Direct detection of long-duration intense X-ray flux with SiPM

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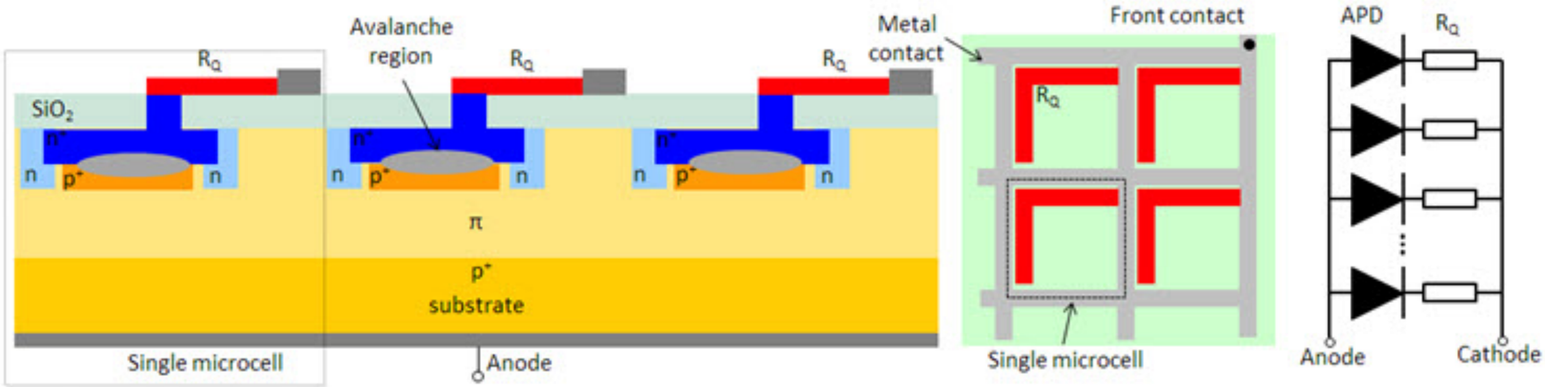
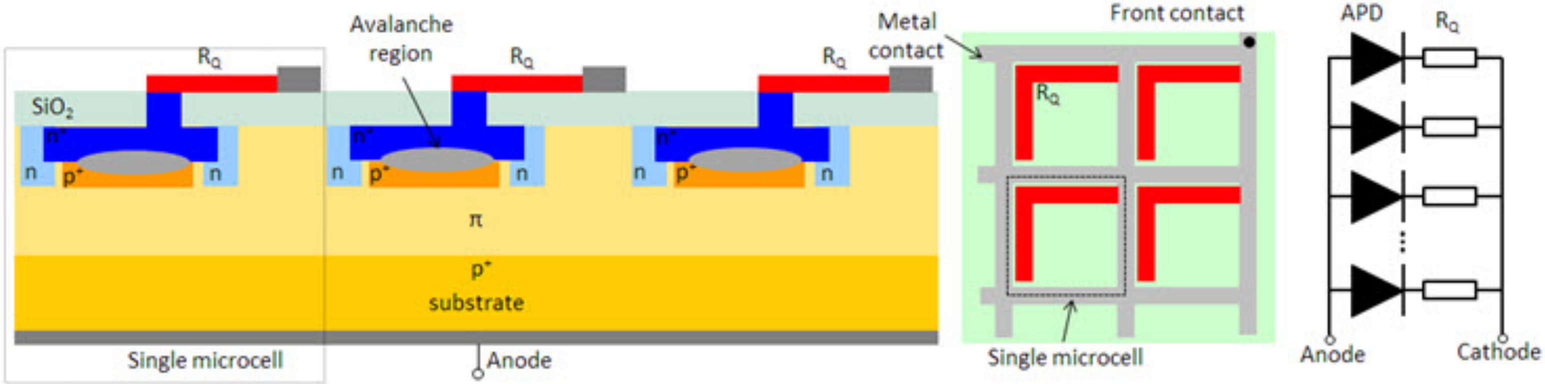
Siena, Italy

SiPM



- ✓ **Array of Single Photon Avalanche Diodes (SPAD) operated in Geiger mode**
- ✓ Detection efficiency (PDE) maximized for IR-UV photons.
- ✓ Compact (~10^3 cells/mm^2), robust, insensitive to external magnetic fields, fast response (~ns), operated with bias voltage $V_B < 50$ V.

SiPM



- Silicon Photomultiplier has been developed for single photon applications (e.g. IACT)
- Sometimes people use it for very high intensity short duration light (e.g. calorimetry)

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Direct X-ray detection with SiPMs

- ✓ Standard approach for X-ray real-time monitoring: coupling of active sensor (ex. SiPM) with passive material to convert X-ray to IR-UV

- ✓ Medical and industrial applications require **real-time monitoring of high intensity X-ray beams with minimum material budget exposed to the beam**

- ✓ **Direct detection without any converter would be preferred.**

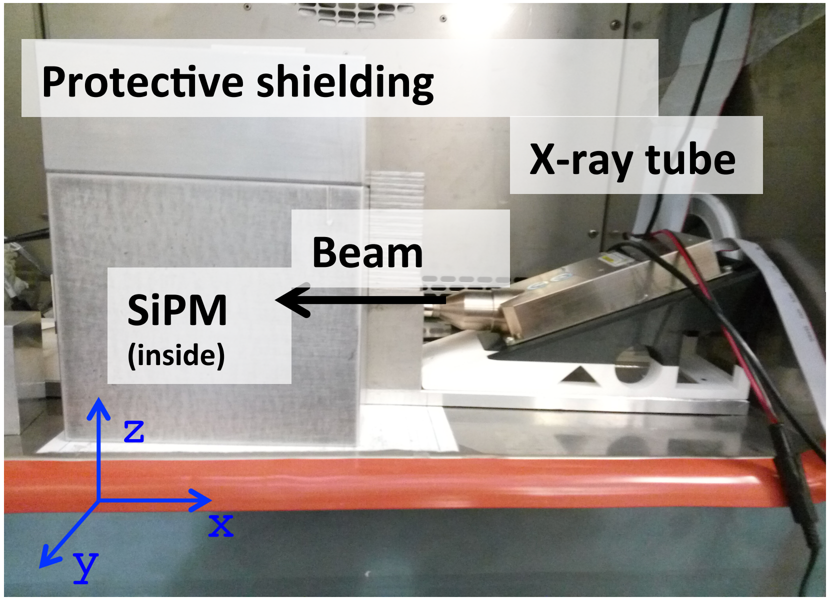
- ✓ **Simple measurement without any external amplification would be another advantage**

