HIGH-D

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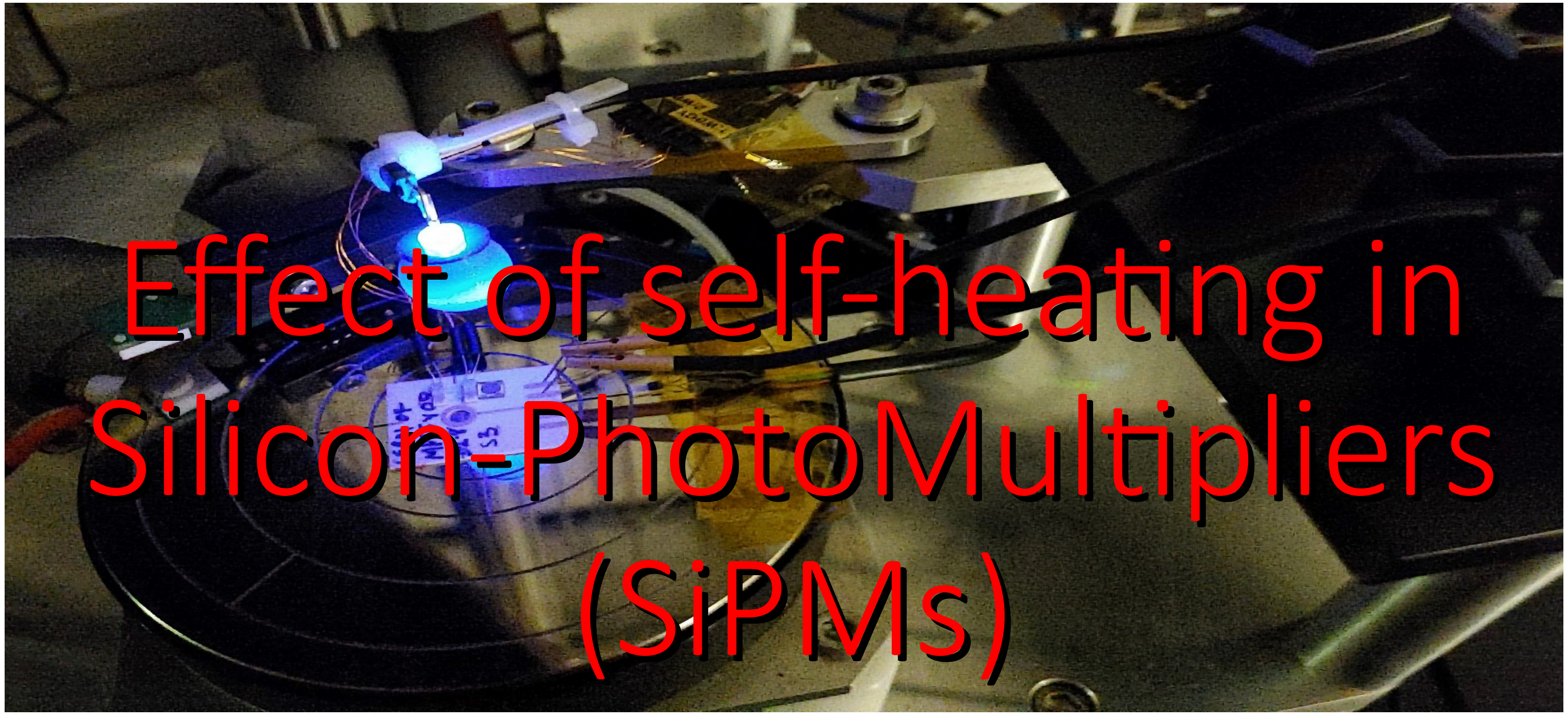

Effect of self-heating in Silicon-PhotoMultipliers (SiPMs)

C. Villalba[a], E. Garutti[a], R. Klanner[a], E. Popova[b], S. Martens[a], J. Schwandt[a]

a) University of Hamburg, Hamburg, Germany

b) National Research Nuclear University MEPhI, Moscow, Russia

carmen.villalba@desy.de

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Outline

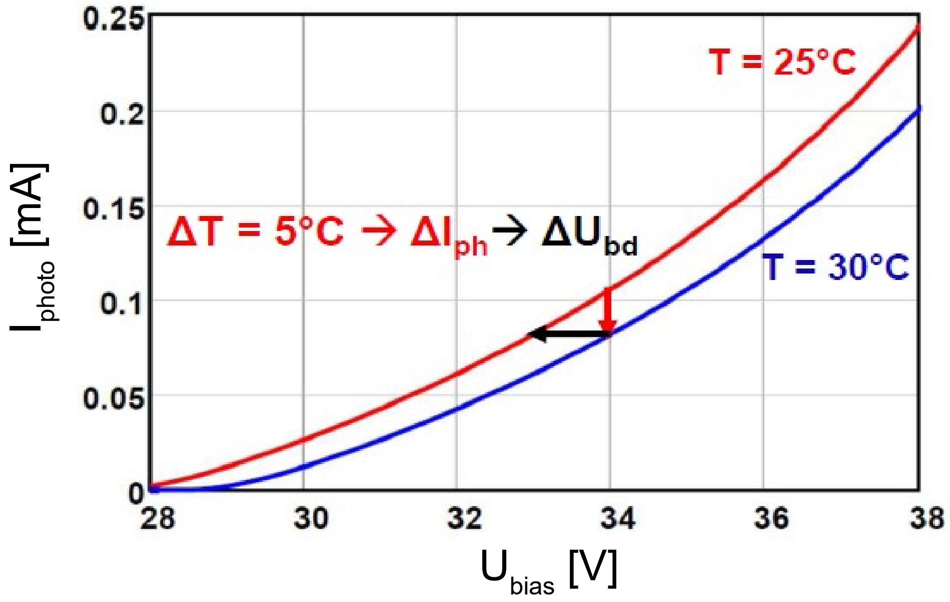
- Introduction
- Aim of the study
- Method developed
- Setup used
- First results
- Cross-check
- Summary
- Next steps

Introduction

- The most critical effect of radiation damage is the increase in dark current (I_{dark}) which is proportional to the fluence:
  - ➢ Increase in I_{dark} leads to a significant power dissipation;
  - ➢ If the power dissipated is not properly cooled, it heats the SiPM, whose performance parameters depend on temperature:

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

Photo-current at known T



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

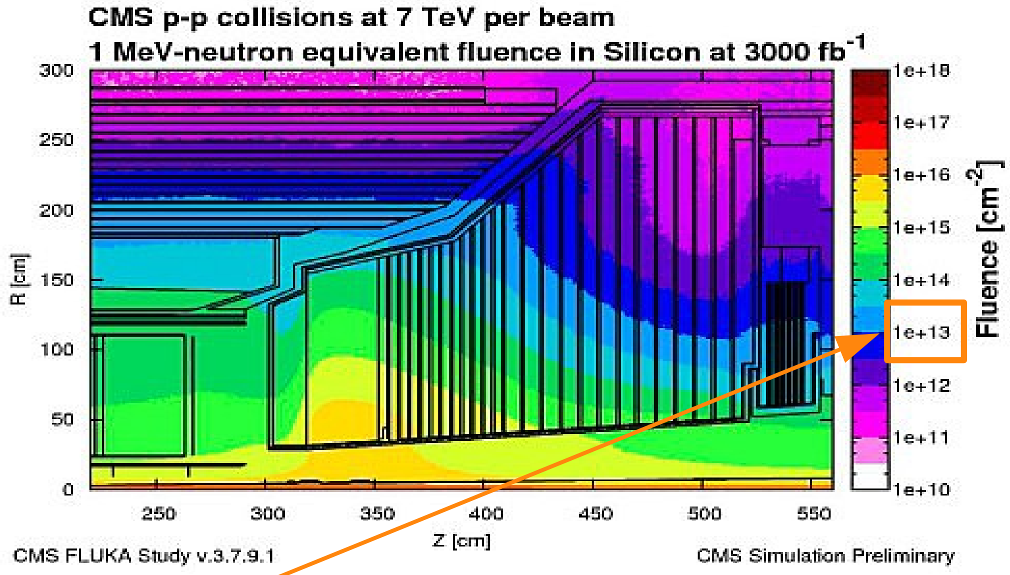
$$I_{photo}\propto PDE(T)\cdot Gain(T)$$

