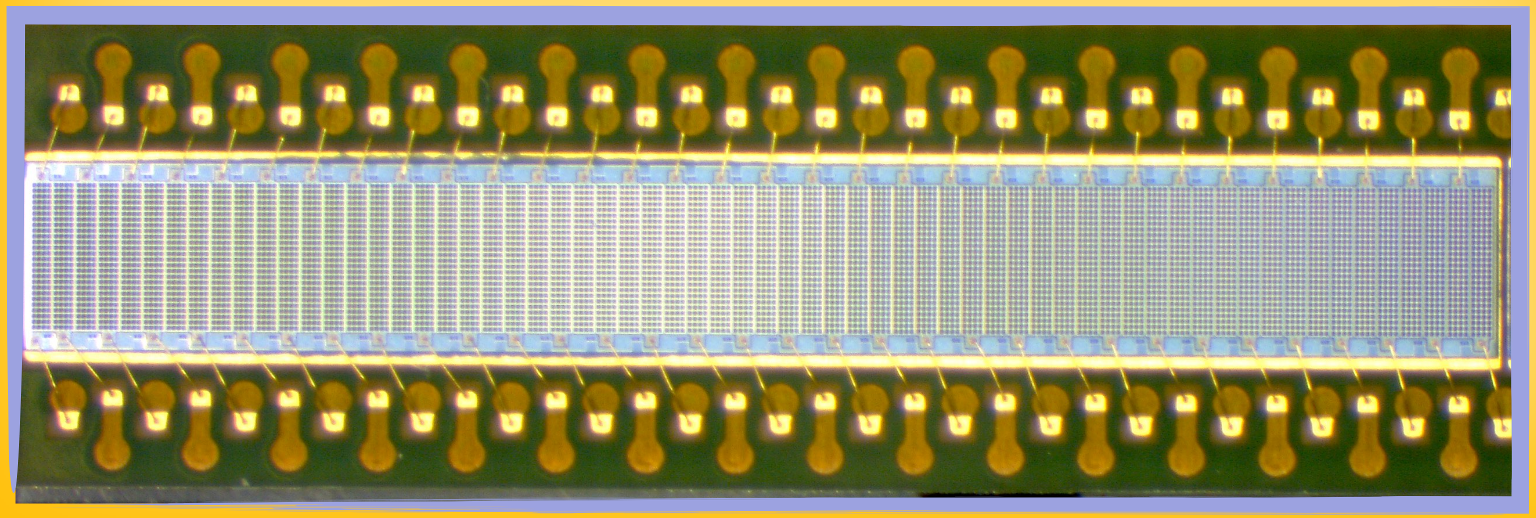

Characterisation of multi-channels Silicon Photomultipliers

Maria Elena Stramaglia

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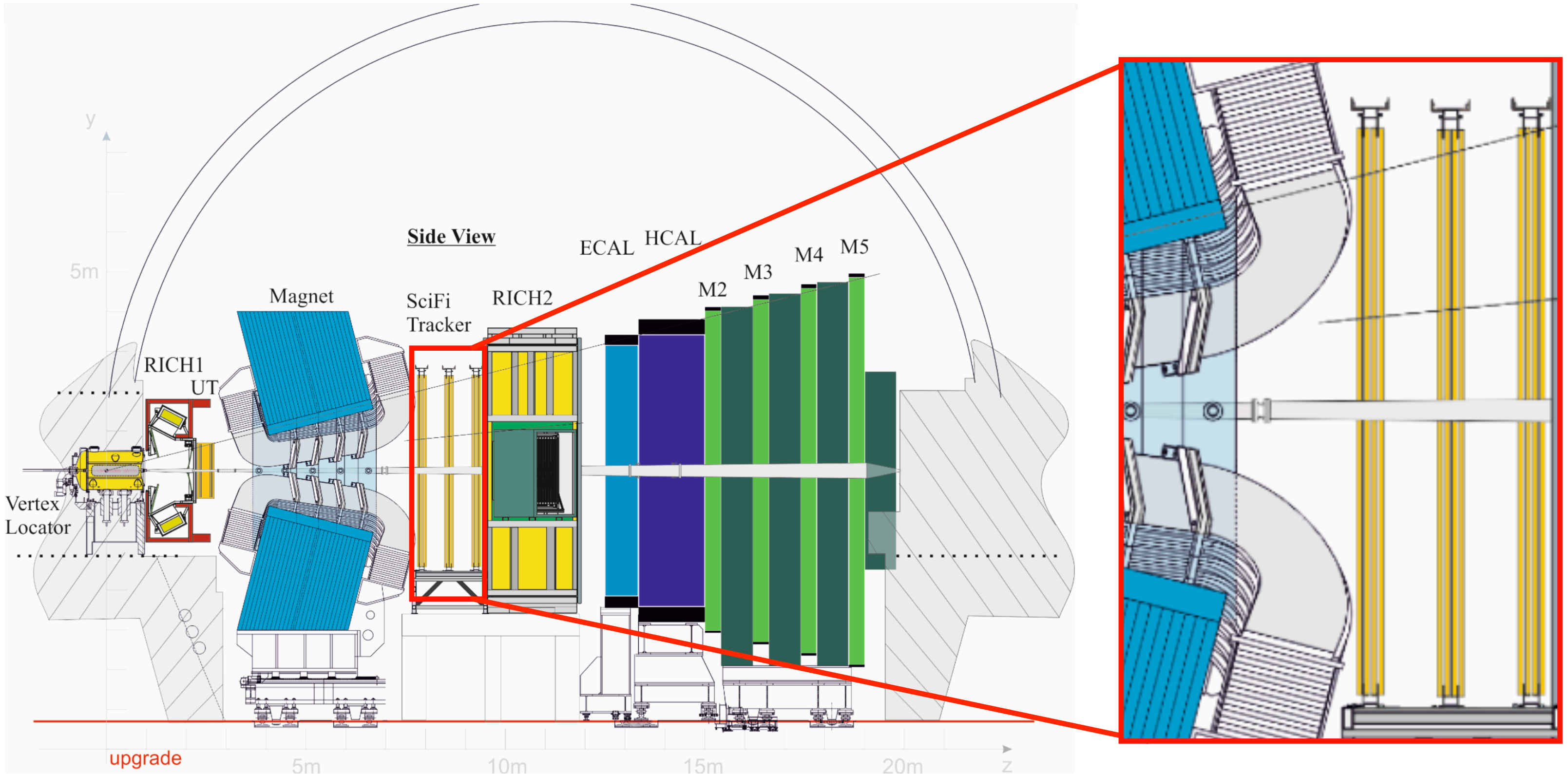
LHCb upgrade requirements

- LHCb is being upgraded for Phase-II with the Sci-Fi tracker (more by Vladimir Macko, Guillaume Pietrzyk and Lino Ferreira Lopes)
  - cover a large area: 340 m^2
  - $X/X_0 \leq 1\%$ per detection layer
  - single hit spatial resolution in the bending plane of the magnet ≤100 μm
  - 10 years to collect an integrated luminosity up to 50 fb^{-1}

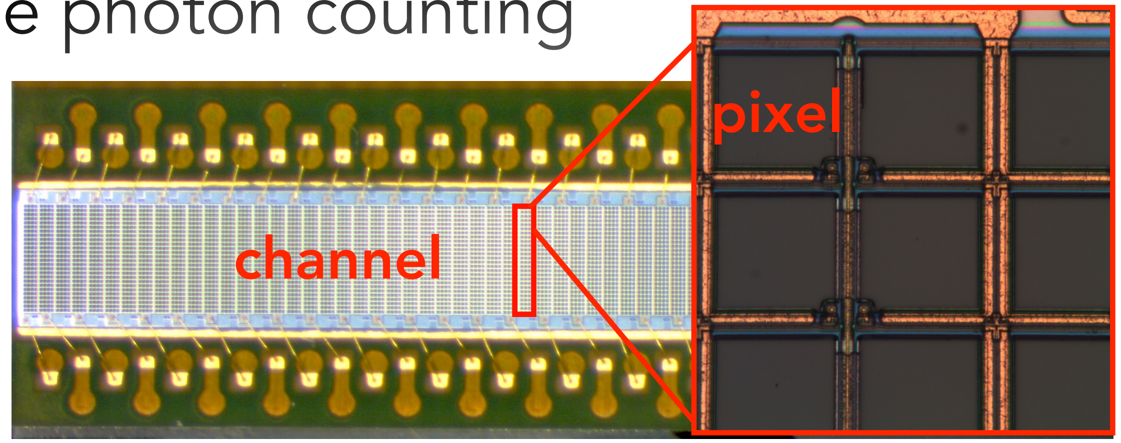


- 3 stations of scintillating fibres
  - 4 layers per station
    - 2 layers inclined of 5°
- Segmented vertically in two
  - each 2.5 meters high
  - read out at outermost sides
- Average 20 photons collected at the readout side

  - hit detection efficiency ≈ 98% until the end of the lifetime when the light yield of the fibres reduces of 40% due to radiation damage
  - noise cluster rate at any location < 10%
  - readout at 40 MHz

Multi-channels Silicon Photomultipliers

- produce a pulse proportional to the number of collected photons
- possible single photon counting



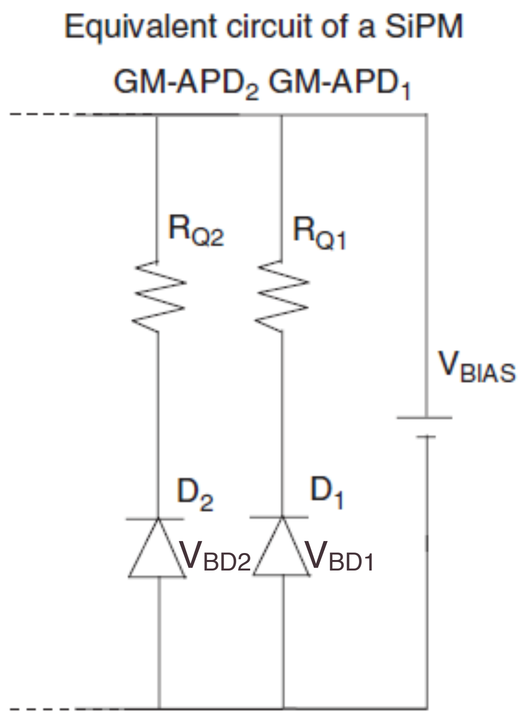
- total area: ~0.45 mm^2
- 128 channels:
  - 250 μm wide
  - 104 pixels per channel
  - pixel size: 57.5 μm x 62.5 μm

- key characteristics:
  - gain ~ 1.1 x 10^6 e/V
  - low correlated noise (cross-talk between pixels reduced by optical trenches)
  - photo detection efficiency close to 50%
  - tolerance to the expected level of radiation ~6×10^{11} n_{eq}/cm^2
  - uniform breakdown voltage among channels < 1 V

- various technologies tested:

detector type	WxH	pixel	R_Q [kΩ]	coating
Hamamatsu H2015	230 μm × 1.625 mm	57.5 × 62.5 μm^2	200	epoxy (120 μm)
KETEK	252 μm × 1.62 mm	60 × 63 μm^2	480	glass (3 μm)
Hamamatsu H2017	**230 μm × 1.625 mm**	57.5 × 62.5 μm^2	**450**	**epoxy (120 μm)**