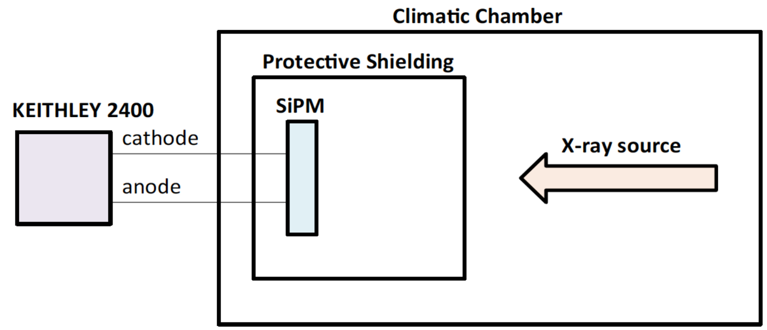
Direct X-ray detection with SiPMs

- **We investigated the possibility of measuring the current produced in SiPM directly exposed to intense and long-duration X-ray beam, without any converter material**

- **We analyzed the response of devices directly exposed to the radiation produced by an X-ray tube (Direct detection of high intensity X-ray fluxes with silicon photomultipliers, E. Fiandrini *et al.* 2019 *JINST* 14 P05016)**

SiPM current vs X ray intensity





- SiPM illuminated with steady flux from X-ray tube (Newton Scientific BJ7252 50kV 10W) operated at V_x=15 kV.
- Current signal read-out with Keithley 2400 SMU.
- Temperature set to 22°C (surgery room) and to 0°C (to operate the SiPM at reduced thermal dark noise conditions).
- Response of the SIPM verified below and above the breakdown voltage (V_{bd} ~ 27 V) for different X-ray beam intensities (I_x in [10-190] μA)

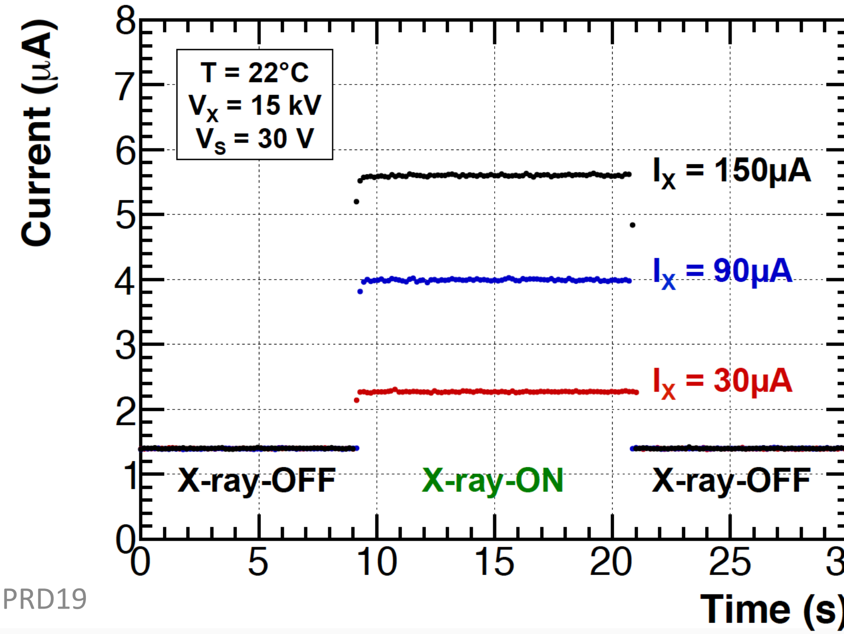
Current measurements

- SiPM p-on-n NUV-HD Low CT have been used
- Designed for CTA-pSCT collaboration by Fondazione Bruno Kessler (TN)
- Optimized for Near UV Cherenkov Light
- 6x6 mm^2 with 22810 microcell of 40 μm size and a fill factor FF = 0.72

V_b (0°C)	V_b (22°C)	d	PDE (350 nm, 25°C, +5 OV)
(26.5 ± 0.1) V	(27.0 ± 0.1) V	40 μm	(58 ± 5)%

	G ($\times 10^6$)		τ_r (ns)	DCR (kHz/mm^2)		P_{ct} (%)	
	+3 OV	+6 OV	+6 OV	+3 OV	+6 OV	+3 OV	+6 OV
T = 22°C	2.2 ± 0.1	4.2 ± 0.2	≈100	≈60	≈100	≈13	≈28
T = 0°C	2.3 ± 0.1	4.3 ± 0.2	≈85	≈20	≈40	≈13	≈28