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

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

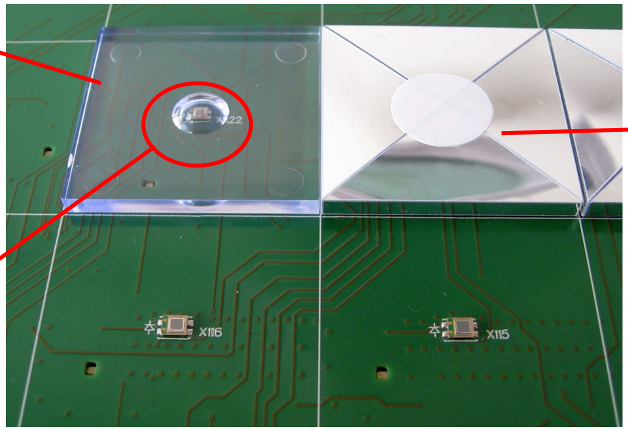
Aim

- **Develop a method to determine SiPM temperature increase induced by power dissipated (self-heating)** $\Delta T_{SiPM}(P)$ with $P = I_{SiPM} \cdot U_{bias}$

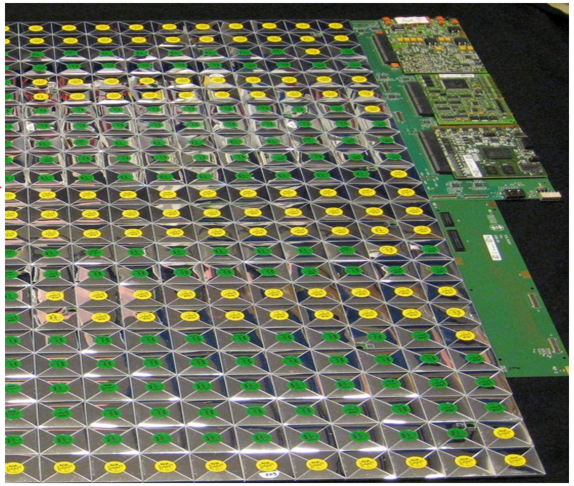


- Relevant for applications of SiPMs in:
  - High background light experiments → *High I_{photo}*
    - Light Detection and Ranging (LIDAR), astrophysics
  - High radiation environment → *High I_{dark}*
    - Satellite experiments, HL-LHC *(~1 mA, T = -30 °C, ϕ_{eq}~10^{13} cm^{-2})*

Scintillator Tile



SiPM

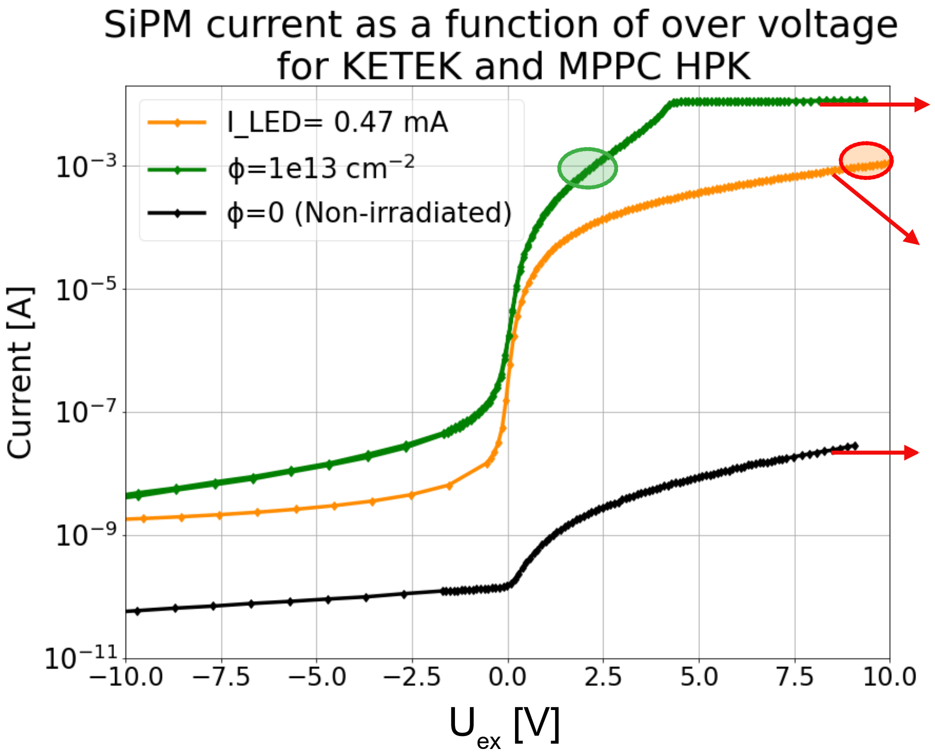


Replacement of the CMS calorimeter endcaps with the High Granularity Calorimeter (HGCAL)

Aim

- I_{dark} increases with fluence, in particular for this study we want to **emulate the power dissipated by I_{dark} in an irradiated SiPM**
  - → Operate a non-irradiated SiPM, under LED illumination, to produce the same power as expected for an irradiated SiPM

