

Experimental SiPMs parameter characterisation from avalanche triggering probabilities

Giacomo Gallina

F. Retière, J.Kroeger, P. Margetak, F. Edalatfar
M. Ward, G. Zhang, P. Giampa, L. Doria

TRIUMF

Structure of the presentation and goal of this work

The goal of this talk is to show a parametrisation of the photo detection efficiency (PDE) starting from the avalanche triggering probability.

We will then use this configuration to extract information of the junction configuration and we will use this parametrisation to probe the source of Dark Noise, After Pulse and Crosstalk

Structure of this work

Derivation of an equation to fit avalanche triggering probability

Use of this equation to characterise 3 devices (2 Hamamatsu devices + 1 FBK Device)

Apply this model to gain information on DN, AP and CT measurement

Background

Set-up and methods for SiPM Photo-Detection Efficiency measurements Zappalà et all.

3

$$\text{PDE}(\lambda, \theta) = \text{FF} \times P_p(V) \times \eta_e(\lambda, \theta) = \text{FF} \times P_p(V) \times \eta_i(\lambda) \times \eta_0(\lambda, \theta)$$

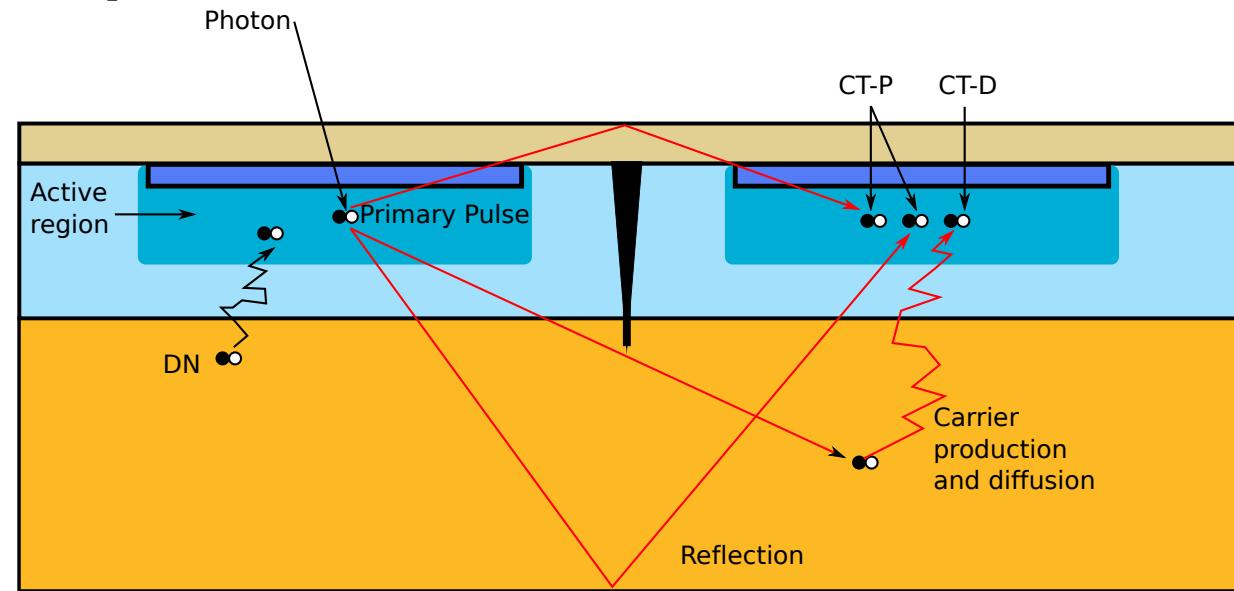
FF Fill Factor : Area Reduction

$\eta_e(\lambda, \theta)$ External quantum Efficiency

$\eta_i(\lambda)$ Internal Quantum Efficiency

$\eta_0(\lambda, \theta) = (1 - R(\lambda, \theta))$ Optical quantum Efficiency, with R Reflectivity

$P_p(V)$ Avalanche Triggering Probability assumed Position independent



Background

$$\text{PDE}(\lambda, \theta, V) = \text{FF} \times P_p(V) \times \eta_e(\lambda, \theta) = \text{FF} \times P_p(V) \times \eta_i(\lambda) \times \eta_0(\lambda, \theta)$$

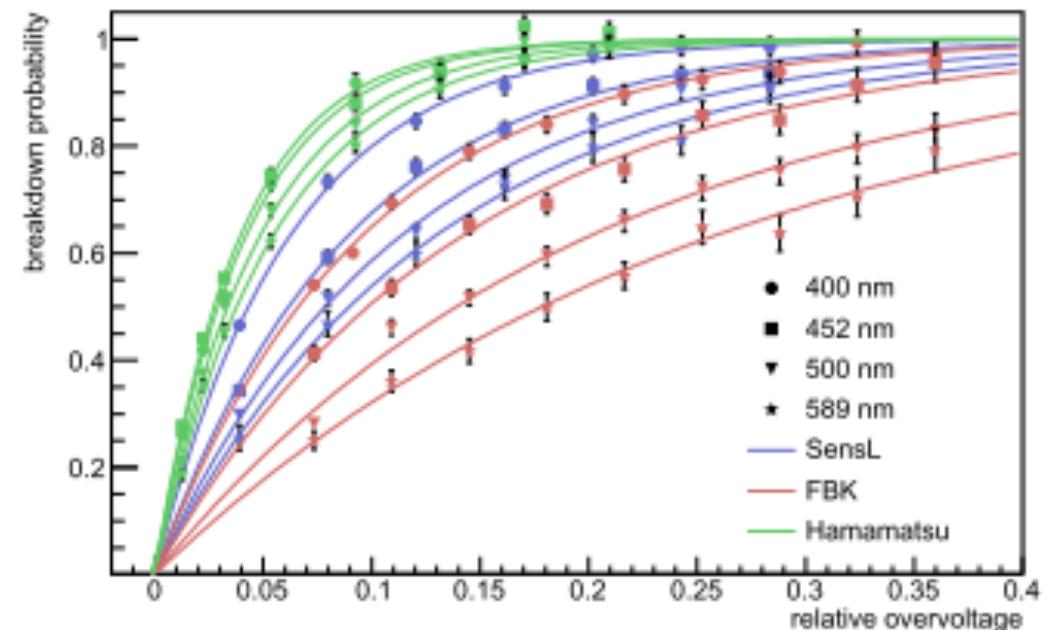
The PDE for a given wavelength usually is parametrised as $\text{PDE}(\lambda, \theta) \sim \text{PDE}_{\text{MAX}}(\lambda, \theta) \times P_p(V)$

Characterisation of Three High Efficiency and Blue Sensitive Silicon Photomultipliers Adam - Nepomuk Otte and all.

The P_p is often parametrised driven by the data.

$$\text{PDE} = \text{PDE}_{\text{max}} \left(1 - e^{\frac{-(V - V_{BD})}{a}} \right) \rightarrow P_p = \left(1 - e^{\frac{-(V - V_{BD})}{a}} \right)$$