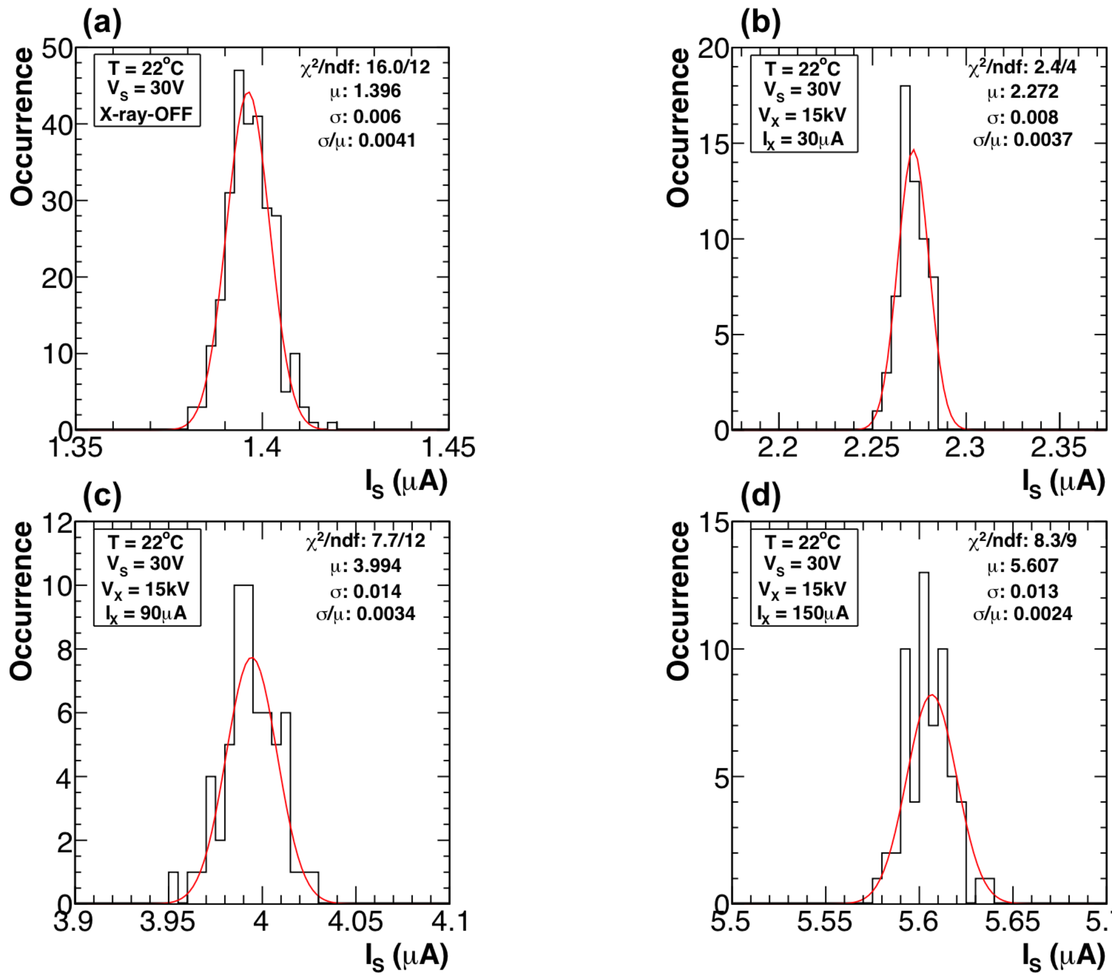
Current from SiPM measured before, during and after the X ray irradiation (for T~ 12 s) at different X ray tube intensities and overvoltages



Stability of the SiPM currents

X ray OFF

I_x = 30 μA



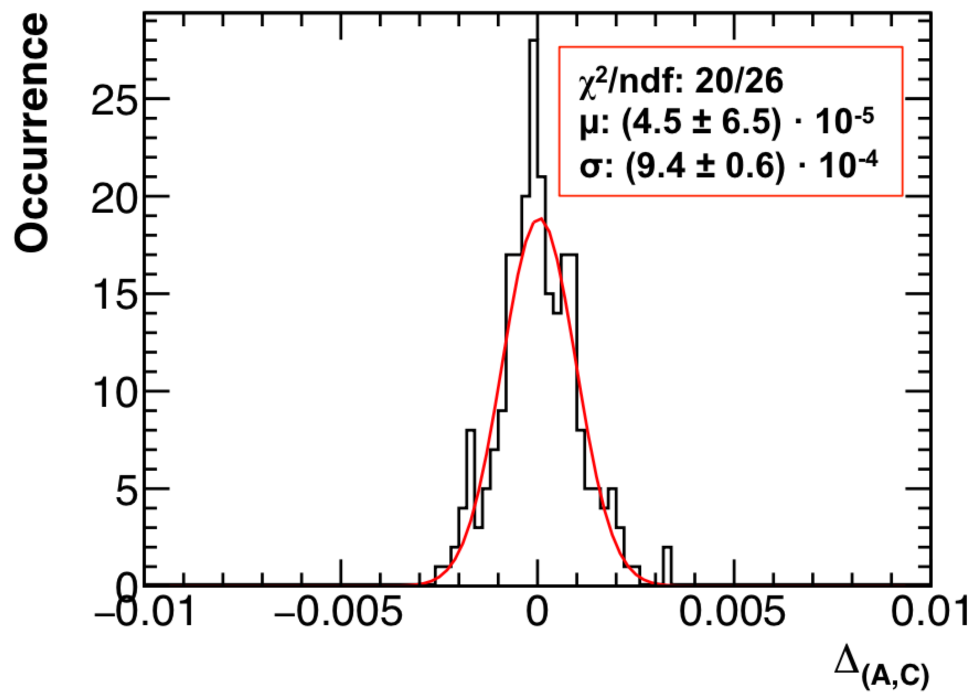
I_x = 90 μA

I_x = 150 μA

SiPM $\delta I_S/I_S$ below 2% for T = 0°C and below 1% for T = 22°C.

Stability of measurements

For all runs, the relative differences $\Delta_{(A,C)}$ between the average SiPM current measured before (I(A)) and after (I(C)) irradiation are consistent at the level of 0.1%.

