Simulation studies and detectors characterization for the LHCb SciFi Tracker

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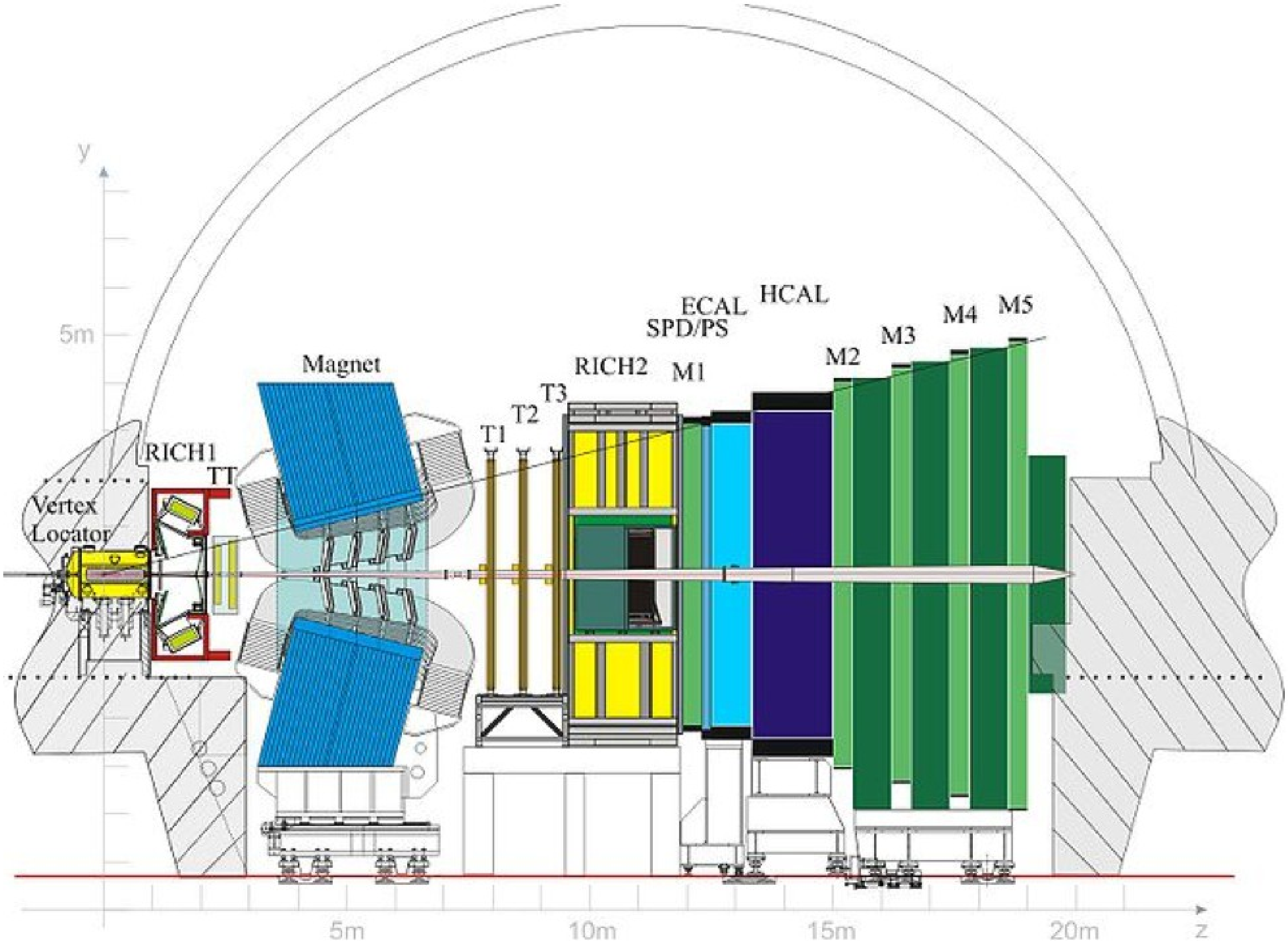
LHCb experiment at CERN

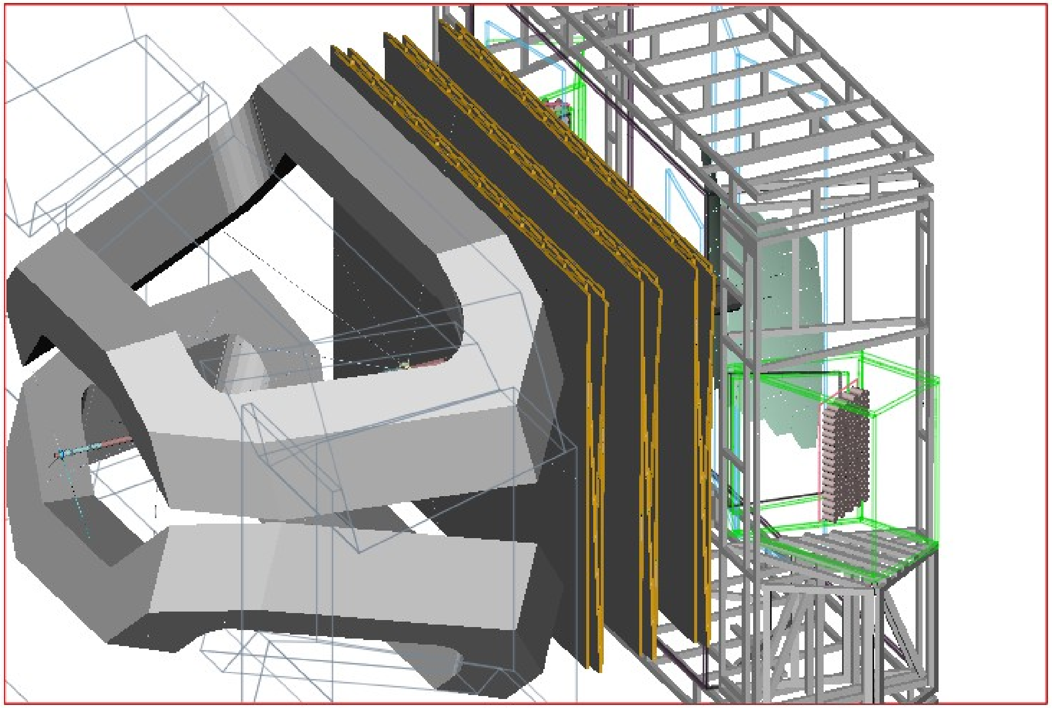


LHCb Upgrade: the SciFi Tracker

- The upgraded LHCb will operate at a luminosity of 2x1033cm-2s-1.
- T1, T2, T3 will be replaced by a Scintillating Fibre Tracker (SciFi Tracker).
- Detector: long scintillating fibres read-out with Silicon Photomultipliers (SiPMs).

