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Thermal Conductivity of Proton-irradiated TPG

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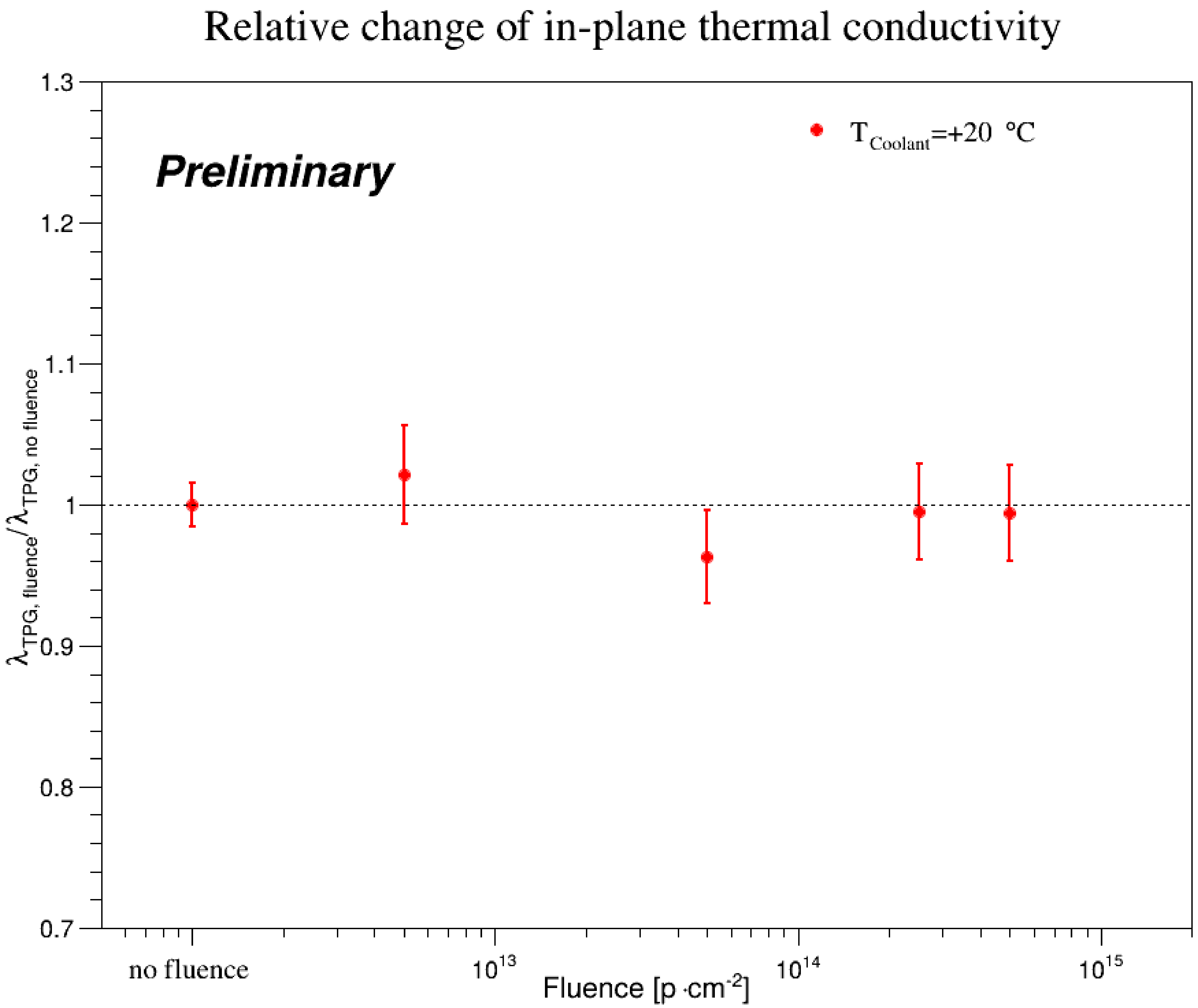
2nd General VTX Workshop DESY, 21.04.2026

Agenda

Take-home message: No degradation observed up to 5x10^{14} p/cm² (25 MeV)

1. Radiation Damage in TPG
2. Characterization Setup
3. Irradiation Campaign
4. Analysis

(Backup: Comparison with other Measurements)

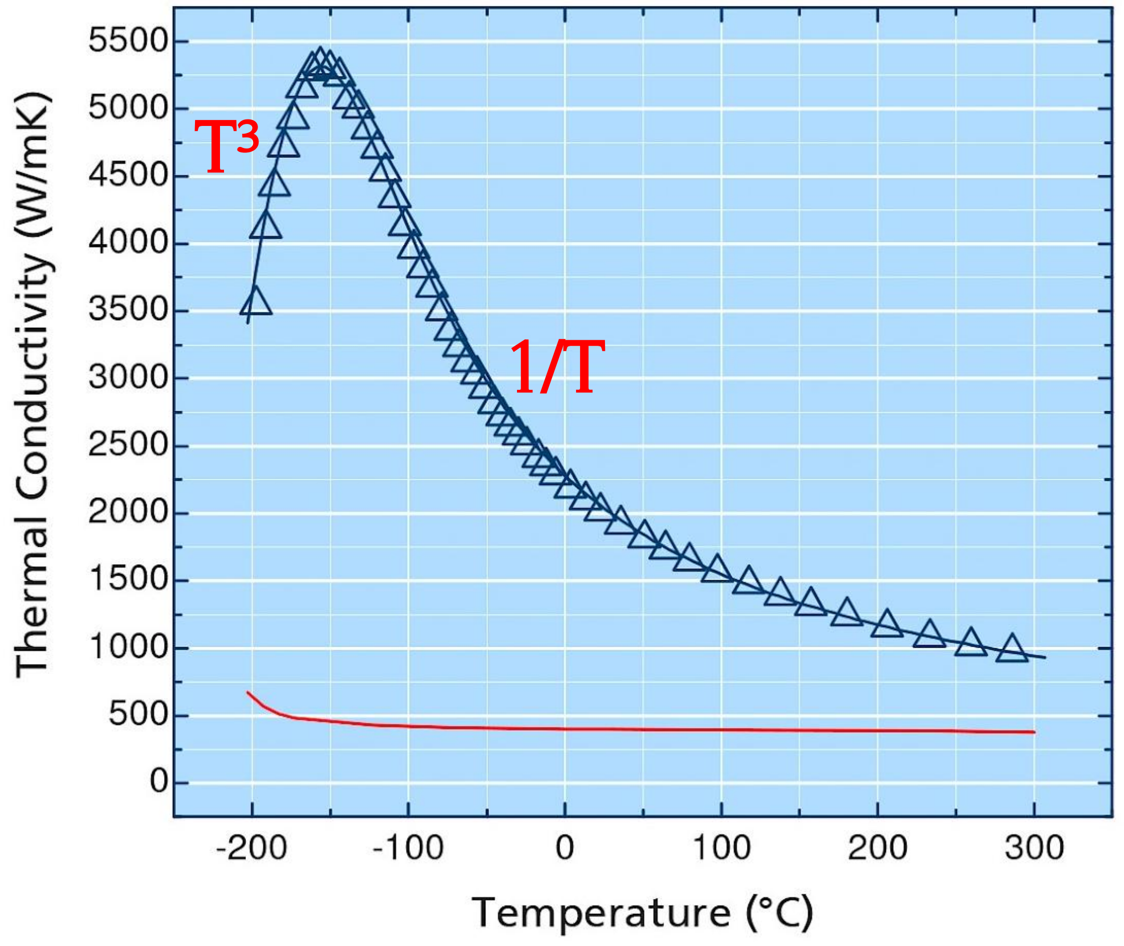


Radiation Damage in TPG

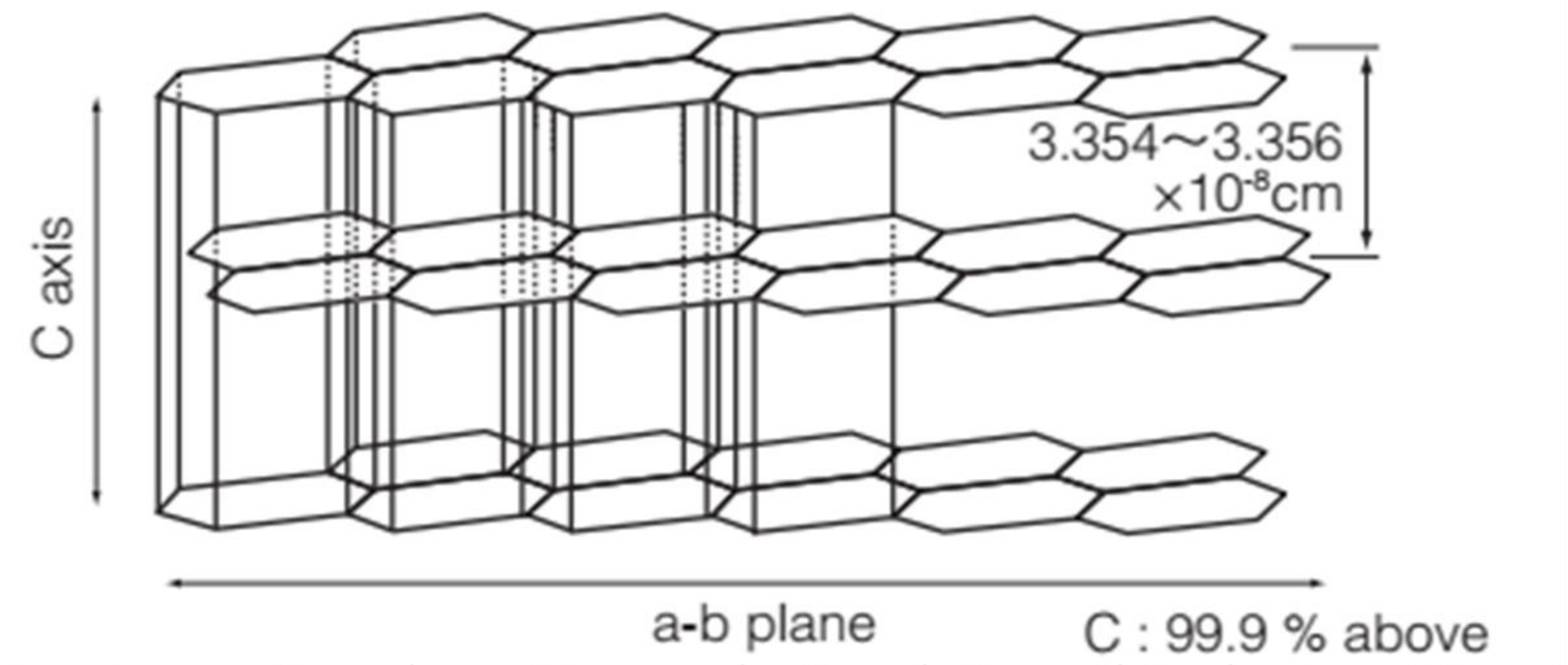
Thermal Conductivity

Highly anisotropic behavior

→ Heat transport by phonons (like diamond)
→ Electronic contribution, especially at high T
→ High thermal conductivity in plane
→ > 1500 W/m/K, up to ~2000 W/m/K

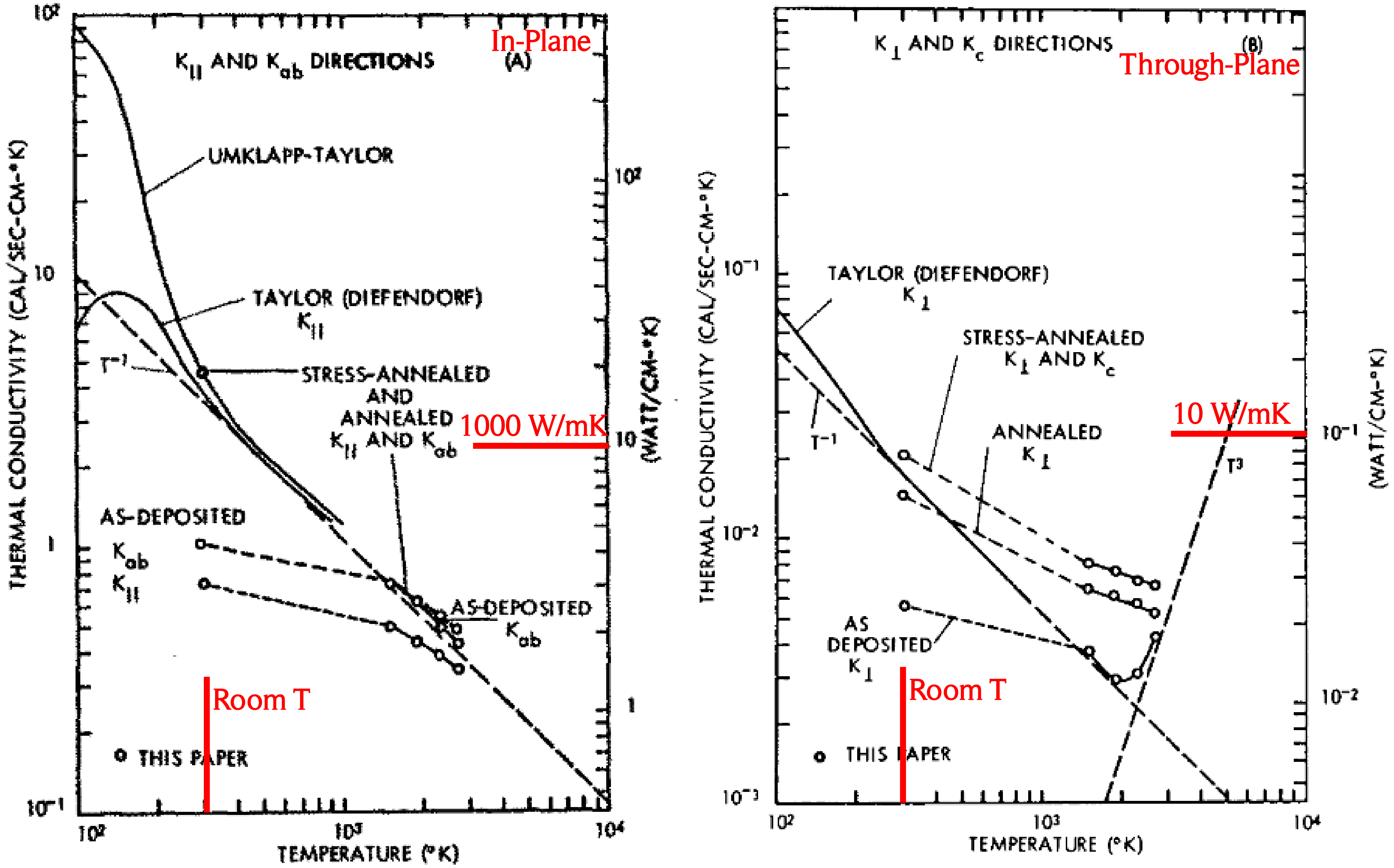


https://www.diamond-materials.com/en/cvd-diamond/thermal/
https://doi.org/10.1524/9783110358704



https://www.wwritratech.com/store/product/pyrolytic-graphite-sheet-pgs-70-um/

More measurements:
https://www.mpp.mpg.de/~sct/welcomeaux/papers/NIMA480_463_469.pdf

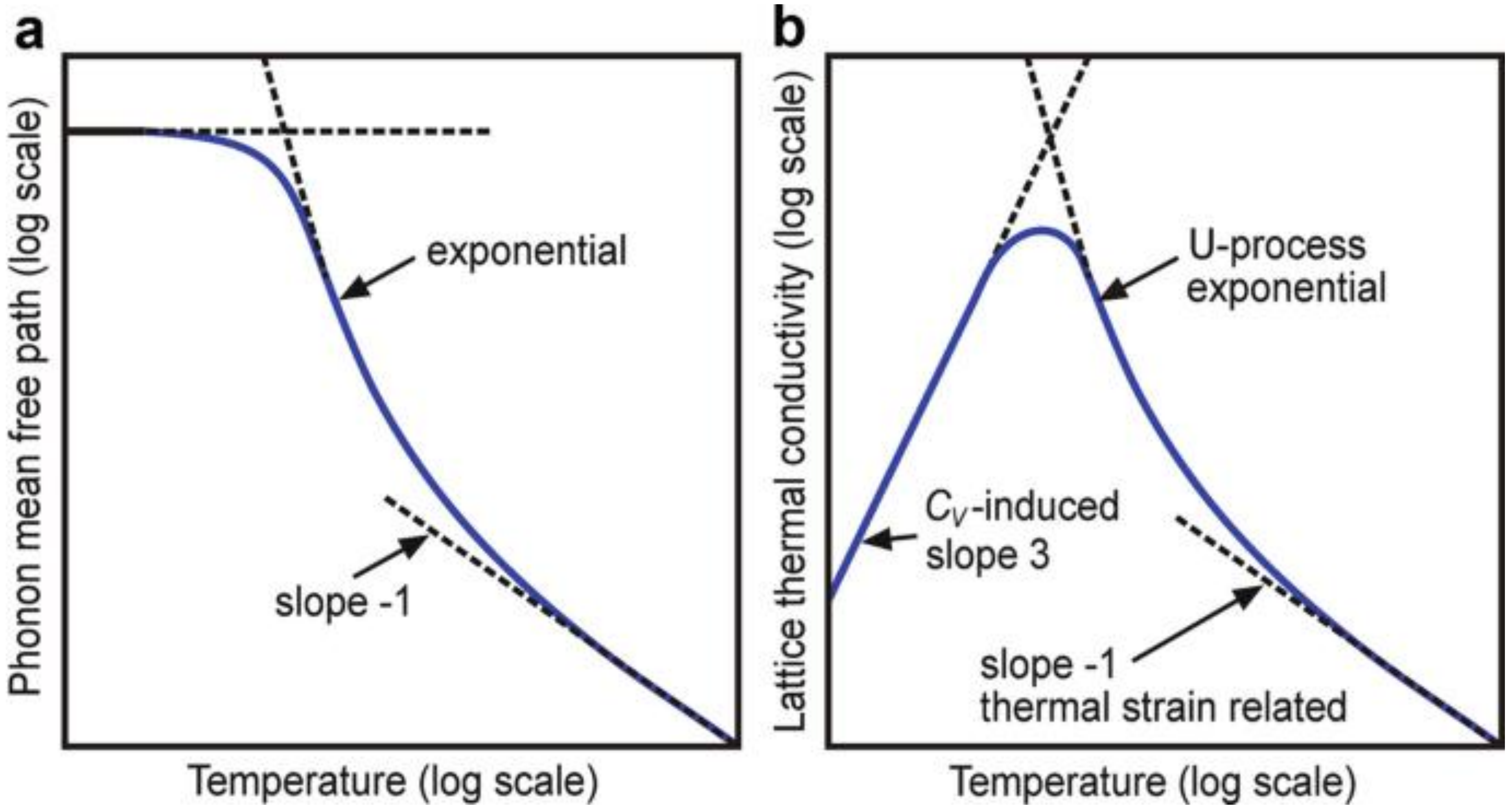


Union Carbide https://www.sciencedirect.com/science/article/pii/0008622373900584

Damage Mechanisms

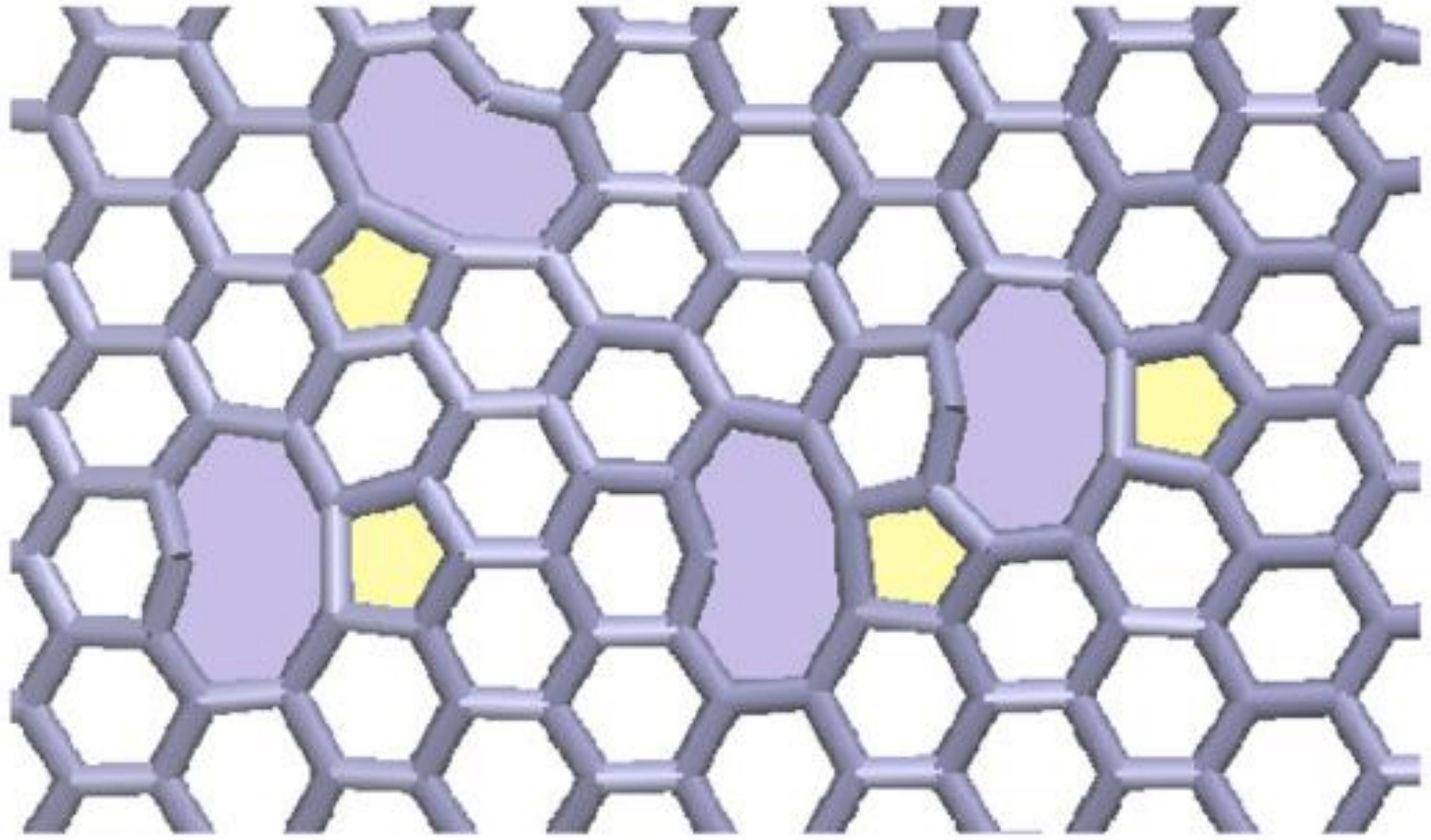
Thermal conductivity due to high orientation
→ Deterioration by lattice damage (phonon scattering)
→ Point, cluster, Stone-Wales (rotated bond)

Relevant at BELLE II or CBM fluences?
→ Not for thick plates?
→ But critical for thin foils?

