Thermal conductivity measurements of high-purity Al for the CUORE cryogenic upgrade

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PRIN Meeting

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CUORE/CUPID cryogenic upgrade

- Cryogenic upgrade of CUORE cryostat:
  - ➢ comply with the thermal requirements for cryostat operation after CUPID installation;
  - ➢ improve thermal/mechanical coupling between Pulse Tubes (PT) and cryostat;
  - ➢ three main interventions:
    1. 5 CUORE Cryomech PT415 → 4 Cryomech PT425;
    2. install gas-gap thermal switches to isolate the not operative PT;
    3. replace PT thermalizations: OFHC-Cu → HP-Al.

- Advantages of HP-Al w.r.t. Cu thermalizations:
  - ➢ higher thermal conductivity at low temperatures;
  - ➢ Young modulus: $E_Y(\mathrm{Al}) \sim 69$ GPa < $E_Y(\mathrm{Cu}) \sim 130$ GPa;

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    Al is softer and more flexible than Cu;

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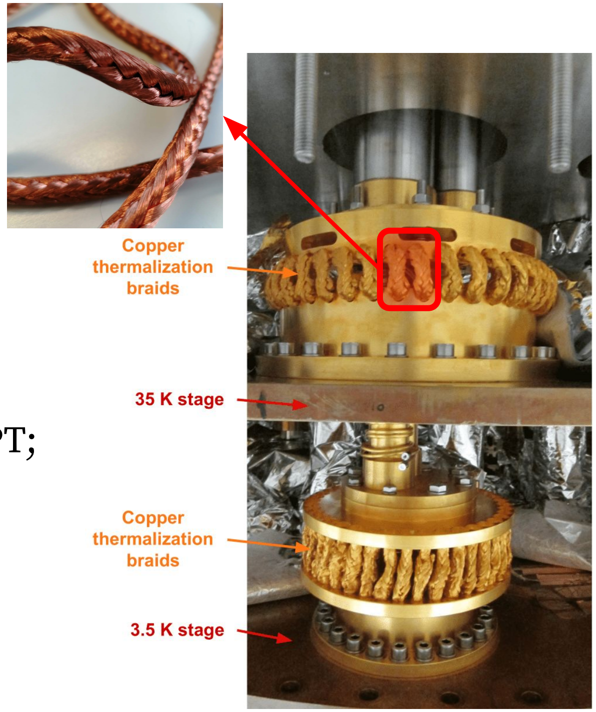
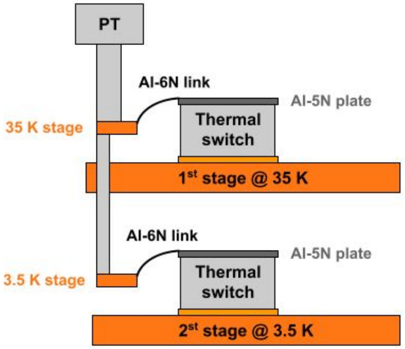
    damp vibrations propagation from PT to cryostat and detectors.

- LNGS 2024: campaign of comparative thermal conductivity measurements between OFHC-Cu (from CUORE thermalizations) and HP-Al samples.





Experimental setup

Cryostat & Cu/HP-Al samples

- GM (Gifford-McMahon) cryostat:
  - ➢ $T_{base} \sim$ 11 K @ 10 K stage;
  - ➢ copper sample holder thermally decoupled from 10 K stage;
  - ➢ two thermometers + one heater installed on each stage