V_{BD} Breakdown Voltage



Structure of the PN junction used

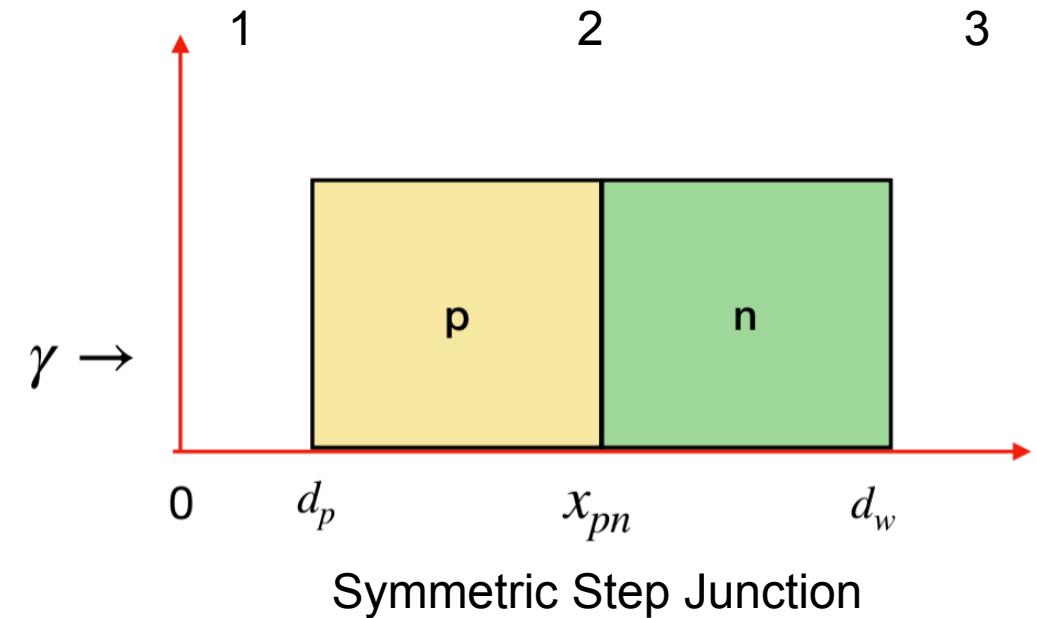
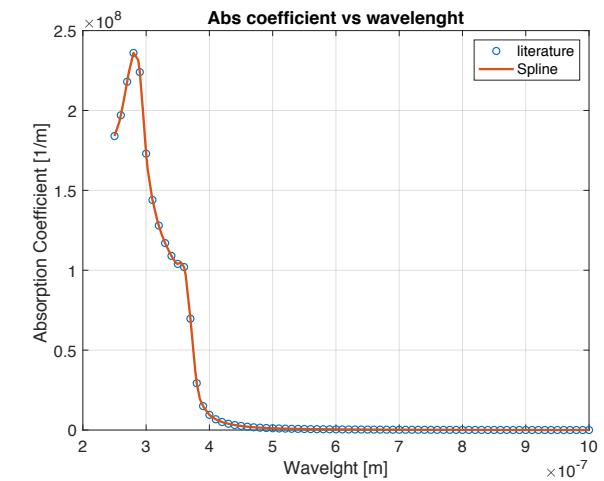
$$\text{PDE}(\lambda, \theta) = \text{FF} \times (1 - R(\lambda, \theta)) \times \left\{ P_1 + P_2 + P_3 \right\}$$

1: Photon are absorbed in the front "zero field" region.
Then electrons diffuse in the avalanche region triggering avalanches.

2 : Photon are absorbed in the avalanche region.
Both electron and holes can trigger an avalanche.

3 : Photon are absorbed in the back layer.
Then holes diffuse back in the avalanche region
triggering avalanches.

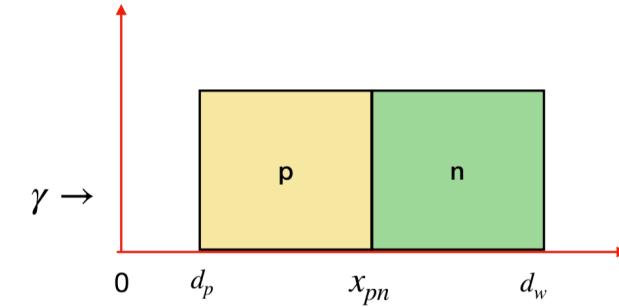
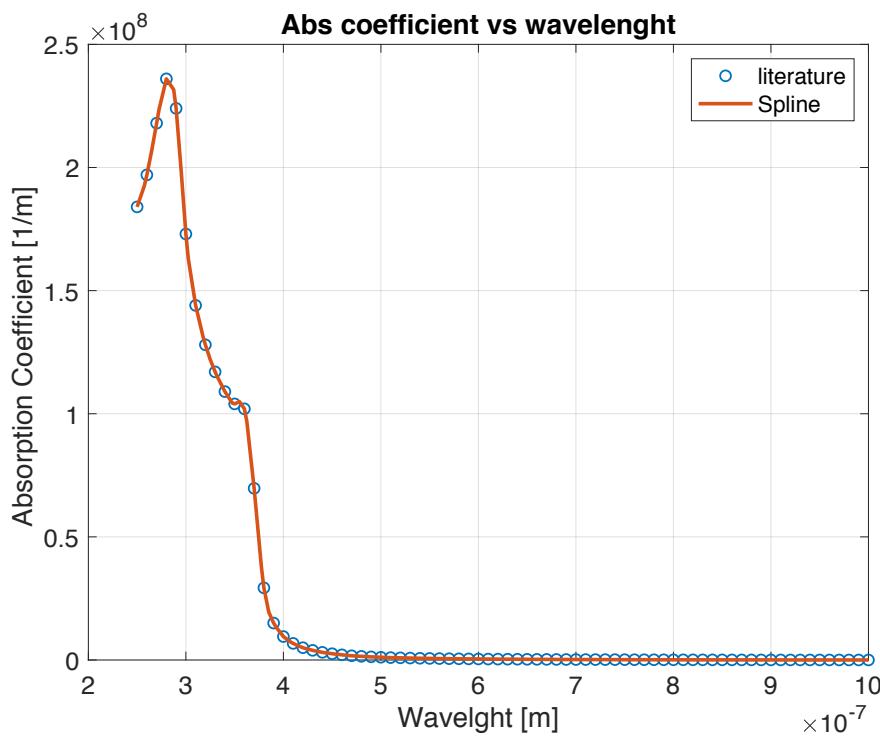
Since we are interested in “prompt” efficiency I will focus
on the parametrisation of P_2



Parametrisation of Mechanism 2

$$P_2 = \int_{d_p}^{d_w} \alpha \exp(-\alpha t) \times P_p(t) dt$$

$\alpha(\lambda)$ Absorption Coefficient



6

P_p avalanche triggering probability

On the Avalanche Initiation Probability of Avalanche Diodes Above the Breakdown Voltage ROBERT J. McINTYRE

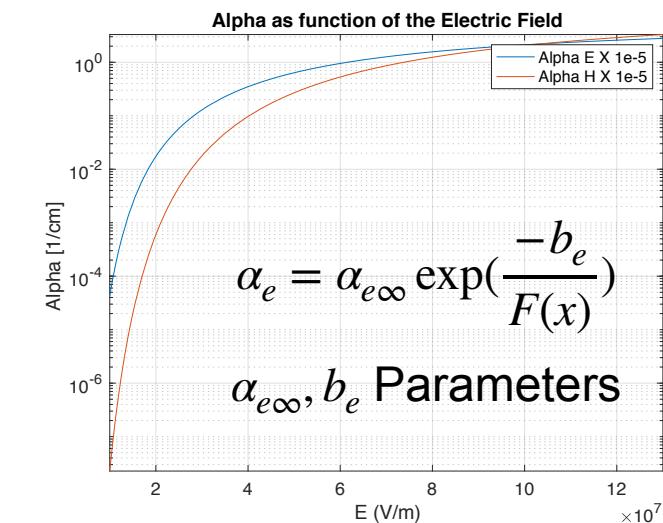
DOI 10.1109/T-ED.1973.17715

$$P_p(x) = \frac{P_e(d_p)f(x)}{P_e(d_p)f(x) + 1 - P_e(d_p)} \equiv P_e(x) + P_h(x) - P_e P_h(x)$$