Requirements:

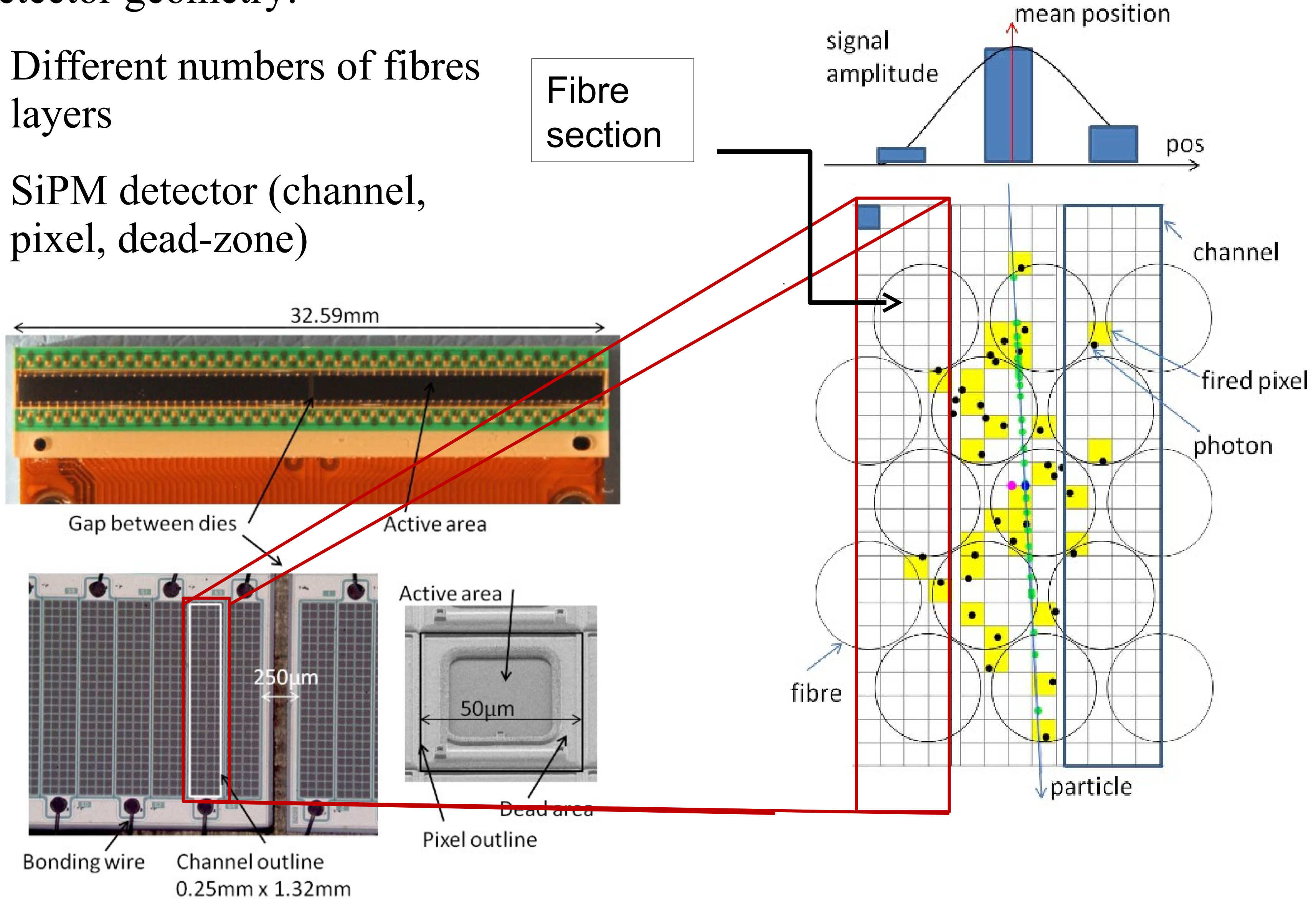
- ✓ Hit detection efficiency: around 98-99% (noise less than 10%).
- ✓ Spatial resolution less than 100 um.
- ✓ Minimum amount of material in the acceptance region (multiple scattering).
- ✓ Readout electronics at 40 MHz and short recovery time for the detectors.
- ✓ Operation at required performance for an integrated luminosity up to 50 fb-1 (radiation damage).



T1, T2, T3

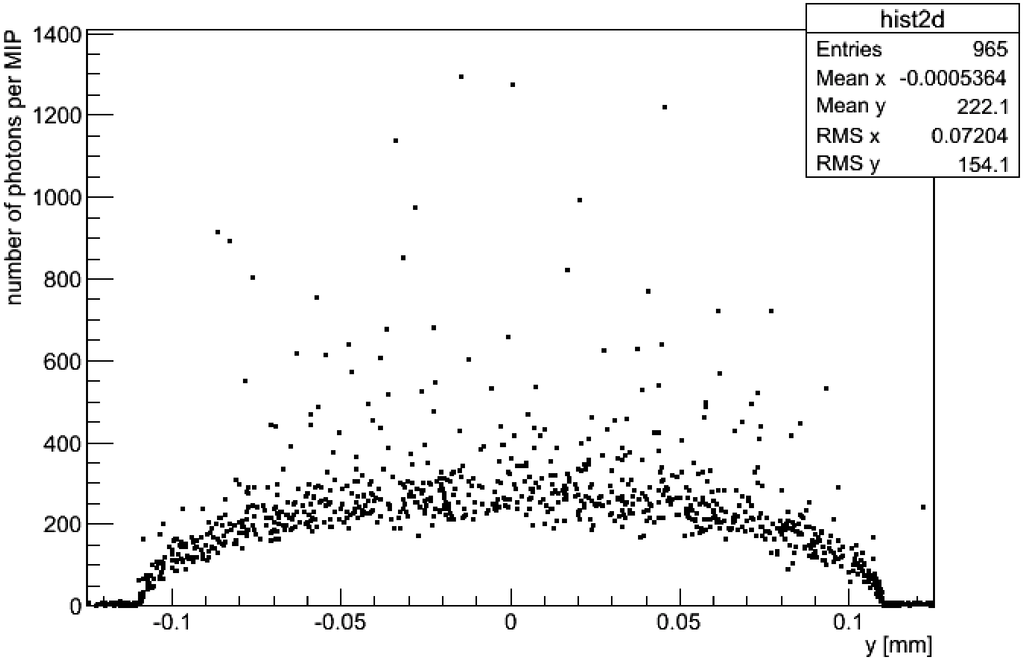
Simulation

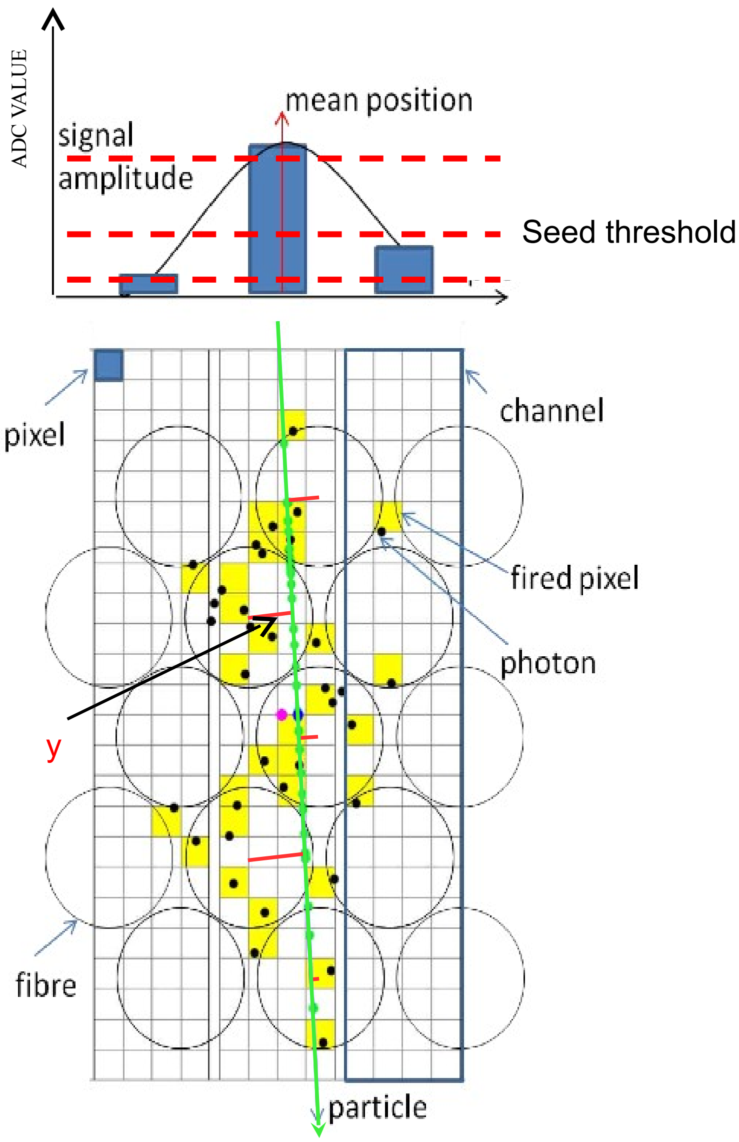
- Detector geometry:
  - Different numbers of fibres layers
  - SiPM detector (channel, pixel, dead-zone)



