Characterisation of Hamamatsu silicon photomultiplier arrays for the LHCb Scintillating Fibre Tracker Upgrade

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Presented by
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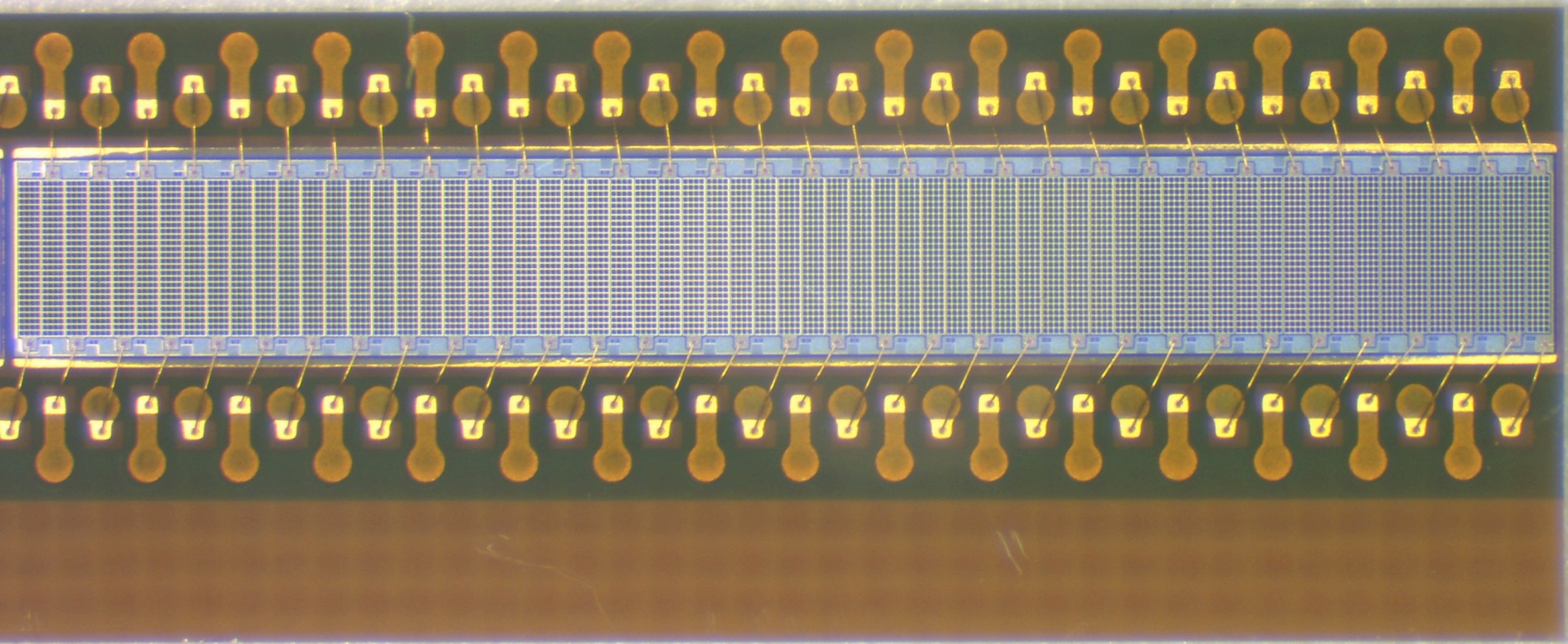
On behalf of the LHCb SciFi Tracker group

Outline

- LHCb Upgrade and the Scintillating Fiber Tracker (SciFi) project
- Silicon photomultipliers (SiPMs) and the measurement of its characteristics
- SiPM challenges in the context of the LHCb SciFi Tracker

Related talks at TIPP 2017:
- SciFi - A large Scintillating Fibre Tracker for LHCb, by Ulrich Uwer -> Tuesday
- A readout ASIC for the LHCb Scintillating Fibre (SciFi) tracker, by Xiaoxue Han -> Tuesday

The LHCb Upgrade and the Scintillating Fiber Tracker (SciFi) project



The LHCb Upgrade

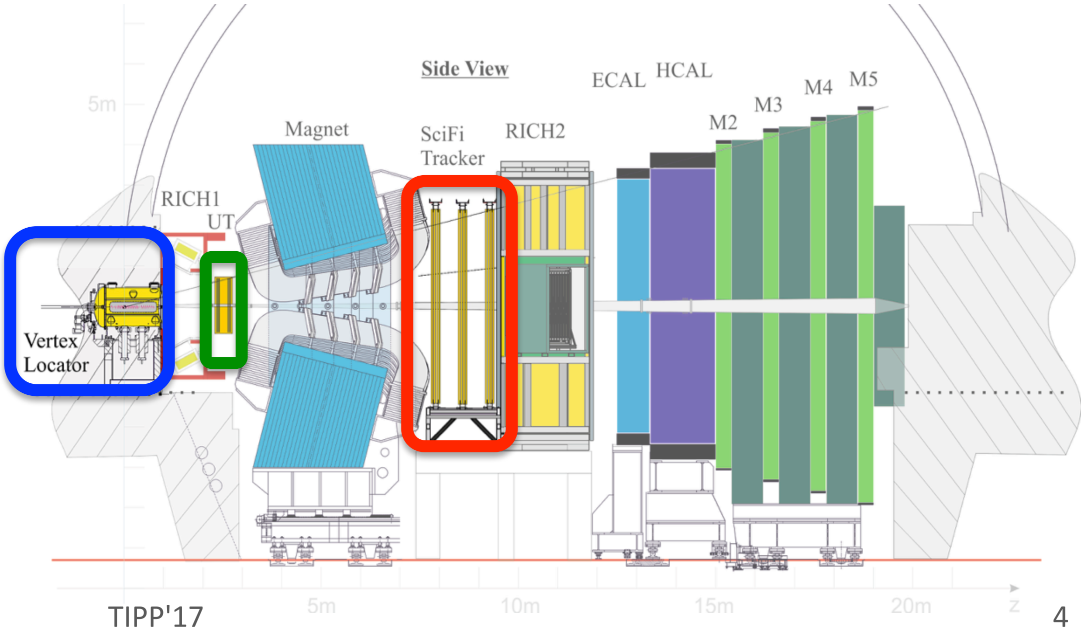
LHCb will collect data until the LS2 (2019). Parts of the current detector will be replaced

Goal:

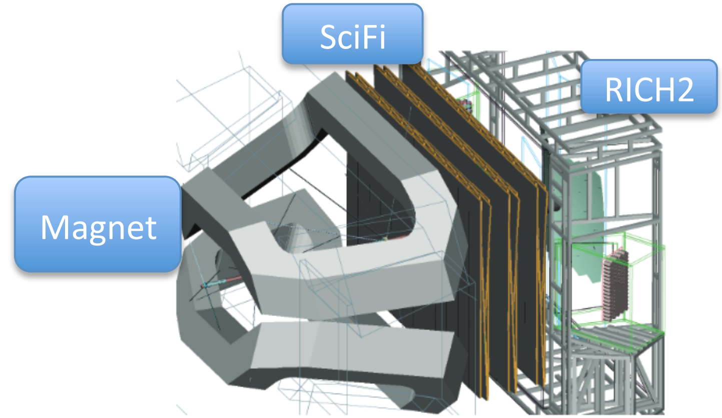
- raise the operational luminosity to improve the measurements with higher statistics (integrated luminosity ≈ 50 fb^{-1})
- improve the trigger efficiency:
  - Replace Level-0 hardware trigger (1MHz) by a software trigger (40MHz).
  - New sub-detectors, front-end electronics in particular, must be compatible with 40 MHz readout.

LHCb Tracking upgrade:

- New VELO, Si-pixel
- New Upstream tracker (UT), Si-strip
- SciFi Tracker, scintillating fibres

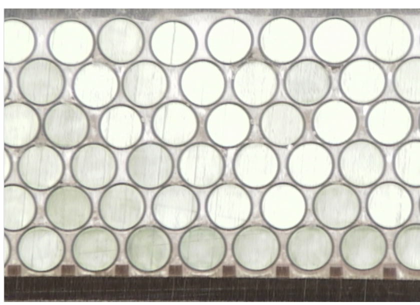


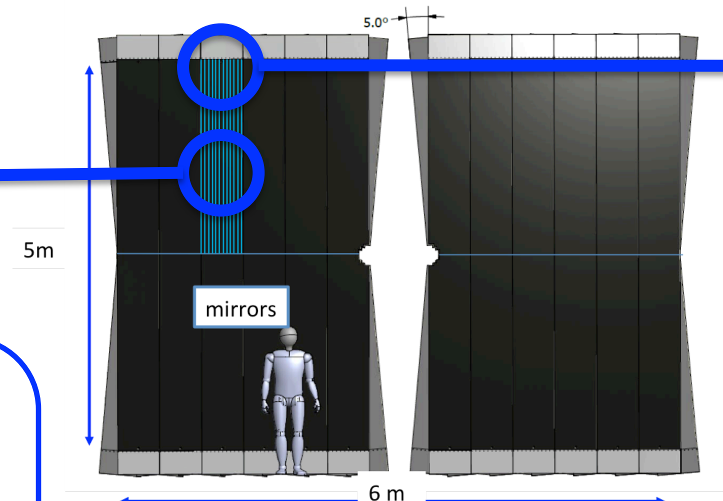
The LHCb SciFi Tracker

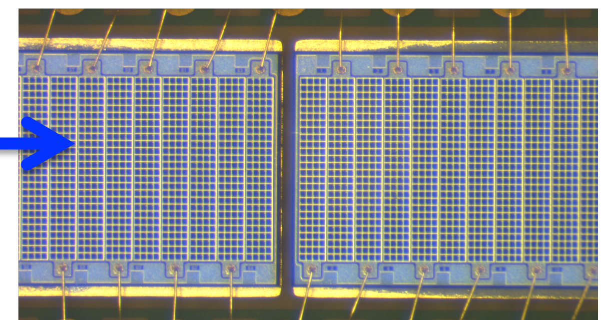


Requirements :

- Hit detection efficiency higher than 98%
- Spatial resolution better than 100µm
- 40MHz readout without dead time
- Operation in radiation environment, fibres 35 kGy and SiPMs 6x10^{11} 1MeV n_{eq}/cm^2 (with neutron shielding) + 100 Gy ionising dose
- Low material with X/X0≤1% per detection layer







Scintillating fibres:

- 2.5m long, 250µm diameter, Kuraray SCSF-78M
- Mirrored at one end, SiPM on the other
- Six layer in each module (1.5mm stacking height)

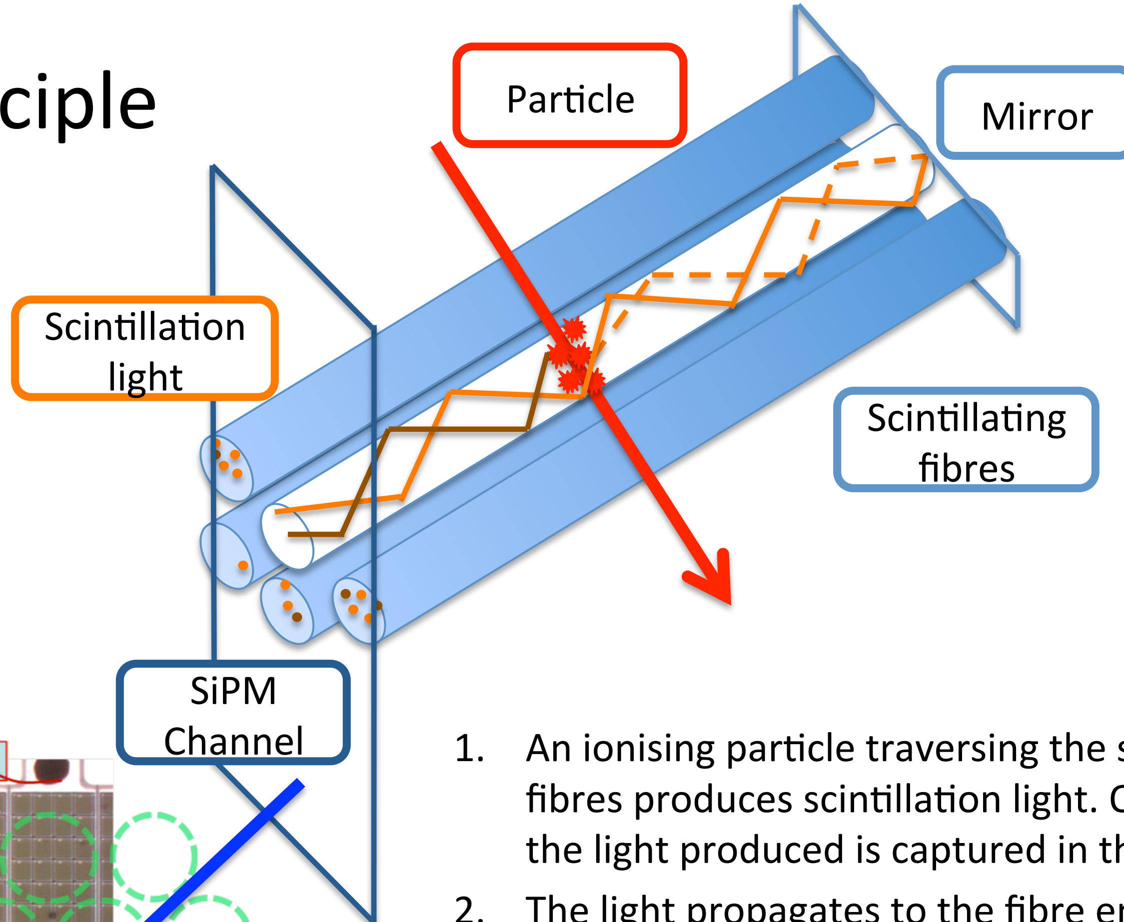
Structure:

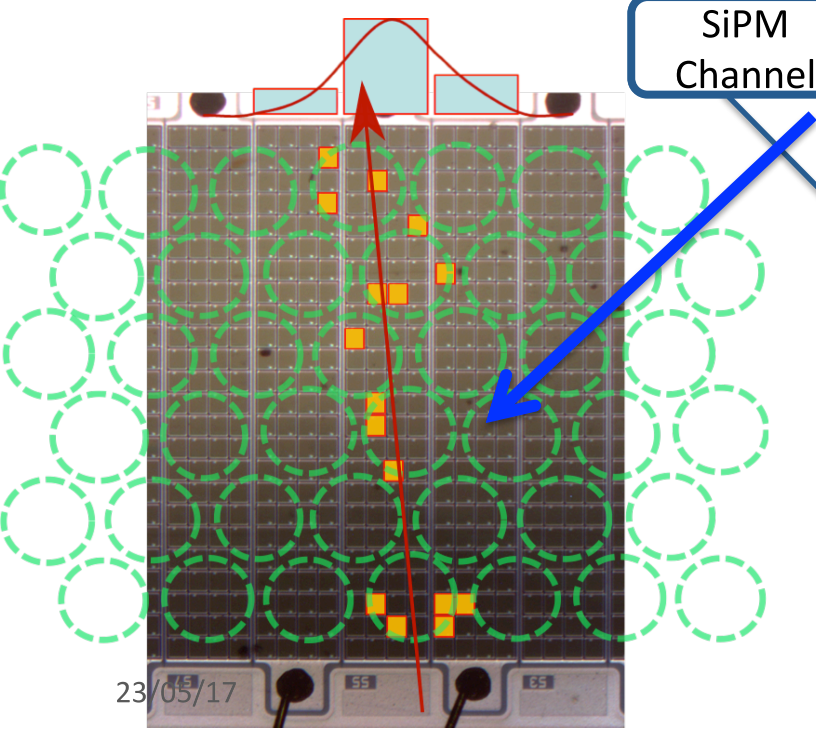
- 3 stations
- 4 detection planes
- 12 modules per detection plane

SiPM:

- SiPM multichannel array from Hamamatsu S13552-HRQ
- 128 channels per arrays, 104 pixels per channel
- 57x62µm^2 pixels, channel size is 0.25x1.62mm^2

Working principle



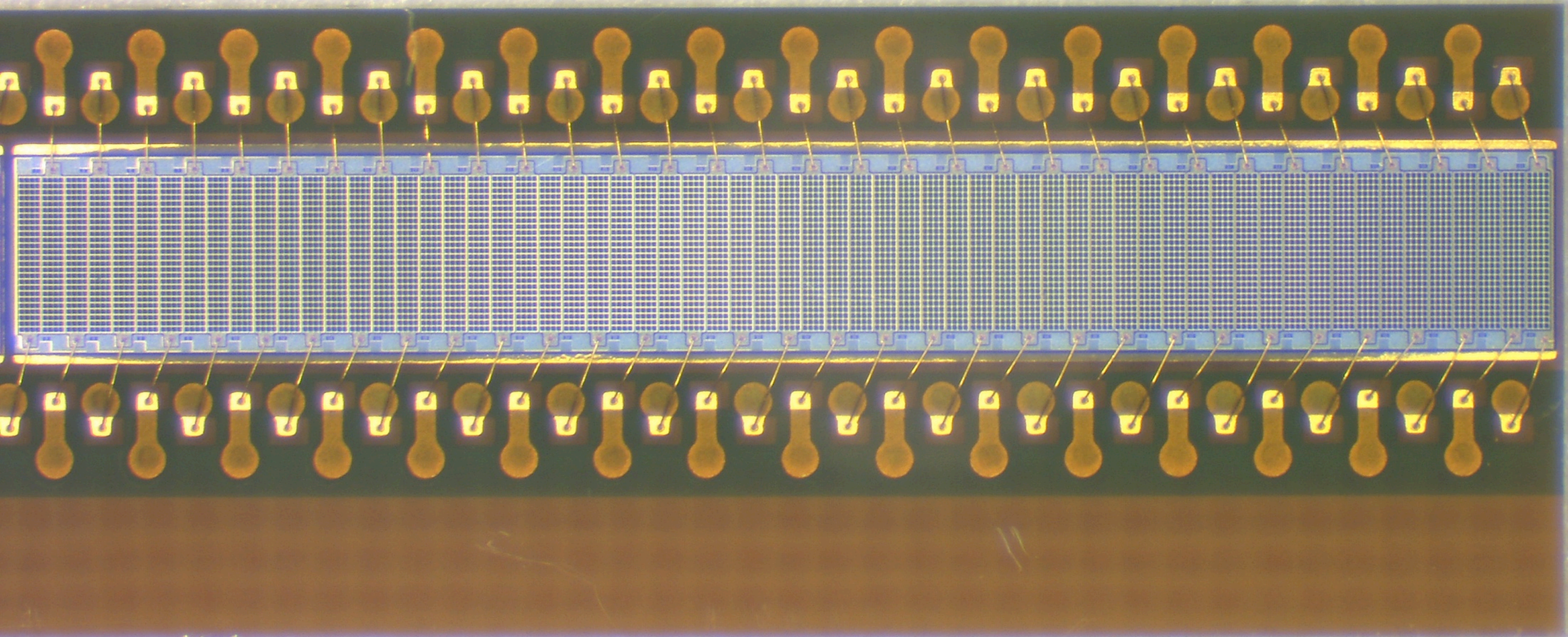


1. An ionising particle traversing the scintillating fibres produces scintillation light. Only 10% of the light produced is captured in the fibres.
2. The light propagates to the fibre end is either reflected by a mirror or detected by the SiPMs (firing pixels are indicated in yellow).
3. The signal from neighbouring channels is combined to a cluster (zero suppression)
4. The particle position is calculated by a weighted mean of the signal in the cluster.

Related talks at TIPP 2017:

- SciFi - A large Scintillating Fibre Tracker for LHCb, by Ulrich Uwer -> Tuesday afternoon

SciFi SiPM general characteristics

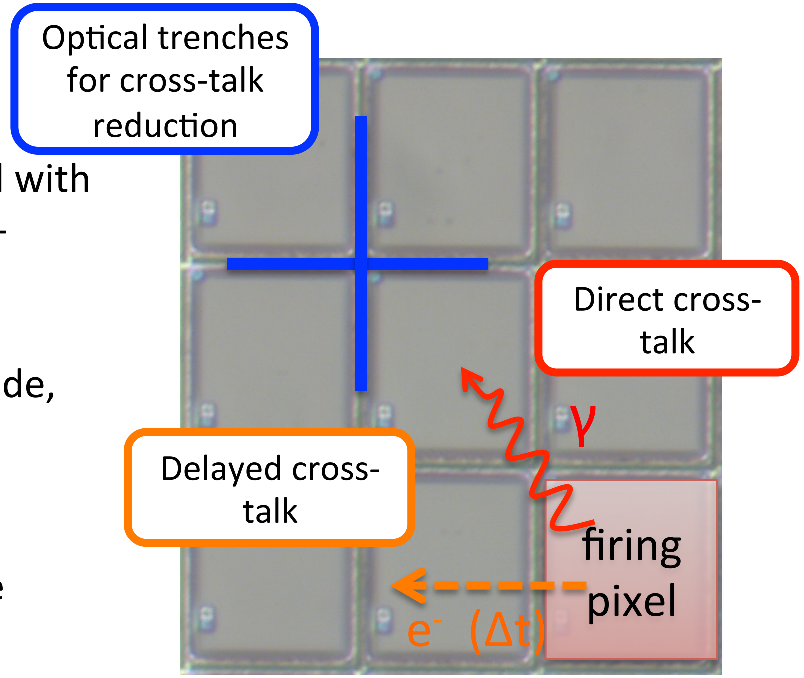


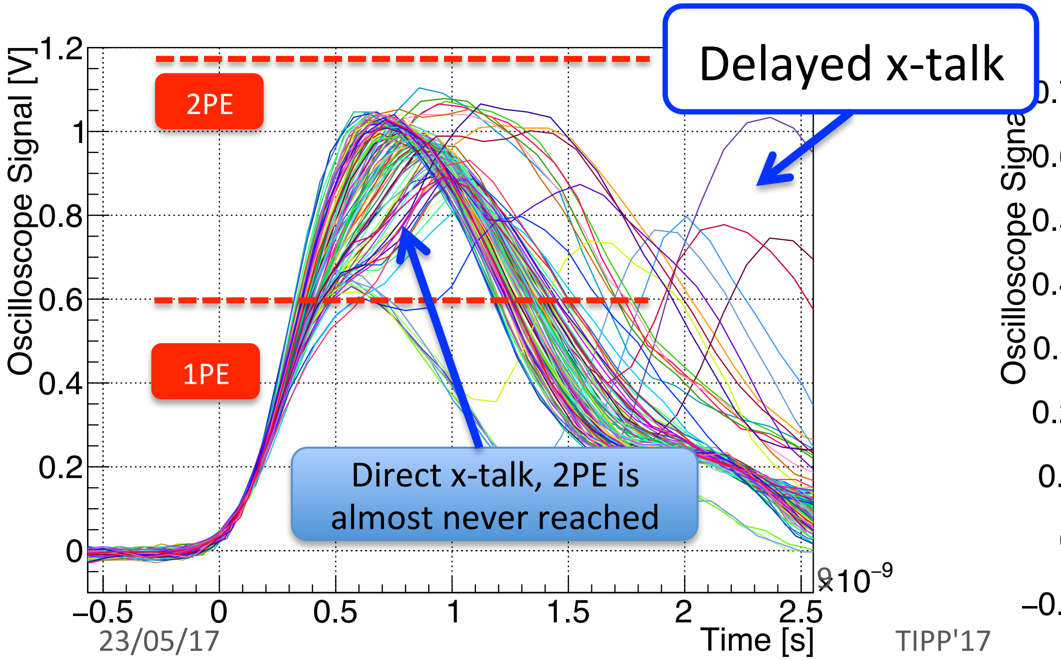
Correlated noise

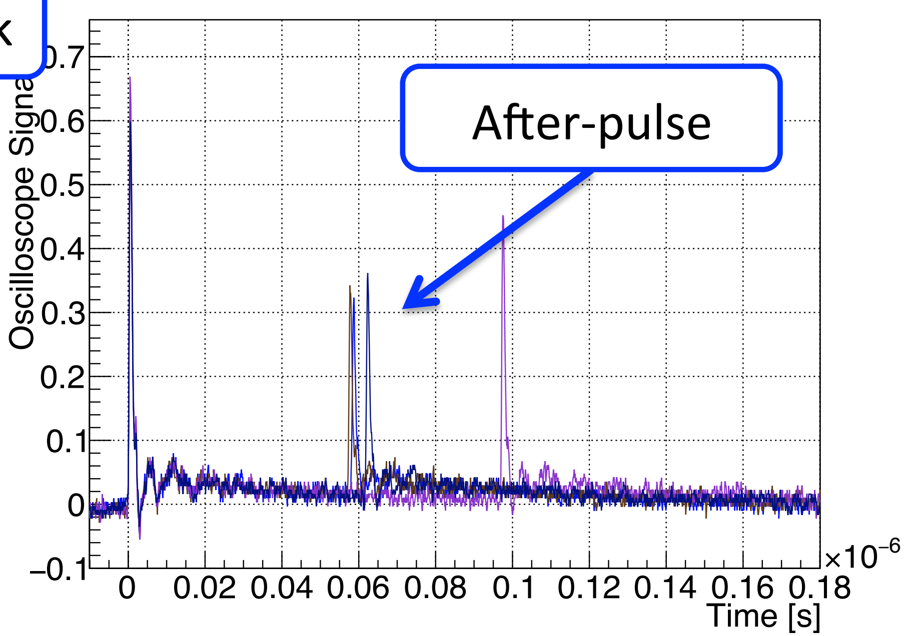
1. Direct cross-talk: pixel to pixel cross-talk, fully correlated with primary avalanche -> Signal amplitude between 1Photo-electron (PE) and 2PE

2. Delayed cross-talk: delayed in time but with full amplitude, strongly correlated with the primary avalanche
-> Signal amplitude is 1PE

