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HIGH-D

Studies of self-heating effect on SiPMs

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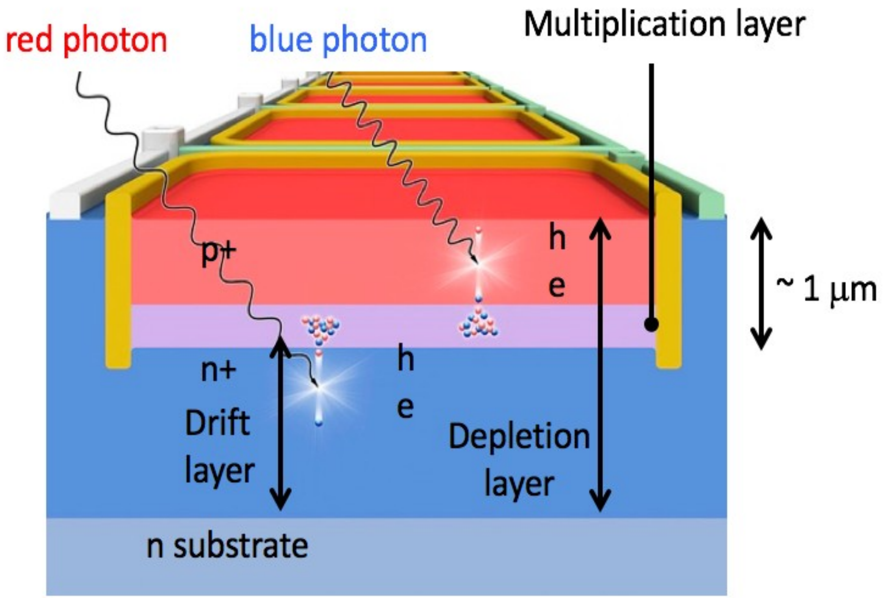
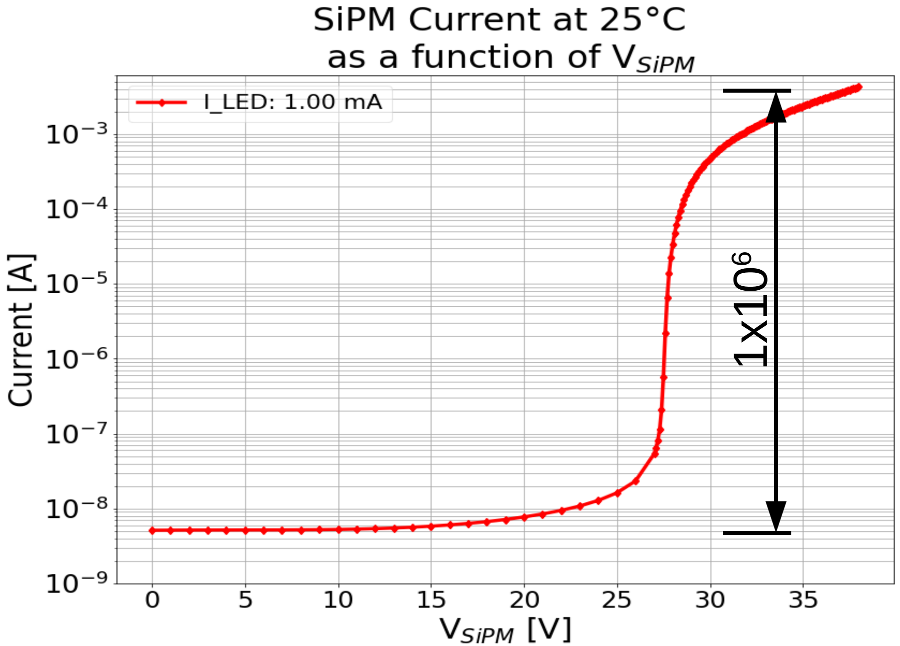
High-D Consortium Meeting

Avalanche multiplication in a SiPM





- When a **photon hits a pixel**, the **generated charge carriers** (e-h pairs) **trigger an avalanche multiplication** in the p-n junction by impact ionization.

- Gain >10^5 is reached applying a reverse bias voltage above the breakdown level (V_{bd})
- I_{SiPM} increase when increasing applied V;
- I_{SiPM} ranges from nA to mA (6 orders of magnitude).

SiPM response also depends on temperature

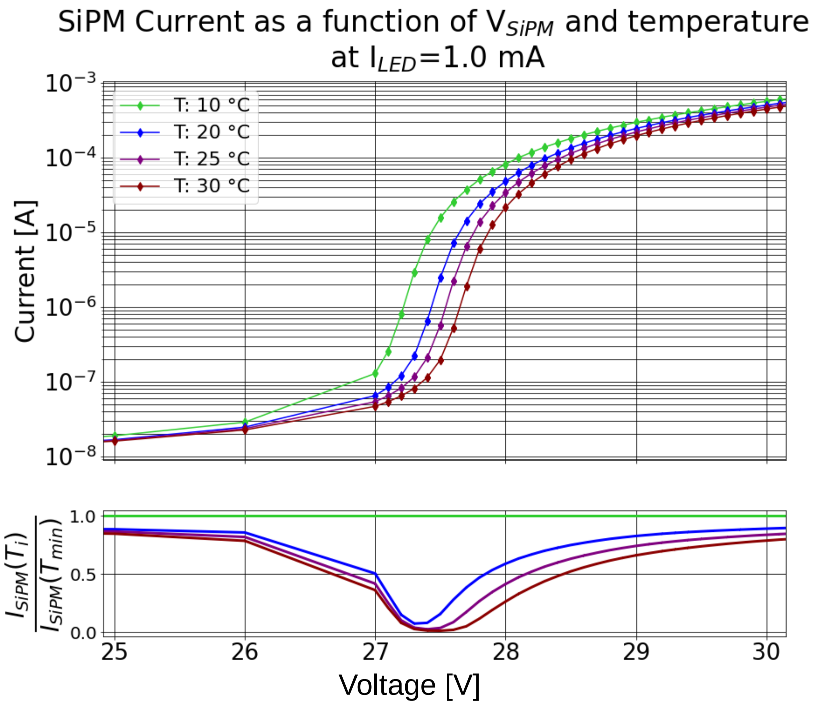
- Higher temperature → shorter mean free path of the charge carriers→ the critical E field necessary to keep a the avalanche increases, therefore V_{bd} increases as well.

- Photo-current $\left(I_{photo} = I_{SiPM} - I_{dark}\right)$ at constant bias voltage, V_{bias} , and constant photon rate, decreases with temperature:

$$I_{photo} \propto PDE(T) \cdot Gain(T)$$

  - Explained, among other effects, by the temperature dependence of breakdown voltage, V_{bd}:

$$Gain \propto \frac{1}{q_0} C_{pix} \left(V_{bias} - V_{bd}(T)\right)$$



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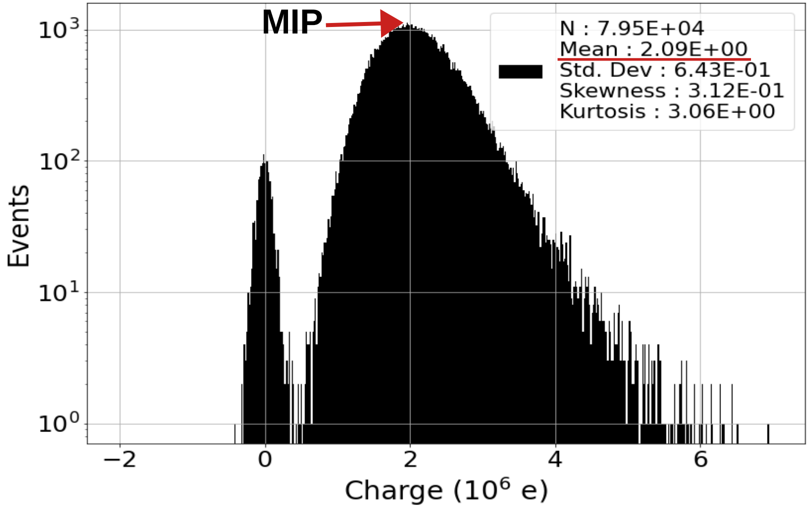
SiPM response to a minimum ionizing particle

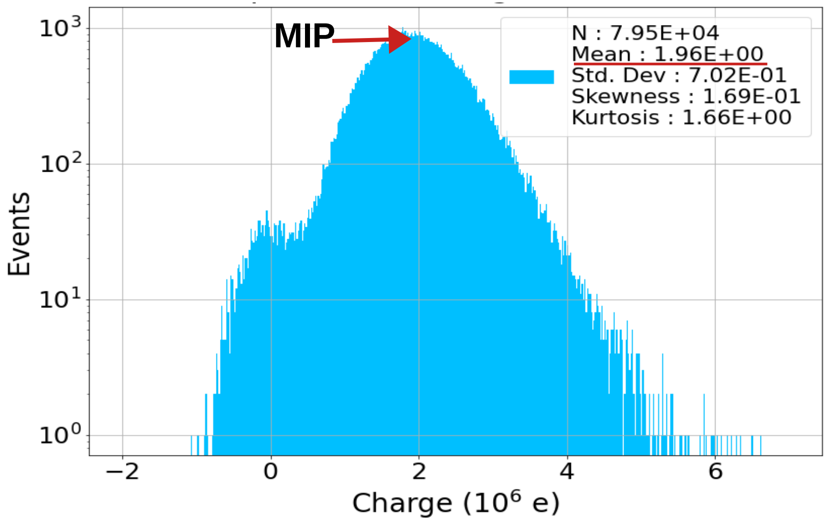
- To **detect charged particles** the **SiPM is coupled to a scintillator** (plastic or inorganic). The minimum signal depends on the application: either single photon or minimum ionizing energy from a charged particle.
- **SiPMs operating on harsh radiation environment** or high ambient light show **high dark count rates**. The single photon resolution is not possible in this case.