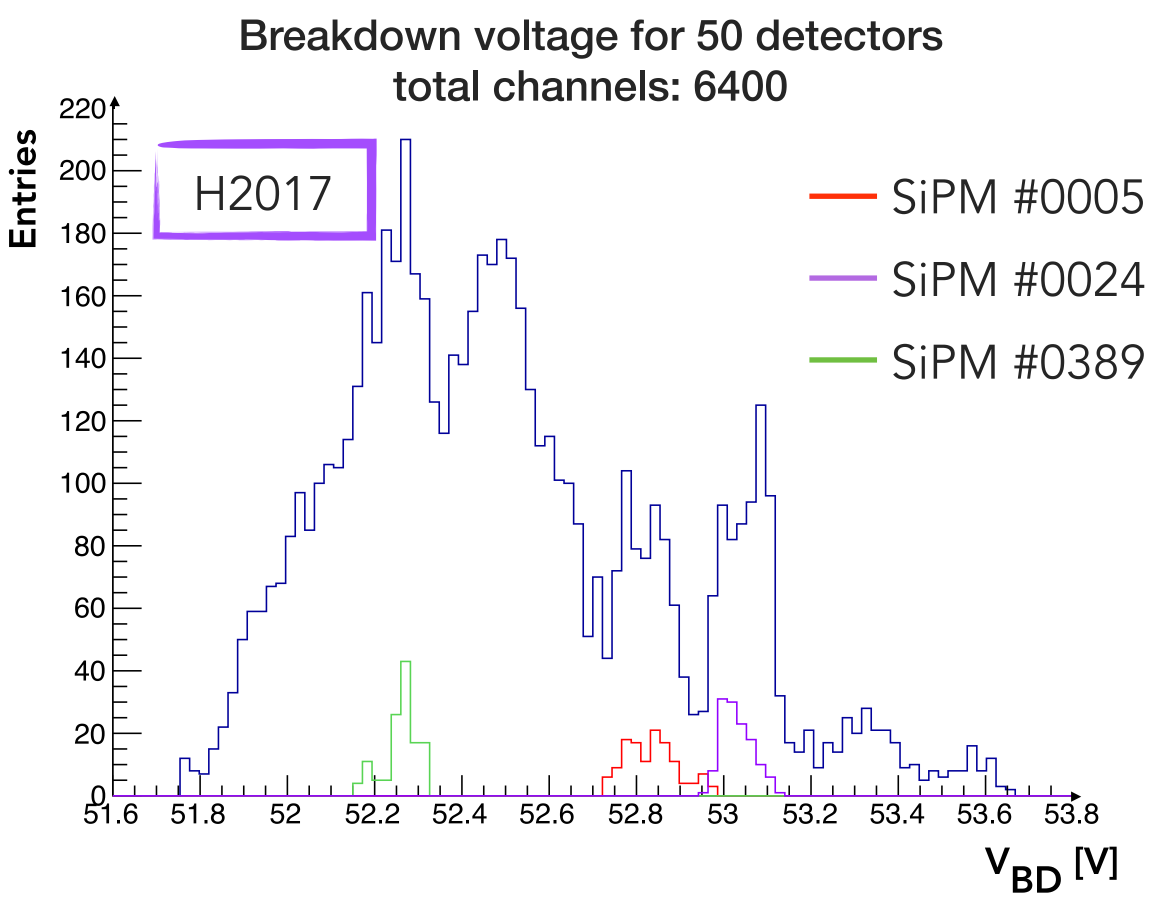
Breakdown voltage V_{BD} measurements



R_Q: quenching resistance

V_{bias}: applied voltage

$V_{BD} \leq V_{bias}$: breakdown voltage (voltage where amplification sets in)



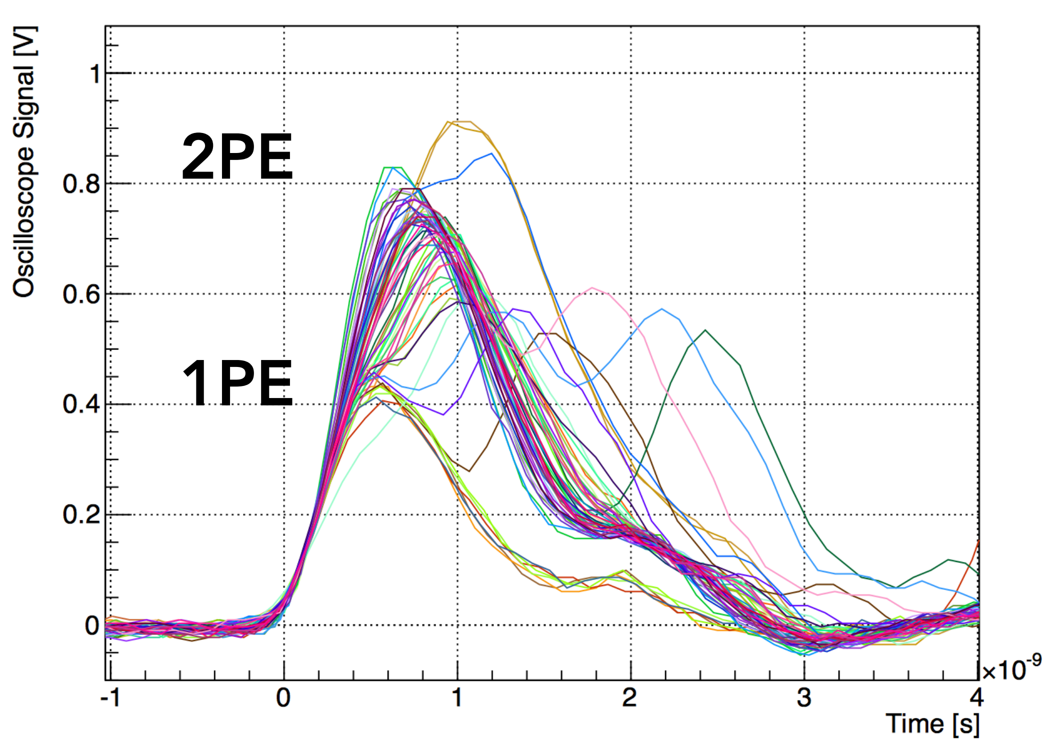
- Breakdown voltage: largest **reverse voltage** that can be applied without causing sensible increase in current due to avalanche
- V_{BD} value can be determined by a scan over V_{bias} (IV scan) or low light photon counting
- Good uniformity of the V_{BD} allows to apply the same V_{bias} to all channels/detectors with uniform response

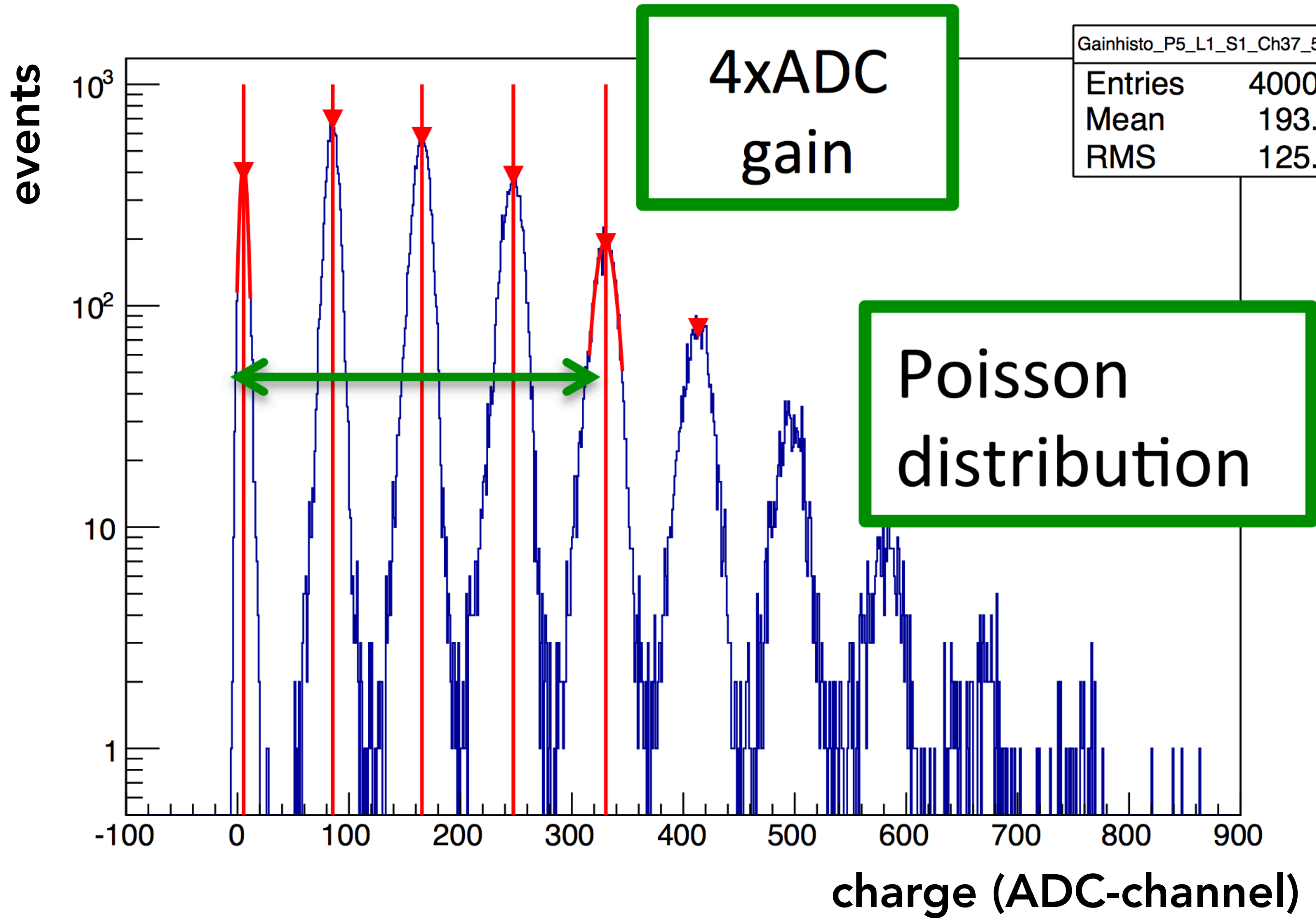
RESULTS:

- Possibility to run 6 V (V_{OV}) without loosing linearity
- Breakdown voltage spread within 2 Volts for different SiPMs
- Maximum spread within one SiPM is smaller than 0.7 Volts