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



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

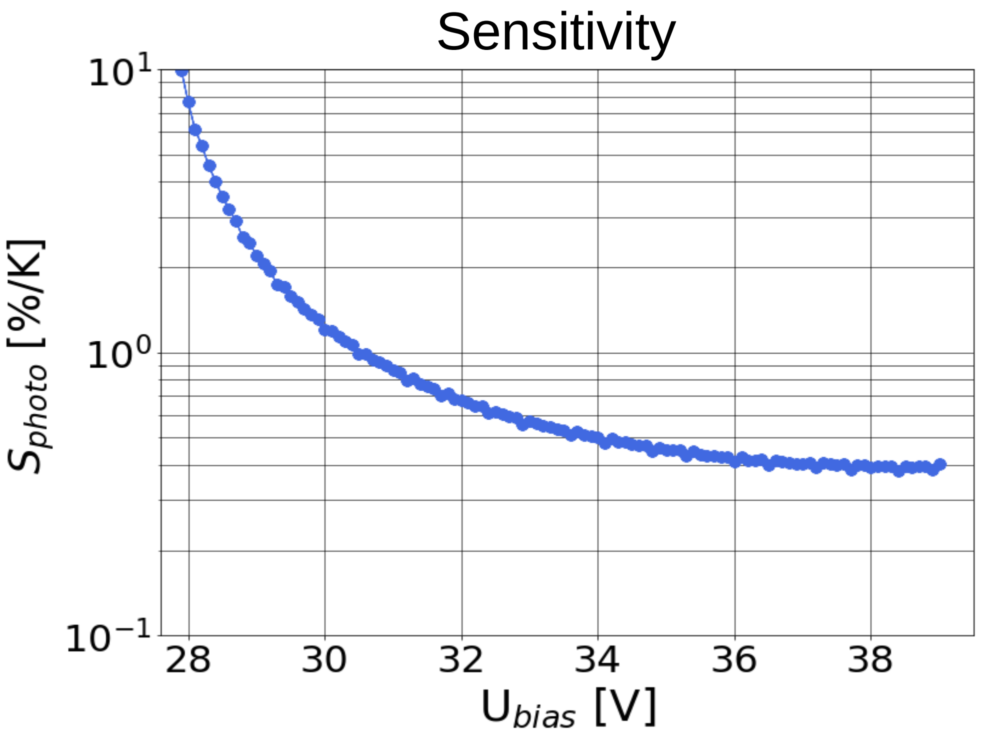
Method

- 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**

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

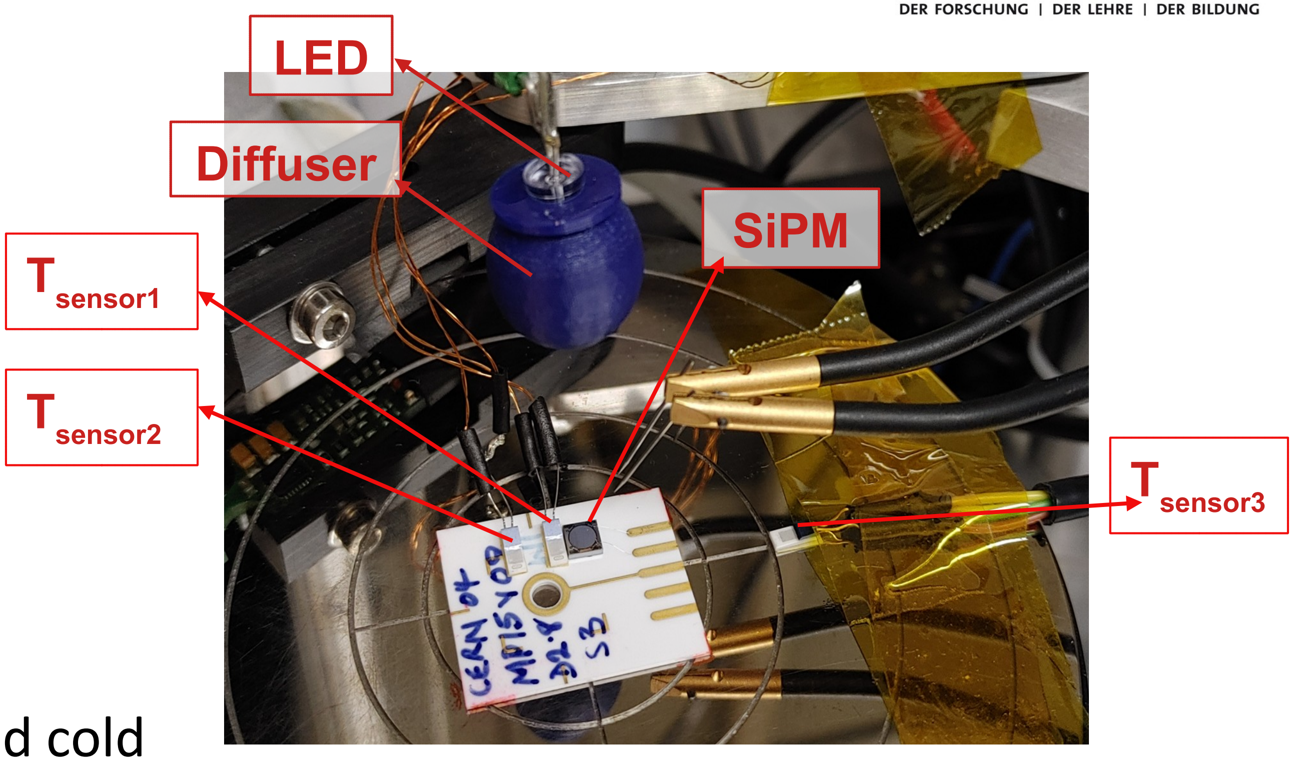
Sensitivity: $S_{photo}(U_{bias}, T_{chuck}) = \frac{1}{I_{photo}} \cdot \frac{dI_{photo}}{dU} \cdot \frac{dU_{bd}}{dT} \left[\frac{\%}{K}\right]$

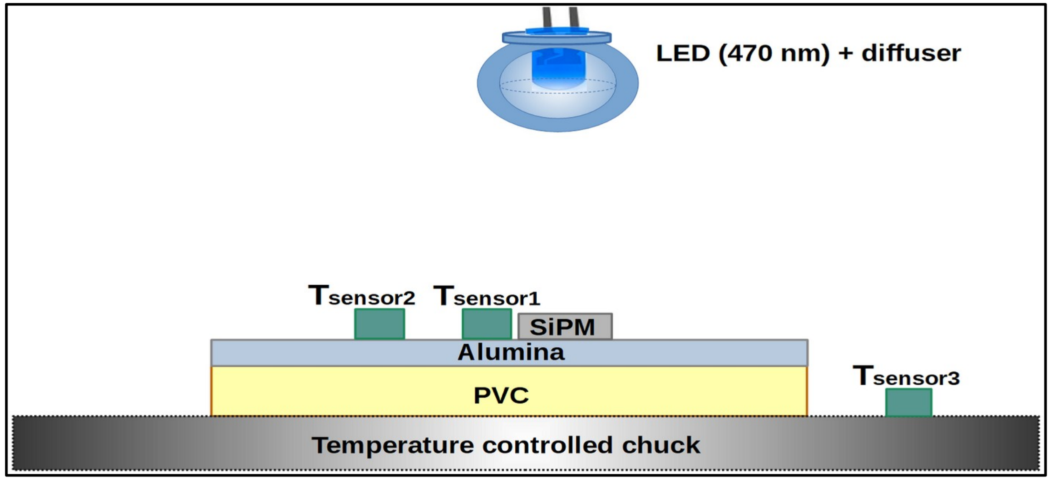
- Typical sensitivity: (0.4 – 1) %/K
- Precision data required:
  LED-stability, I-measurement, U-setting.
- Extract T_{SiPM} from I_{SiPM} in a cycle at constant U_{bias} and changing light intensity.
- Lucchini et al propose a method with constant illumination, and T_{SiPM} is derived from the changes in I_{SiPM} when the U is switched on, or thermal conditions change by switching on a fan. [doi:10.1016/j.nima.2020.164300]



Setup

- SiPM KETEK *non-irradiated* (MP15V09 D2.8)
  - d_{Si} = 700 µm
  - U_{bd} = 27.5 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
- PVC (1.2 and 3.1 mm) between the alumina and cold chuck to emulate degraded thermal contact.
- Three 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)