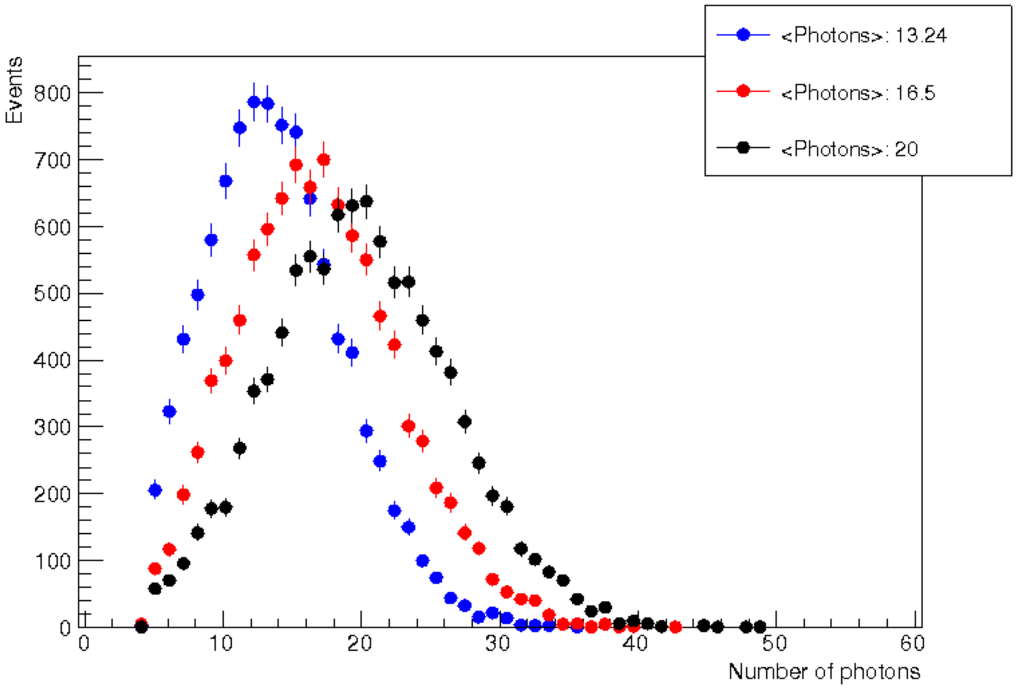
Fast Simulation

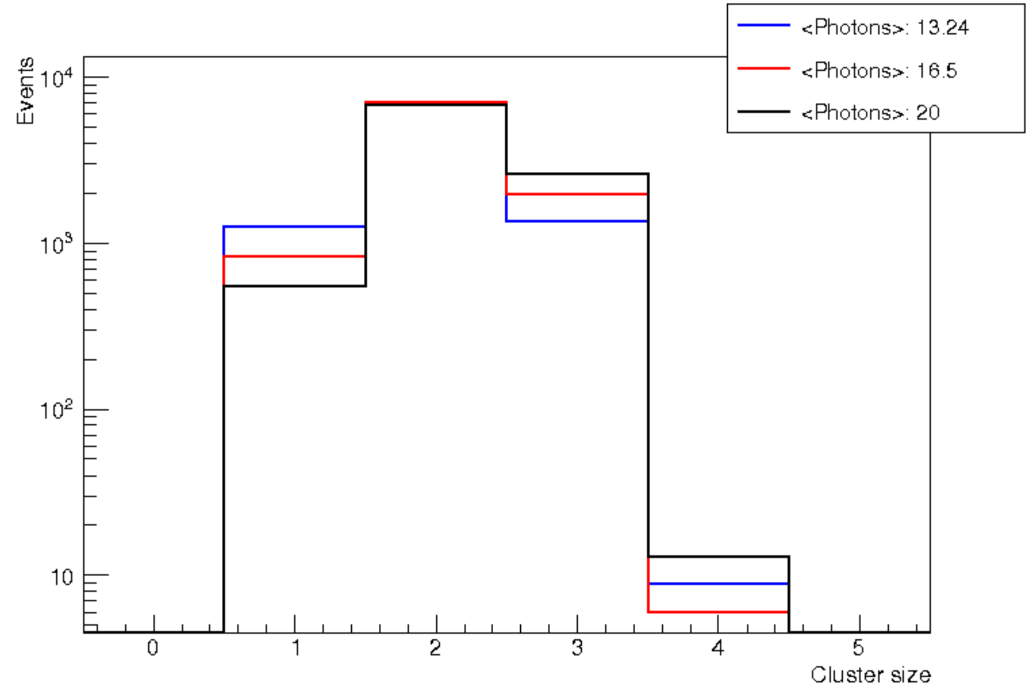
- Input: Geant 4 data for 1 scintillating fibre.
- Generation of the signal:
  - PDE
  - Saturation
  - DCR, X-talk, after-pulse