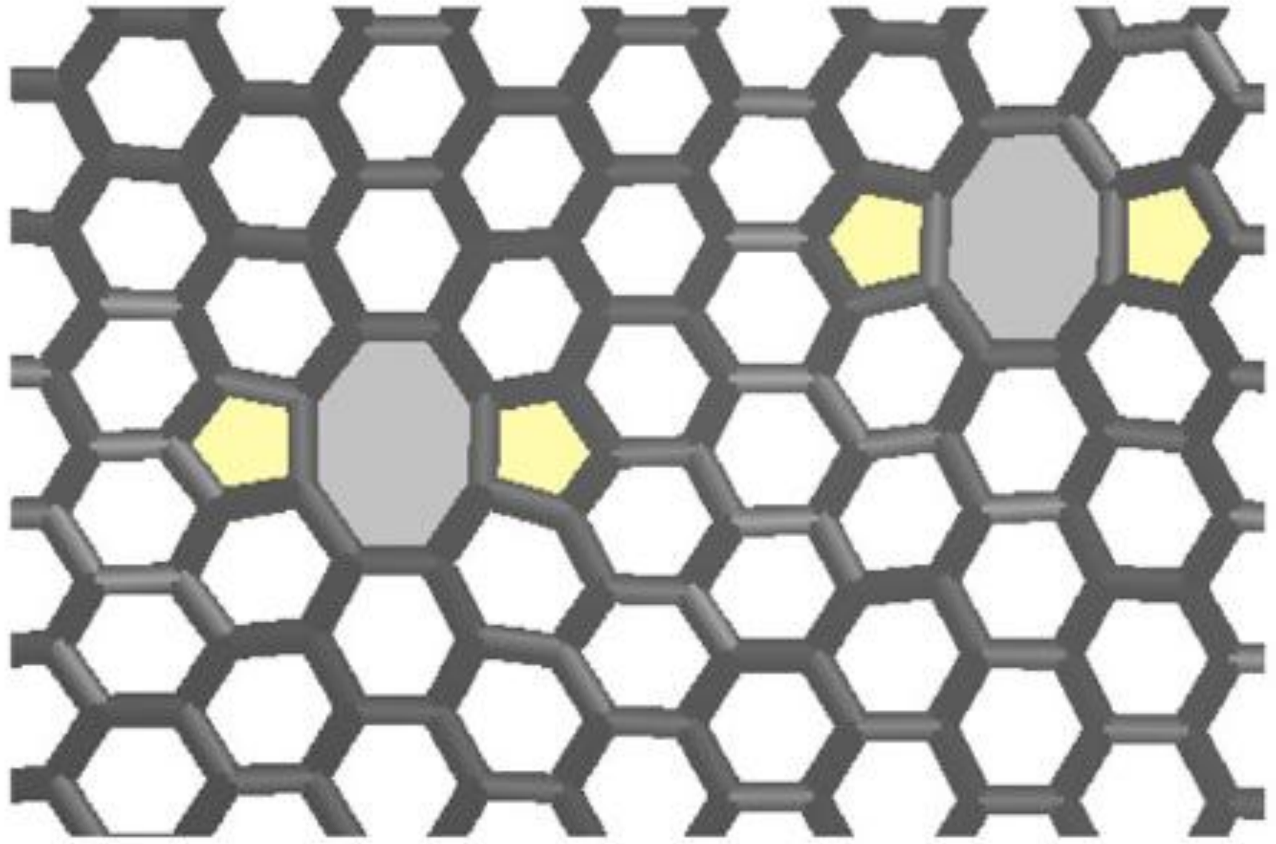


https://link.springer.com/rwe/10.1007/978-3-319-06540-3_5-4

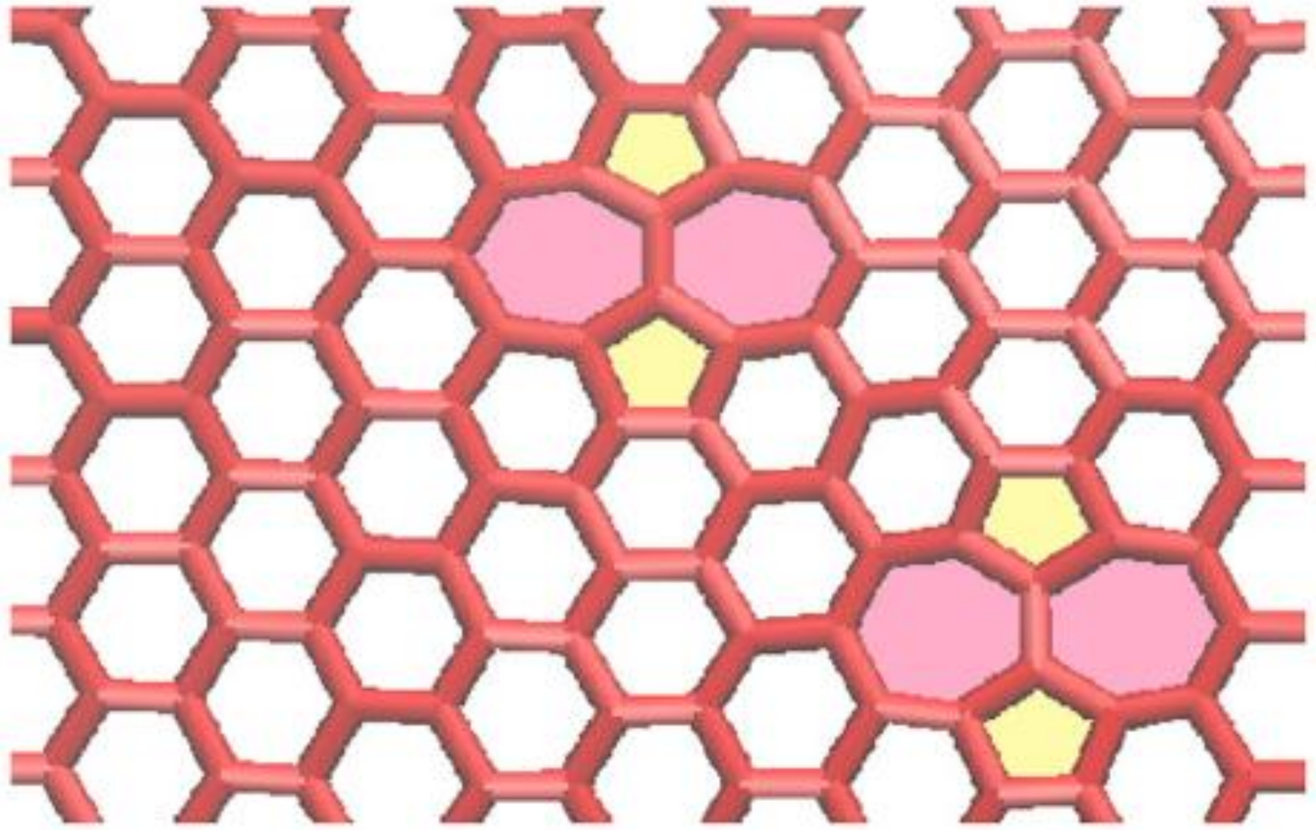
https://www.sciencedirect.com/science/article/pii/S0008622313006398?via%3Dihub



(a) Point vacancy



(b) Bivacancy



(c) Stone-Wales

Characterization Setup

“UFO” Test Stand

“UFO” test stand for validation of thermal performance

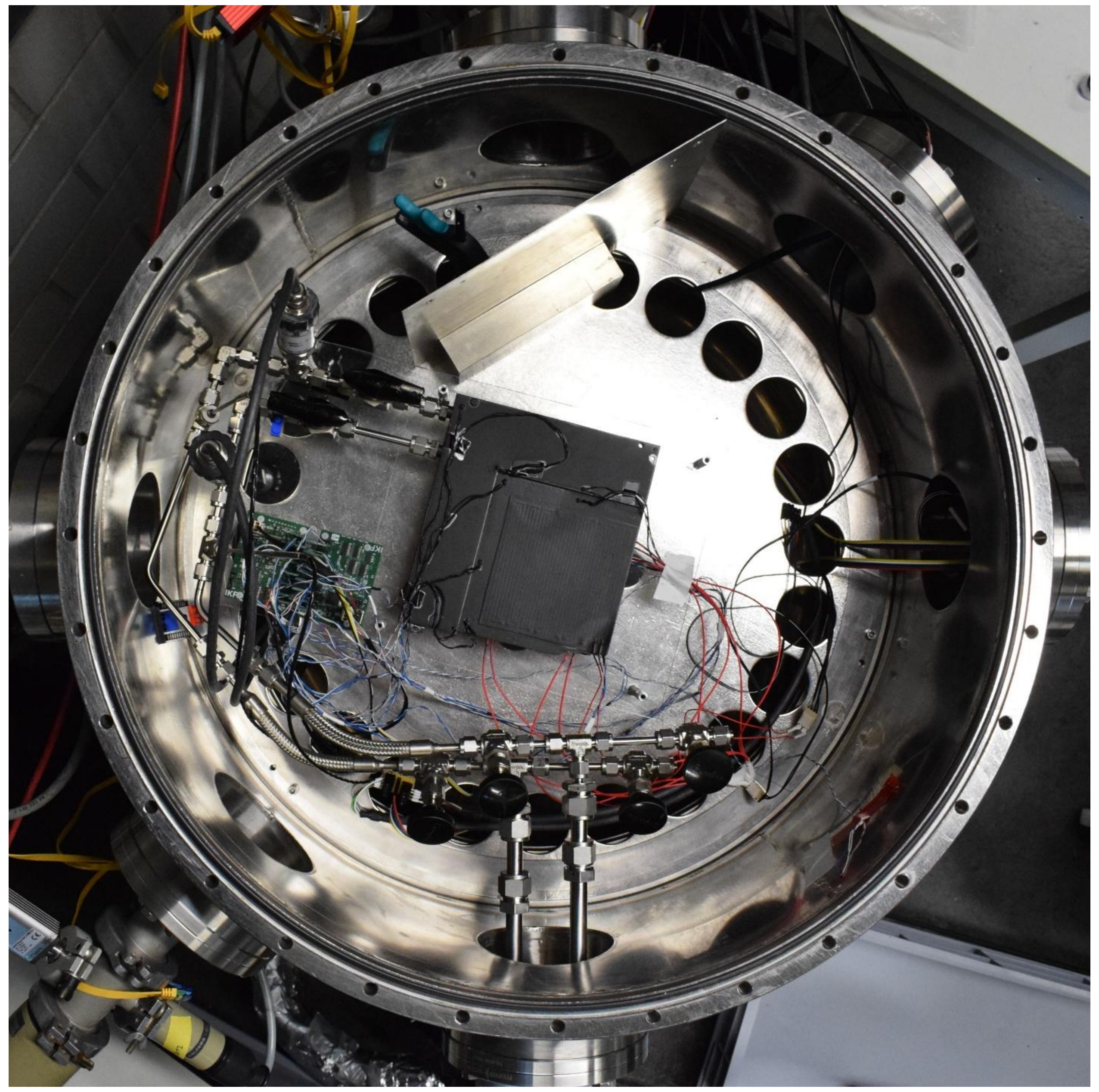
→ Large vacuum chamber

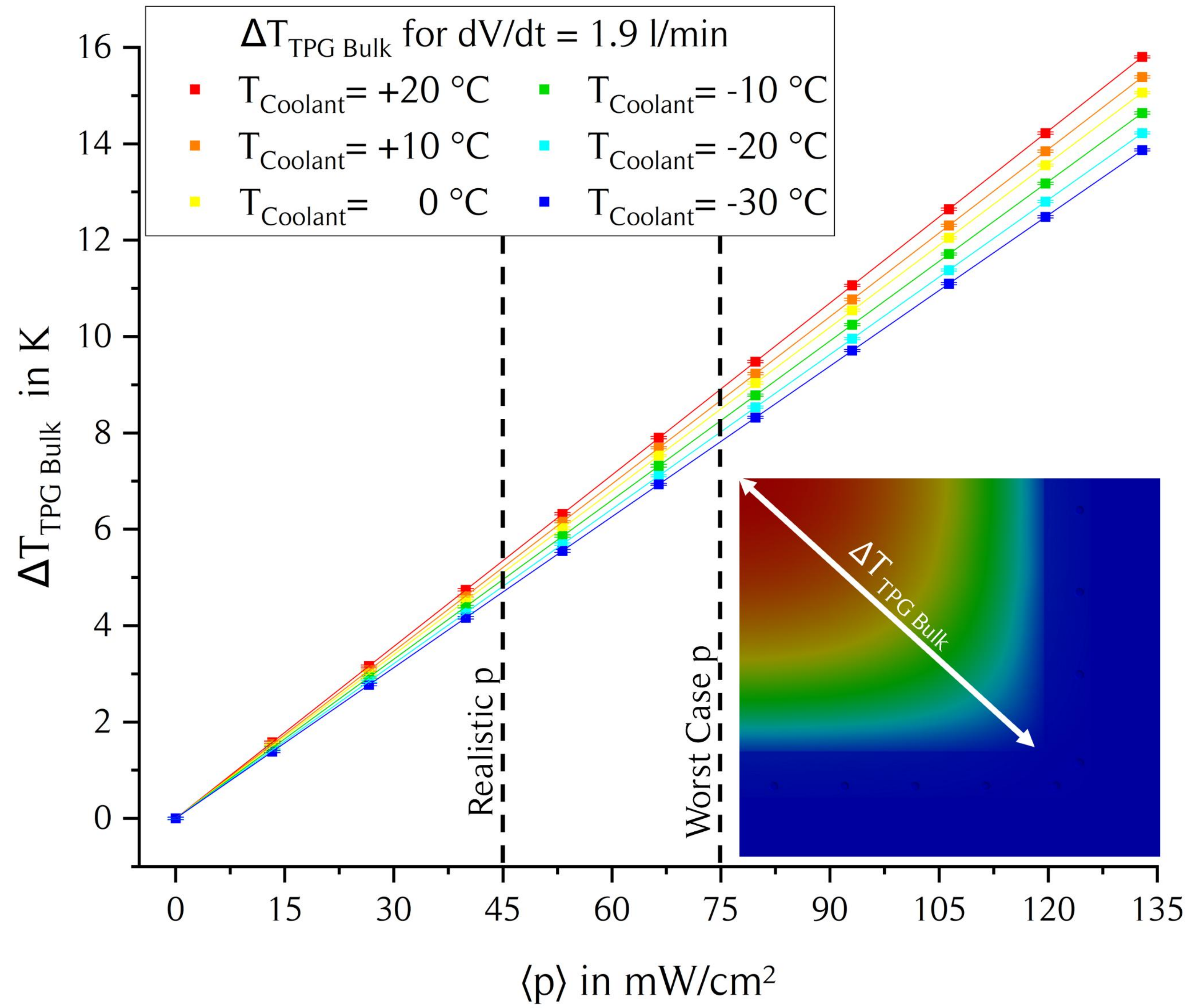
→ Julabo Presto A 40 with Novec-649

→ MVD pre-production heat sinks

→ MVD: TPG carriers with Kapton heaters, Pt100 temperature sensors

https://www.julabo.com/en/products/highly-dynamic-temperature-control-systems/presto-process-systems/presto-a40





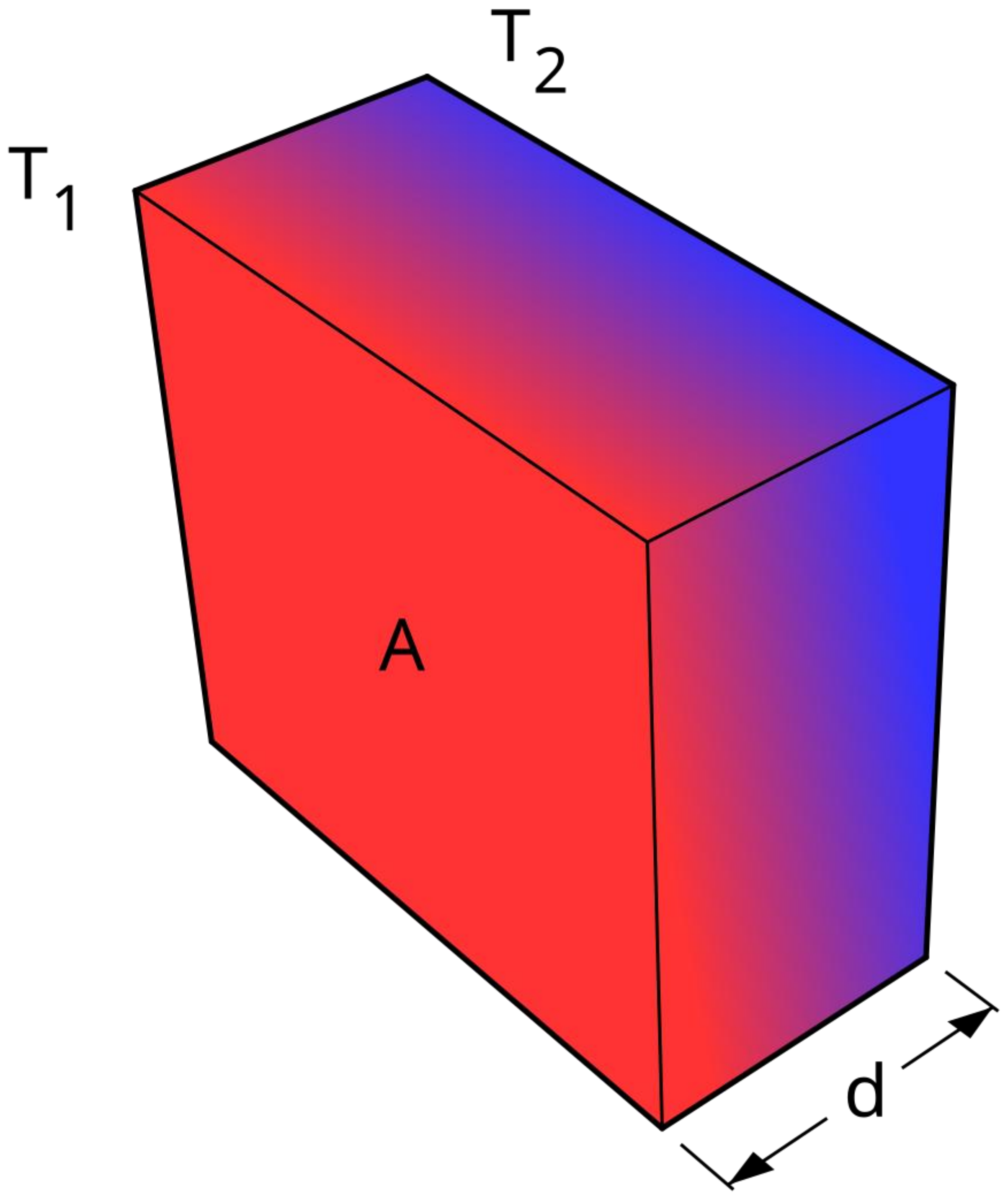
Details on the cooling performance:
https://www.sciencedirect.com/science/article/pii/S0168900224008507

Thermal Conductivity Measurements

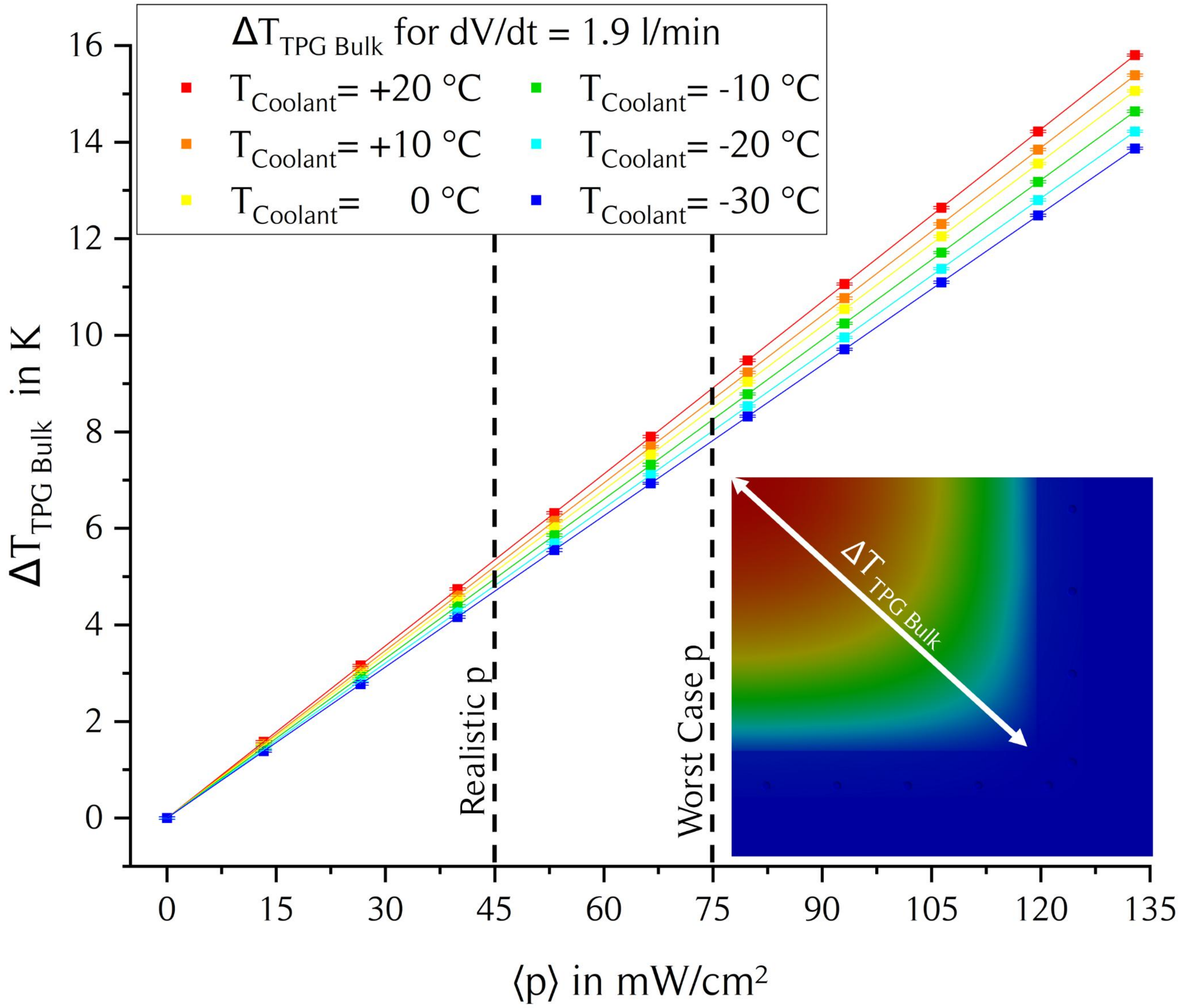
$$\vec{q} = -k\vec{\nabla}T$$

$$\Delta T = \frac{P \cdot d}{\lambda \cdot A}$$

Power: electric heater
Temperature: Pt100s, thermistors, …
Geometry (ideally 1D heat transfer)



https://de.wikipedia.org/wiki/W%C3%A4rmeleitung



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https://www.sciencedirect.com/science/article/pii/S0168900224008507