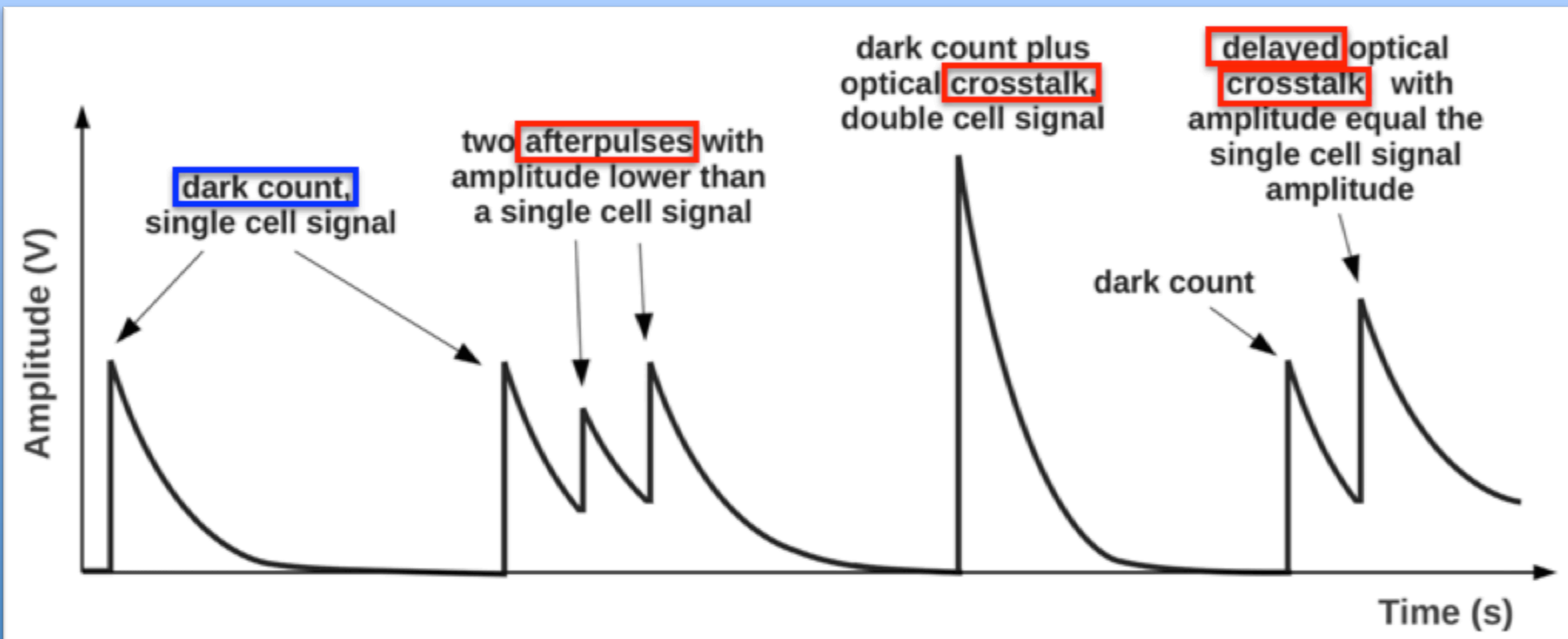
3. After-pulse: due to an avalanche in the same pixel as the primary avalanche
-> Signal amplitude is given by the pixel recovery state



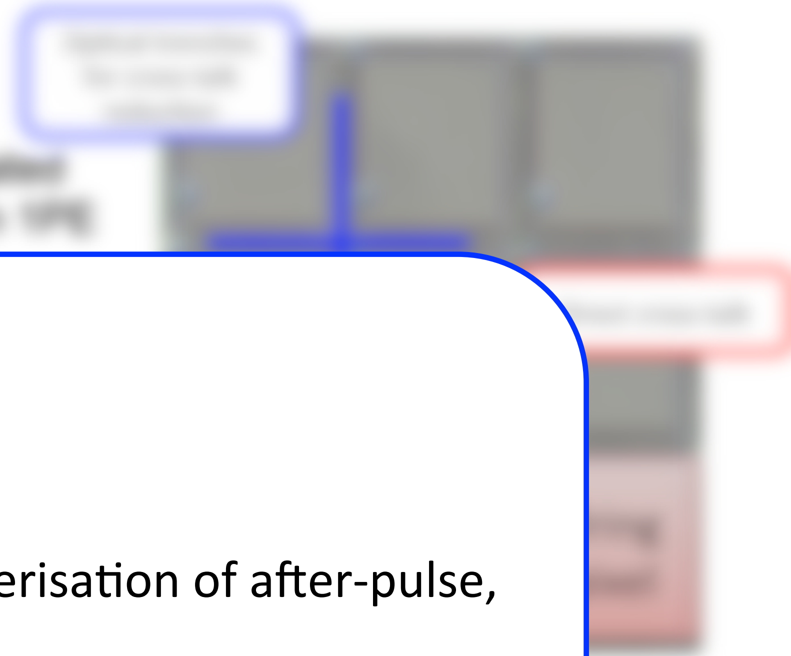




Correlated noise



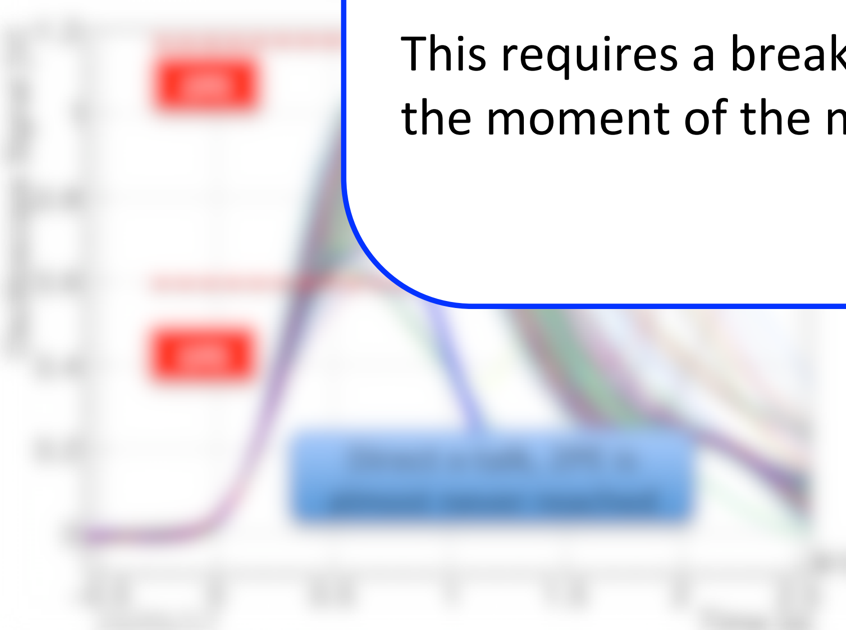
Correlated noise

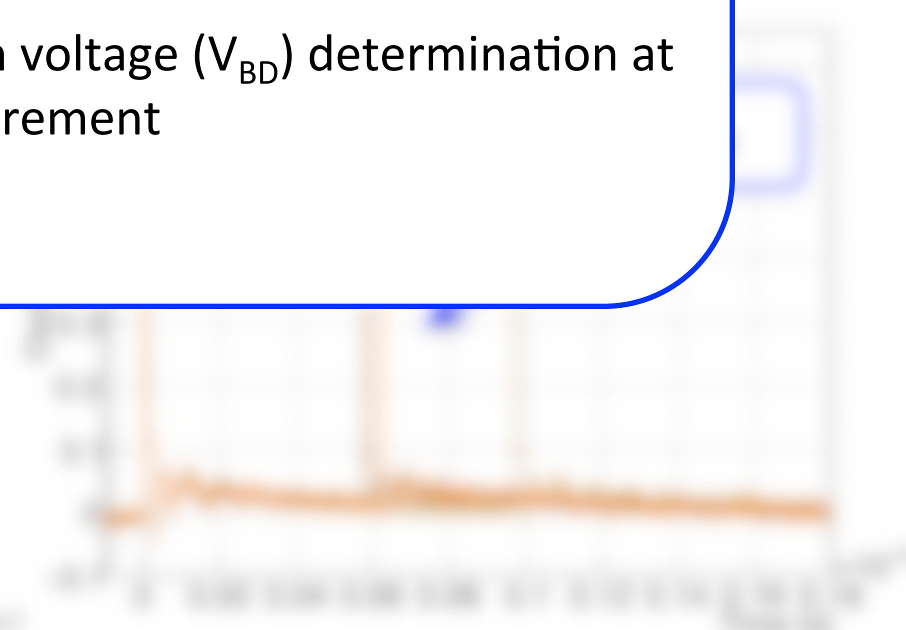


Goal:

Over-voltage dependent characterisation of after-pulse, direct and delayed crosstalk.

This requires a breakdown voltage (V_{BD}) determination at the moment of the measurement

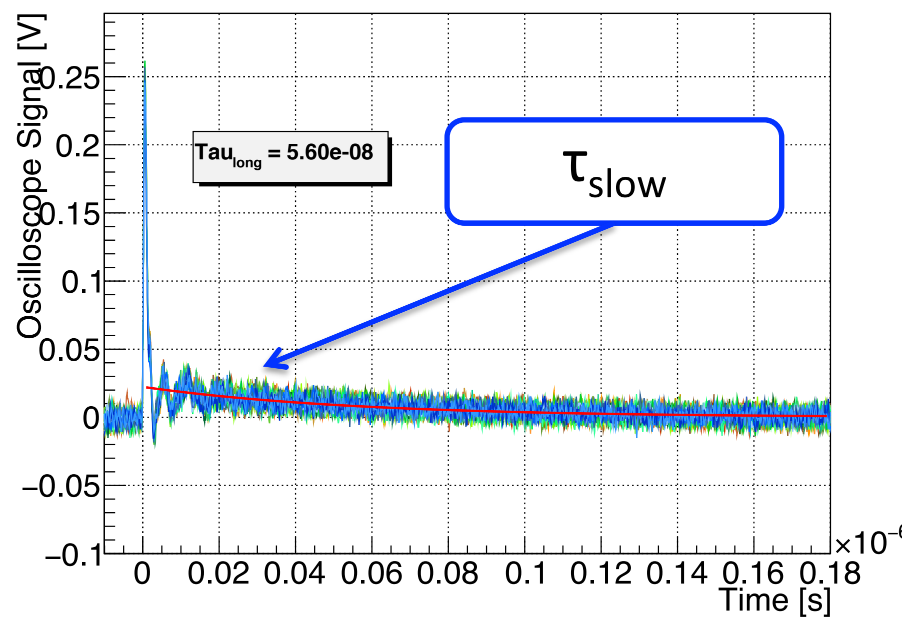


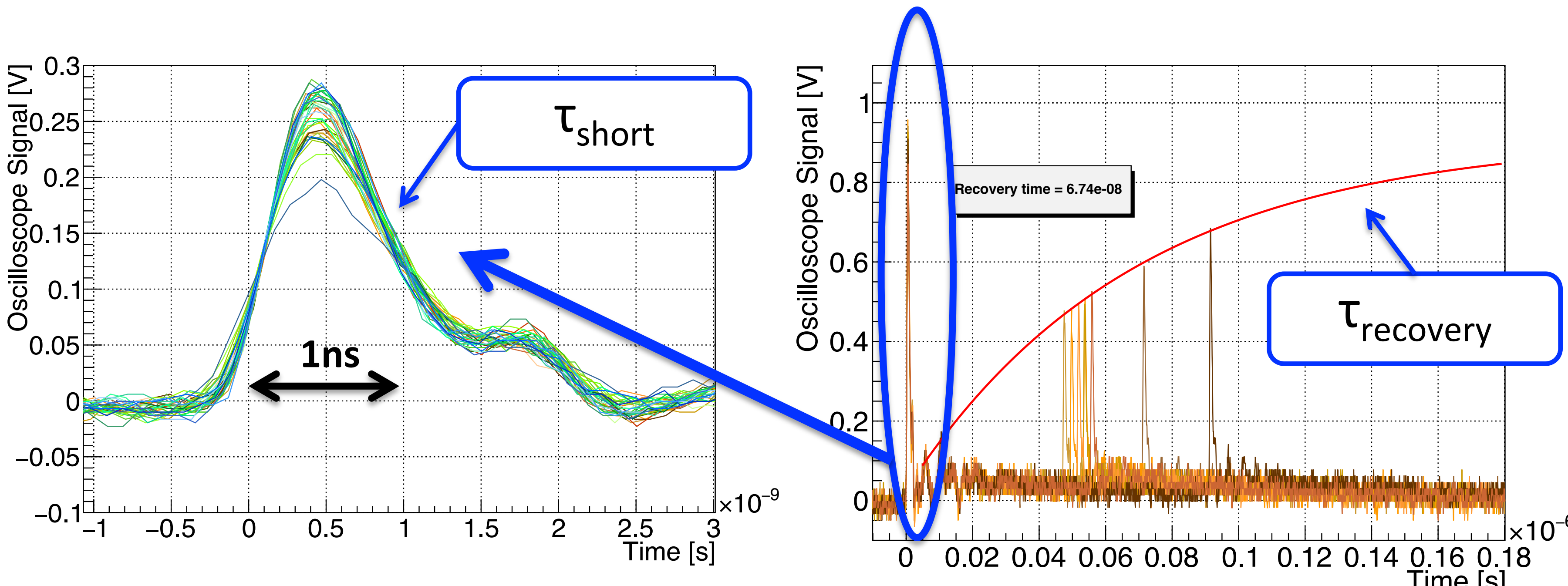


Pulse shape

We distinguish three types time constants:

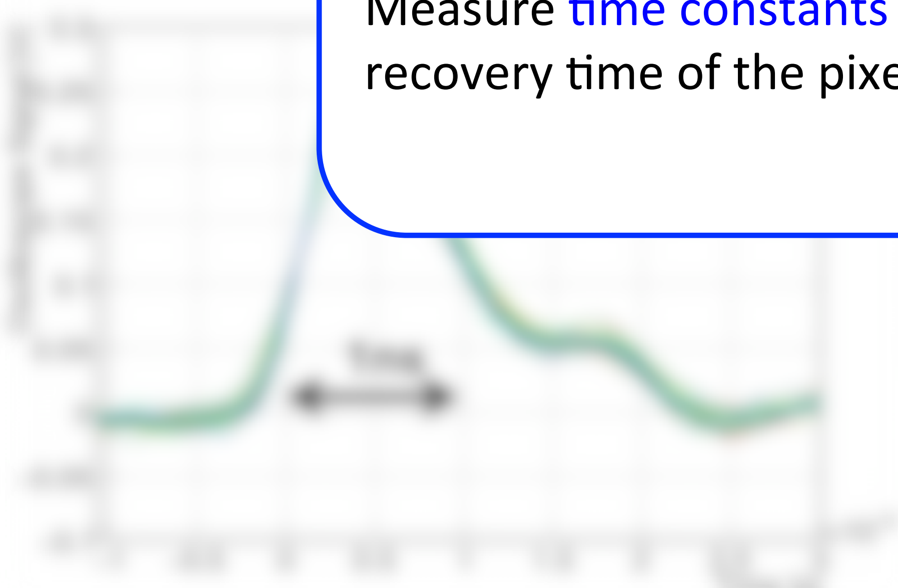
- τ_{short} : < 1ns (measurement affected by DAQ bandwidth)
- τ_{slow} : ~50ns, estimated by fitting the slow component
- $\tau_{recovery}$: ~70 ns, obtained from the fit of the “after-pulses” amplitude vs time

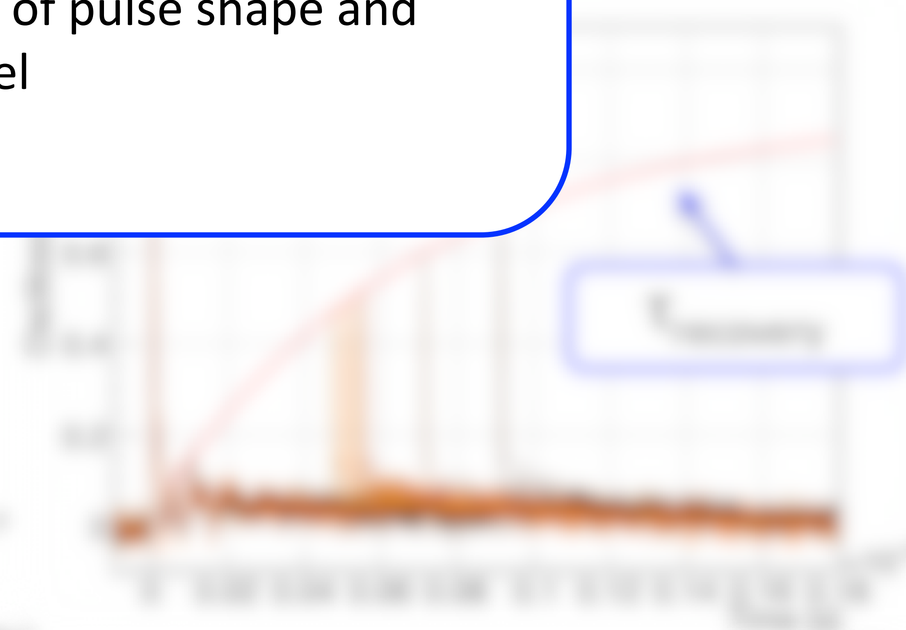




Pulse time constant

We distinguish three types time constants





Goal:

Measure time constants of pulse shape and recovery time of the pixel

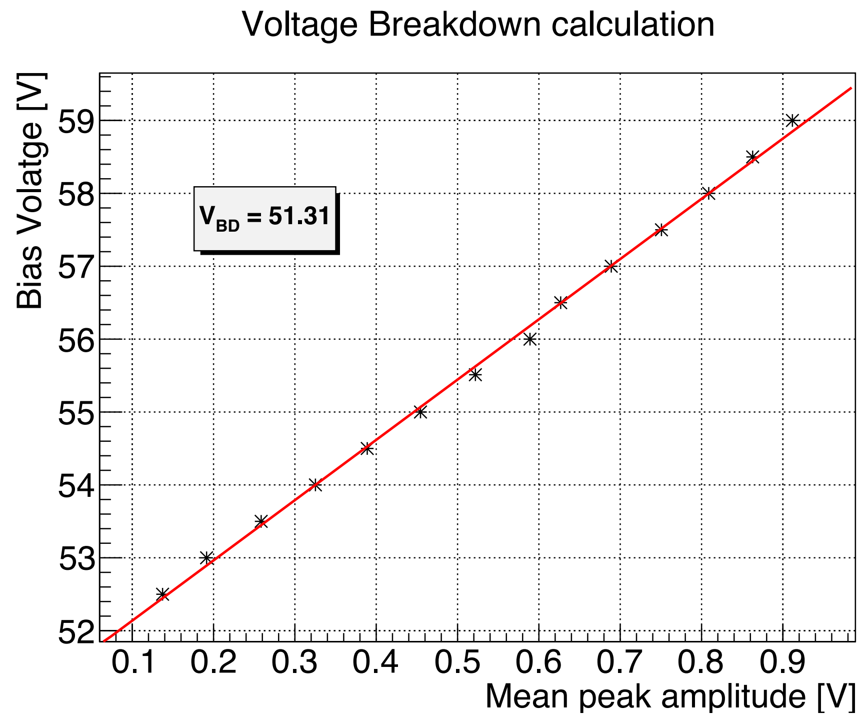
Pulse shape analysis

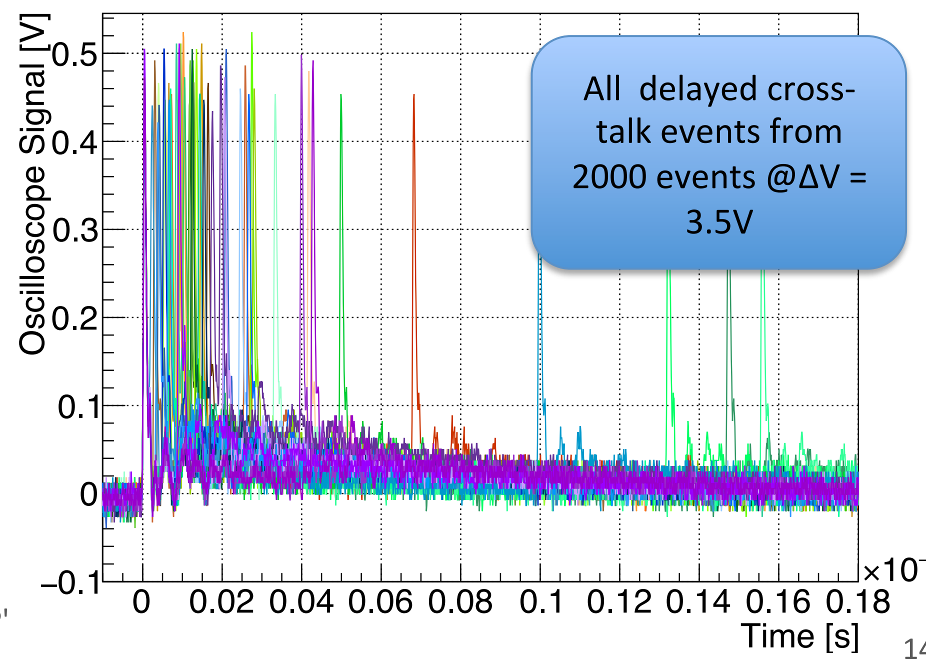
Instrumentation

Use fast (1GHz) oscilloscope with fast pre-amplifier (2GHz, x10 or x100) to record waveforms

Method

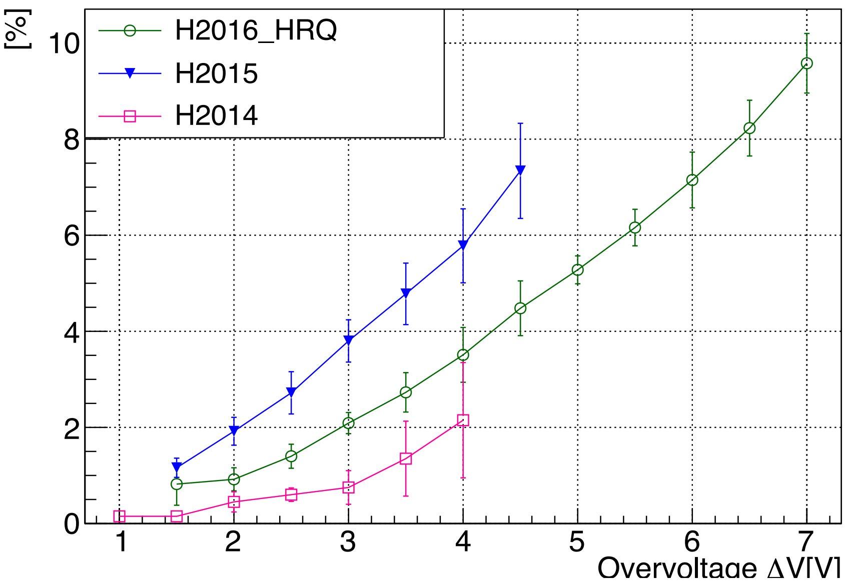
- The trigger is set to 0.5PE to record a sample of ~2000 dark counts events for off-line analysis
- Calculation of V_{BD} by fitting the triggered pulse amplitude for every bias value
- Analysis is performed with a threshold based peak finding and selection algorithm
- Pulse shape is obtained by fitting the selected pulse



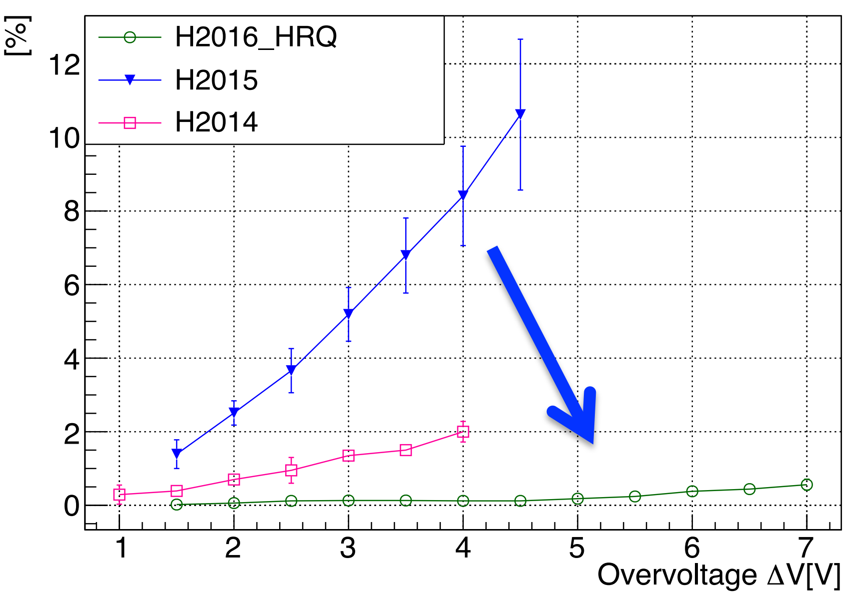


Improvement by R&D

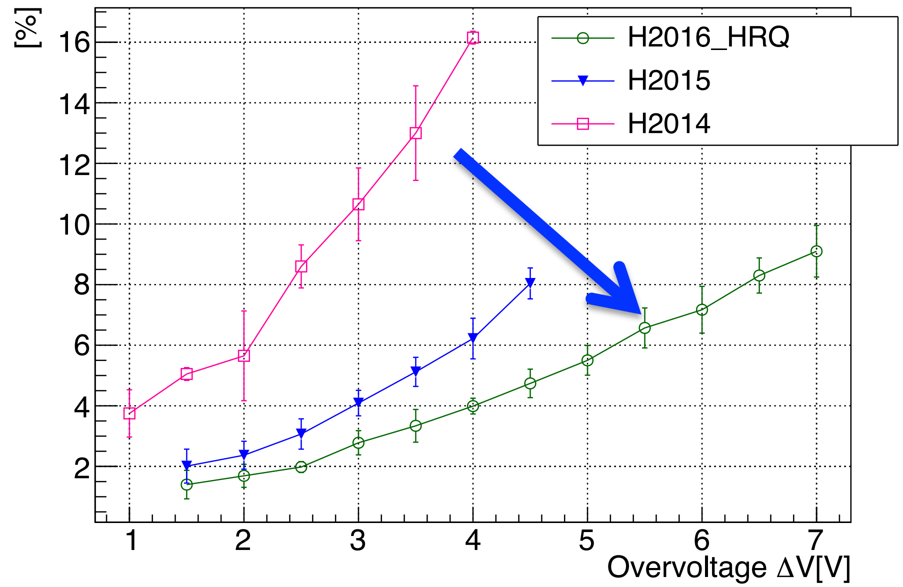
Delayed x-talk prob.



After-pulse prob.



Direct x-talk prob.



