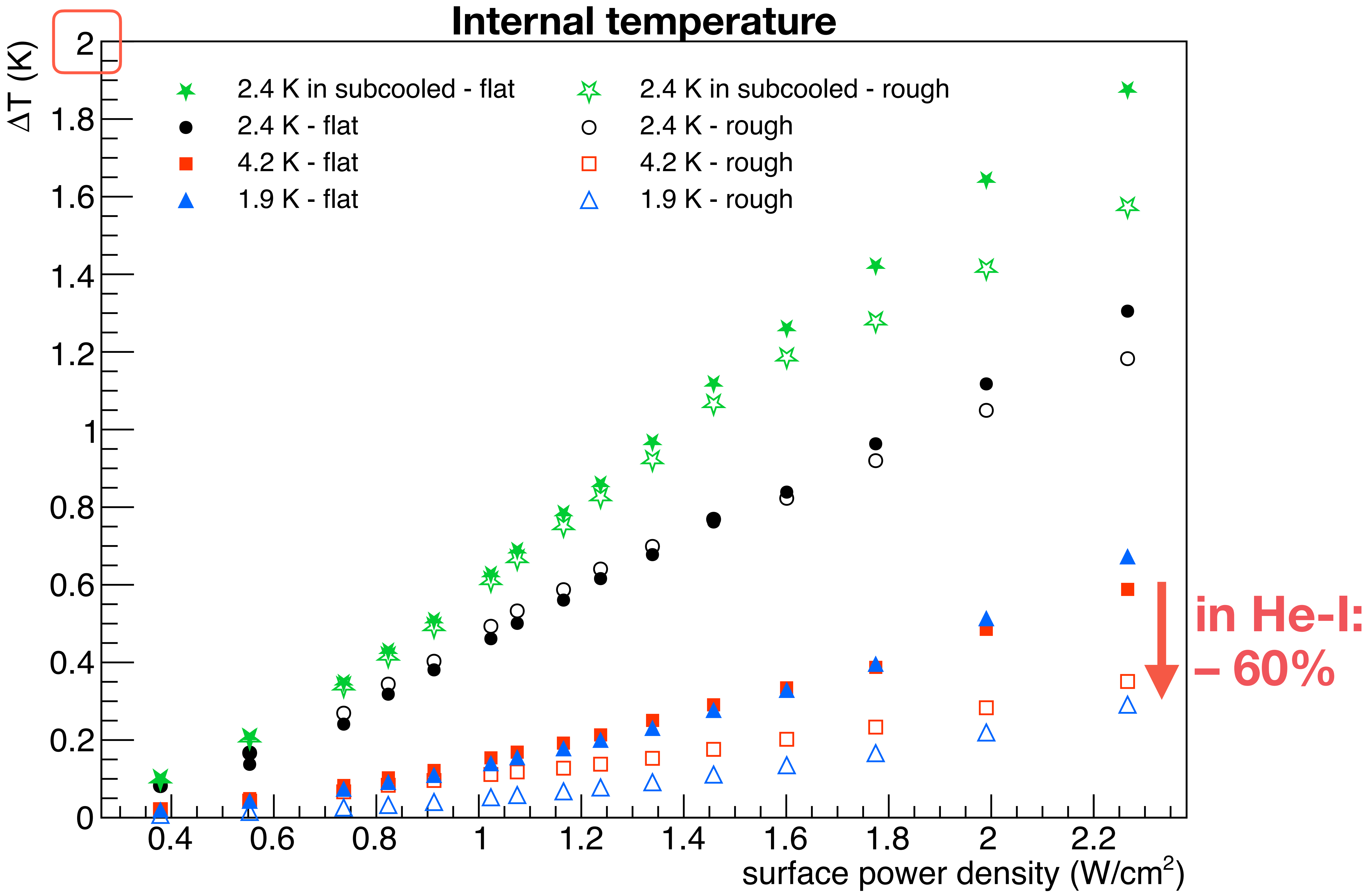
K. Jinsub et al., *Effect of surface roughness on pool boiling heat transfer at a heated surface having moderate wettability,* 2016

Flat and Rough Copper Surfaces

In rough copper surfaces the internal and external **temperature turns out to be lower** than that **in flat surfaces** for all conditions of liquid He bath





