Silicon Photomultipliers for the LHCb Upgrade Scintillating Fibre Tracker

TIPP 2014

2-6 June, Amsterdam

Presented by

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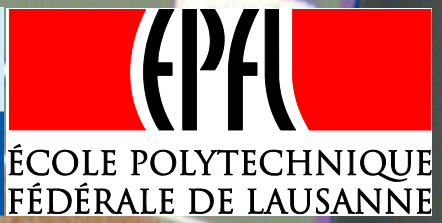
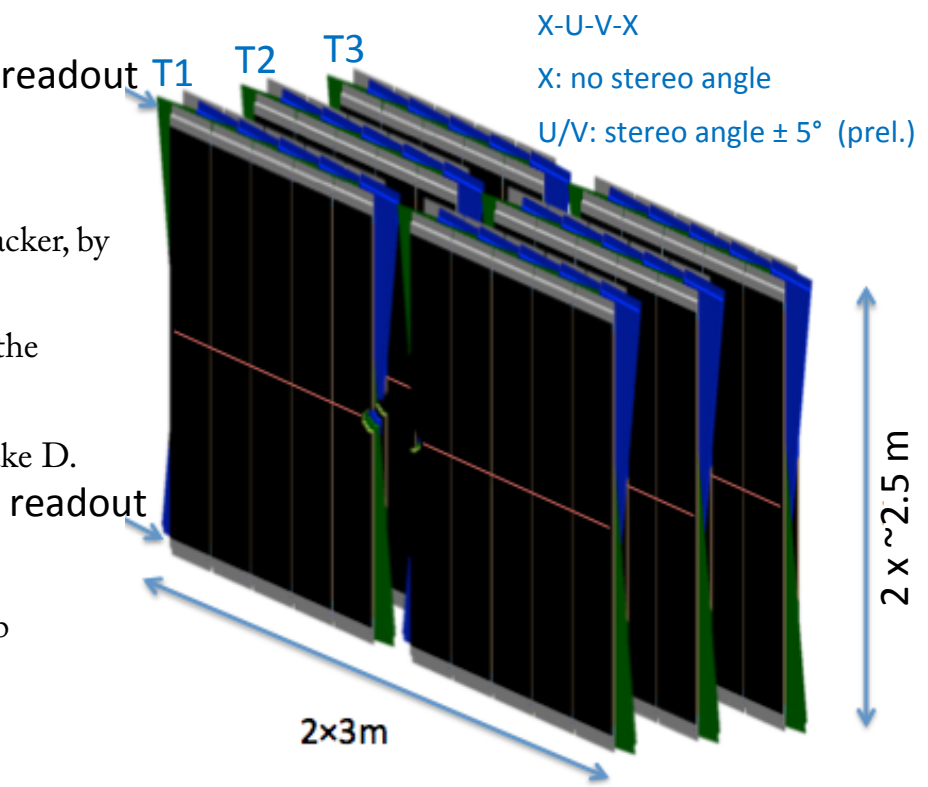
EPFL Lausanne, Switzerland

(On behalf of the LHCb SciFi Tracker group)



The LHCb SciFi Tracker



Related talks at TIPP 2014:

- Cooling for the LHCb Upgrade Scintillating Fibre Tracker, by Petr Gorbounov, June 2nd
- Scintillating Fibre and Radiation Damage Studies for the LHCb Upgrade, by Mirco Deckenhoff, June 4th
- The LHCb Upgrade Scintillating Fibre Tracker, by Blake D. Leverington, June 6th

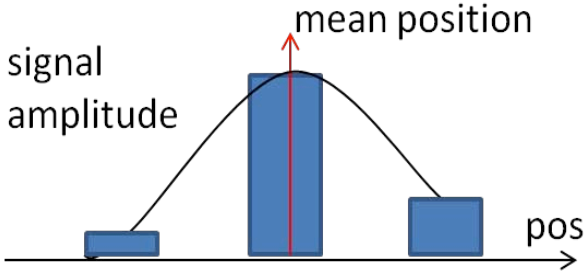
Technical Design Report:

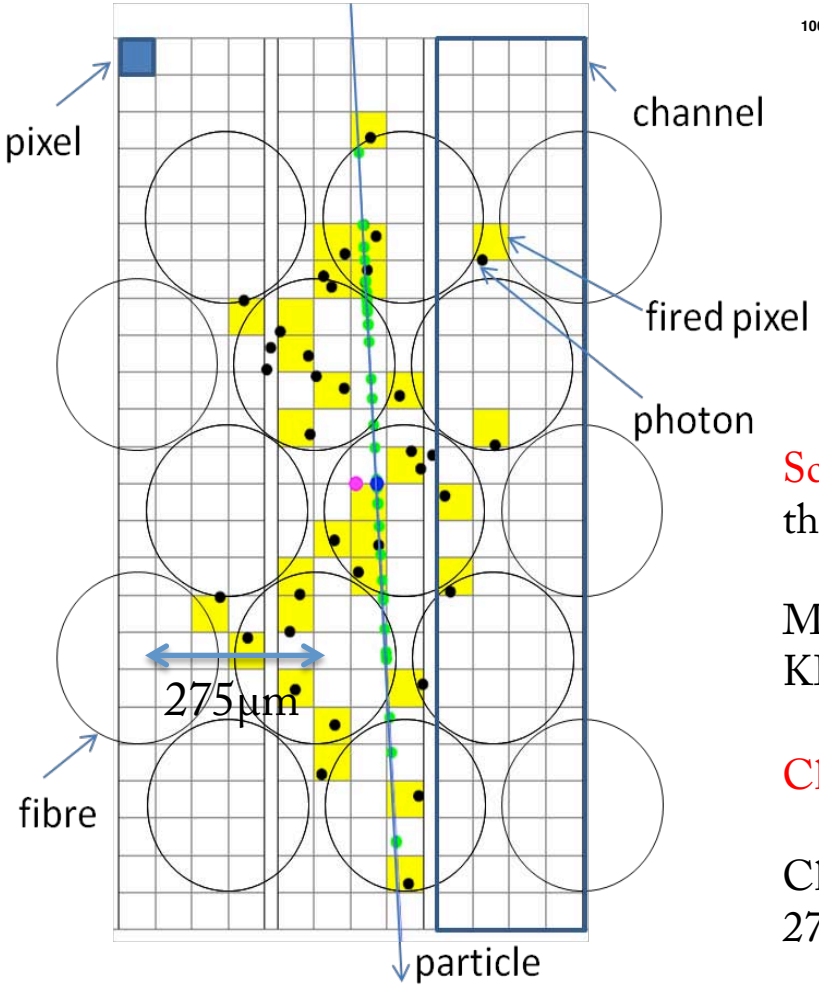
LHCb Tracker Upgrade Technical Design Report, LHCb Collaboration, LHCB-TDR-015, Feb. 2014.

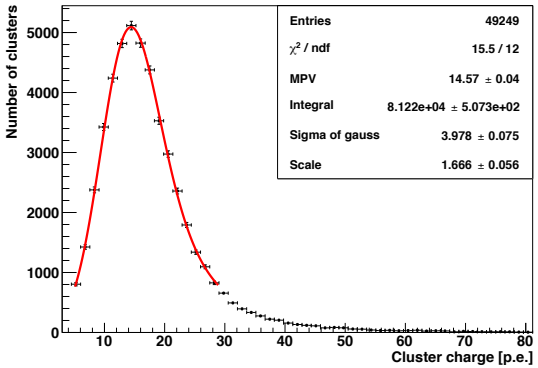
Requirements on detector performances:

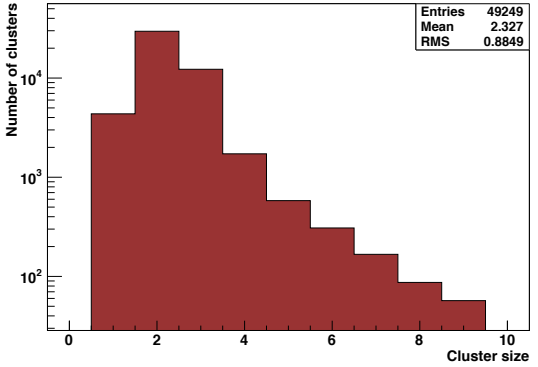
- Hit detection efficiency greater than 98%, with noise less than 10% of signal
- Spatial resolution better than 100 μm
- Operation at 25 ns interaction rate, 40 MHz readout
- High occupancy, up to 2.5 clusters for a detector array of 128 channels (32mm) in the hottest region
- Low material with $X/X_0 \leq 1\%$ per detection layer
- Radiation environment, fibres up to 35 kGy, SiPMs $6\times10^{11} n_{eqv}/cm^2$ fluence (with neutron shield) + 100 Gy ionising dose