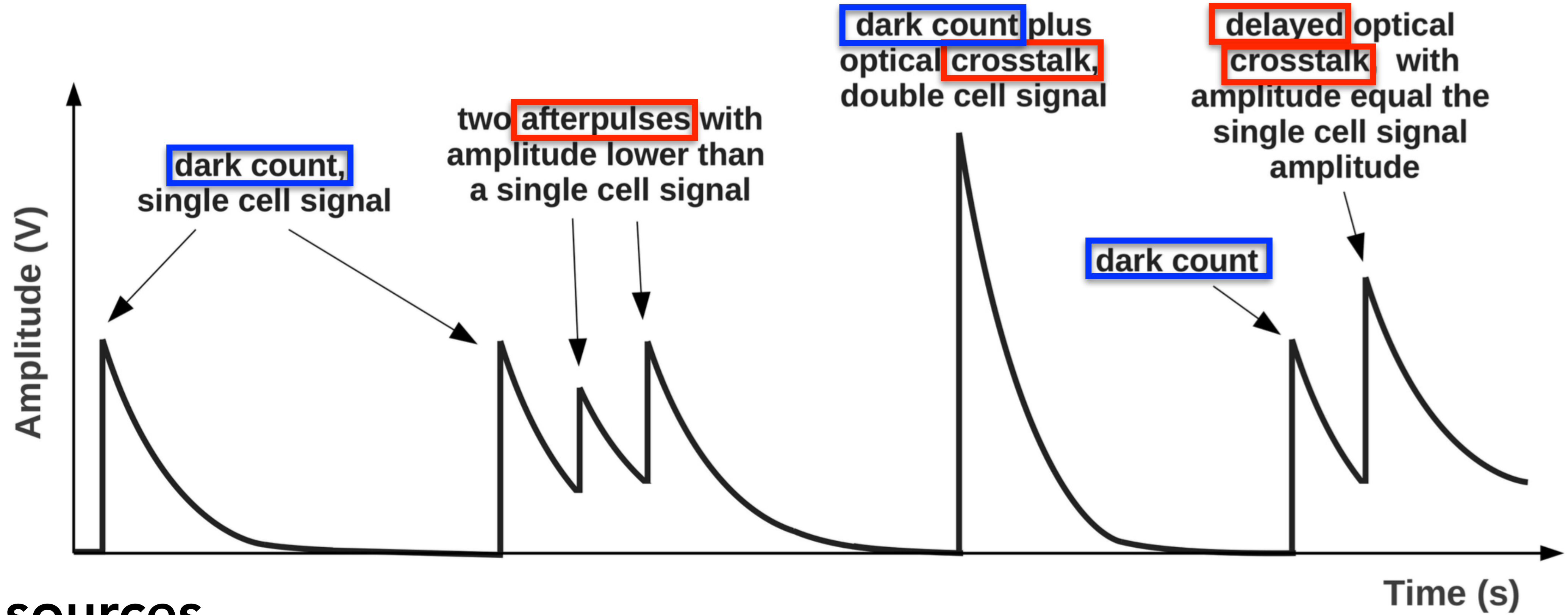
Gain measurement

- Gain: **number of carriers generated** in response to an **absorbed photon**
- At fixed V_{OV}, every detected photon results in a highly quantised output pulse
- Peaks due to successive numbers of detected photons (PE) in charge spectrum are well separated





Pulse shape



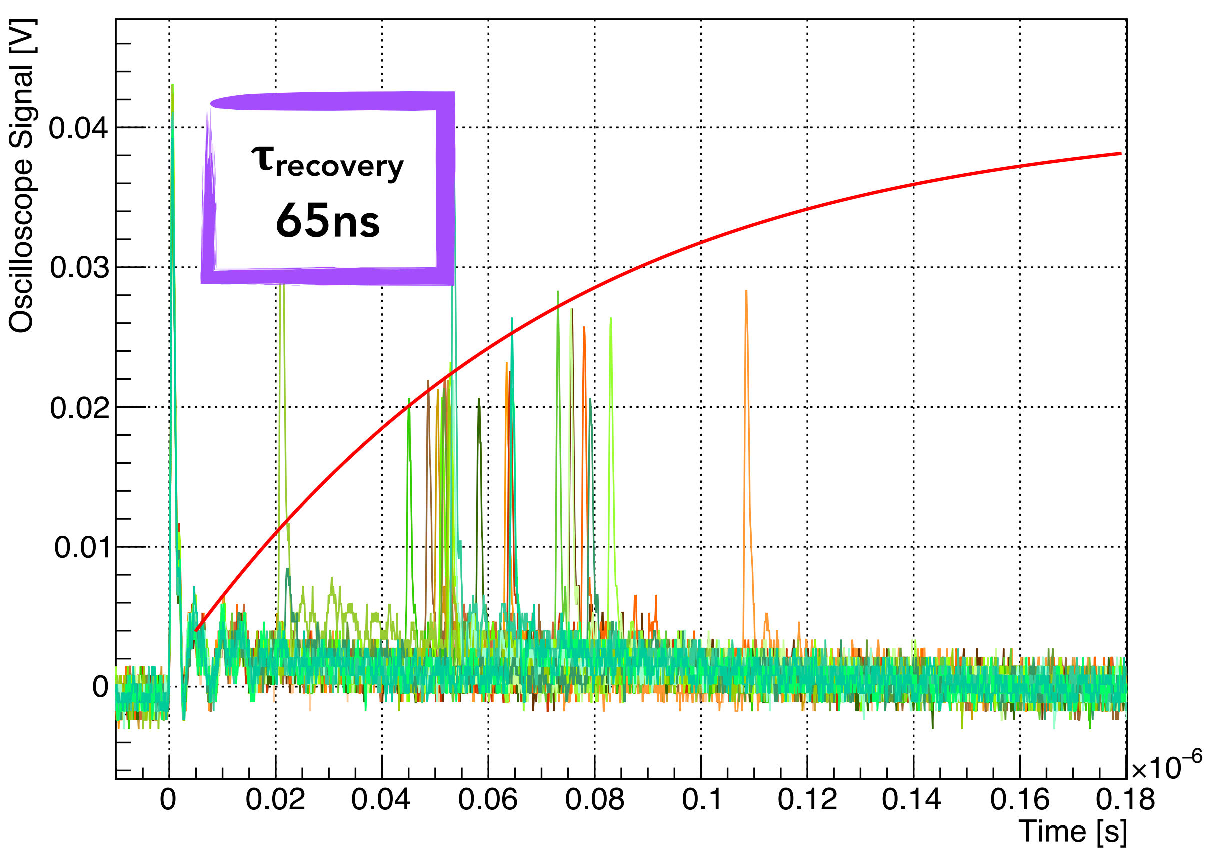
Noise sources

- Dark Counts: thermal / tunnelling generation
- Afterpulse (AP): carriers trapped during the avalanche can produce delayed secondary pulses with amplitude depending on recovery state (~1% @3.5 V for H2017)
- Direct crosstalk (XT): avalanche produced photons, trigger another avalanche in a neighbouring cell instantaneously (~4% @3.5 V for H2017)
- Delayed crosstalk (D-XT): photons create carriers in the vicinity of neighbouring avalanche region triggering a secondary delayed avalanche (~4% @3.5 V for H2017)
- Higher order contributions

Noise characterisation

- 10% of total correlated noise at first order for Hamamatsu H2017, 17% for H2015
- Afterpulse events employed to estimate the recovery time
  - afterpulse and recovery time dependent on the quench resistance, more than twice higher in 2017