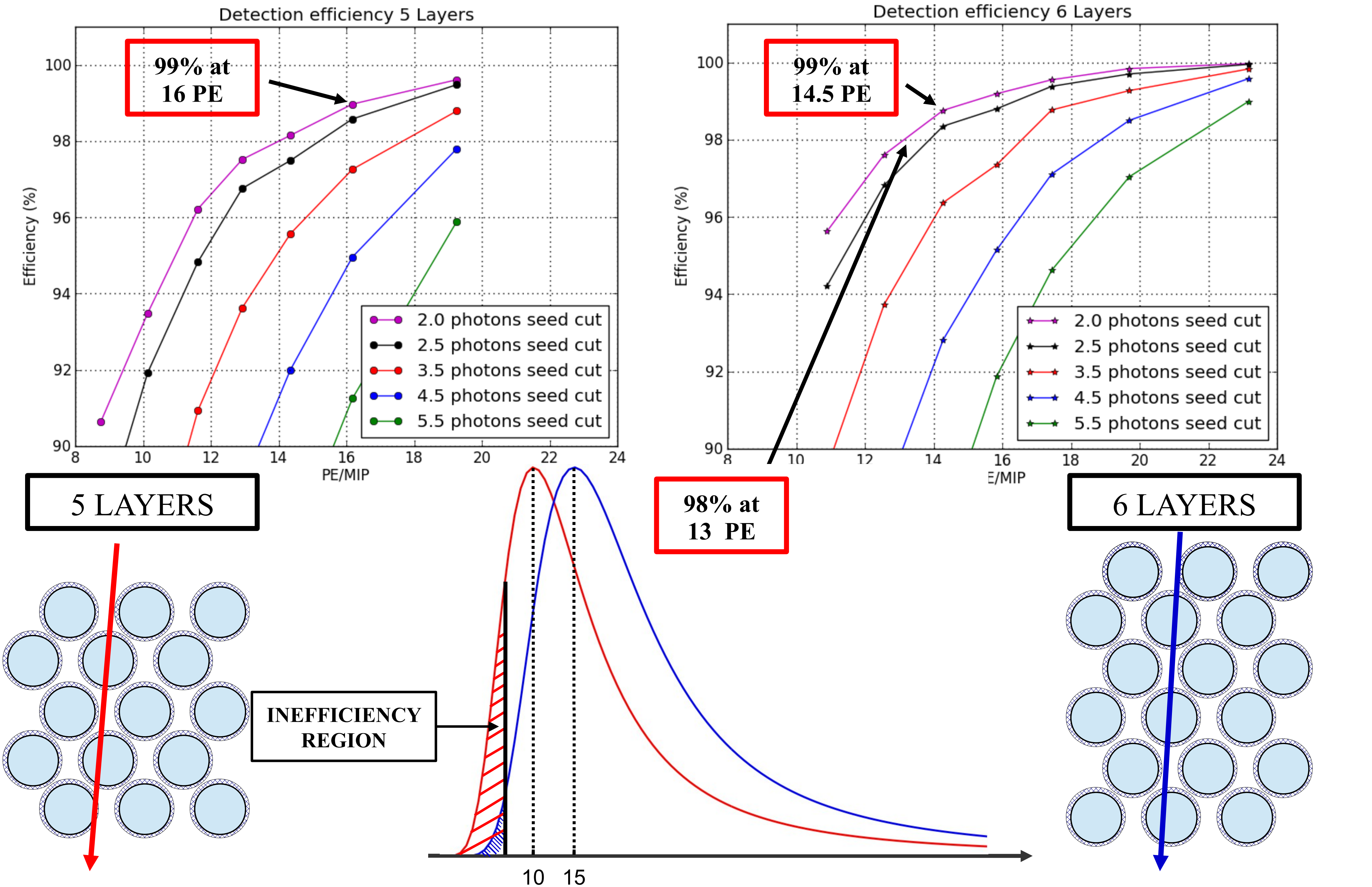
Simulated signal and cluster size





- Simulated signal for different light yield.
- Clustering algorithm (3 thresholds).
- The cluster size increases for high yield of collected light.

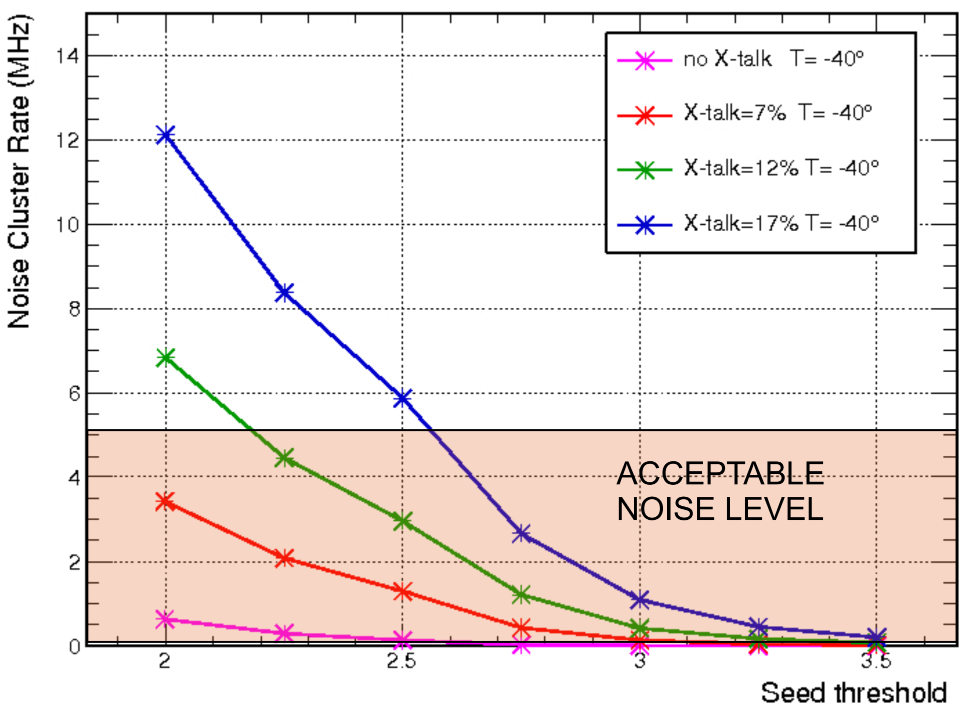
Hit detection efficiency depending on number of layers

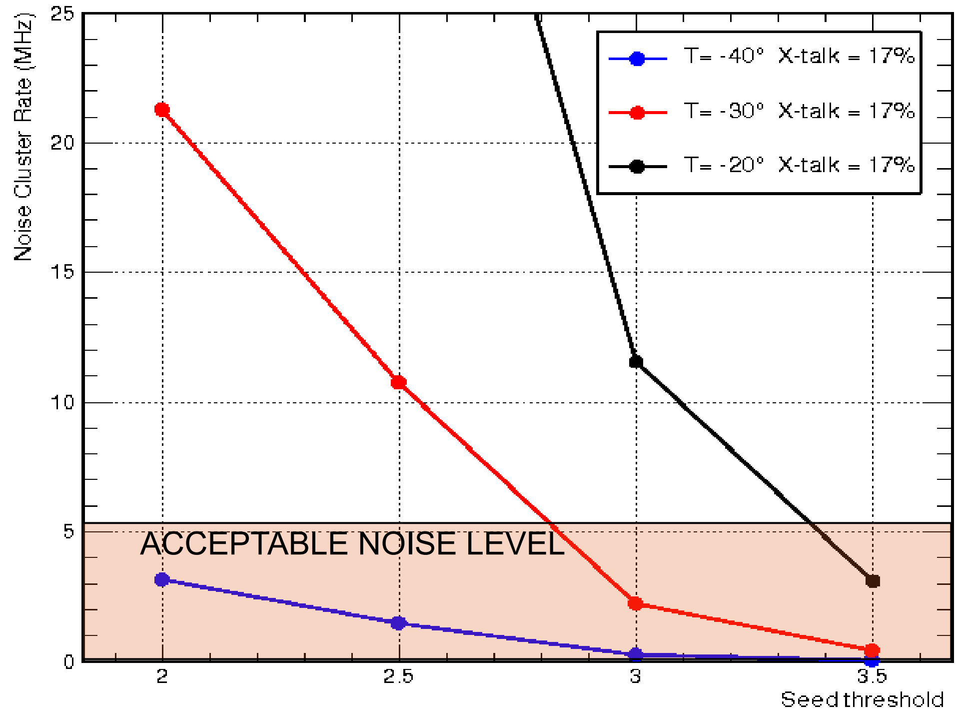


Noise cluster rate simulation

- Dependence on temperature, irradiation, crosstalk, shaping time, clustering algorithm.

- Primary noise is proportional to neutron fluence and the frequency is simulated decreasing by a factor 2 every 10 degrees.