SciFi working principle









Threshold based clustering algorithm is used to calculate the hit position
Typical signal produced by a traversing particle is larger than one channel

Scintillating fibres: 250μm diameter, 2.5m long, 6 layers near the beam-pipe and 5 every where else

Multichannel array of SiPM 128 channels (Hamamatsu or KETEK devices under development

Channel: size 0.25×1.5mm^2, 96 pixels (57.5x62.5μm^2)

Channel and fibres are not aligned (250μm channel and 275μm fibre pitch)

Noise cluster rate

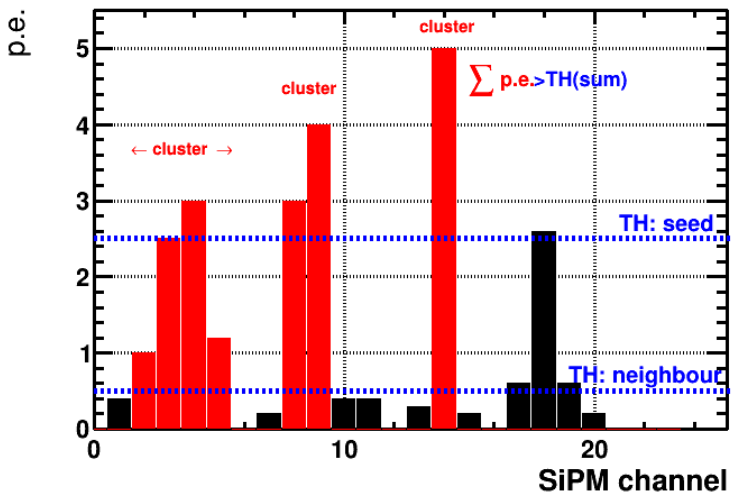
The noise cluster rate $\mathbf{f_C}$ is defined as the frequency of noise clusters for a 128Ch SiPM array which depends on:

DCR: the thermal noise increase with over-voltage (ΔV), depends on the temperature (T), the total surface of the detector (S) and the neutron fluence ($N_{fluence}$)

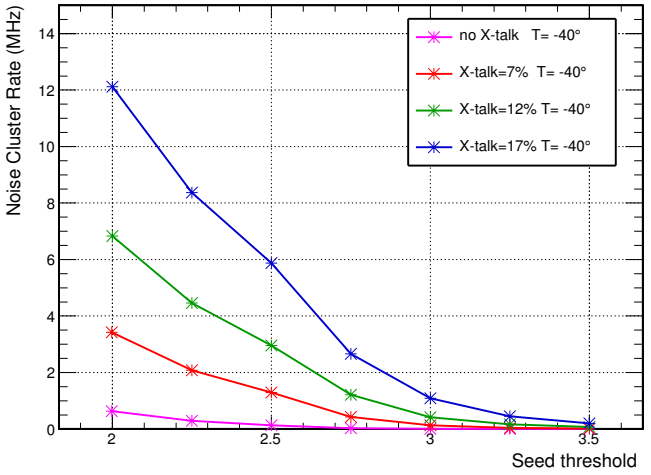
Clustering algorithm: the algorithm combines single channels into clusters, depends on the thresholds

X-talk: The pixel to pixel optical x-talk probability increases linearly with ΔV and increases significantly the $\mathbf{f_C}$

Illustration of the clustering algo.



Simulation for different x-talk

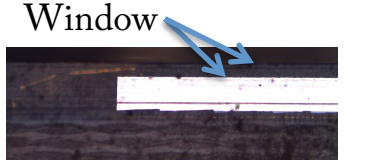


After-pulsing: Small effect for LHCb SciFi application (because of very fast shaping)

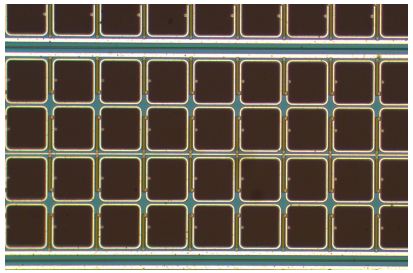
Shaping: Fast integration and shaping O(20 ns) allows to cope with high DCR

Important characteristics of the SiPMs for the LHCb SciFi Tracker

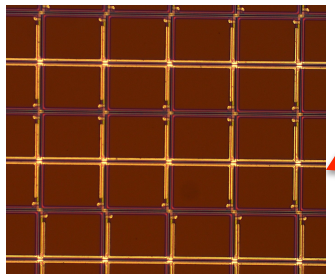
- High PDE! The 2.5m long fibres and the radiation damage of the fibres in the center of the detector, reduce the light output.
- Low x-talk! The noise cluster rate increases exponentially with x-talk. With the high DCR after irradiation, the noise cluster rate exceeds the acceptable level.
- Support 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.
- Thin entrance window! The entrance window defuses the light and therefore the thick window increases the cluster size and makes the spatial resolution worse.



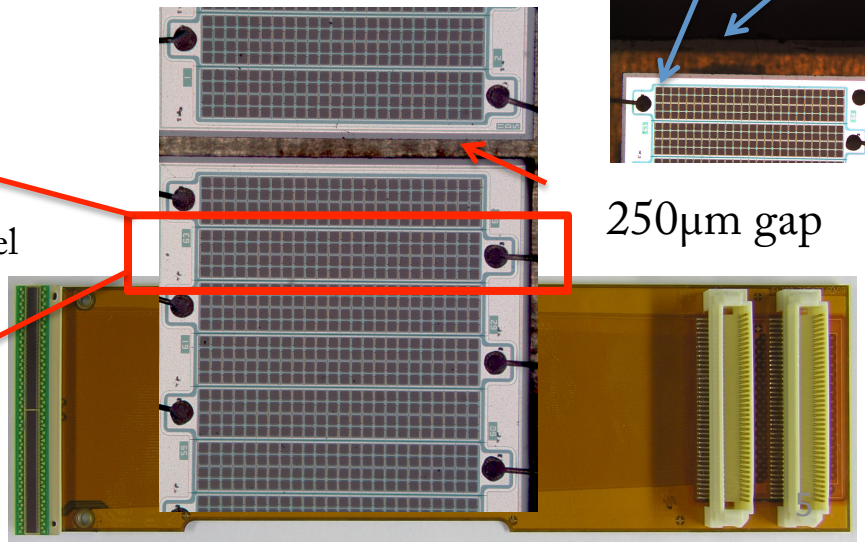
Hamamatsu (2010)
(Hamamatsu Photonics K.K., Japan)

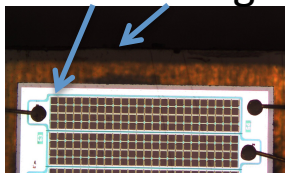


KETEK (highest possible fill factor)
(KETEK GmbH, Germany)