MIP response before (black) and after (blue) irradiation:

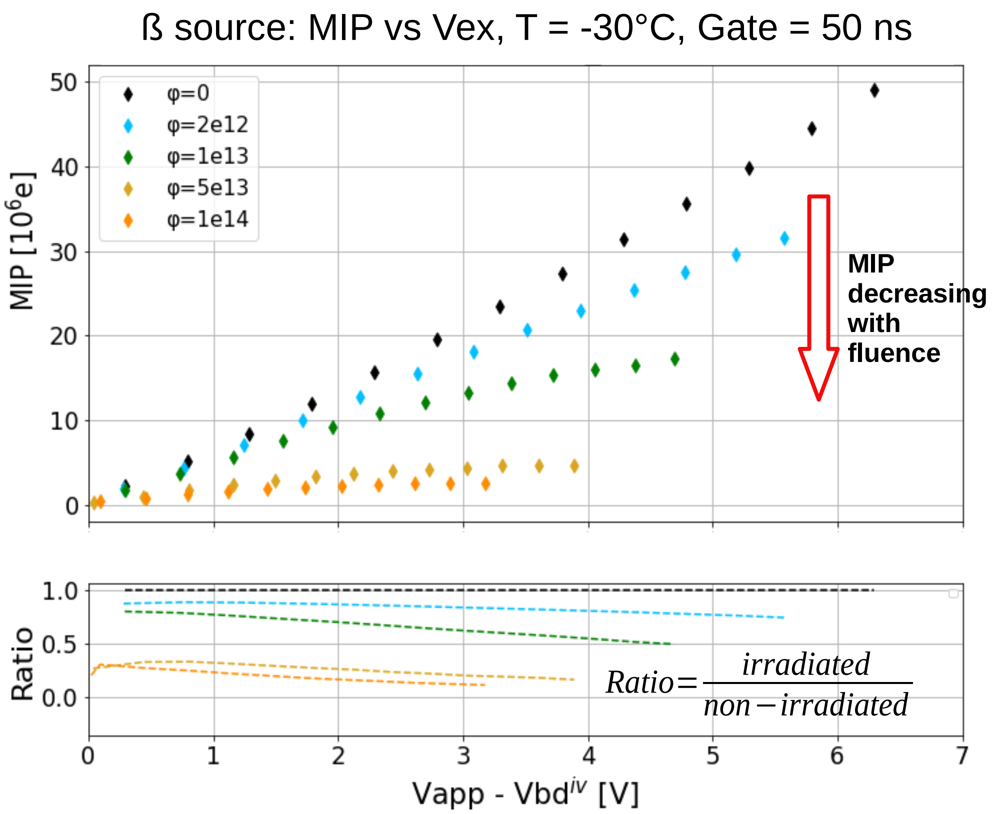
Non-irradiated SiPM



Neutron irradiated SiPM ($2x10^{12}$ cm^{-2})



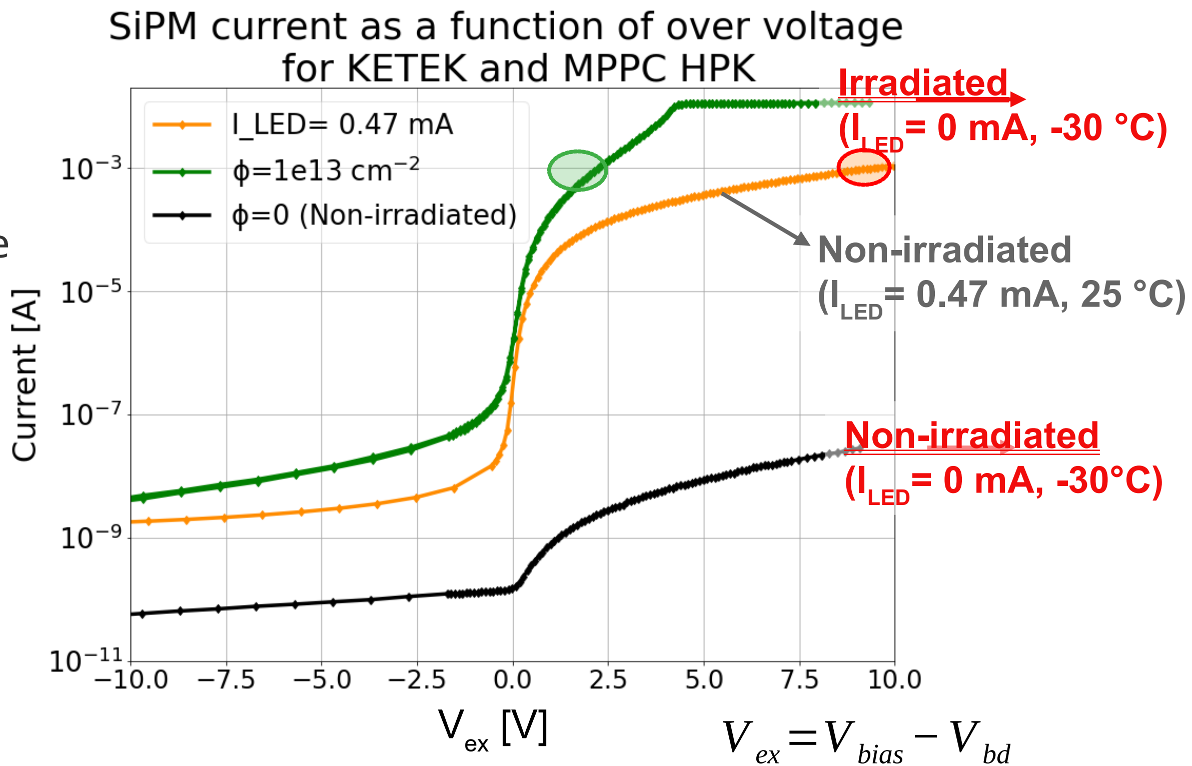
Reduction on the SiPM response after irradiation



- A ~40% reduction in the MIP response in a plastic scintillator with SiPM irradiated to $\phi_{eq}=10^{13}$ cm^{-2} and operated at 2 V above breakdown (2 OV).
- Is unclear if these results are consequence of radiation damage in the SiPM or of the self-heating effect .

Dark current increase → Self- heating effect

- *What is self-heating effect?*
  - **Increase in dark current**, up to 6 order of magnitude, **leads to large power dissipation** (heat) and therefore produce an **increase on SiPM temperature**.
- *Why is this effect important?*
  - If the **heat is not cooled down** fast enough, the **increase on temperature changes the SiPM performance.**
- *How do we want to perform the studies?*
  - Operate a **non-irradiated SiPM**, under LED illumination, to **produce the same power ($P = V_{bias} * I_{SiPM}$) as expected for an irradiated SiPM.**

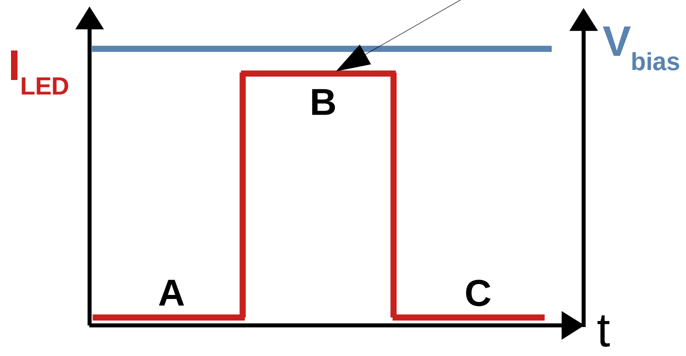


$$V_{ex} = V_{bias} - V_{bd}$$

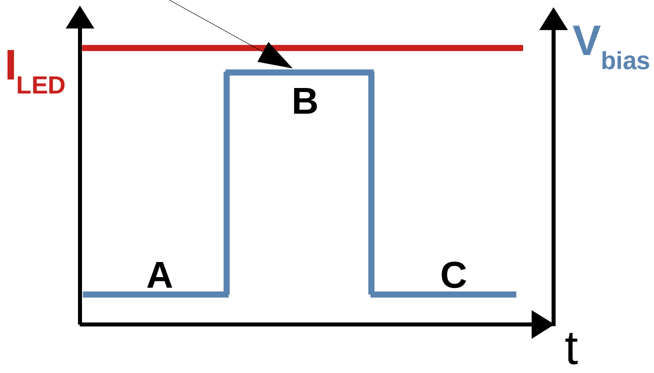
- **P ~ 50 mW induced by I_{dark}** (Irrad. at **ϕ = 1e13** cm^{-2} at V_{ex} = 2 V, V_{bd} = 36.7 V @ -30 °C)
- **P ~ 50 mW induced by high I_{LED}** (non-irrad. I_{LED}~0.5 mA at V_{ex} = 10 V, V_{bd} = 27.5 V @ 25 °C)

I_{LED} and V steps measurements cycles

- **Determine ΔT_{SiPM} from an induced ΔI_{SiPM} with a predefined cycle:**
  - I_{SiPM} increased either by increasing light intensity at constant V_{bias} or by changing V_{bias} under constant light illumination.
  - 2^{nd} interval (B) is the comparison stage between the cycles:
    - **Regardless prior conditions → Same power induced applying same V_{bias} and I_{LED}**