$$f(x) = \exp \left[\int_{d_p}^x (\alpha_h - \alpha_e) dx \right]$$

$P_e(d_p)$ Electron Boundary Condition

$P_h(d_w)$ Hole Boundary Condition

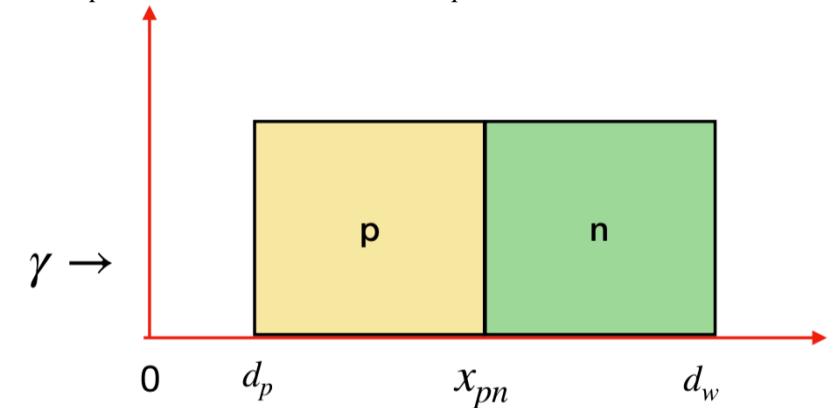


P_p is strongly position dependent

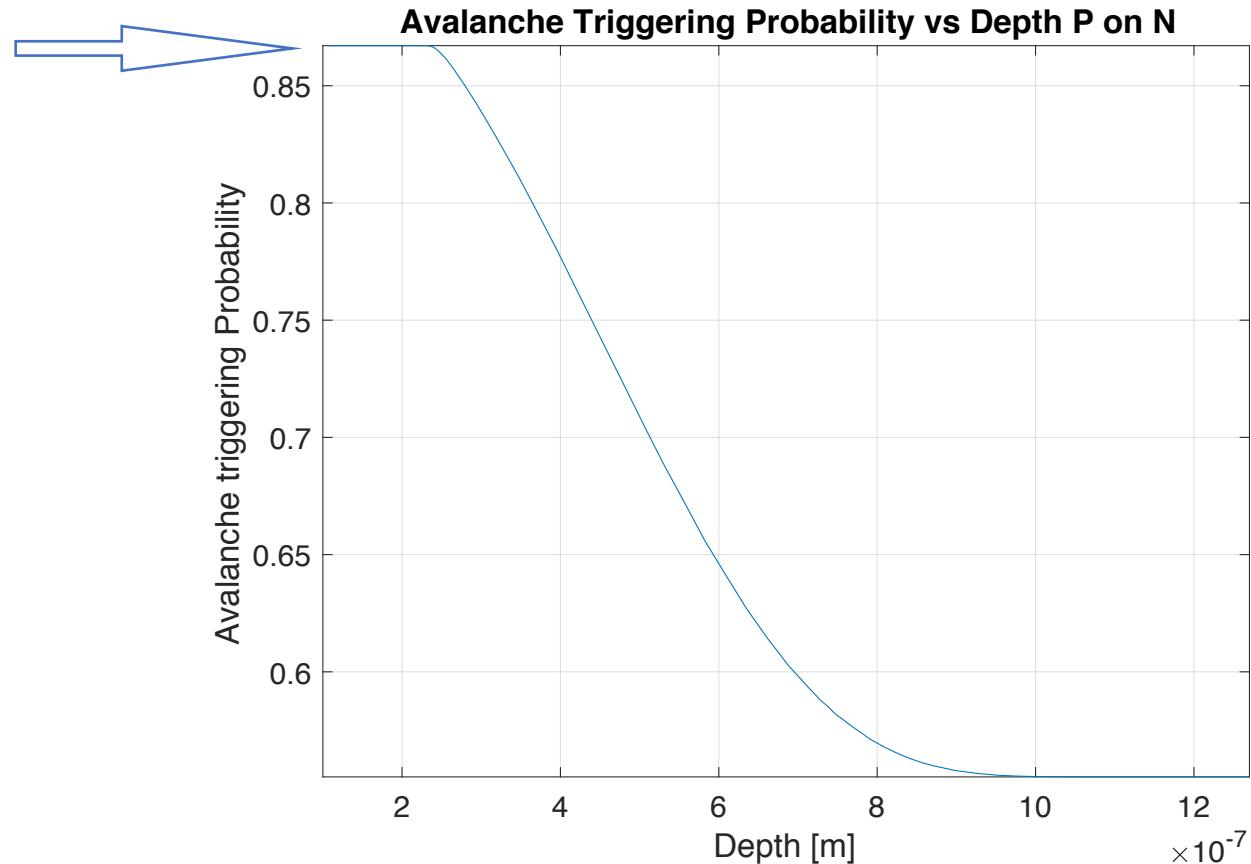
$$P_p(x) = \frac{P_e(d_p)f(x)}{P_e(d_p)f(x) + 1 - P_e(d_p)} \equiv P_e(x) + P_h(x) - P_e P_h(x)$$

$$f(x) = \exp\left[\int_{d_p}^x (\alpha_h - \alpha_e)dx\right]$$

$$\text{PDE}(\lambda, \theta, V) = \text{FF} \times P_p \times \eta_e(\lambda, \theta) = \text{FF} \times P_p(V) \times \eta_i(\lambda) \times \eta_0(\lambda, \theta)$$



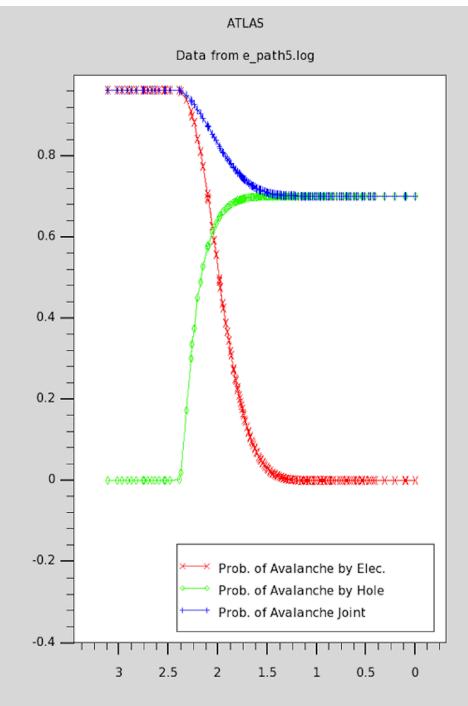
Electron
Side
P side



Example of Numerical Simulation
of Avalanche triggering Probability

$$\begin{cases} P_h(d_p) = 0 \\ P_e(d_w) = 0 \end{cases}$$

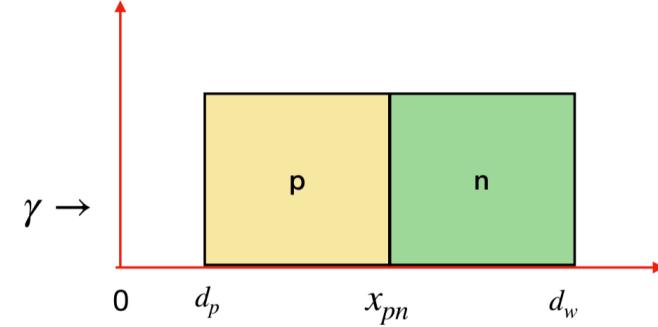
N side
Hole Side



Parametrisation of Mechanism 2

How can we then evaluate P_2 ?

Let's first suppose to work at fixed Bias Voltage



$$P_2 = \int_{d_p}^{d_w} \alpha \exp(-\alpha t) \times P_p(t) dt \quad P_p(x) = \frac{P_e(d_p)f(x)}{P_e(d_p)f(x) + 1 - P_e(d_p)} \equiv P_e(x) + P_h(x) - P_e P_h(x) \quad f(x) = \exp\left[\int_{d_p}^x (\alpha_h - \alpha_e) dx\right]$$

P_2 is not easily integrable.. The integrand of $f(x)$ can then be expanded around the maximum Electric field position x_{pn} and $P_p(x)$ can be approximated taking its asymptotic values at the junction boundaries.

$$P_p(x) \sim \begin{cases} P_e(d_p) & \text{if } x \leq x_{pn} \\ \frac{P_e(d_p)\exp(\mu_{av}(2 - e^{\frac{d_p - x_{pn}}{d_{av}}}))}{P_e(d_p)\exp(\mu_{av}(2 - e^{\frac{d_p - x_{pn}}{d_{av}}})) + 1 - P_e(d_p)} \sim P_h(d_w) & \text{if } x > x_{pn} \end{cases}$$

$P_e(d_p)$ Electron Boundary Condition

$P_h(d_w)$ Hole Boundary Condition

μ_{av} d_{av} Parameters Electric field dependent

➡

$$\begin{aligned} P_2(\lambda, V)_{\text{norm}} &= P_2 / \exp(-\alpha d_p) \\ P_2(\lambda, V)_{\text{norm}} &= \left(P_e(d_p) \times f_e + P_h(d_w) \times (1 - f_e) \right) \\ f_e &= 1 - \exp(-\alpha(x_{pn} - d_p)) \end{aligned}$$

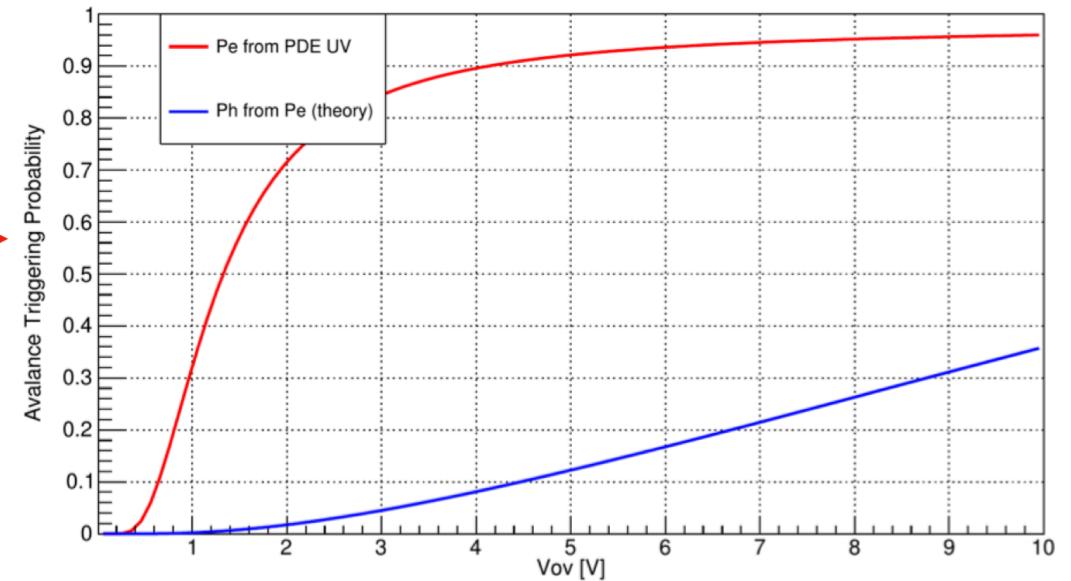
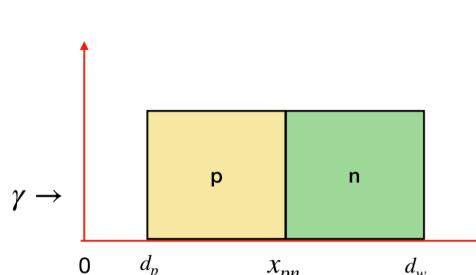
Fraction of e- avalanches