- Important: reduce cross-talk.
- Noise cluster rate is 2.5 MHz at - 40º and seed=2 photons.

CLUSTER NOISE FREQUENCY IS NORMALIZED AT 40 MHZ READ-OUT

SiPMs for the SciFi Tracker

- High PDE: The 2.5 m long fibres and the radiation damage of the fibres in the center of the detector, reduce the light output.
- Low x-talk: The noise cluster rate increases exponentially with x-talk. With the high DCR after irradiation, the noise cluster rate exceeds the acceptable level.
- Support the radiation environment: DCR increases with neutron fluence.
- Small temperature dependence: The operation temperature of the detector is set to -40°C. Temperature non-uniformity is expected for different regions of the detector.
- Small dead regions: Dead regions at the edges between adjacent SiPM arrays reduce the overall hit detection efficiency.

SiPMs characterization

- SiPMs sample with different pixel size and different technology.

Detector type	Pixel size [μm^2]	T_C[mV/K]	V_{BD} [V]	Over-voltage [V]*	Gain [e/PE]
Ham. S10262-11-050C	50×50	56	69	1.3	$0.75*10^6$
Ham., with trench (2013)	50×50	43	55	3.5	$2.0*10^6$
KETEK, W1C2, with trench	60×62.5	15	23.5	3.5	$8.5*10^6$
KETEK, W1C3, with trench	82.5×62.5	15	23.5	3.5	$12.0*10^6$
KETEK, W7C3, double trench	82.5×62.5	22	32.4	3.5	$9.5*10^6$

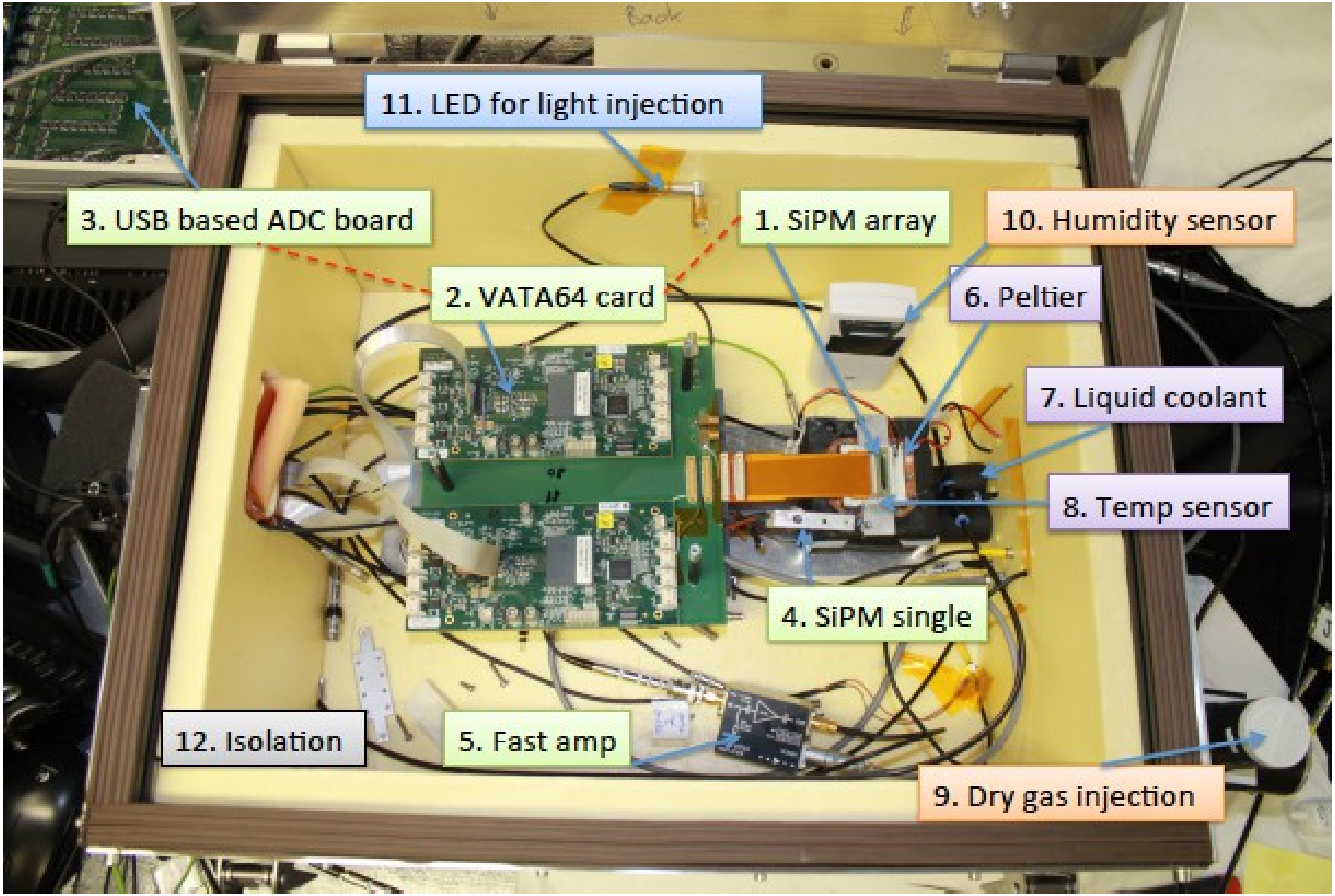
- New KETEK technology has an additional trench:

 - y opaque line for chip 2.

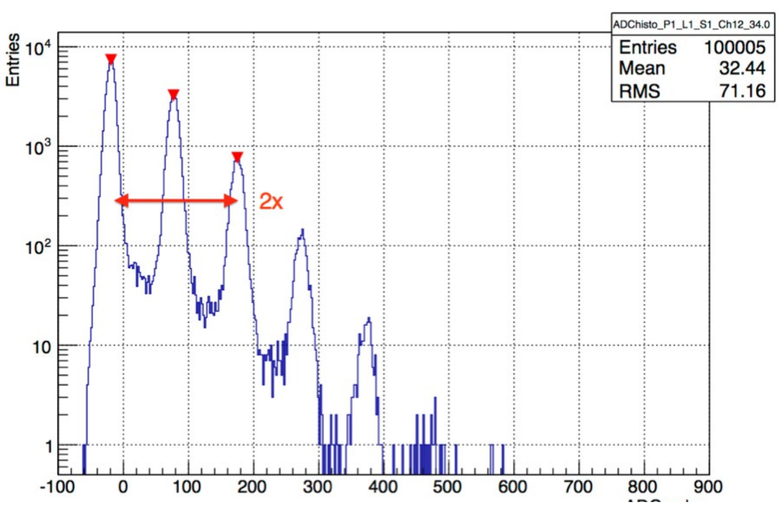
 - x-y opaque line for chip 3.