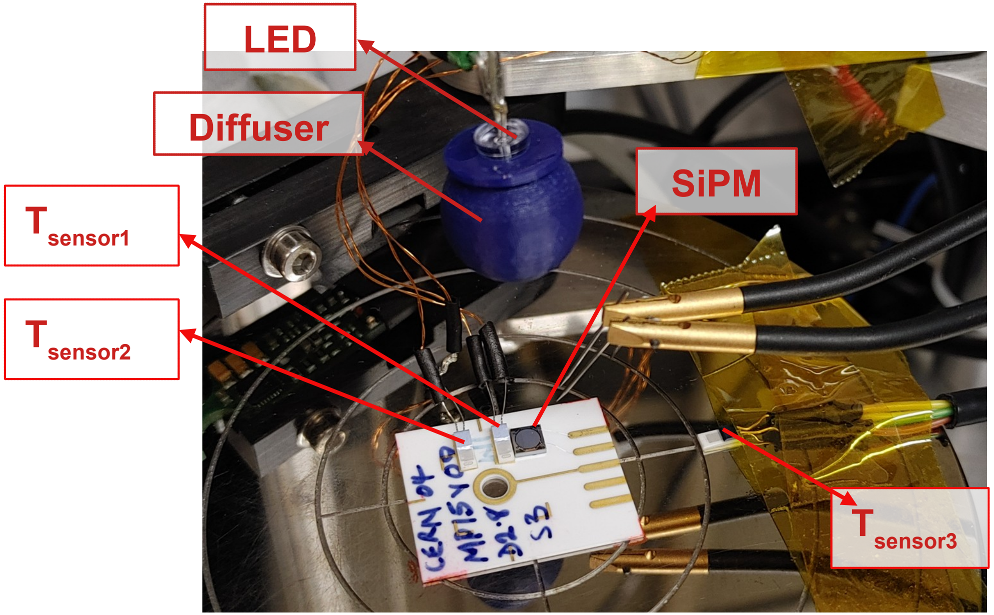
Constant V_{bias} changing I_{LED}
(I-steps)

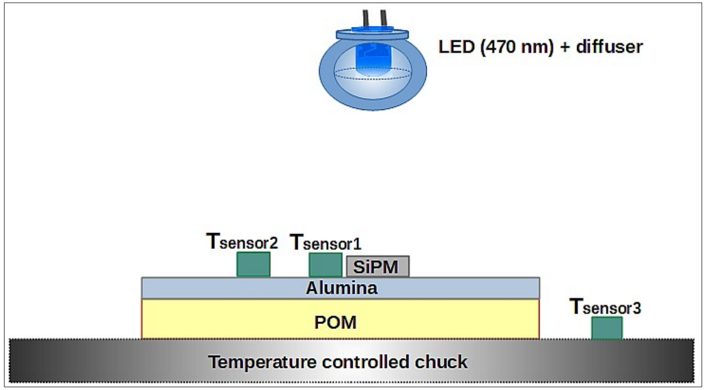


Constant I_{LED} changing V_{bias}
(V-steps)

Measurement setup with a SiPM

- SiPM KETEK *non-irradiated* (MP15V09 D2.8)
  - d_{Si}= 700 µm
  - V_{bd}= 27.6 V @25°C, C_{pix}= 18 fF, τ = 14 ns
  - Pixel size = 15 µm, 27000 pixels
- SiPM glued on alumina (Al_2O_3) substrate:
  - d_{Al2O3}= 600 µm
- Cooling system: temperature-controlled chuck
- POM (1.5 and 3.0 mm) between the alumina/PCB and cold chuck to emulate degraded thermal contact.
- 3 T sensors (PT-100): at 3.1 mm ($T_{sensor1}$) and 7.6 mm ($T_{sensor2}$) from the SiPM center, $T_{sensor3}$ on the chuck.
- Illumination: LED (470 nm)

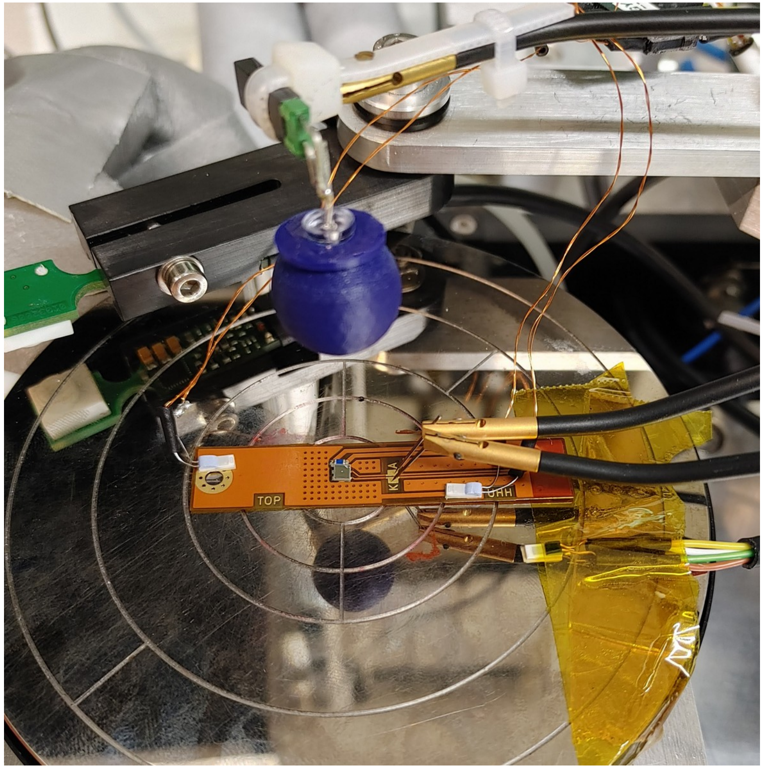




Ketek and MPPCs (HPK)

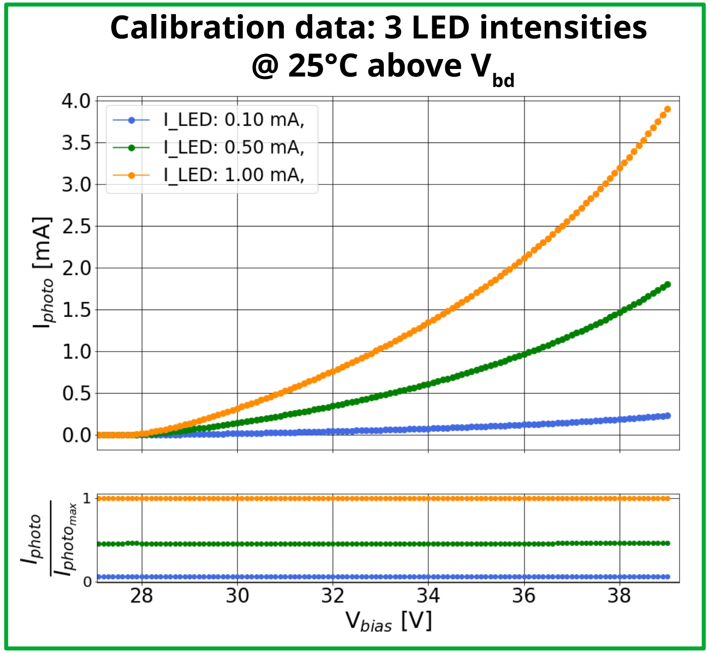
- Samples used:

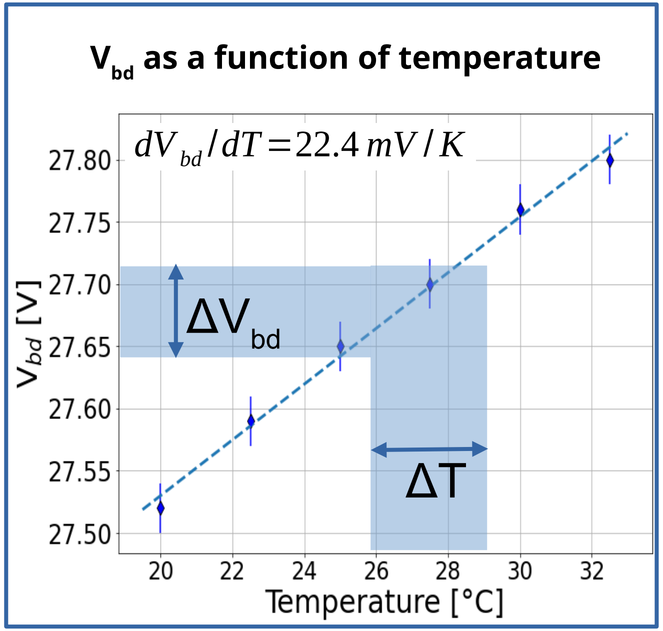
	S6	MPPC S14160-9766
	Ketek	HPK
# pixels	27367	8480
Pixel size [µm]	15	15
Active area [mm^2]	6.2	1.4 x 1.4
Substrate	Alumina	PCB
V_{bd} (@ 25°C)	27.6 V	38.2 V
dV_{bd}/dT [mV/K]	22.4	33.3
S_{photo}	0.46% (10.4 OV)	0.58% (7.8 OV)