Influence from the Environment

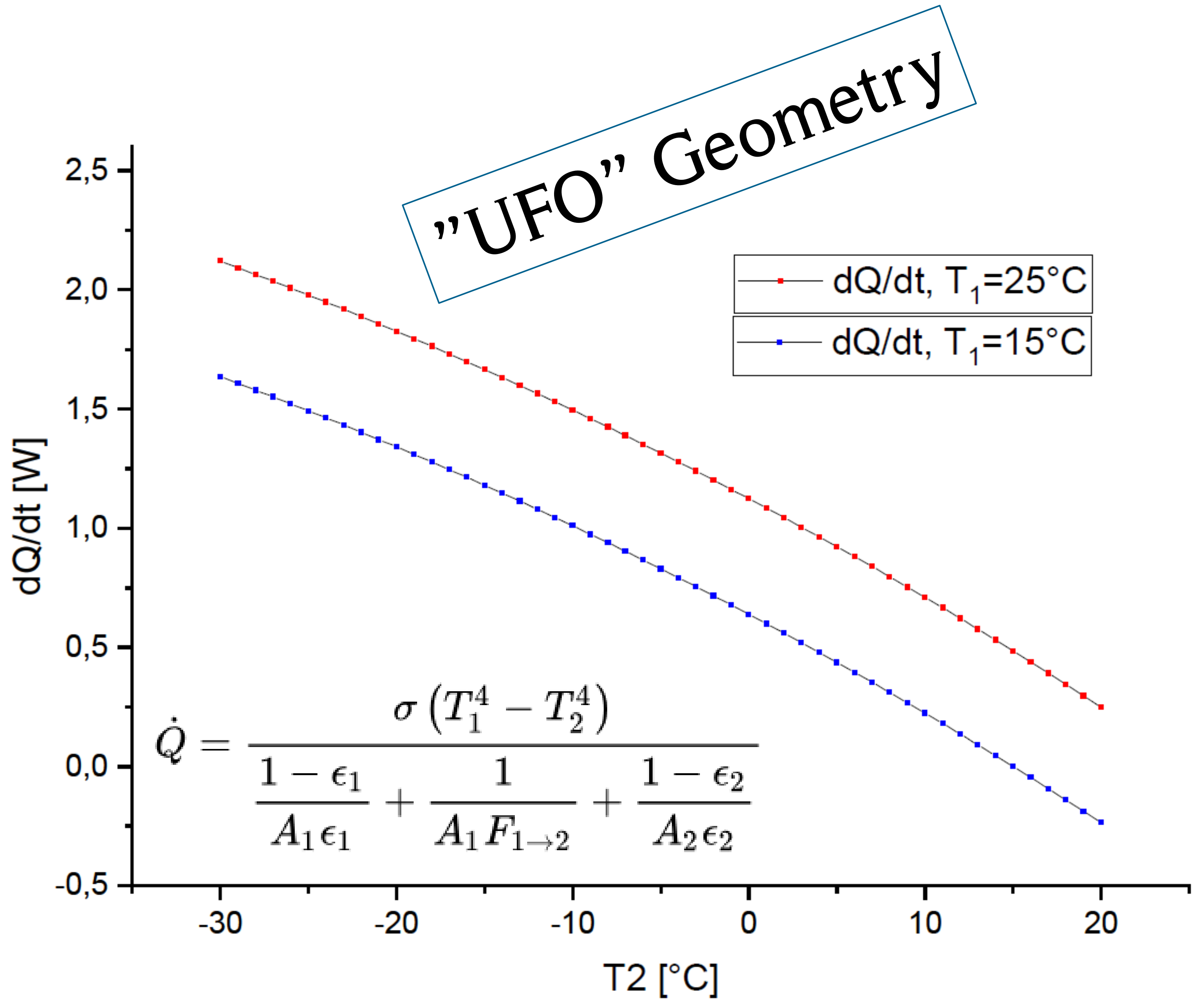
Convection

→ Suppressed by ~10^{-2} mbar vacuum

Thermal radiation

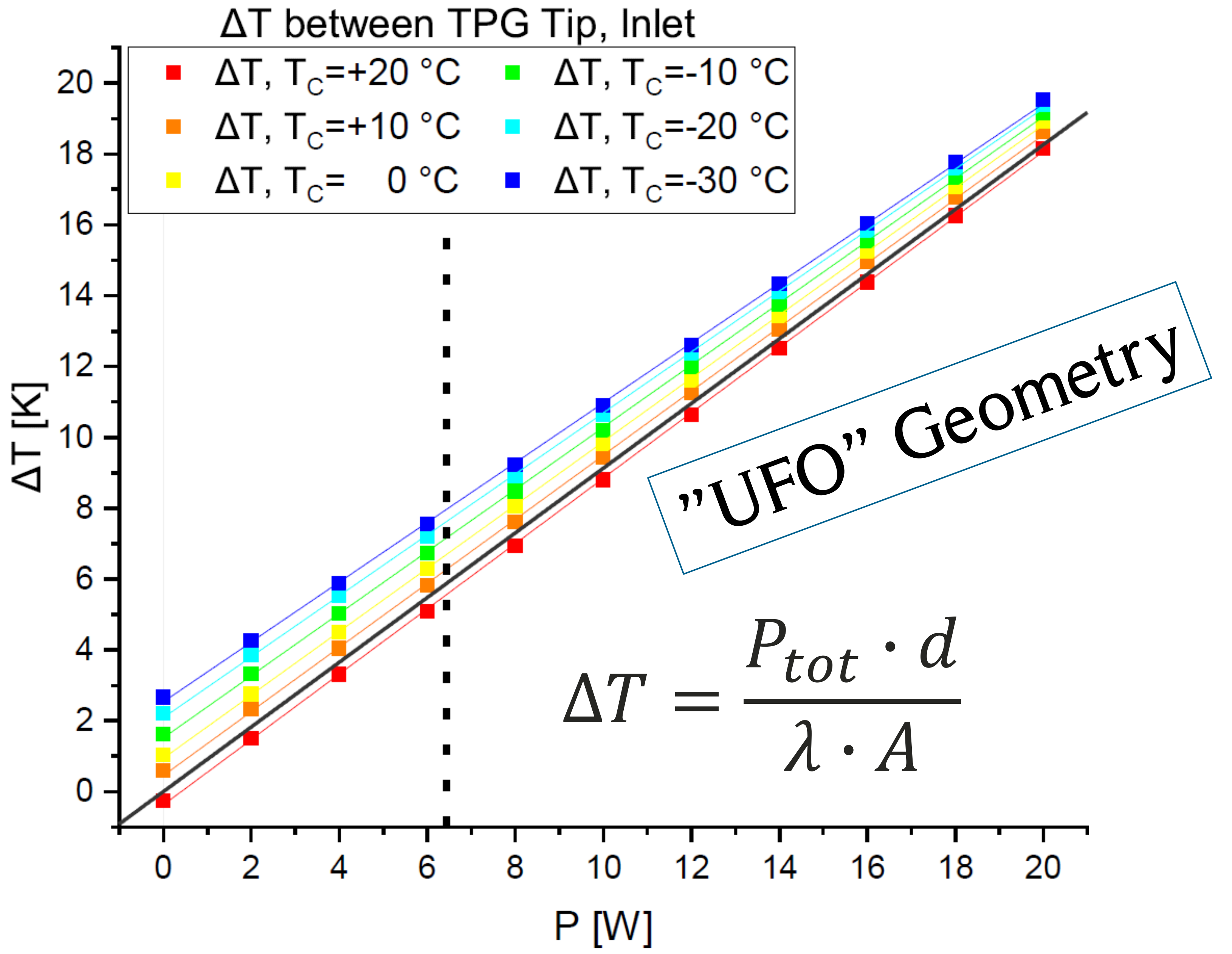
→ Dominating background contribution

→ Large surface to volume unfavorable



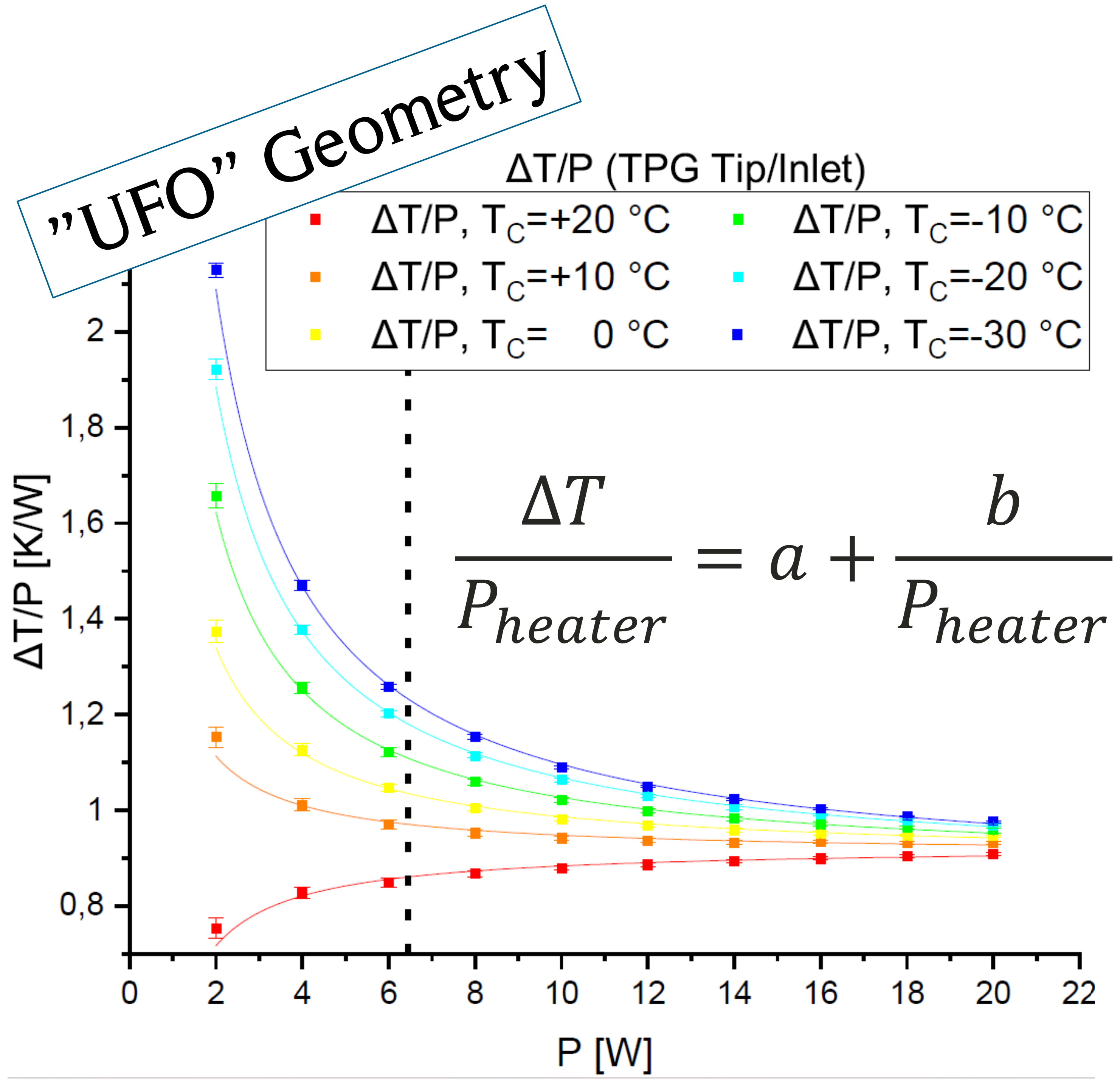
$$\dot{Q} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\epsilon_1}{A_1\epsilon_1} + \frac{1}{A_1 F_{1\to 2}} + \frac{1-\epsilon_2}{A_2\epsilon_2}}$$

Example: Calculated radiative heat entry from UFO walls onto (black) MVD quadrant



$$\Delta T = \frac{P_{tot} \cdot d}{\lambda \cdot A}$$

Offset: Thermal radiation
Different slopes: (Mostly) T-dependence of λ



$$\frac{\Delta T}{P_{heater}} = a + \frac{b}{P_{heater}}$$

Fit-based correction for radiative heat entry (assumes constant T, λ of sample)

Sample Preparation

8 TPG samples

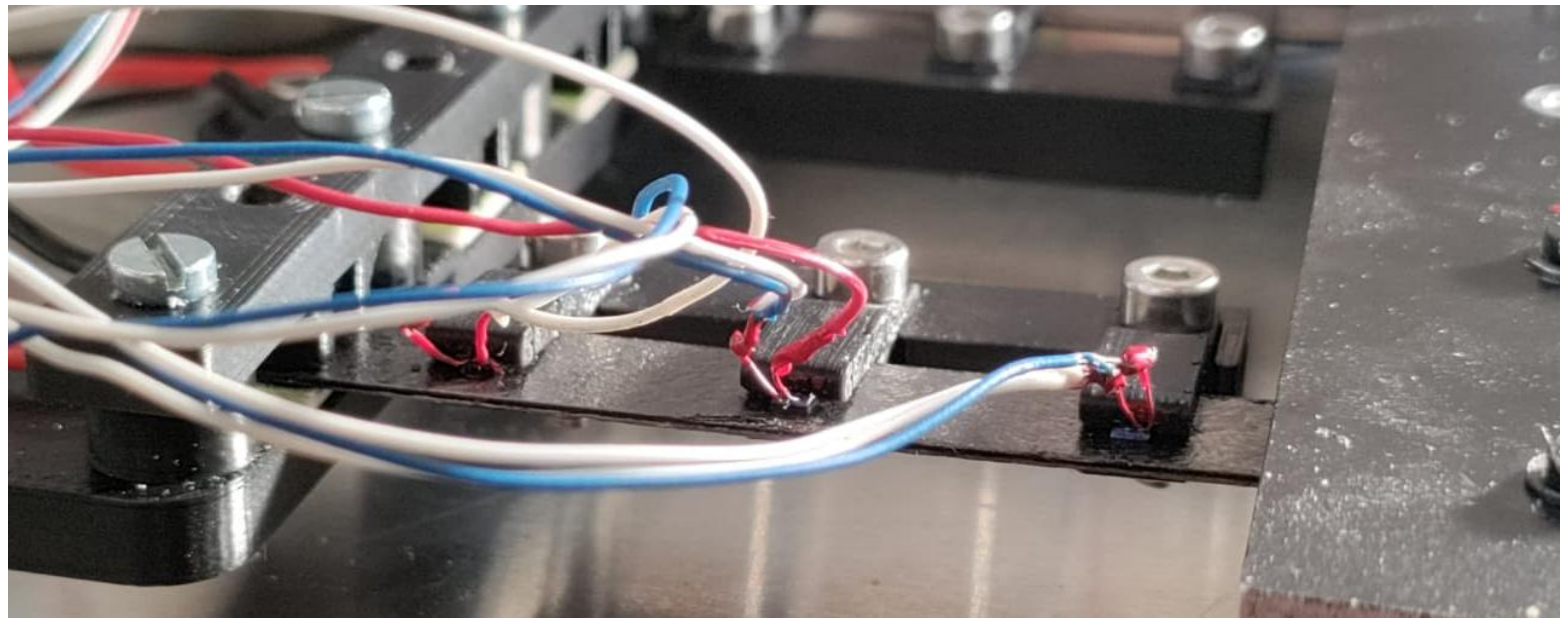
→ Laser-cut from one sheet for precise geometry
→ 70x10x0.5 mm³ TPG samples

https://laser-depaneling.lpkf.com/de/products/lpkf-cuttingmaster-2000

Measurement Setup

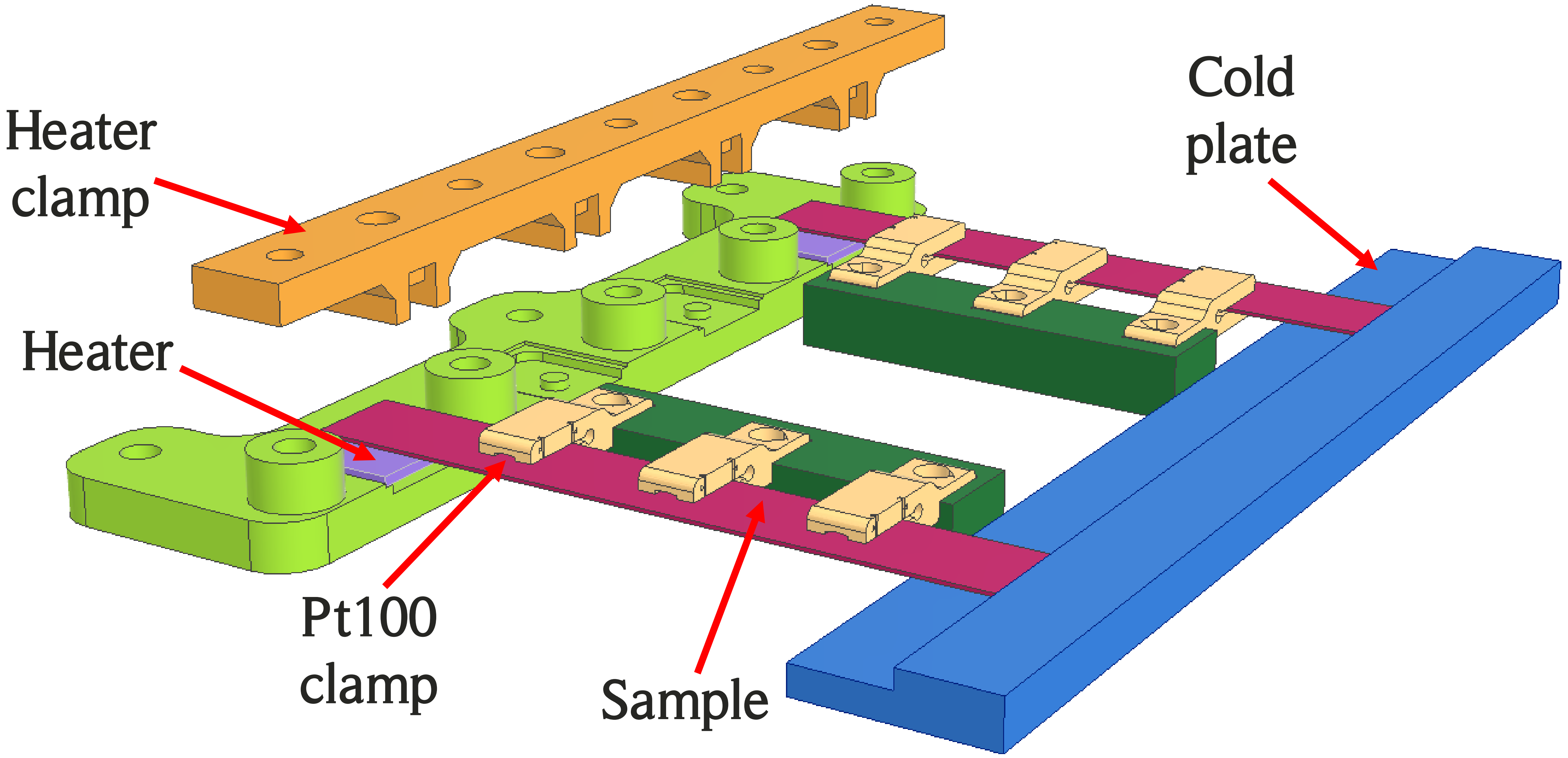
2 samples in parallel

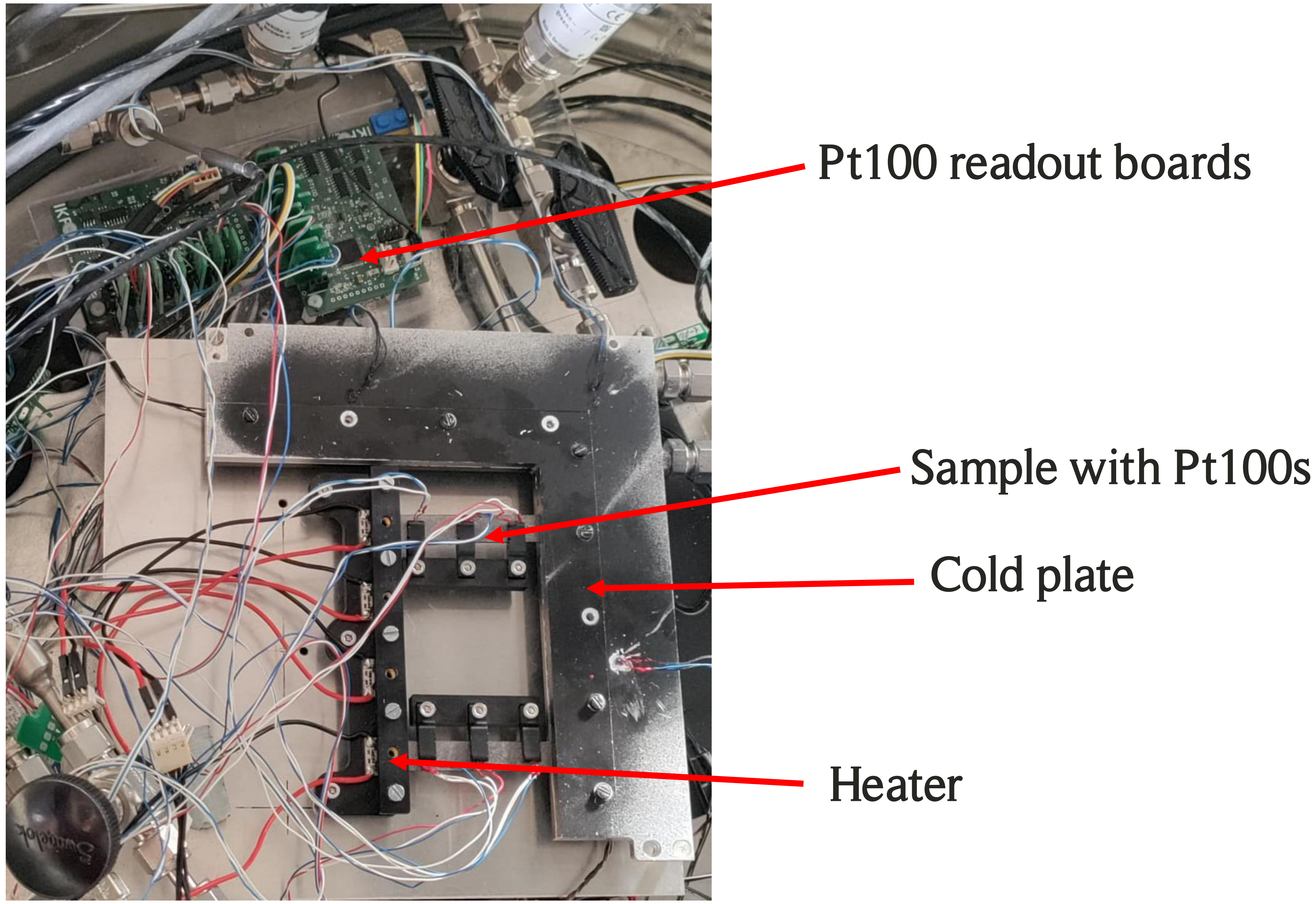
→ Vacuum (~ 10^{-2} mbar)
→ Heat entry measured individually
→ Low-λ support structure (minimize conduction and thermal radiation)
→ No radiation shielding, projective geo of UFO



3 Pt100 sensors

→ Equal spacing
→ In-plane thermal conductivity





Thermal Interfaces

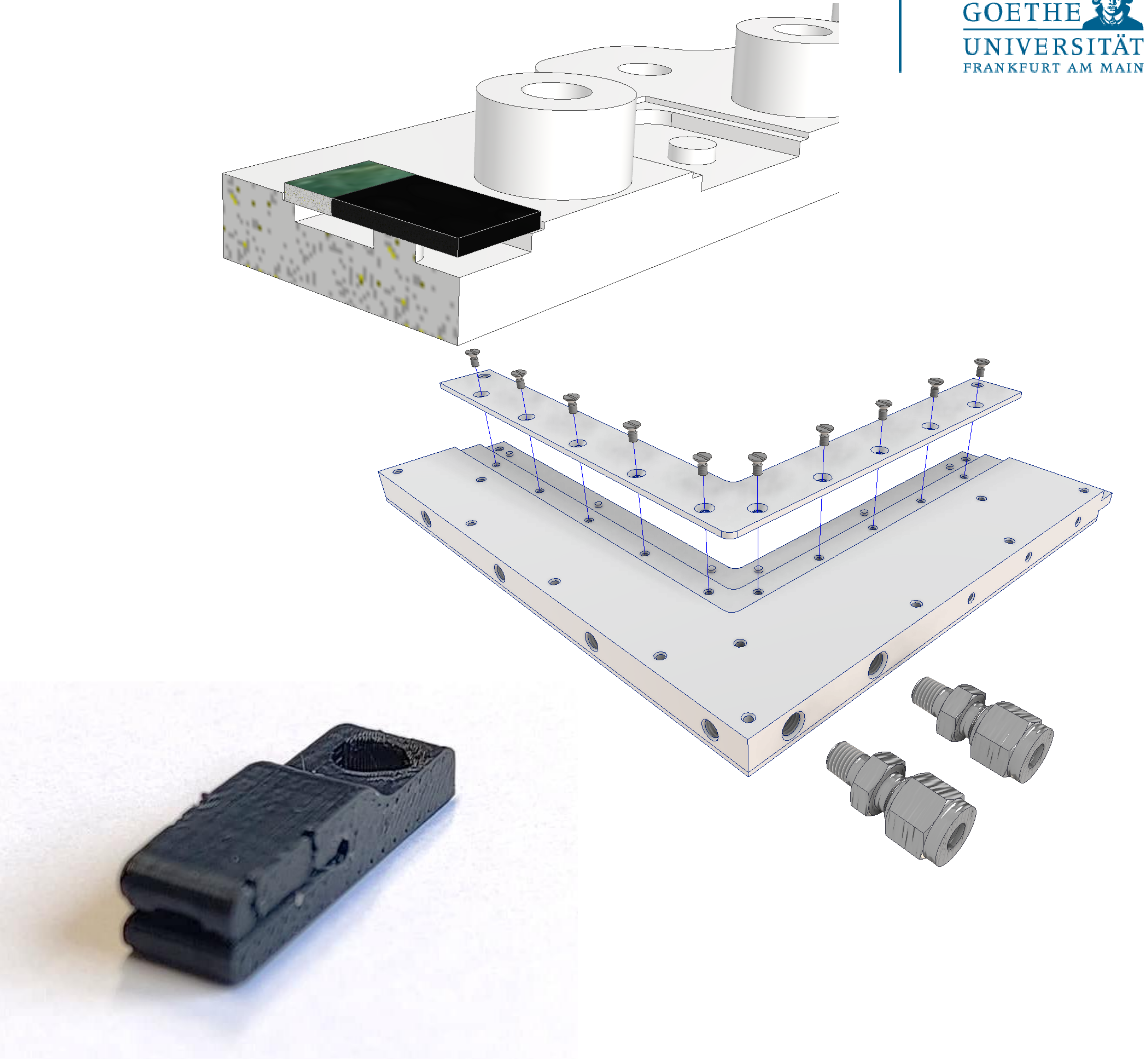
Vacuum grease
→ 0.2 W/mK

Heater side
→ Low-λ support (ABS), small thermal contact
→ Important for well-defined heat entry