Channel





250μm gap

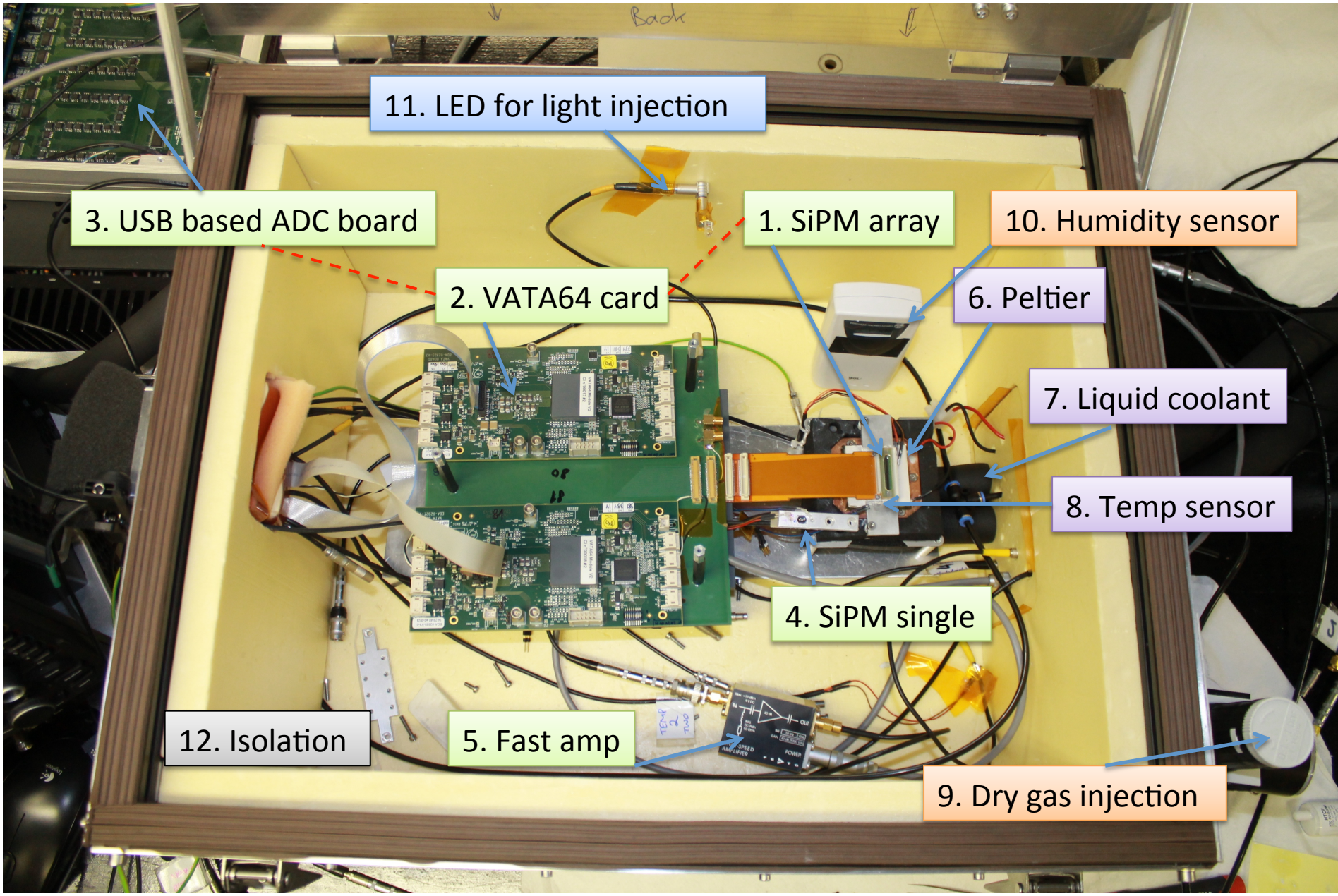
General characteristics

Detector type	Pixel size [µm²]	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	$9.5*10^6$

* Possible operation point for SciFi application (note that the DCR increases with over-voltage)

- Detectors with trenches can be operated at higher over-voltage (3.5V) which leads to a better gain uniformity $\delta G/G \propto \delta(\Delta V)/\Delta V$ for same V_{BD} variation.
- Higher gain uniformity within an array doesn't 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.

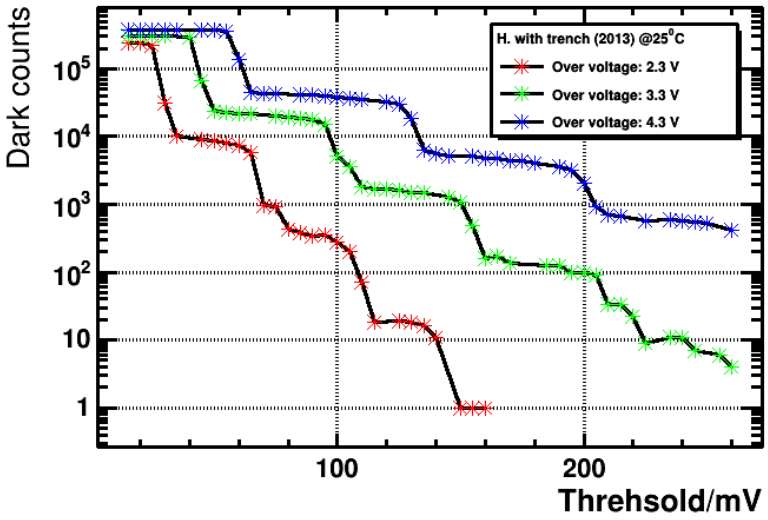
Cold box for SiPM characterization



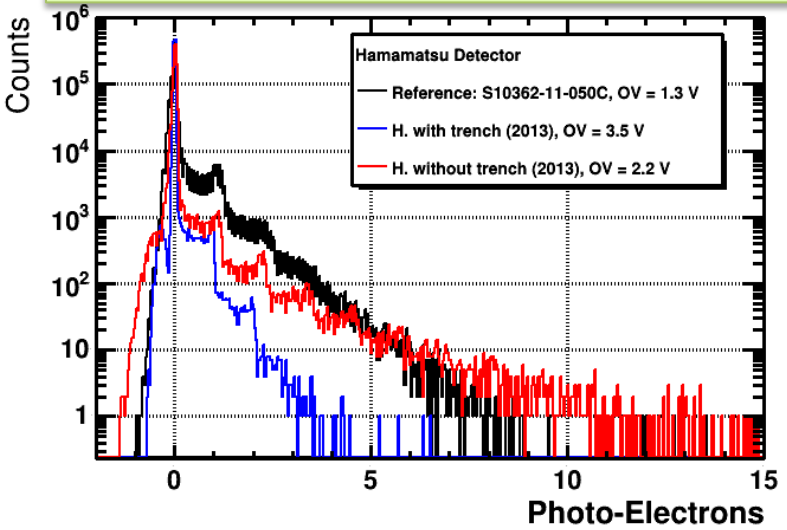
X-talk

- With low DCR (probability for two random pulses within shaping window small), the probability of x-talk is given by ratio $DCR_{th=1.5\ pe}/DCR_{th=0.5pe}$
- Two methods (systems) were used to measure x-talk.
  - Use a fast (single channel) amplifier (FEMTO 2GHz bandwidth) and record threshold scan. This allows to measure x-talk without after-pulsing due to the fast shaping.
  - Record dark spectrum with custom multichannel data acquisition system based on a VATA64 chip (64 channels, >50ns shaping time, sample and hold mode with serial readout, 12-bit ADC). 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.

Hamamatsu, 50um pixel with trench (2013), different over-voltages, threshold scan.



Hamamatsu, 50um pixel, standard (ref.), with trench (2013), without trench (2013), at typical over-voltage, recorded with VATA64.



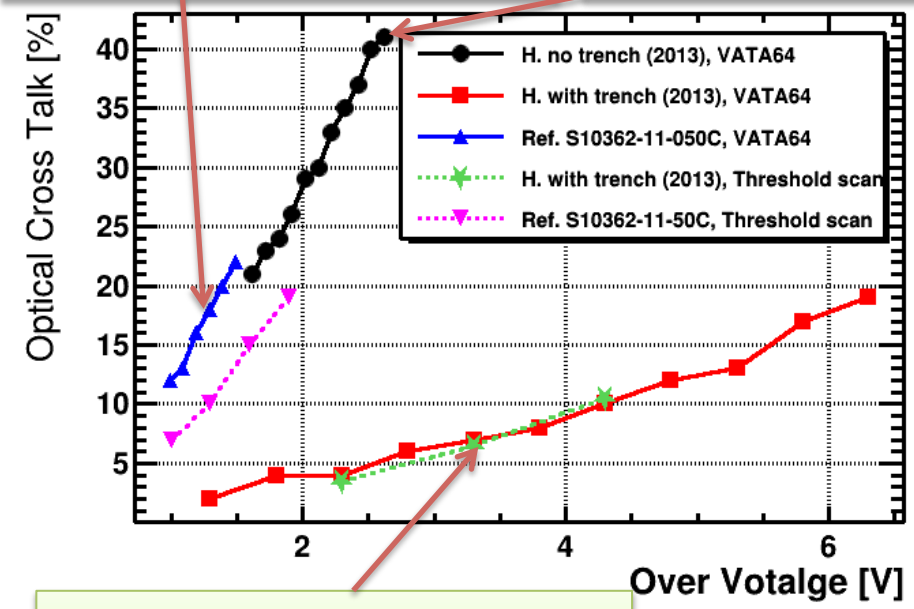
X-talk Hamamatsu and KETEK

Comparison of different Hamamatsu 50um pixel devices.

Comparison of different KETEK devices with different pixel sizes.