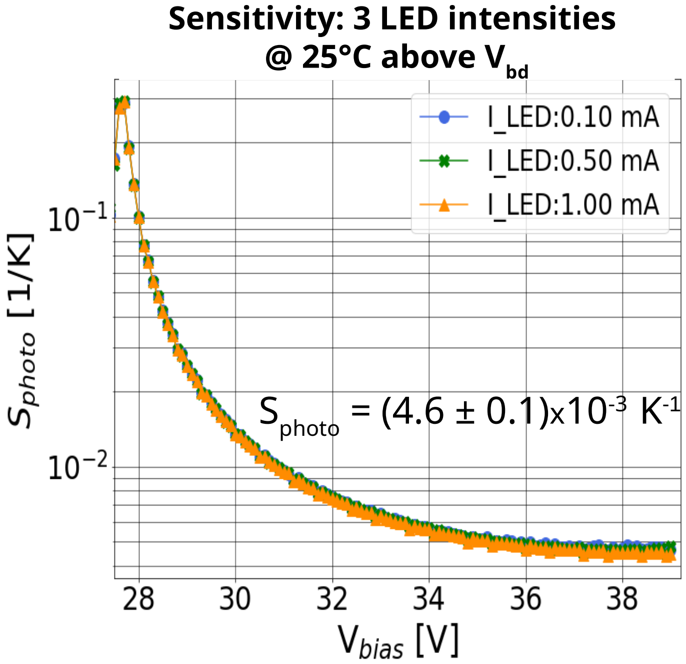


Method for self-heating studies with I_{photo}

- Express the temperature (T) dependence of I_{photo} as: $\frac{dI_{photo}}{dT} = \frac{dI_{photo}}{dV} \cdot \frac{dV_{bd}}{dT}$
- A relative change in I_{photo} is related to a change in T by the **sensitivity**: $S_{photo}(V_{bias}, T_{chuck}) = \boxed{\frac{1}{I_{photo}} \cdot \frac{dI_{photo}}{dV}} \cdot \boxed{\frac{dV_{bd}}{dT}} \left[\frac{\%}{K}\right]$
  - Calibration data is measured at known and stable T_{chuck}:
  - Calibration data at several LED currents leads to the same sensitivity curve:



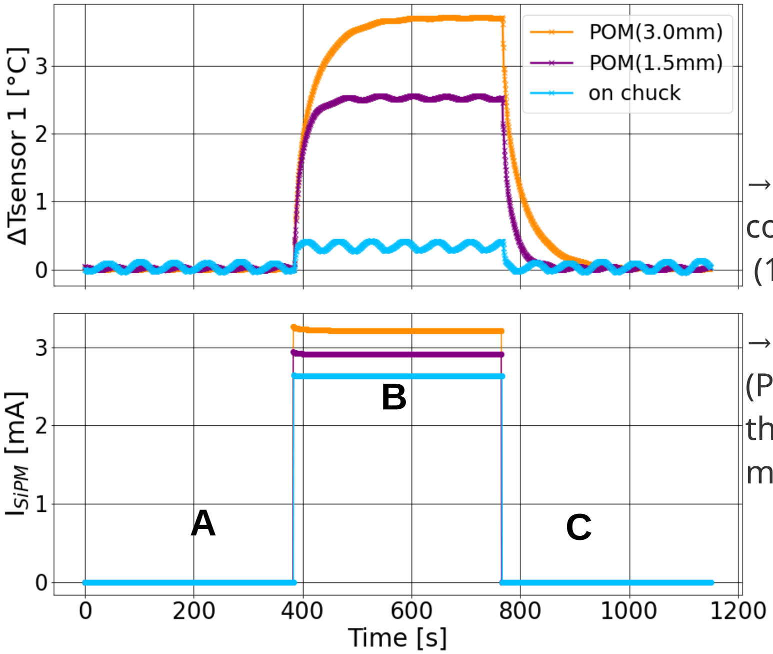




Method for self-heating studies

- Instead of the usual I(V) measurements, this **method require to measure current vs time, I(t).**
- **Determine ΔT_{SiPM} from an induced power (I and V steps):**

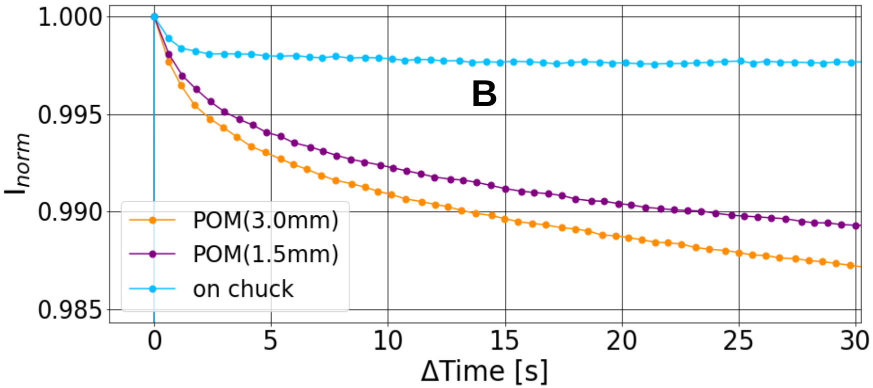
- Example of constant illumination and V step from below to 10 V above V_{bd} with the SiPM on top of:



→ HGCAL PCB: thermal conductivity K=0.3 W/m*K (1.6 mm thick).

→ We use POM-C (Polyoxymethylene) with the same K (1.5 and 3.0 mm thick)

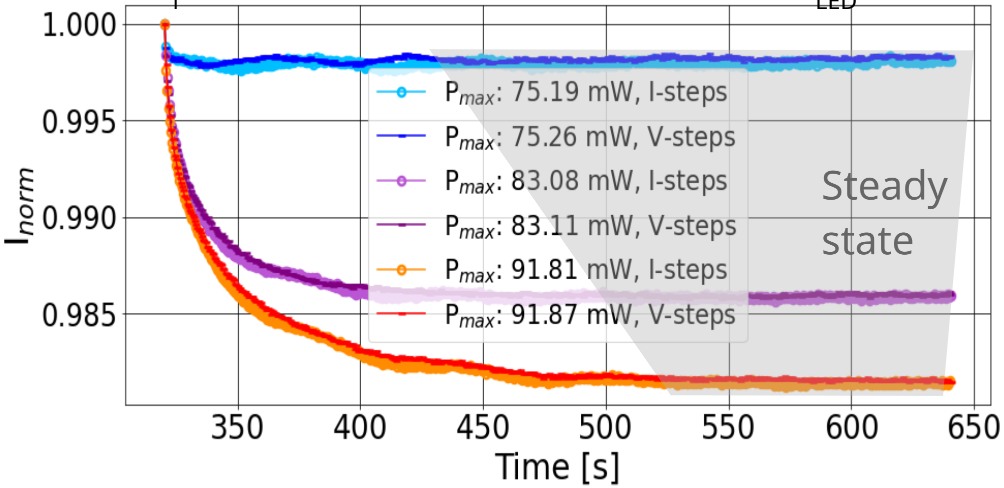
- I_{SiPM} normalized to the first data point after the switch



- SiPM with good thermal contact → τ ~ 1 s
- SiPM with bad thermal contact→ τ ~ 10 s

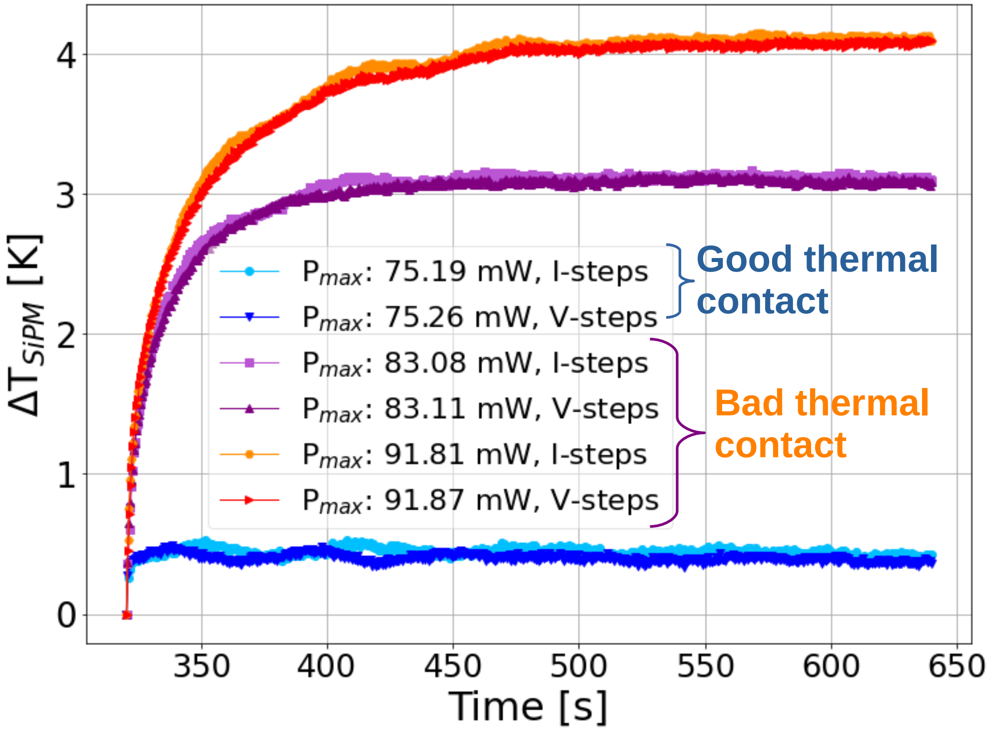
ΔT_{SiPM} for I and V steps: good and degraded thermal contact

