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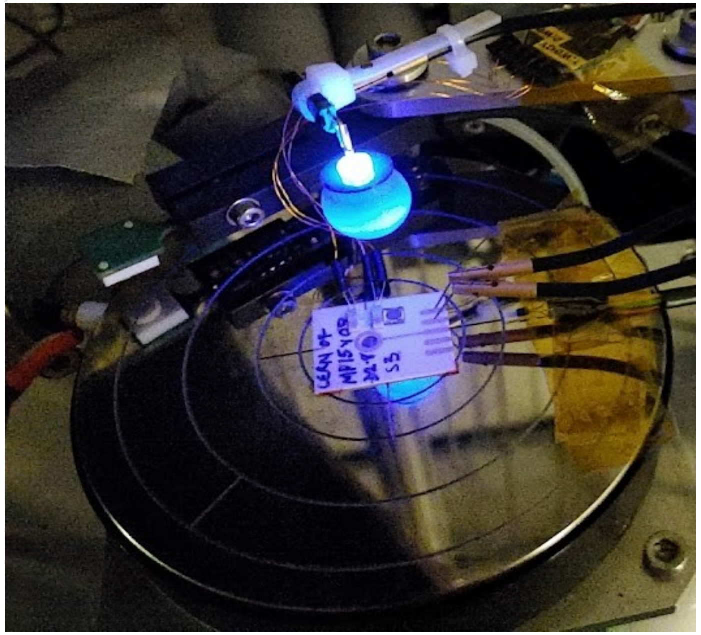

Effect of self-heating in silicon-photomultipliers

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Aim

- **Develop a method for determining SiPM temperature increase induced by dissipated power (self-heating) $\Delta T_{SiPM(P)}$** with $P = I_{SiPM} \cdot U_{bias}$
- Relevant for applications of SiPMs in:
  - High background light (LIDAR, HEP, astrophysics) → High I_{photo}
  - High radiation environment (LHC, FCC, satellite experiments) → High I_{dark} (~1 mA, T = -30 °C, ϕ_{eq} ~10^{13} cm^{-2})
- The SiPM performance changes with T:
  - Photo-current at fixed U_{bias} and constant photon rate, decreases with T

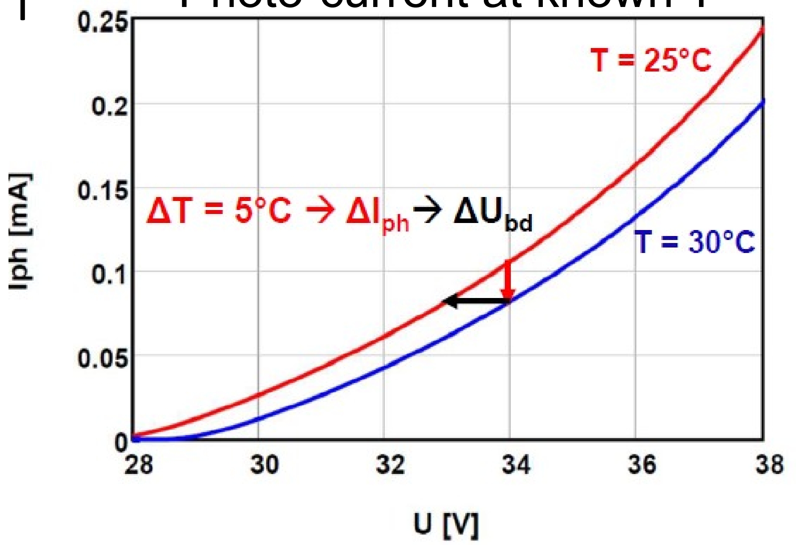
$$I_{photo} \propto PDE(T) \cdot Gain(T)$$

  - Explained by T dependence of breakdown voltage (U_{bd}):

$$\frac{dU_{bd}}{dT} \sim 20 - 40\ \frac{mV}{K} \quad \left\{ \begin{array}{l} Gain \propto \frac{1}{q_0} C_{pix}\left(U_{bias} - U_{bd}(T)\right) \\ PDE(T) \propto PDE\left(U_{bias} - U_{bd}(T)\right) \end{array} \right.$$

Calibration $I_{ph}(U,T)$:

Photo-current at known T



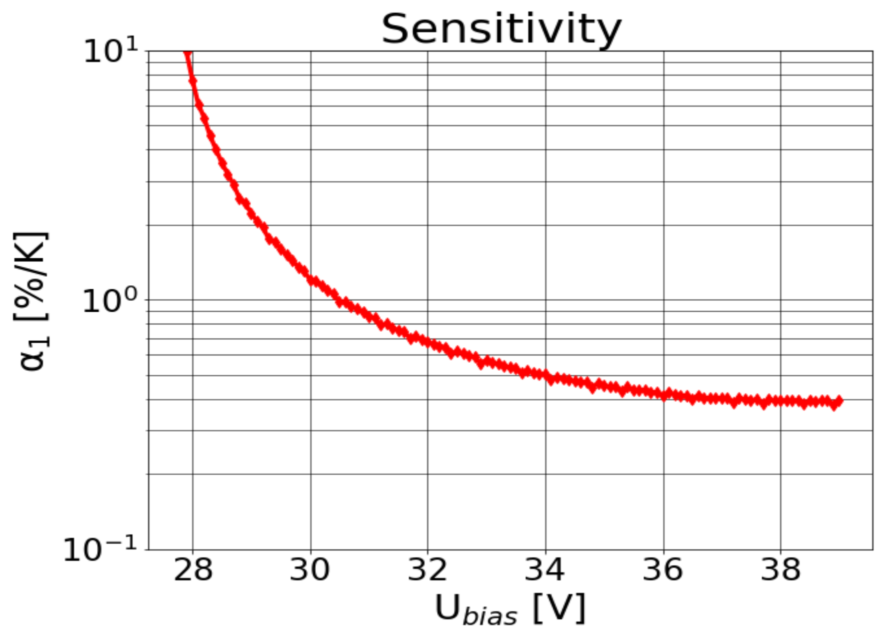
Method

- Express the T dependence of photo-current as: $\frac{dI_{photo}}{dT} = \frac{dI_{photo}}{dU} \cdot \frac{dU_{bd}}{dT}$
- A relative change in photo-current is related to a change in T by the **sensitivity**