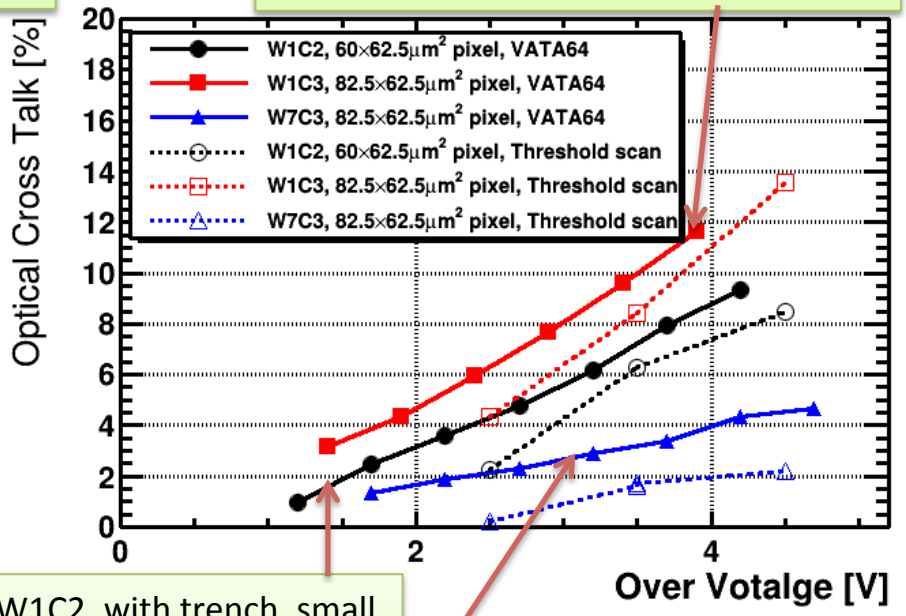
Difference due to after-pulsing (1.3V over-voltage) (17% vs 10%)

No trench, extremely high x-talk



With trench, low after-pulsing, 7% x-talk at 3.5V over-voltage

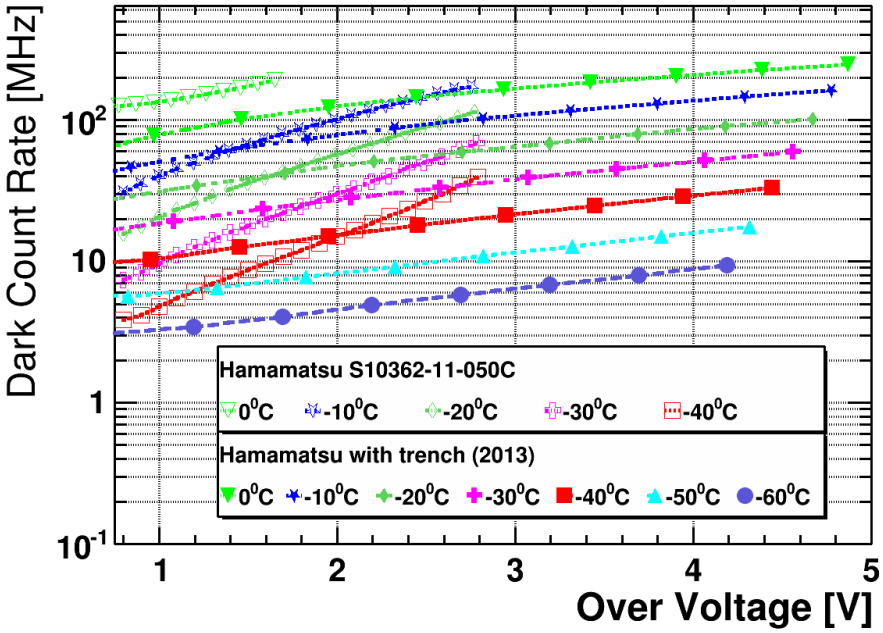
W1C3, with trench, large pixels (3.5V over-voltage) (10% vs 8%)



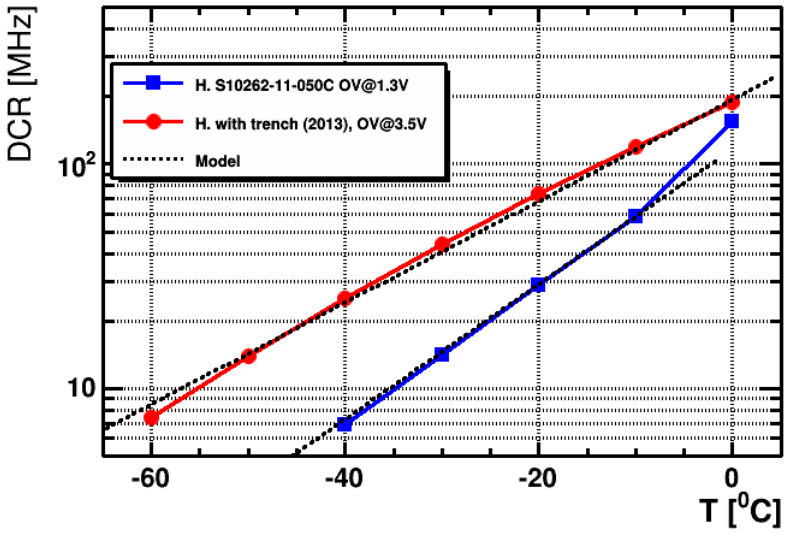
W1C2, with trench, small pixels (3.5V over-voltage) (8% vs 7%)

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

DCR for Hamamatsu detector



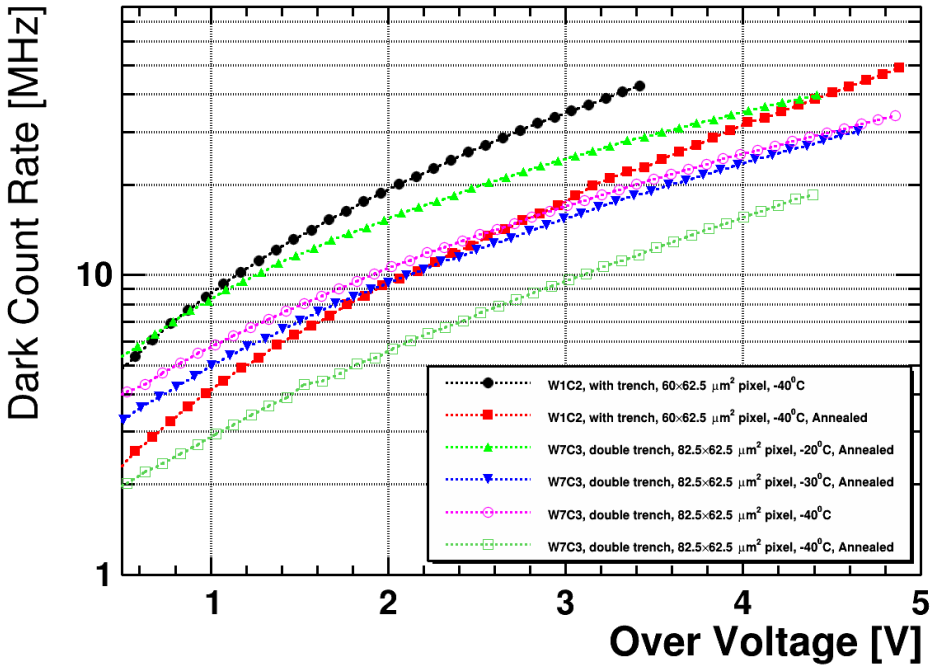
1mm² single channel, 3.1×10^{11} n_{eqv}/cm^2 fluence at different temperatures

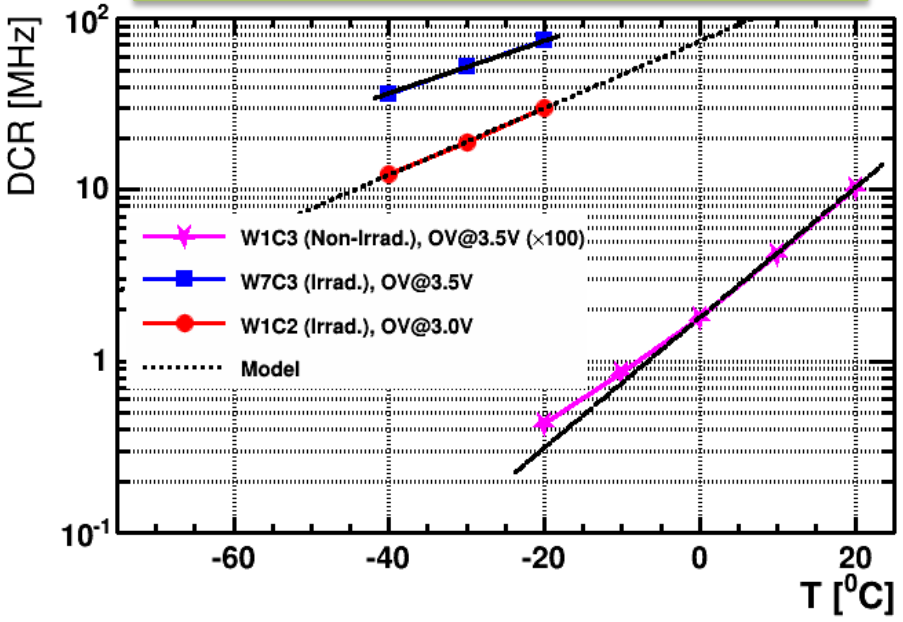


- The temperature dependence of the DCR is an important characteristic for the SciFi Tracker in LHCb. Cooling to -40°C is foreseen to reduce the DCR to an acceptable level.
- We express the dependence in a temperature difference required to reduce the DCR by a factor 2 ($\mathbf{K_{1/2}}$). The temperature dependence of the DCR is related to different SiPM technologies.
  - Hamamatsu S10262-11-050C, after irradiation $K_{1/2}$=10°C
  - Hamamatsu detector with trenches (2013), after irradiation $K_{1/2}$=12.8°C
- The detector with trenches (2013) can work at a higher over-voltage (to increase the PDE) but this increases the DCR!
- The detectors were annealed after irradiation (at 40°C, one week) to reduce the DCR. Annealing effect can reduce the DCR by a factor 2-2.5 for detectors operated at low temperature.