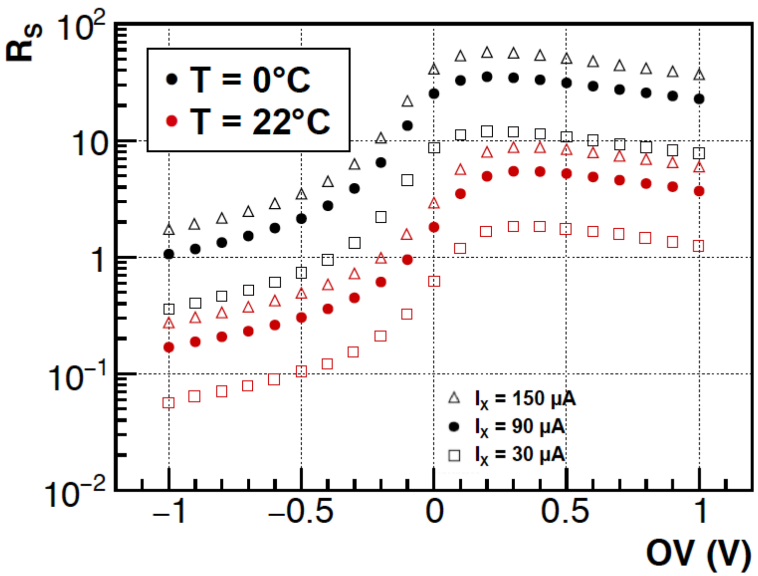


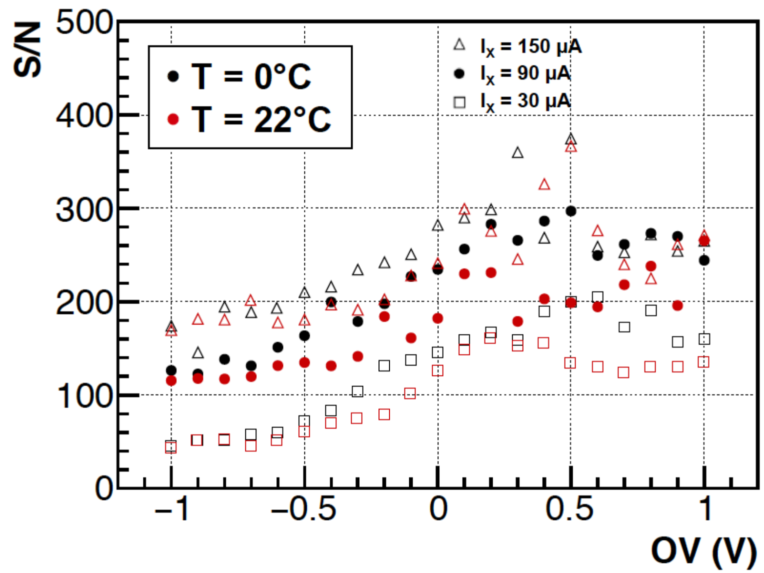
$$\Delta_{(A,C)} = \frac{\overline{I_S^{(A)}} - \overline{I_S^{(C)}}}{\overline{I_S^{(A)}} + \overline{I_S^{(C)}}}$$

Model independent characterization

$I_S^{(ON)}$: current during X-ray irradiation
$I_S^{(OFF)}$: current without X-ray irradiation
$I_S^{(sig)} = I_S^{(ON)} - I_S^{(OFF)}$: current signal

$R_S = I_S^{(sig)} / I_S^{(OFF)}$: **signal intensity**
$S/N = I_S^{(sig)} / [\Delta I_S^{(sig)} \oplus \Delta I_S^{(OFF)}]$





Maximum R_S and S/N just above breakdown (T dependence)
To be further analyzed for the determination of the operating point

Parametrization of the SiPM response

The rate of cell firing in a "ideal" SiPM (zero recovery time τ_r) would be

$$\dot{n}_g = \dot{n}_{ph} + \dot{n}_{dcr}$$ = photo-generation + thermal generation

- In a realistic SiPM with a finite τ_r, the response depends on the pulse light duration t_p compared to τ_r and on cell number N

- When $t_p >> \tau_r$, the rate of firing cells can be approximated as due to a steady-state process with a balance between repetitive retriggering and recovering of the SiPM microcells, i.e. non-paralizable dead time model for Geiger counters

$$\dot{n}_f = \frac{\dot{n}_g}{1 + \dot{n}_g \tau_r / N}$$

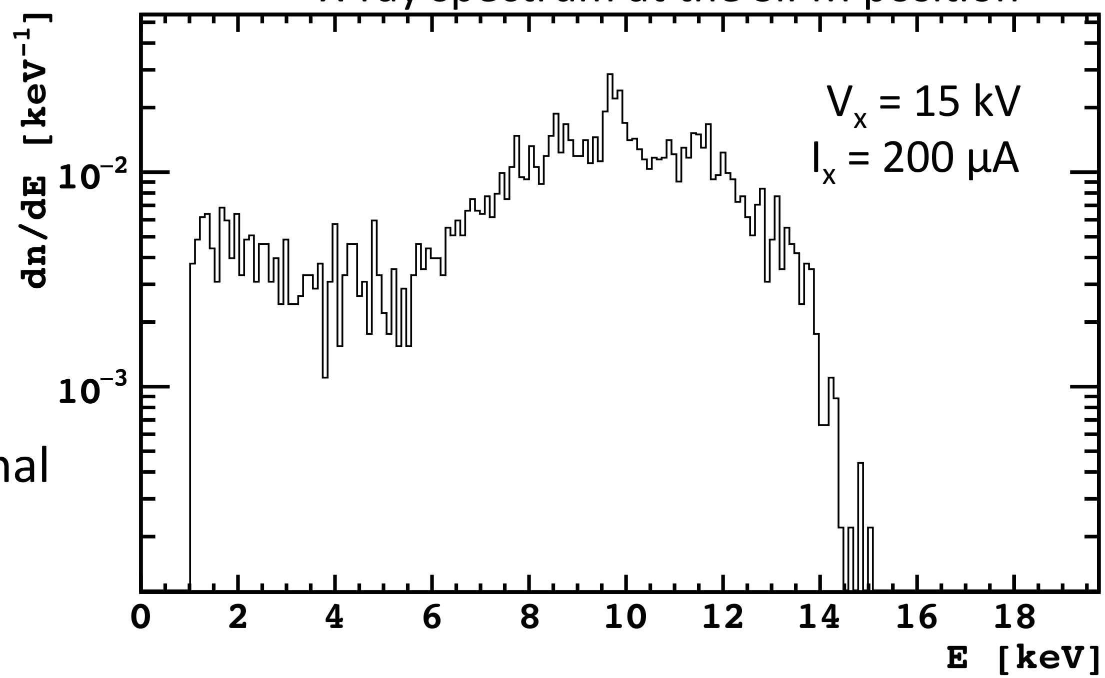
Parametrization of the SiPM response

The X-ray tube provides a spectrum $j_\gamma(E)$ of photons with $E_{min} < E < E_{max} = eV_x$
The rate of avalanche photo-generation can be parametrized as

$$\dot{n}_{ph} = \alpha k(V_X) \cdot ECF \cdot V_X I_X$$

- ✓ α(S,r) = geom. acceptance of SiPM,
- ✓ $K(V_x)$ = convolution of the PDE with the photon spectrum,
- ✓ ECF = Excess Charge Factor

X-ray spectrum at the SiPM position



- ❑ X ray tube current I_x proportional to X ray count rate at V_x const.
- ❑ → use I_x as a measure of the X ray flux intensity

The SiPM current output is

$$I_S = eG \cdot \dot{n}_g \approx \frac{eG\dot{n}_{ph} + I_{dcr}}{1 + \dot{n}_{ph}\tau_r / N} = \frac{AI_X + I_{dcr}}{1 + BI_X}$$