$$\frac{\Delta I_{photo}}{I_{photo}} = \alpha_1 \cdot \Delta T$$

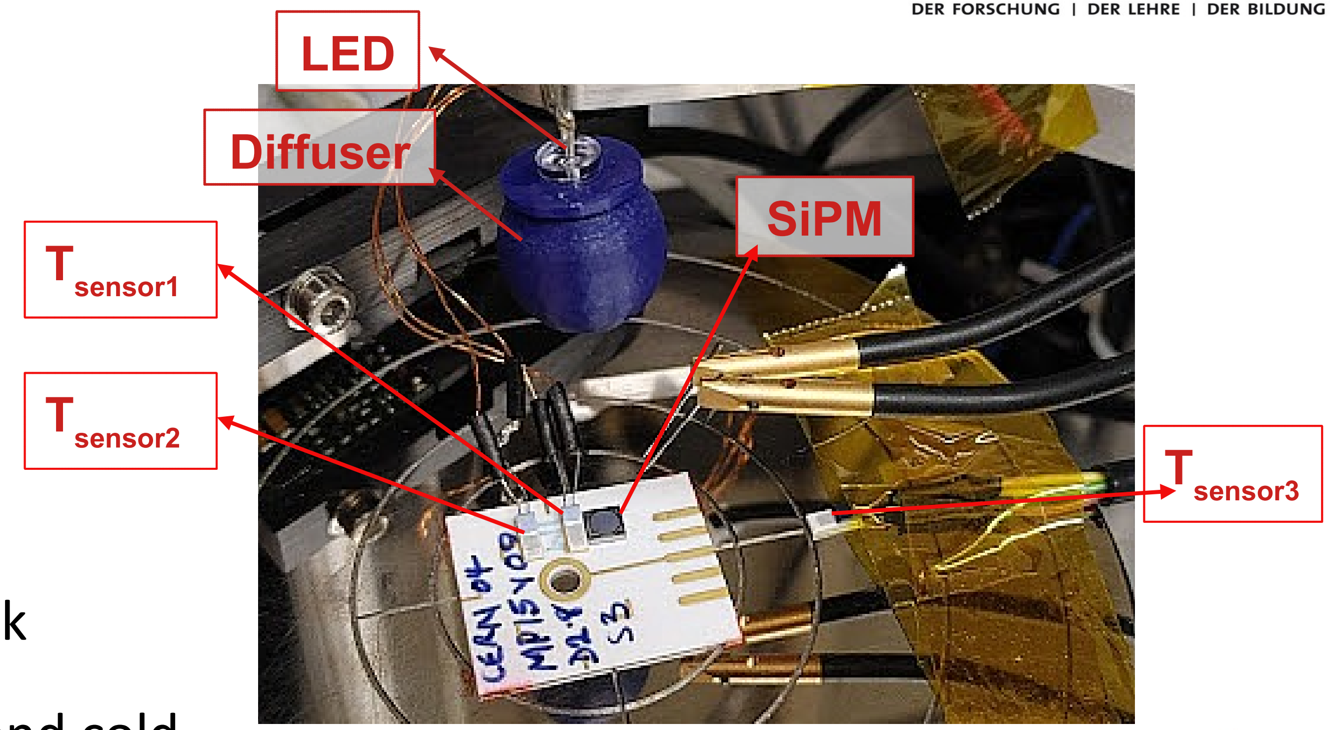
Sensitivity: $\alpha_1 = \frac{1}{I_{photo}} \cdot \frac{dI_{photo}}{dU} \cdot \frac{dU_{bd}}{dT} \left[\frac{\%}{K}\right]$

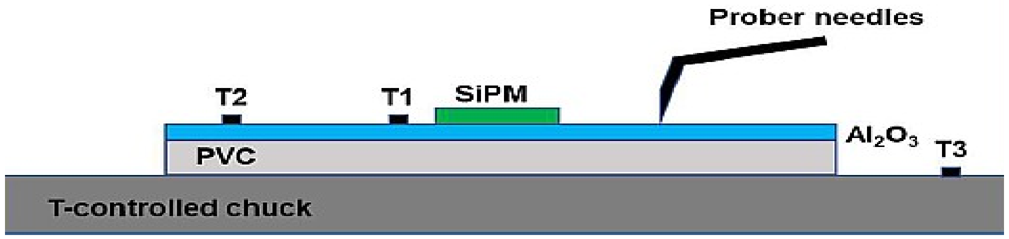
- Typical sensitivity: (0.4 – 1) %/K
- Precision data required:
  LED-stability, I-measurement, U-setting.



Setup

- SiPM KETEK *non-irradiated* (MP15V09 D2.8)
  - d_{Si}= 700 µm
  - V_{bd}= 27.5 V @25°C, C_{pix}= 18 fF, τ = 14 ns
  - Pixel size = 15 µm, 27000 pixels
- SiPM mounted on alumina (Al_2O_3) substrate:
  - d_{Al2O3}= 600 µm
- Cooling system: temperature-controlled chuck
- PVC (1.2 and 3.2 mm) between the alumina and cold chuck to emulate degraded thermal contact.
- Three T sensors (PT-100)
- Illumination: LED (470 nm)