Summary

If the wavelength is short enough

$$P_2(\lambda, V)_{\text{norm}} = \left(P_e(d_p) \times f_e + P_h(d_w) \times (1 - f_e) \right) \sim P_e(d_p)$$

The idea is then:



Use UV light to measure as function of the voltage $P_e(d_p)$

Propose Fitting of $P_e(d_p)$ as function of the voltage (Poisson Derivation)

$$P_e(d_p) \sim (1 - e^{-k_e e^{-\frac{k_e 2}{\Delta V}}})$$

Then extract $P_h(d_w)$ as function of voltage using

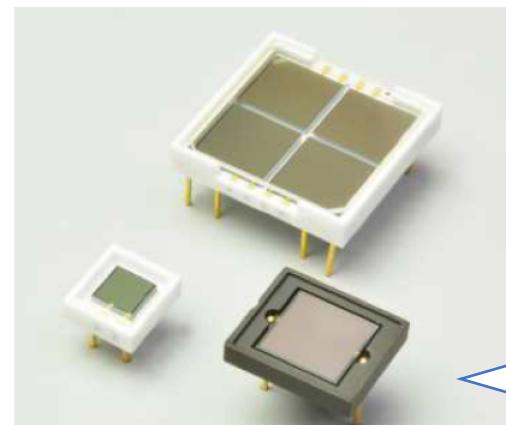
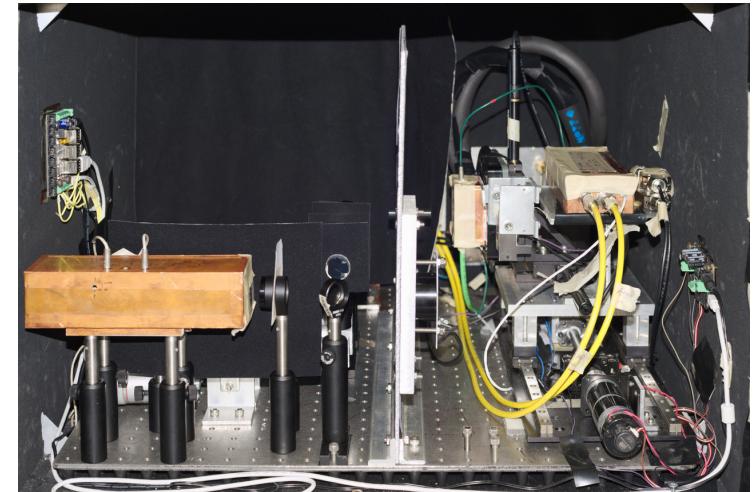
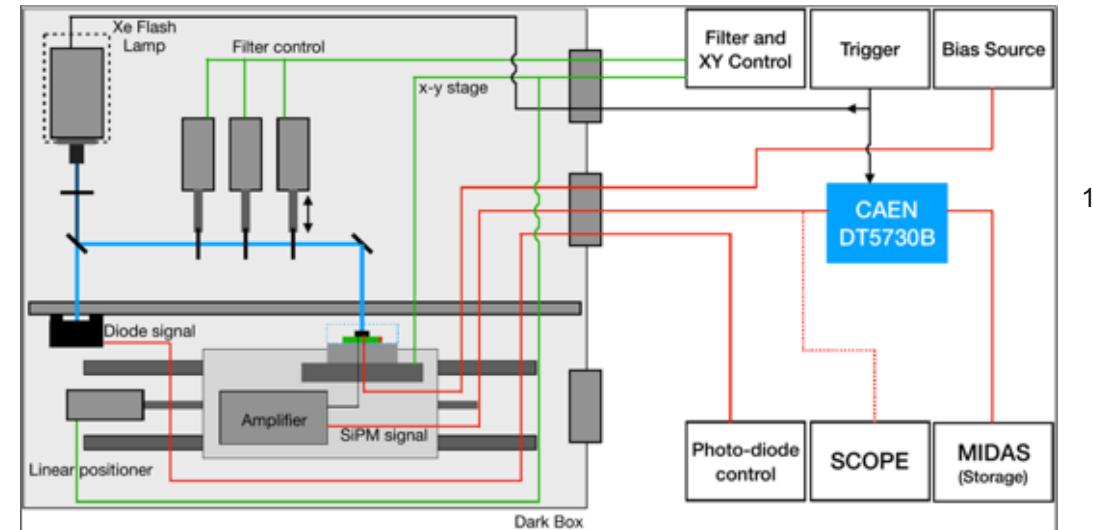
$$\frac{P_e(d_p) \exp(\mu_{av} (2 - e^{\frac{d_p - x_{pn}}{d_{av}}}))}{P_e(d_p) \exp(\mu_{av} (2 - e^{\frac{d_p - x_{pn}}{d_{av}}})) + 1 - P_e(d_p)}$$

Finally obtain the fitting equation for a generic wavelength using

$$f_e = 1 - \exp(-\alpha(x_{pn} - d_p)) \quad P_2(\lambda, V)_{\text{norm}} = \left(P_e(d_p) \times f_e + P_h(d_w) \times (1 - f_e) \right)$$

Application of this Concept for the Hamamatsu VUV4

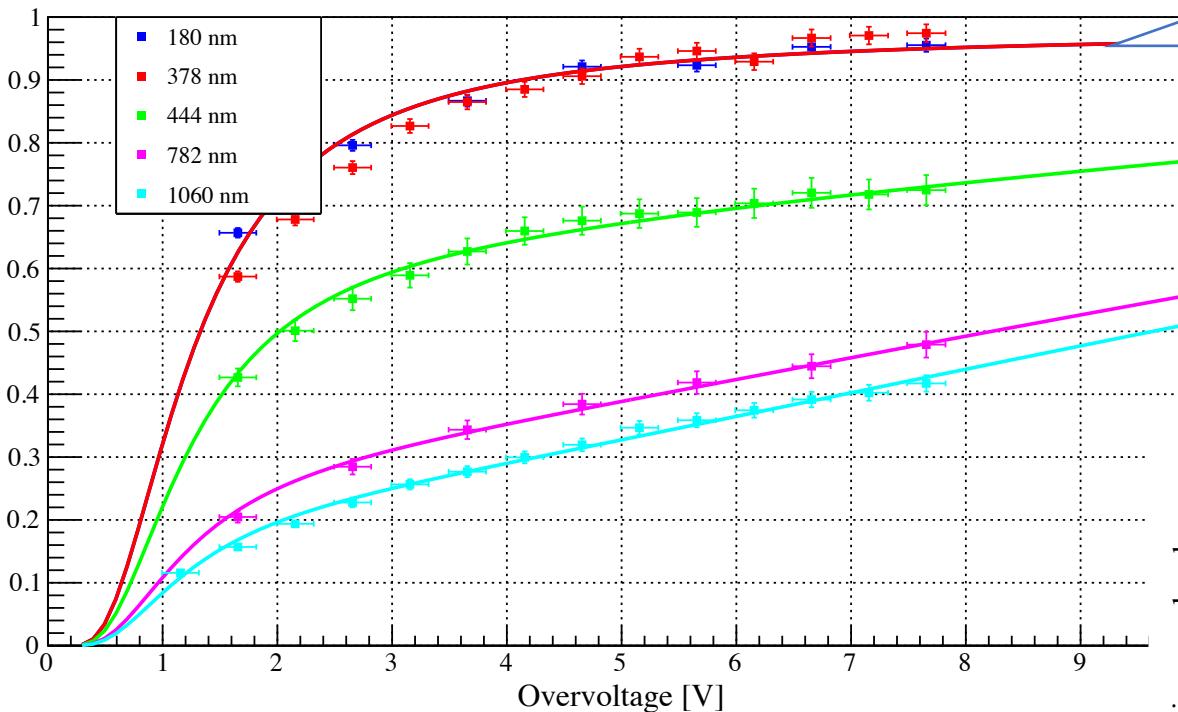
- Light-tight box
- Waveform analysis
- Wavelengths analyzed:
 - 180 nm (Xe flash lamp)
 - 378 nm (Hamamatsu laser)
 - 444 nm (Hamamatsu laser)
 - 782 nm (Hamamatsu laser)
 - 1060 nm (LED)
- Xe flash lamp has a broad spectrum
--> use UV filter to select 180 nm
- Other wavelengths:
--> bring fibre from outside into the black box



$6 \times 6 \text{ mm}^2$

Application of this Concept for the Hamamatsu VUV4

Avalanche Triggering Prob.