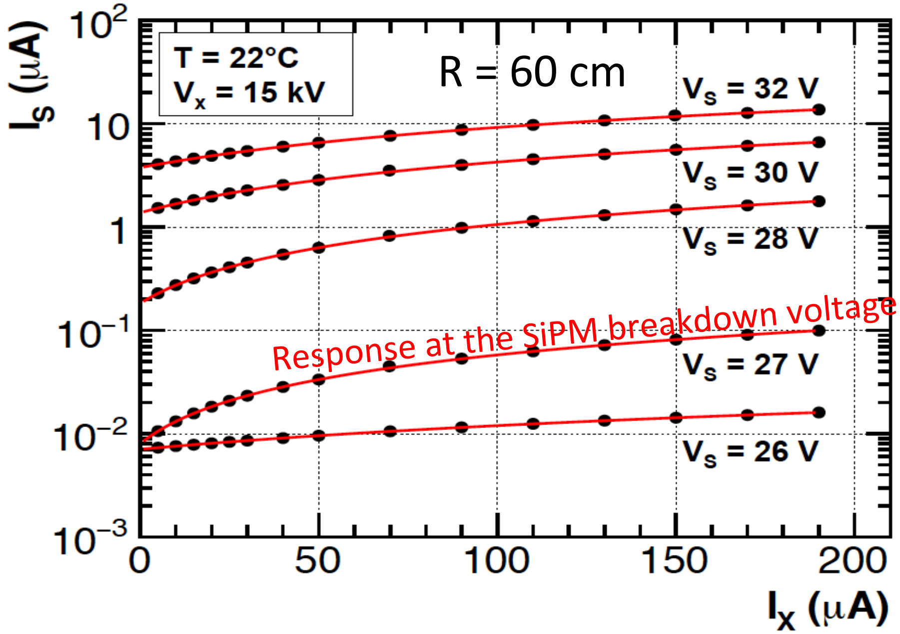
A: SiPM response factor
B: SiPM saturation factor
I_{DCR}: SiPM dark current