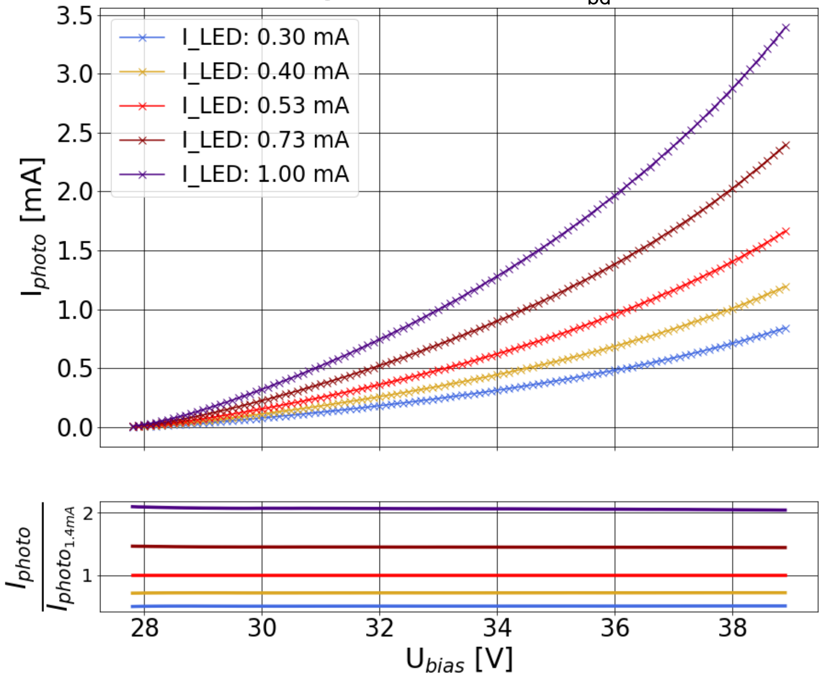
Sensitivity calibration

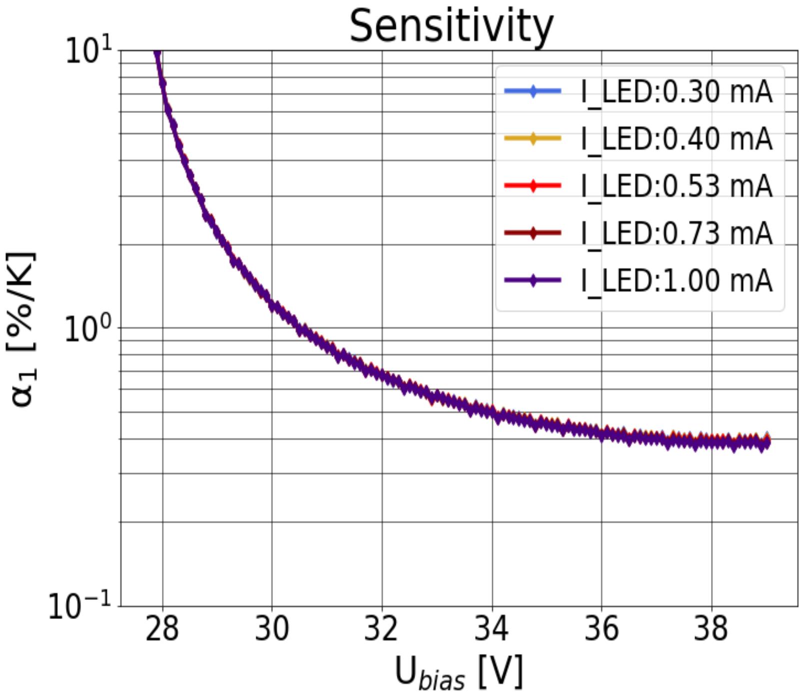
Sensitivity: $\alpha_1 = \frac{1}{I_{photo}} \cdot \frac{dI_{photo}}{dU} \cdot \frac{dU_{bd}}{dT} \left[\frac{\%}{K}\right]$

- Measure the calibration at known and stable T_{chuck}, avoiding saturation due to occupancy (~1%):

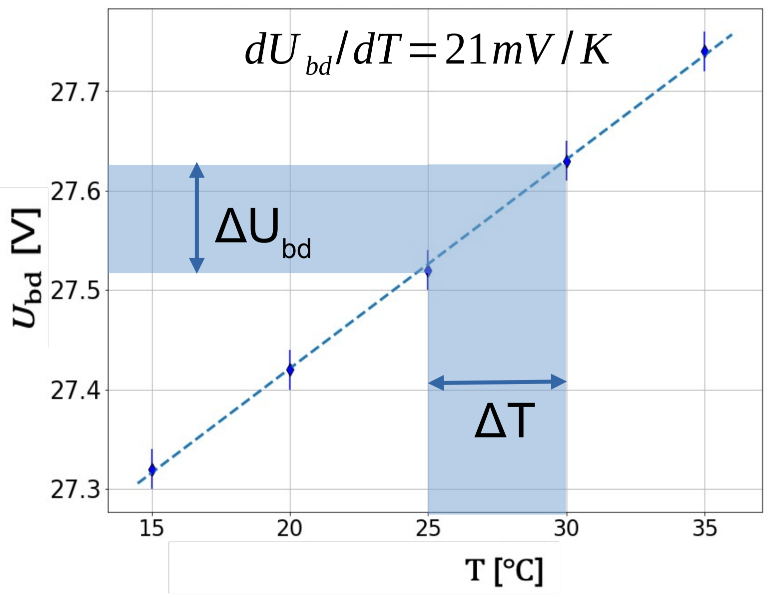
- Calibration at several LED currents leads to the same sensitivity curve.
- Measure in the T range of relevance

Calibration data: 5 LED intensities @ 25°C above V_{bd}





KETEK MP15V09



Analysis method

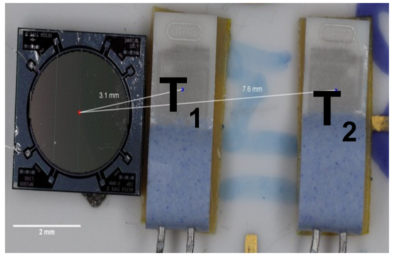
Exemplary demonstrated for measurements with:

- PVC 3.1 mm, U_{bias} = 38 V
- I_{LED} = 0.47 mA, P = 58 mW:

$$\Delta T_{SiPM(t_1,t_2)} = \frac{\left(I_{photo}(t_2) - I_{photo}(t_1)\right)}{\alpha_1 . I_{photo(t_1)}} = \frac{\Delta I_{photo}}{\alpha_1 . I_{photo(t_1)}}$$

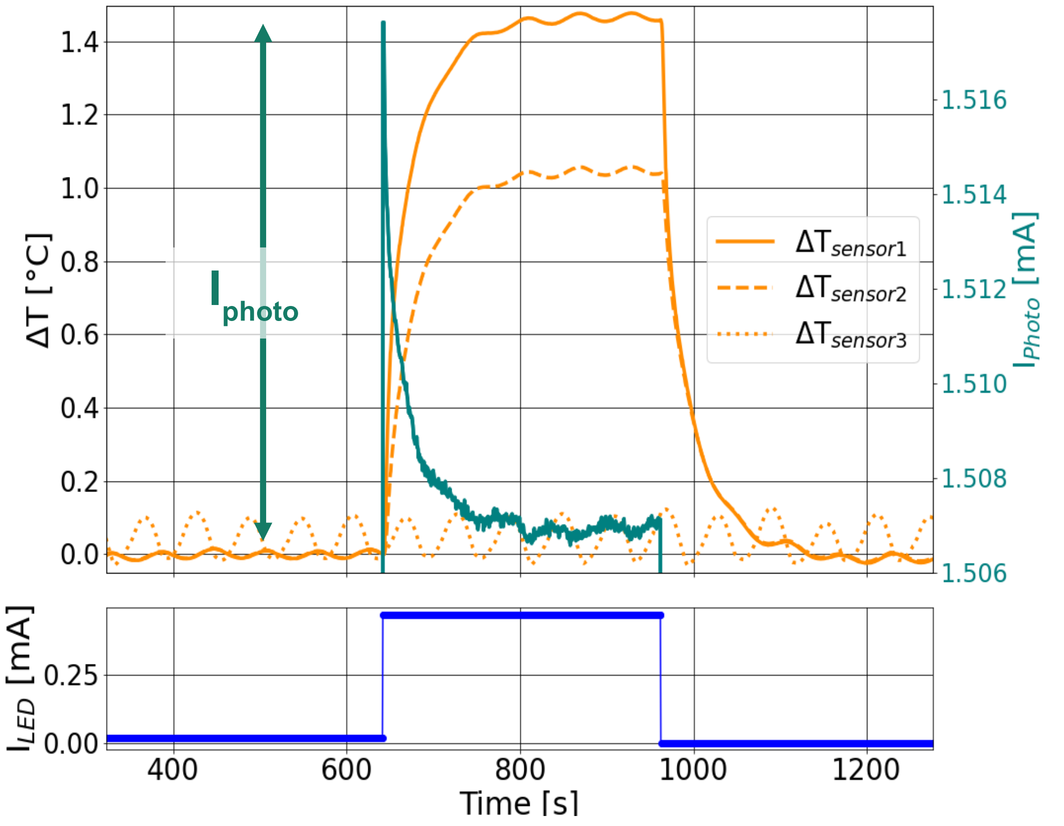
with t_1 time of the 1st measurement after switching on the LED.