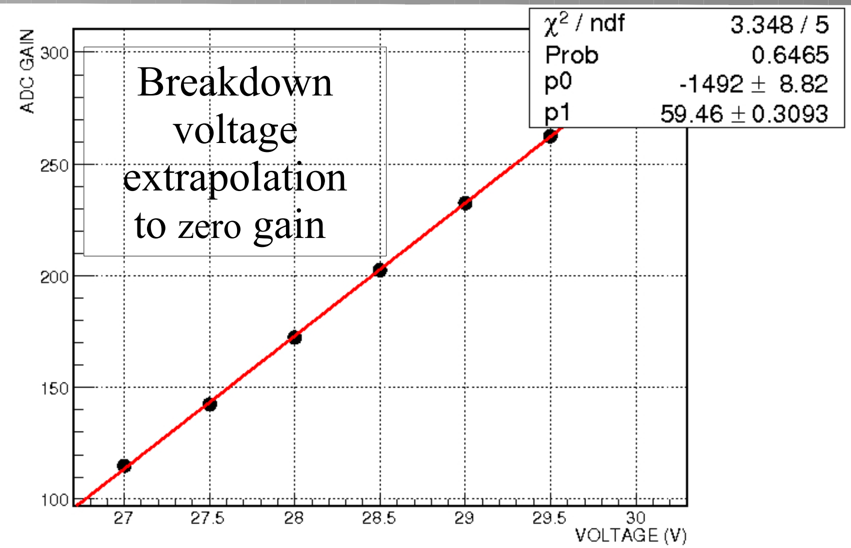
GOAL: to characterize several samples and choose the more suitable for LHCb SciFi tracker

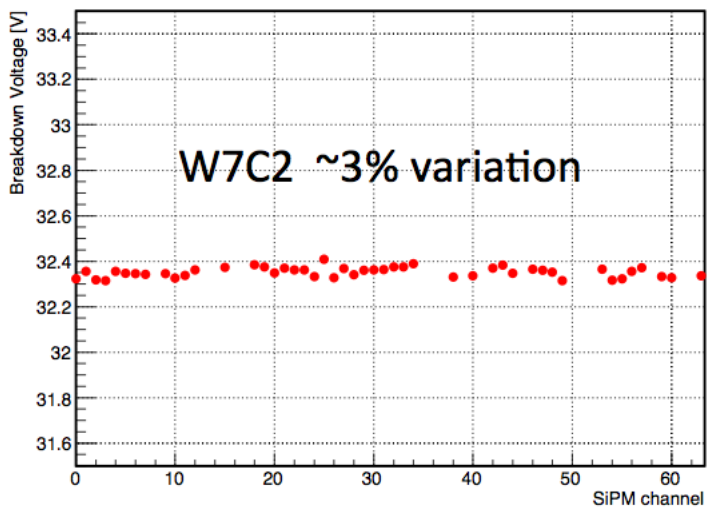
Cold box for SiPM characterization



SiPMs: general characteristics







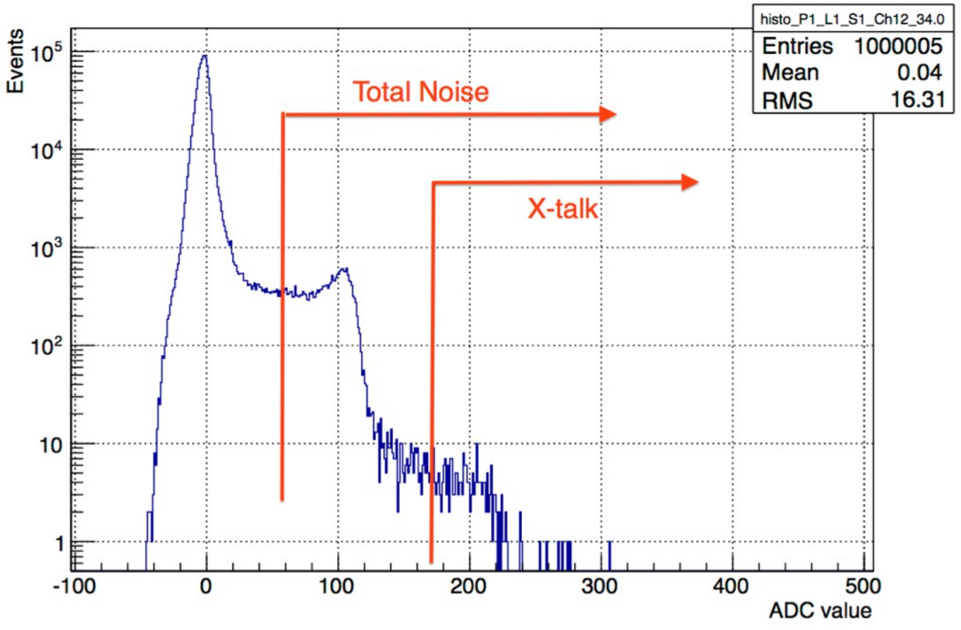
Gain: spacing between photon peaks.

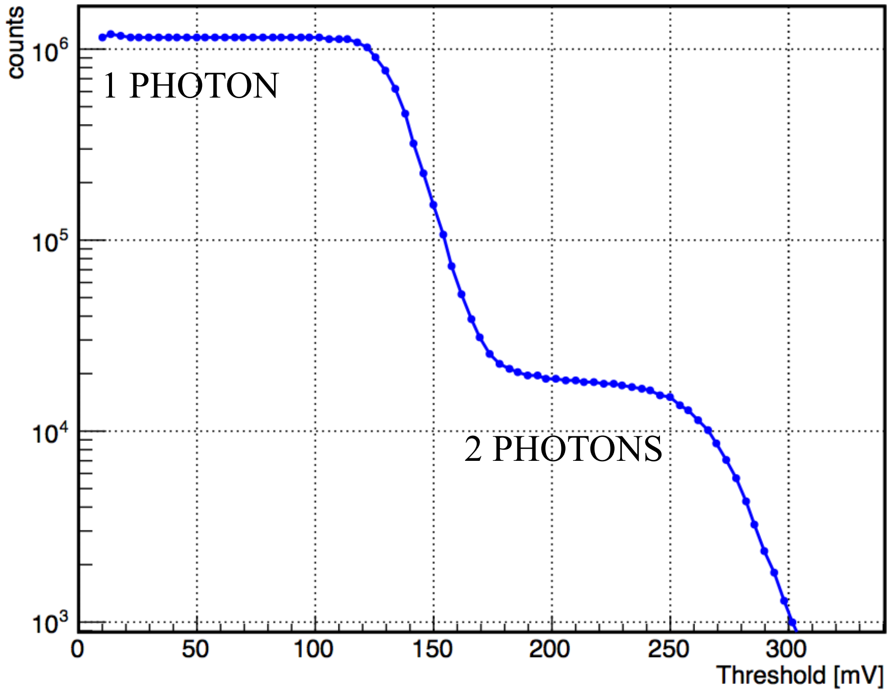
Gain depends linearly on the operational voltage.

- Detectors with trenches can be operated at higher over-voltage (3.5 V) which lead to a better gain uniformity .
- High gain uniformity within an array does not require channel individual gain tuning.
- Lower bias voltage decreases break down voltage temperature coefficient (T_C) and increases gain.
- Low T_C and high over-voltage reduces temperature dependence of the gain to 2-6% for 5K.

Cross-talk measurements

- Not irradiated detectors (measurements at 25º)
- With low DCR (probability for two random pulses within shaping window small), the probability of x-talk is given by the ratio $DCR_{th\equiv1.5pe}/DCR_{th\equiv0.5pe}$
- Two methods (system) were used to measure x-talk.
  - Use a fast (single channel) amplifier and record threshold scan. This allows to measure x-talk without after-pulsing due to the fast shaping.
  - Record dark spectrum with multichannel data acquisition system based on a VATA64 chip (64 channels, >50ns shaping time). This cannot separate x-talk and after-pulsing due to the slow shaping.
- The difference between the two methods allows to estimate the effect from after-pulsing.