The Fit allows to constrain thickness of electron dominated region and hole dominated region.

Error on these parameters can be reduced using more wavelengths (see next slide)

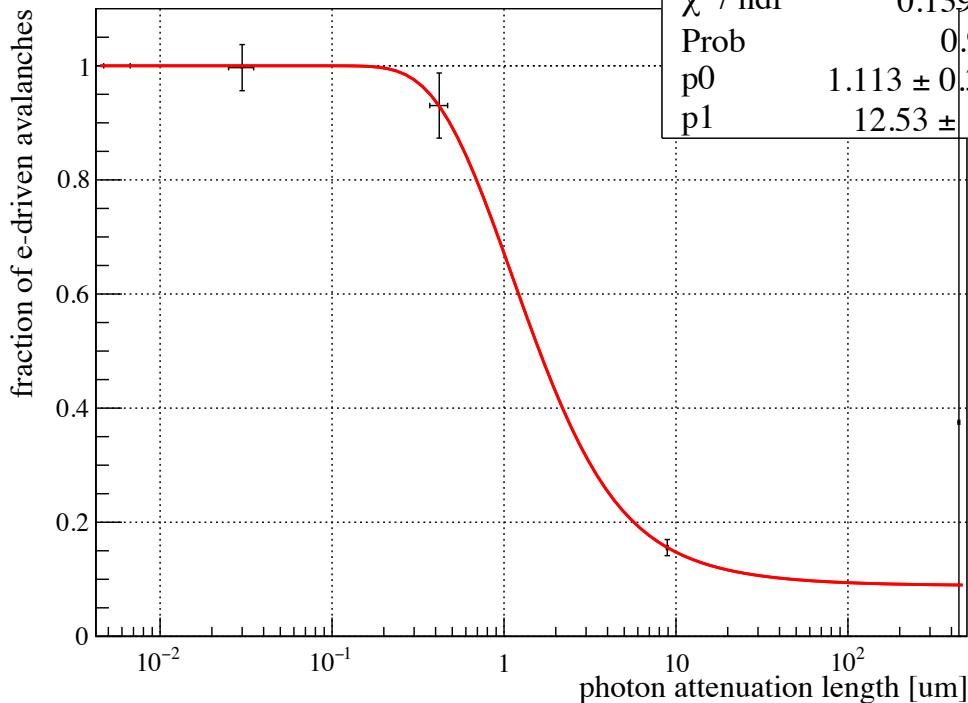
$$P_e(d_p) \sim (1 - e^{-k_e} e^{-\frac{k_e 2}{\Delta V}})$$

$$P_h(d_w) \sim \frac{P_e(d_p) \exp(\mu_{av}(2 - e^{\frac{d_p - xpn}{d_{av}}}))}{P_e(d_p) \exp(\mu_{av}(2 - e^{\frac{d_p - xpn}{d_{av}}})) + 1 - P_e(d_p)}$$

$$P_2(\lambda, V) \text{norm} = \left(P_e(d_p) \times f_e + P_h(d_w) \times (1 - f_e) \right)$$

$$f_e \text{ Only free parameter } f_e = 1 - \exp(-\alpha(x_{pn} - d_p))$$

χ^2 / ndf	0.1392 / 3
Prob	0.9867
p0	1.113 ± 0.3612
p1	12.53 ± 8.72



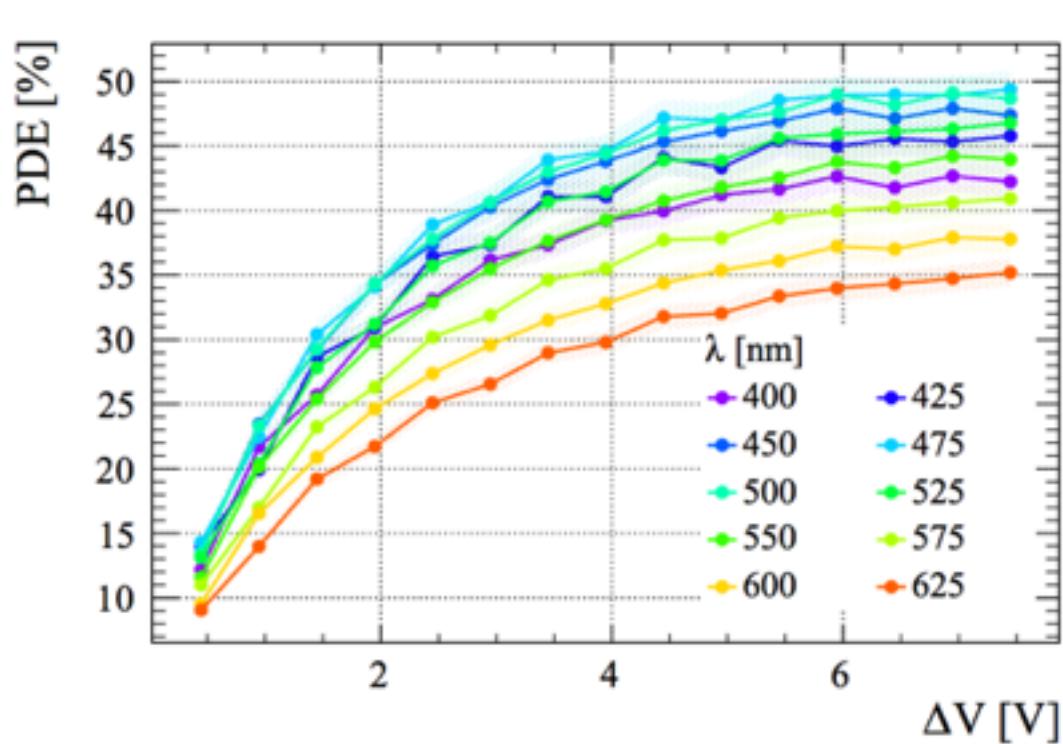
Application of this Concept for the H2017 Hamamatsu

12

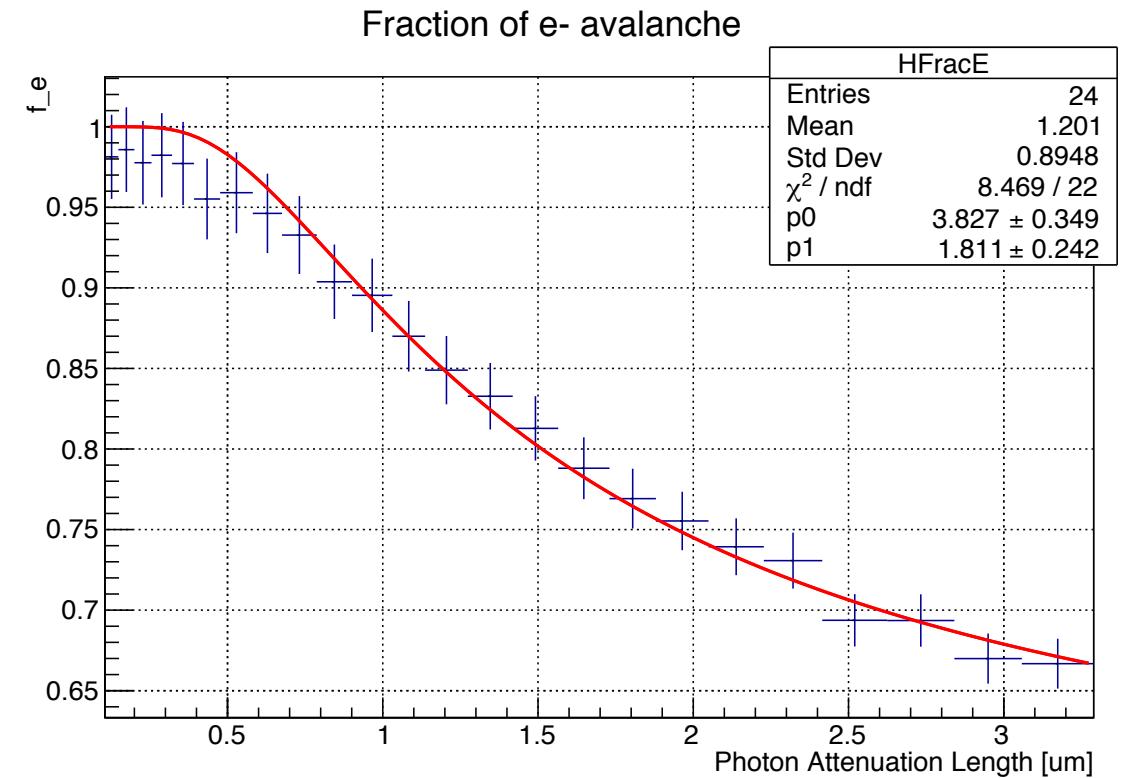
Characterisation of silicon photomultipliers based on statistical analysis of pulse-shape and time distributions