- From sensitivity calibration for U_{bias} = 38 V → α_1 = 0.39 %
- Observed: $\frac{\Delta I_{photo}}{I_{photo}} = 0.73\,\%$
- Calculated: ΔT_{SiPM} = 1.87 K



- As expected from heat flow:
  $\Delta T_{sensor1}$ = 1.47 °C > $\Delta T_{sensor2}$ = 1.06 °C >> $\Delta T_{sensor3}$ = 0.04 °C

3.1 mm PVC, T_{chuck} = 25 °C



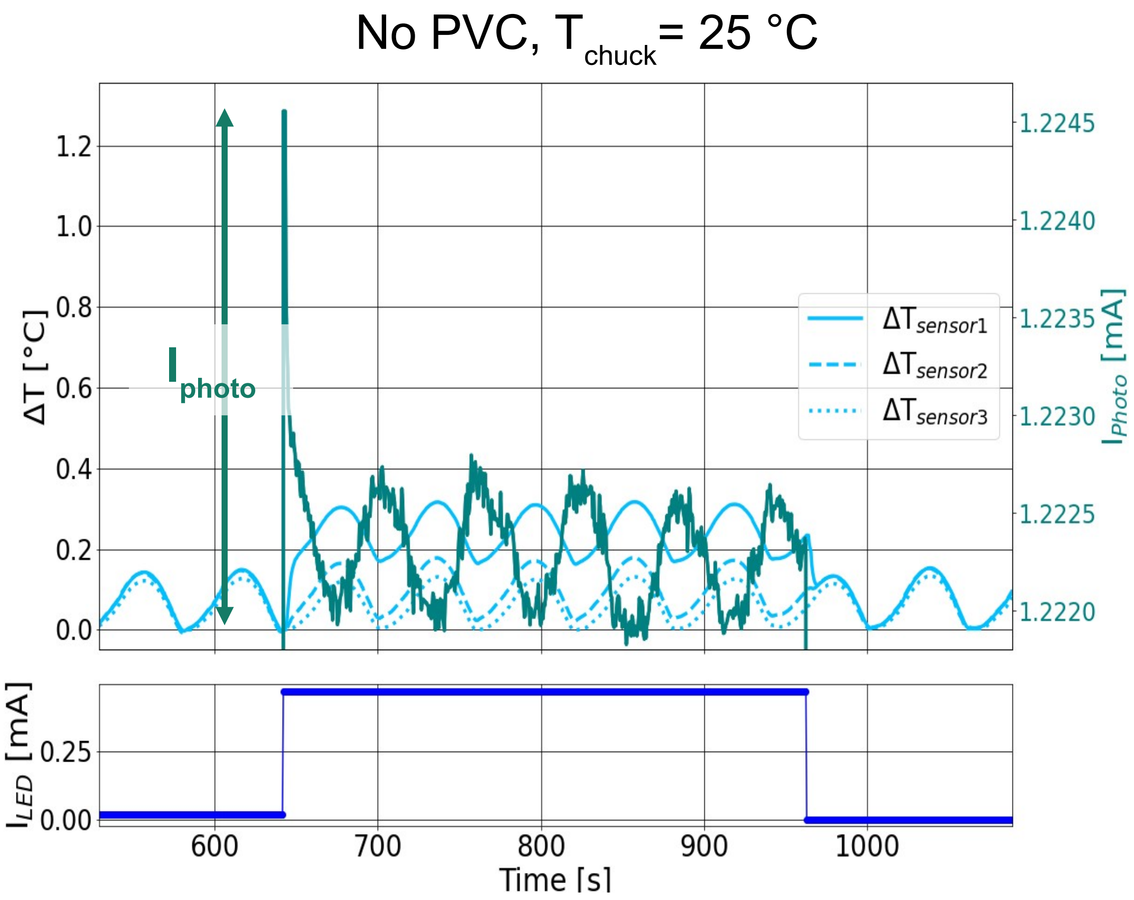
T oscillations due to feedback loop of the temperature-controlled chuck

Results for good thermal contact (no PVC)

- ΔT_{SiPM} ~0.5 K, for P = 47 mW reached in ~ 2 s.
  ΔU_{bd}= 12 mV

- T oscillations due to feedback loop of the temperature-controlled chuck:
  - $T_{sensors}$ with the same amplitude and phase
  - T_{SiPM} anti-correlated with I_{photo}, an increase in T_{SiPM} causes a decrease of I_{photo}

    → Phase shift of 180° between $T_{sensors}$ and I_{photo} demonstrates good thermal contact between chuck and SiPM multiplication region.



U_{meas} = 38 V,
I_{LED} = 0.47 mA.

Results for degraded thermal contact (1.2 mm PVC)