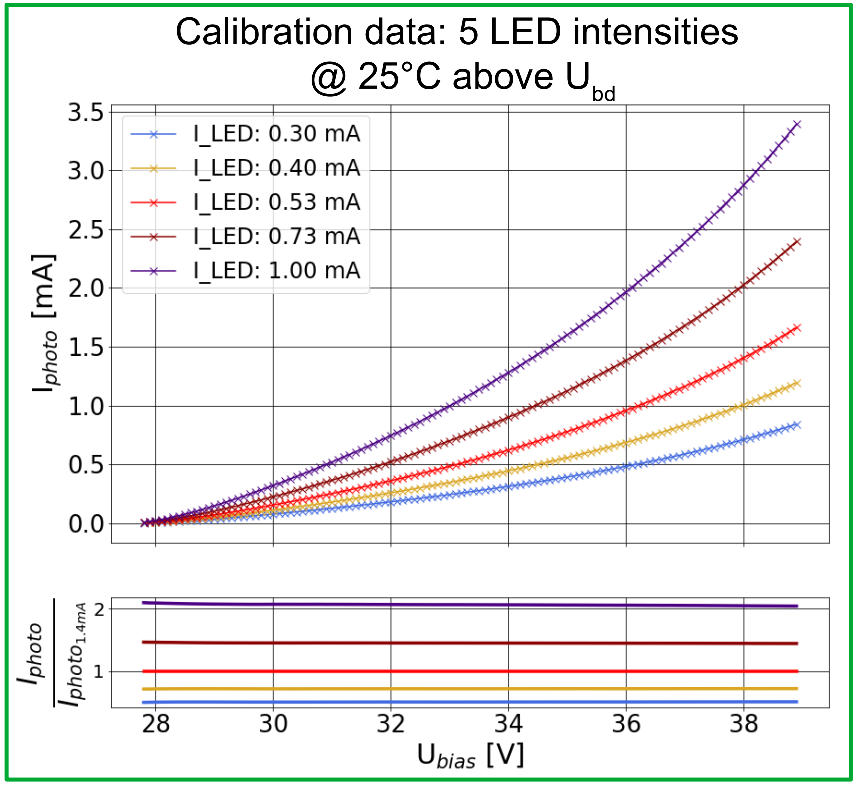


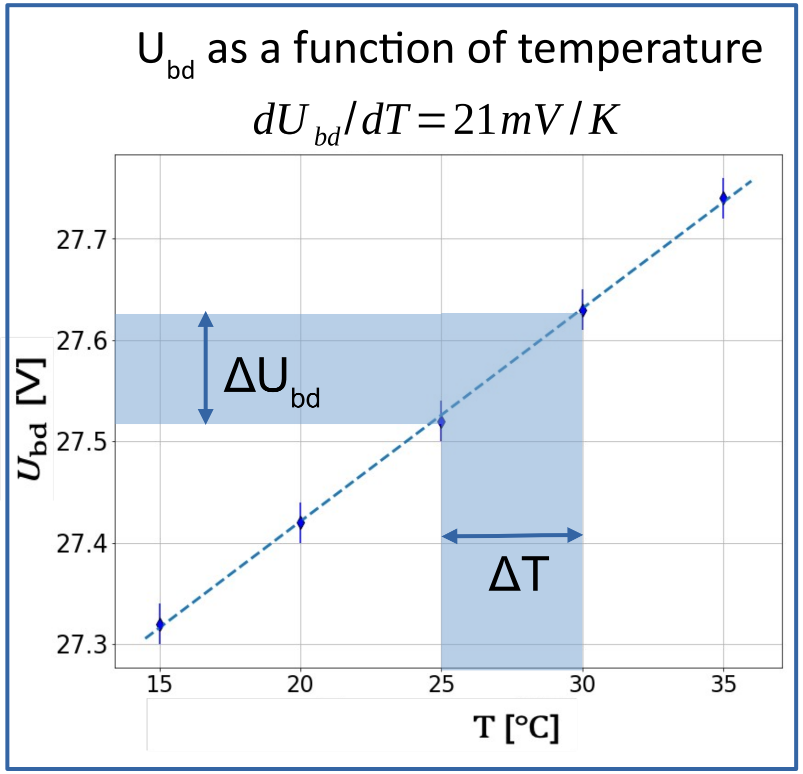


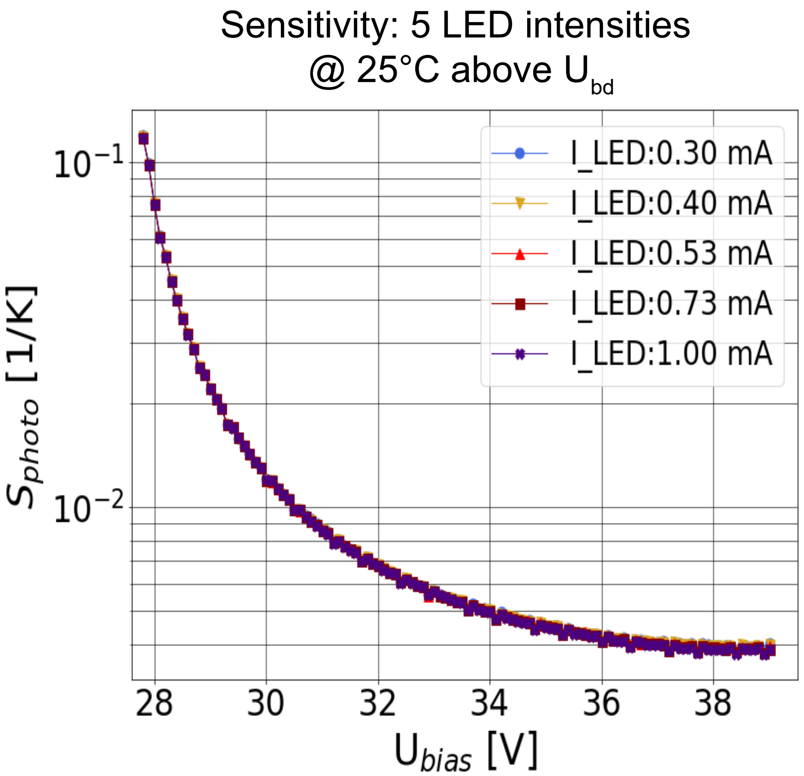
Sensitivity calibration

Sensitivity: $S_{photo}(U_{bias}, T_{chuck}) = \frac{1}{I_{photo}} \cdot \frac{dI_{photo}}{dU} \cdot \frac{dU_{bd}}{dT} \left[\frac{\%}{K}\right]$

- Calibration data is measured at known and stable T_{chuck}, avoiding saturation due to occupancy (~1%):
- Calibration data at several LED currents leads to the same sensitivity curve.
- Measure in the T range of relevance







Results for degraded thermal contact (3.1 mm PVC)

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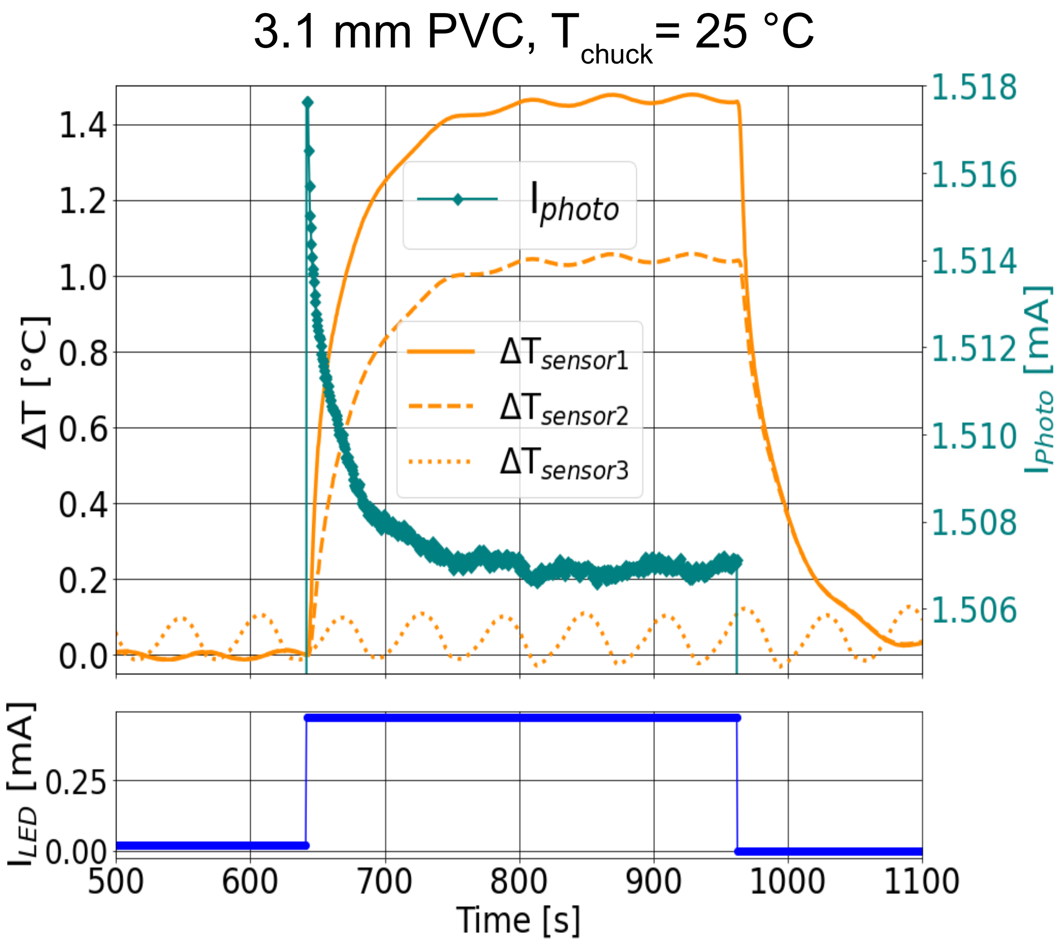
- U_{bias} = 38 V, I_{LED} = 0.47 mA, P = 58 mW:

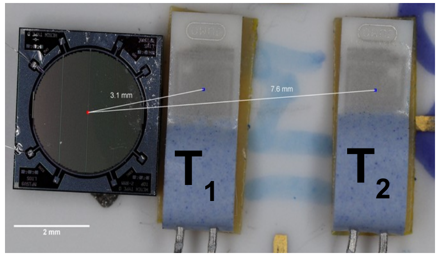
$$\Delta T_{SiPM} = \frac{\Delta I_{photo}}{S_{photo} \cdot I_{photo}}$$

- From sensitivity calibration for U_{bias} = 38 V → $S_{photo} = 0.39\ \%$
- Observed: $\frac{\Delta I_{photo}}{I_{photo}} = 0.73\ \%$
- Calculated: ΔT_{SiPM} = 1.87 K, reached in ~ 60 s, ΔU_{bd} = 39 mV



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

- As expected from heat flow: $\Delta T_{sensor1} > \Delta T_{sensor2} >> \Delta T_{sensor3}$



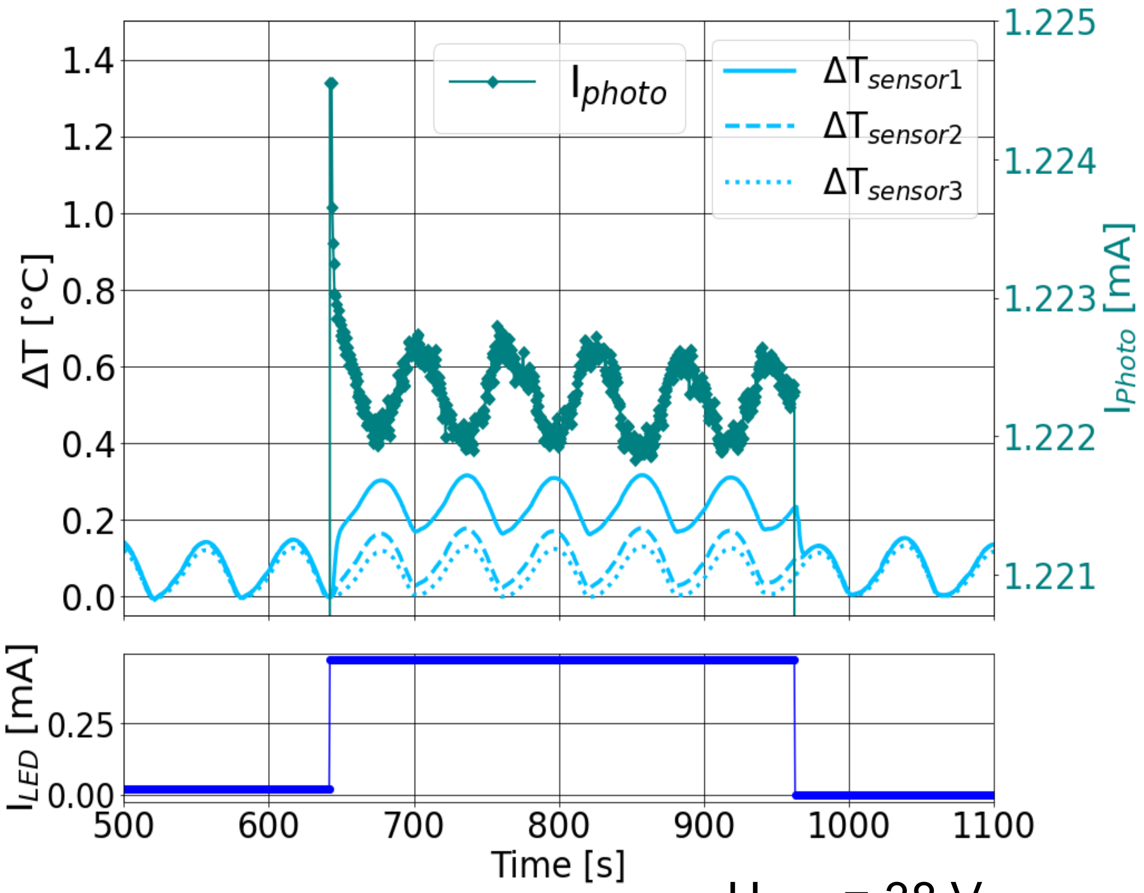
- Due to the increased thermal resistance → change of the amplitude and phase of $\Delta T_{sensor1}$ and $\Delta T_{sensor2}$ relative to $\Delta T_{sensor3}$

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.