O. Girard^a, G. Haefeli^{a,*}, A. Kuonen^a, L. Pescatore^a, O. Schneider^a, M. E. Stramaglia^a

^aLaboratory for High Energy Physics, Ecole polytechnique fédérale de Lausanne (EPFL), BSP - Cubotron, 1015 Lausanne, Switzerland



H2017 Hamamatsu



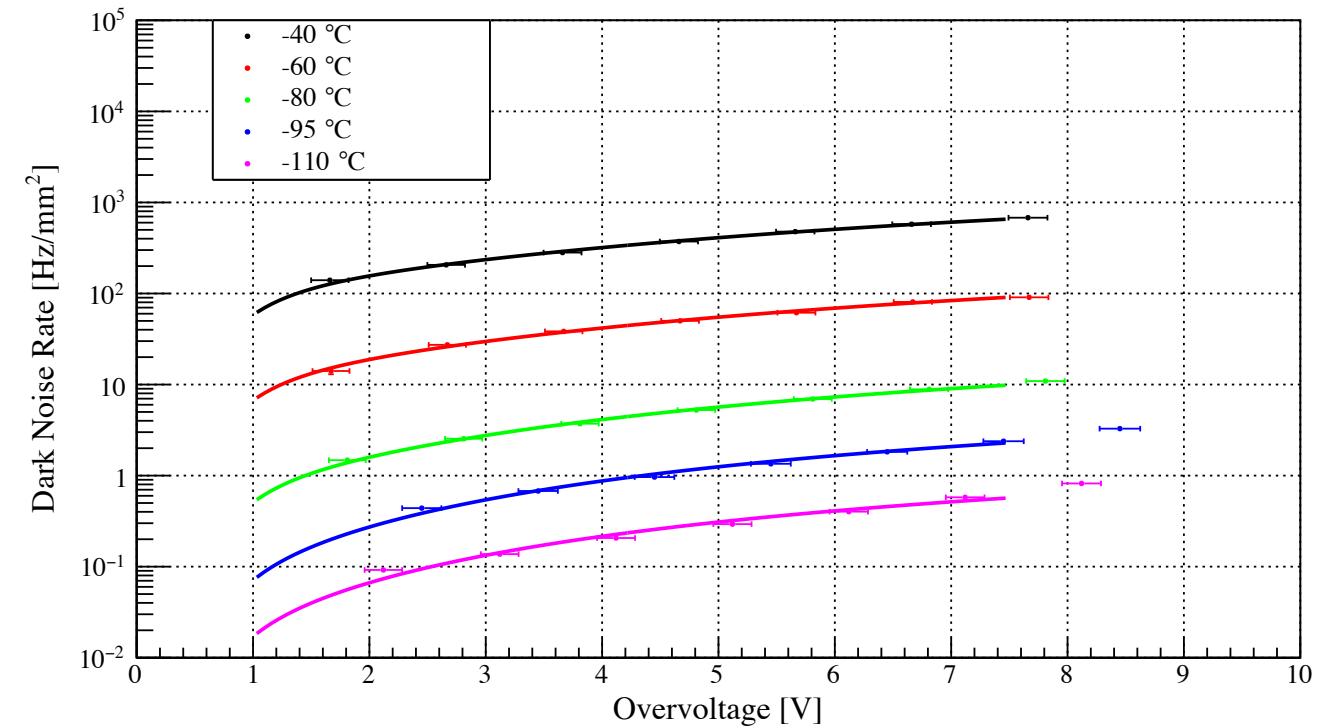
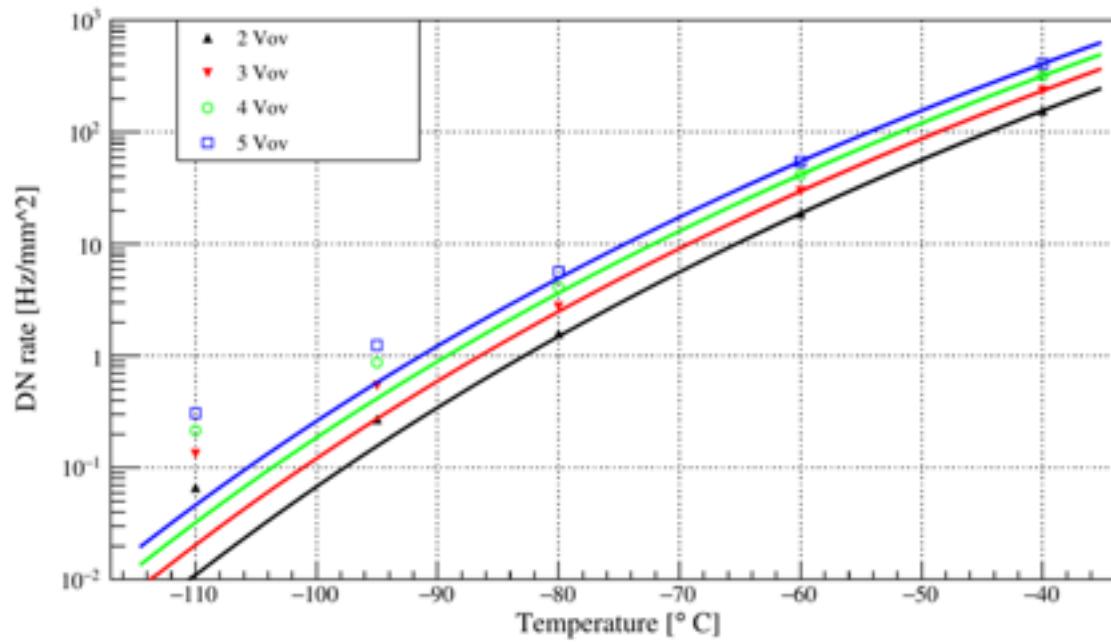
Extension of the Previous concept for DN -AP and CT fitting for Hamamatsu VUV4

13

$$R_{DN} \sim R_0(T) \left(P_e(d_p) \times f_{eDN} + P_h(d_w) \times (1 - f_{eDN}) \right)$$

Conclusion (for Hamamatsu VUV4)
 $f_{eDN} < 0.1$ Dominated by holes

$R_0(T)$ must be modified since at lower temperature is not only T dependent $R_0(T) \rightarrow R_0(T, V)$