Characteristic at operation point ΔV=3.5V and 25°C	SciFi SiPM
Direct cross-talk	3%
Delayed cross-talk	2.5%
After-pulse	0%
Total correlated noise	5.5%

Time constants	SciFi SiPM
Recovery time	69ns
Long component	50ns
Short component	<1ns

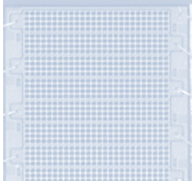
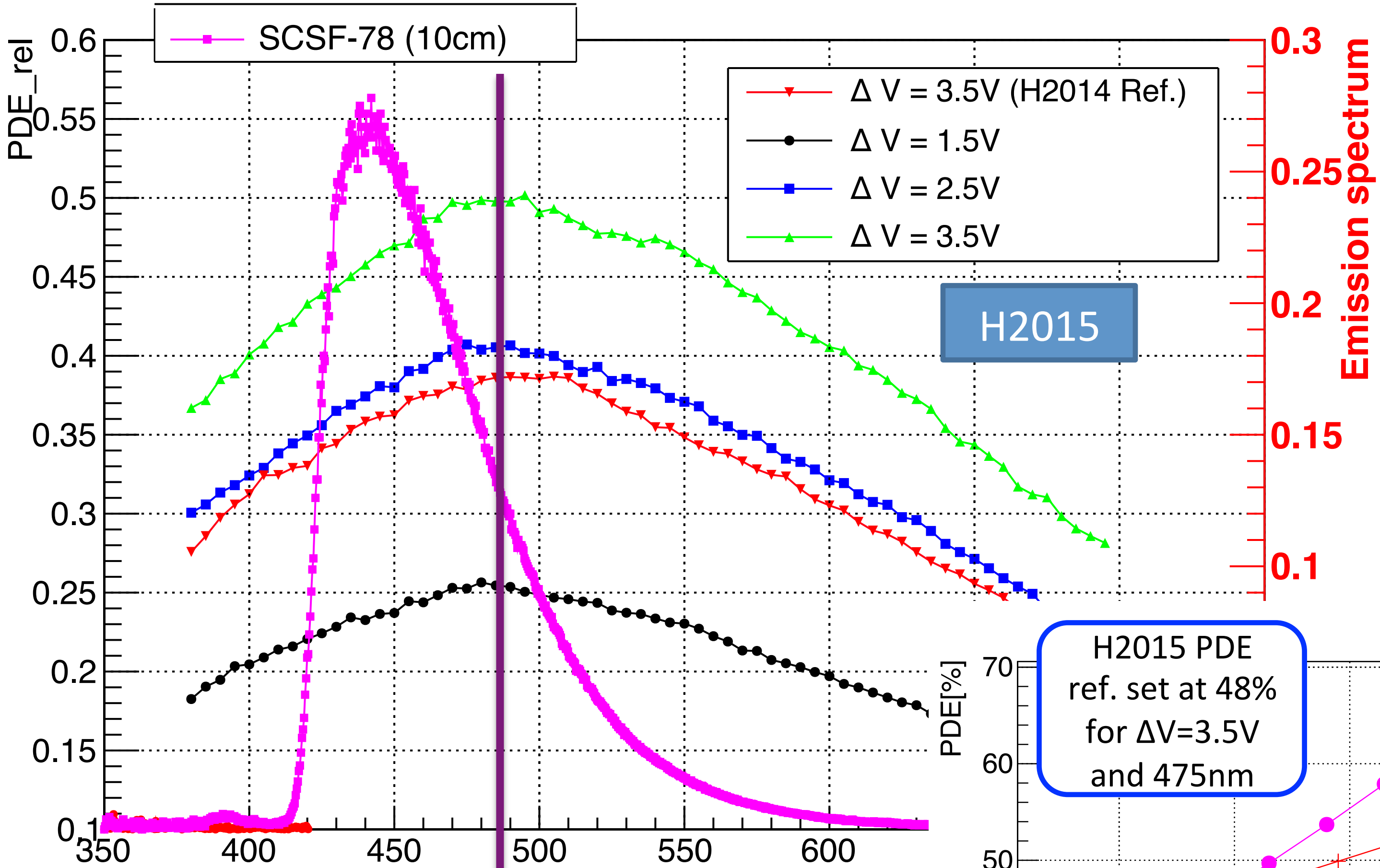
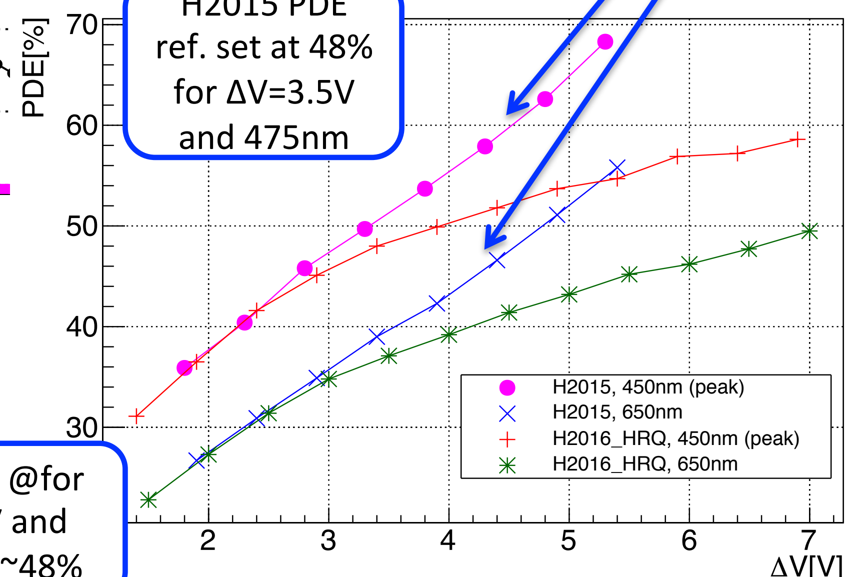


Photo detection efficiency



Unstable detector regime

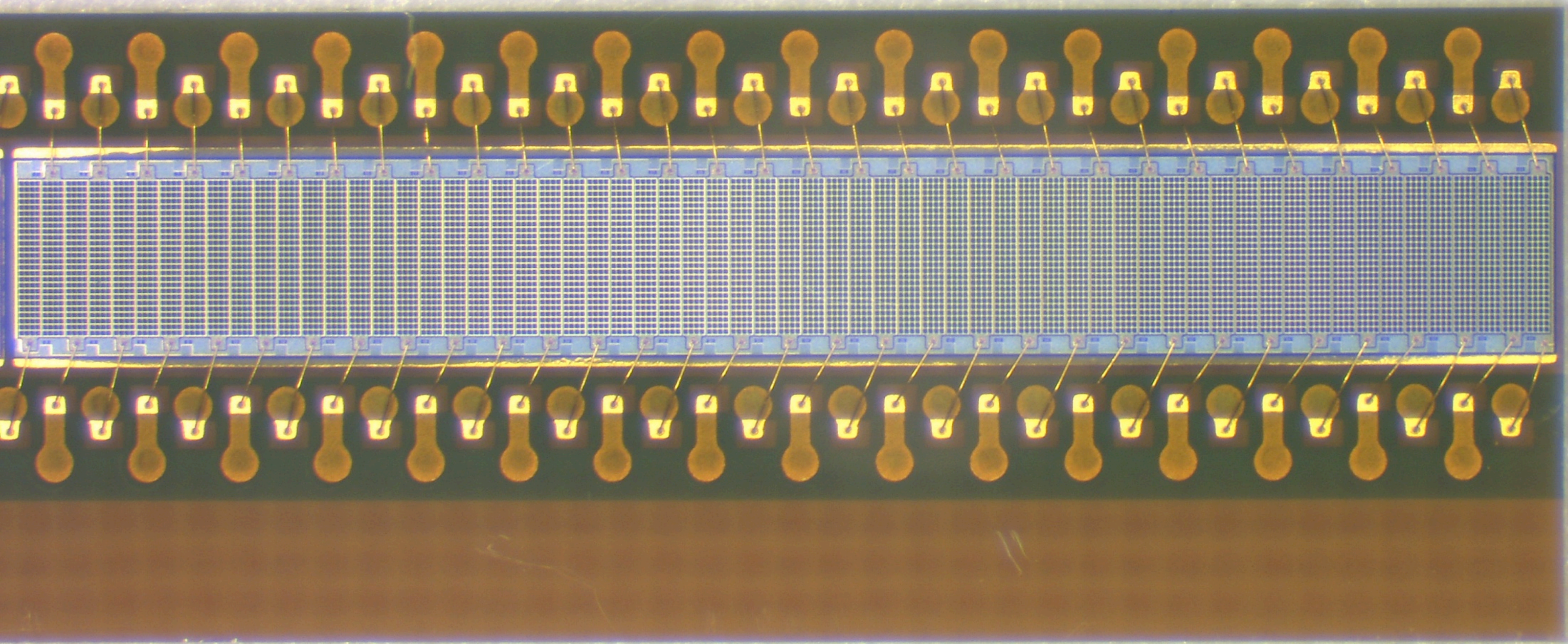
H2015 PDE ref. set at 48% for ΔV=3.5V and 475nm



$$PDE(\Delta V) = FF \times QE \times P_{Avalanche}(\Delta V)$$

PDE peak @for ΔV=3.5V and 475nm = ~48%

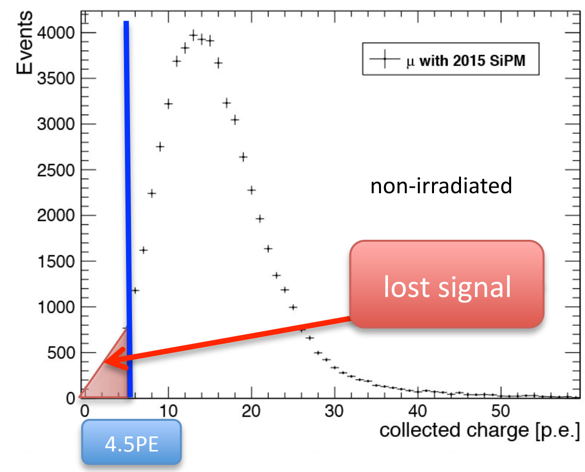
SiPM challenges in the context of the LHCb SciFi Tracker



Low light – high noise ?! How can it work ?

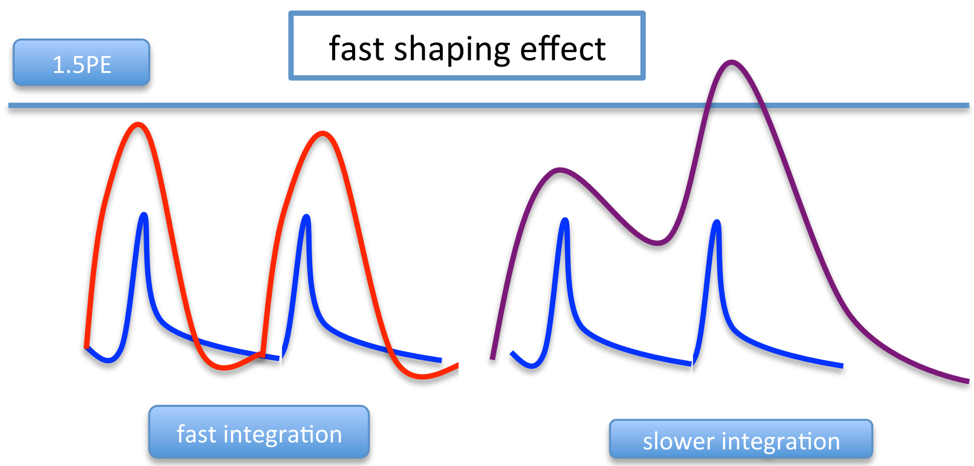
Challenges:

- The fibre light output for particle crossing far from SiPM (2.5m) is about 14PE.
- The dark count rate (the DCR is due to thermal noise) and therefore the noise cluster rate (NCR) produced by the SiPM is dramatically increased due to the radiation damage.



Solutions:

- SiPM are cooled down to -40°C to reduce the DCR by a factor 2 every 10°C
- Fast readout electronics to reduce random overlap from consecutive dark pulses (20-25ns integration time)
- Combining signals from different channels to clusters and use the cluster information for efficient noise rejection.