Afterpulse H2017, R_Q: 490 kΩ



Afterpulse H2015, R_Q: 210 kΩ

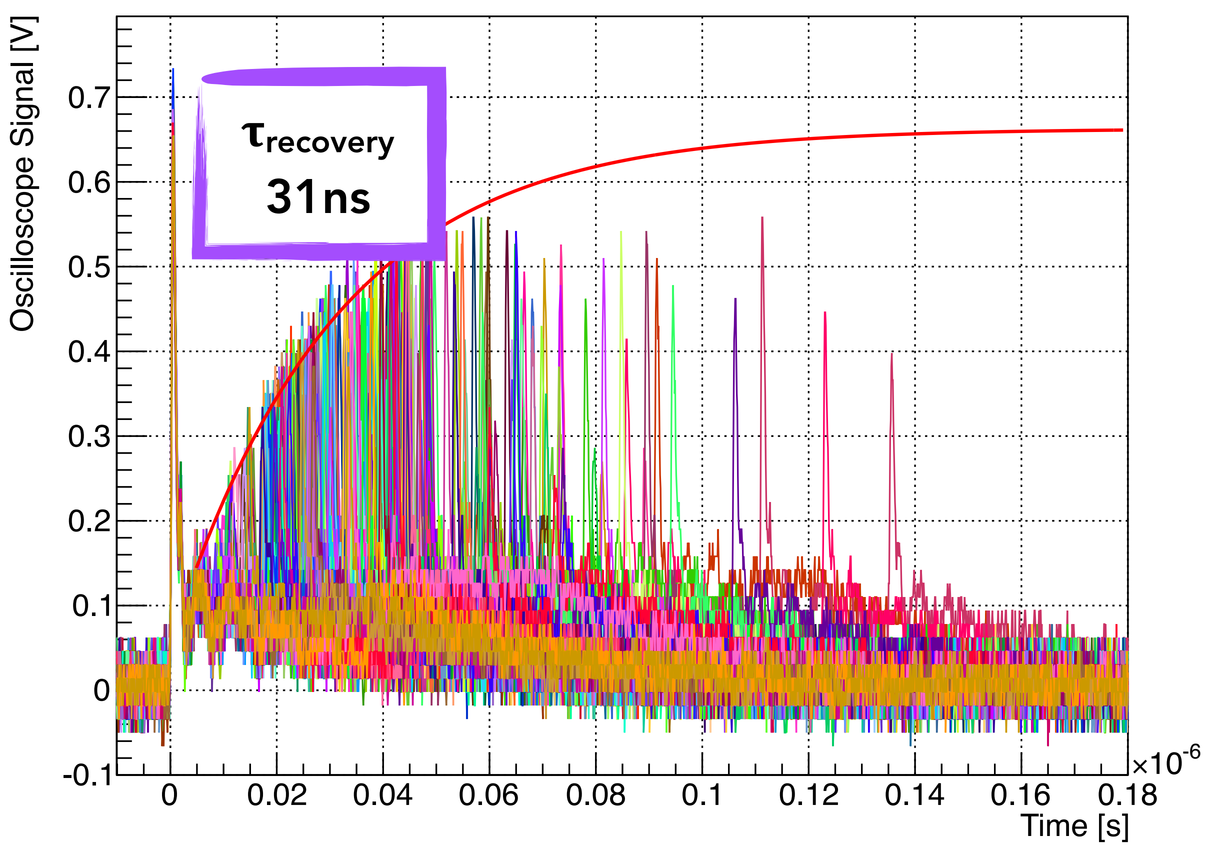
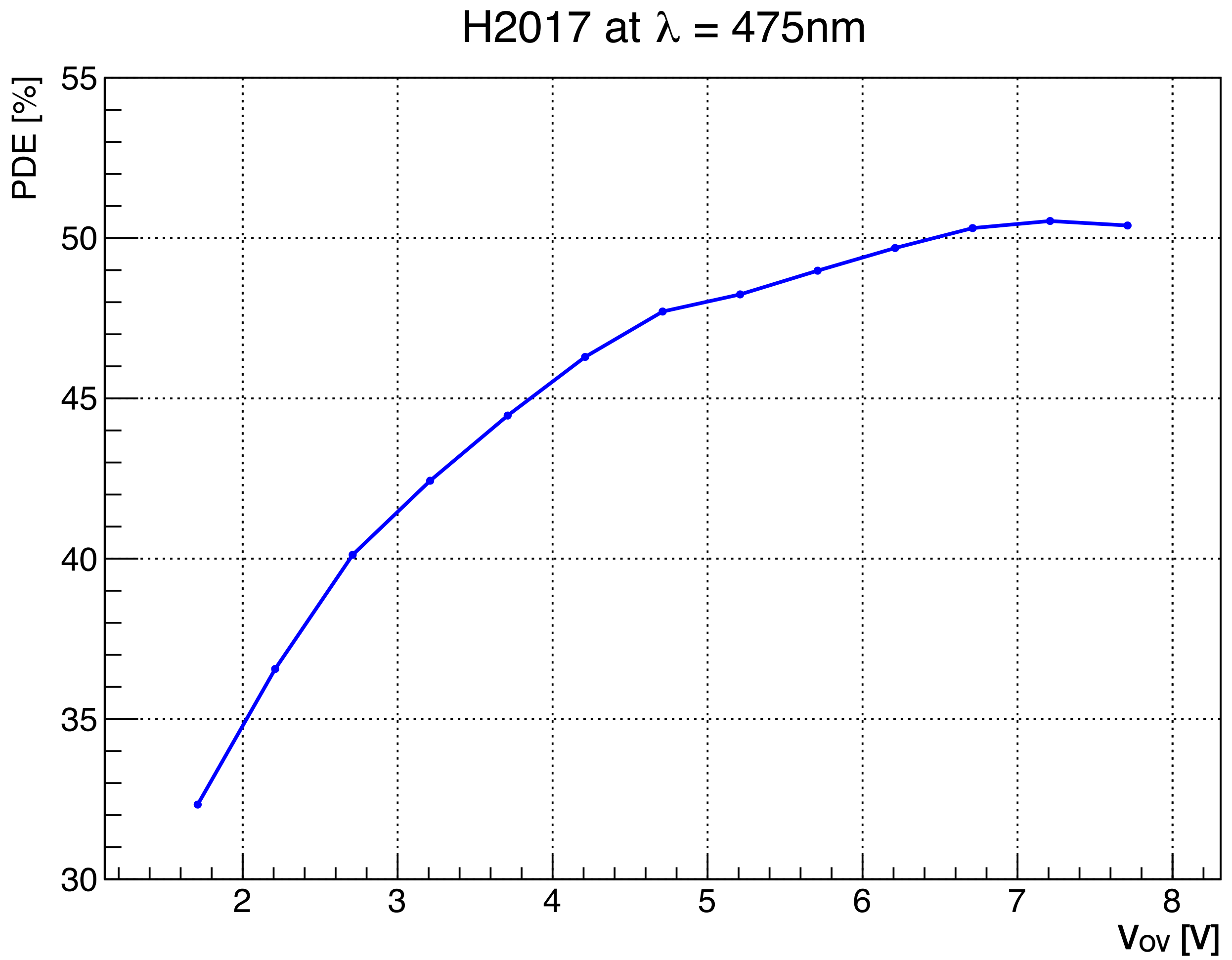
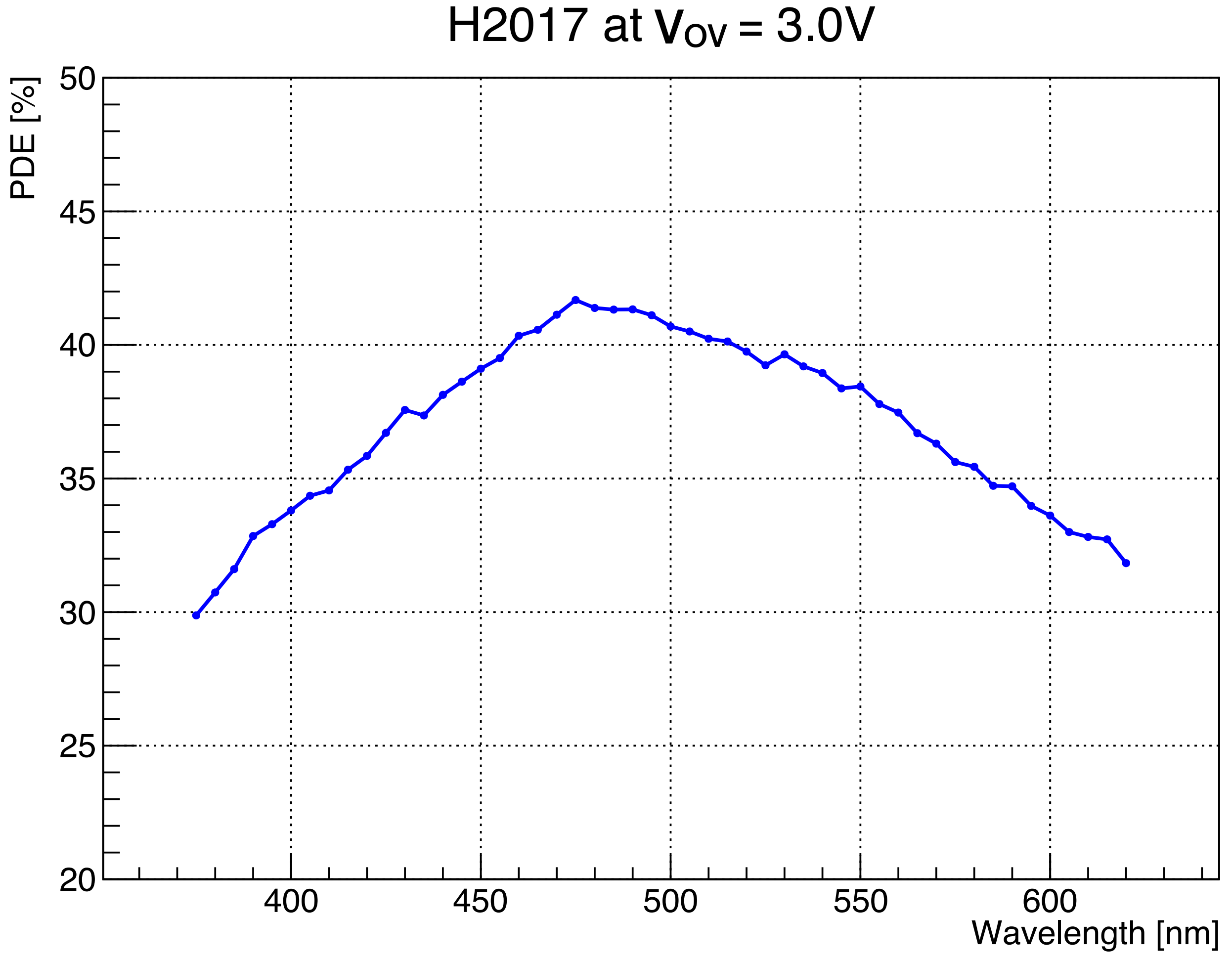


Photo-detection efficiency

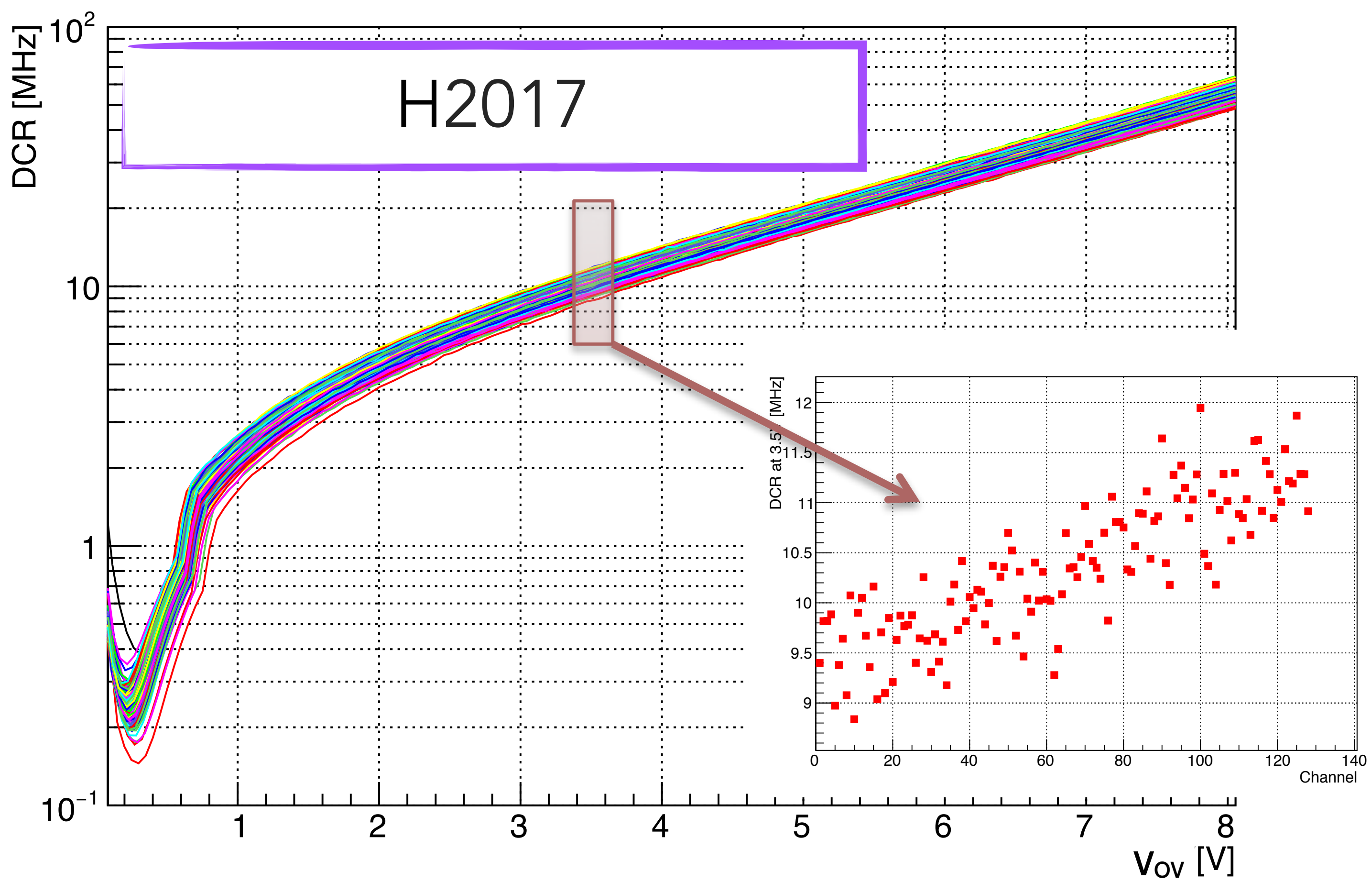
- **Photo detection efficiency:** ratio between the number of detected photons and the number of incident photons
- PDE obtained as a relative measurement between SiPMs
- Photodiode to calibrate the light intensity of the lamp at different wavelengths
- Measurement performed at different wavelengths and different over-voltages
- Number of peaks corrected for noise





Irradiation studies

- Detectors sent to Ljubljana (**neutron** irradiation) :
  - irradiation @ $3*10^{11}$ n_{eq}/cm^2, $6*10^{11}$ n_{eq}/cm^2, $12*10^{11}$ n_{eq}/cm^2
- The dark count rate (DCR) increases linearly with neutron fluence
- Dark count rate: **14 MHz** per channel at – 40°C and V_{OV} = 3.5 for $6*10^{11}$ n_{eq}/cm^2
- Dark count rate variation of **±1.5MHz** over the 128 channels



Dose [n_{eq}/cm^2]	DCR[MHz] @ 3.5V and -40°C
$3*10^{11}$	6.0
$6*10^{11}$	14.3
$12*10^{11}$	28.0

~factor 2

Conclusions

- A system to fully characterise the detectors was developed and employed as benchmark
- This allows to be active part of the R&D and select the Hamamatsu H2017 as the optimal choice for the SciFi tracking detector
- Low noise, radiation tolerance, wide range of stability and high photo-detection efficiency are the key characteristics for the scintillating fibre tracker
- Hamamatsu has started the production of 5500 H2017 ordered by the LHCb collaboration
- We are currently going for the characterisation of 704k channels
- The first 500 detectors have been delivered and fully characterised


рахмат
danke
謝謝
ngiyabonga
spas
teşekkür ederim
Баярлалаа
mersi
kia ora
barka
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mahalo
tapadh leat
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SOME
MORE
...