Fitting the SiPM current response

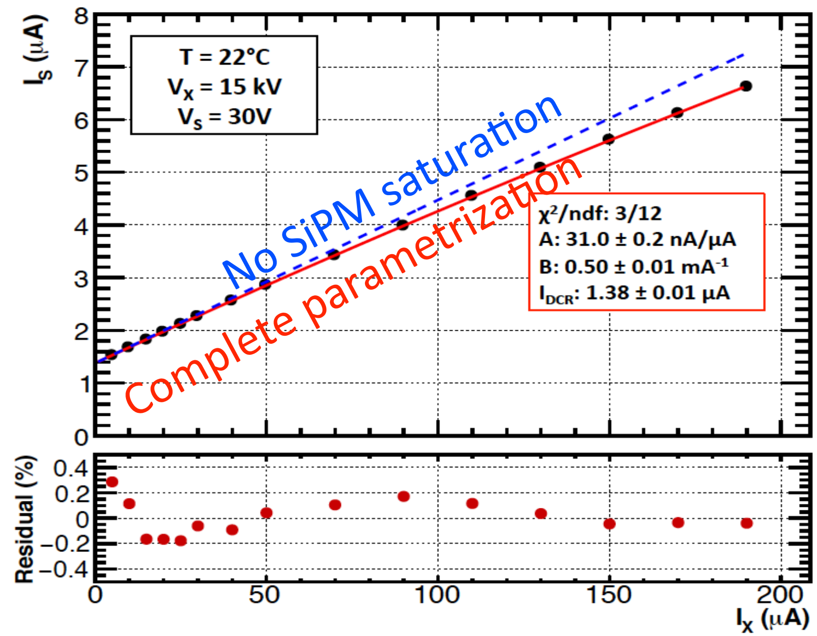
- Data
- Best Fit

$$I_S = \frac{A\, I_X + I_{dcr}}{1 + B\, I_X}$$

A: SiPM response factor
B: SiPM saturation factor
I_{DCR}: SiPM dark current

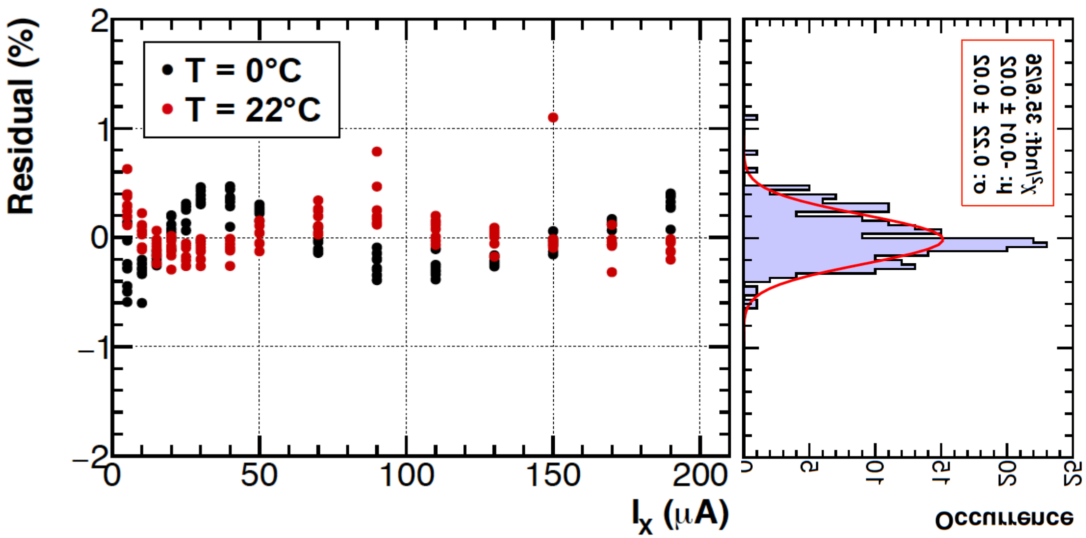


Fit to the SiPM current measured at 22°C for different SiPM bias voltages



The best fit compared to SiPM response with no saturation effects

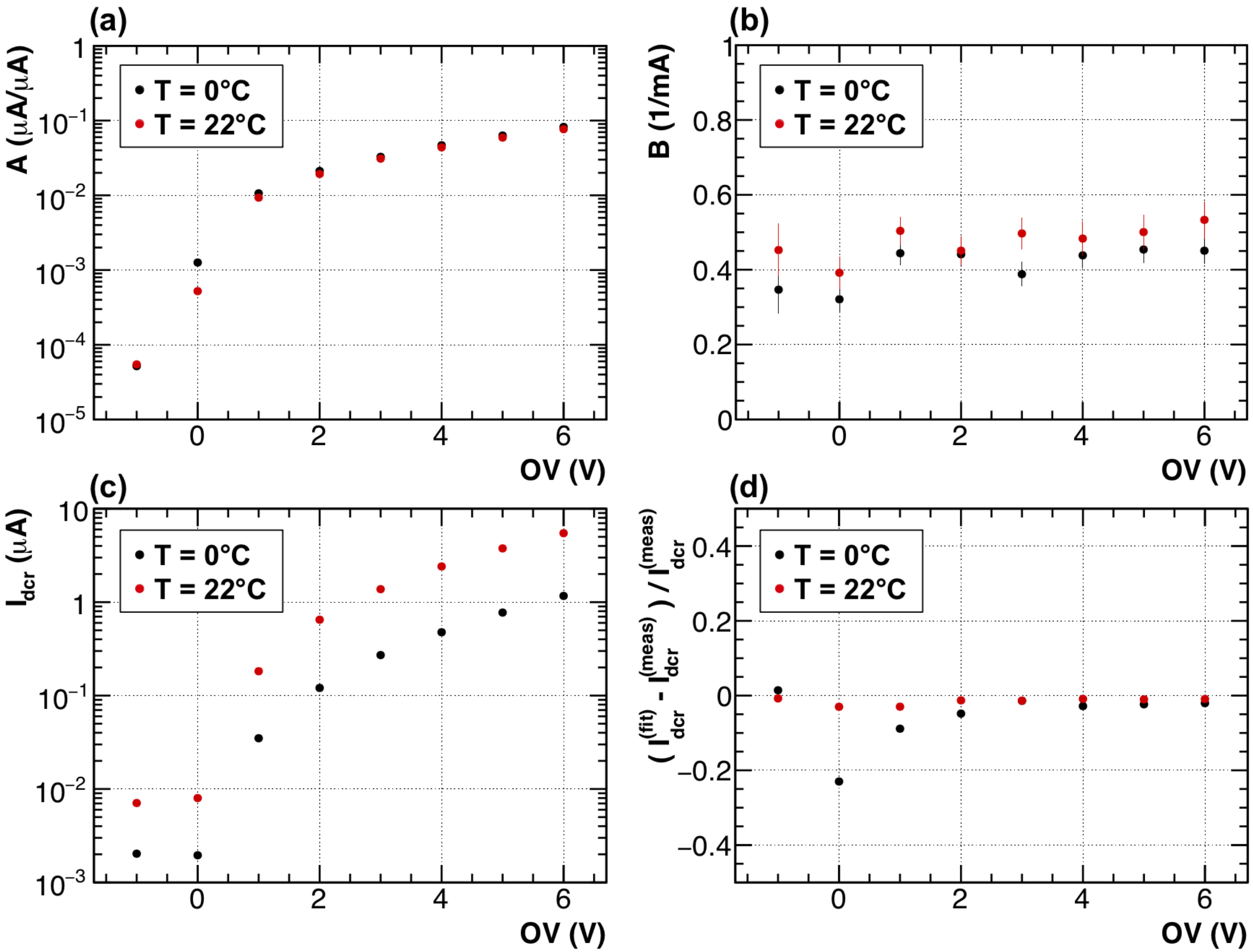
Goodness of parametrization



Residual of best fit parametrization as a function of the X-ray beam intensity.

The parametrization describes the SiPM response with accuracy of ~0.2% up to X-ray intensities corresponding to 10% saturation of the SiPM response (observed for I_x=190μA)

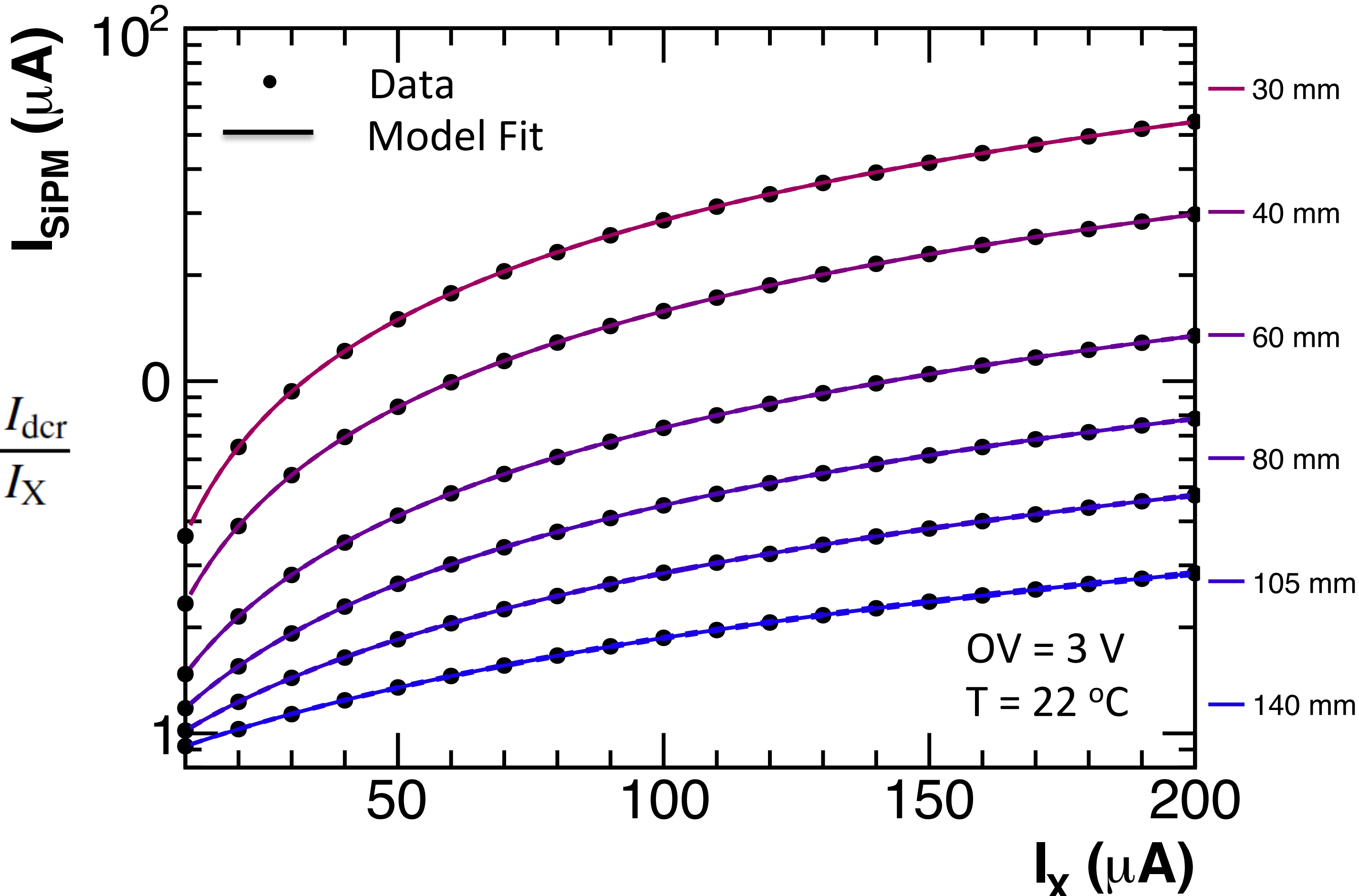
SiPM response vs OV



Parameters obtained from the fit to the data using $I_S = \frac{A\, I_X + I_{dcr}}{1 + B\, I_X}$