t_1 = 1st measurement after the V or I_{LED} switch



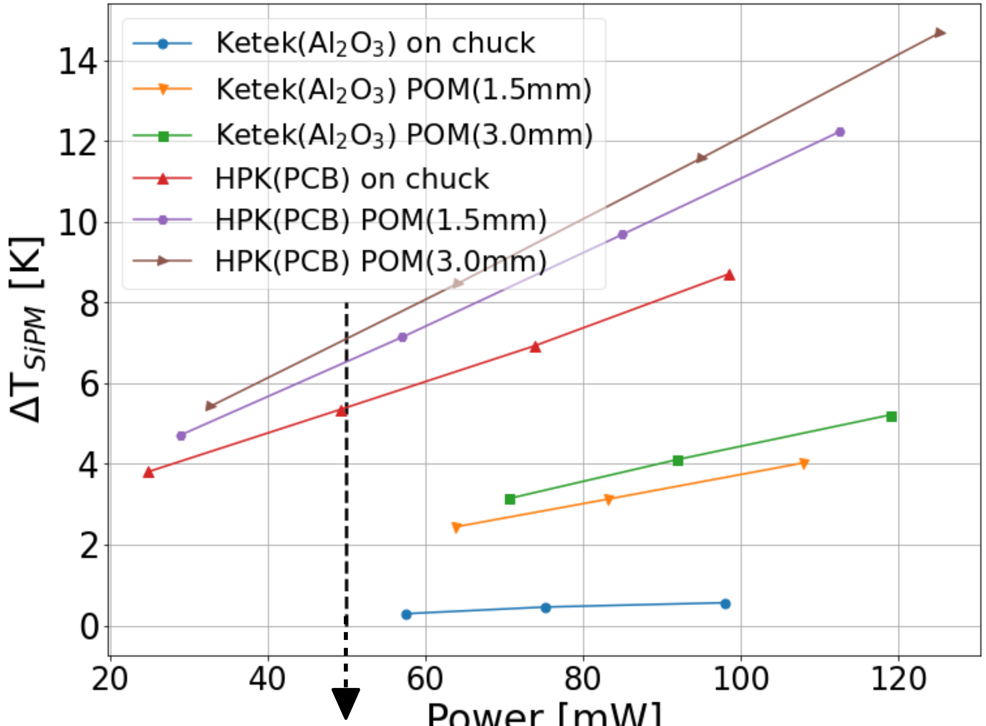
$$\Delta I_{diff} = \frac{I_{photo}[t_1] - I_{photo}[t]}{I^{steady}_{photo}} \Rightarrow \Delta T_{SIPM} = \frac{\Delta I_{diff}}{S_{photo}}$$

Same steady state current for I and V steps in the interval of interest.



Maximum ΔT_{SiPM} as a function of power for:

- Good thermal contact (SiPM+Alumina on top of the chuck surface):
  - Increase up to 0.5 K
- Degraded thermal contact (POM layers between the chuck surface):
  - SiPM+Alumina ~5 K for thicker POM layer.
  - For the SiPM+PCB ~15 K for thicker POM layer.

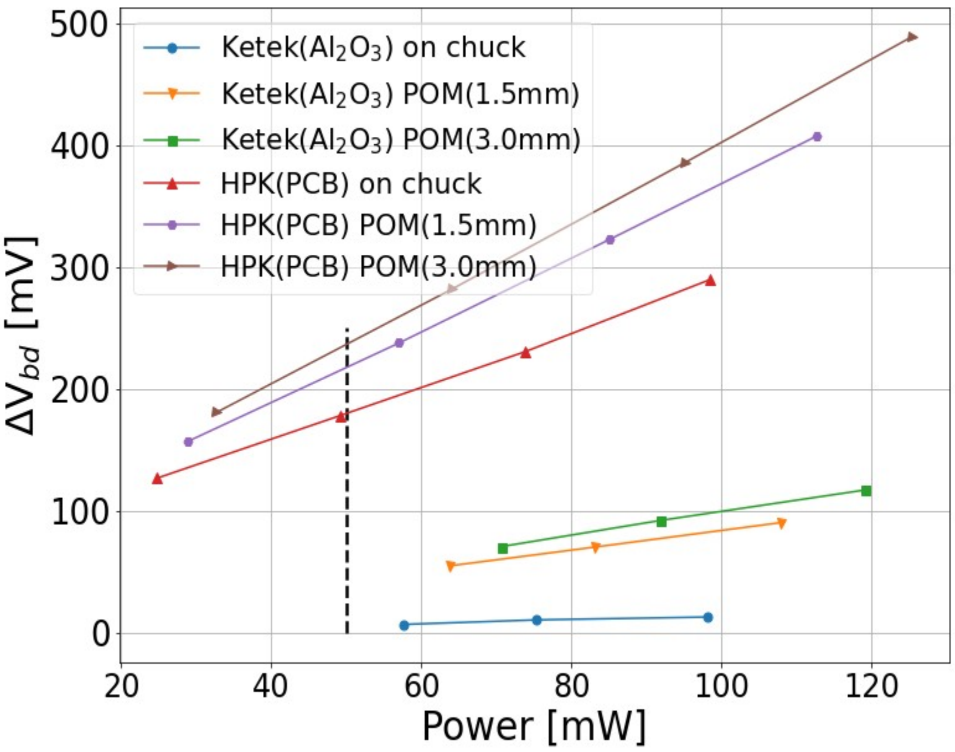


- For a SiPM soldered on a PCB:
  - 50 mW → T_{SiPM} ~ 5 K

Expected P for irradiated SiPM

Maximum shift on V_{bd} as a function of power

- Good thermal contact (SiPM+Alumina on top of the chuck surface):
  - Shift on V_{bd} up to 15 mV
- SiPM+PCB on top of the chuck surface:
  - Shift on V_{bd} up to 300 mV
- Degraded thermal contact (SiPM+Alumina+POM layers between the chuck surface):
  - Shift on V_{bd} up to 120 mV
- Degraded thermal contact (SiPM+PCB+ POM layers between the chuck surface):
  - Shift on V_{bd} up to 500 mV



In summary

- Developed method to determine the heating of SiPMs from its current, as a function of:
  - Induced power, thermal contact and SiPM packages.
- The method has been used to determine the temperature increase of a SiPM with P ~ 50 mW, expected for instance in SiPM (MPPC HPK) irradiated to ϕ_{eq}~10^{13} cm^{-2} operated ~ 2V (OV)
- Heating causes a decrease in I_{photo} (increase in I_{dark}) and a shift on V_{bd}:
  - For good thermal contact: ΔT_{SiPM}~0.5 K, ΔV_{bd} = 15 mV
  - For degraded thermal contact (SiPM mounted on PCB): ΔT_{SiPM}~5 K, ΔV_{bd} = 180 mV. However, this shift on V_{bd} does not explain the significant MIP response reduction observed in previous studies.

  - Next steps:
    - Apply the method for irradiated samples.
    - Compare the results with thermal simulations.

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- Next steps:
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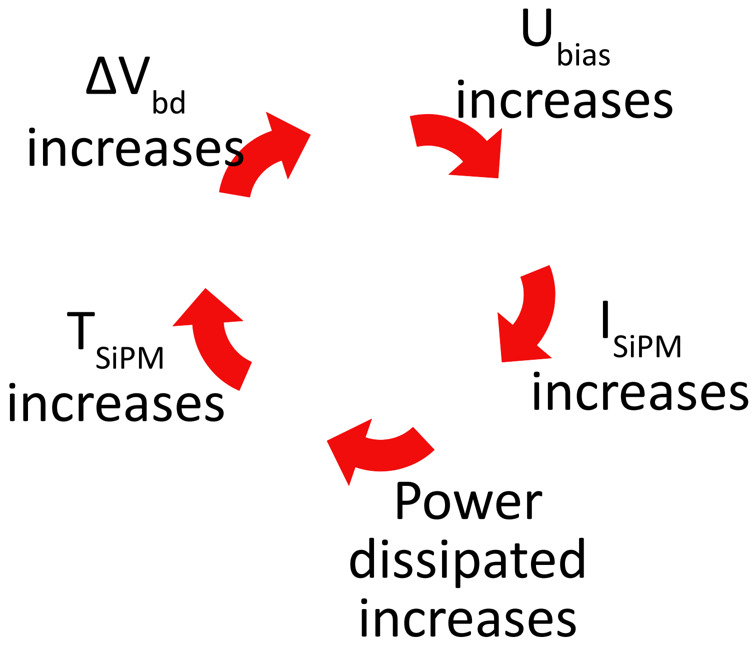
Thanks for your attention!
Let's go for lunch!!!

Backup slides

Implications of self-heating on SiPMs

- If the shift of 40 mV is not compensated, operating ~ U_{ex} = 2 V → reduction of gain by 2 % + reduction of PDE by 2 %
- Reduction of signal about 4 %
- Increasing U_{bias} is a possible solution, **but**:

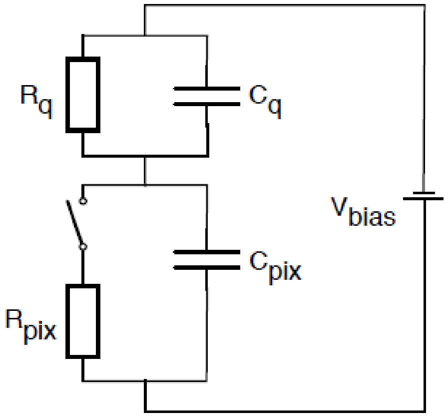


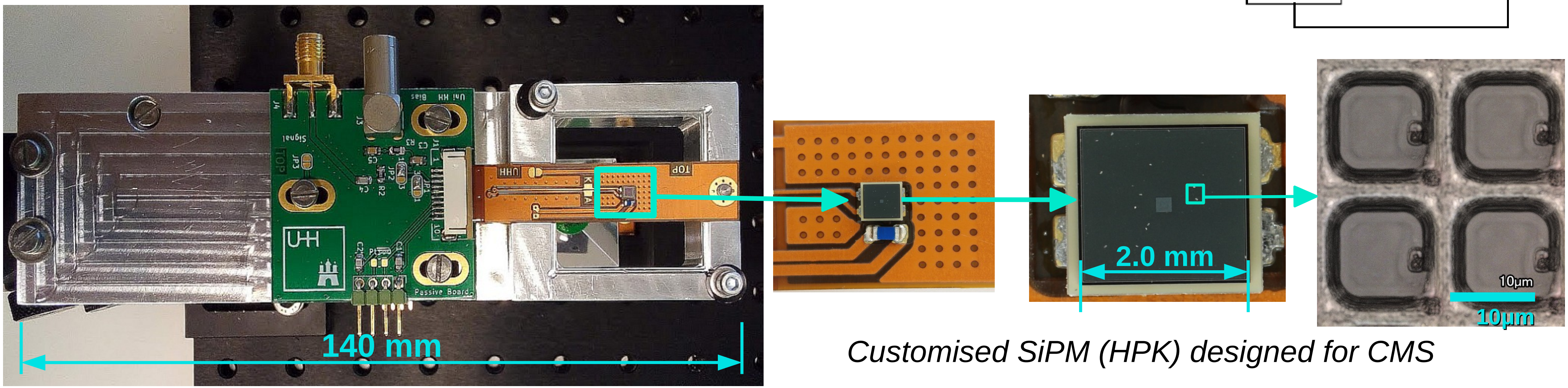
⇒ It is a loop! Cannot be fully compensated.