Radiation environment

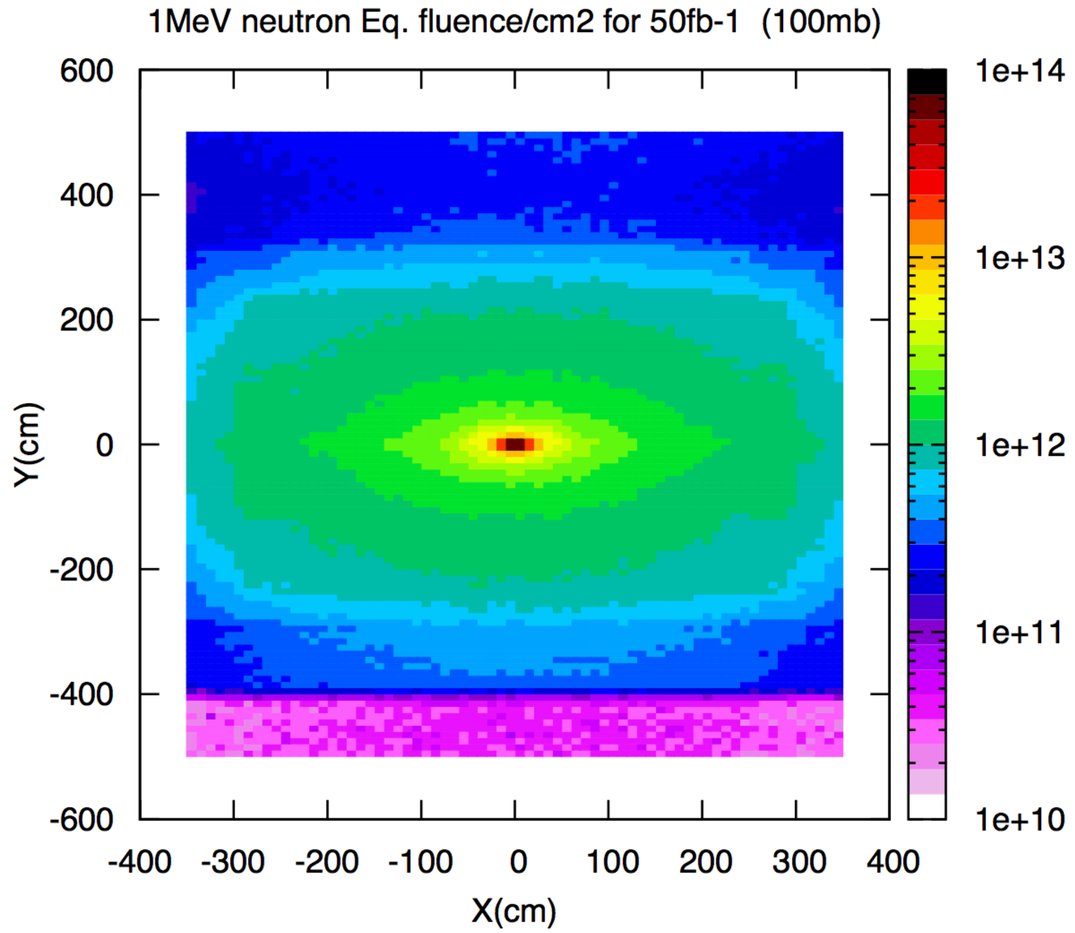


Figure 3.1: The expected 1-MeV neutron equivalent fluence per cm^2 at $z = 783$ cm after an integrated luminosity of 50 fb^{-1}.

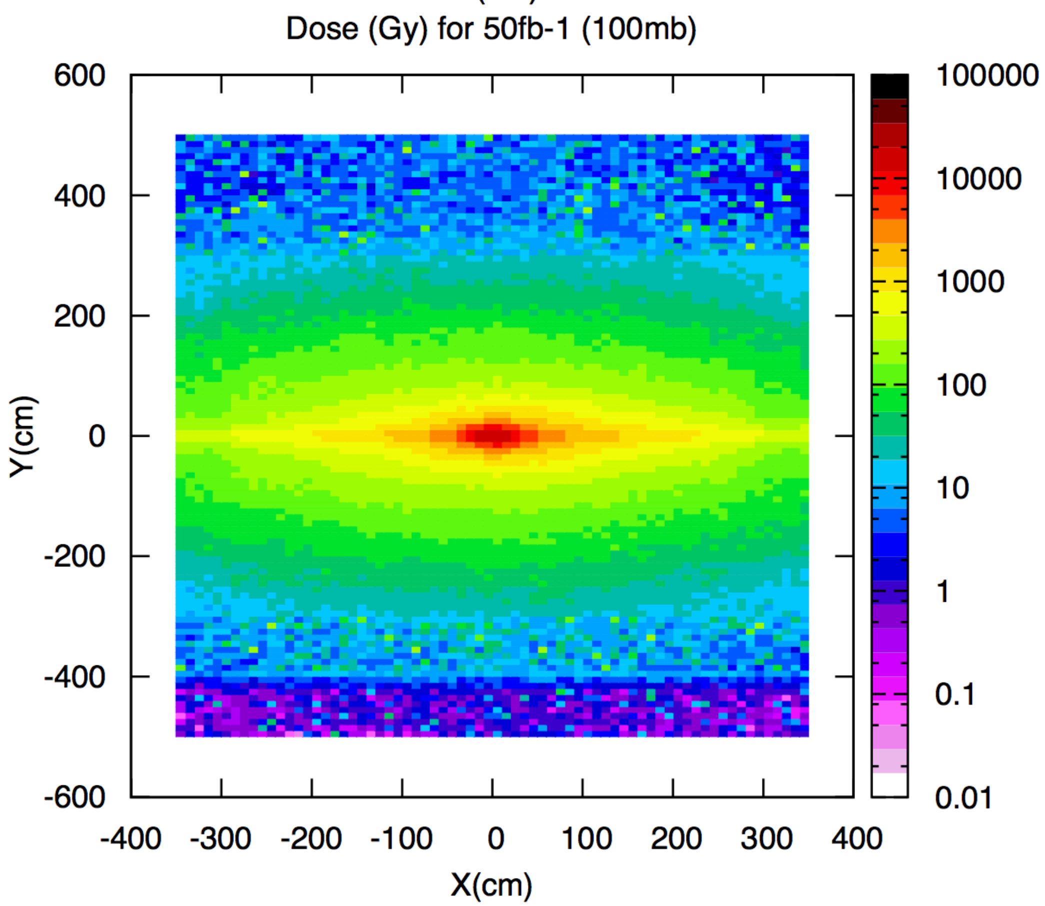


Figure 3.2: The expected dose in the $x - y$ plane at $z = 783$ cm after an integrated luminosity of 50 fb^{-1}.

Last generation of Hamamatsu detectors

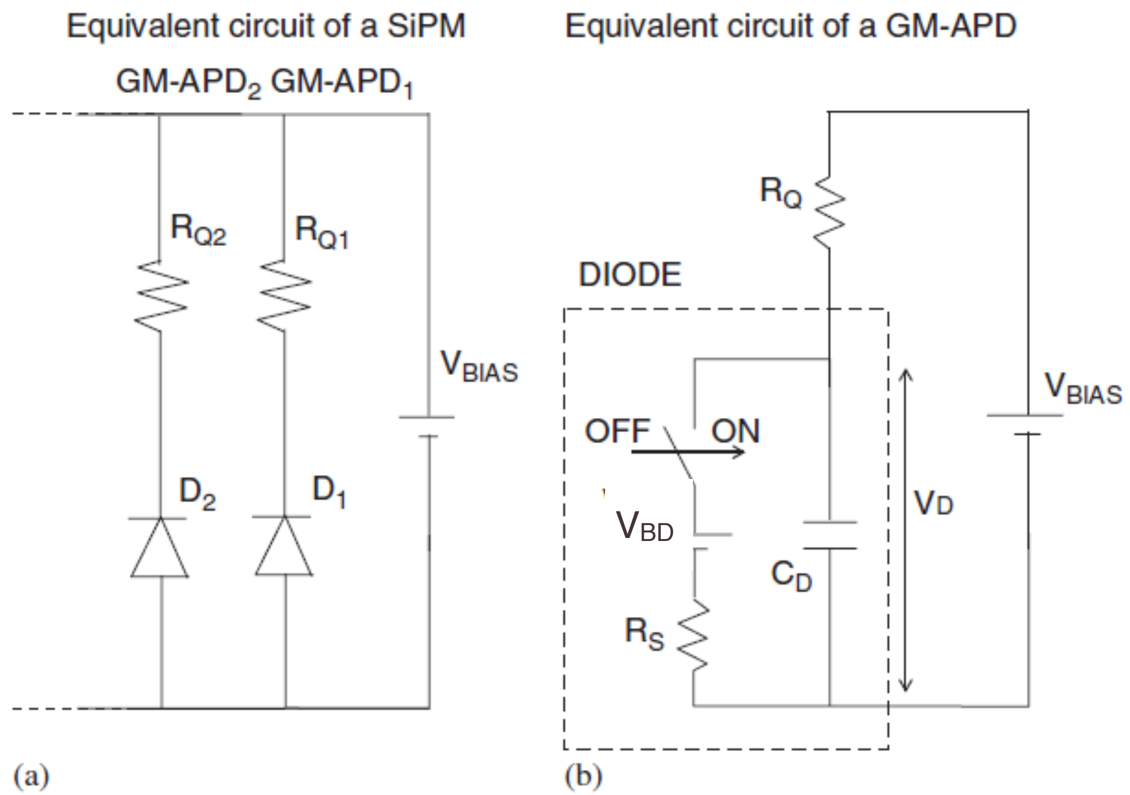
- H2016 last ordered (Mix technology of H2015 and H2014; same channel size as H2015)
- H2016 HRQ (high quench resistance): R&D test @ Hamamatsu, got for free

producer measurements

Batch	Channel size [µm]	LCT type	Trench type	RQ [kΩ]	Direct xt @3.3V OV	Delayed xt @3.3V ΔV	Afterpulse @3.3V ΔV	Noise Sum	PDE @3.5V ΔV
H2014	230x1500	LCT4	shallow	160	12,0%	0,5%	2,0%	14,5%	40%
H2015	230x1625	LCT5	deep	200	3,2%	4,8%	9,8%	17,8%	47,7%
H2016	230x1625	LCT4	deep	160	2,8%	2,1%	8,0%	12,9%	43,5%
H2016 HRQ	230x1625	LCT5	deep	470	3,1%	2,6%	1,5%	7,2%	47,6%