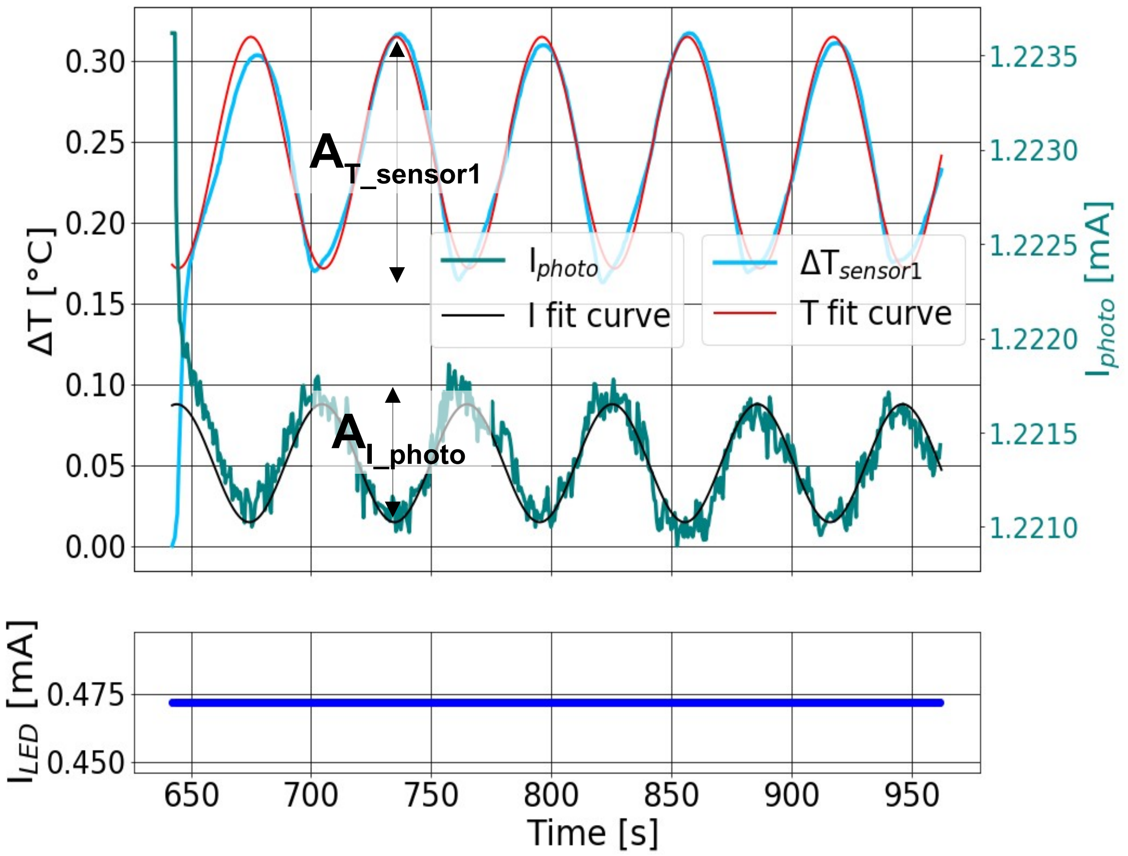


U_{meas} = 38 V,
I_{LED} = 0.47 mA.

Cross-check

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

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



- No PVC and I_{photo} = 1.22 mA:
  - Fitting data to obtain amplitude of both T and I_{photo}

$$\alpha = \frac{A_{T_{sensor\,1}}}{A_{I_{photo}}} = 0.23 \left[\frac{K}{\mu A} \right]$$

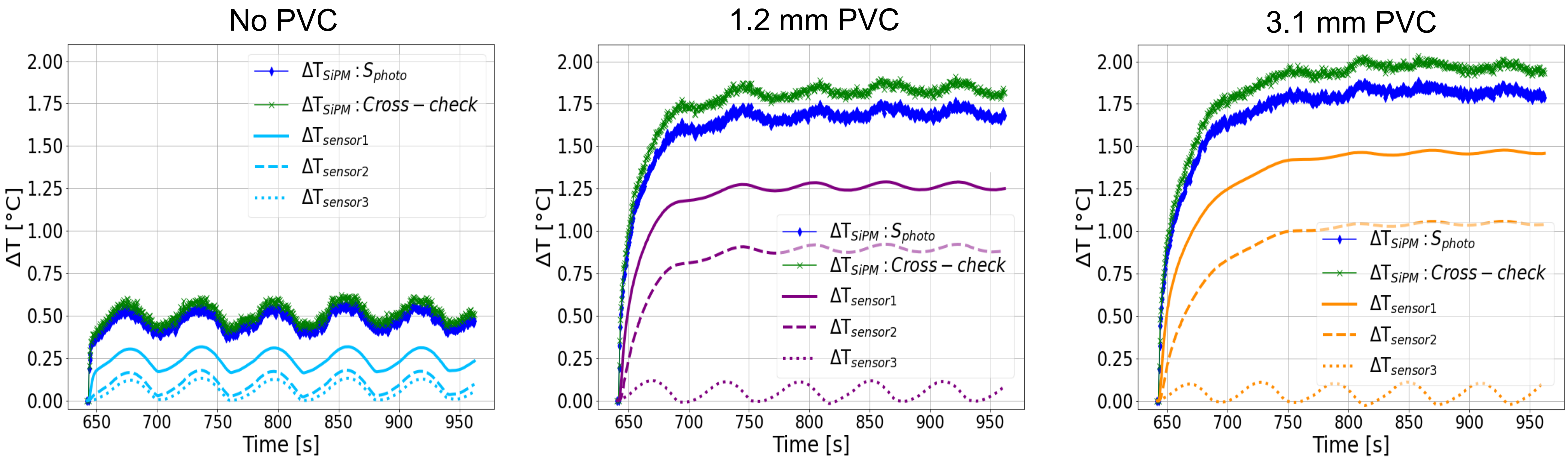
  - Current normalized to the maximum value of the data without PVC

$$\Delta T_{SiPM} = \alpha \cdot \Delta I_{photo}$$

  - For good thermal contact, P = 47 mW

    → ΔT_{SiPM} = 0.62 K

Summary of preliminary results



- Sensitivity method and cross-check agree: same ΔT_{SiPM} from the measured current within 10%

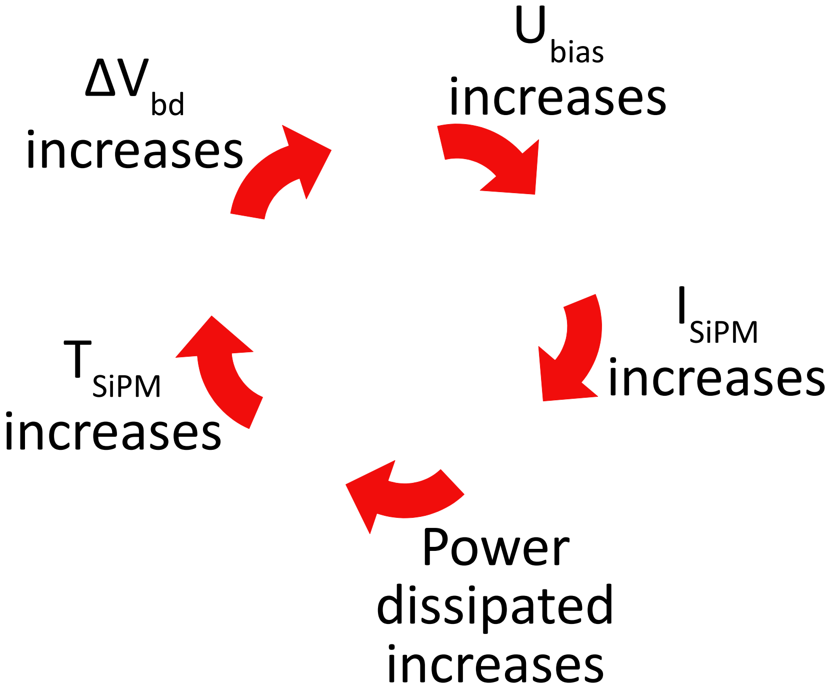
U_{bias} = 38 V T_{chuck} = 25 °C	P [mW]	ΔU_{bd} [mV]	ΔT_{SiPM} [K]	Cross-check ΔT_{SiPM} [K]	Rel. difference
no PVC	46.55	12	0.56	0.62	10.3%
PVC (1.2 mm)	50.81	37	1.74	1.91	9.5%
PVC (3.1 mm)	57.68	39	1.87	2.03	8.6%

~SiPM on top of cooling system → no PVC

~ SiPM mounted on PCB → PVC (1.2 mm), PVC (3.1 mm)

Implications:

- 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.

Next Steps:

- Extend the method to determine T_{SiPM} using I_{dark} during the cool down phase after switching off the LED
- Study the self-heating as function of dissipated power
- Investigate the self-heating of irradiated SiPMs
- Compare the measurements to predictions from thermal simulations

Next Steps:

- Extend the method to determine T_{SiPM} using I_{dark} during the cool down phase after switching off the LED
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Many thanks for your attention!