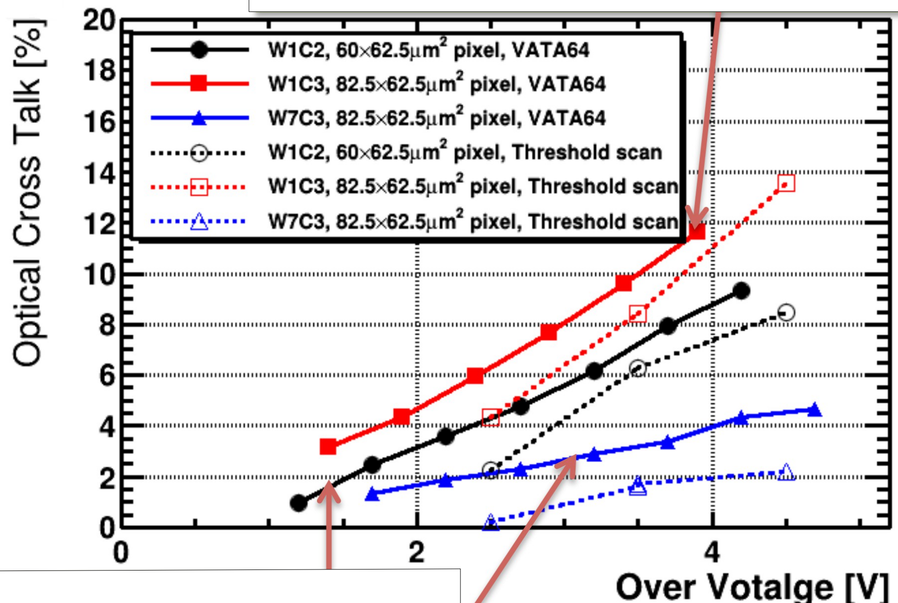




Cross-talk measurements

Comparison of different KETEK devices with different pixel sizes

W1C3, with trench, large pixels (3.5V over-voltage) (10% vs 8%)



W1C2, with trench, small pixels (3.5V over-voltage) (8% vs 7%)

W7C3, double trench, large pixels (3.5V over-voltage) (3% vs 2%)

- Standard technology: cross-talk higher for larger pixel size (as expected).
- New technology: cross-talk almost completely removed in chip with double opaque line trench.

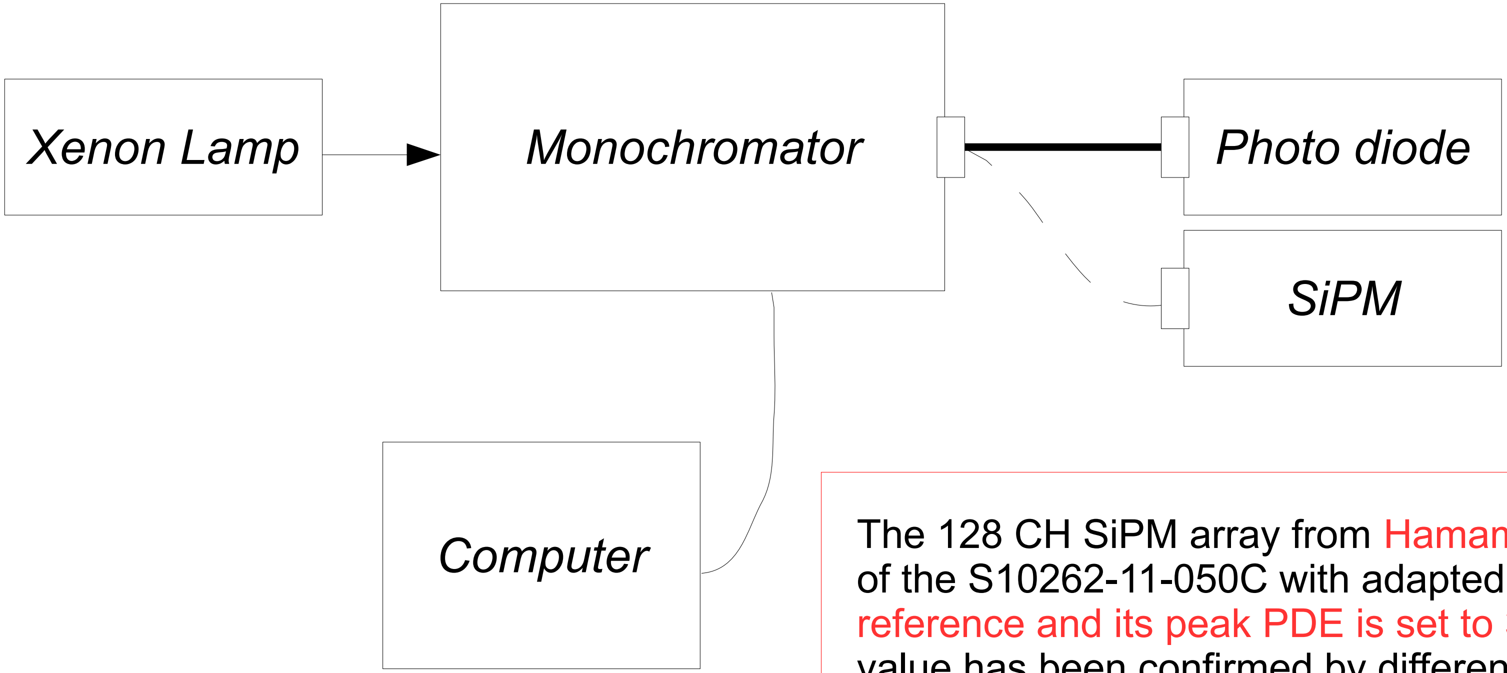
Difference between dotted line (open markers) and full line (full markers) is due to the after-pulses.

Photon Detection Efficiency

We perform a relative Photon Detection Efficiency (PDE) measurement:

$$PDE_{rel,SiPM}(\lambda) \propto (I_{SiPM}(\lambda) - I_{dark}) / (1 + P_{x-talk}) / G * QE_{PD} / I_{PD}(\lambda)$$

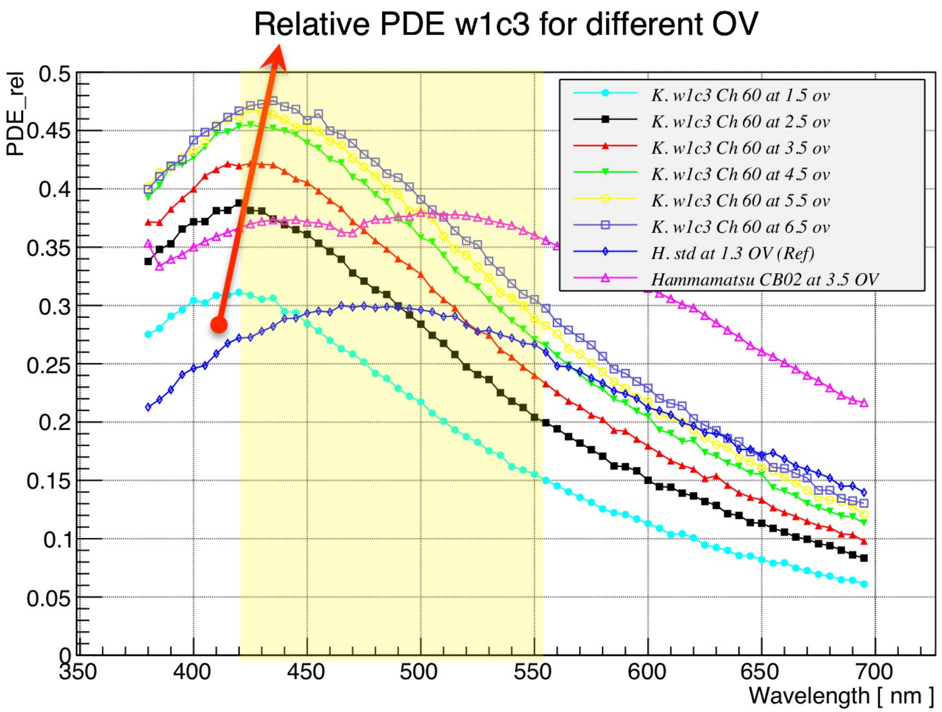
Corrections for: Dark current (I_{dark}), x-talk (+after pulse) ($P_{x\text{-}talk}$), lamp emission ($I_{PD}(\lambda)$)