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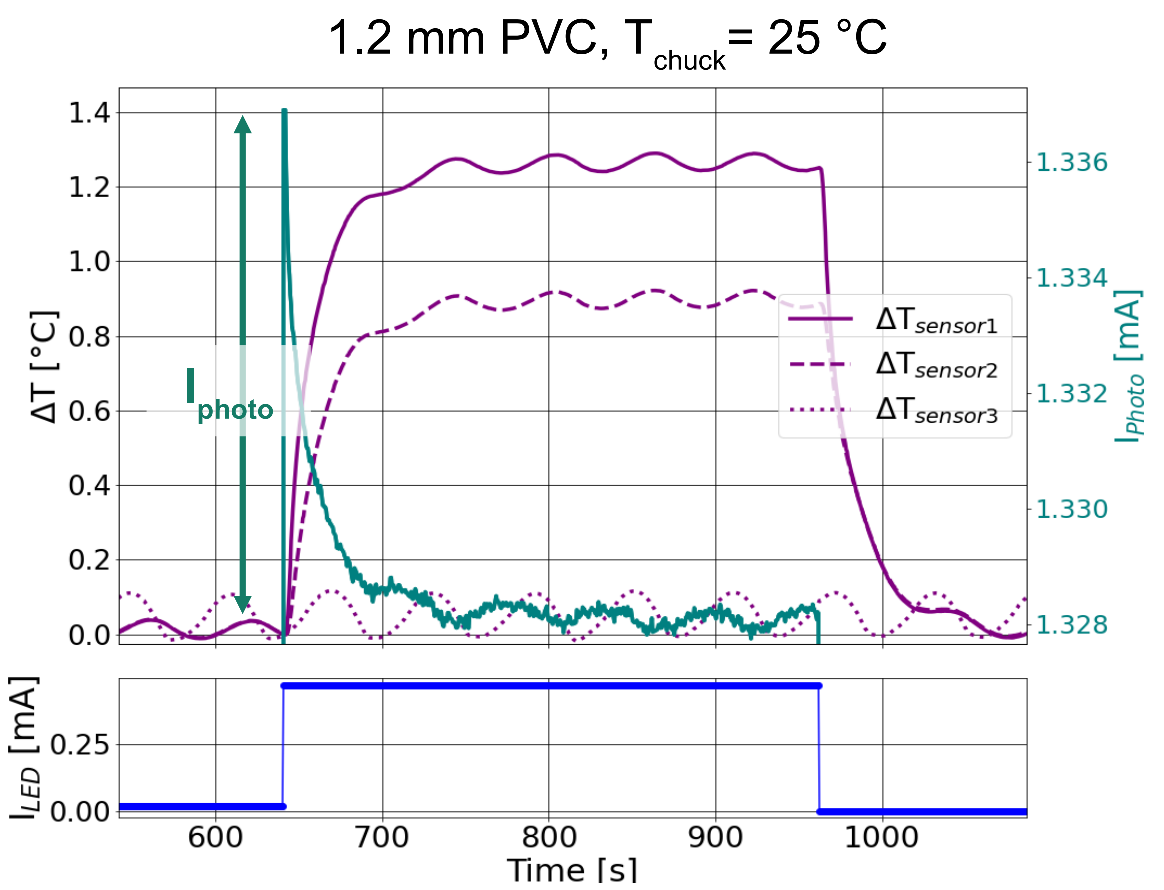
- ΔT_{SiPM} ~2 K , for P = 51 mW, reached in ~ 60 s.
  ΔU_{bd} = 37 mV
- T oscillations due to feedback loop of the temperature-controlled chuck:
- Due to the increased thermal resistance → change on the amplitude and phase of $\Delta T_{sensor1}$ and $\Delta T_{sensor2}$ relative to $\Delta T_{sensor3}$

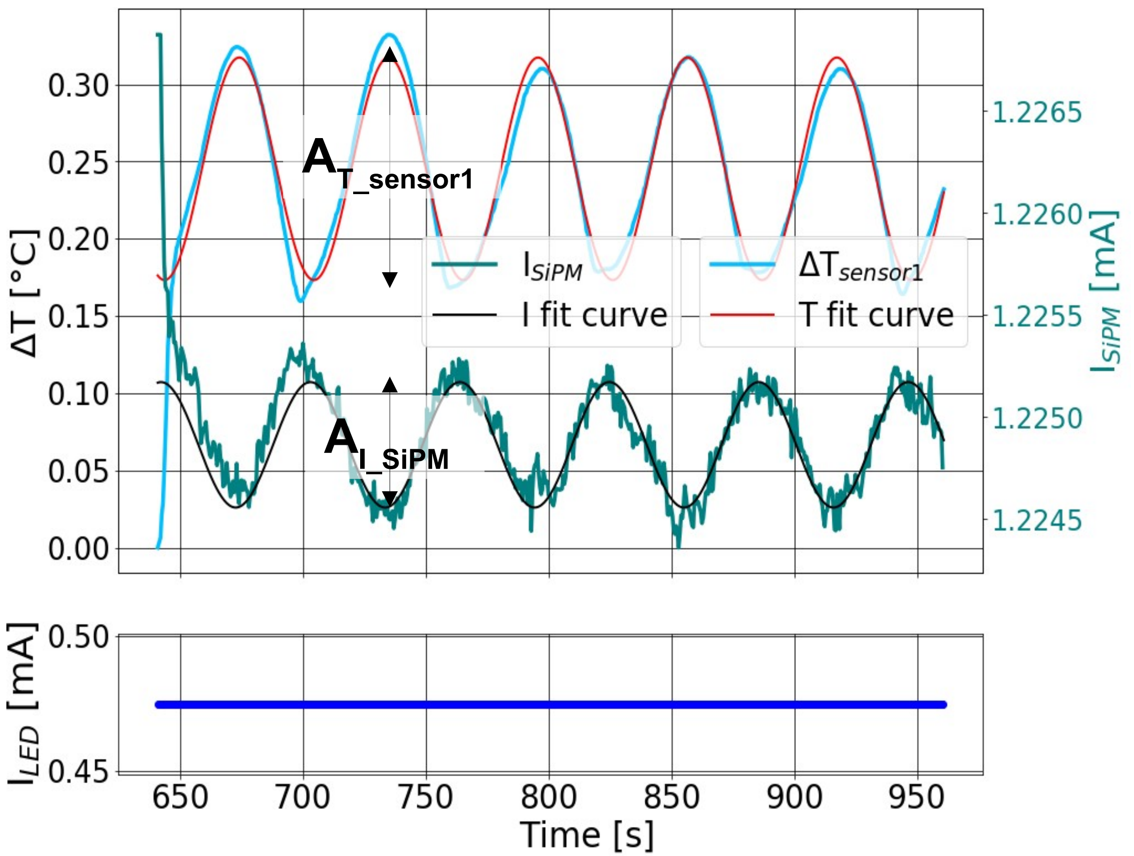


U_{meas} = 38 V,
I_{LED} = 0.47 mA.

Cross-check

- T-oscillations to check ΔT_{SiPM} determination:

No PVC: $T_{sensor1}$ and $I_{SiPM.}$ T_{chuck} = 25 °C



- No PVC and I_{photo} = 1.225 mA:
  - Fitting data to obtain amplitude of both T and I_{SiPM}