Backup slides

Heat in the multiplication region (single Geiger discharge)

Data for MP15V09 D2.8:

- C_{pix} = 18 fF
- V_{bias} = 38 V
- V_{bd} = 27.5 V
- r_{dis} = 5 µm
- d = 2 µm
- # Pixels = 27367

⇨ Heat of 1 discharge ΔT = 24 mK

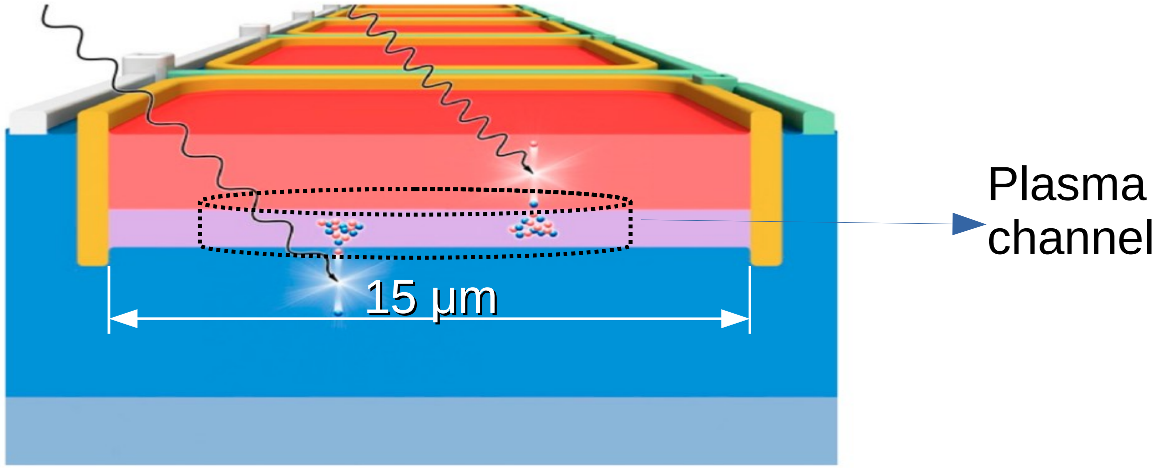
⇨ Heat for 0.3% of the pixels ΔT ~ 2 K

- Geiger discharge through a plasma channel;
- Temperature change:

$$\Delta T_{dis} = W_d/(c_{Si} \cdot M_{Si}) \equiv \frac{1}{2} \frac{C_d \cdot (V_{bias}^2 - V_{off}^2)}{r_{dis}^2 \cdot \pi \cdot d \cdot \rho_{Si} \cdot c_{Si}},$$

Thermal parameters: Different sources give quite different values

	k [W/(cm K)]	c [J/(g K)]	D [cm^2/s]	ρ [g/cm^3]
Si	1.5	0.7	0.92	2.328



Implementation of Analysis method for constant U_{meas}

1) The I_{SiPM} is normalised to I_{cal} (U_{cal}, T_{chuck}): $I_{cal}^{norm} = \frac{I_{cal}(U_{cal}, T_{chuck})}{I_{cal}(U_{bias}, T_{chuck})}$.

2) A cubic spline fit is used to obtain U : $U_{spl}(I_{cal}^{norm})$

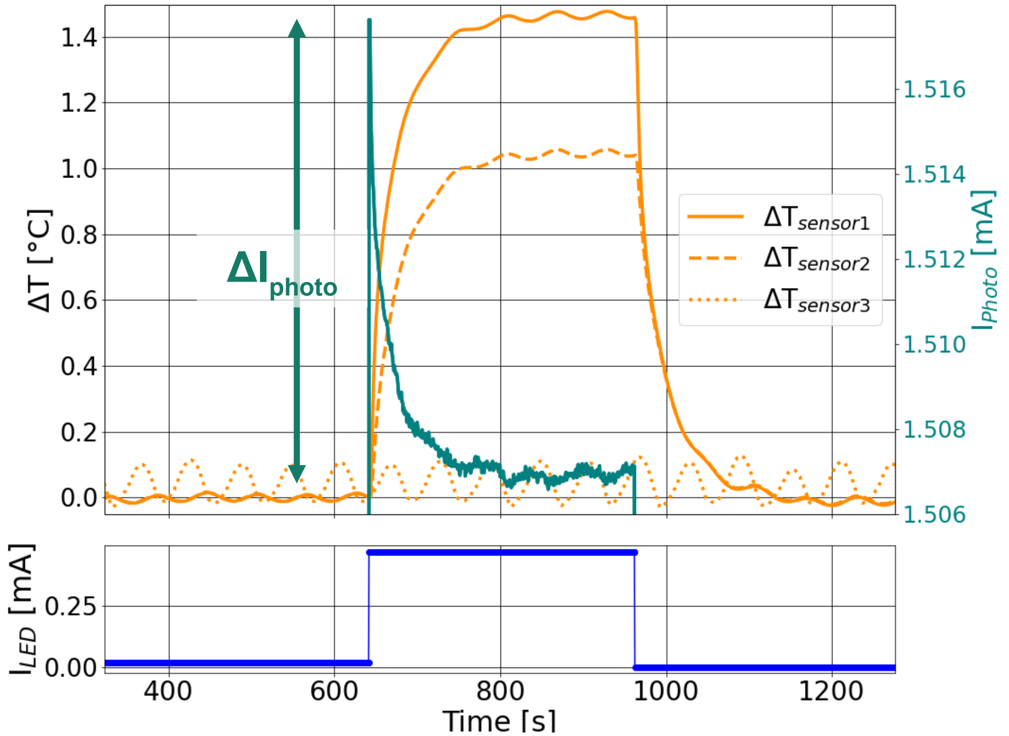
3)The measured $I_{SiPM(t)}$ is normalised:

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

4) The change in current is converted into a voltage change using $\Delta U(t) = U_{bias} - U_{spl}(I_{SiPM}^{norm}(t))$

5) And the increase in temperature is determined using: $\Delta T_{SiPM} = \frac{\Delta U(t)}{dU_{bd}/dT}$, $dU_{bd}/dT = 21 mV/K$

3.1 mm PVC, T_{chuck}= 25 °C



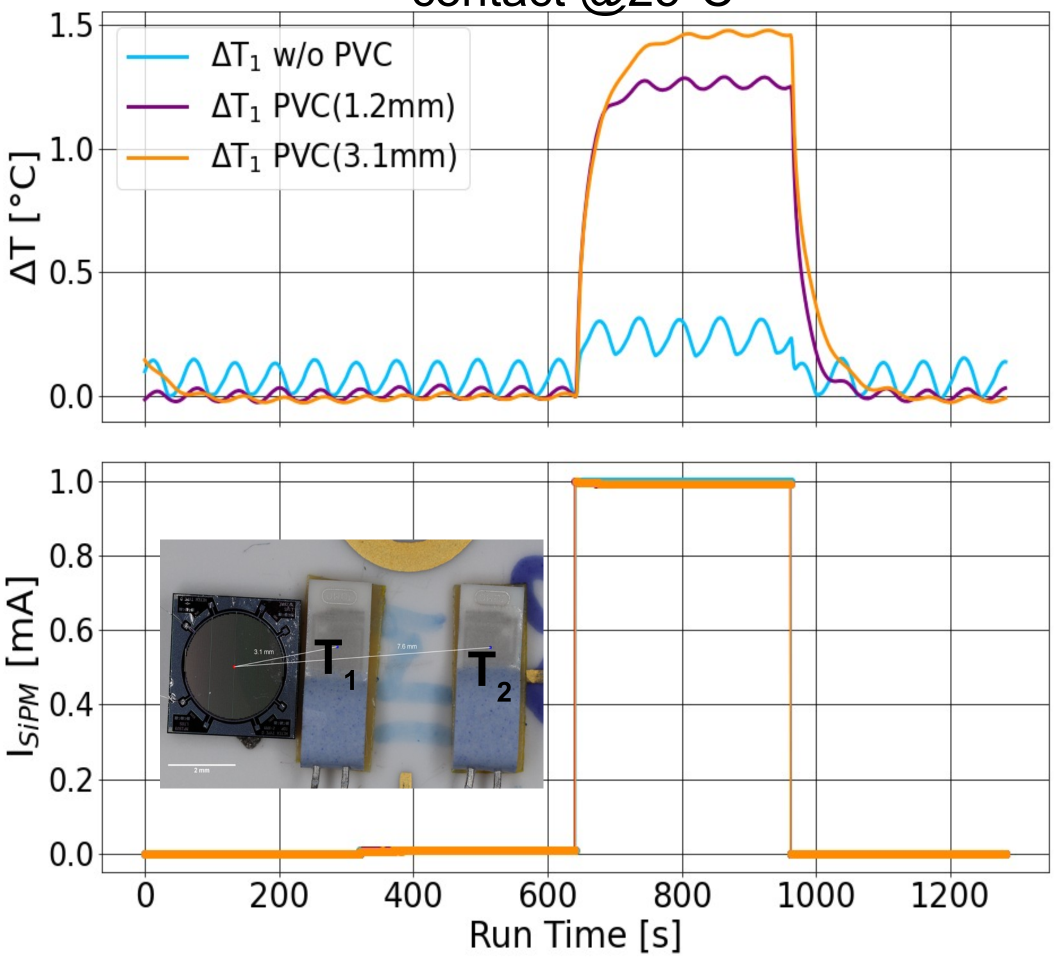
$\frac{\Delta I_{photo}}{I_{photo}} = 0.73\%$