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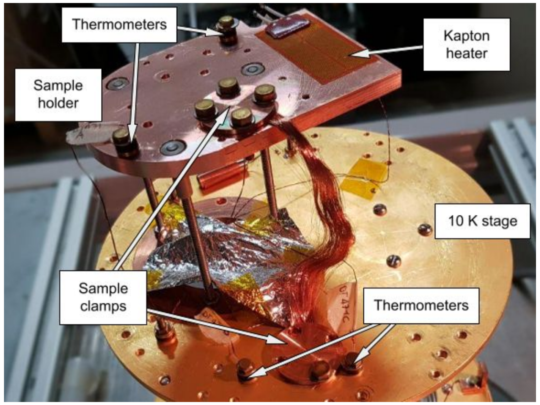
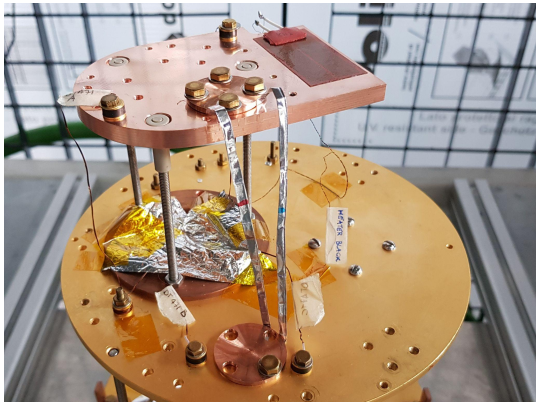
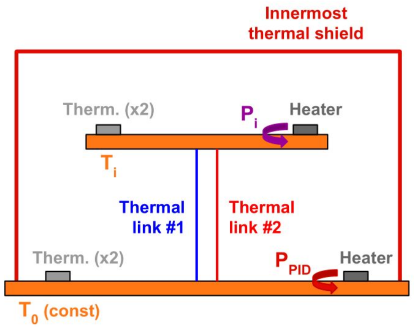
    stabilize temperature of 10 K stage,
    change temperature of copper holder.

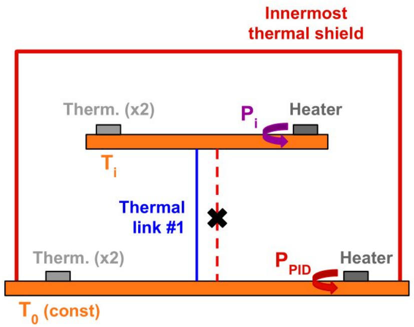
- Cu/HP-Al samples are clamped at 10 K stage and copper holder.

- To verify the measurements reproducibility,
  each sample is measured twice in consecutive cool-downs:
  - ➢ full Cu braid → cut half of the Cu braid;
  - ➢ two HP-Al strips/wires → cut one HP-Al strip/wire.









Material	Purity	Geometry
OFHC-Cu	RRR ~ 400	Braid (section ~2 mm^2)
Al-5N	99.999 %	Wire (Ø ~ 0.5 mm)
Al-6N	99.9999 %	Strip (0.1 mm thick)
		Wire (Ø ~ 1.0 mm)

Thermal conductivity measurements

Procedure

- Measurements procedure:
  - fix and stabilize the temperature T_0 of 10 K stage;
  - increase holder temperature T_i through power injection P_i;
  - thermal conductivity $k(T)$:

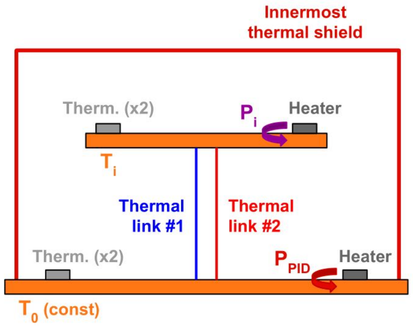
$$P_i = \int_{T_0}^{T_i} G(T)\,dT = \int_{T_0}^{T_i} k(T)\frac{A}{l}\,dT$$

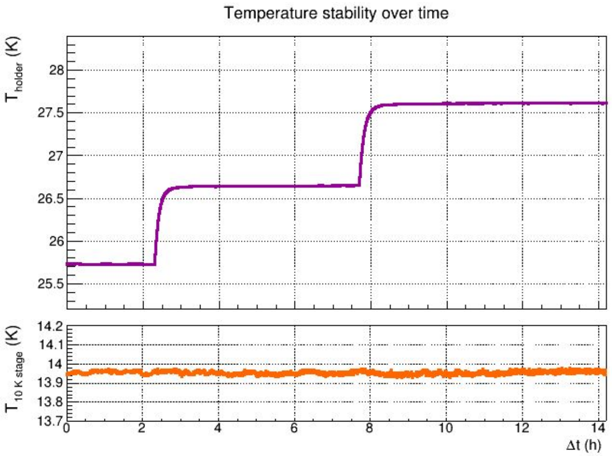
Injected power — Stage temperatures — Thermal conductance — Thermal conductivity — Sample section / length

  - differential measurements between steps i, i-1:

$$k\left(T = \frac{T_{i-1}+T_i}{2}\right) = \frac{P_i - P_{i-1}}{T_i - T_{i-1}} \frac{\rho\, l\, L}{m}$$