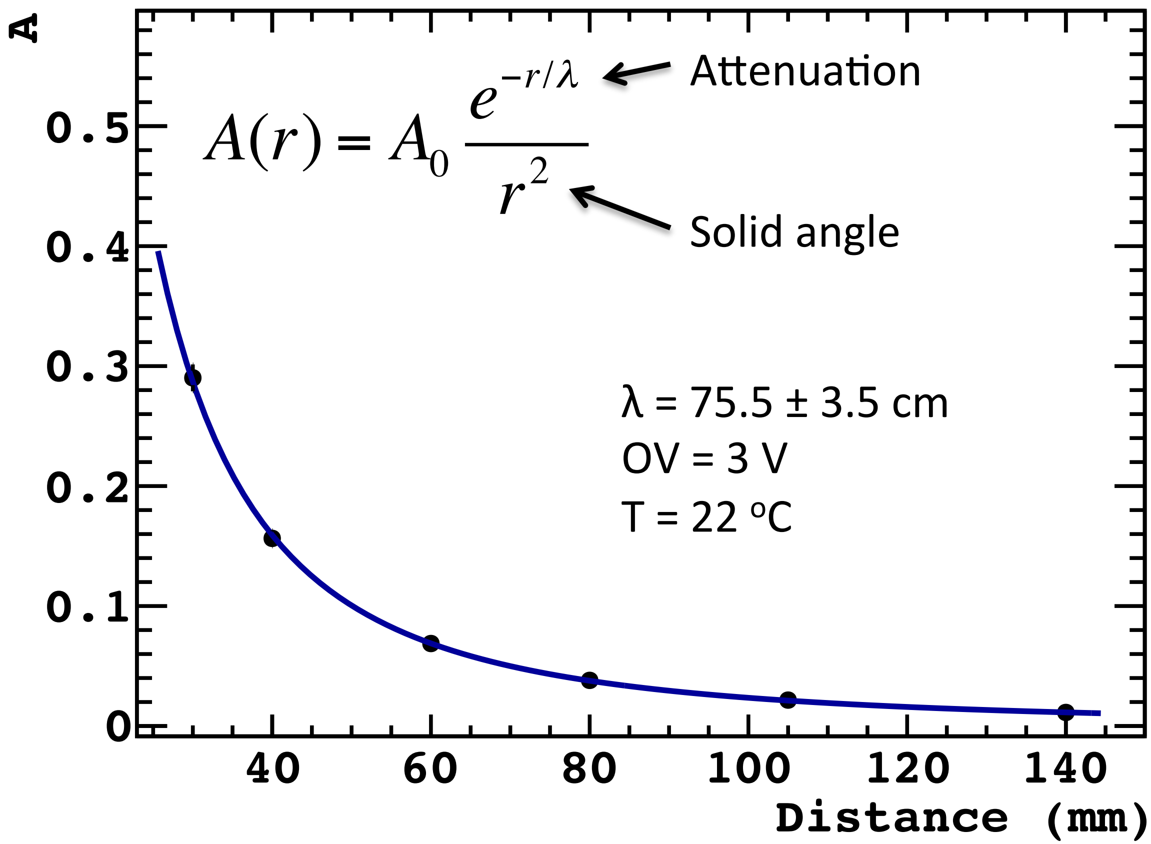
SiPM Current vs X ray source Distance

$$I_S = \frac{A\, I_X + I_{dcr}}{1 + B\, I_X}$$



- The model fits very well the currents for all the distances
- Varying distance is equivalent to change the photon rate on the SiPM at the same I_x
- → The model reproduces tha data for a large interval of photon fluxes