What is a SiPM

- Single-Photon Avalanche Diode (SPAD) = photo-diode reverse biased, operating above the breakdown voltage level, V_{bd} → Geiger mode (avalanche multiplication)→ Gain > 10^5
- Silicon Photo-Multiplier (SiPM) = array of SPADs connected in parallel. The single SPADs in a SiPM → pixels.

Pixel Electrical representation

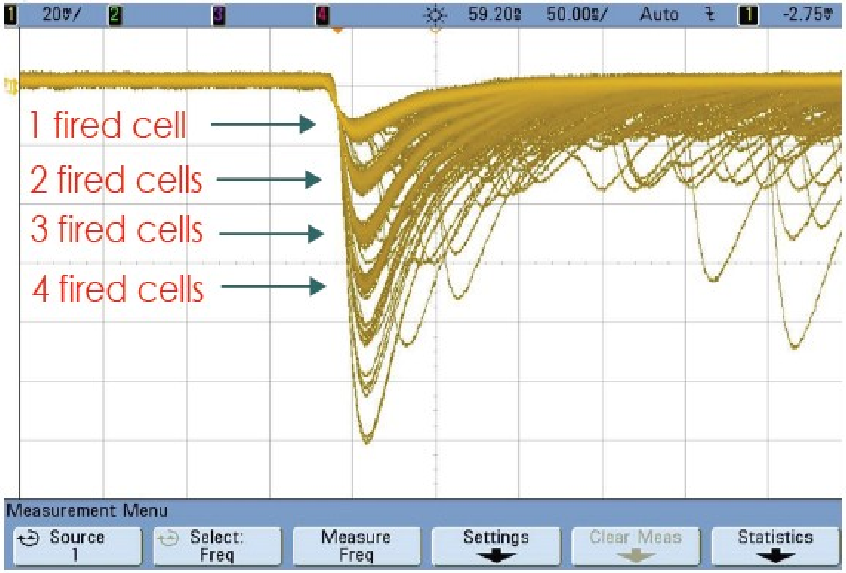


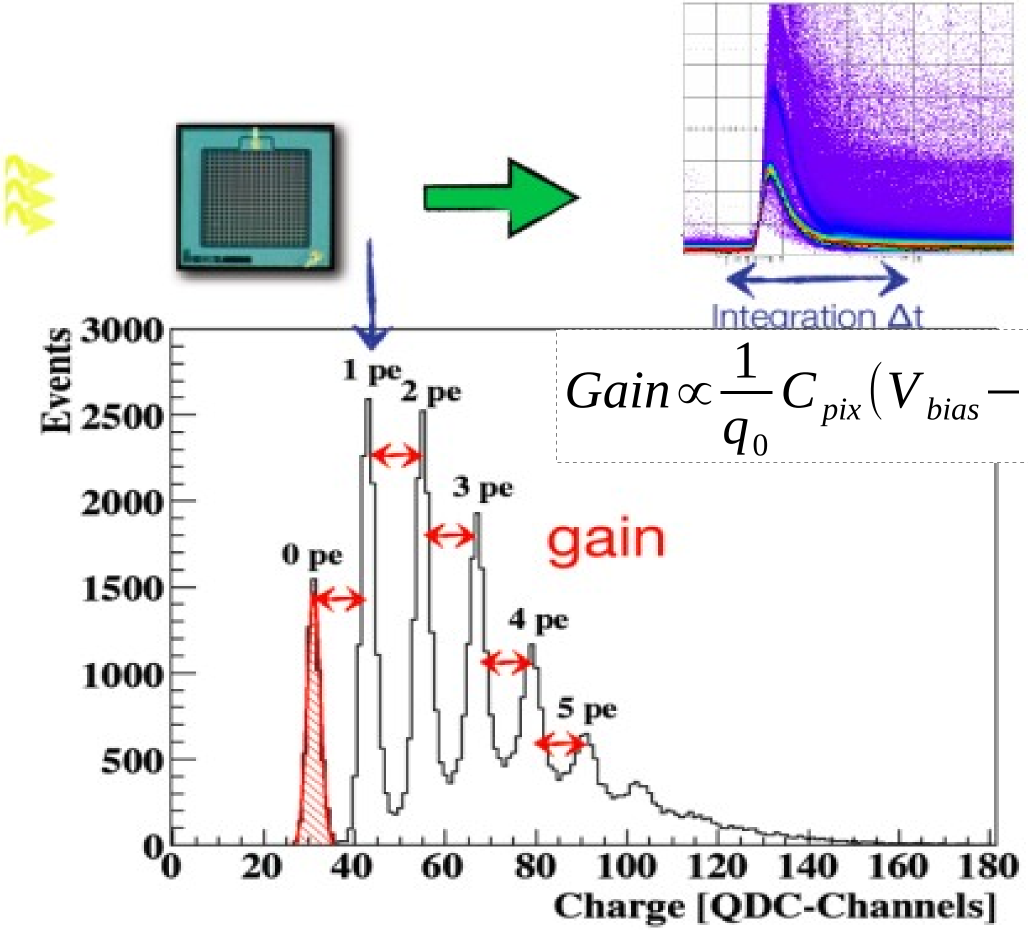


Customised SiPM (HPK) designed for CMS

SiPM response to low light intensity

- 1 fired cell or pixel = 1 photo-electron (p.e) detected

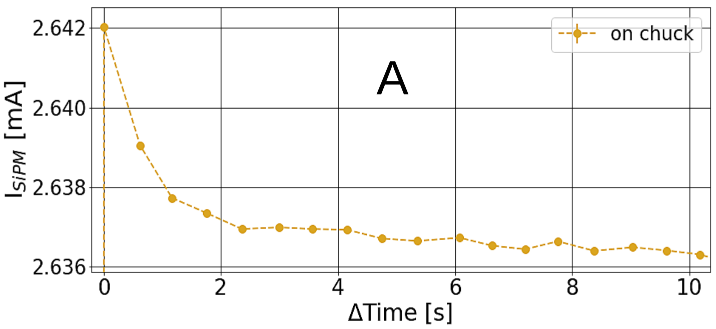




$$Gain \propto \frac{1}{q_0} C_{pix} \left(V_{bias} - V_{bd} \right)$$

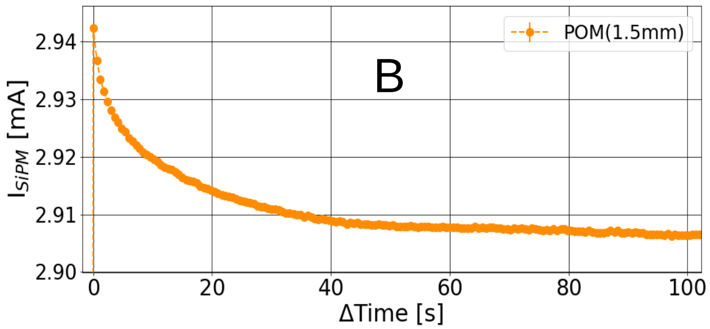
I_{SiPM}(t) time constant dependence on thermal contact

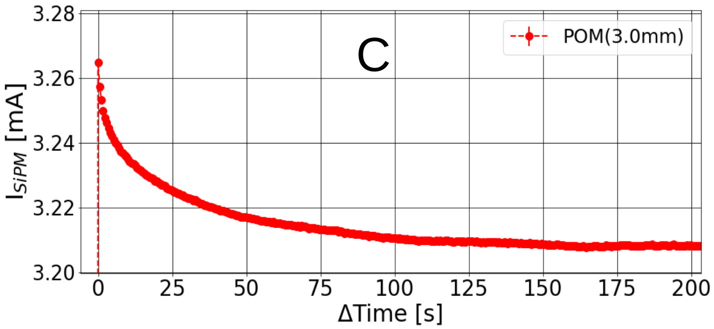
- I_{SiPM} as a function of time for I_{LED} steps, using KETEK S3 sample. At 25 °C. Normalizing the time to the first data point after the switch. For the cases with the SiPM on direct contact with the chuck (A), with a 1.5 mm (B) and 3.0 mm thick (C) POM layer between the SiPM and the chuck.