Holder variables — Geometric factor





- Thermal conduction in metals is driven by electrons:

$$k(T) = \frac{1}{\alpha T^2 + \frac{\beta}{T}}$$

e⁻ - phonons scattering — e⁻ - impurities scattering

$T \lesssim \theta_{Debye}/10$

$\theta_{Debye}(\mathrm{Cu}) = 343$ K

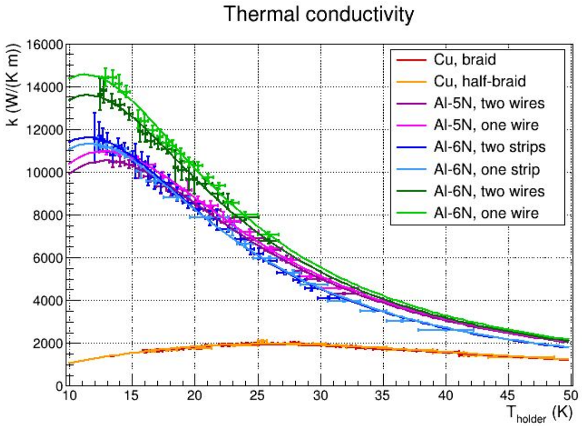
$\theta_{Debye}(\mathrm{Al}) = 428$ K

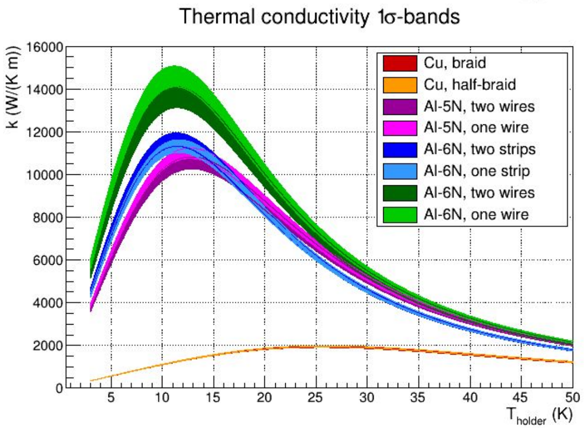
Thermal conductivity measurements

Results

- Fit results:

Material	Geometry	α (10^{-7} m/W/K)	β (10^{-4} K^2 m/W)	T_{peak} (K)
Cu	Braid	2.63 ± 0.04	88.4 ± 1.0	25.63 ± 0.17
	Half braid	2.55 ± 0.06	88.0 ± 1.3	25.83 ± 0.23
Al-5N	Two wires	1.91 ± 0.04	8.14 ± 0.23	12.87 ± 0.16
	One wire	1.88 ± 0.04	7.72 ± 0.17	12.72 ± 0.13
Al-6N	Two strips	2.20 ± 0.04	6.55 ± 0.20	11.41 ± 0.14
	One strip	2.18 ± 0.05	6.85 ± 0.19	11.63 ± 0.14
	Two wires	1.87 ± 0.05	5.61 ± 0.22	11.43 ± 0.19
	One wire	1.81 ± 0.04	5.14 ± 0.20	11.23 ± 0.17





- ➢ electrons-impurities scattering term β decreases in higher purity materials;
- ➢ *k(t)* evaluated over full/half samples are in agreement (max. discrepancies < 6.7% ~ 1.5 σ @ 12 K);
- ➢ ***k(T, HP-Al)* ~ 11-17 · *k(T, Cu)* @ 3.5 K , *k(T, HP-Al)* ~ 2-2.4 · *k(T, Cu)* @ 35 K;**
- ➢ discrepancy in *k(T, Al-6N)* evaluated for strip and wire geometries → due to Kapitza resistance?

Kapitza resistance subtraction

Sample & procedure

- HP-Al samples were oxidized → insulating Al_2O_3 layer → Kapitza boundary thermal resistance.

- Dedicated Al-6N sample geometry:
  two strips sharing the clamped surface
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  decouple the Kapitza resistance contribution.