Related talks at TIPP 2017:

- A readout ASIC for the LHCb Scintillating Fibre (SciFi) tracker, by Xiaoxue Han

Irradiation studies

- Expected dose at the end of lifetime is $6*10^{11}$ 1MeV n_{eq}/cm^2
- Detectors are regularly sent for irradiation to Ljubljana (irradiation dose controlled with pin diode)

Method:

- Annealing at 35°C during one week after irradiation
- T varied from 20 to -50°C, monitored by a T sensor mounted below the SiPM array
- Measurement (by automated multiplexer, covering 128 channels) of :
  - IV curves
  - DCR, from the recorded current:

$$f_{DCR} = \frac{I}{G \cdot e}$$

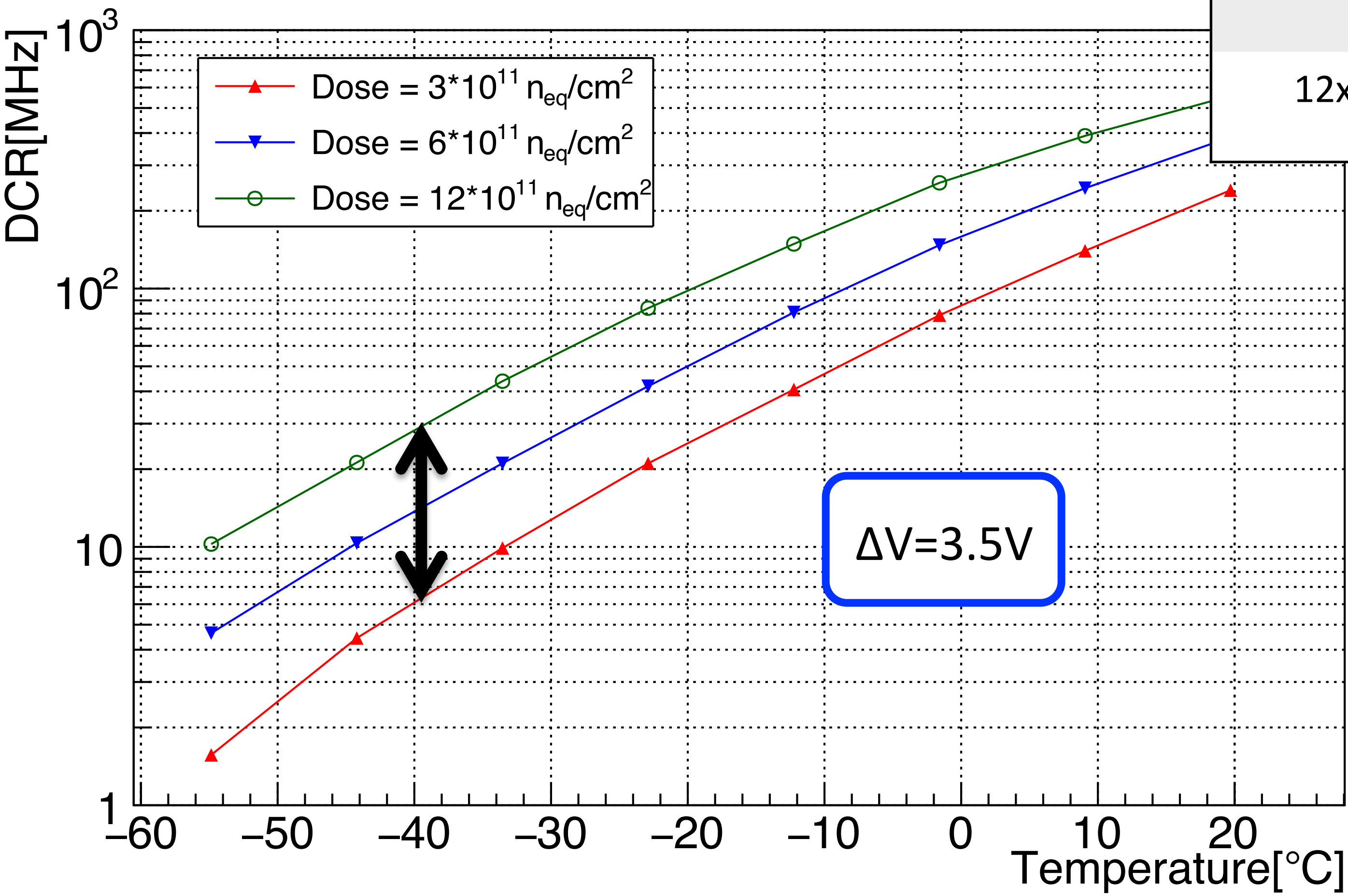
as a function of dose and T

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168

DCR after irradiation

- The DCR is 14 MHz per channel (T=-40°C , ΔV = 3.5V, D=6*10^{11} n_{eq}/cm^2)
- The DCR increases linearly with the dose

Dose [n_{eq}/ cm^2]	DCR[MHz] @ 3.5V and -40°C
$0x10^{11}$	0.04
$3x10^{11}$	6.0
$6x10^{11}$	14.3
$12x10^{11}$	28.0



Clustering and noise cluster rate

Clustering Motivation:

- Clusters are a good criteria for signal/noise separation. DCR is a random occurrence per channel while the signal is grouped
- Mean hit position calculation
- Data reduction. Only one position value for a cluster is saved

The noise cluster rate (NCR) is the number of cluster generated from noise (DCR+correlated noise)

NCR is calculated for 128 channels read out at a frequency of 40MHz:

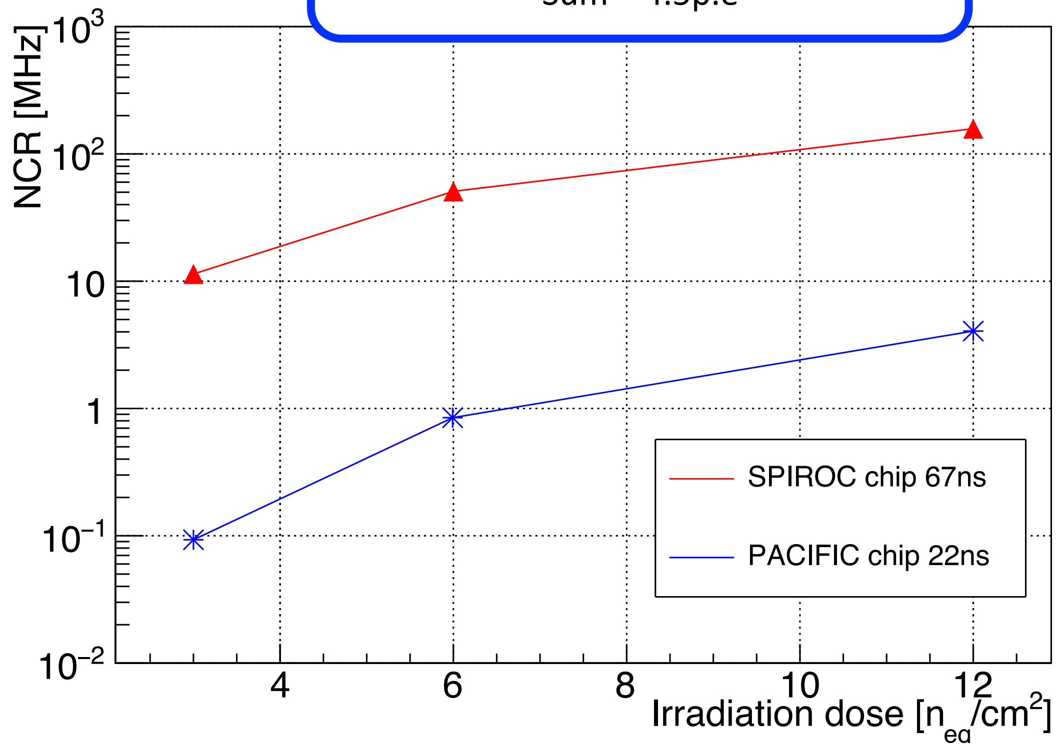
$$NCR = N_{NC}/N_{ev} \times 40MHz$$

Irradiation studies summary

ΔV = 3.5V SPIROC	H2016_HRQ
DCR $6*10^{11}N_{eq}/cm^2$ per channel	14.3 MHz
Correlated noise	5.5% Direct & delayed
NCR/128 ch.	50.8MHz
NCR/ch.	0.4MHz

Irrad level [10^{11} N_{eq}/cm^2]	H2016_HRQ [MHz] @ΔV=3.5V	
	SPIROC 67ns	PACIFIC 20ns
3	11.4	0.093
6	50.8	0.845
12	157.9*	4.056

ΔV = 3.5V / T=-40°C
Seed = 2.5p.e / Neighbour = 1.5p.e
Sum = 4.5p.e



The NCR is dominated by random overlap (integration) of several uncorrelated DCR pulses.

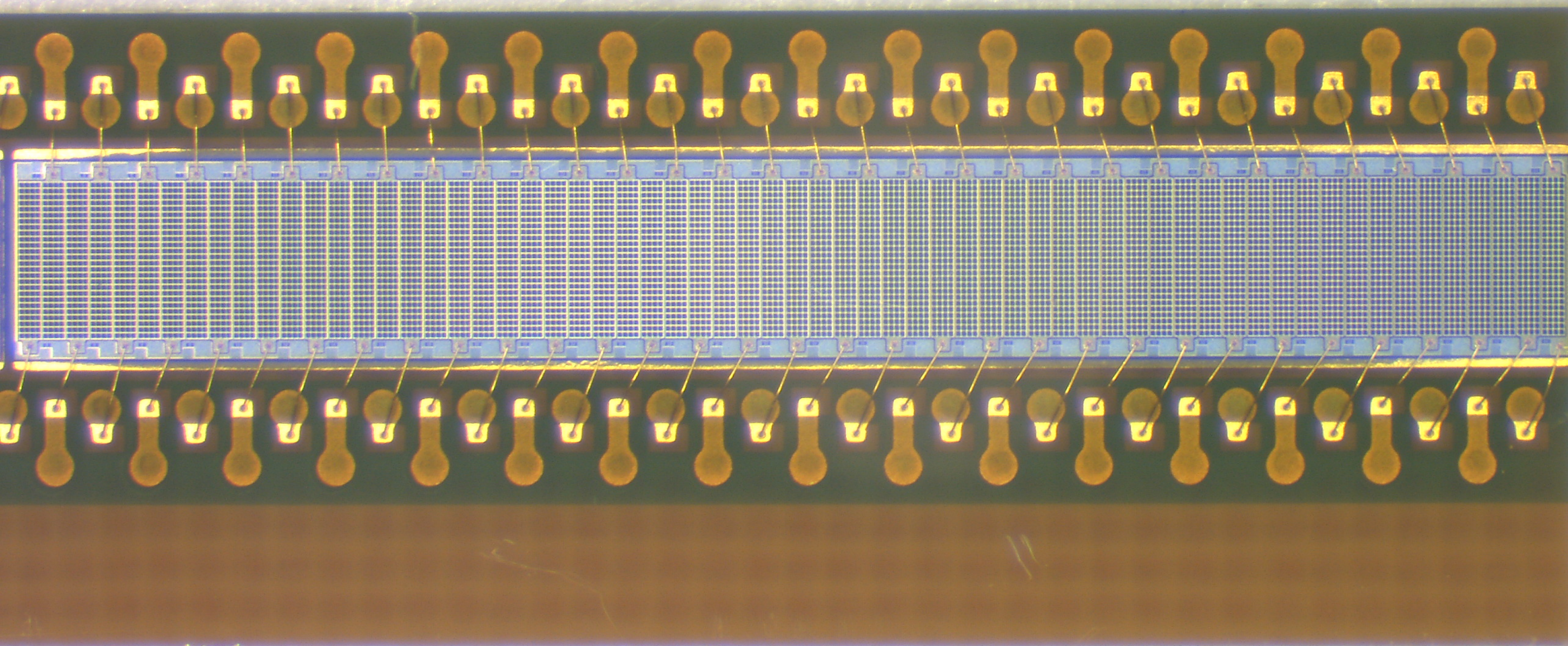
*noise saturation: noise clusters merge which reduces artificially the NCR

Summary

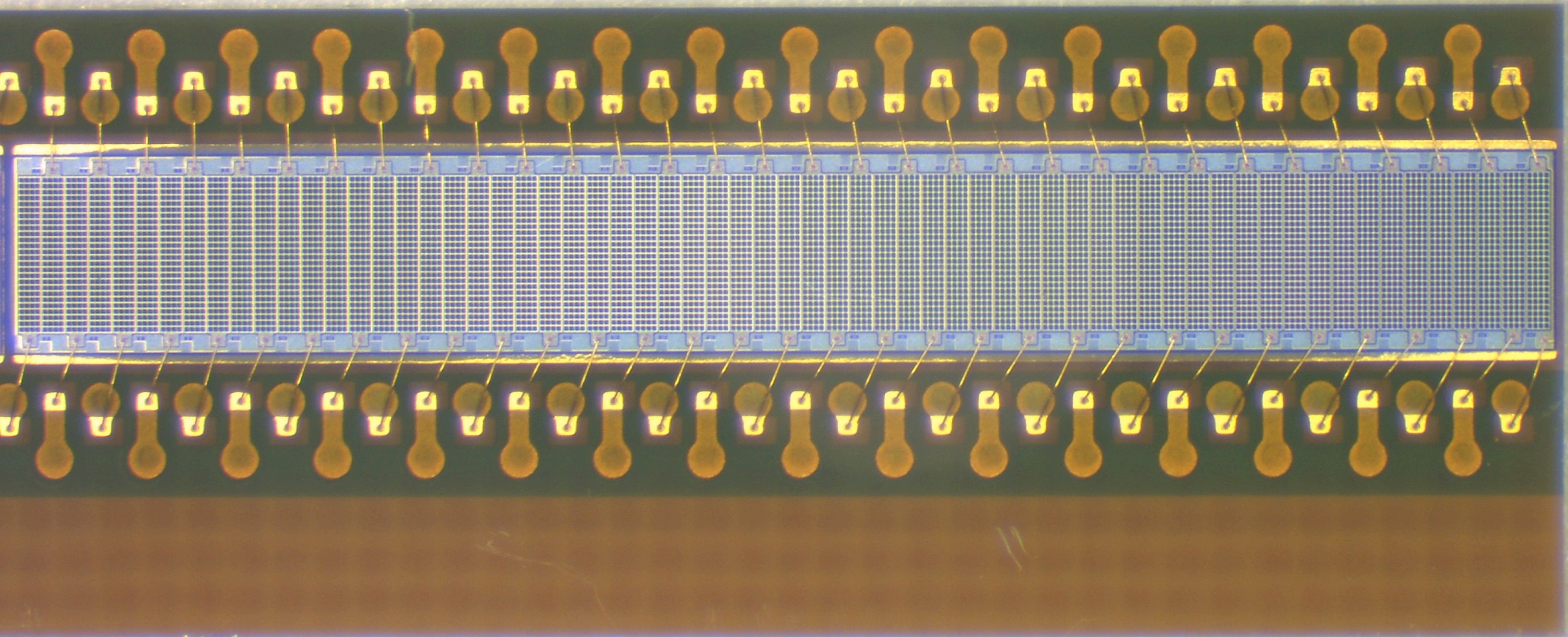
Characteristics @ $\Delta V = 3.5V$	H2016_HRQ
Direct x-talk	3%
Delayed x-talk	2.5%
After-pulse	0%
Peak PDE @ 475nm	48%
Recovery time	69ns
Long component	50ns
Short component	<1ns
DCR @$6x10^{11}n_{eq}/cm^2$, -40°C	14.3MHz

- We have presented a generic method that can be applied to many other SiPM applications to fully characterise and quantitatively analyse the SiPM response.
- High performant SiPMs arrays from Hamamatsu with 128 channels, high PDE (48%), low correlated noise and fast recovery time are obtained.
- For the operation in the radiation environment, single photon detection capability can be retained up to $6*10^{11}N_{eq}/cm^2$ by cooling to -40°C, fast integration and shaping of the signal.