Heat sink side
→ Al clamp, fixed torque

Pt100 sensors
→ ABS clamp

Highly relevant for systematic uncertainties



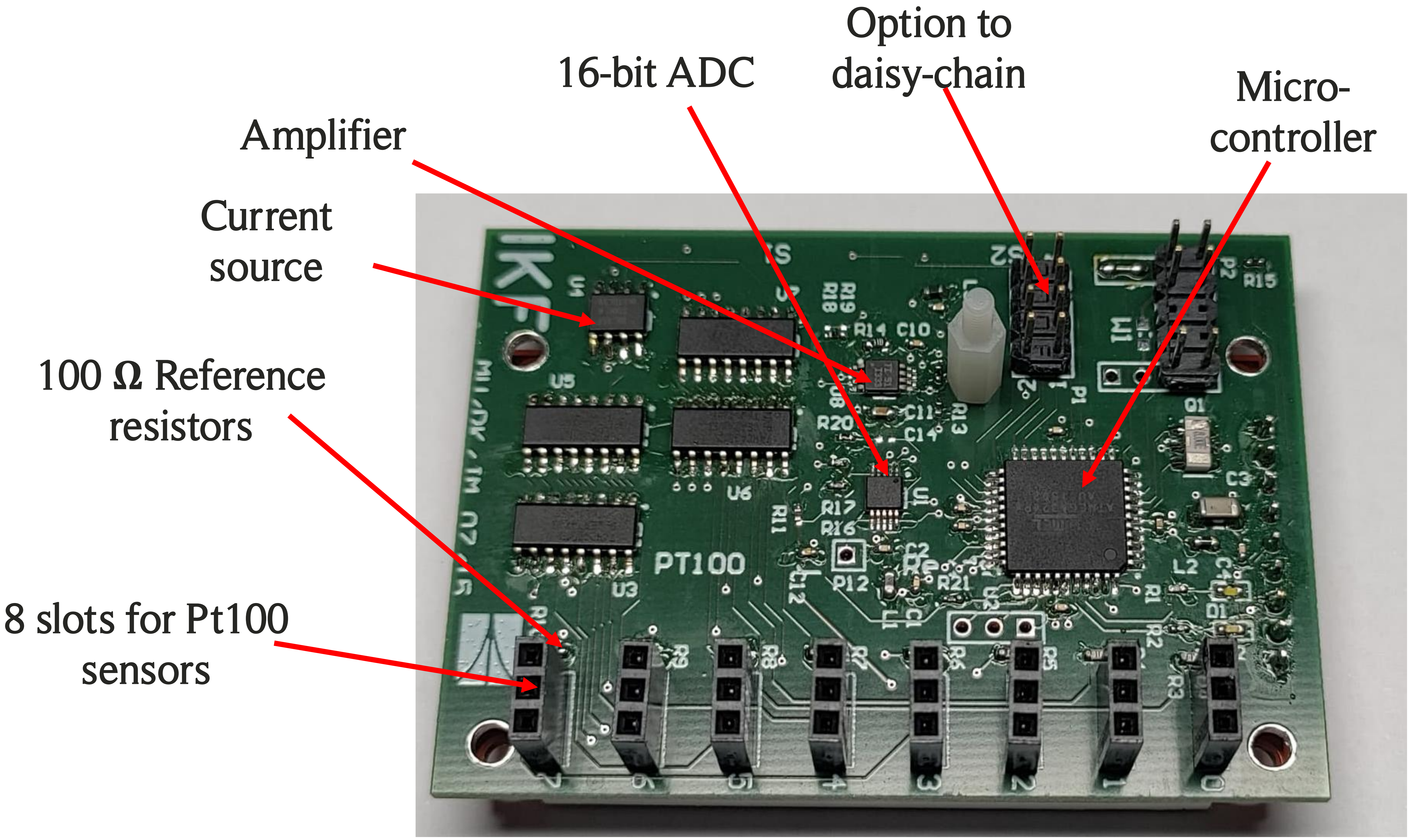
Temperature Measurement

Pt100 readout system

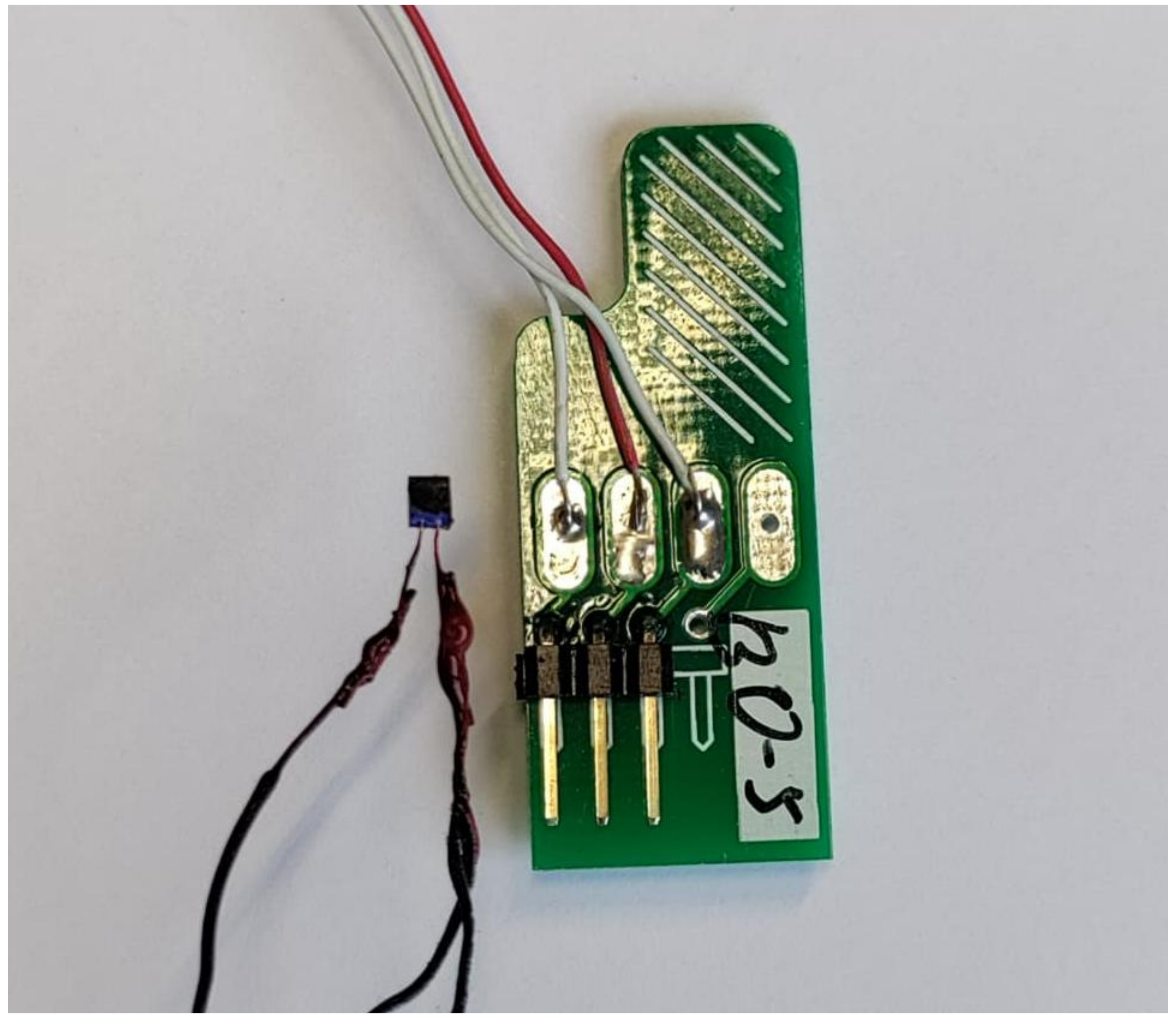
→ Custom PCB (0.1% 100Ω reference resistor)

→ Pt100 sensor boards (sense-wired)

→ Digital interface



Custom Pt100 readout board



Pt100 board and sensor

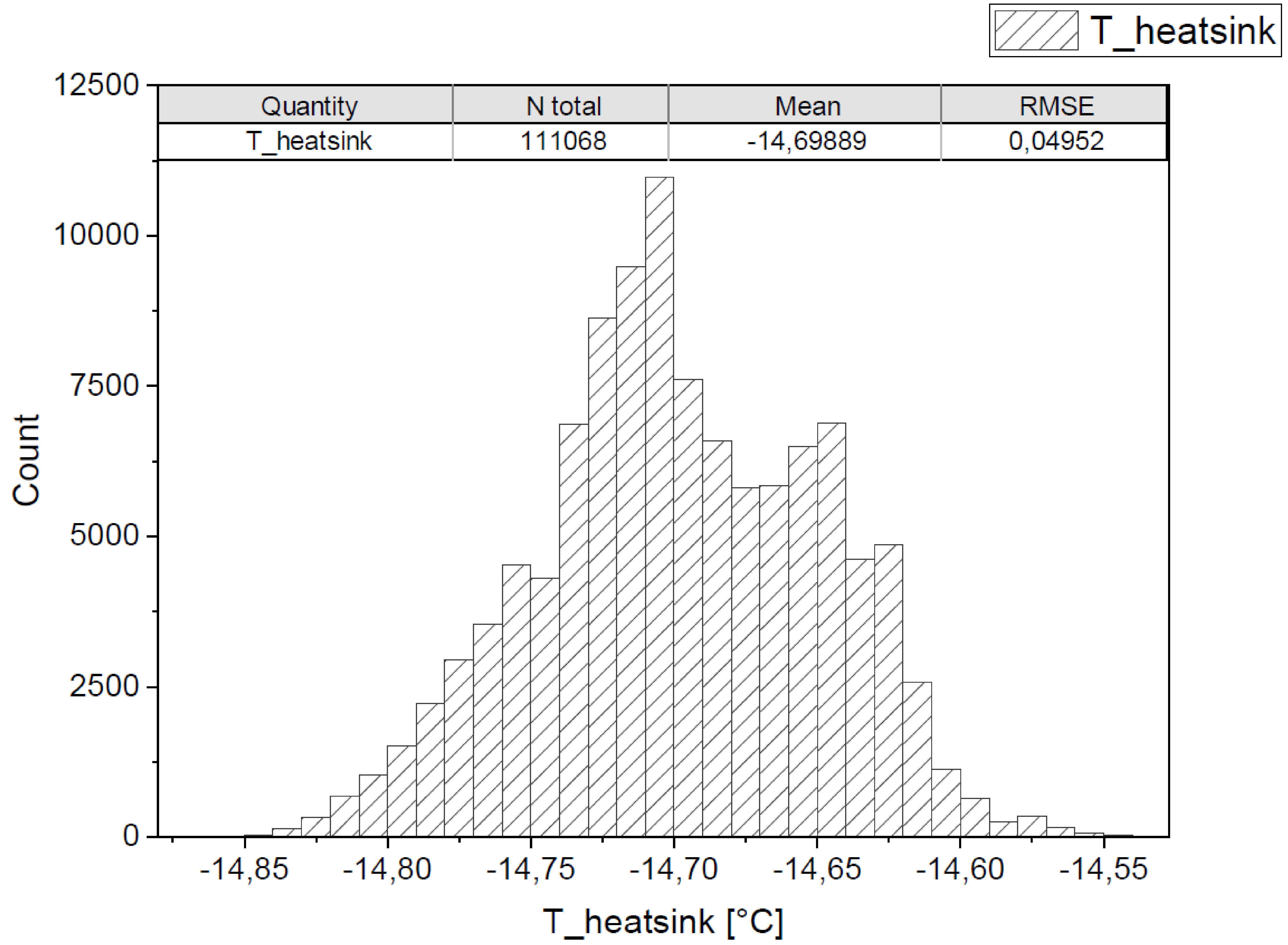
Temperature Measurement Precision

Systematics

→ Grade 1/3 DIN B Pt100 sensors
→ ± (0,1 + 0,0017 | t |) °C
→ .1% from reference resistor

Statistics

→ RMSE of ~.05 K



Quantity	N total	Mean	RMSE
T_heatsink	111068	-14,69889	0,04952

Statistical uncertainty temperature measurement

Measurement Overview

Negative temperature coefficient expected
→ Temperature scan in steps of 10 K, –30, … , +20 °C (± <0.1 K)

Significant impact of thermal radiation
→ Power scan from 0 to 2.3 W, 8 steps

Possible systematic uncertainties between measurement slots
→ Measure each sample in both slots

Optimize total testing time vs relaxation times
→ 30 minutes for system cool-down
→ 2.5 minutes between thermal load changes
→ 1 minute of measurement (300 data points per Pt100)

Irradiation Campaign

Irradiation Setup @ CYRCé

4 samples delivered January 6th, irradiated January 13th at CYRCé (IPHC)

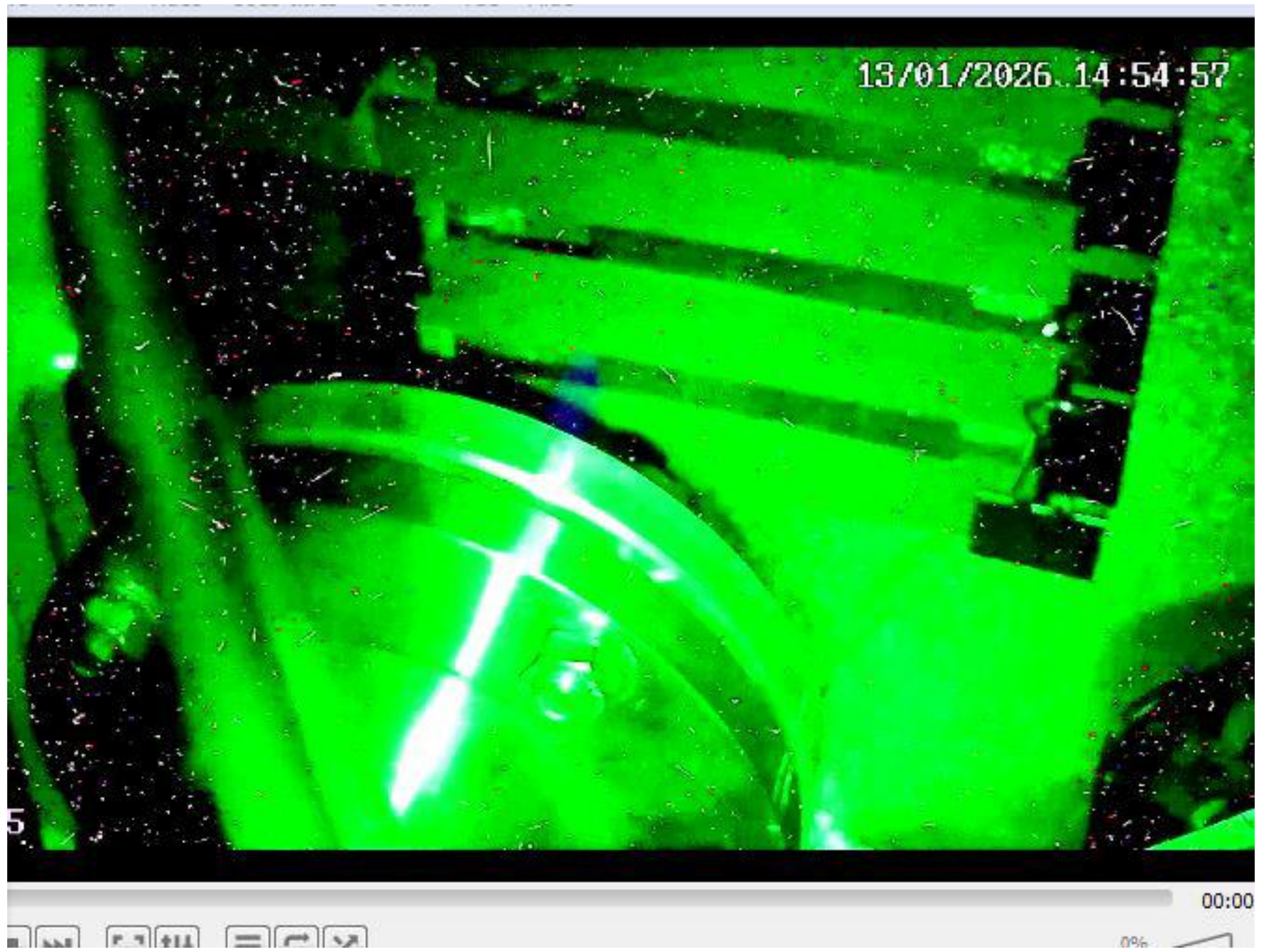
→ 70 x10 x 0.5 mm^3

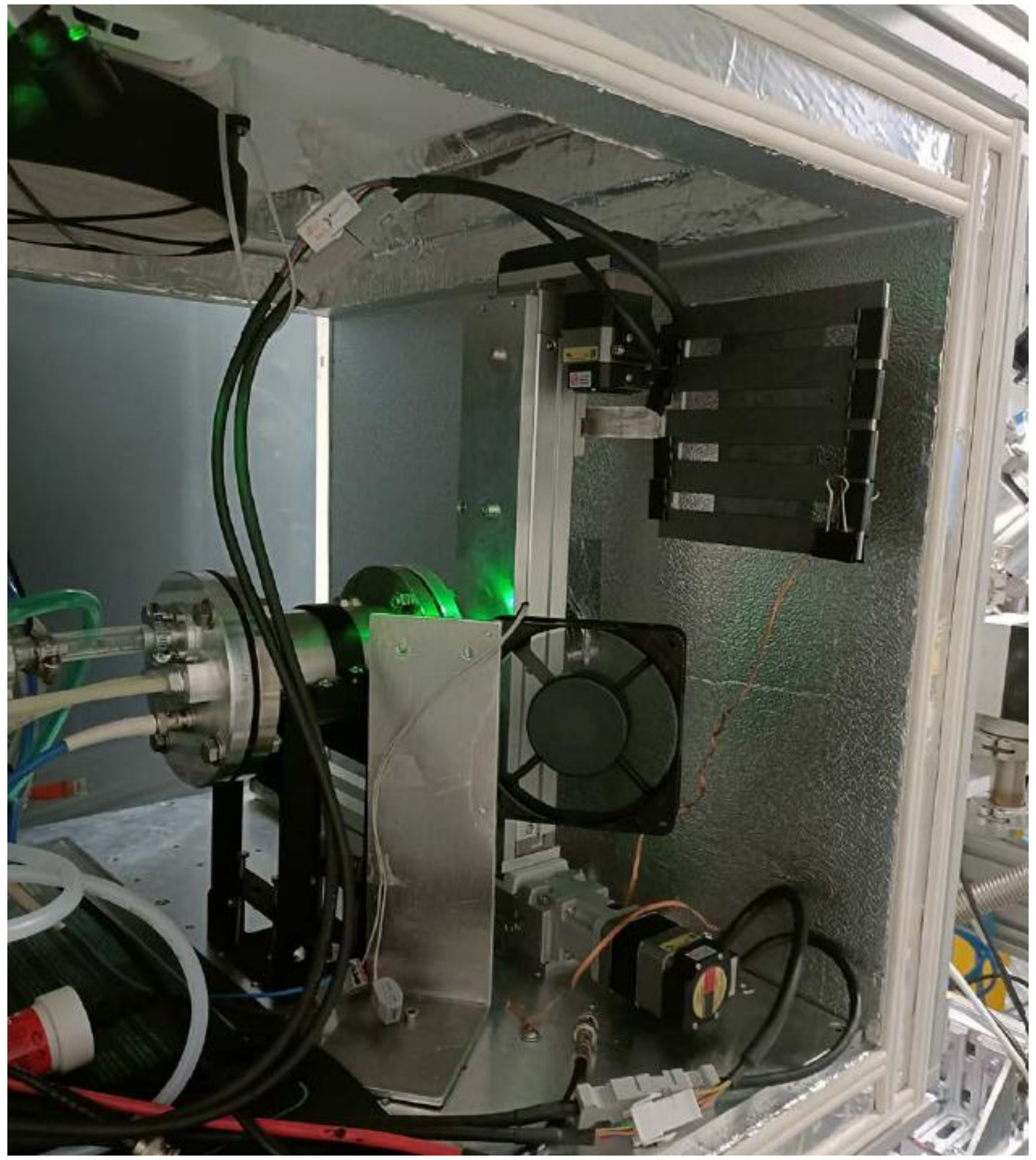
→ Thanks to M. Goffe!

5x10^{12}, 5x10^{14}, 2.5x10^{13} & 5x10^{14} p/cm^2 (25 MeV)

→ For Si: 1x10^{13}, 1x10^{14}, 5x10^{14} & 1x10^{15} n$_{eq}$/cm^2

→ Highest dose: 20 min





Irradiation Setup

Damage function not known for carbon

→ Irradiation at fixed energy

→ Fluences as expected in CBM/Belle II

Energy loss

→ dE/dx≈20 MeVcm²/g for 25 MeV protons on carbon
(calculated with https://www.isotopea.com/webatima/)

→ Total cross section few 100 mbarn *(estimation)*

CIRCé environment vs CBM environment (heavy ions, slow particles, …)?

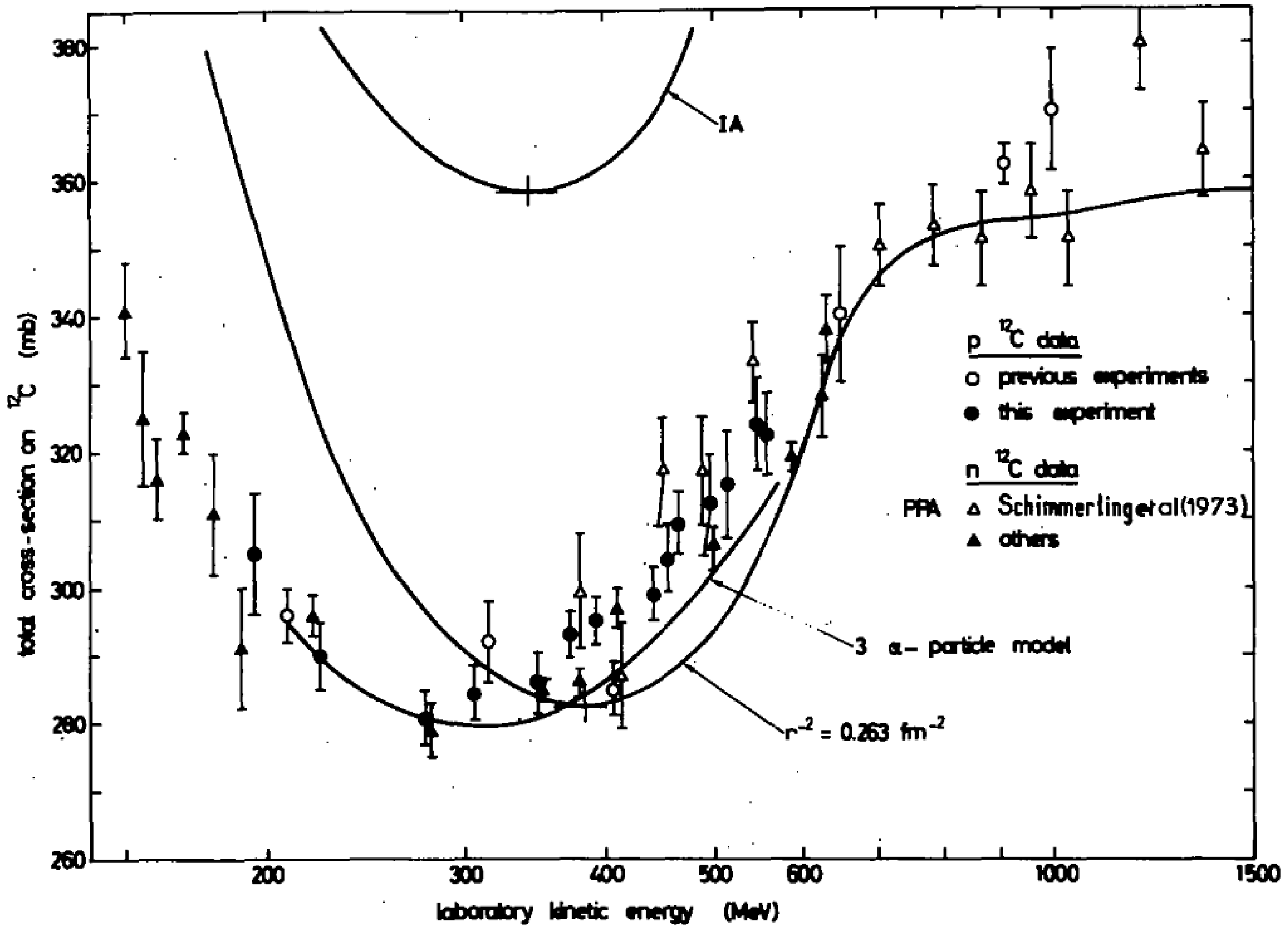
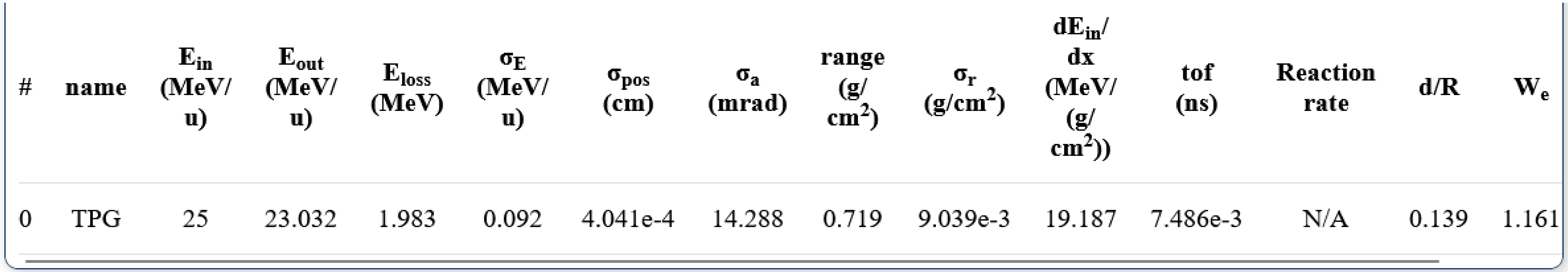


Fig. 10. Total cross sections for protons and neutrons on ^{12}C.

http://hermes.ihep.su:8001/pool/mass/NP_A316_317.pdf

Proton & Neutron Carbon, 100–1400 MeV



#	name	E_{in} (MeV/u)	E_{out} (MeV/u)	E_{loss} (MeV)	σ_E (MeV/u)	σ_{pos} (cm)	σ_a (mrad)	range (g/cm^2)	σ_r (g/cm^2)	dE_{in}/dx (MeV/(g/cm^2))	tof (ns)	Reaction rate	d/R	W_e
0	TPG	25	23.032	1.983	0.092	4.041e-4	14.288	0.719	9.039e-3	19.187	7.486e-3	N/A	0.139	1.161