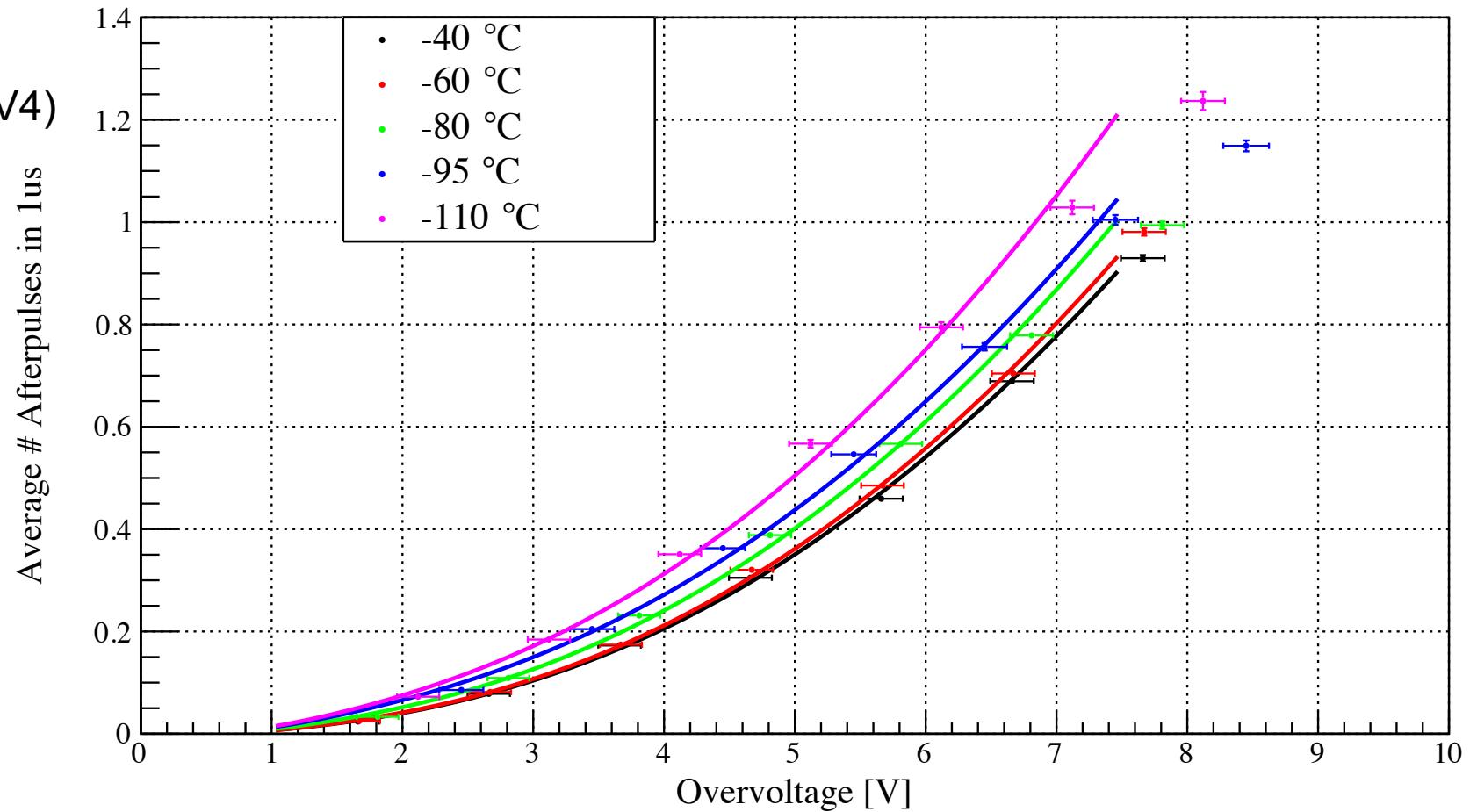
Extension of the Previous concept for DN - AP and CT fitting for Hamamatsu VUV4

14

$$P_{AP} = \frac{C\Delta V \gamma_{ap}}{e} \left(P_e(d_p) \times f_{eAP} + P_h(d_w) \times (1 - f_{eAP}) \right)$$

Conclusion (for Hamamatsu VUV4)

$f_{eAP} < 0.1$ Dominated by holes



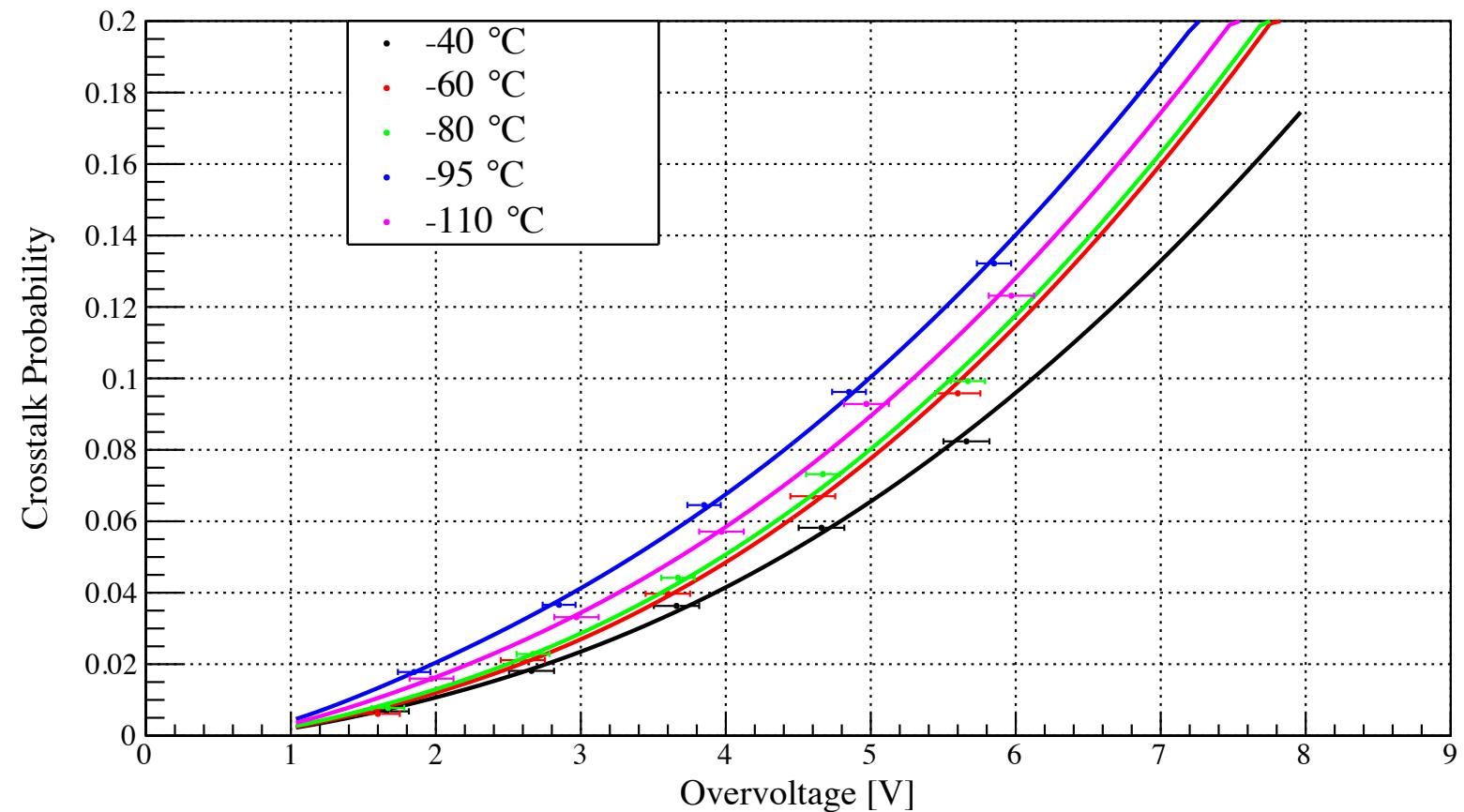
Extension of the Previous concept for DN -AP and CT fitting for Hamamatsu VUV4

15

$$P_{CT} = \frac{C\Delta V\gamma_{XT}}{e} \left(P_e(d_p) \times f_{eXT} + P_h(d_w) \times (1 - f_{eXT}) \right) \equiv k_{XT} \left(P_e(d_p) \times f_{eXT} + P_h(d_w) \times (1 - f_{eXT}) \right)$$

Conclusion (for Hamamatsu VUV4)