$$\alpha_2 = \frac{A_{T_{sensor\ 1}}}{A_{I_{SiPM}}} = 0.23 \frac{°C}{\mu A}$$

  - Current normalized to the maximum value of the data without PVC

$$\Delta T_{SiPM} = \alpha_2 * \Delta I_{SiPM}$$

  - For P = 47 mW → ΔT_{SiPM} = 0.62 K

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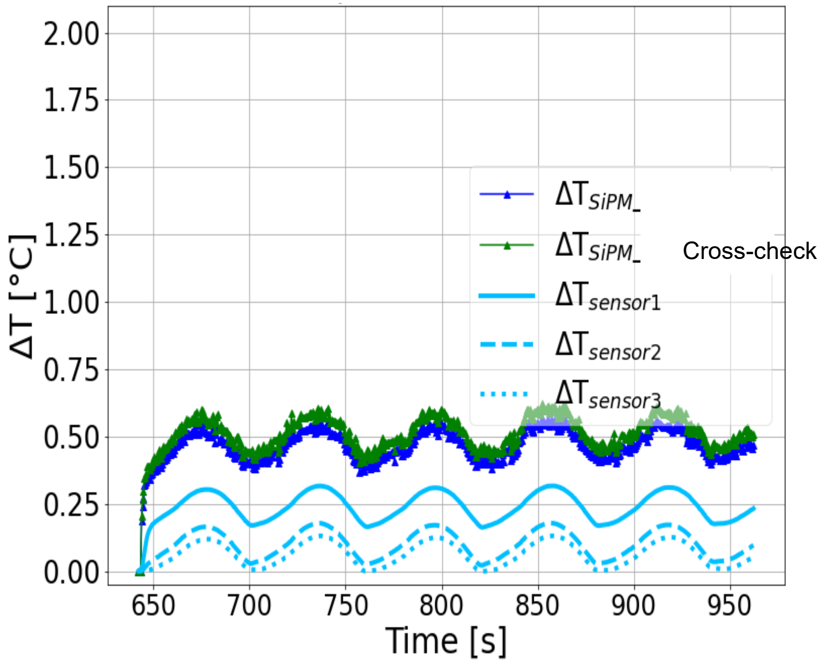
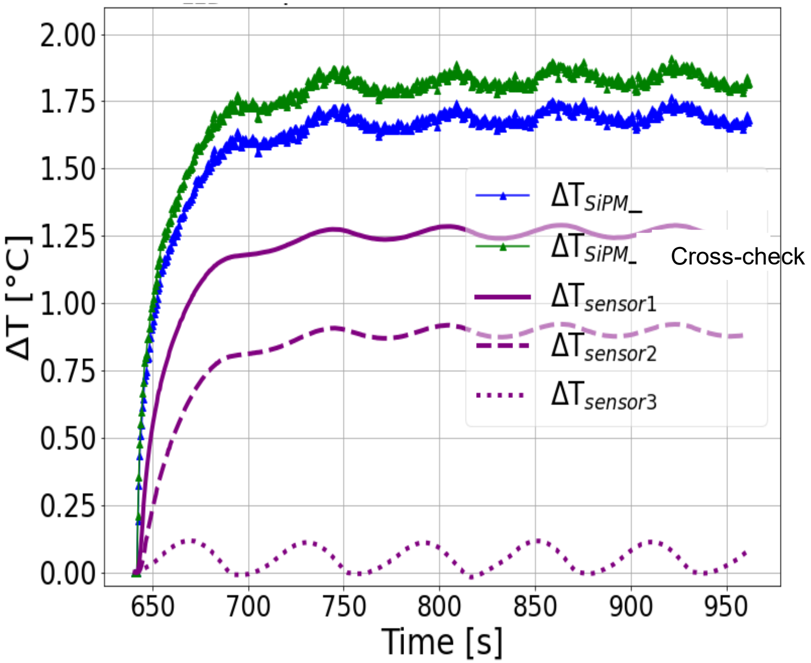
Cross-check of results

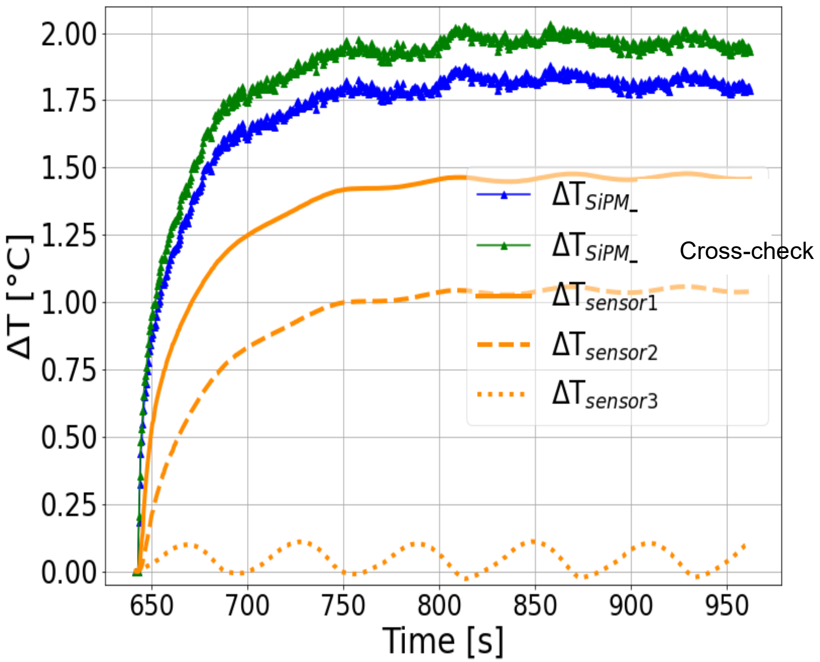
No PVC



1.2 mm PVC



3.1 mm PVC



- Both methods agree: same T_{SiPM} increase from the measured current within a 10%

U_{bias} = 38 V
T_{chuck} = 25 °C

	P [mW]	ΔT_{SiPM}[K]	Cross-check ΔT_{SiPM} [K]	Rel. difference
no PVC	46.55	0.56	0.62	10.3%
PVC (1.2 mm)	50.81	1.74	1.91	9.5%
PVC (3.1 mm)	57.68	1.87	2.03	8.6%

Conclusions: results presented are preliminary

- Development of a method to determine the heating of SiPMs from its current
- The SiPM is illuminated by a LED and $I_{SiPM}(t)$ is measured at constant U_{bias} and changing the LED current
- Heating causes an increase in U_{bd} and a decrease in I_{SiPM}. For the SiPM investigated $dU_{bd}/dT = 21 mV/K$ using calibration data.
- The method has been used to determine the temperature increase and time constants of a SiPM with P ~ 50mW, expected for instance in SiPM (MPPC HPK) irradiated to ϕ_{eq}~10^{13} cm^{-2} operated ~ 2V (OV)
- For different thermal resistances between SiPM and the temperature-controlled chuck, we obtained:
    - For good thermal contact: ΔT_{SiPM}~0.5 K, ΔU_{bd} = 12 mV
    - For degraded thermal contact (similar to SiPM mounted on PCB): ΔT_{SiPM}~2 K, ΔU_{bd} = 40 mV
    - Only minor difference in heat increase with different thickness of PVC isolation.
- Simple cross-check with a calibration obtained at high I_{LED} confirms within 10% the T_{SiPM} increase.

Conclusions: results presented are preliminary

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Many thanks for your attention!