Thank you for your attention !



Backup slides



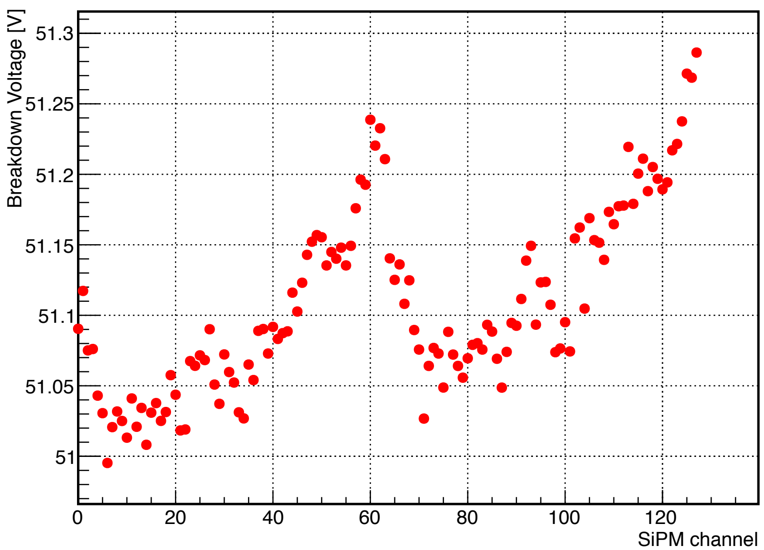
SciFi SiPM characteristics

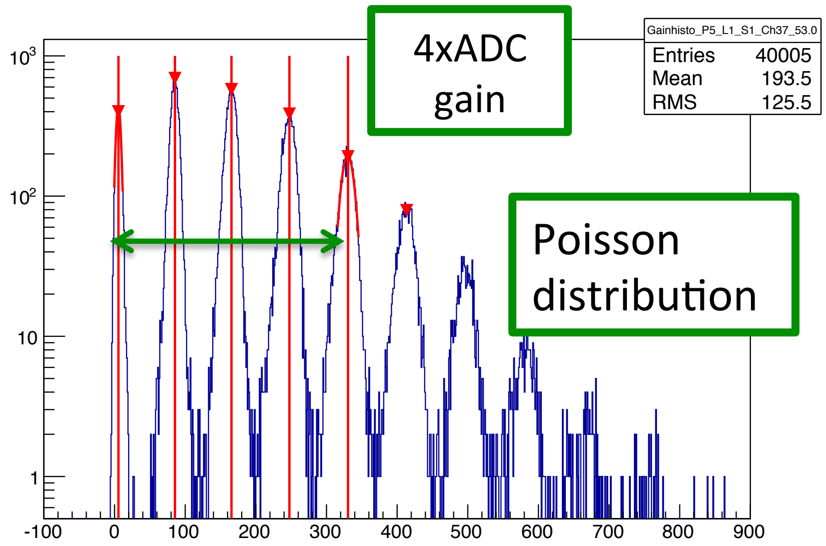
Characteristic at operation point ΔV=3.5V and 25°C	H2016 High quench resistor Hamamatsu S13552-HRQ*
Breakdown voltage	51.0V±250mV on chip±500mV series
Gain	$4x10^6$ e^-/ph
Temperature coefficient	53.7mV/K
Mean quench resistor	490kΩ
Peak photo detection efficiency	48%

* Detector selected for the SciFi

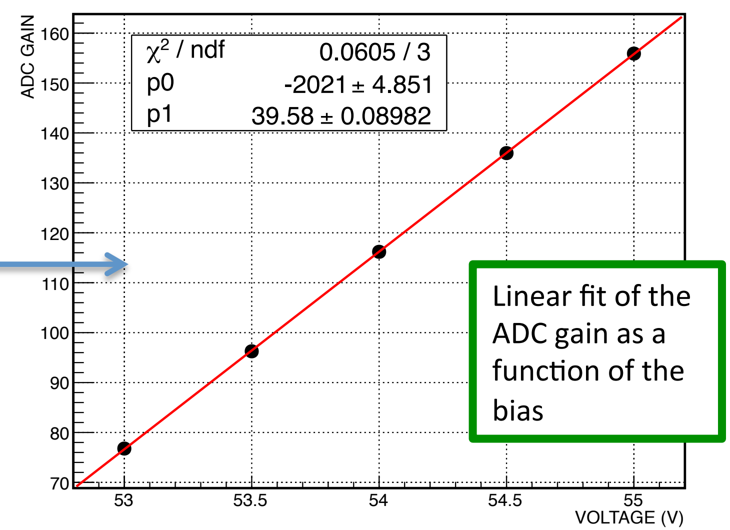
- **Breakdown voltage (V_{BD})** is the voltage where amplification sets in. The over-voltage is defined by: $\Delta V = V_{bias} - V_{BD}$
- V_{BD} is **temperature dependent** and is changing by 53.7mV/K. Typical gain variation for 1K at ΔV=3.5V is 1.5%
- The **quench resistor** stops the avalanche. A higher quench resistor value increases the overall stability of the detector (stable at higher over-voltage)
- The **photo detection efficiency** is the ratio between the number of detected photons and the number of incident photons. It is the product of three factors: fill factor (depend of the pixel size), quantum efficiency and the avalanche probability (depend of ΔV).

Breakdown voltage determination



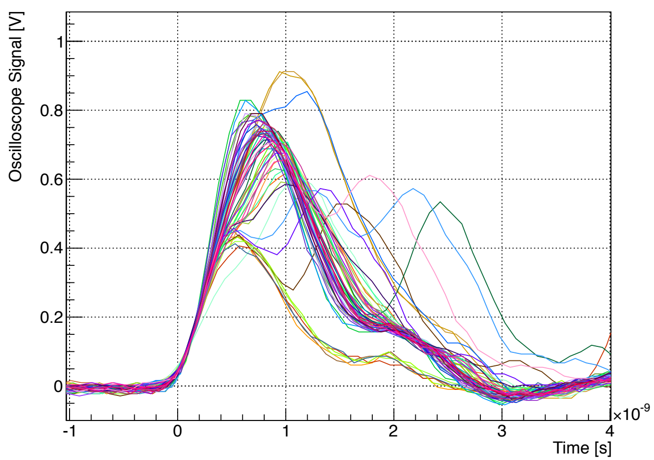


- Obtained by gain 0 extrapolation
- V_{BD} variations on one chip is ±0.3V
- V_{BD} variation between the detector batch is ±1.0V
- Seen typical patterns for V_{BD} over the 128 channels -> unavoidable