	$\Delta T(0,0)$ [K]	$\Delta T(0.14,0))$ [K]	$\langle \Delta T \rangle$ [K]	R_{th} [K/W]	ΔW [J]	τ_h [s]	τ_c [s]
Si	0.18	0.086	0.15	0.44	4.8×10^{-4}	5.0×10^{-3}	1.1×10^{-3}
$Si + Al_2O_3$	0.60	0.39	0.51	1.46	7.6×10^{-3}	32×10^{-2}	8.5×10^{-3}
+ 1.3 mm PVC	10.2	9.9	10.1	28.7	6.9	20	5.4
+ 3.15 mm PVC	19.0	18.6	18.8	53.7	15.1	44	31

Table 2: Simulated temperature change of the SiPM multiplication region and estimated heating- and cooling- time constants for a power of Pow = 350 mW dissipated in the multiplication region of the SiPM. Given are the temperature change of the multiplication region at the SiPM center, $\Delta T(0,0)$, at the periphery, $\Delta T(0.14\,\mathrm{cm},0)$, and the mean $\langle \Delta T \rangle$. $R_{th} = \langle \Delta T \rangle / Pow$ is the thermal resistance. ΔW is the energy deposited in all materials, and $\tau_h = R_{th} \cdot \Delta W / \langle T \rangle$ an estimate of the heating-time constant, and τ_c an estimate of the cooling-time constant.

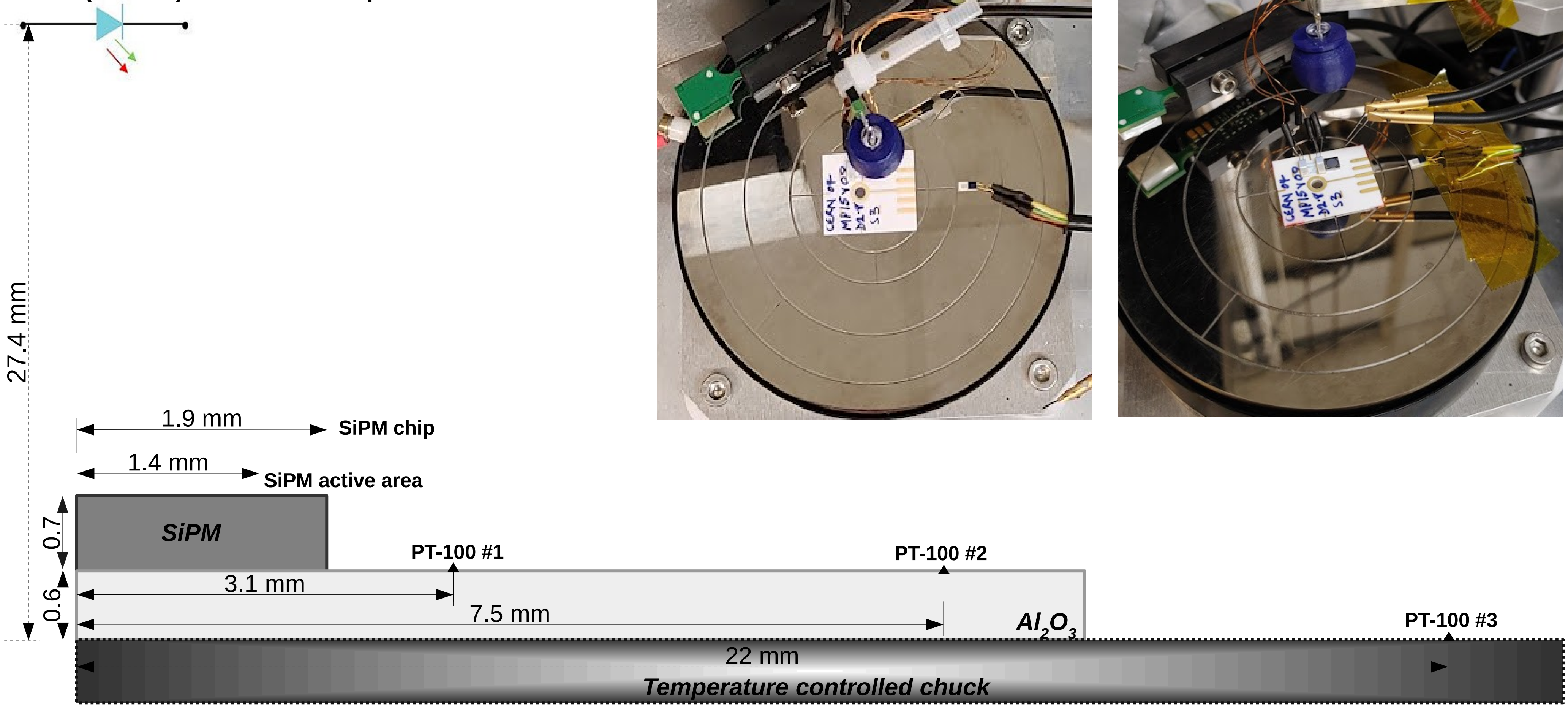




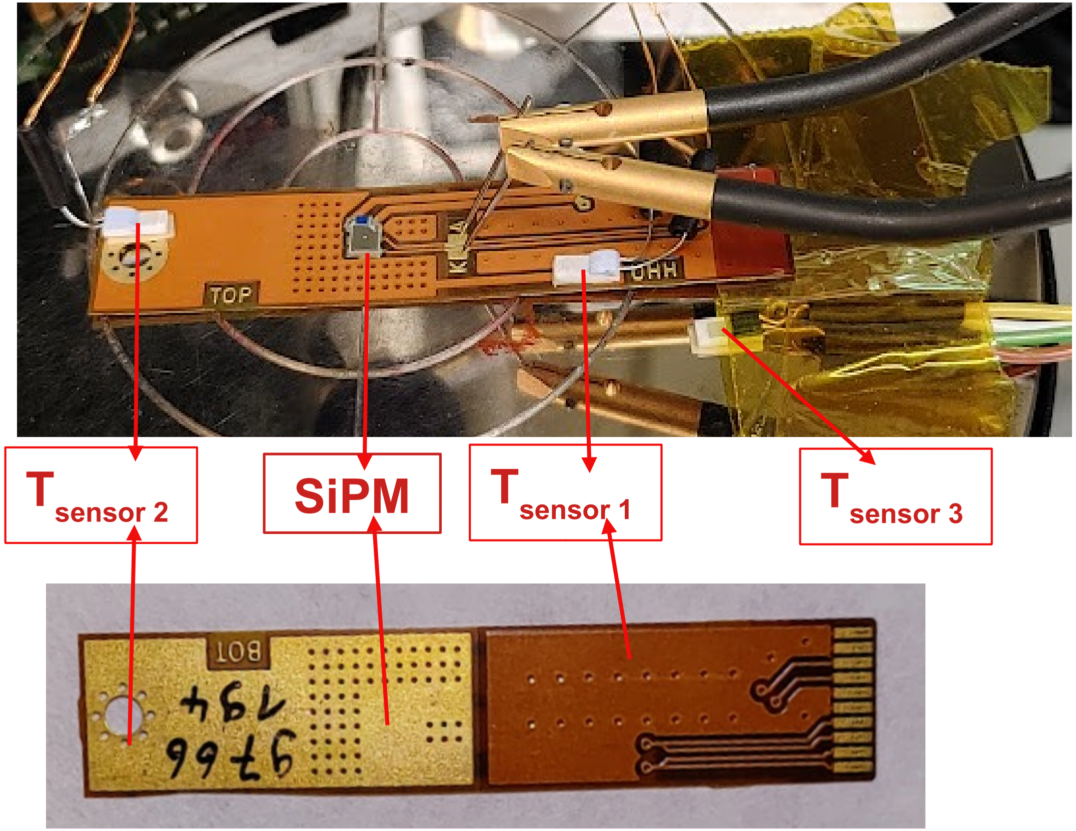
WL FOLIE 404 11 Heat conducting foil, double-sided adhesive (0.127 mm thick), K= 0,37 W/m*K