DCR for KETEK detector

1/3mm^2 , 2×10^{11} n$_{eqv}$/cm^2 fluence at different temperatures





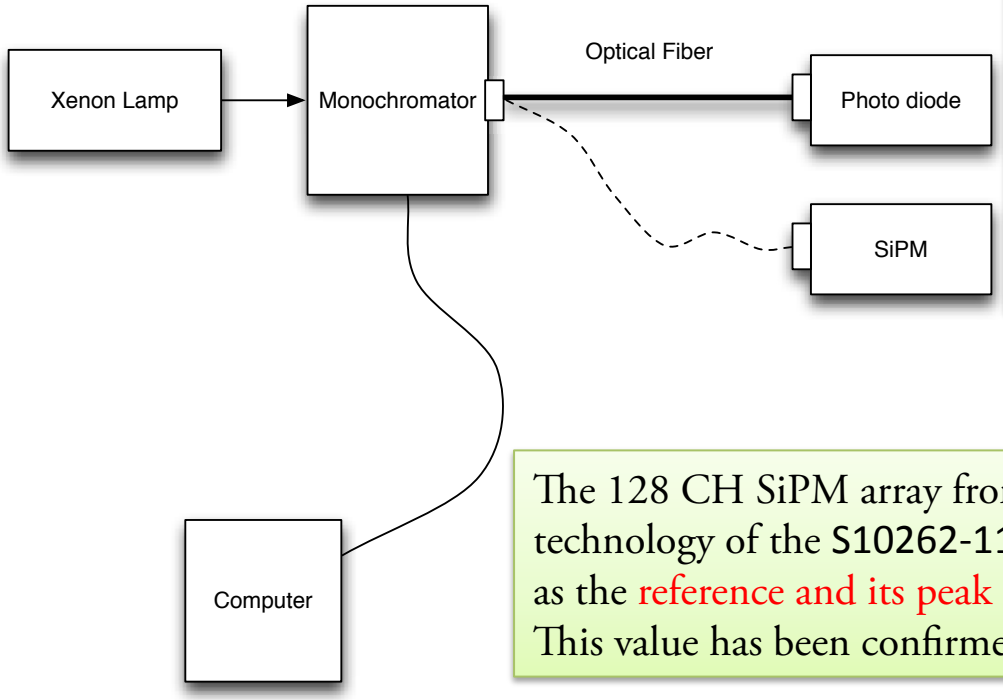
- The temperature $K_{1/2}$ dependence of the DCR also changes between, before and after irradiation.
- The DCR for the double trench KETEK device is a factor 2-3 higher than Hamamatsu with trench, at 3.5V over-voltage and -40°C. Note that the measurements need to be scaled to the same surface and the same neutron fluence.

Photon Detection Efficiency

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

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

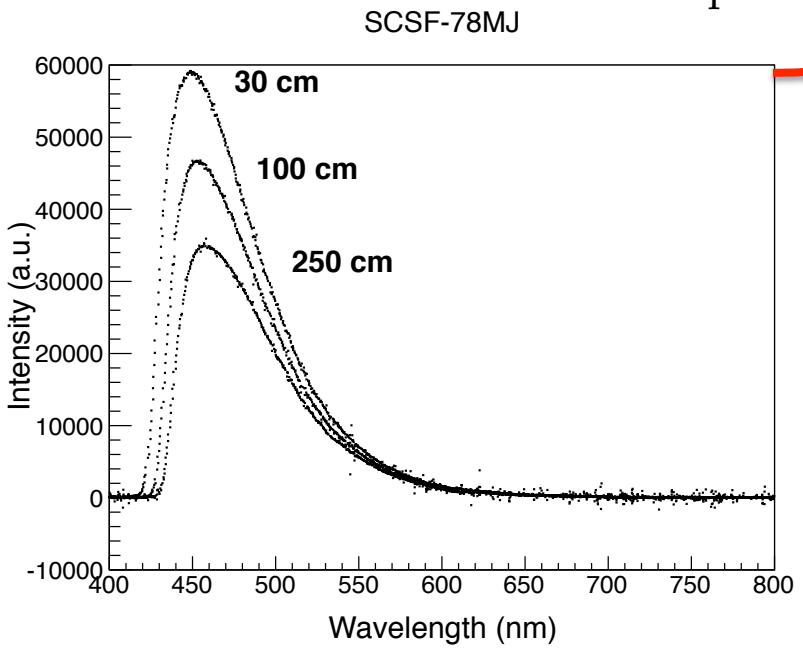
Corrections for: Dark current (I_{dark}), x-talk (+after pulse) ($P_{x\text{-}talk}$), lamp emission ($I_{PD}(\lambda)$)



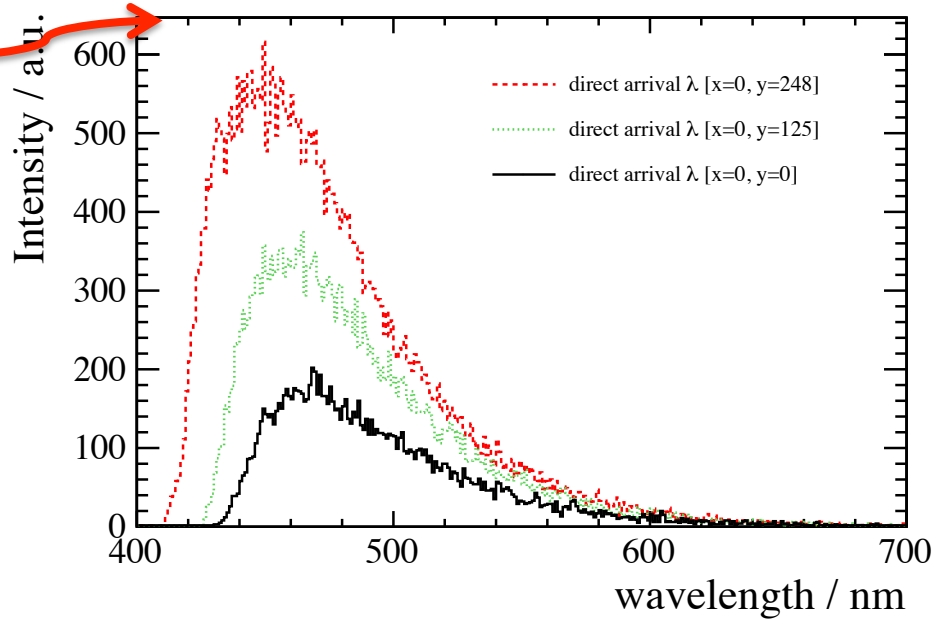
- Calibrated light source with photo diode
- Monochromator for wavelength selection
- Light coupled to optical fibre and optional illuminating PD or SiPM

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.

Emission spectrum of the SCSF-78MJ fibre



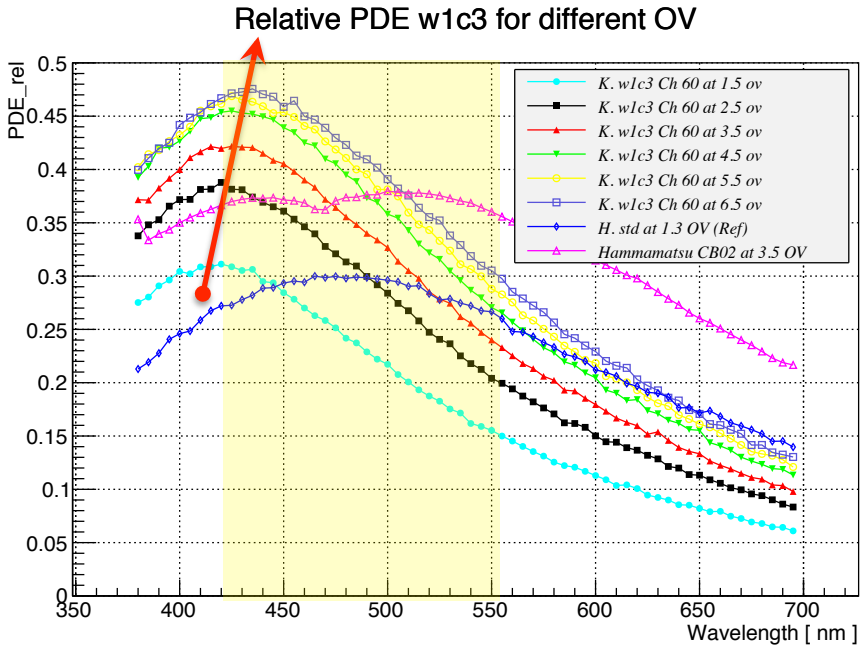
Expected after irradiation (35kGy) based on MC study