- Measure thermal conductance *G(T)* before and after cutting one strip:
  - ➢ monotonic increasing conductances ratio $G_{\text{two strips}}(T) / G_{\text{one strip}}(T)$, from ~1.43 @ 12 K to ~1.65 @ 30 K;
  - ➢ variation of the sample geometry factor: ~1.7;

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  G(T) ratio can not be addressed only by the geometry factor;

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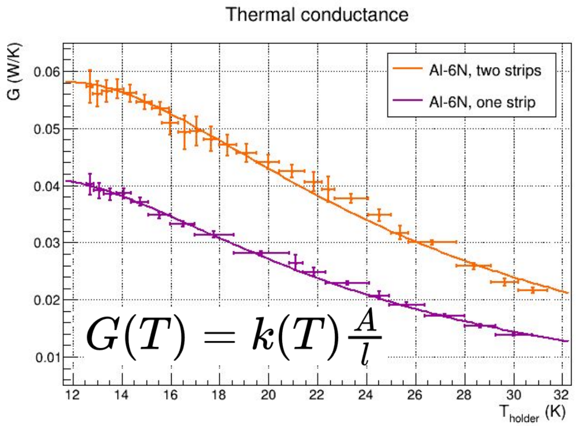
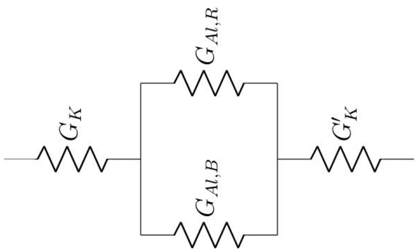
  non negligible contribution from Kapitza resistance in HP-Al samples.



Kapitza resistance subtraction

Procedure

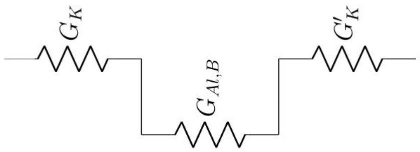
- Full-sample thermal circuit:



$$\frac{1}{G_{eff,2}} = \frac{1}{G_K} + \frac{1}{G_{Al,B}+G_{Al,R}} + \frac{1}{G'_K}$$

Effective *G(T)* of full-sample — **Kapitza resistance**

- Half-sample thermal circuit:



$$\frac{1}{G_{eff,1}} = \frac{1}{G_K} + \frac{1}{G_{Al,B}} + \frac{1}{G'_K}$$

Effective *G(T)* of half-sample

$$G_{Al,B} = k_{Al}\frac{A_B}{l}$$

$$G_{Al,R} = k_{Al}\frac{A_R}{l}$$

Thermal conductivity of HP-Al after kapitza resistance subtraction

$$k_{Al} = \frac{G_{eff,2}\, G_{eff,1}}{G_{eff,2}-G_{eff,1}} \frac{A_R\, l}{A_B\,(A_B+A_R)}$$

Geometric factor

Kapitza resistance subtraction

Fit results

- Fit results:

Material	Geometry	α (10^{-7} m/W/K)	β (10^{-4} K^2 m/W)	T_{peak} (K)
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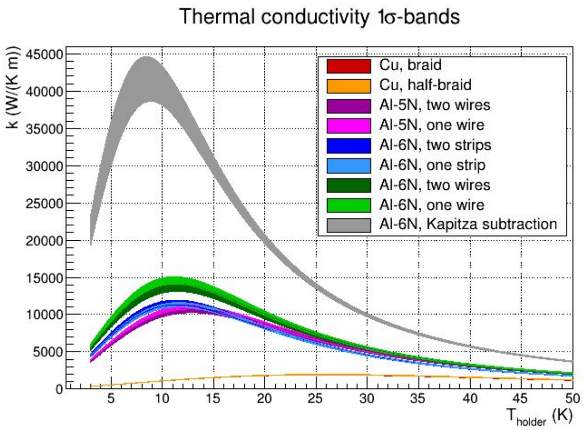
	Two wires	1.87 ± 0.05	5.61 ± 0.22	11.43 ± 0.19
	One wire	1.81 ± 0.04	5.14 ± 0.20	11.23 ± 0.17
	Kapitza resistance subtraction	1.07 ± 0.02	1.40 ± 0.14	8.68 ± 0.29



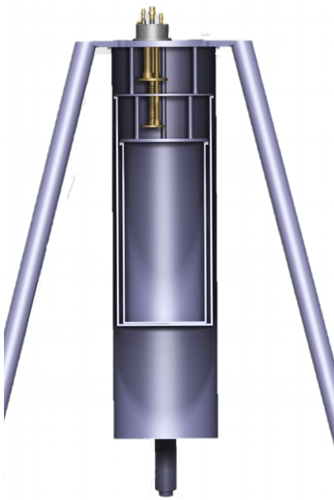
➢ ***k(T, Al-6N)* ∼ 61 · *k(T, Cu)* @ 3.5 K , *k(T, Al-6N)* ∼ 4 · *k(T, Cu)* @ 35 K.**

Summary

- Comparative thermal conductivity measurements of:
  - ➢ non-high-purity Cu from CUORE PT thermalizations;
  - ➢ high-purity Al-5N and Al-6N.