- Received 10 detectors for each batch, all channels fully functional

Breakdown voltage V_{BD} measurements



C_D: diode capacitance

R_S: series resistance

R_Q: quenching resistance

V_{bias}: applied voltage

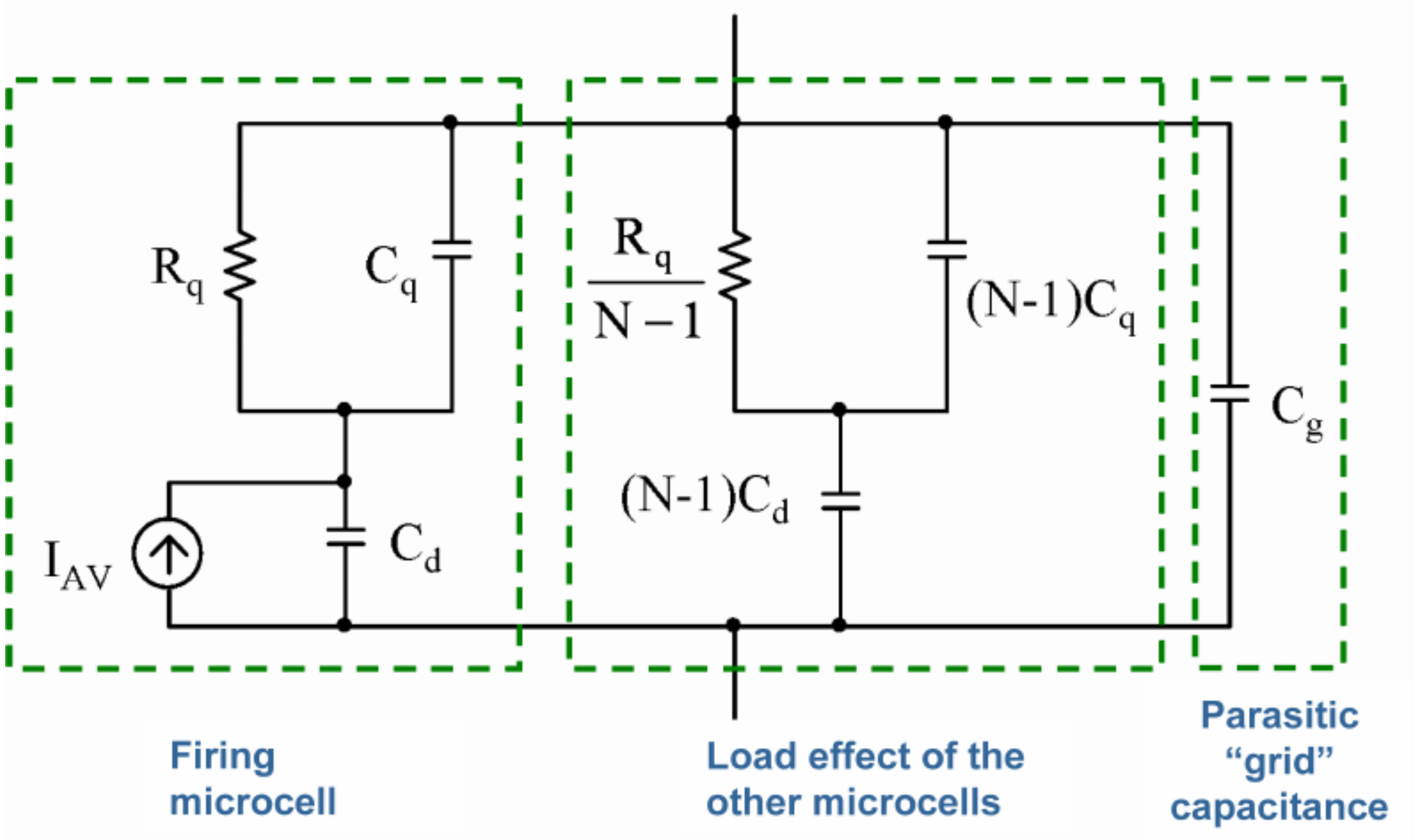
$V_{BD} \leq V_{bias}$: breakdown voltage (voltage where amplification sets in)

Switch: avalanche trigger

- A scan over V_{bias} (IV scan) allows to identify when the current I ~ 0 → → $V_{bias} \sim V_{BD}$ and determine the V_{BD} value
- In a certain range of stability, current proportional to the applied voltage
- The linearity range is a good operational range
- A good uniformity of the V_{BD} allows to apply the same V_{bias} to all channels/detectors

Gain measurement

- A bit more detailed SiPM electrical scheme:



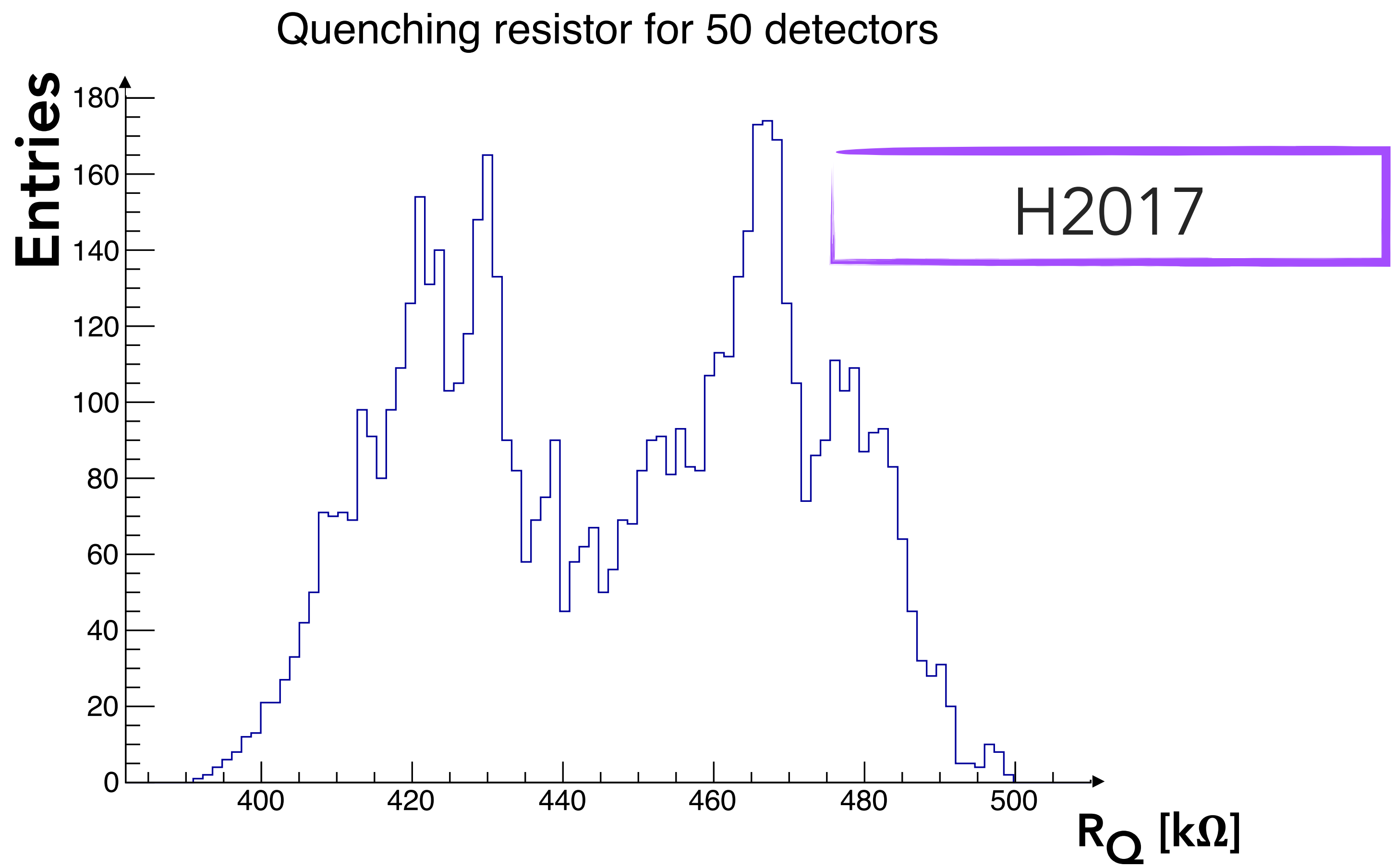
given by the discharge of (C_d+C_q) from V_{bias} to V_{BD}:

V_{bias} $(V_{BD} + V_{OV})$

$G = (C_d+C_q) \cdot V_{OV}/q_e$

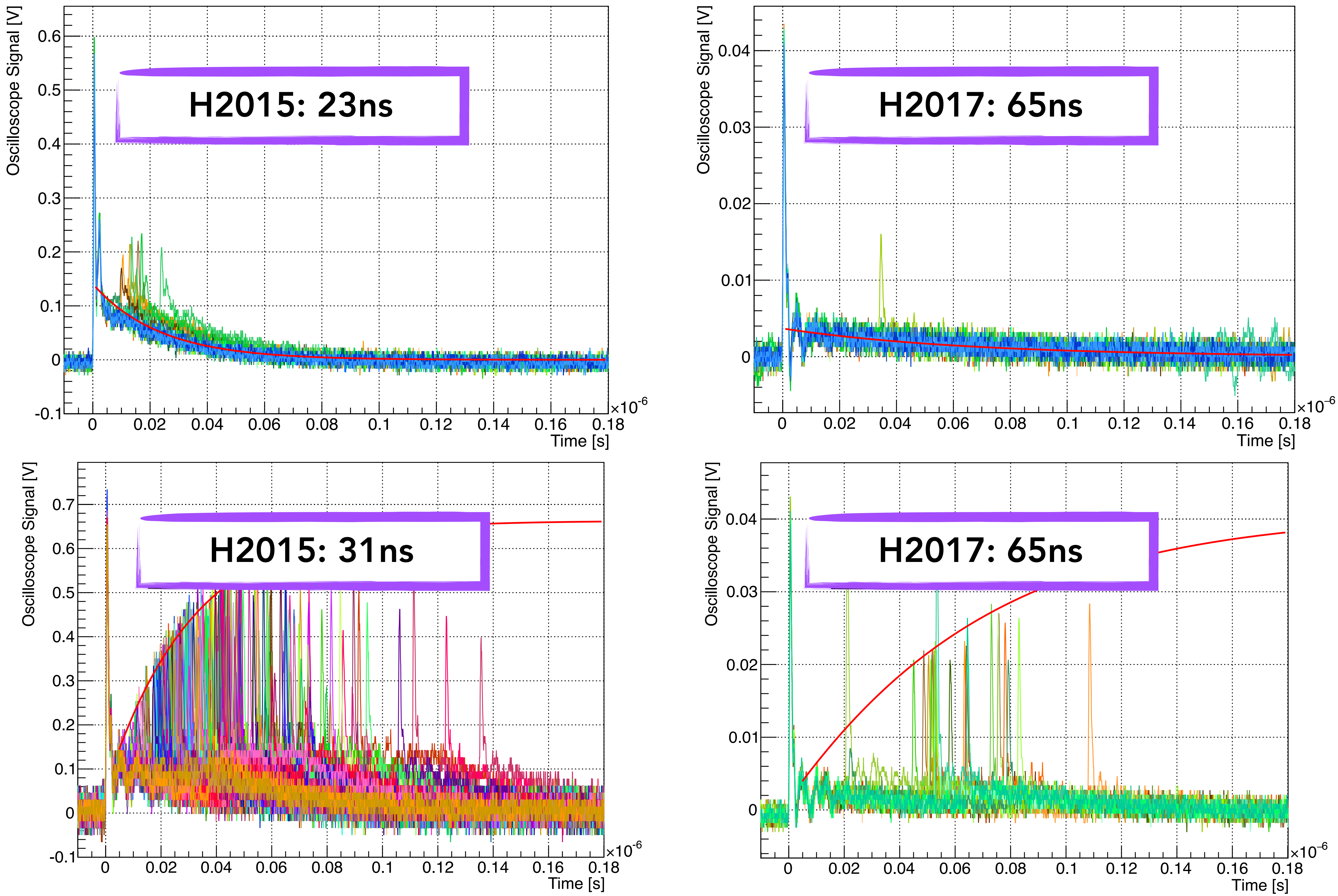
Quench resistor measurement

- A series resistor R_Q which limits the current drawn by the diode during breakdown
- Slope in the IV curve: ($V_{OV} = I \cdot R_Q$)