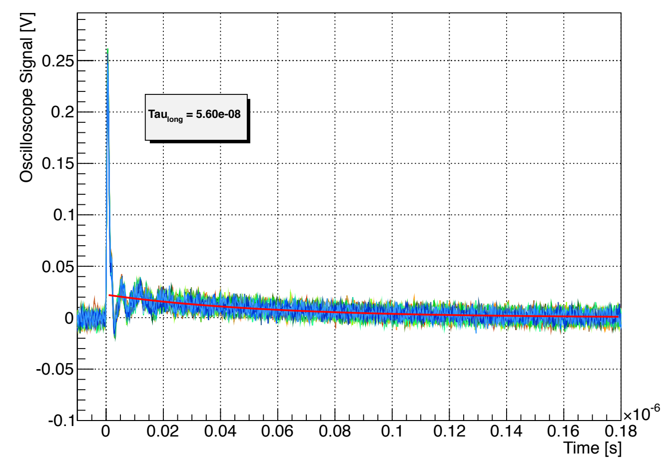


Pulse shape analysis for H2016_HRQ

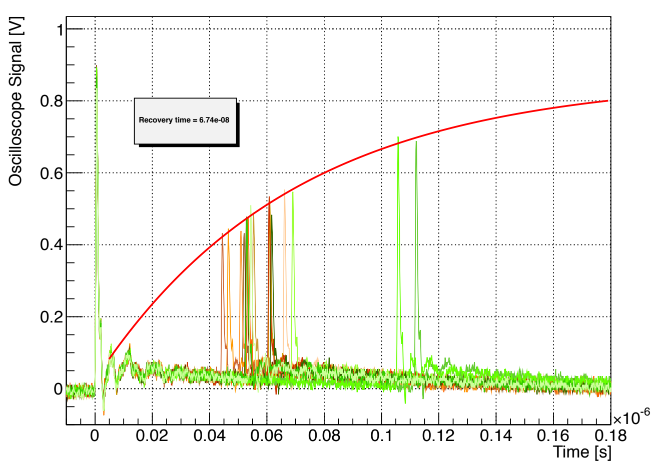
Direct CrossTalk OV = 3.58 V



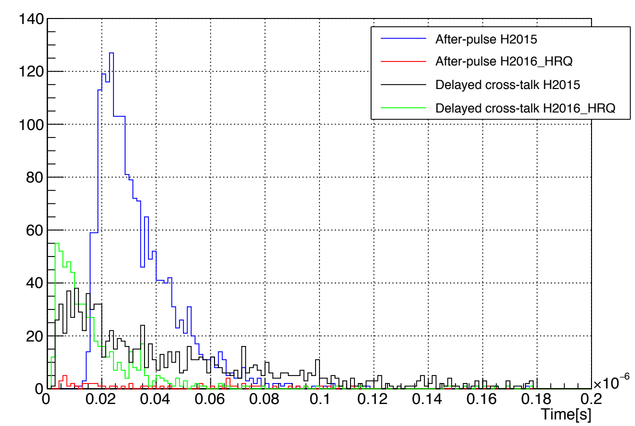
Clean pulse OV = 2.08 V



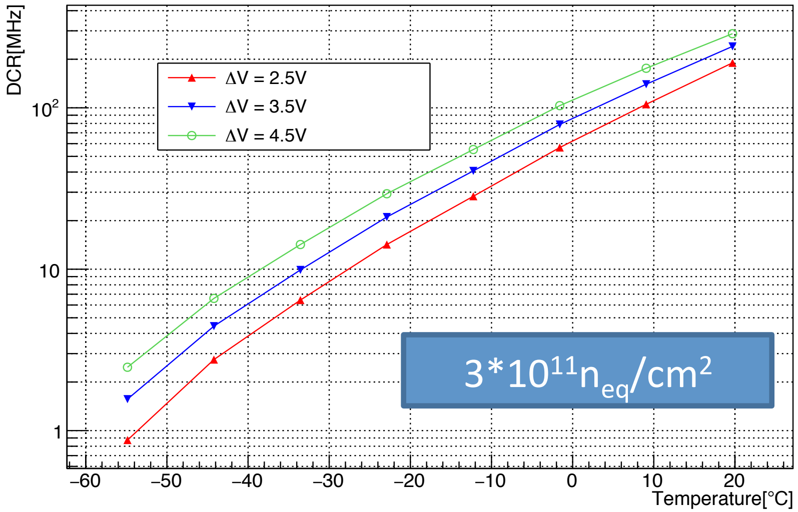
After pulse OV = 7.08 V

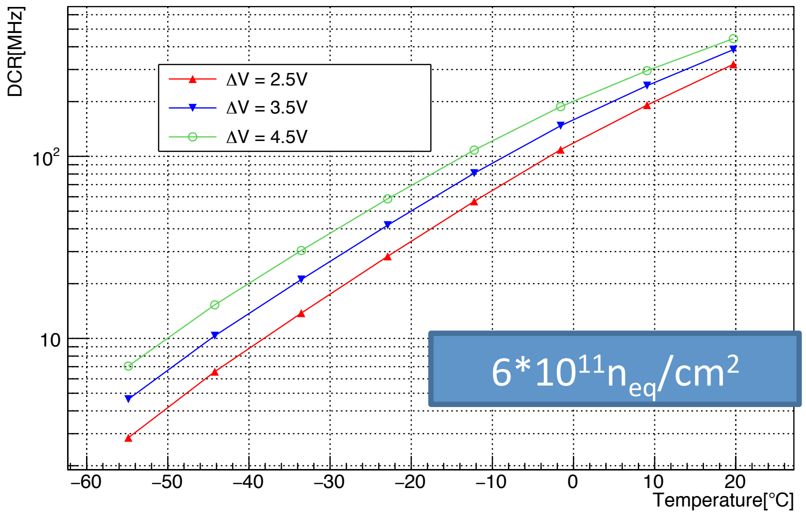


Correlated noise arrival time

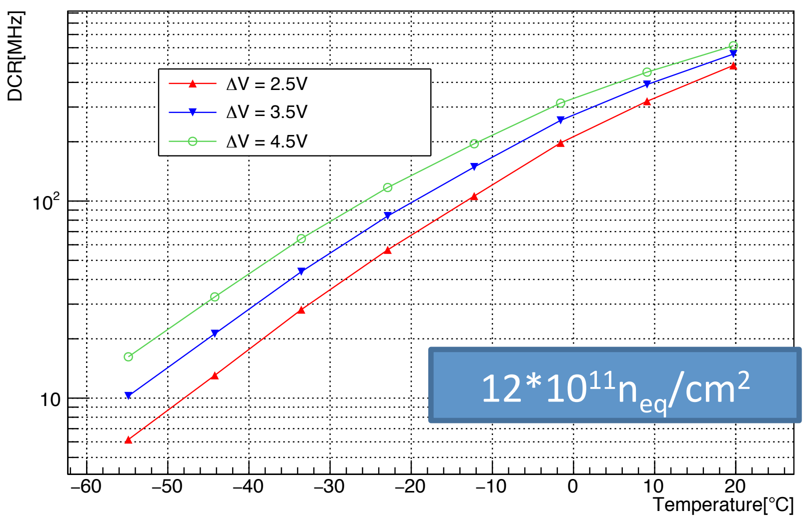


DCR as a function of T for 3 different ΔV

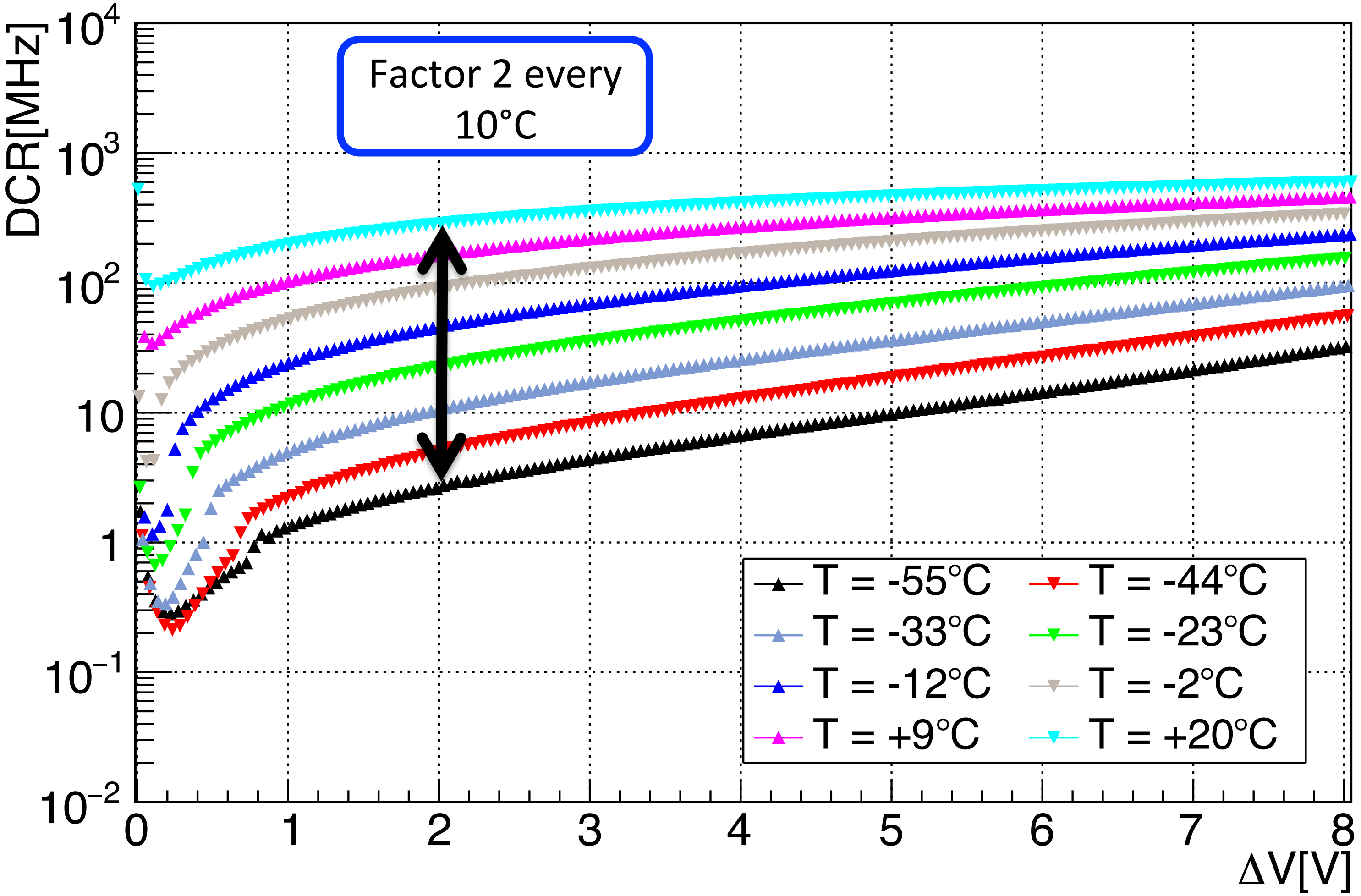




- At high T, saturation appears (only 104 pixels at ~100MHz)
- At low T, NTC calibration is less precise

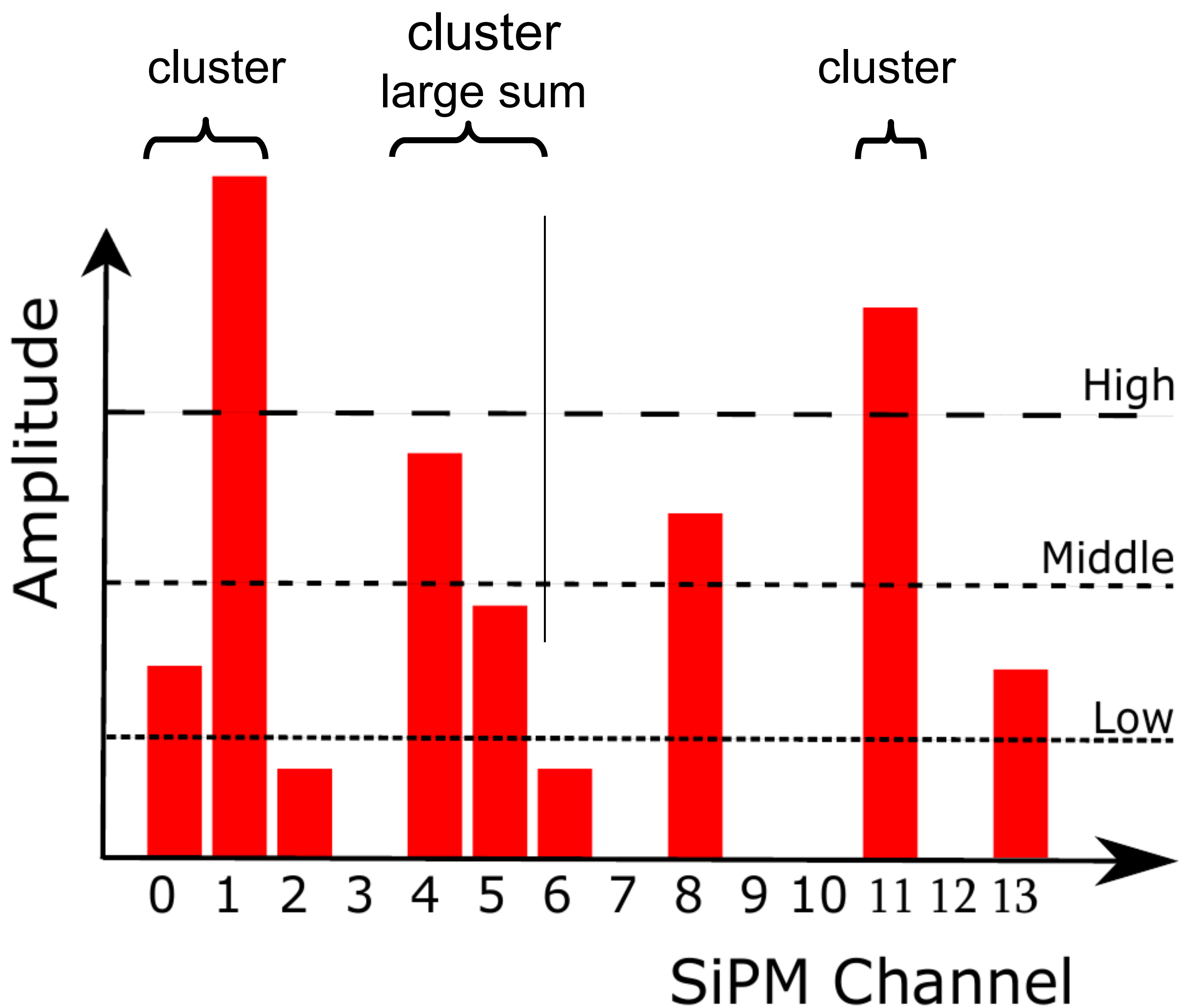


Temperature dependence and $T_{1/2}$



DCR is reduced of a factor two every 10°C ($T_{1/2}$)

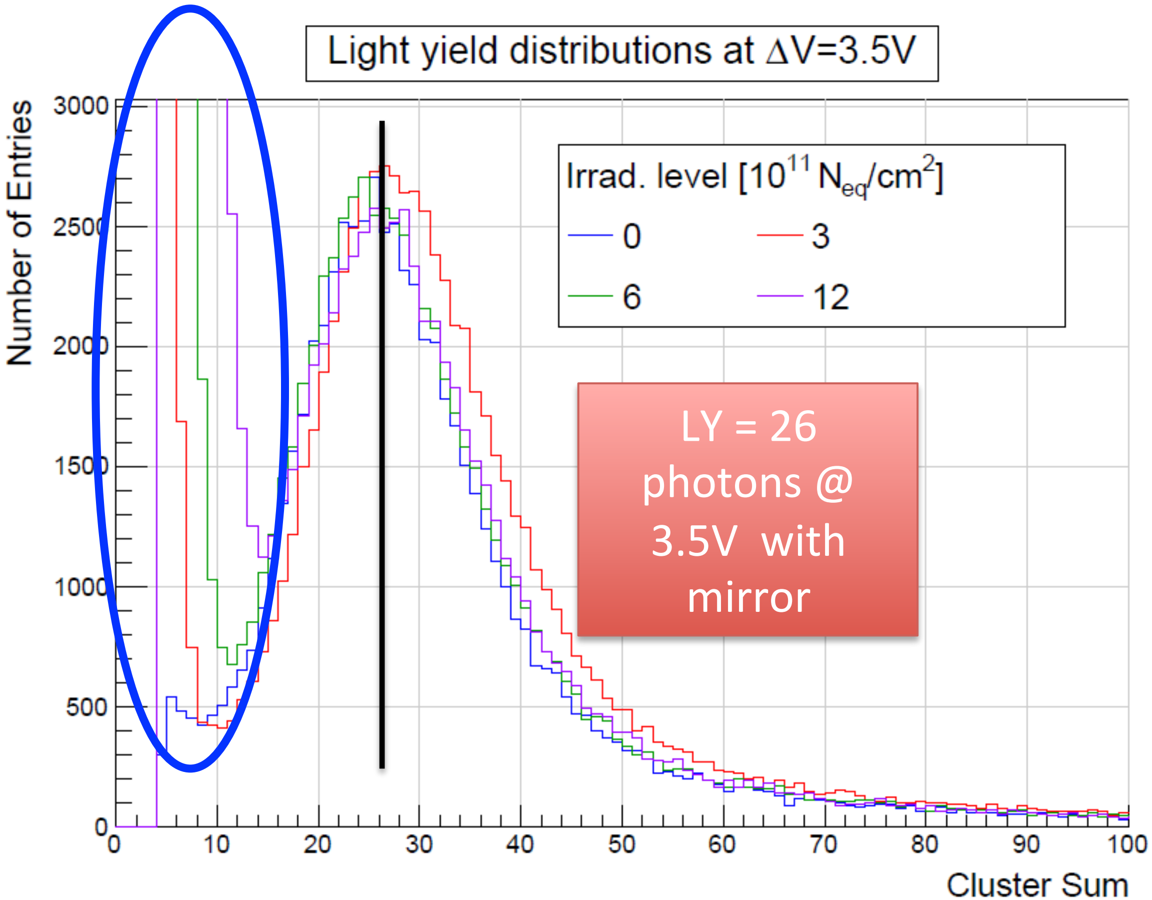
Clusterisation



2 bit/channel
low, middle,
high threshold
passed

Light yield measurement

The light yield at the different irradiation levels are similar as for example here at 3.5V. One can observes higher noise cluster sum at higher irradiation



Summary

Characteristics $\Delta V = 3.5V$	H2016_HRQ	H2015
V_{bd} at 25°C Temperature coefficient	51.0V ± 250mV on chip ± 500mV series 53.7mV/K	52.2V ± 200mV on chip 60mV/K
Gain area Gain current	$3.8 \cdot 10^6$ $4.0 \cdot 10^6$	$3.25 \cdot 10^6$ $3.6 \cdot 10^6$
Direct cross-talk Delayed cross-talk After-pulse	3% 2.5% 0%	4.5% 5.5% 6.5%
Peak PDE Max PDE wavelength Light Yield	48% 450nm 26.0	47% [6] 480nm 27.7 photons
Mean R_Q at 25°C Mean R_Q at -40°C	490kΩ ± 1kΩ TBD	210kΩ ± 5kΩ 225kΩ ± 5kΩ
Recovery time ($\tau_{recovery}$) Long component (τ_{slow}) at 25°C Short component (τ_{short}) at 25°C	69ns 50ns <1ns	35ns 40ns <1ns
DCR, $6 \cdot 10^{11}$ n_{eq}/cm^2, -40°C $T_{1/2}$	14.3 MHz 10°C	15.0 MHz 10°C