- HP-Al features superior thermal conductivity w.r.t. Cu:
  - ➢ measured (including Kapitza resistance contribution):
    $k(T, HP\text{-}Al) \sim 11\text{-}17 \cdot k(T, Cu)$ @ 3.5 K , $k(T, HP\text{-}Al) \sim 2\text{-}2.4 \cdot k(T, Cu)$ @ 35 K;
  - ➢ estimated (after Kapitza resistance decoupling):
    $k(T, Al\text{-}6N) \sim 61 \cdot k(T, Cu)$ @ 3.5 K , $k(T, Al\text{-}6N) \sim 4 \cdot k(T, Cu)$ @ 35 K;
  - ➢ **HP-Al is a viable option for the PT thermalizations in CUORE/CUPID cryostat.**

- Future activities:
  - ➢ extend $k(T)$ measurements at $T < 11$ K
    ↓
    commissioning of PT cryostat ($T_{base} < 2.5$ K) at LNGS;
  - ➢ procedure to remove Al_2O_3 layer and prepare
    Al samples in O_2-free atmosphere to prevent re-oxidation.



Backup slides

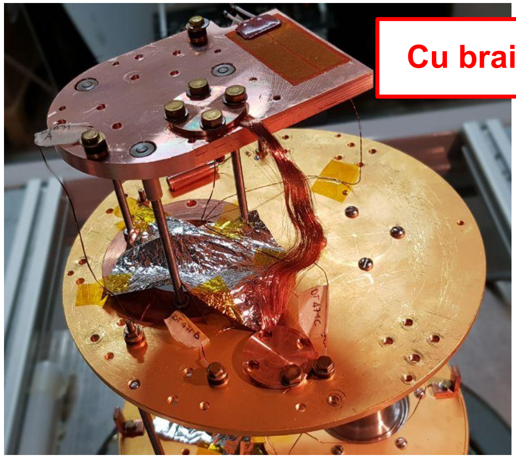
Experimental setup
Cu, HP-Al samples

- Geometric parameters of Cu and HP-Al samples:

Material	**Geometry**	**Mass** *m* **(g)**	**Total lenght** *L* **(cm)**	**Unclamped length** *l* **(cm)**	**Section size**	***A/l*** **(m)**
Cu	Full braid	2.357	16	11	$\sim$ 2 mm^2	$1.49 \cdot 10^{-5}$
	Half braid	1.151	16	11	-	$0.73 \cdot 10^{-5}$
Al-5N	Red wire	0.077	15	11	Ø $\sim$ 0.5 mm	$1.72 \cdot 10^{-6}$
	Blue wire	0.075	15	11	Ø $\sim$ 0.5 mm	$1.68 \cdot 10^{-6}$
Al-6N	Red strip	0.126	15	11	3 x 0.1 mm^2	$2.81 \cdot 10^{-6}$
	Blue strip	0.121	15	11	3 x 0.1 mm^2	$2.69 \cdot 10^{-6}$
	Red wire	0.314	15	11	Ø $\sim$ 1.0 mm	$7.02 \cdot 10^{-6}$
	Blue wire	0.316	15	11	Ø $\sim$ 1.0 mm	$7.07 \cdot 10^{-6}$
	Red sub-strip	-	15	11	3.5 x 0.1 mm^2	$3.01 \cdot 10^{-6}$
	Blue sub-strip	-	15	11	2.5 x 0.1 mm^2	$2.15 \cdot 10^{-6}$