Cold chuck Setup Sketch

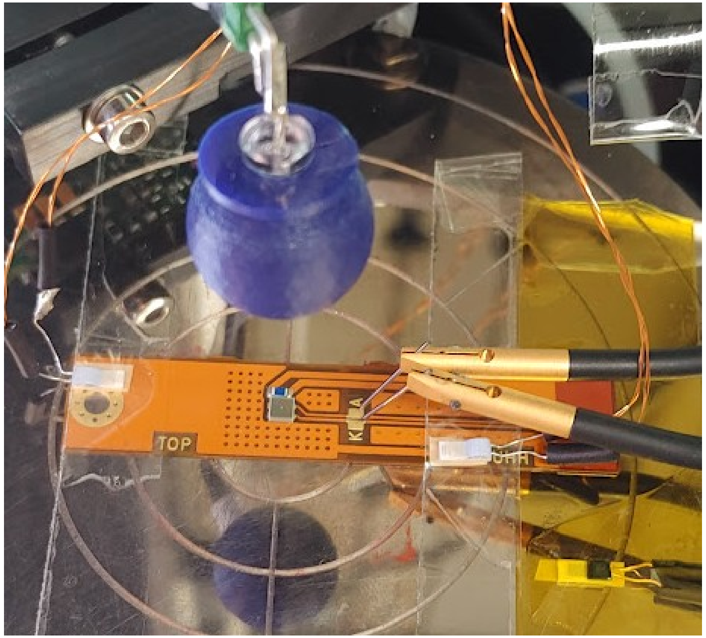
LED (470 nm) + diffuser on top of SiPM

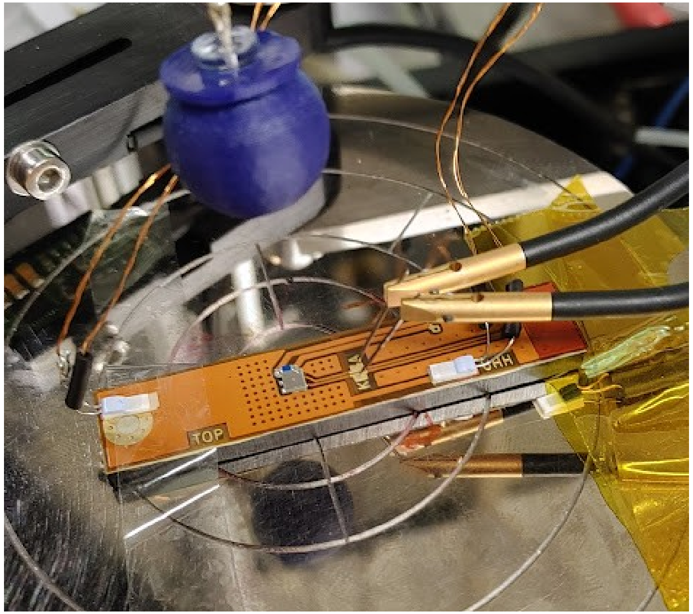


MPPC samples soldered on flexprint



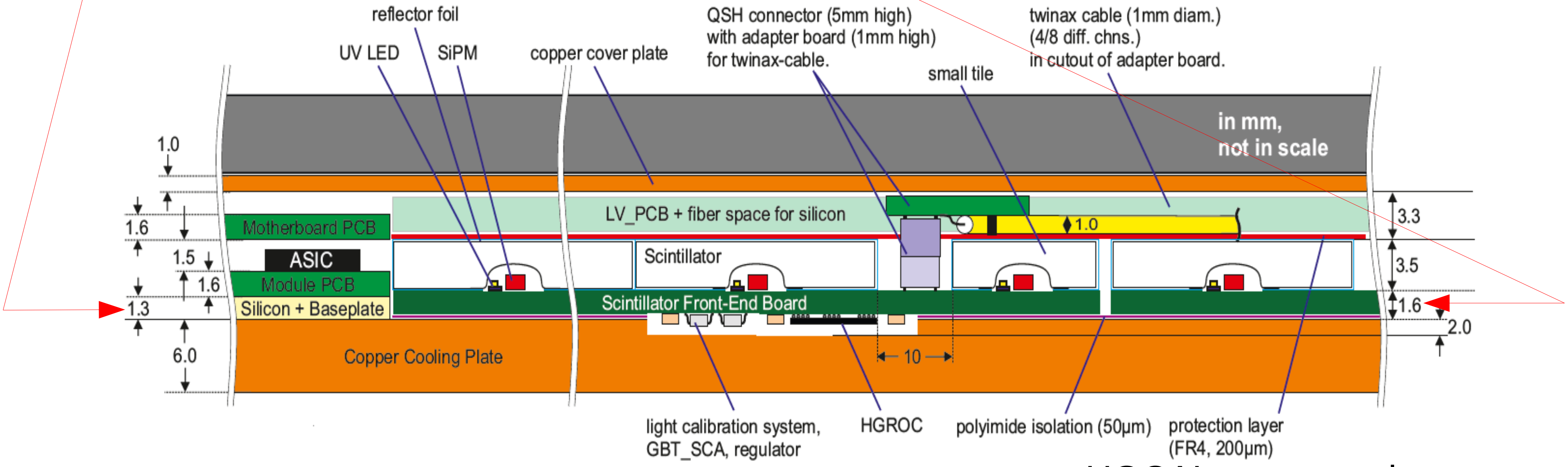
Data acquired using the samples on the flexprint





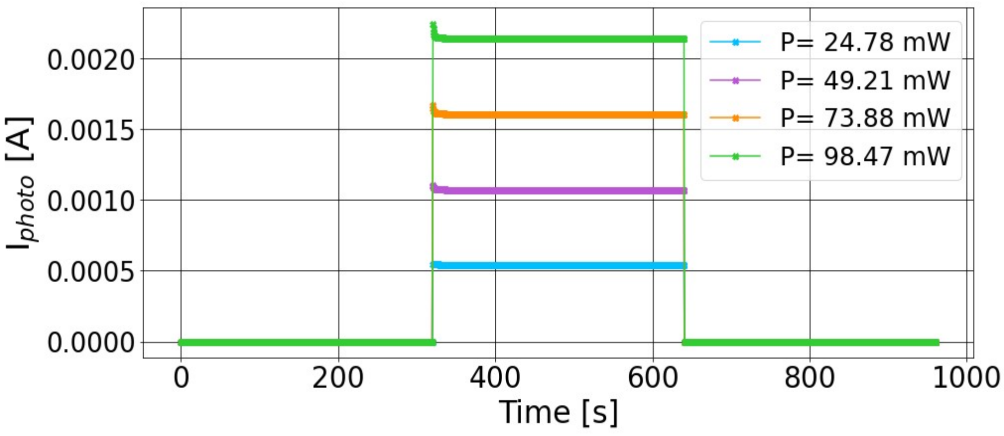
Material and thickness for layers to emulate bad thermal contact

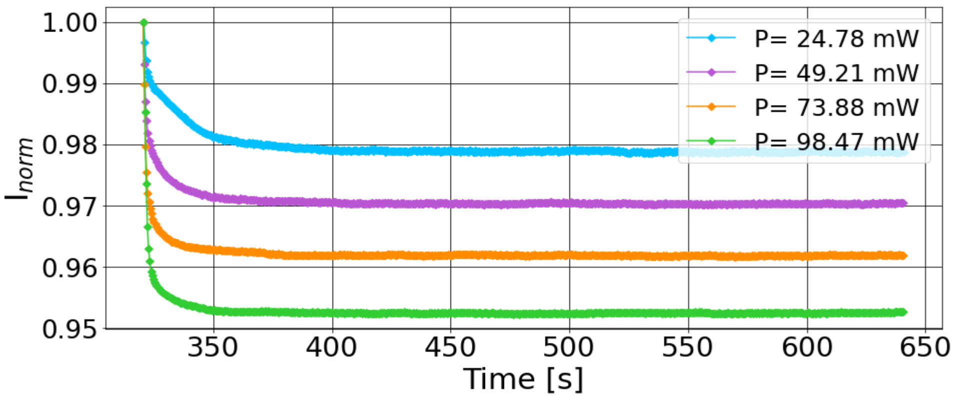
- As a reference: HGCAL is using FR4 (glass epoxy laminate material) for the PCB and they use 0.3 W/m*K as thermal conductivity, POM-C (Polyoxymethylene) has the same thermal conductivity.
- PCB is only 1.3mm thick. Including the polyimide isolation layer (50µm thick) between PCB and heat sink (cooper), total thickness 1.6mm.

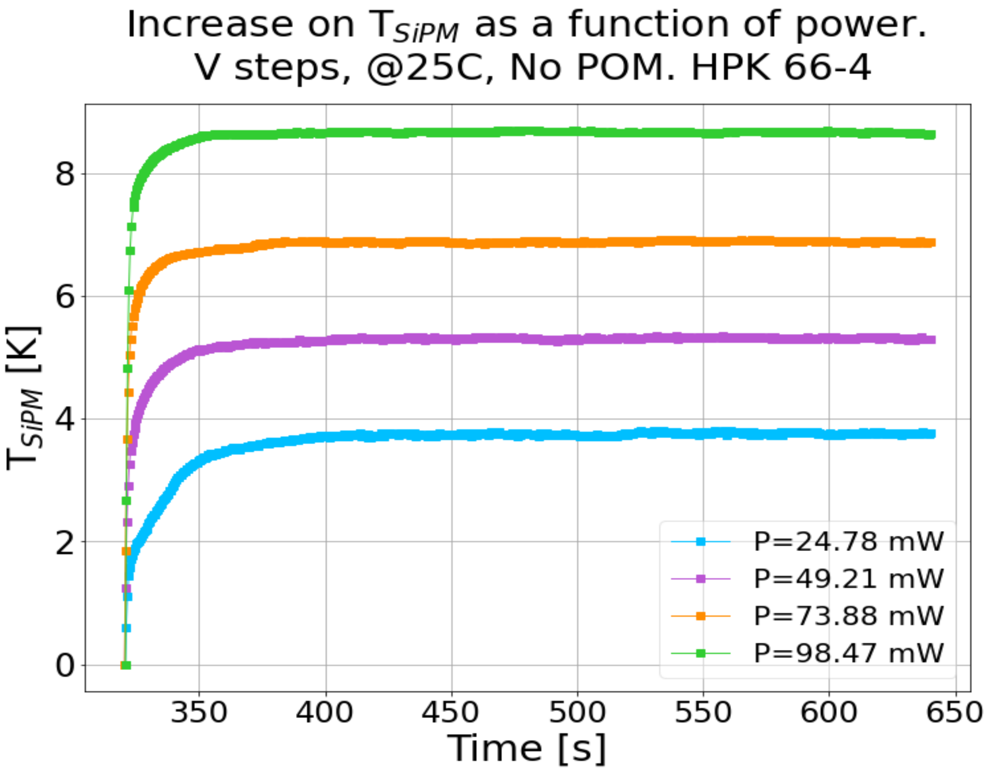


HGCAL cross section

ΔT_{SiPM} for I_{LED} steps good thermal contact







$$\Delta T_{SIPM} = \frac{I_{diff}}{S_{photo}}, \quad with \quad I_{diff} = \frac{\Delta I_{photo}}{I_{photo}} \qquad \Delta V_{bd} = \frac{dV_{bd}}{dT} \cdot \Delta T_{SiPM}$$