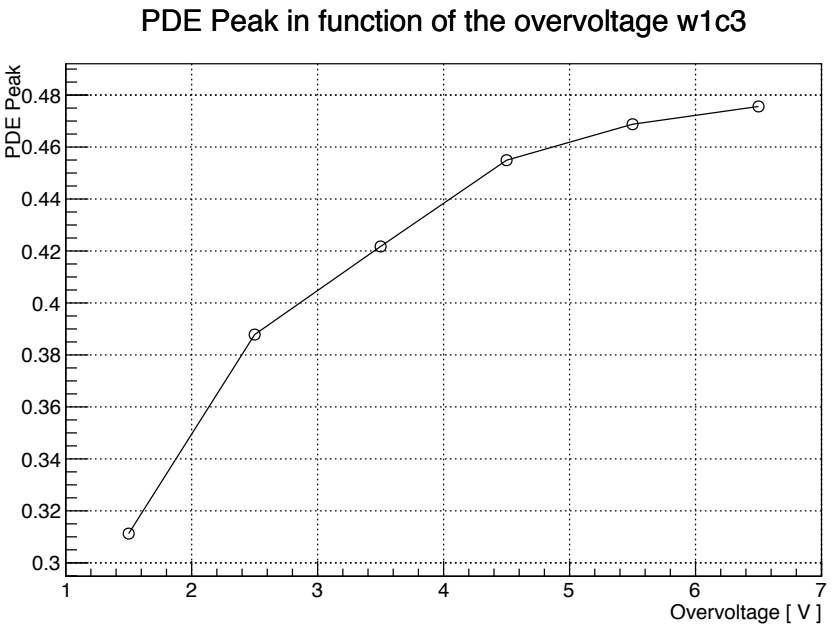


Non irradiated: Fibre emission spectrum (SCSF-78MJ). It extends from 400 to 600 nm and peaks at 450 nm.

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

PDE Hamamatsu and Ketek





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

Summary

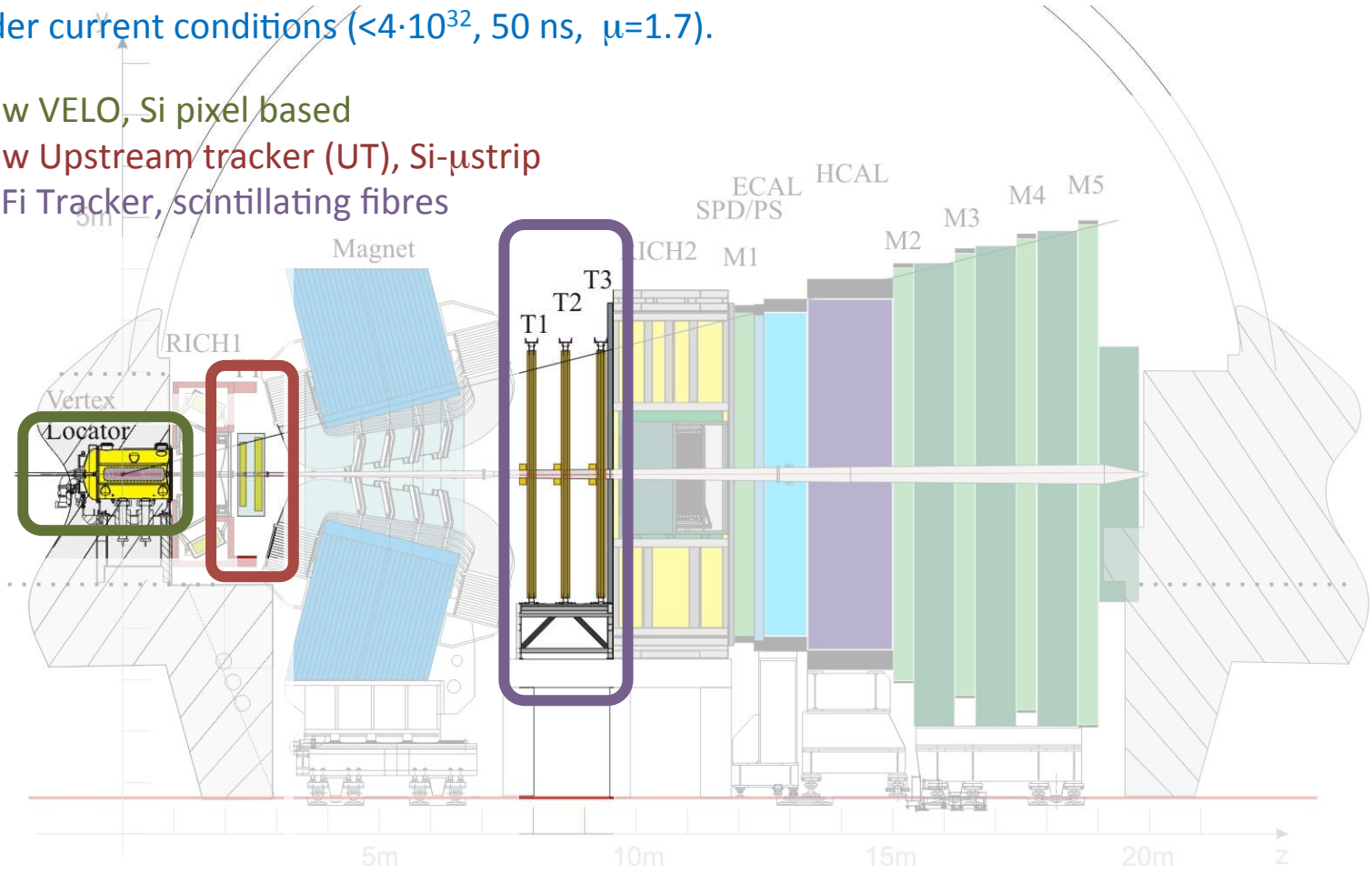
Detector type	H. S10262-11-050C	H. with trench (2013)	K. W1C2, with trench	K. W1C3, with trench	K. W7C3, double trench
Surface [mm^2]	1	1	1/3	1/3	1/3
Pixel size [μm^2]	50×50	50×50	60×62.5	82.5×62.5	82.5×62.5
T_C [mV/K]	56	43	15	15	22
Over-voltage [V]	1.3	3.5	3.5	3.5	3.5
X-talk + After-pulsing	17%	7%	8%	10%	3%
V_{BD} [V]	69	55	23.5	23.5	32.4
Gain [e/PE]	0.75×10^6	2.0×10^6	8.5×10^6	12.0×10^6	9.5×10^6
PDE @peak	30%	37%	42%	44%	40%
Weighted PDE integral	1.26	1.61	1.44	1.55	1.47
Irradiation [n_{eqv}/cm^2]	~3	~3	~2		~2
DCR (annealed), -40°C [MHz]	~7	~25	~ 25		~12

- For LHCb SciFi Tracker we evaluated custom SiPM arrays from KETEK and Hamamatsu, which both have high PDE, low x-talk and sufficient radiation hardness.
- 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 overv-oltage.
- Detectors with (double) trenches have low x-talk and better gain uniformity due to lower T_C and higher over-voltage.
- The high DCR for these detectors require cooling to -40°C in order to reach an acceptable noise cluster rate. $K_{1/2}$ dependence for different technologies might lead to lower DCR.