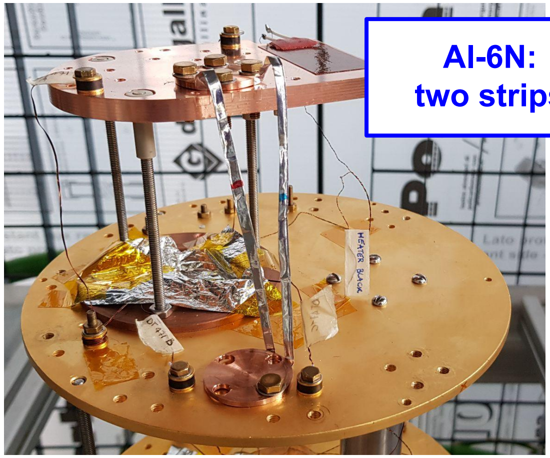
Experimental setup

Sample installations

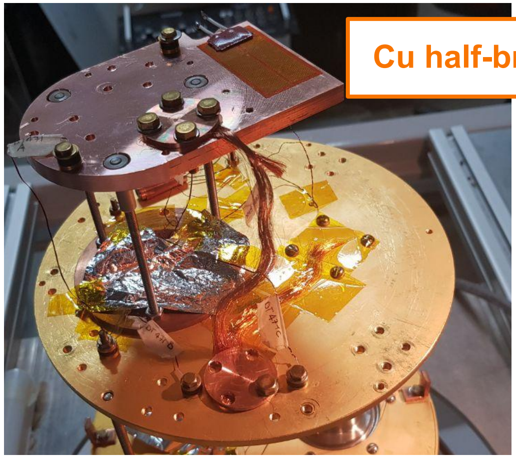


Cu braid

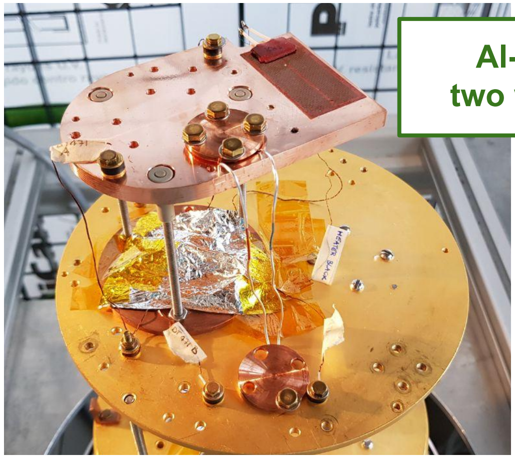
Al-5N:
two wires



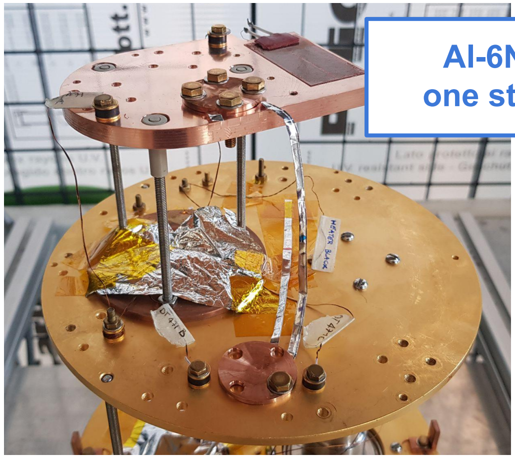
Al-6N:
two strips



Cu half-braid



Al-6N:
two wires

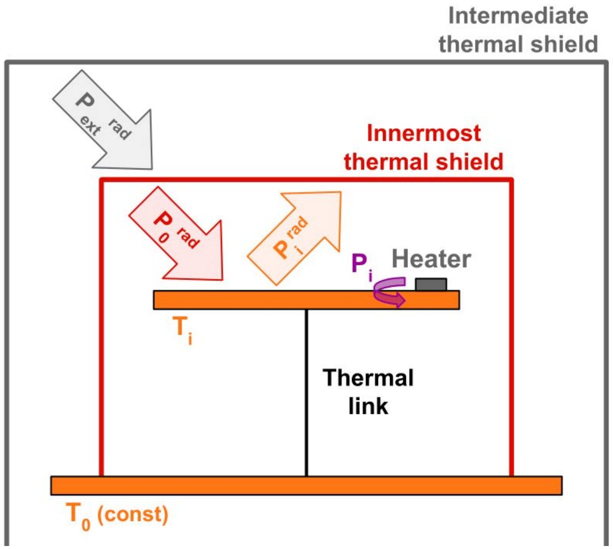


Al-6N:
one strip

Thermal conductivity measurements

Differential measurements

- Thermodynamic equilibrium:



$$\underbrace{P_i^{tot} - P_{i-1}^{tot}}_{\text{Total dissipated power}} = (\underbrace{P_i - P_{i-1}}_{\text{Heater dissipated power}}) + (\underbrace{\dot{Q}_i - \dot{Q}_{i-1}}_{\text{Net radiative heat transfer}}) = (P_i - P_{i-1}) - \sigma \varepsilon_i A_i (T_i^4 - T_{i-1}^4)$$

$T_i - T_{i-1} \ll T_i - T_0$