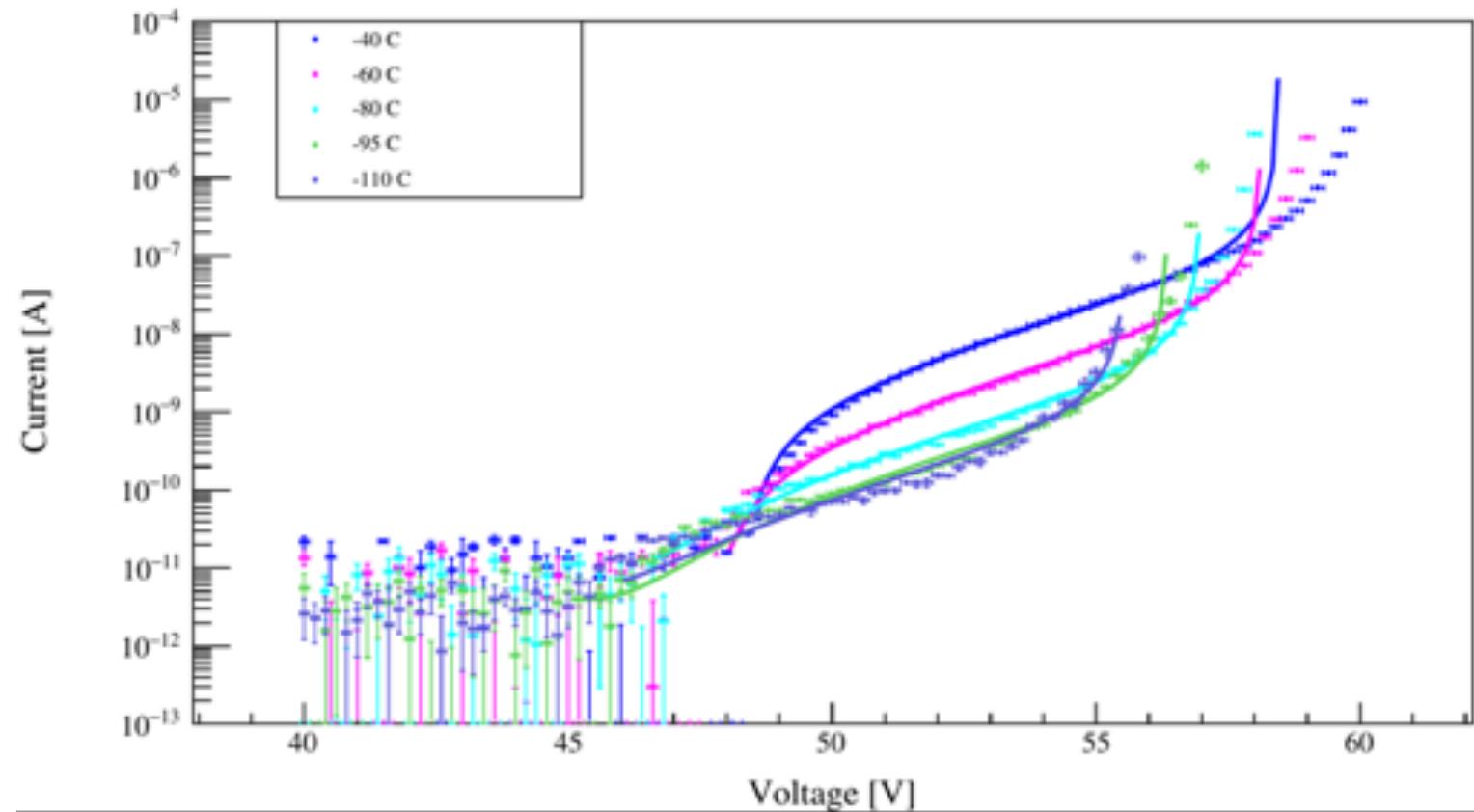
$f_{eXT} < 0.1$ Dominated by holes



IV curves

$$I = C \times \Delta V \times \left(R_0(T) \left(P_e(d_p) \times f_{eDN} + P_h(d_w) \times (1 - f_{eDN}) \right) \right) \times \left(1 + q \frac{P_{AP}}{1 - q \times P_{AP}} + P_{CT} \right) + I_0$$

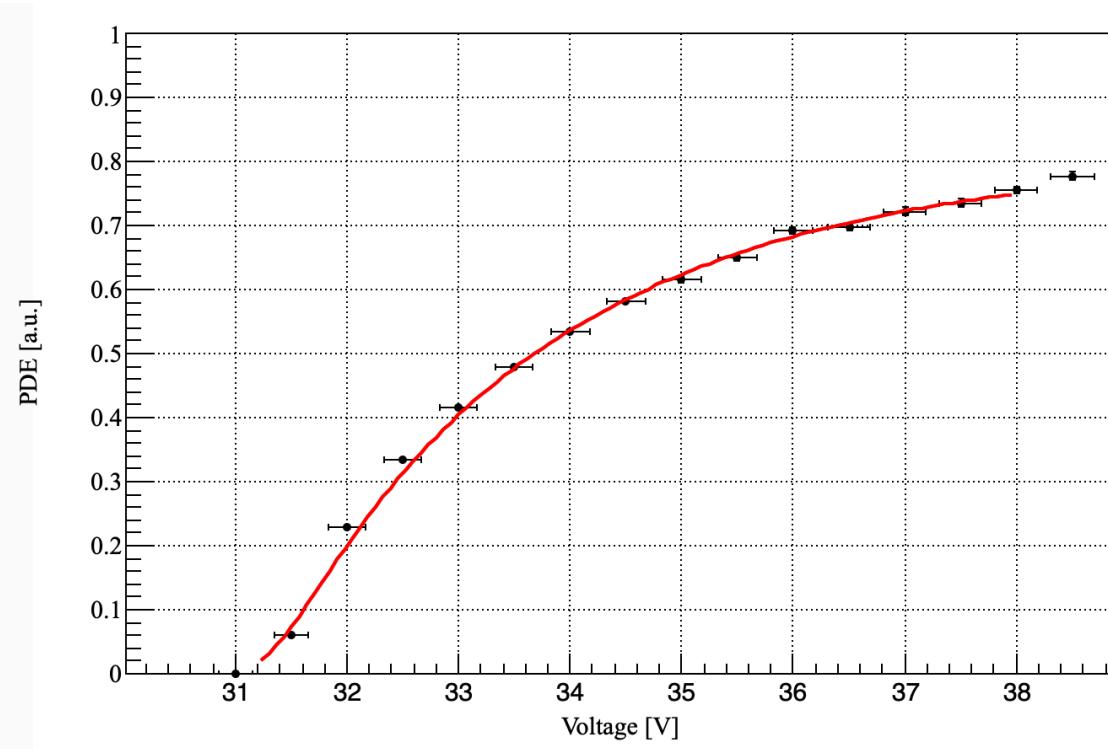
q: average fraction of charge carried by afterpulse



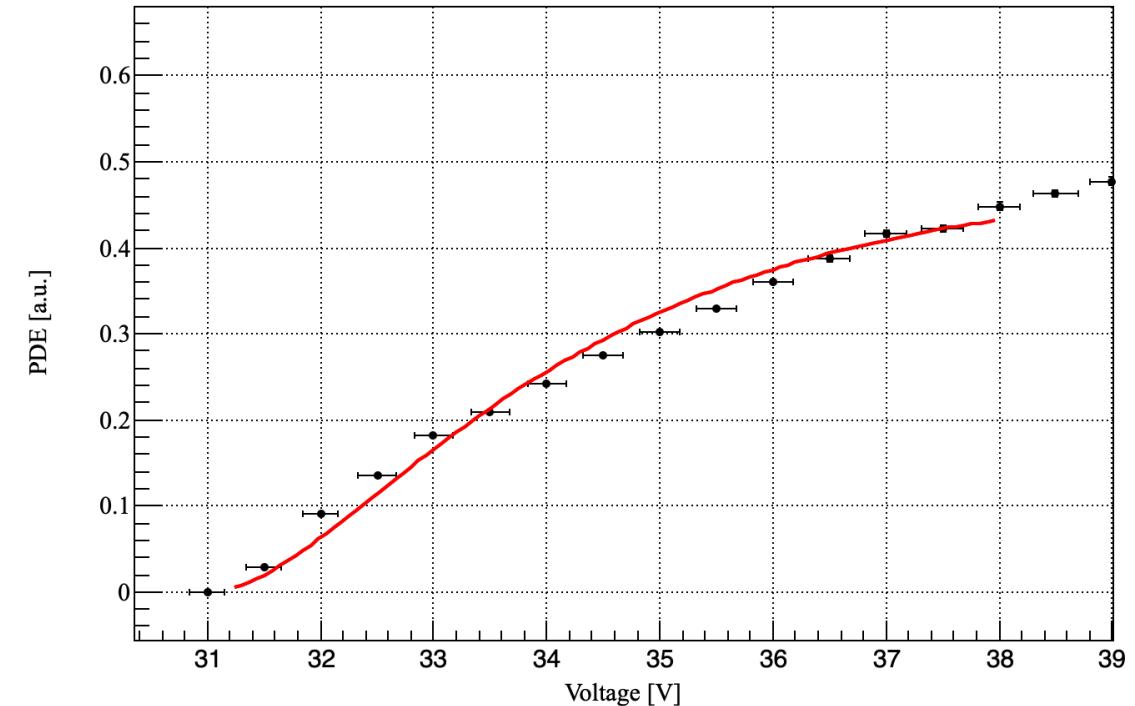
Parametrisation of FBK LF device

Not normalised to same light flux

17



378 nm



782 nm

Fit is not good and f_e has not the expected trend.
Probably this suggest a different junction structure

Conclusion

18

We have showed a parametrisation of the photo detection efficiency (PDE) starting from the avalanche triggering probability.

The parametrisation is quite successful for Hamamatsu devices.

We have then used this parametrisation to extract information of the junction length

We have used this parametrisation to probe the source of Dark Noise, After Pulse and Crosstalk

We are applying now the theory to FBK devices.

Thank you

www.triumf.ca