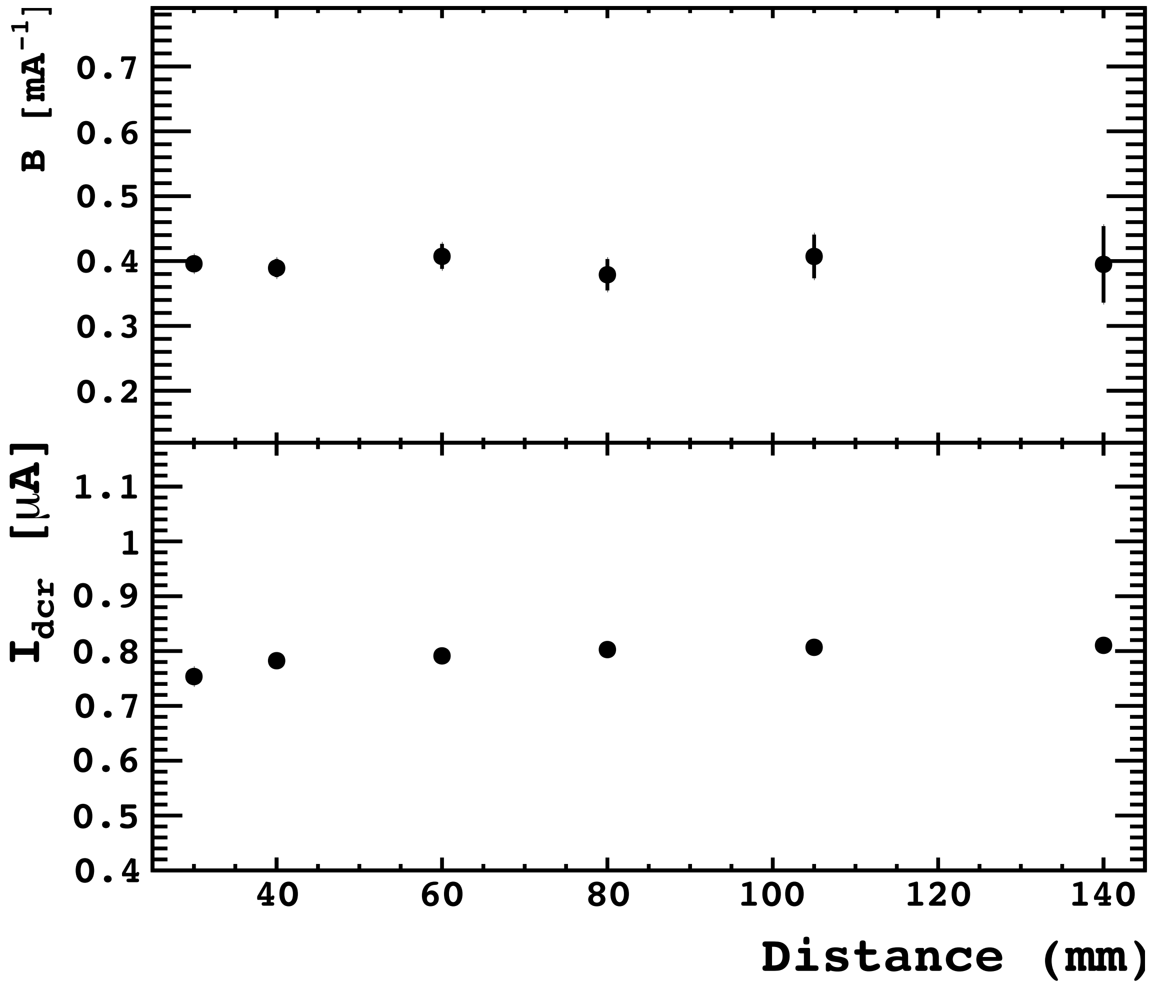
Attenuation of the X-ray beam in air



$$I_S = \frac{A\, I_X + I_{dcr}}{1 + B\, I_X}$$

- ❑ **It is a measurement of X-ray absorption length in air**
- ❑ **SiPM is really measuring the X-ray flux**

Model Par. vs Distance



The saturation factor B and the dark current I_{dcr} depend only the SiPM properties, as expected

Outlook and prospects

- ✓ **The current response of a SiPM directly exposed to a steady, high-intensity X-ray flux is well correlated to the intensity of the X-ray beam.**

- ✓ **The SiPM signal current is well above the dark current below and above the SiPM breakdown voltage, such that no amplification is needed for read-out.**

- ✓ **The model describes the SiPM response to the X ray beam with accuracy of ~0.2% up to deviations from linearity of 10%**

- ✓ **These results indicate that the SiPM current response is a potential dosimetric variable that can be calibrated to perform real time measurements of high-intensity X-ray fluxes with minimum material exposition to the beam.**

- ✓ Further experimental tests on the SiPM response as function of SiPM microcell size, of the X-ray beam spectrum and at higher X-ray beam intensities are ongoing to validate the parametrization for a larger interval of operating parameters.

Parametrization of the SiPM response

- Direct X-ray single photon detection in pulse mode with SiPMs is inefficient
- For intense and long lasting X ray fluxes, the small fraction of interacting photons is able to produce a large current in the device
- The rate of cell firing in a "ideal" SiPM (zero recovery time τ_r) would be

$$\dot{n}_g = \dot{n}_{ph} + \dot{n}_{dcr}$$ = photo-generation + thermal generation

Parametrization of the SiPM response

- In a realistic SiPM with a finite τ_r, the response depends on the pulse light duration t_p compared to τ_r and on cell number N

- When $t_p >> \tau_r$, the rate of firing cells can be approximated as due to a steady-state process with a balance between repetitive retriggering and recovering of the SiPM microcells, i.e. non-paralizable dead time model for Geiger counters

$$\dot{n}_f = \frac{\dot{n}_g}{1 + \dot{n}_g \tau_r / N}$$

The SiPM has been illuminated with a X-ray beam produced by a Newton Scientific BJ7252 tube operated at V_X=15kV, corresponding to a nominal maximum photon en-ergy of the beam E_{max}=eV_X = 15keV.

The nominal opening angle of the X-ray beam is θ_{max} = 0.48 rad around the tube axis, corresponding to a solid angle covered by the X-ray beam of $\Delta\Omega_{beam} \approx 2\pi(1-\cos\theta_{max})$=0.71 sr.

The SiPM is placed along the beam axis at θ=0° with the surface S_{SiPM} oriented perpendicularly to the beam at $r \approx$ 100 mm from the X-ray tube, covering a solid angle to the X-ray beam of $\Delta\Omega = S_{SiPM}/r^2 \approx 3.6\times10^{-3}$ sr.

Assuming a gaussian distribution G(θ) for the angular profile of the beam with width σ = 0.14 rad → $\alpha \approx G(0)\Delta\Omega \approx 3.1\%$

We investigate the possibility of direct detection of high-intensity X-ray fluxes using the measurement of the current produced by silicon photomultipliers directly exposed to the X-ray beam, without any converter material.
We have analyzed the response of devices directly exposed to the radiation produced by an X-ray tube.
The signal-to-noise ratio of the response confirms that the current produced during the irradiation provides information on the X-ray flux intensity.
We parametrize the current response of devices as function of the X-ray flux intensity.
We verify that the parametrization is accurate down to the % level and we study the linearity of the response to investigate the prospects for possible applications in real-time X-ray beam monitoring and beam spatial profiling.

Parametrization of the SiPM response

- Direct X-ray single photon detection in pulse mode with SiPMs is inefficient due to energy dependence of photoelectric cross section (and increased scattering out of Compton electrons).
- For intense and long lasting X ray fluxes, the small fraction of interacting photons is able to produce a large current in the device

The rate of cell firing in a "ideal" SiPM (zero recovery time τ_r) would be

$$\dot{n}_g = \dot{n}_{ph} + \dot{n}_{dcr}$$ = photo-generation + thermal generation

Parametrization of the SiPM response

- In a realistic SiPM with a finite τ_r, the response depends on the pulse light duration t_p compared to τ_r, as well as on the number of concurrently converting photons compared to the number of SiPM microcells N

- When $t_p >> \tau_r$, the rate of firing cells can be approximated as due to a steady-state process with a balance between repetitive retriggering and recovering of the SiPM microcells, i.e. non-paralizable dead time model for Geiger counters

$$\dot{n}_f = \frac{\dot{n}_g}{1 + \dot{n}_g \tau_r / N}$$