Analysis

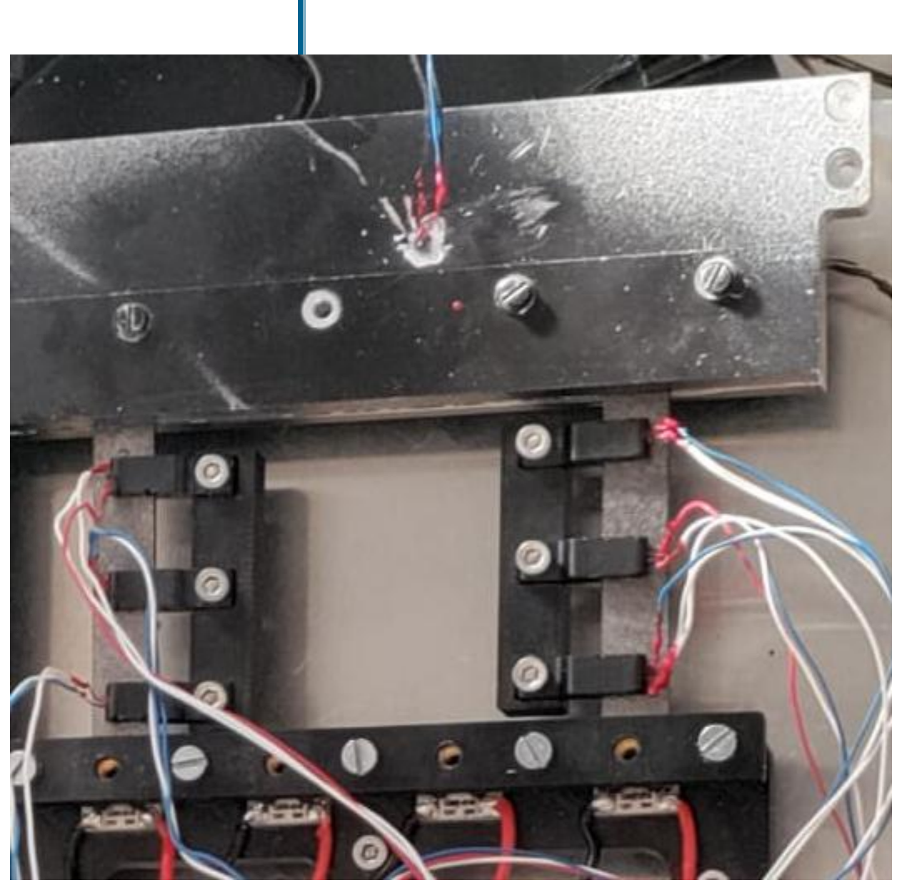
Raw Data

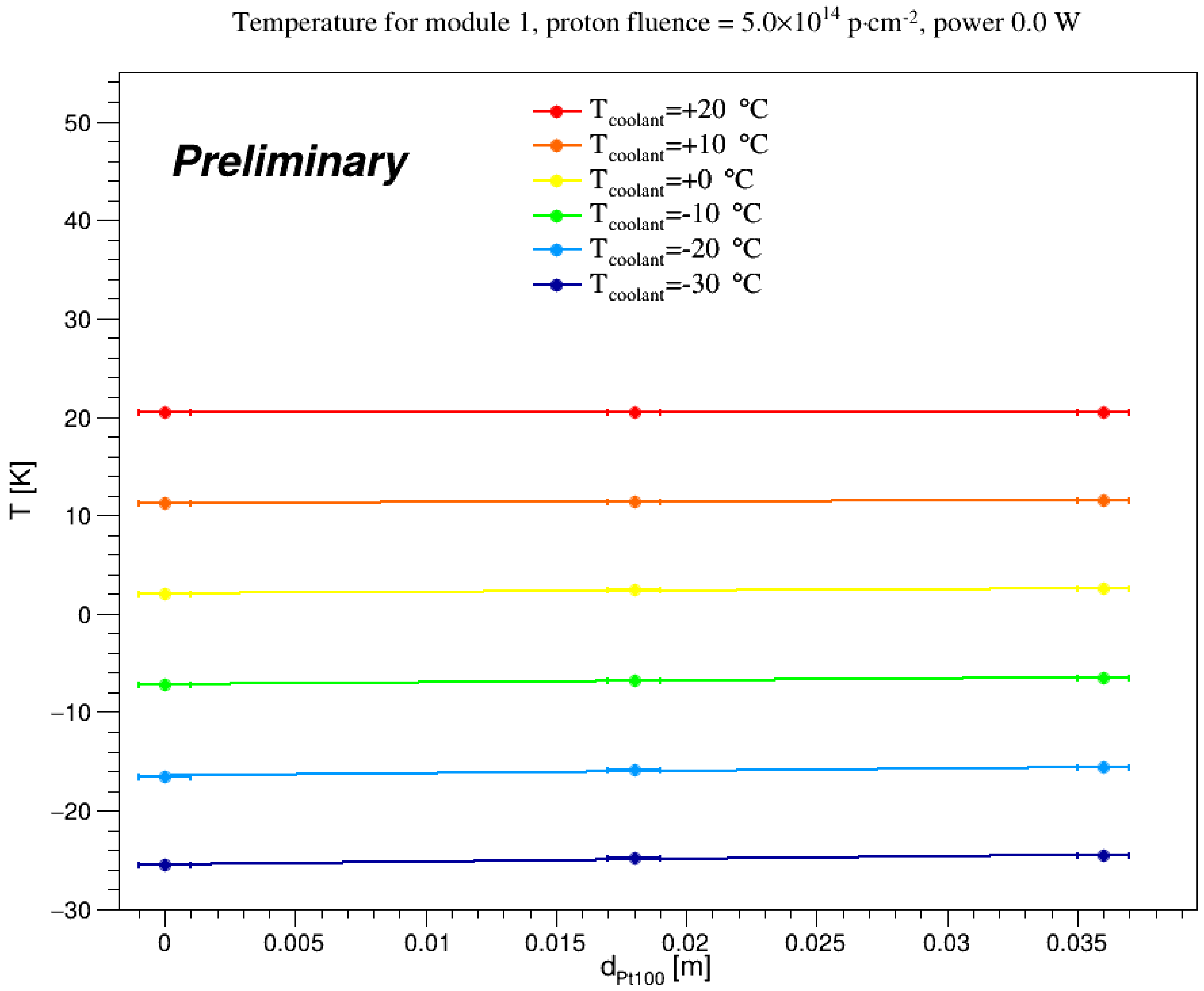
2 iterations per module, one per measurement slot

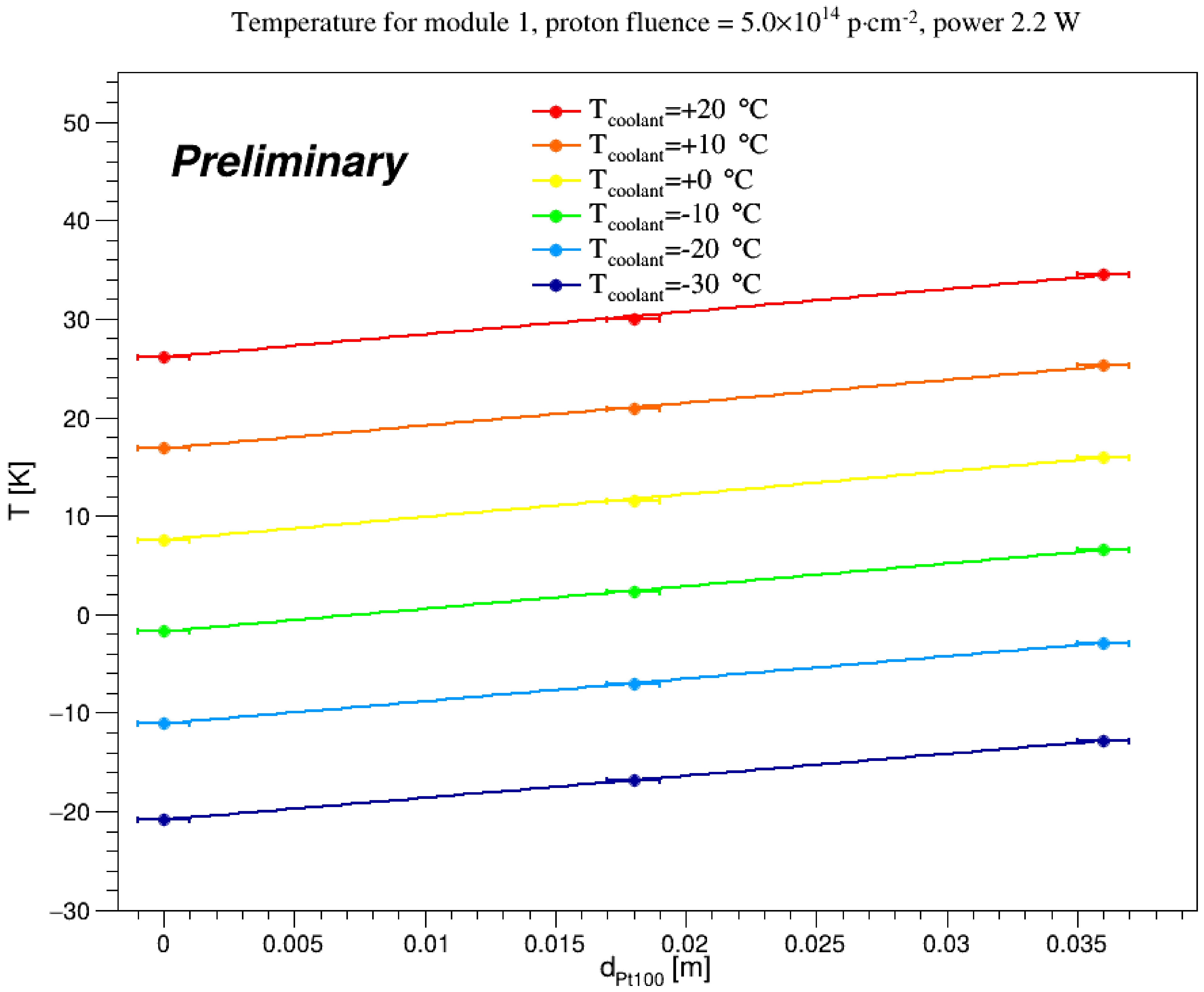
→ ΔT/d for given heat entry from three temperature points

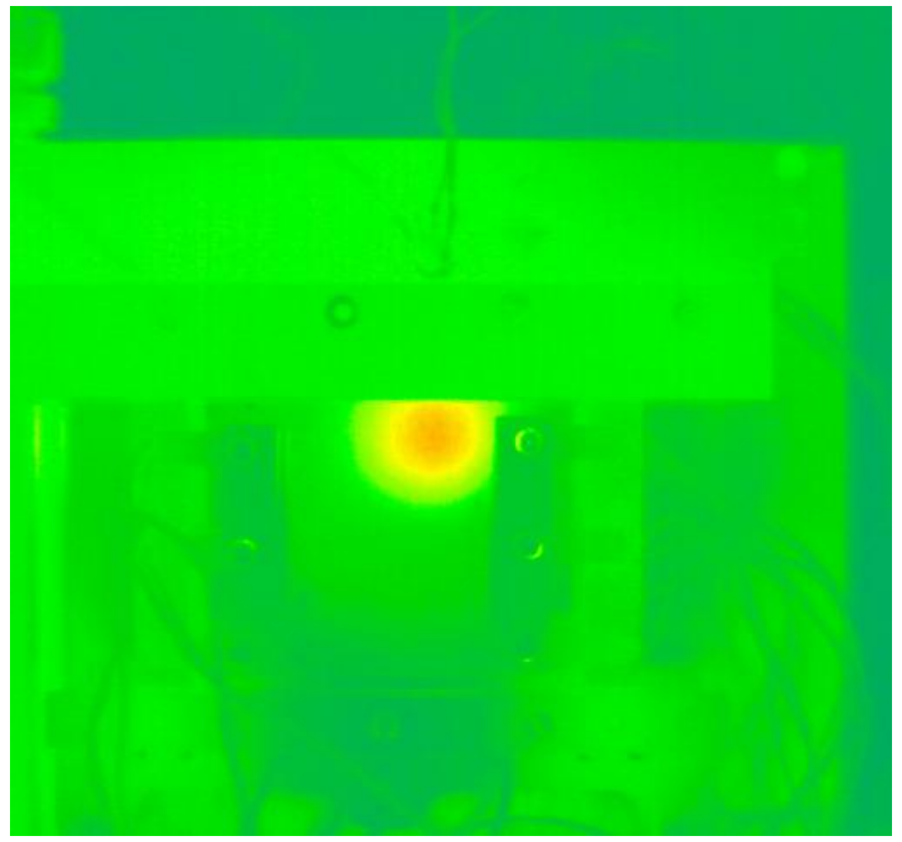
→ Linear behavior (Fourier)

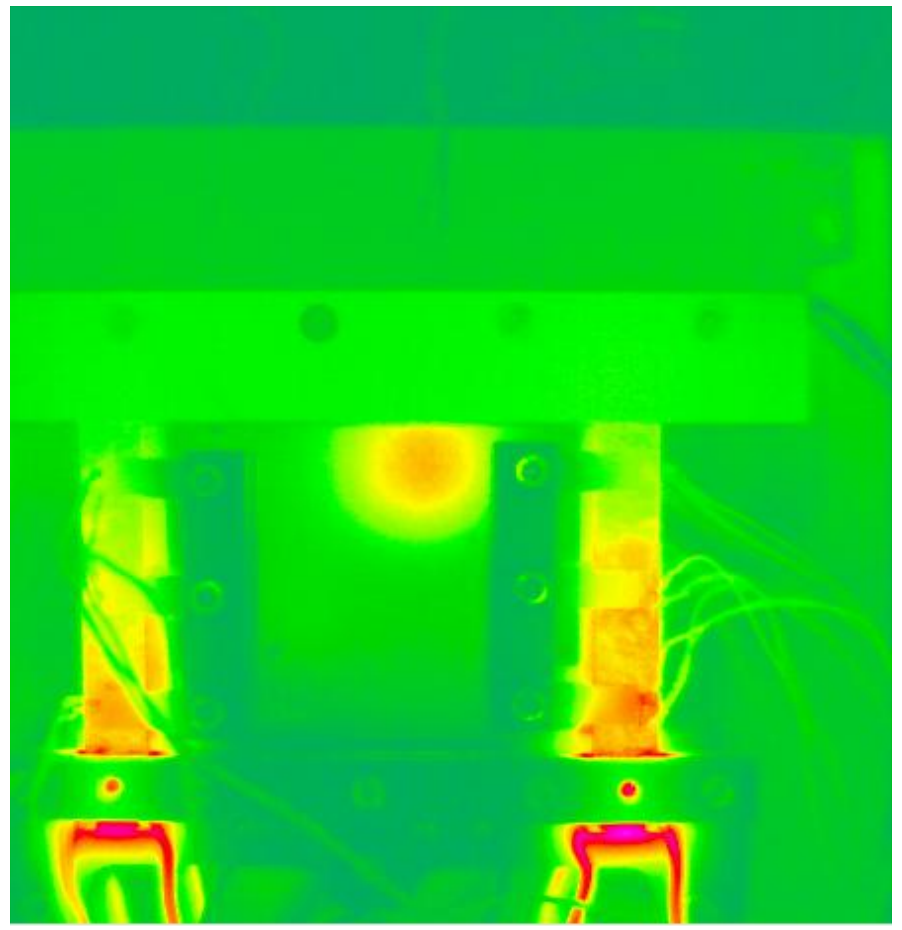
$$\Delta T = d\,\frac{P}{\lambda \cdot A}$$




Temperature for module 1, proton fluence = 5.0×10^{14} p·cm^{-2}, power 0.0 W


Temperature for module 1, proton fluence = 5.0×10^{14} p·cm^{-2}, power 2.2 W





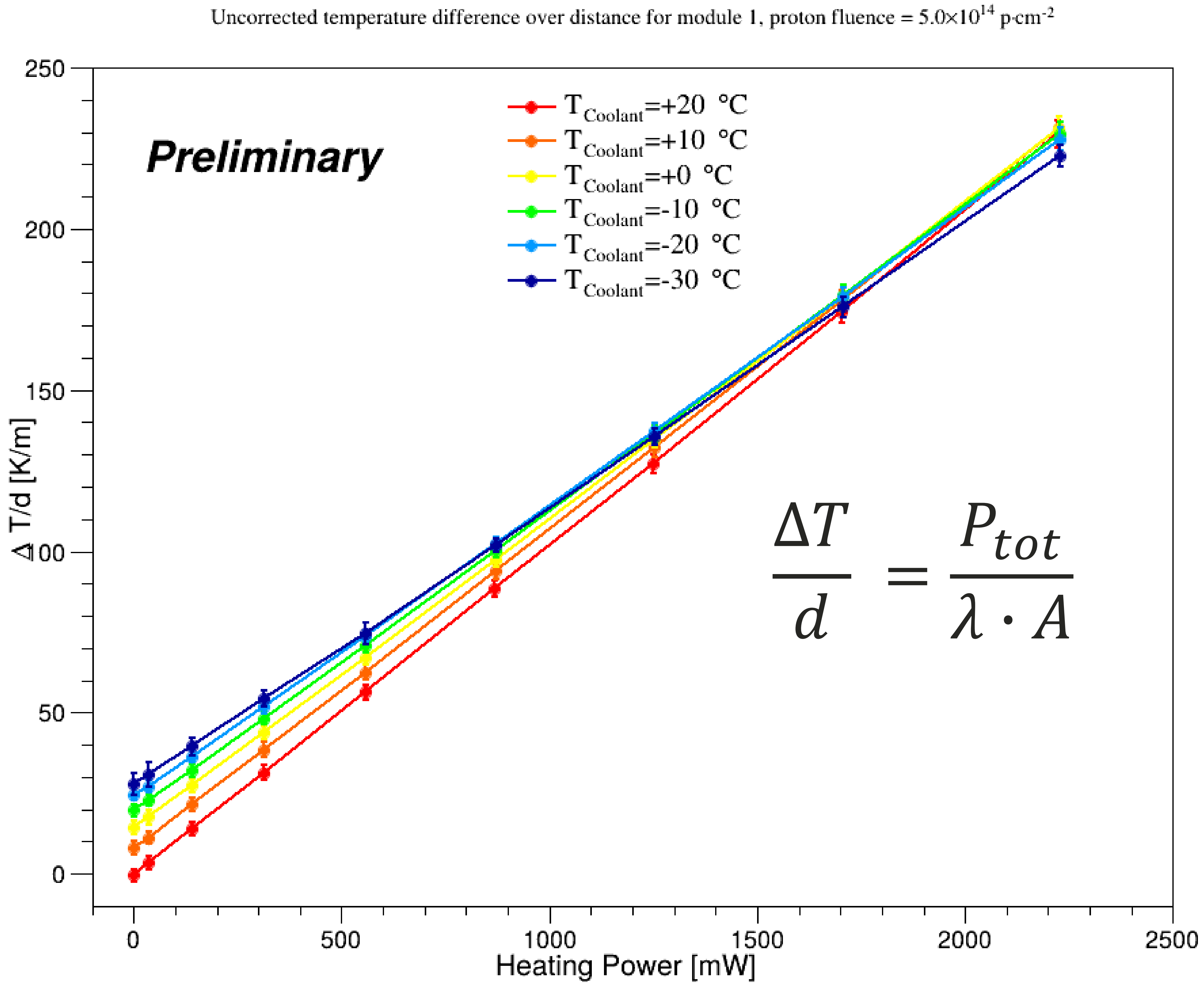
Correction of Thermal Radiation

Assume temperature-independent properties

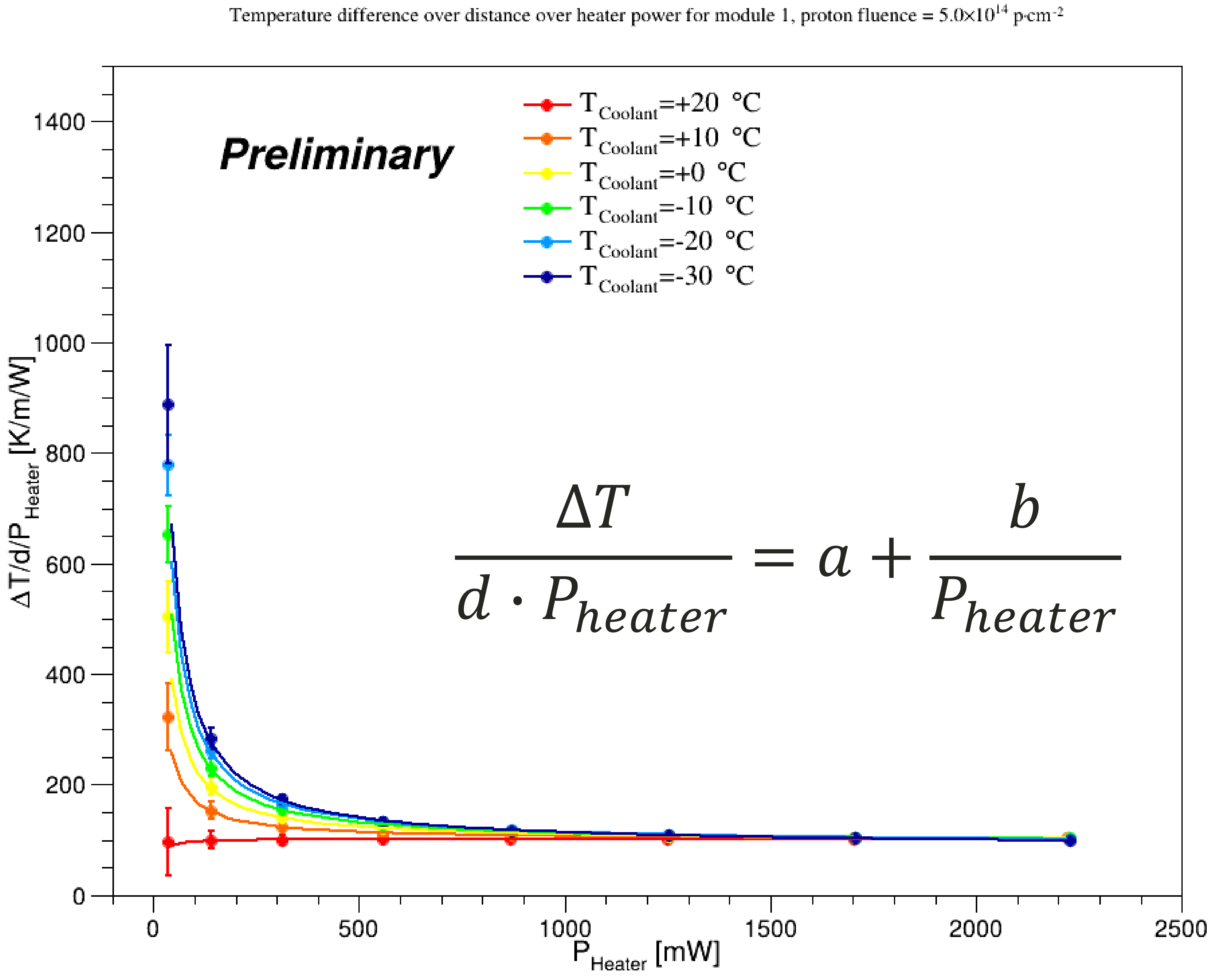
→ Hyperbola fit

→ Parameter *a* encodes geometry and thermal conductivity

→ Parameter *b* encodes external heat entry


Uncorrected temperature difference over distance for module 1, proton fluence = 5.0×10^{14} p·cm^{-2}

$$\frac{\Delta T}{d} = \frac{P_{tot}}{\lambda \cdot A}$$


Temperature difference over distance over heater power for module 1, proton fluence = 5.0×10^{14} p·cm^{-2}

$$\frac{\Delta T}{d \cdot P_{heater}} = a + \frac{b}{P_{heater}}$$

Degradation of Thermal Conductivity

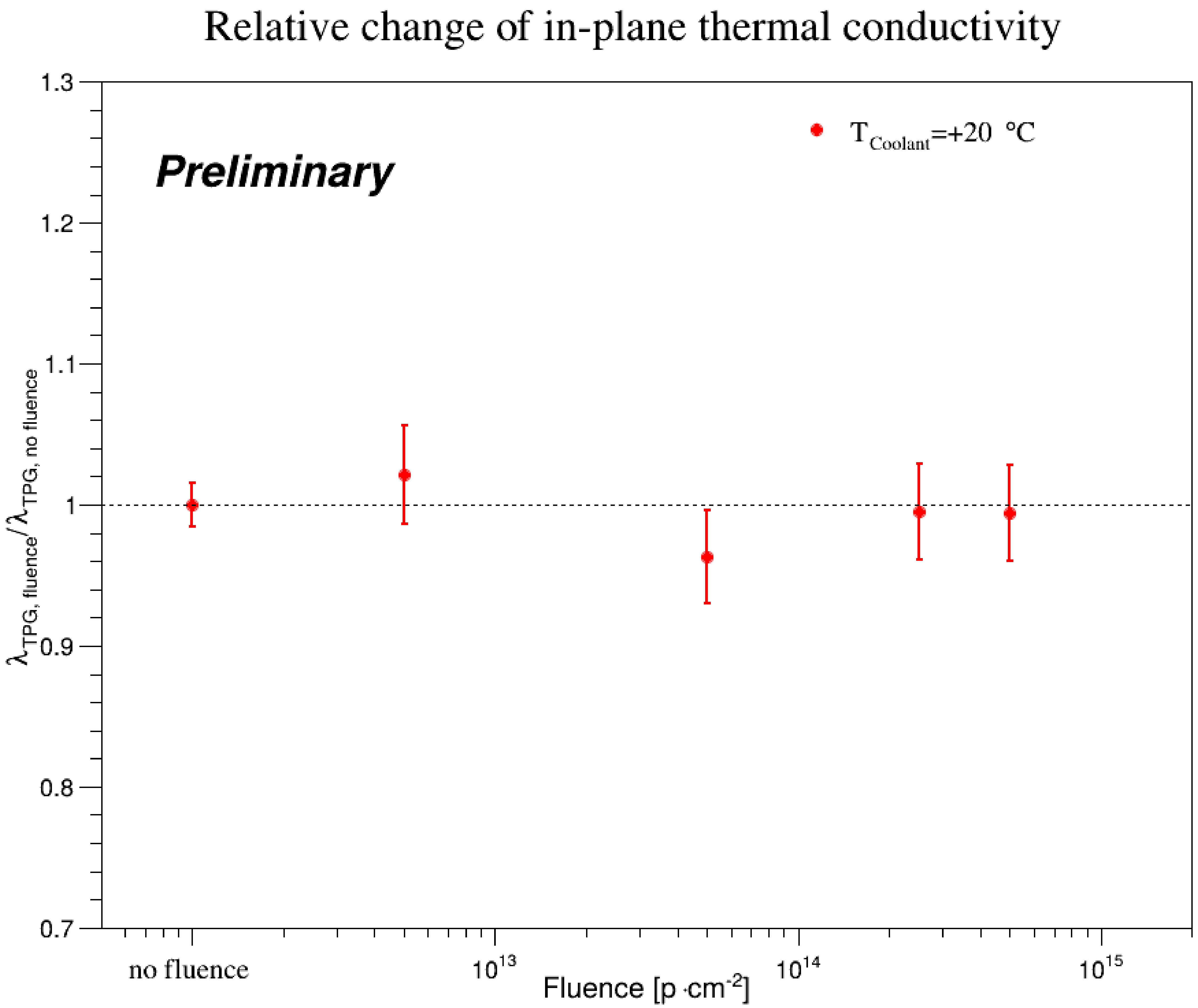
Cancel setup systematics by plotting ratios