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 $I_{SIPM} \sim 1$ 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



Results for degraded thermal contact (1.2 mm PVC)

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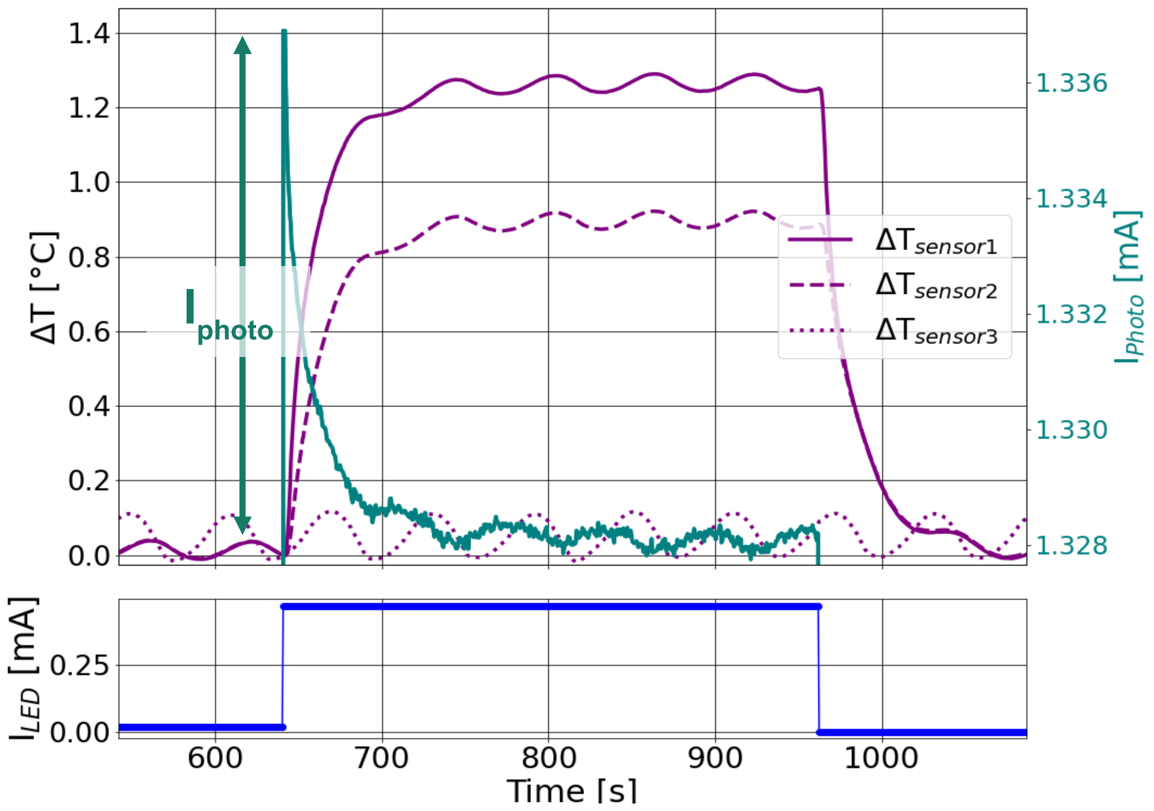
- ΔT_{SiPM}~2 K , for P = 51 mW, reached in ~ 60 s.
  ΔU_{bd}= 37 mV

$$\Delta T_{SiPM} = \frac{\Delta I_{photo}}{S_{photo} \cdot I_{photo}}$$

- 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 $\Delta T_{sensor3}$

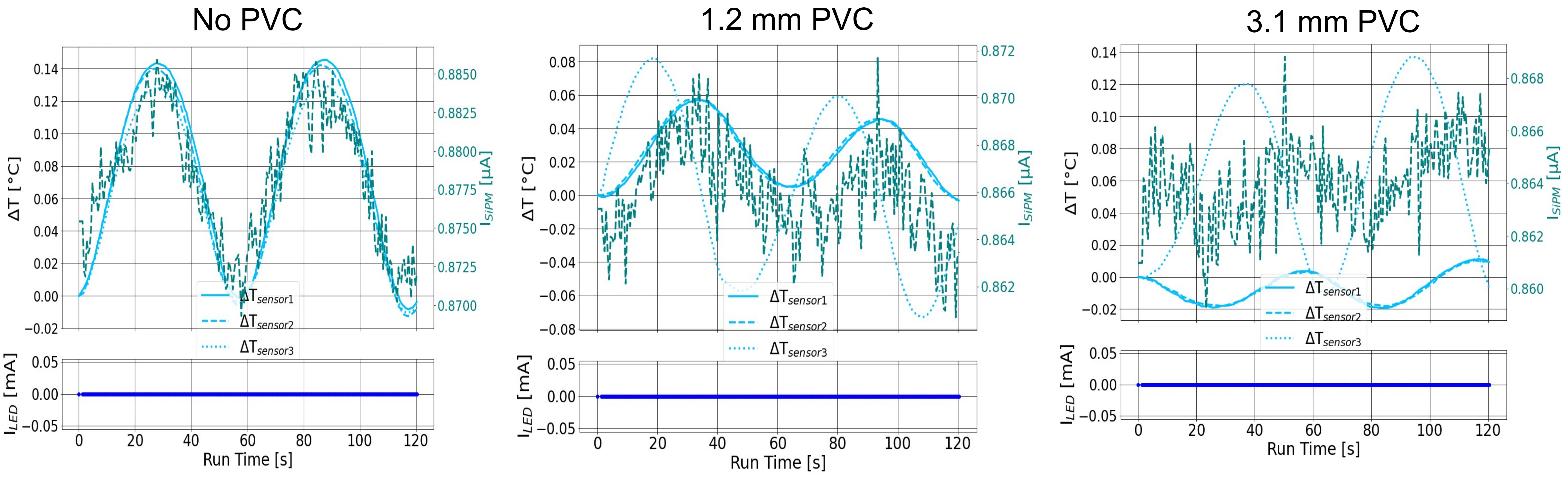
1.2 mm PVC, T_{chuck}= 25 °C



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

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.