Backup slides

Implementation of Analysis method for constant U_{meas}

1) For the calibration data $I_{cal}(U_{cal}, T_{chuck})$:

    1.1) Spline fit to obtain $U_{cal}(I_{cal})$

    1.2) Normalise $U_{cal}(I_{cal})$ to U_{meas}(fixed U_{bias})

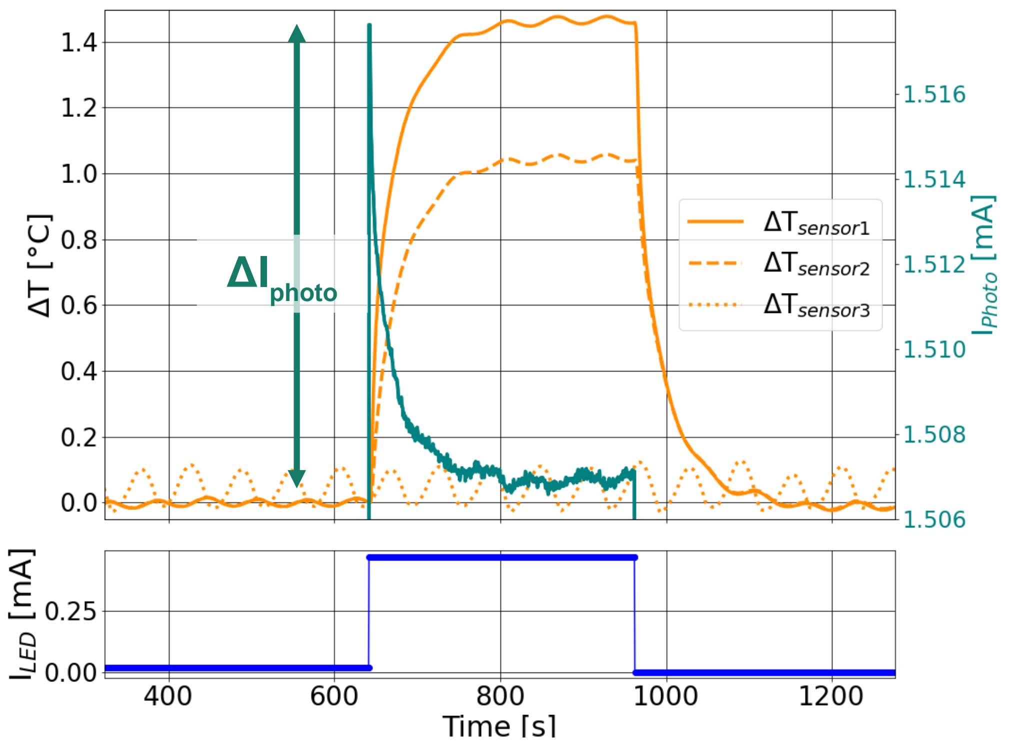
2) For the measured current $I_{meas}(t)$:

    2.1) Normalise $I_{norm}(t) = I_{meas}(t)/I_{meas}(t+)$, where t+ is the time of the 1st measurement after switching I_{LED}

3) Then calculate $\Delta U(t) = U_{meas} - U_{cal}(I_{norm}(t))$

4) Finally, determine $\Delta T_{SiPM} = \frac{\Delta U(t)}{dU_{bd}/dT}$, with $dU_{bd}/dT = 21 mV/K$

3.1 mm PVC, T_{chuck} = 25 °C



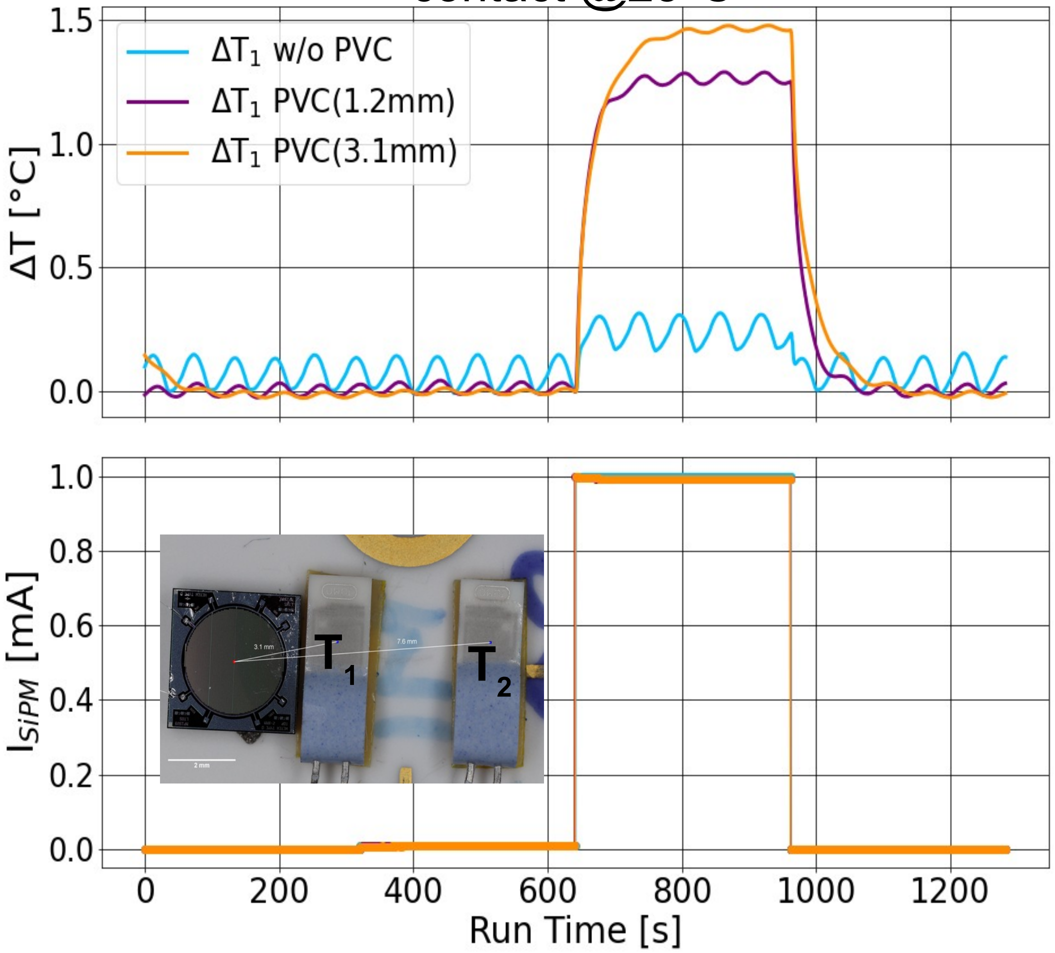
$$\frac{\Delta I_{photo}}{I_{photo}} = 0.73\%$$

U_{meas} = 38 V,
I_{LED} = 0.47 mA,
P = 58 mW.