→ Compare fit parameters a(no fluence)/a(fluence) at fixed coolant T

→ Non-irradiated samples as reference

→ 2-measurement-average per sample

No significant change of thermal conductivity at all coolant T



Absolute Thermal Conductivity

λ calculated from parameter a and TPG cross-sectional area

Consistent over all samples and measurements

→ Negative temperature coefficient

→ $\lambda(T) = (2084 \pm 3_{stat} \pm 260_{syst}) - (7.03 \pm 0.16_{stat} \pm 0.9_{syst}) \times T$ [W/m/K]

Global linear fit, symmetric min/max envelope

→ ATLAS: $\lambda(T) = 1870 - 7.5 \times T$ [W/m/K]

Value likely slightly overestimated

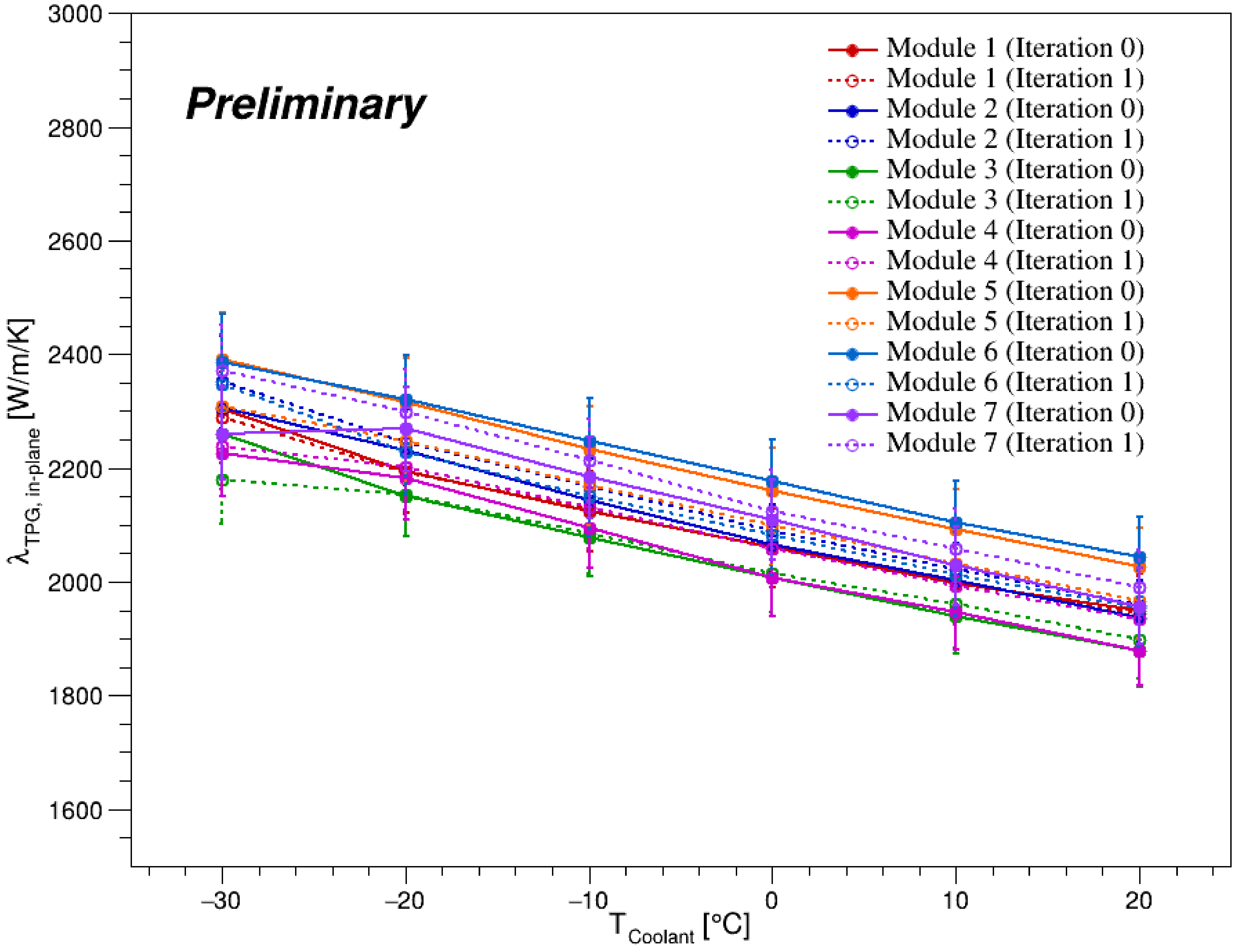
→ Here: (1940±260) W/m/K at room T

→ Vendor: 1500-1900 W/m/K at room T

→ Correction of thermal radiation from sample?

→ Coupling to supports (overestimate of heat entry)?

In-plane thermal conductivity for all modules



Summary & Outlook

Summary & Outlook

Take-home messages

→ No degradation observed up to 5x10^{14} p/cm^2 (25 MeV)

→ 1500 W/m/K appears to underestimate λ

→ Negative temperature coefficient confirmed

Analysis could be further refined (error bars, systematics)

→ Correlation of systematic errors

→ Uncertainty of fluence

→ More elaborate correction of thermal radiation

→ T-dependent lambda (~100 W/m/K over ~10 K)

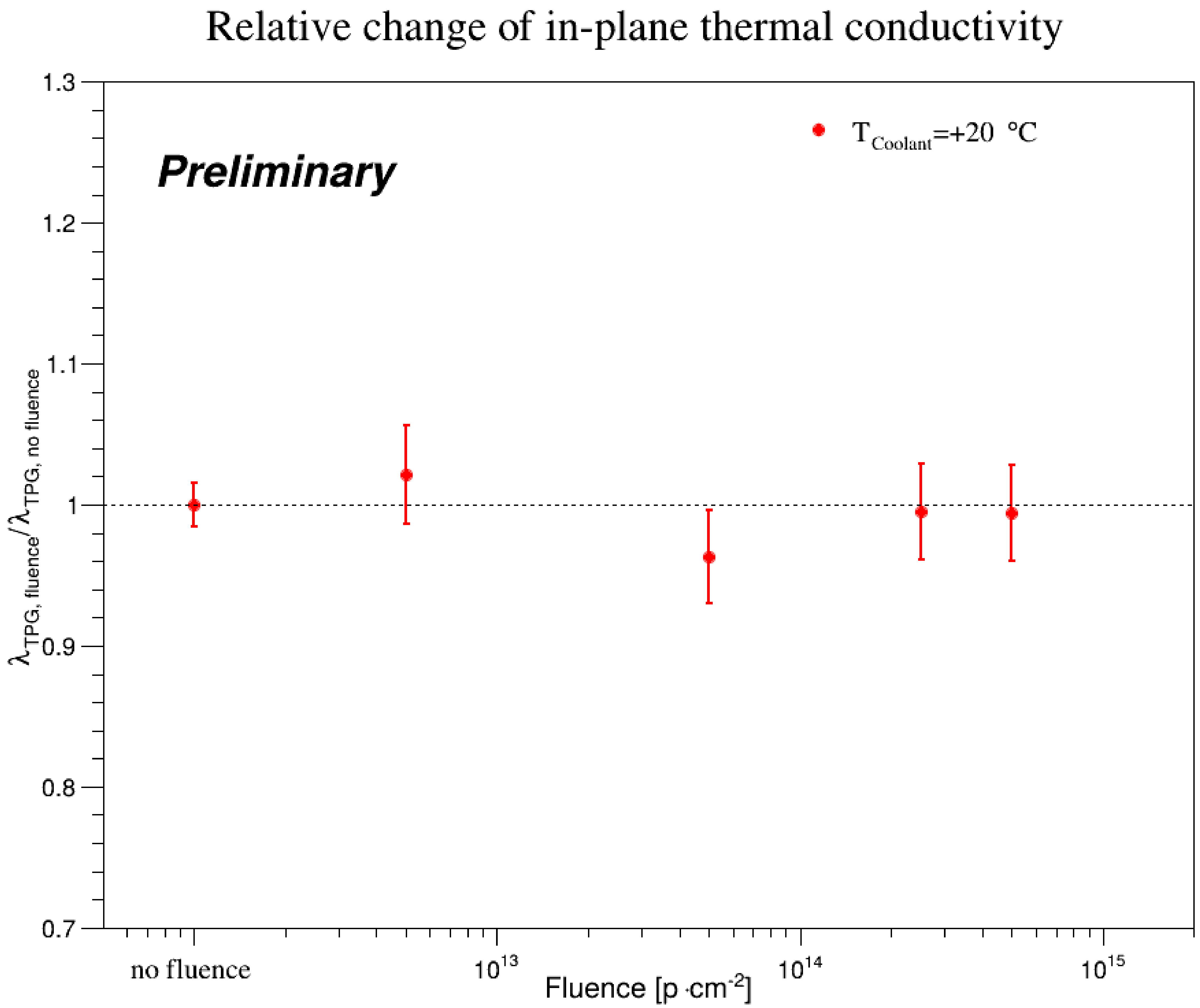
→ Thickness/cross-sectional area not well-defined

10s of µm roughness on 500 µm sheet

We (MVD) are satisfied with the results

→ For us chapter closed

→ Further collaboration is always welcome



Backup

Orthotropic Thermal Conductivity

Thermal simulation to study influence of TPG orthotropy

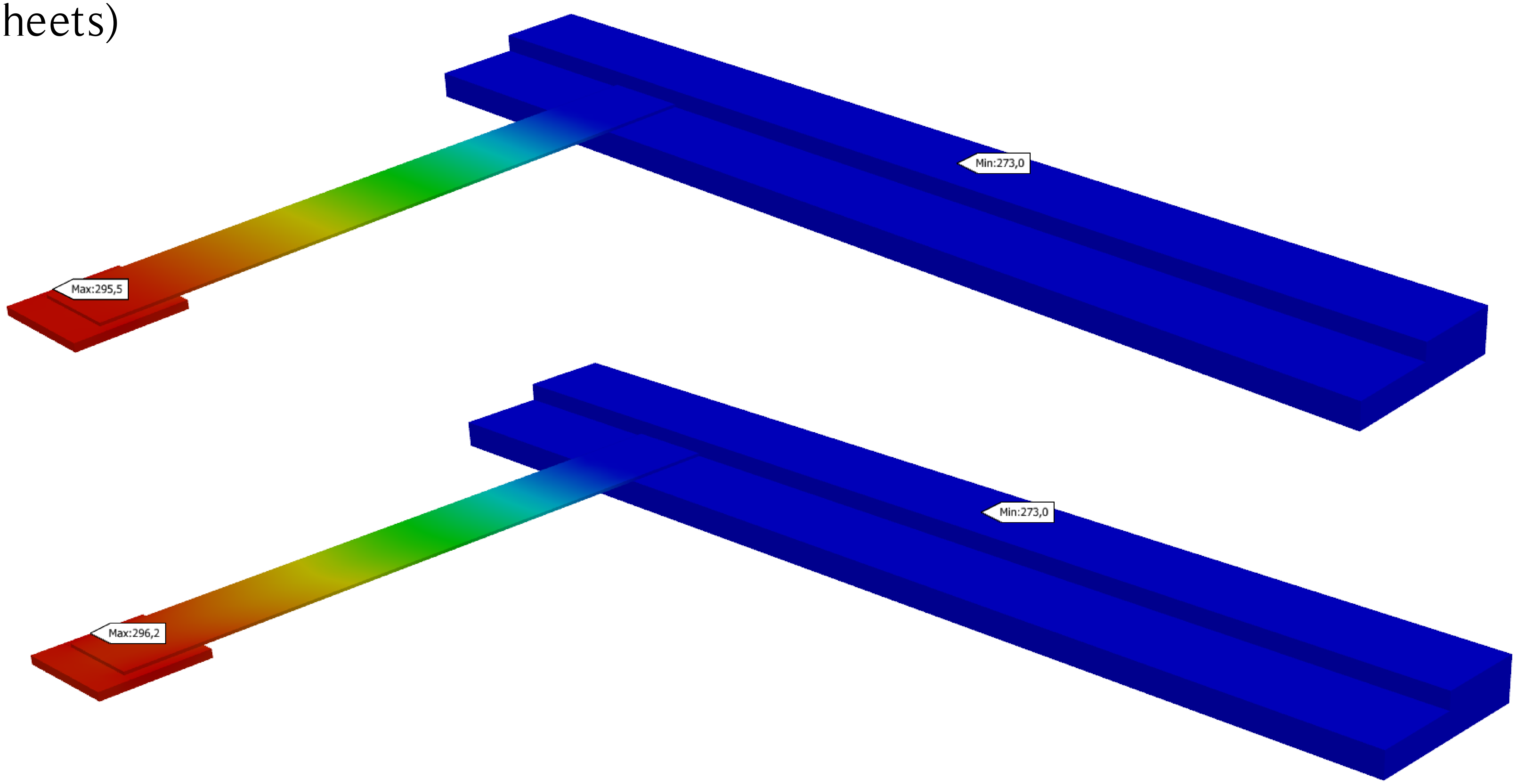
→ Identical geometry, heat entry, FEA mesh, loads, …

→ If $\lambda_x = \lambda_y = \lambda_z$: $\Delta T = 22.5$ K

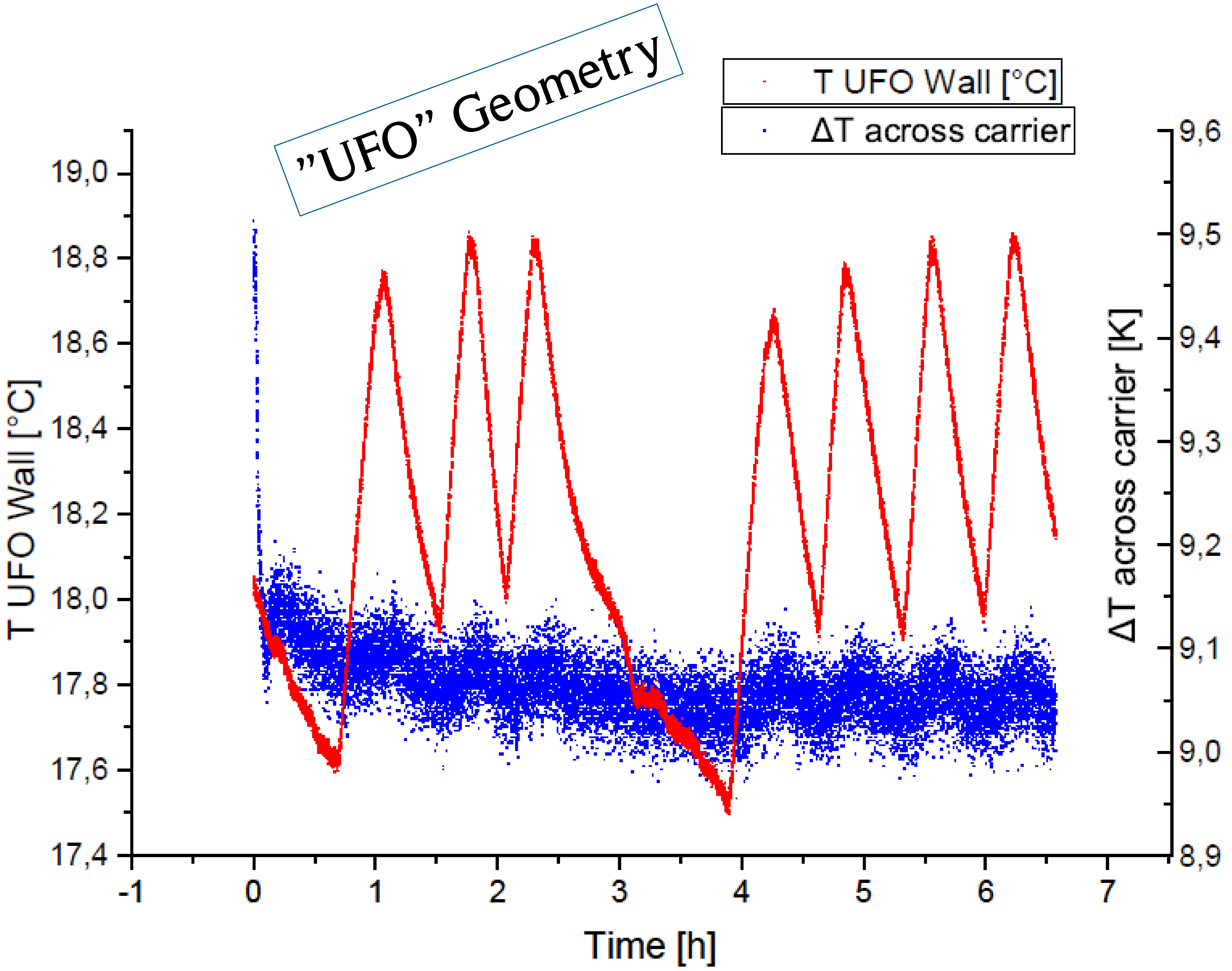
→ If $\lambda_x = \lambda_y = 150 \times \lambda_z$: $\Delta T = 23.2$ K

→ ~3% deviation

→ TPG anisotropy can be neglected (thin sheets)



Relaxation Time



Effect of room ventilation on UFO temperature and radiative heat entry on MVD quadrant

Temperature Dependence

No-degradation hypothesis

→ Consistent over full temperature range

→ Deviations between different coolant temperatures marginal

→ High confidence in setup, measurement

First strategy: Compare same sample before and after irradiation

→ Large systematics observed in setup

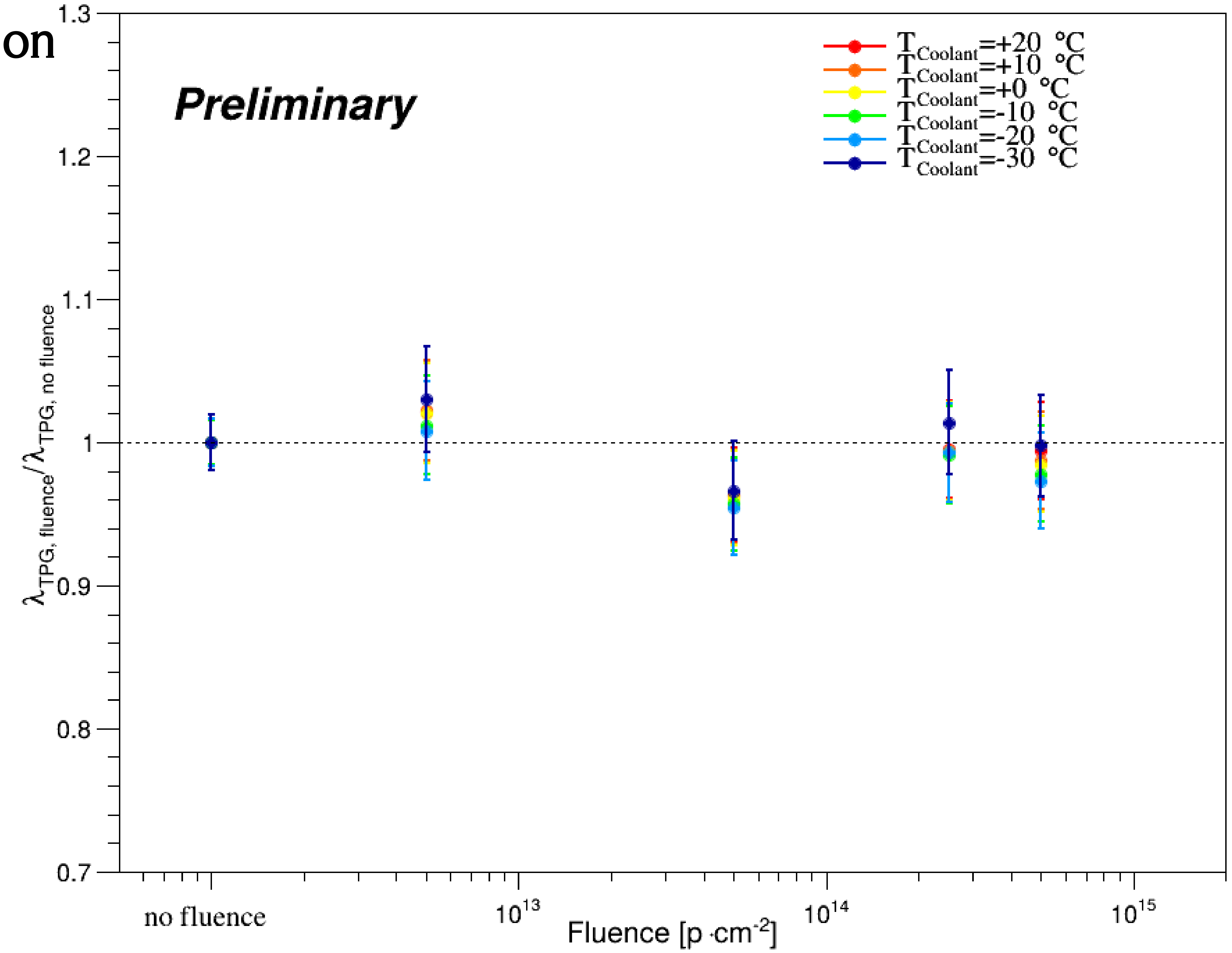
→ Cold-side clamping not ideal

→ No cold-side temperature information on the sample

→ No proper reference before irradiation available

Results shown are all done in new setup

Relative change of in-plane thermal conductivity



Comparison with other Measurements

Measurement ATLAS SCT

Factory new vs. 3x10^{14} p/cm^2 (25 GeV protons)

→ No degradation observed, comparable cross-sections
→ 90x10x0.4 mm^3, Momentive TPG
→ Clamped sample, thermal guard

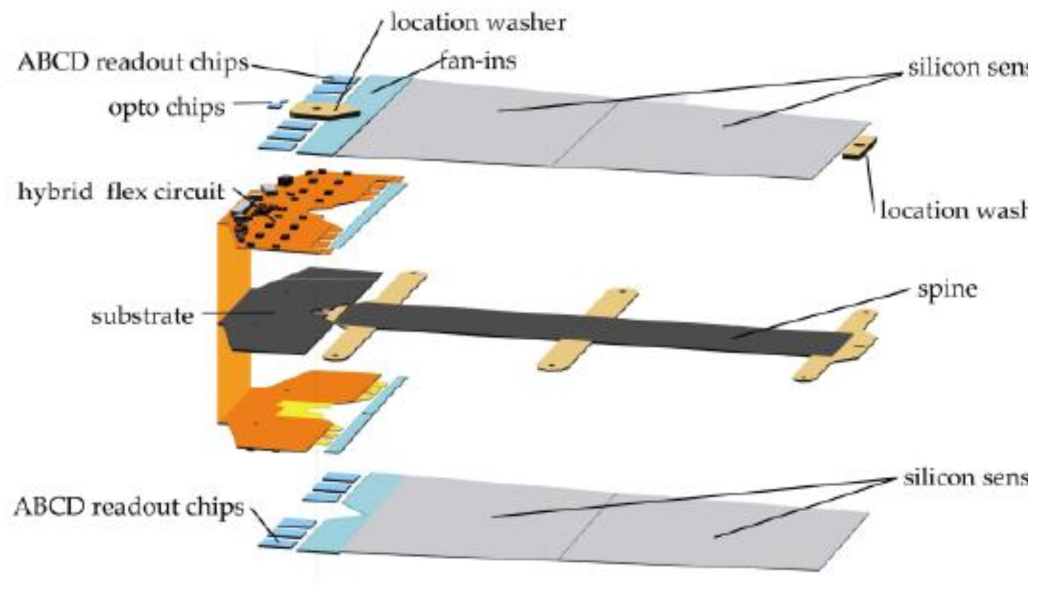


Figure 1.1. Exploded view of an SCT end-cap module showing the different components.