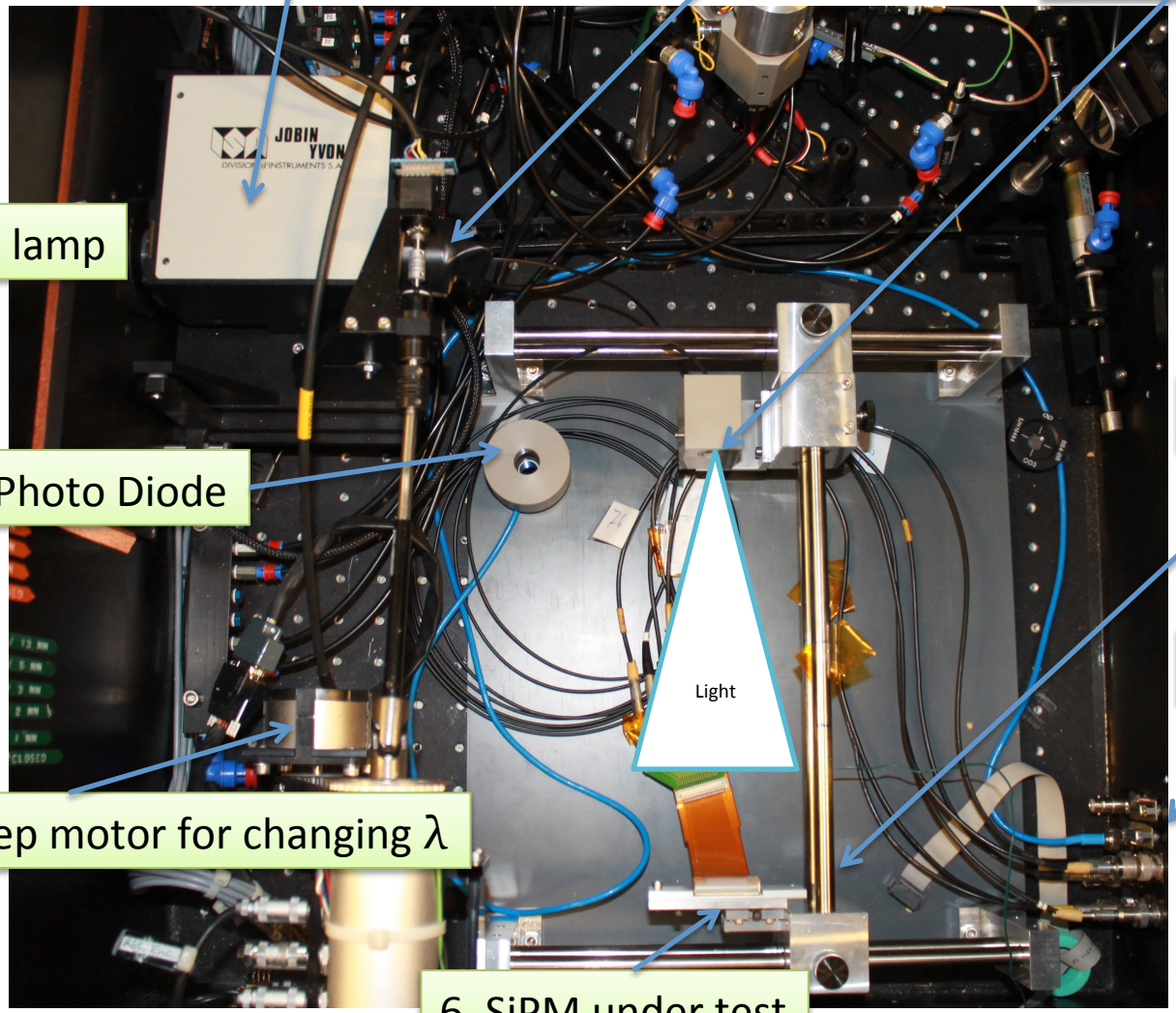
Major tracking upgrade of LHCb (for after LS2, ≥2020, 50fb^{-1})

Aim for the same performance at high luminosity ($2 \cdot 10^{33}$ cm^{-2}s^{-1}, 25 ns, ν =7.6) as under current conditions ($<4 \cdot 10^{32}$, 50 ns, μ=1.7).