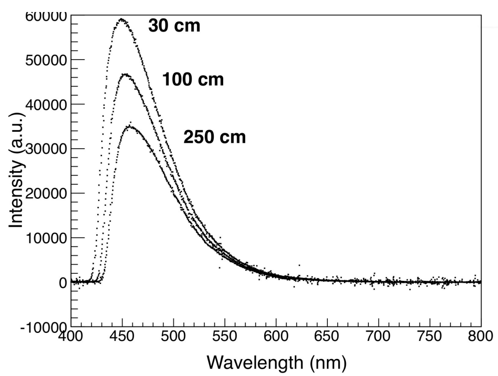
- Calibrated light source with photo diode
- Monochromator for wavelength selection
- Light coupled to optical fibre and optional illuminating PD or SiPM

The 128 CH SiPM array from Hamamatsu (based on the technology of the S10262-11-050C with adapted pixel size) is used as the reference and its peak PDE is set to 30% (after corrections). This value has been confirmed by different groups.

PDE measurements

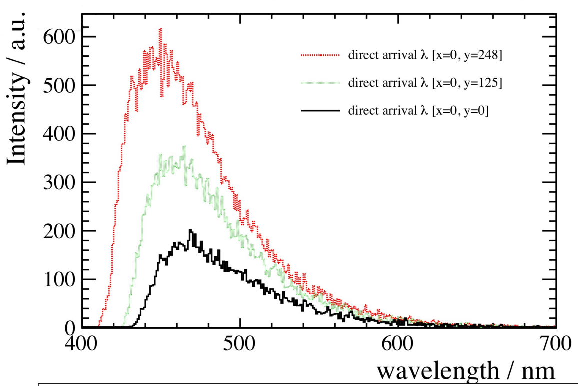


- The emission spectrum from a long and irradiated fibre peaks at 480 nm and is therefore green shifted compared to the peal PDE of SiPMs, especially for KETEK.
- The Hamamatsu with trench (2013) has a peak PDE of 37% and has a rather flat PDE over full emission spectrum of the fibre.
- The KETEK detectors tested reach a peak PDE of up to 43% at 3.5 V over-voltage.
- The weighted integral over the emission spectrum of the fibre reaches identical values for Hamamatsu (pink line) and KETEK (red line) (each detector with trench and at 3.5 V over-voltage)



Non irradiated: Fibre emission spectrum (SCSF-78MJ). It extends from 400 to 600 nm and peaks at 450 nm

ed after irradiation (35kGy) based on MC study



Irradiated fibre: The emission spectrum changes with Irradiation. The simulated spectrum, taking into account a graded irradiation, shows a green shift.

SUMMARY

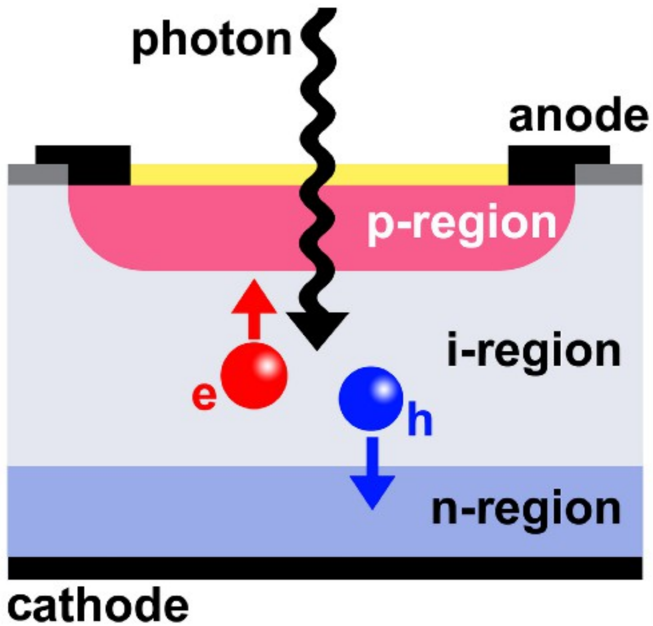
- SciFi simulation: good results obtained and provided for the TDR.
- We tested SiPM arrays from KETEK and Hamamatsu, which both show good performances.
- The KETEK technology shows a very high peak PDE where for the Hamamatsu the broad sensitivity gives an advantage for the green shifted emission spectrum of the fibre. They have equal weighted integral of PDE at the 3.5 V over-voltage.
- Detectors with (double) trenches have low x-talk and better gain uniformity due to lower T_C and higher over-voltage.

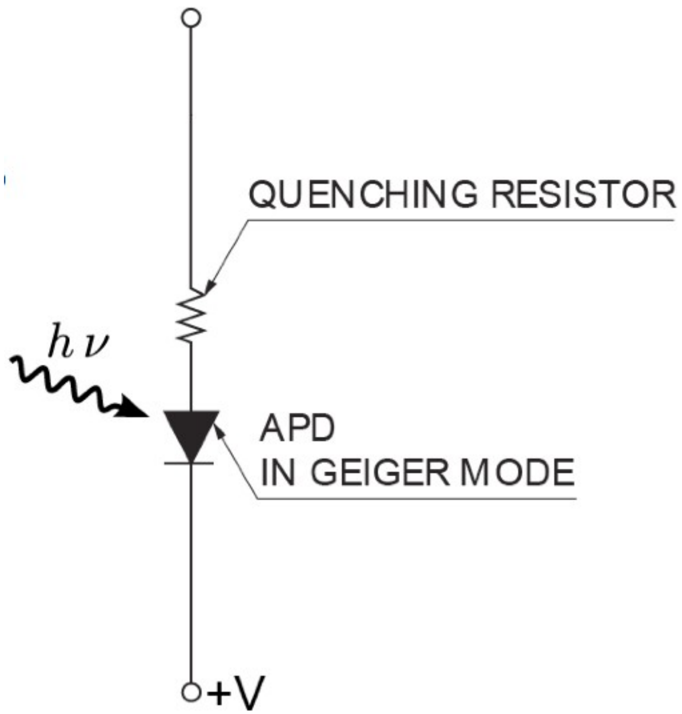
Thank you for your attention !

Backup slides

GEIGER MODE APD

SiPM = many G-APDs connected in parallel to a common load





G-APDs create standard binary signal independent of the number of simultaneously incoming photons. Signal is not proportional to number of primary charge carriers, just YES or NO.

X-talk

- Charge carriers can recombine emitting a photon (average of 3*10-5 photons per charge carrier).
- These photons can trigger additional simultaneous avalanches in other cells