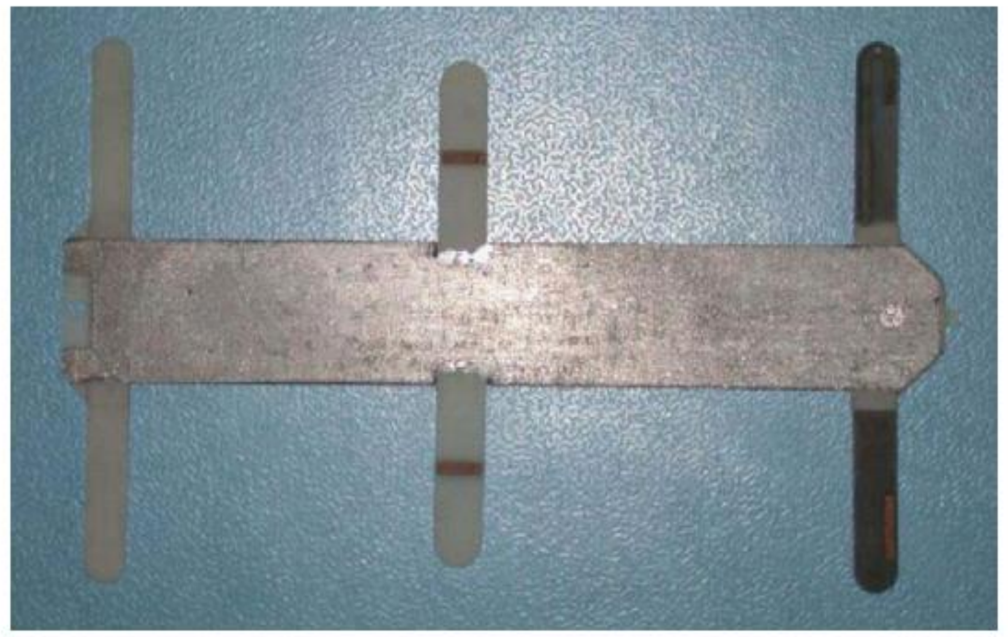
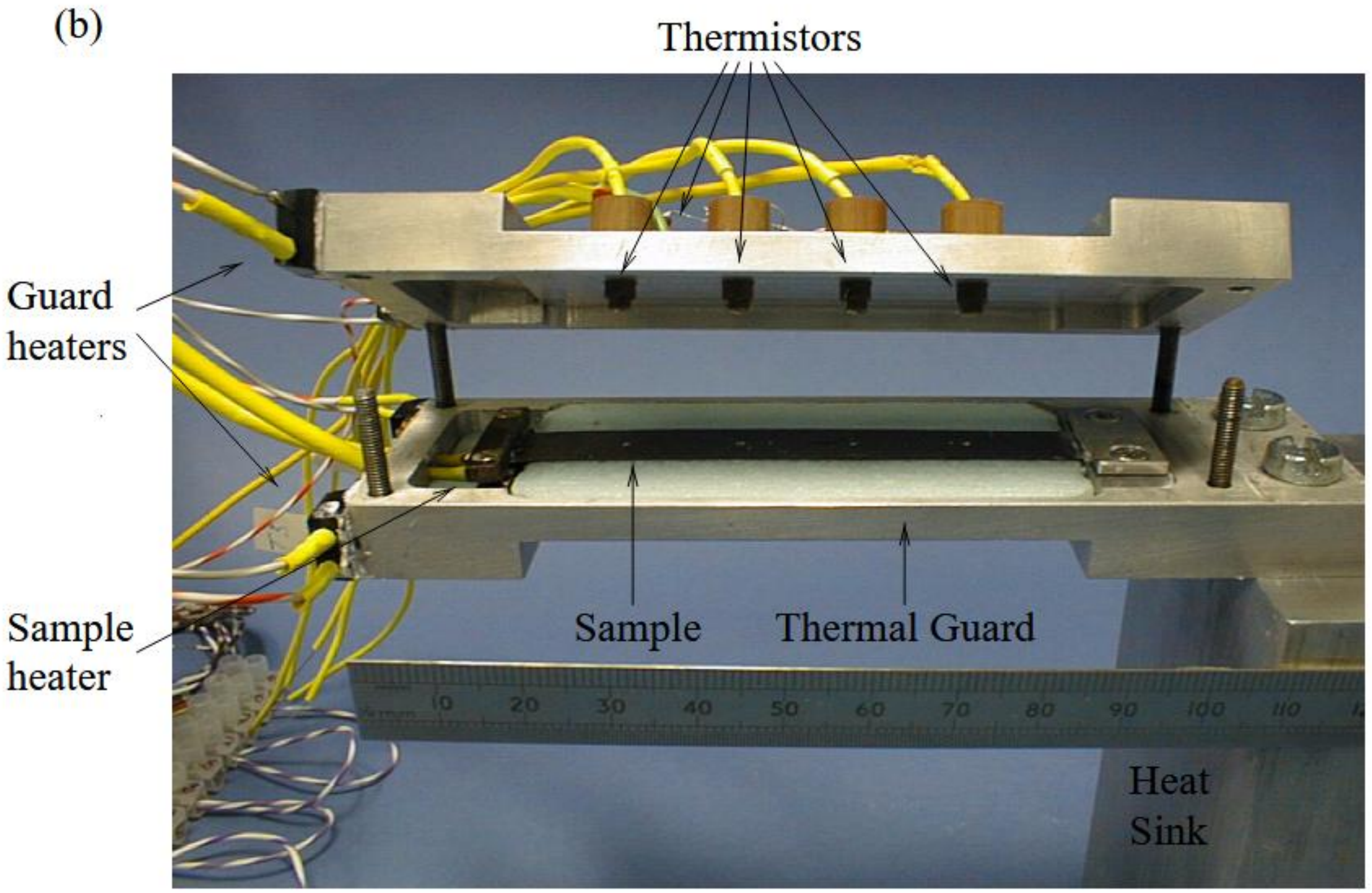


Fig. 20. Photograph of an end-cap module spine.



https://www.sciencedirect.com/science/article/pii/S0168900207003270
https://inspirehep.net/files/2c568cff397457a6ea4a71a520f13841

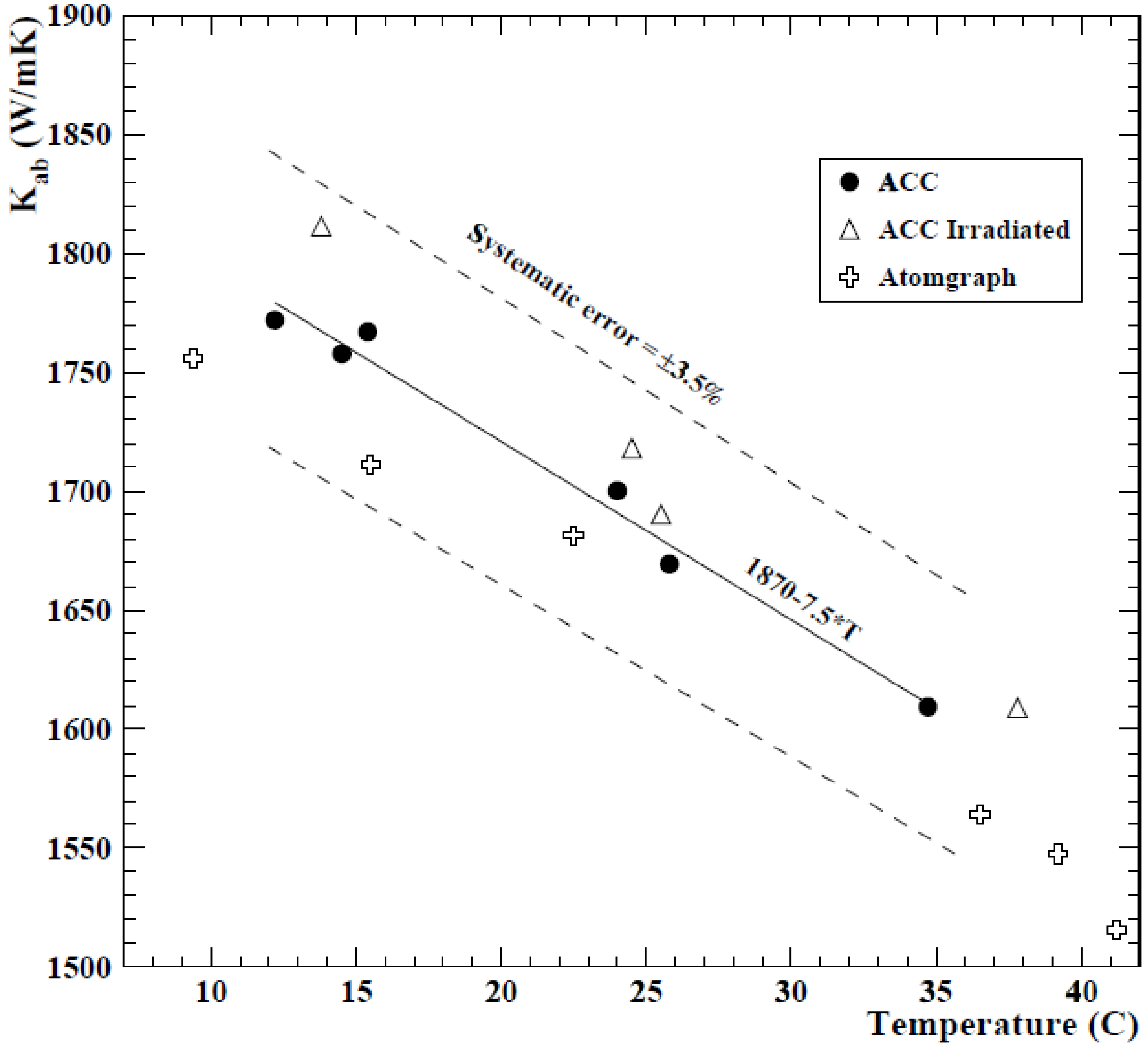


Figure 2: Results for the in-plane conductivity of 0.4mm thick tpg samples as supplied by ACC (fitted data) and ATOMGRAPH. Also shown are results for a second ACC sample irradiated to 3×10^{14}protons/cm^2.

Measurement NUMEN

HOPG foil, 1x1 cm², 2 µm thickness

Factory new vs 3.1x10^{10} n/cm² (14 MeV neutrons)
→ Lattice defects validated w/ AFM, Raman, XRD, SEM, …
→ Strong degradation in all aspects after 5x10^9 n/cm²
→ λ deteriorates by ~50 %
→ Full amorphization at higher doses suggested

Custom setup in closed-cycle cryostat
→ λ at 300K, high-vacuum
→ Samples cut to 4x6mm²
→ 2 µm or 0.2 µm sample thickness?
→ Clamp + silver epoxy thermal interface

https://www.sciencedirect.com/science/article/pii/S0925963524010161?fr=RR-2&ref=pdf_download&rr=96e964673cfbd23a

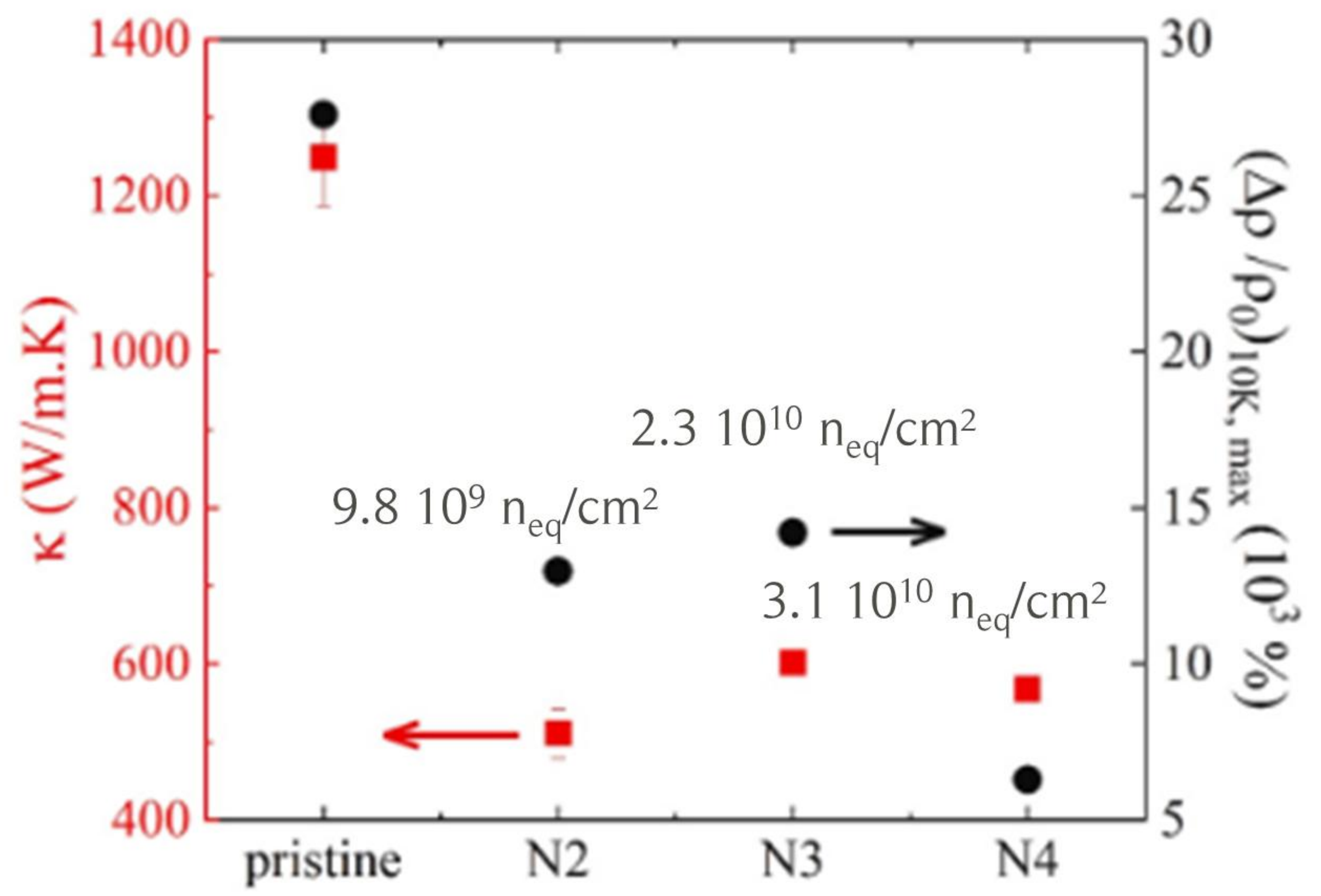
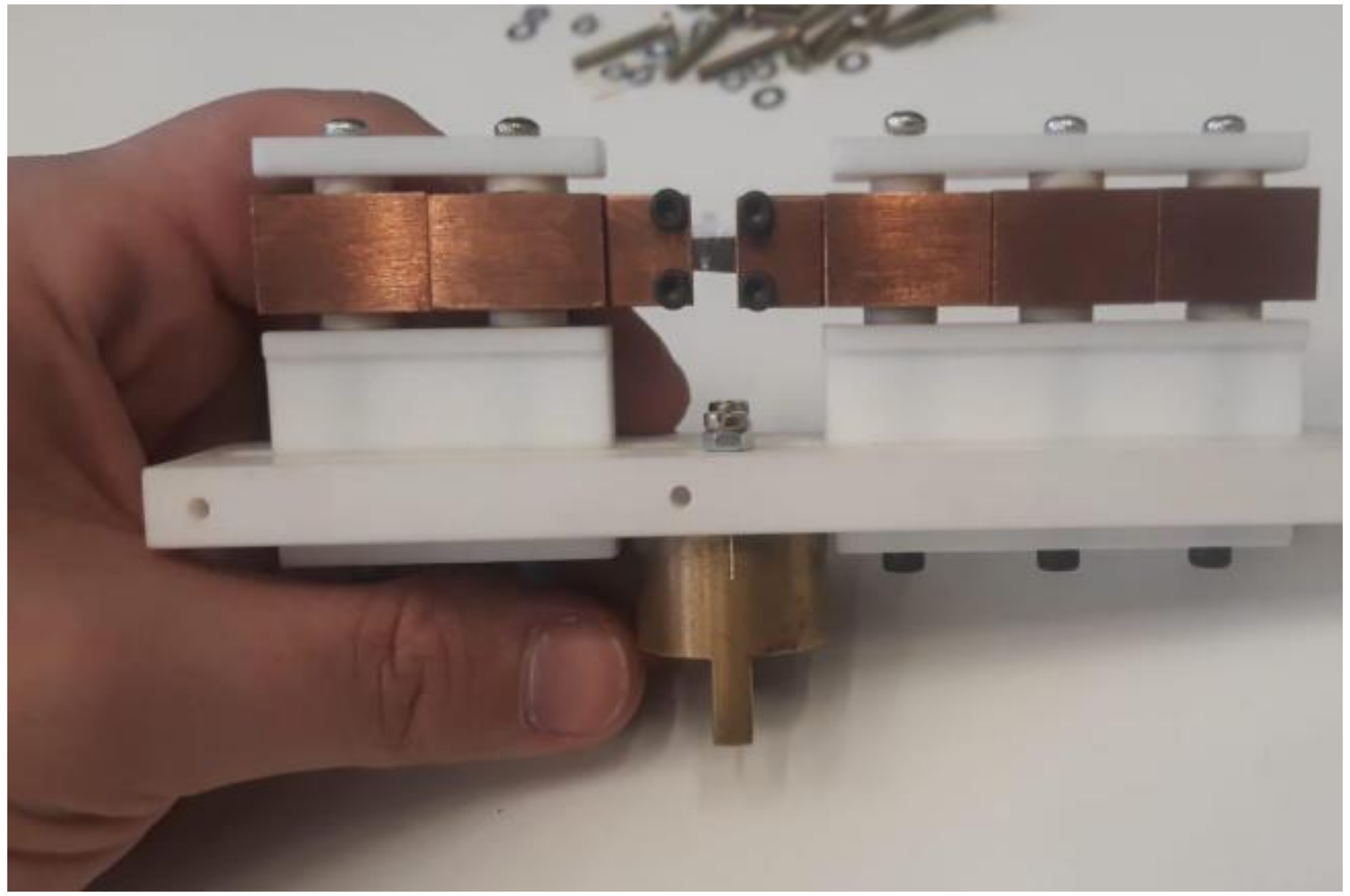


Fig. 7. Thermal conductivity and transverse magnetoresistance as a function of neutron fluences.

https://www.nucleares.unam.mx/lasnpa2024/lasnpa2024_materials/talks/P15_Guazzelli.pdf



Possible Explanations

Different thicknesses

→ Thin-film effect (300 atomic layers in 0.2 µm HOPG)?

→ Grain boundary scattering dominating over defect scattering?

Different total nuclear interaction cross section

→ 0.335 b (20 GeV p) vs 1.3 barn (14 MeV n)

→ Damage of 1.5x10^5 primary interacting neutrons with 4.6x10^{11} protons

→ Slow secondaries (alphas, …) enhance damage factor

→ TID contribution only in p case, should enhance degradation

Systematic effects not discussed

→ Bending, mechanics (likely negligible, c.f. PGS)?

→ Clamping and positioning reproducibility of ultra-thin, small foil

Both measurements do not appear to be consistent with each other

TPG vs other Graphite

Annealing at 1500 °C possible

CC materials, C-fibres, graphites,… studied for use in fusion reactors

Similar behavior, but at higher fluences

TPG much more sensitive to NIEL dose compared to non-oriented graphite?

https://www.sciencedirect.com/science/article/pii/S0008622313006398?via%3Dihub

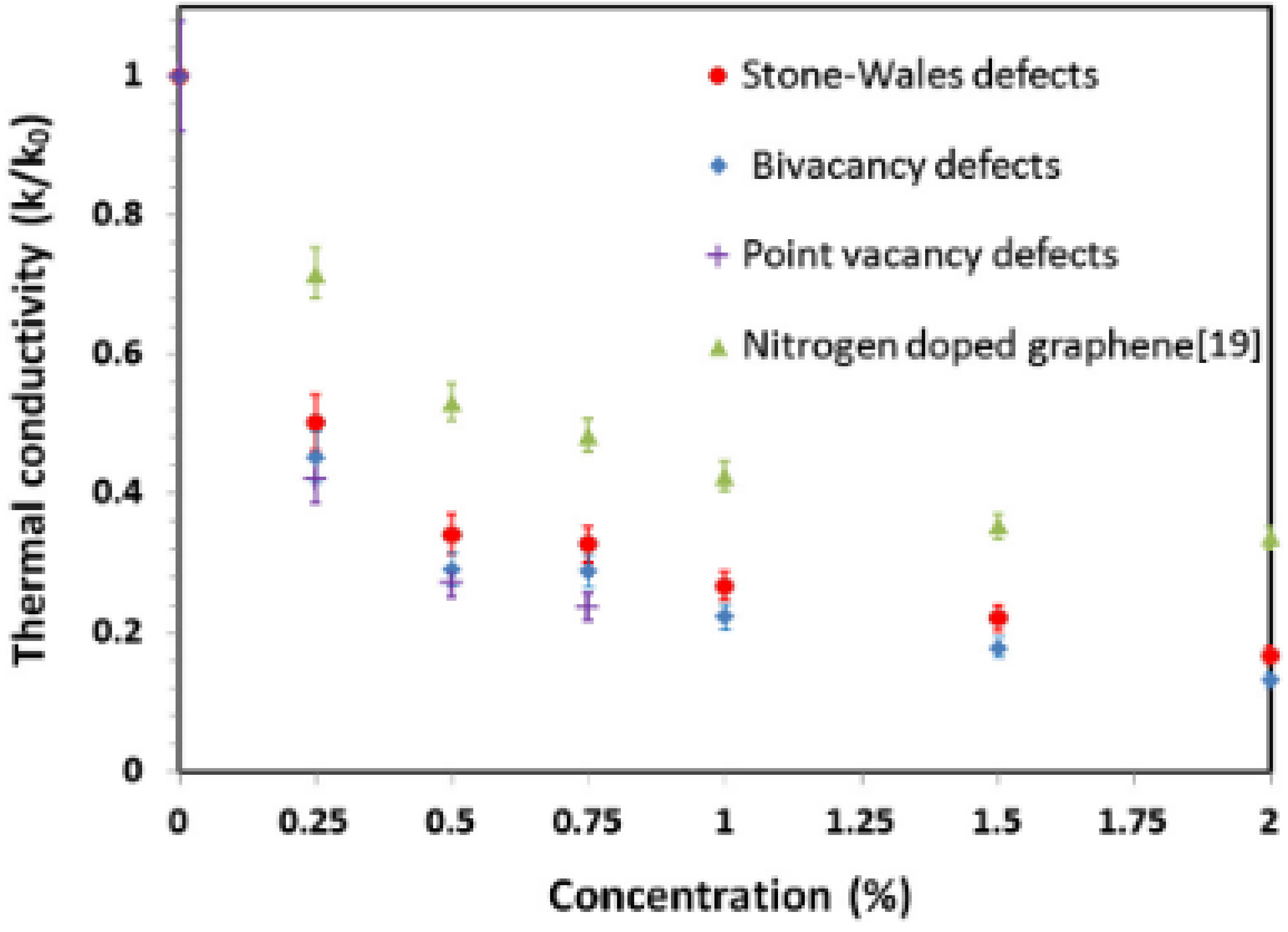


Fig. 8 – Normalized thermal conductivity of graphene as a function of defects concentrations.

https://www.sciencedirect.com/science/article/pii/002231159290362O

0.02 dpa = 1.4 10^{19} n/cm^2 (> 1 MeV)

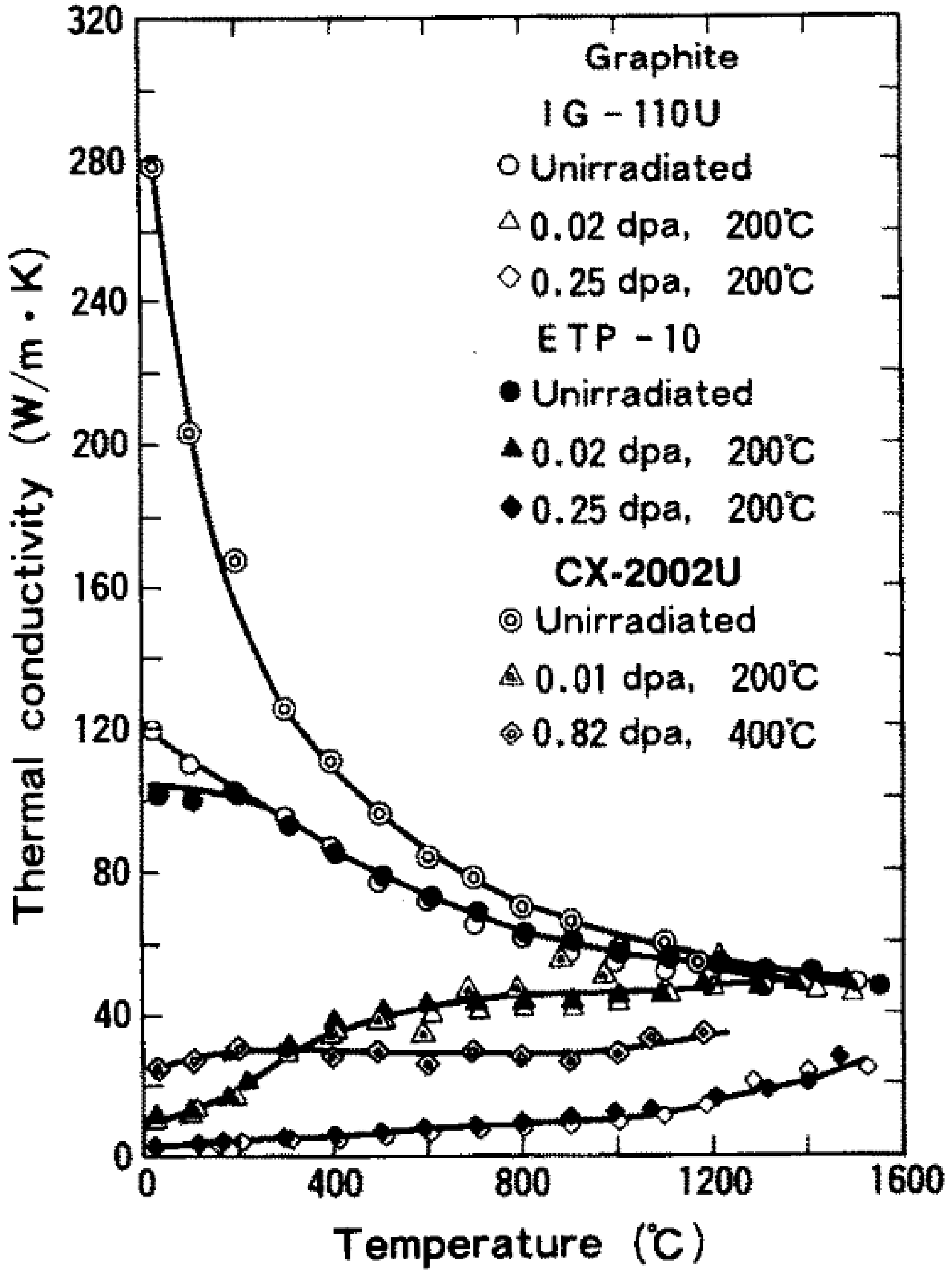


Fig. 1. Thermal conductivity of neutron-irradiated graphites.

https://www.sciencedirect.com/science/article/pii/0022311595000712?ref=pdf_download&fr=RR-2&rr=96e9a1ff180cf2c0