Measurements for self-heating (I_{LED}-steps)

- I_{SIPM} and T sensors recorded with step 0.5 s
- Cycle with fixed applied Voltage:
  - 320 s with LED off (I_{dark}, I_{LED}= 0 mA)
  - 320 s with LED on (I_{dark} + $I_{photo-low}$, I_{LED}= 0.02 mA)
  - 320 s with LED on (I_{dark} + $I_{photo-high}$, I_{LED}= 0.47 mA)
  - 320 s with LED off (I_{dark} , I_{LED}= 0 mA)
- LED intensity tuned to have I_{SIPM} ~1 mA
- Measurements with efficient thermal contact: without PVC
- To degrade the thermal contact: PVC layers of thickness 1.2mm and 3.1 mm

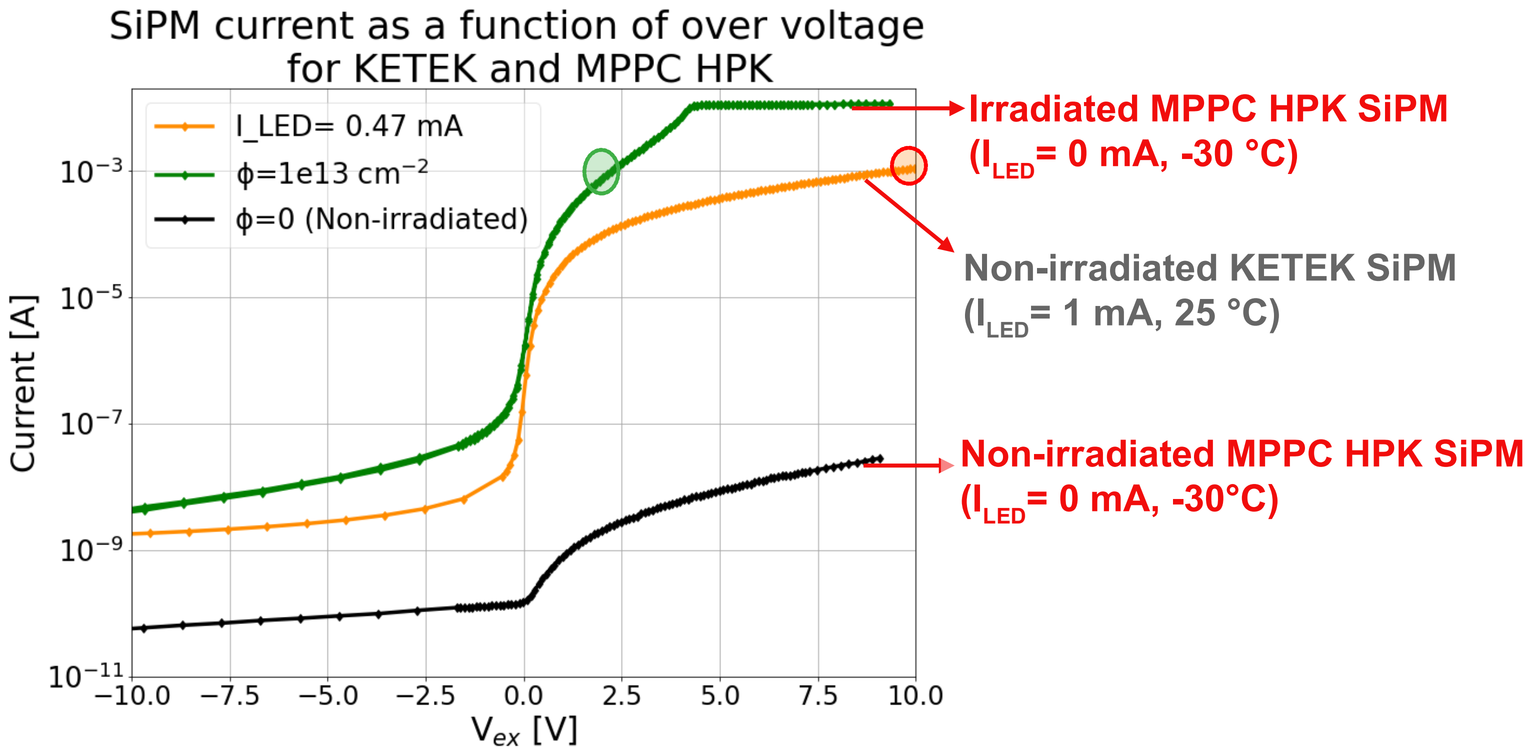
$T_{sensor1}$ and I_{SiPM} for the different thermal contact @25°C



Operation parameters

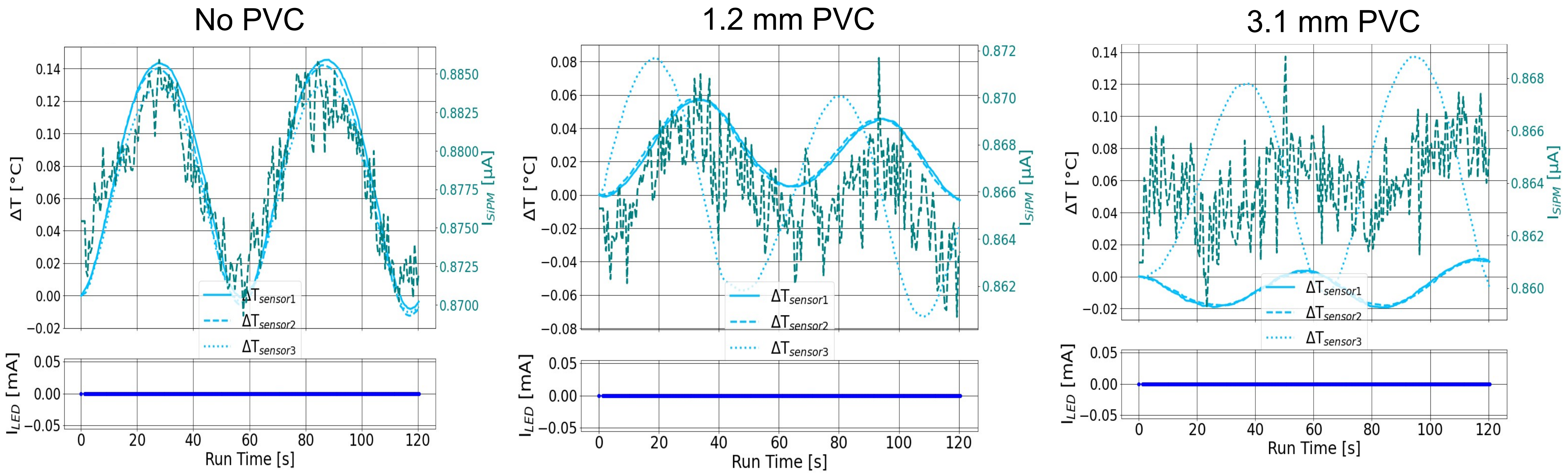
- Operate non-irradiated SiPM under LED illumination at the same current as expected for irradiated SiPM
- Dark current increase with fluence, in particular for this study we want to emulate the power dissipated in an irradiated SiPM:

- Power dissipated (P):
  - **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)



Dark current (LED = 0 mA)

- **U_{bias} = 38 V and T_{chuck} = 25 °C :**



- **For I_{dark} (current depends on thermal generation, T increase and I_{dark} increase as well):**

→ With good thermal contact $T_{sensors}$ and I_{dark} are in phase with the same amplitude

→ For bad thermal contact, due to thermal diffusion there is a change on the amplitude and phase ready $T_{sensor1}$ and $T_{sensor2}$ (on top of the alumina) compared with the sensor on the cold chuck.