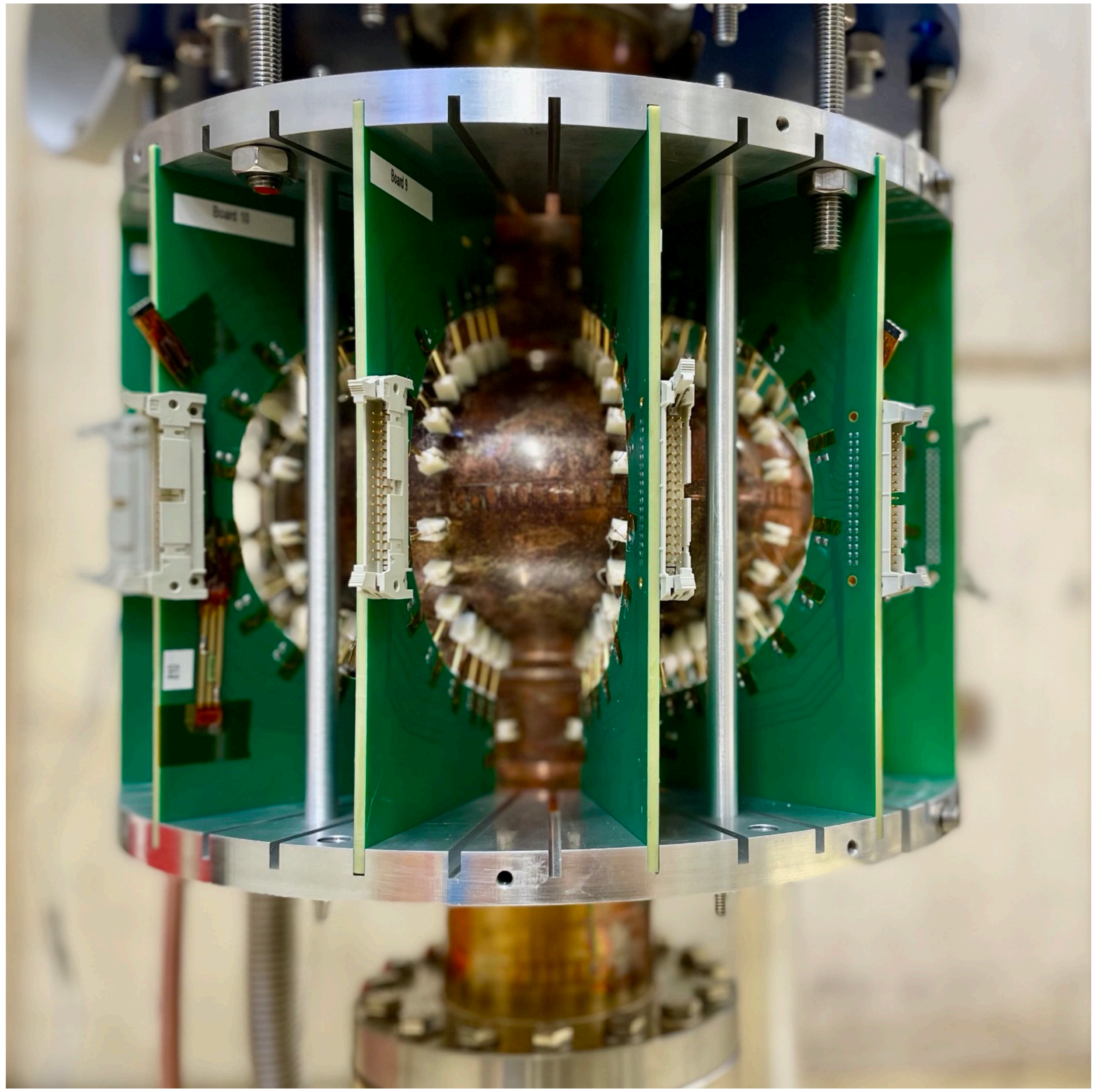


Conclusions and Perspectives

- **Temperature mapping system for niobium-coated copper cavities at CERN:**
  - used for thermal studies in LHe-I, where Nb/Cu cavities usually operate
  - challenging because the heat conduction in copper is much higher than that in bulk niobium
  - possibility to detect and localize heat losses (ohmic losses, field emitters, etc) at 2.4 K in saturated vapor pressure as well as in sub-cooled He

- **Heat dissipation of thin film cavities is not uniform**
  - observation of hotspots as expected, but also, surprisingly, cold areas
  - several hints indicate that the cold area is in nucleate boiling regime

- **Engineering copper surfaces for thin film cavities**
  - roughness of copper substrate may improve the heat dissipation of cavities and, in turn, their performance (studies ongoing)



CERN