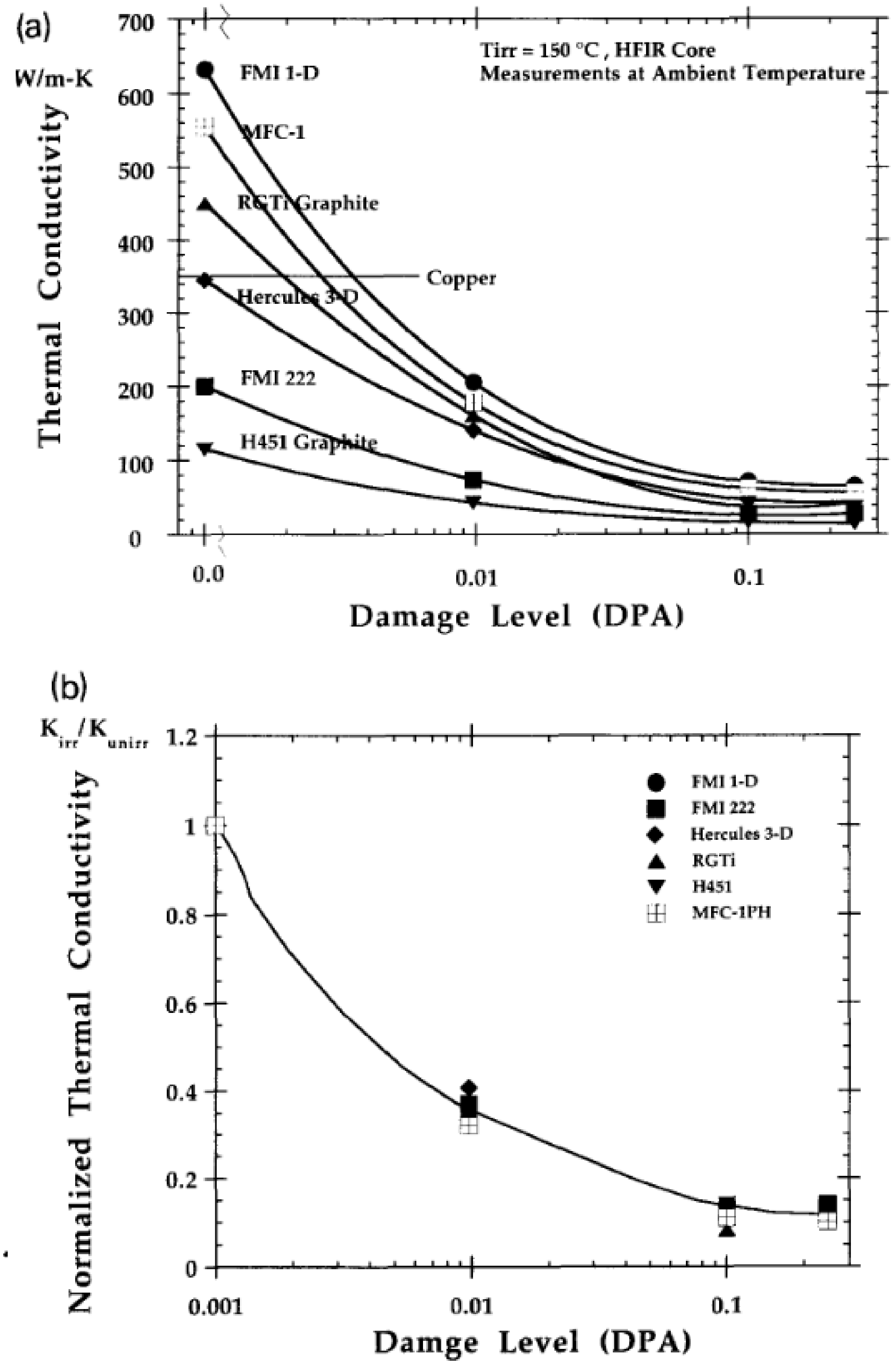
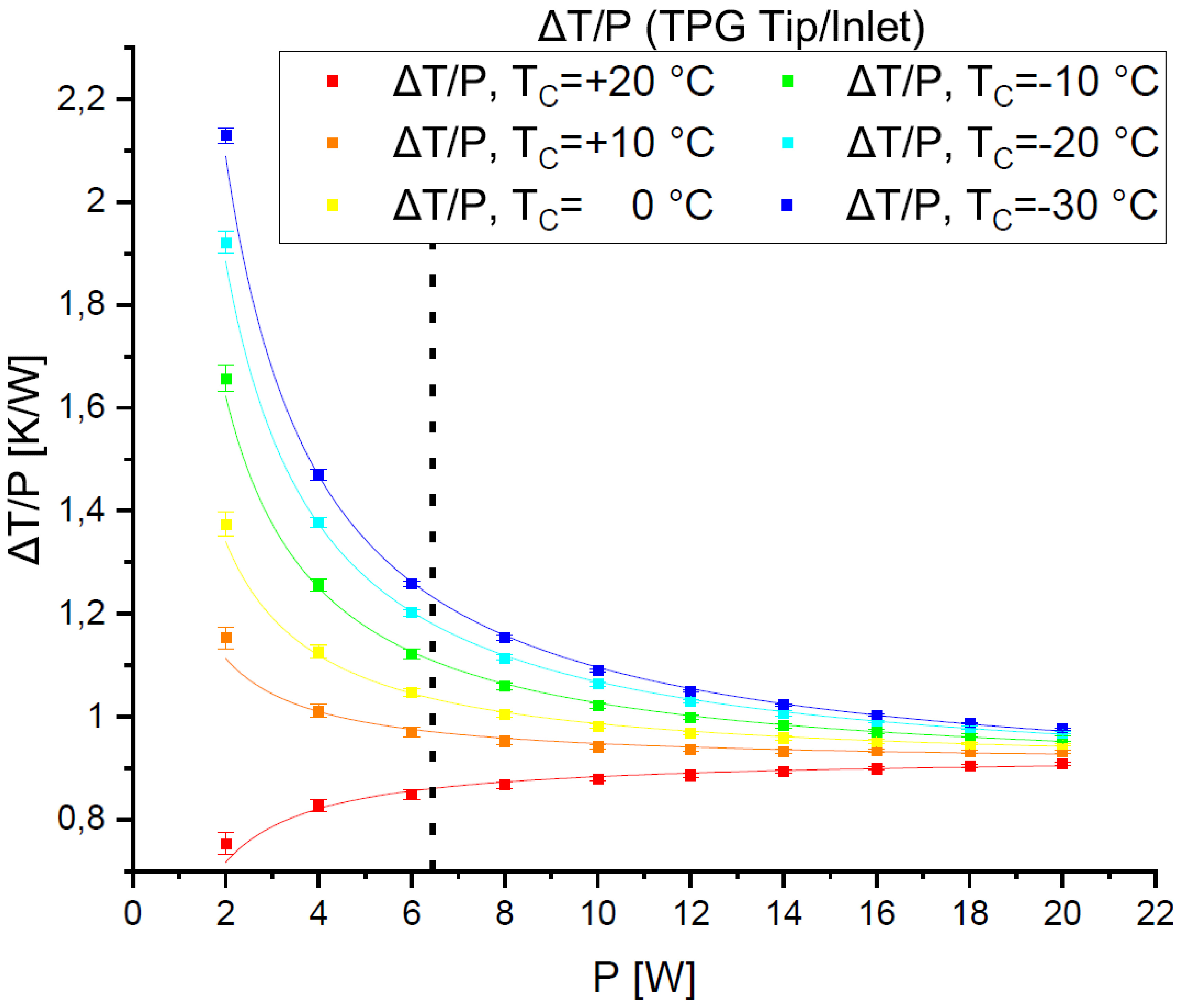
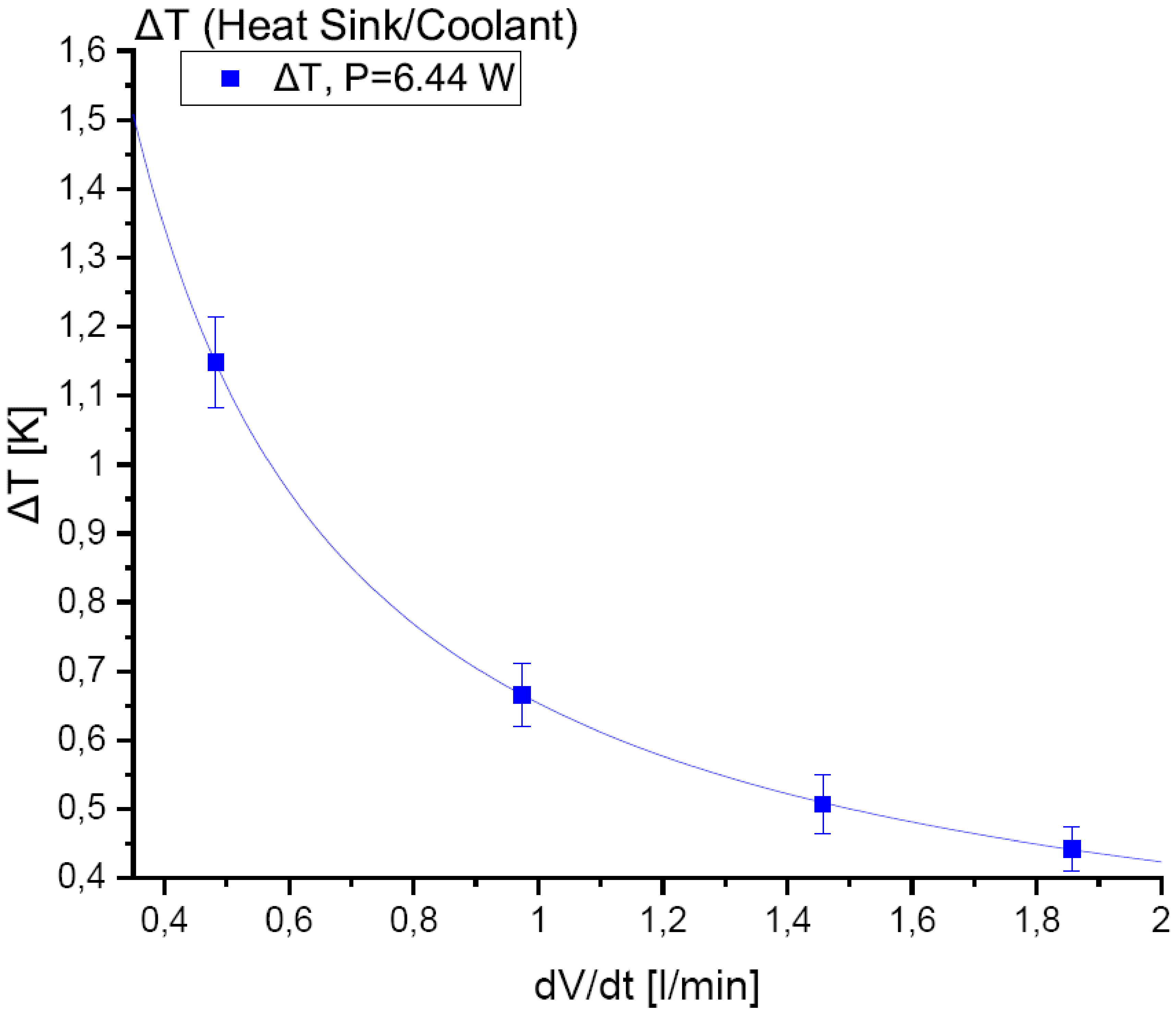


Fig. 2. (a) Irradiation-induced degradation of thermal conductivity. (b) Normalized irradiation-induced degradation of thermal conductivity.

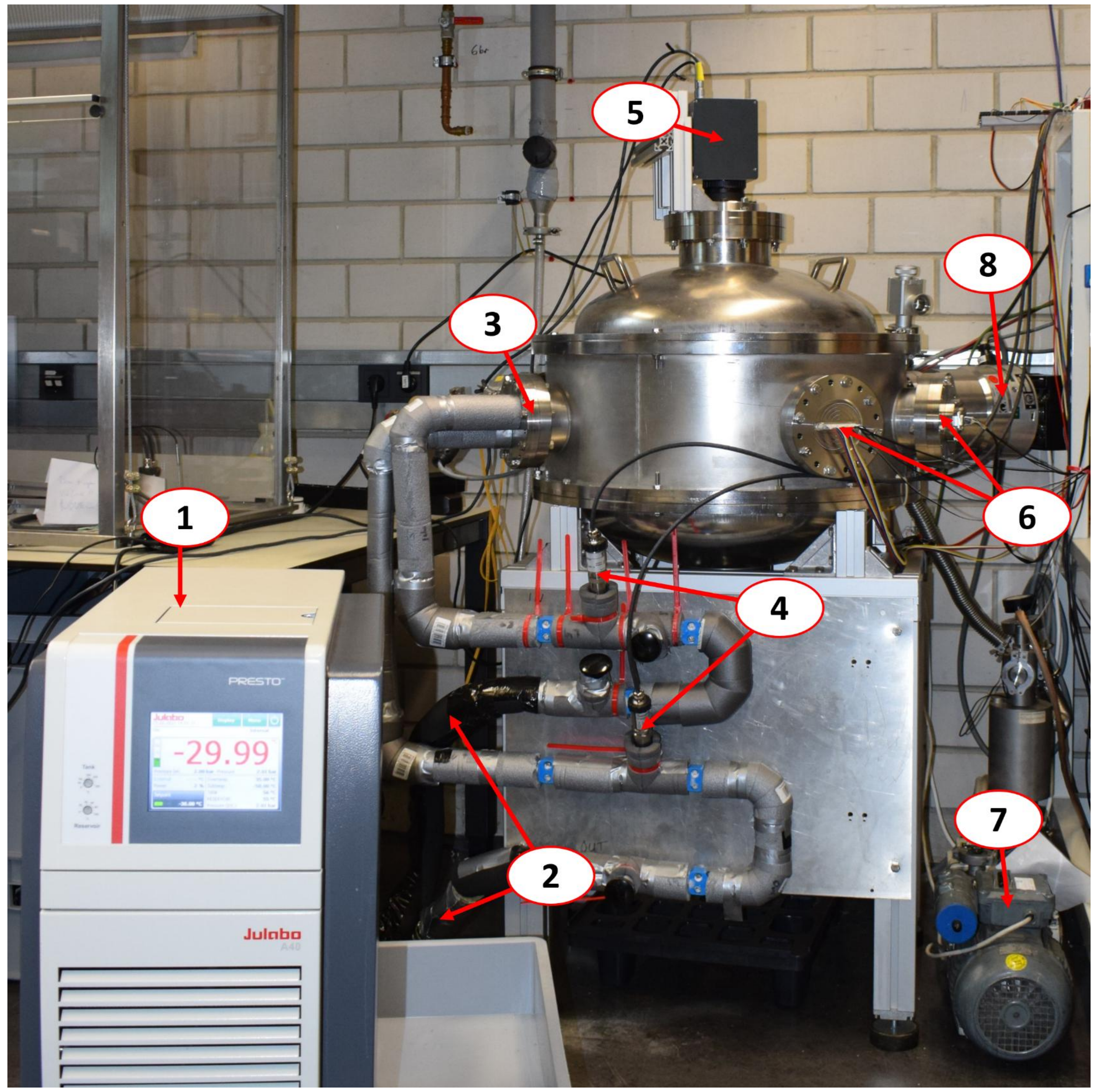
MVD Thermal Performance



Influence of thermal radiation in testing setup



Influence of coolant flow in testing setup



Cross Sections

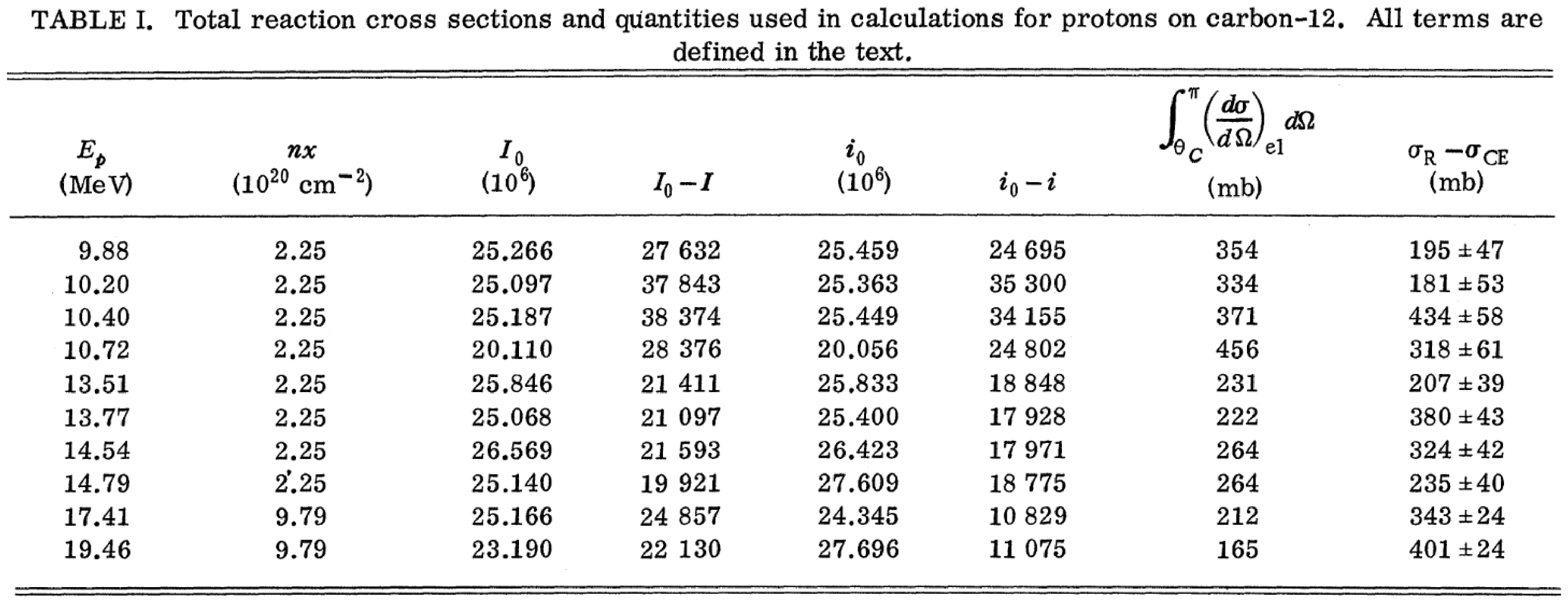


TABLE I. Total reaction cross sections and quantities used in calculations for protons on carbon-12. All terms are defined in the text.

E_p (MeV)	nx (10^{20} cm^{-2})	I_0 (10^6)	$I_0 - I$	i_0 (10^6)	$i_0 - i$	$\int_{\theta_C}^{\pi} \left(\frac{d\sigma}{d\Omega}\right)_{el} d\Omega$ (mb)	$\sigma_R - \sigma_{CE}$ (mb)
9.88	2.25	25.266	27 632	25.459	24 695	354	195 ± 47
10.20	2.25	25.097	37 843	25.363	35 300	334	181 ± 53
10.40	2.25	25.187	38 374	25.449	34 155	371	434 ± 58
10.72	2.25	20.110	28 376	20.056	24 802	456	318 ± 61
13.51	2.25	25.846	21 411	25.833	18 848	231	207 ± 39
13.77	2.25	25.068	21 097	25.400	17 928	222	380 ± 43
14.54	2.25	26.569	21 593	26.423	17 971	264	324 ± 42
14.79	2.25	25.140	19 921	27.609	18 775	264	235 ± 40
17.41	9.79	25.166	24 857	24.345	10 829	212	343 ± 24
19.46	9.79	23.190	22 130	27.696	11 075	165	401 ± 24

https://journals.aps.org/prc/pdf/10.1103/PhysRevC.2.488

Proton Carbon 10–20 MeV

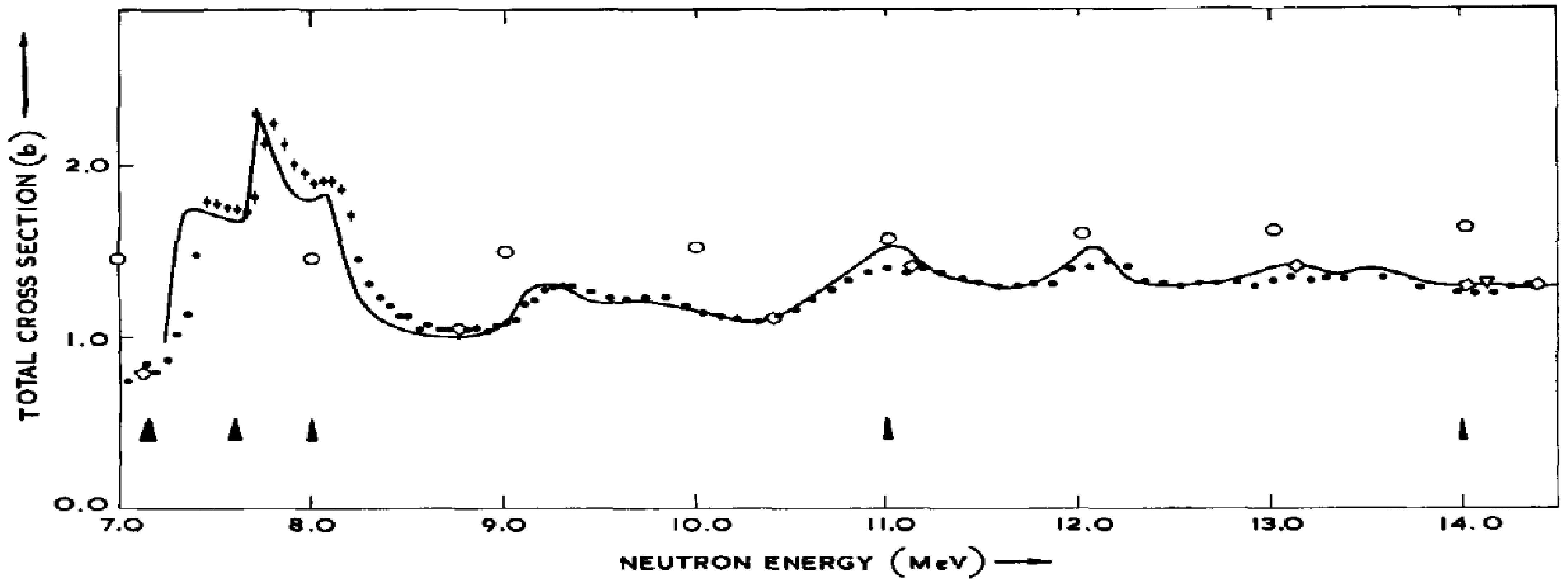
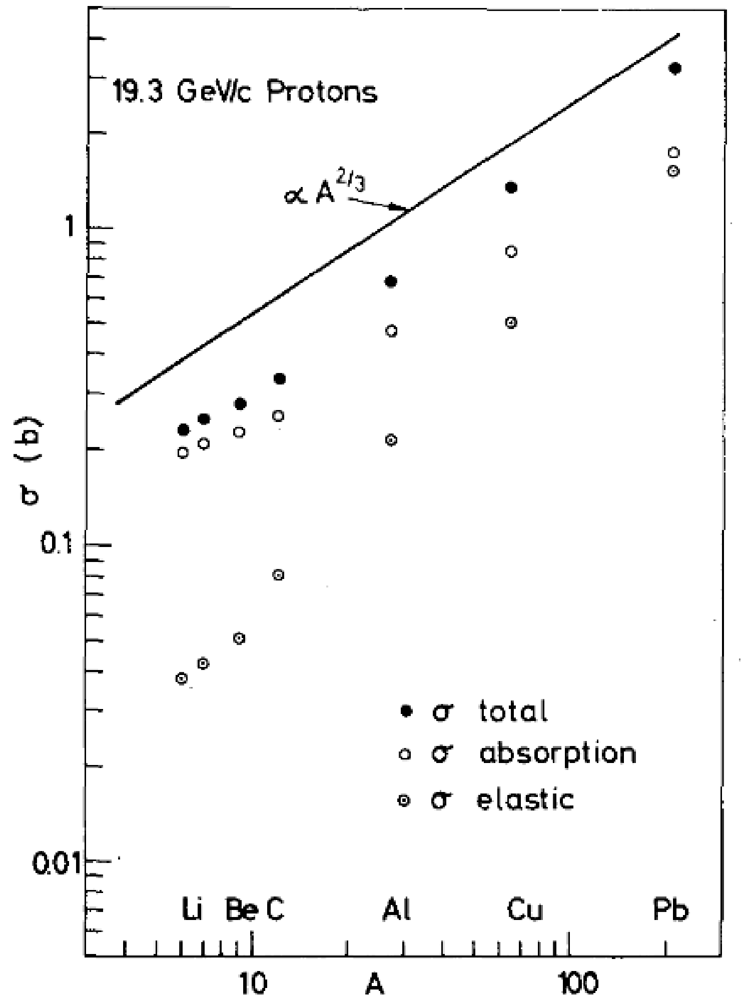


Fig. 4. Total neutron cross section for carbon as a function of neutron energy. The error bars, shown only when they are larger than the solid circles, represent standard deviations and include systematic errors. The black triangles show typical neutron energy spreads. The data of Fossan *et al.* [1]) (solid line), Bratenahl *et al.* [3]) (diamonds) and Coon *et al.* [4]) (inverted triangles) are shown for comparison. The open circles show the results of theoretical calculations by Wilmore and Hodgson [12]).

https://www.sciencedirect.com/science/article/pii/0029558264900355?ref=cra_js_challenge&fr=RR-1

Neutron Carbon 8–14 MeV



4. The total, the elastic and the absorption cross sections measured in this experiment plotted as functions of the mass number *A*.

https://www.sciencedirect.com/science/article/pii/0029558266902677?via%3Dihub

Proton Carbon, 19.3 GeV