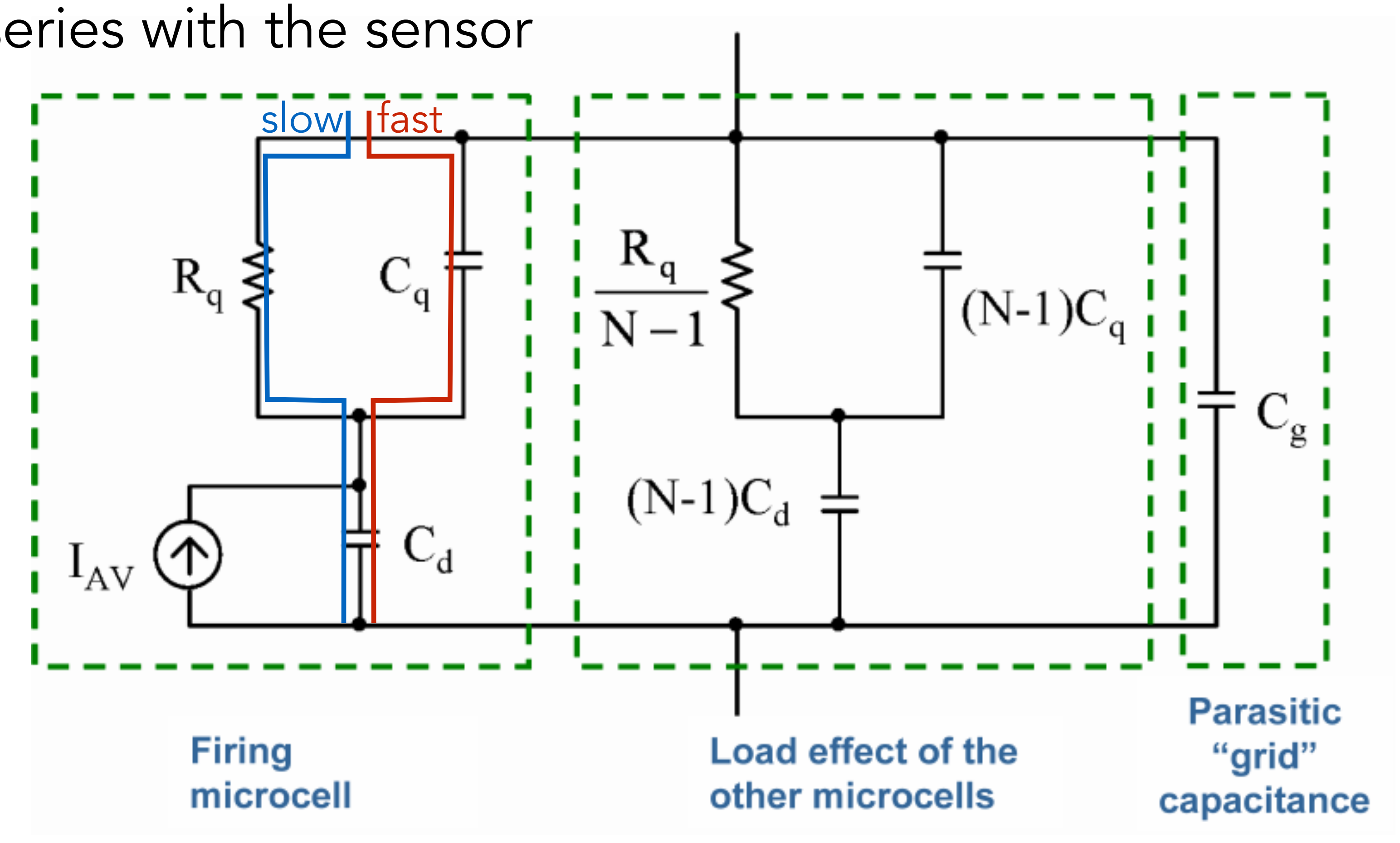
- A high resistance quench resistor reduces the probability of retarded pulses
- The recovery time increases as well
- With lower temperature the resistance increases
- R_Q uniformity allows uniform behaviour of all channels in the detector
  - 6% average spread in a single detector

Different quench resistors



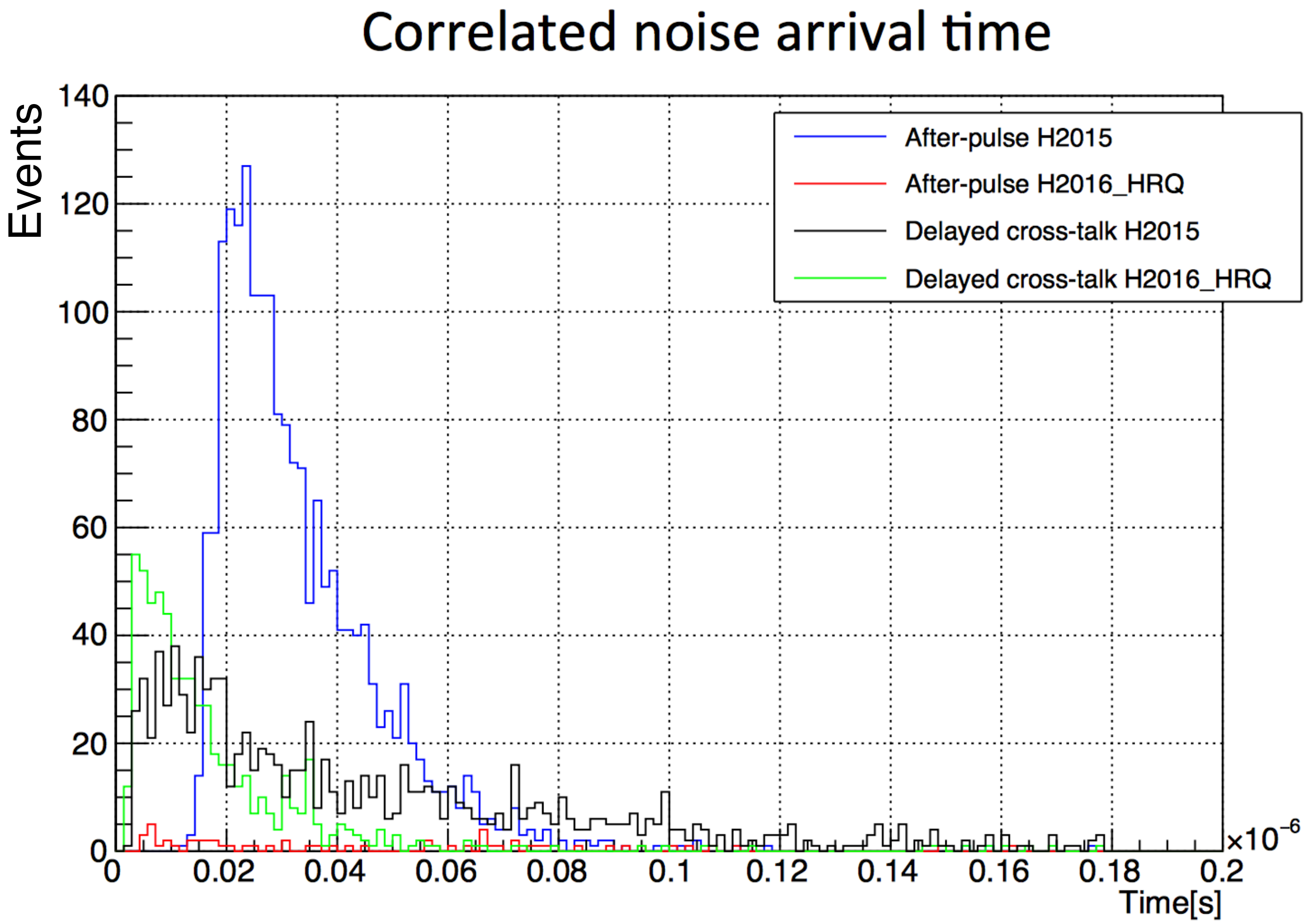
Quench resistor effects on the recovery and decay time

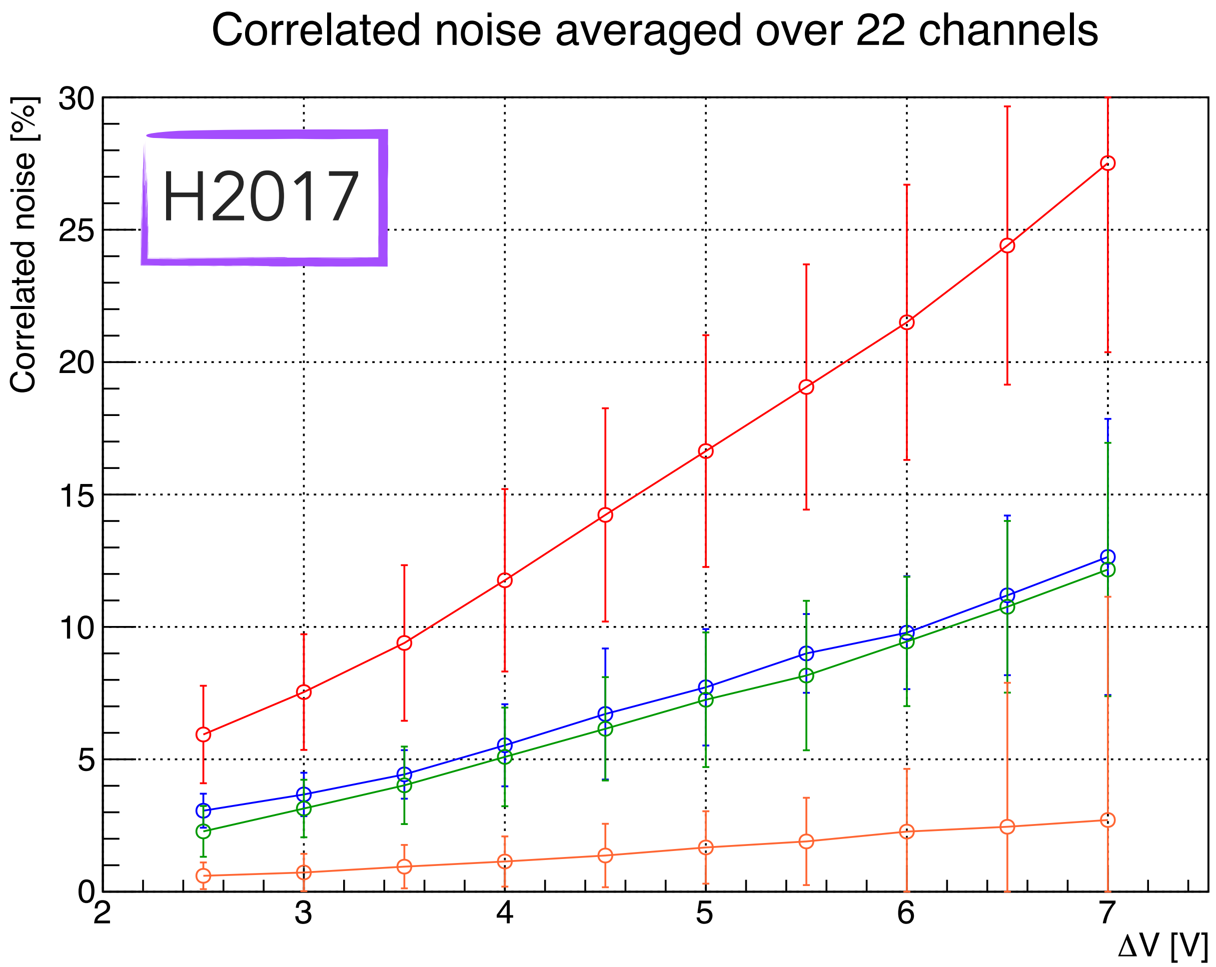
- The recovery time is determined by the microcell recharge time constant, which is given by: $\tau_{recovery} = C_d R_q$
  - where C_d is the effective capacitance of the microcell, R_q the value of the microcell quench resistor
- The capacitance of the microcell depends upon its area
- The decay time is determined by the sum of two components, a fast and a slow one:
  - calling R_s any resistance in series with the sensor
  - $\tau_{fast} = C_{tot} R_s$
  - $\tau_{slow} = (C_q + C_d) R_q$