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



Relative PDE measurement for SiPM with monochromator



2. Monochromator

3. Light to fibre coupling

4. Light out of fibre

1. Xe lamp

Adjustable distance

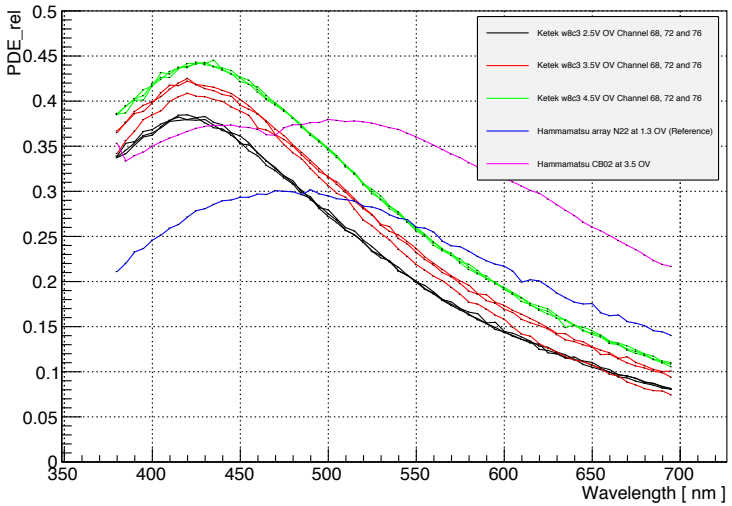
5. Calib. Photo Diode

7. To picoamp meter

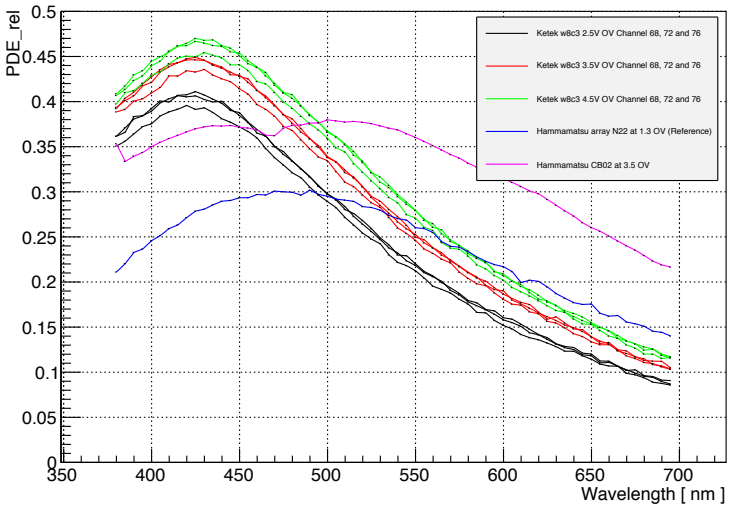
2. Step motor for changing λ

6. SiPM under test

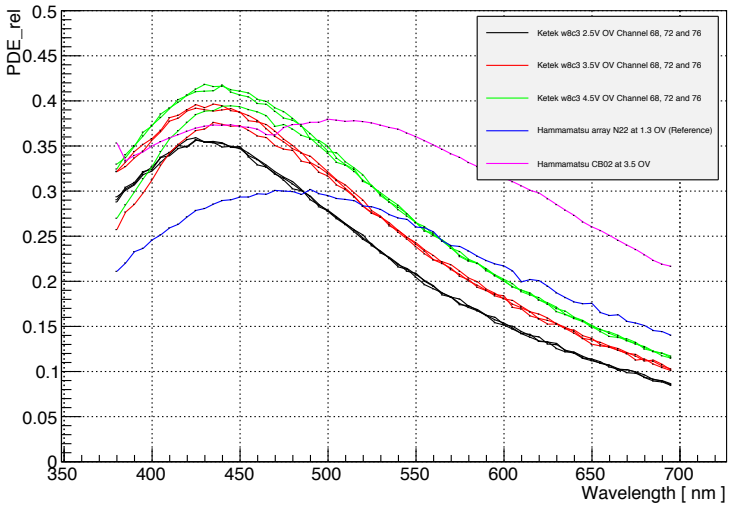
Relative PDE w1c2FW



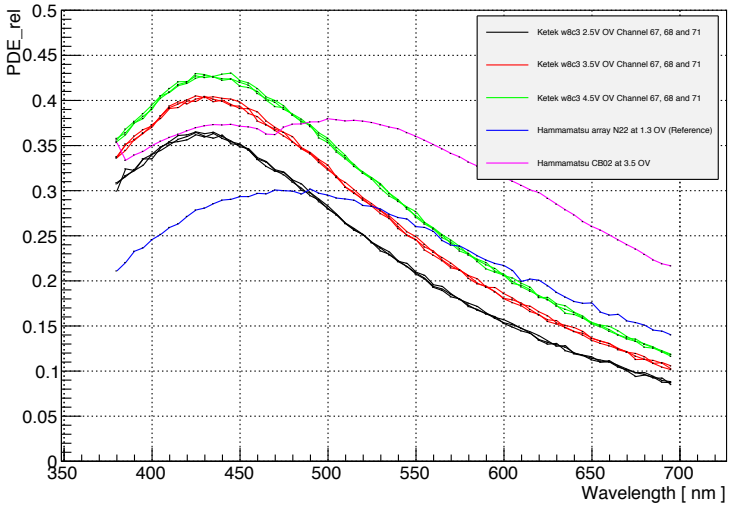
Relative PDE w1c3FW



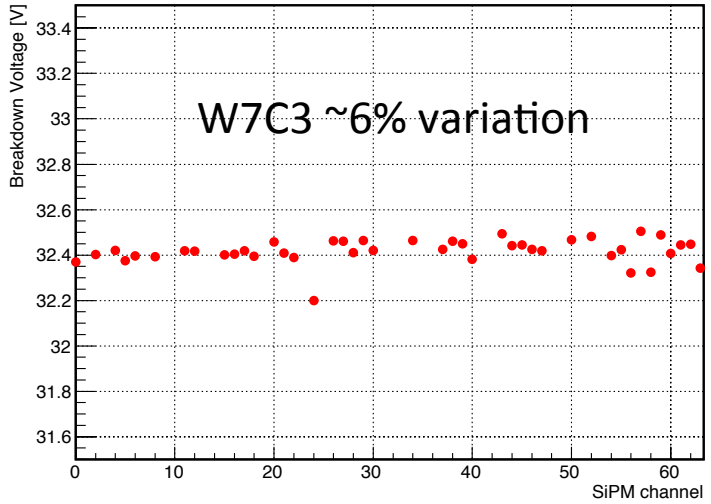
Relative PDE w7c2FW

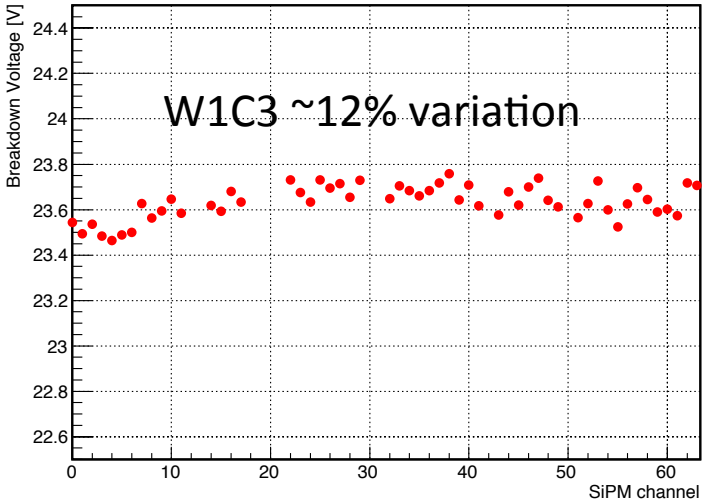


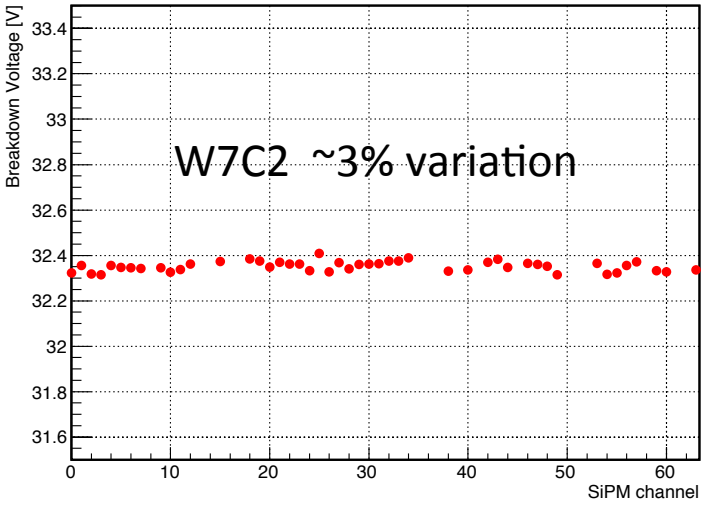
Relative PDE w7c3FW

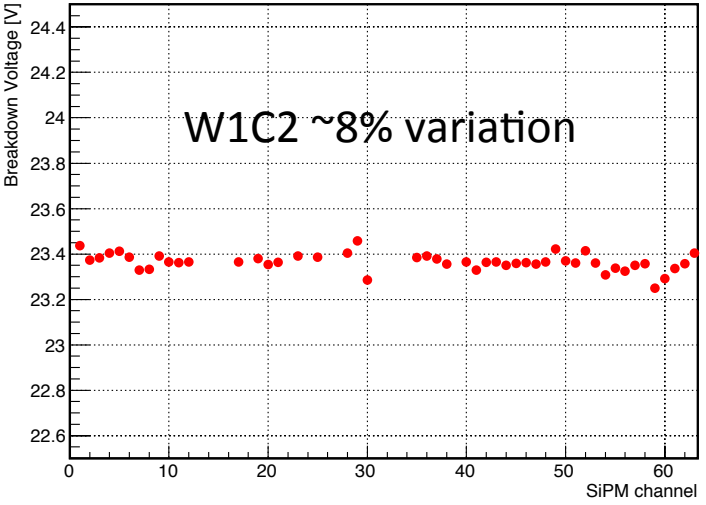
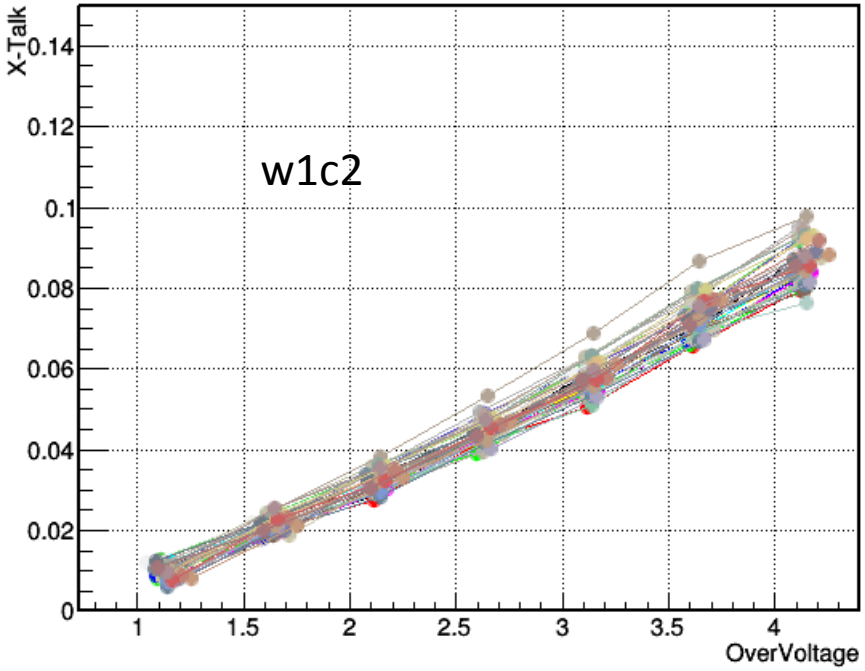
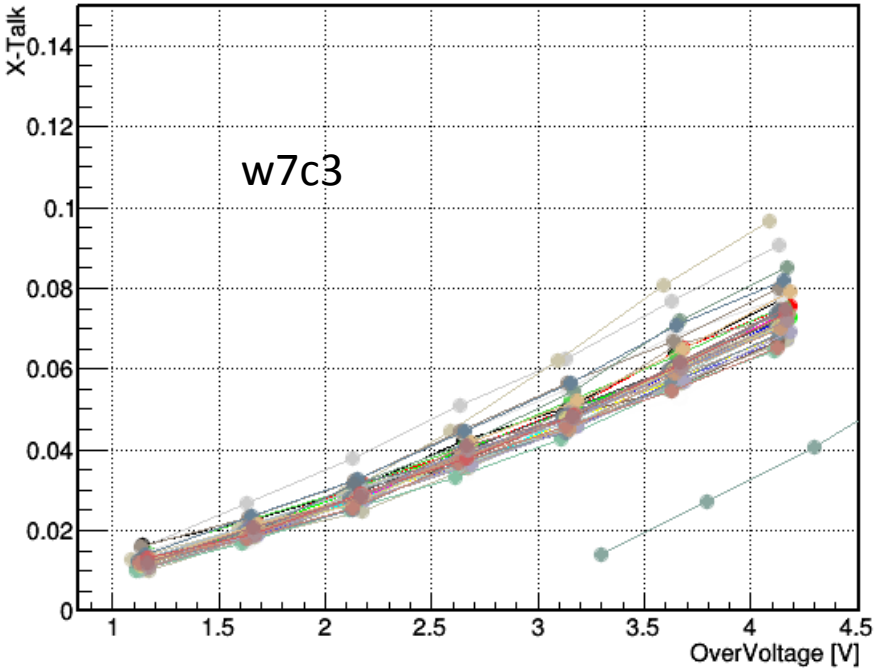


KETEK channel-to-channel uniformity









KETEK x-talk for different channels