Noise characterisation

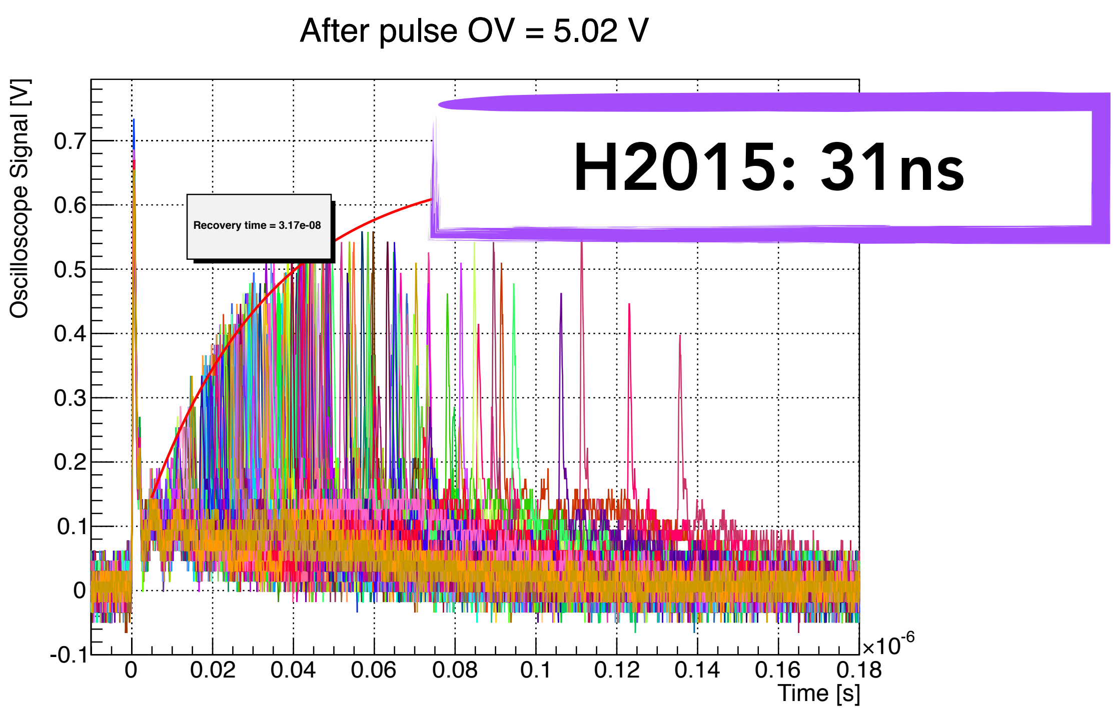
- Time analysis developed tagging every single event with a single noise type
  - only first order noise contribution

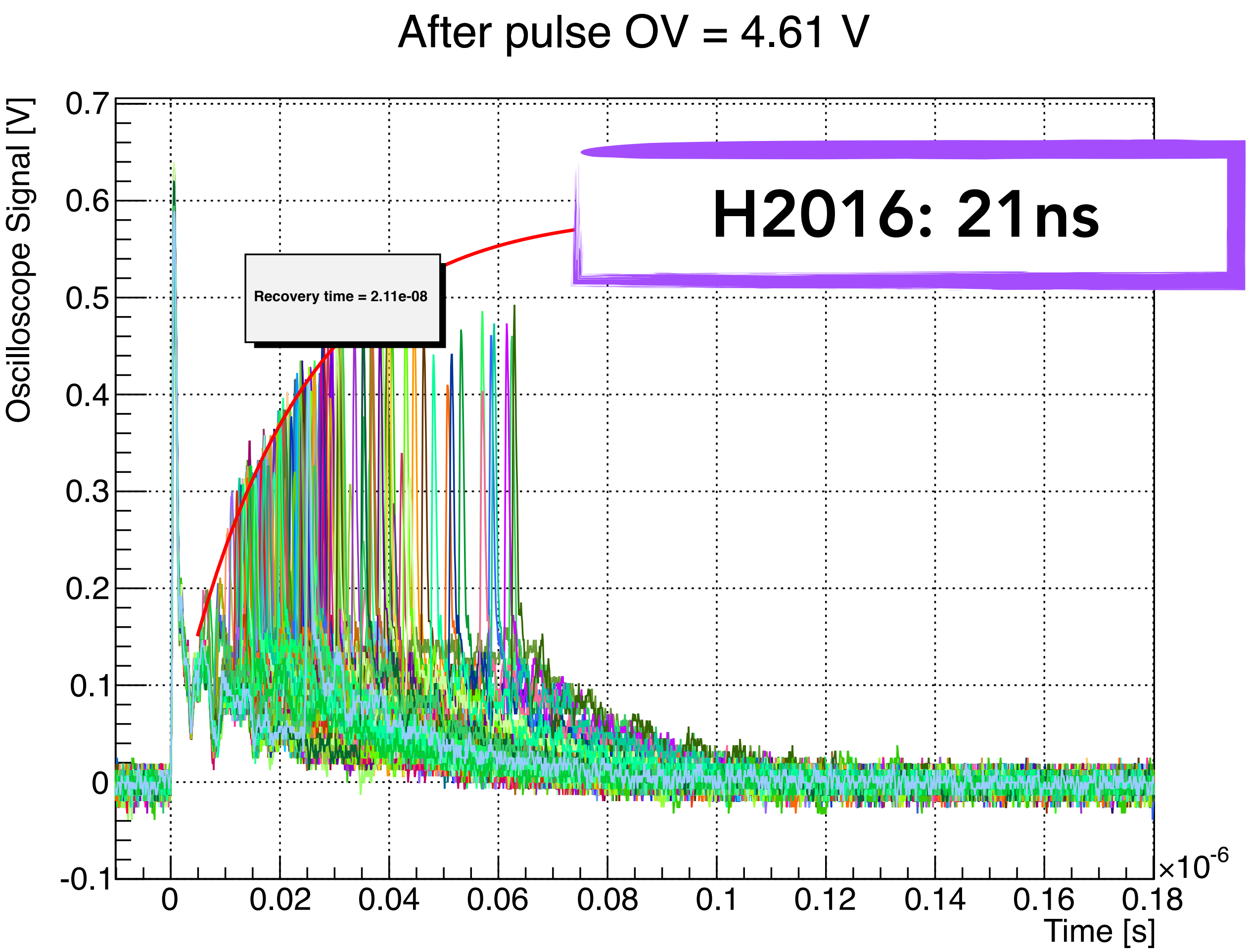




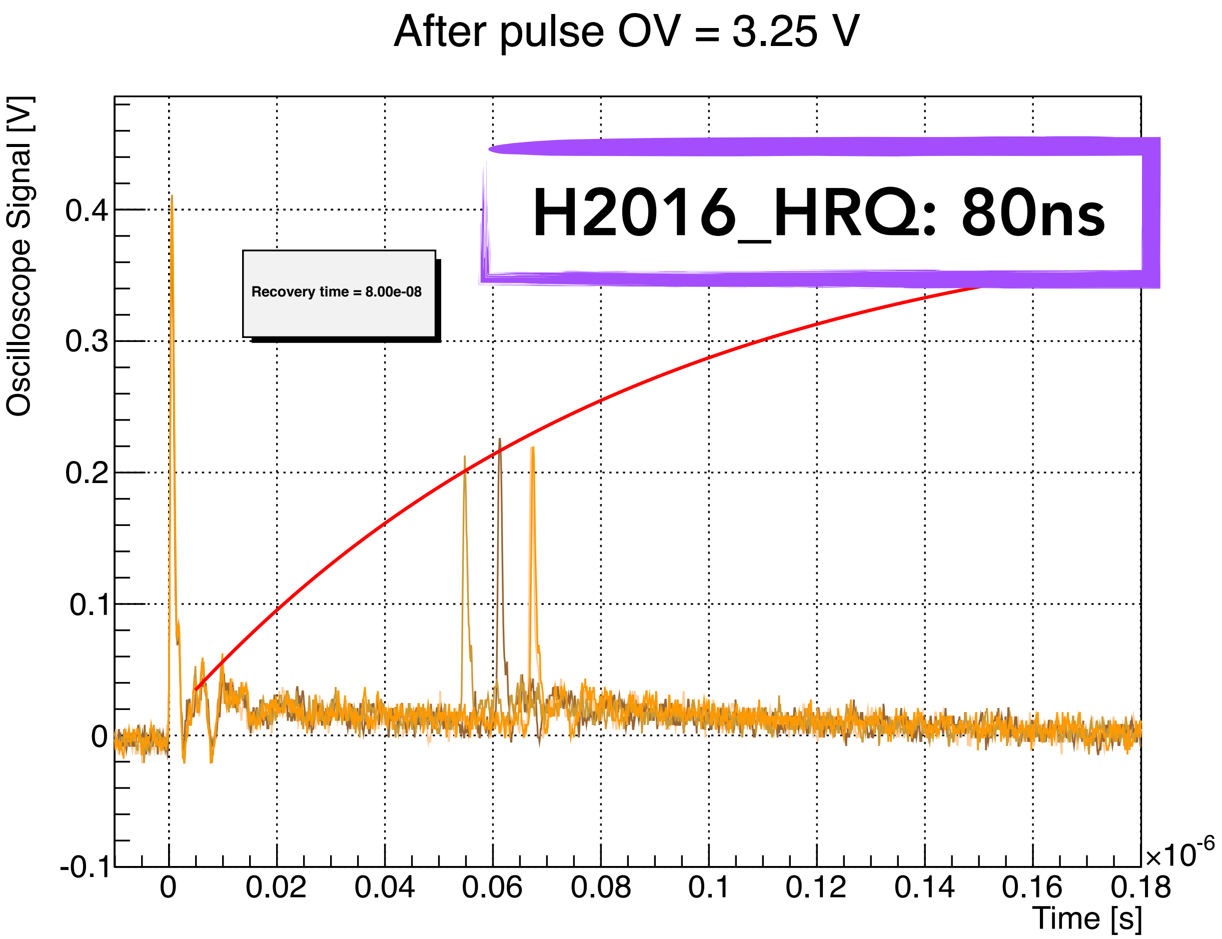
- H2016_HRQ (same technology as H2017) have higher quench resistor, this sensibly lowers the after pulse probability
- Noise probability is less than 10% at the operational over voltage of 3.5 V

Recovery time

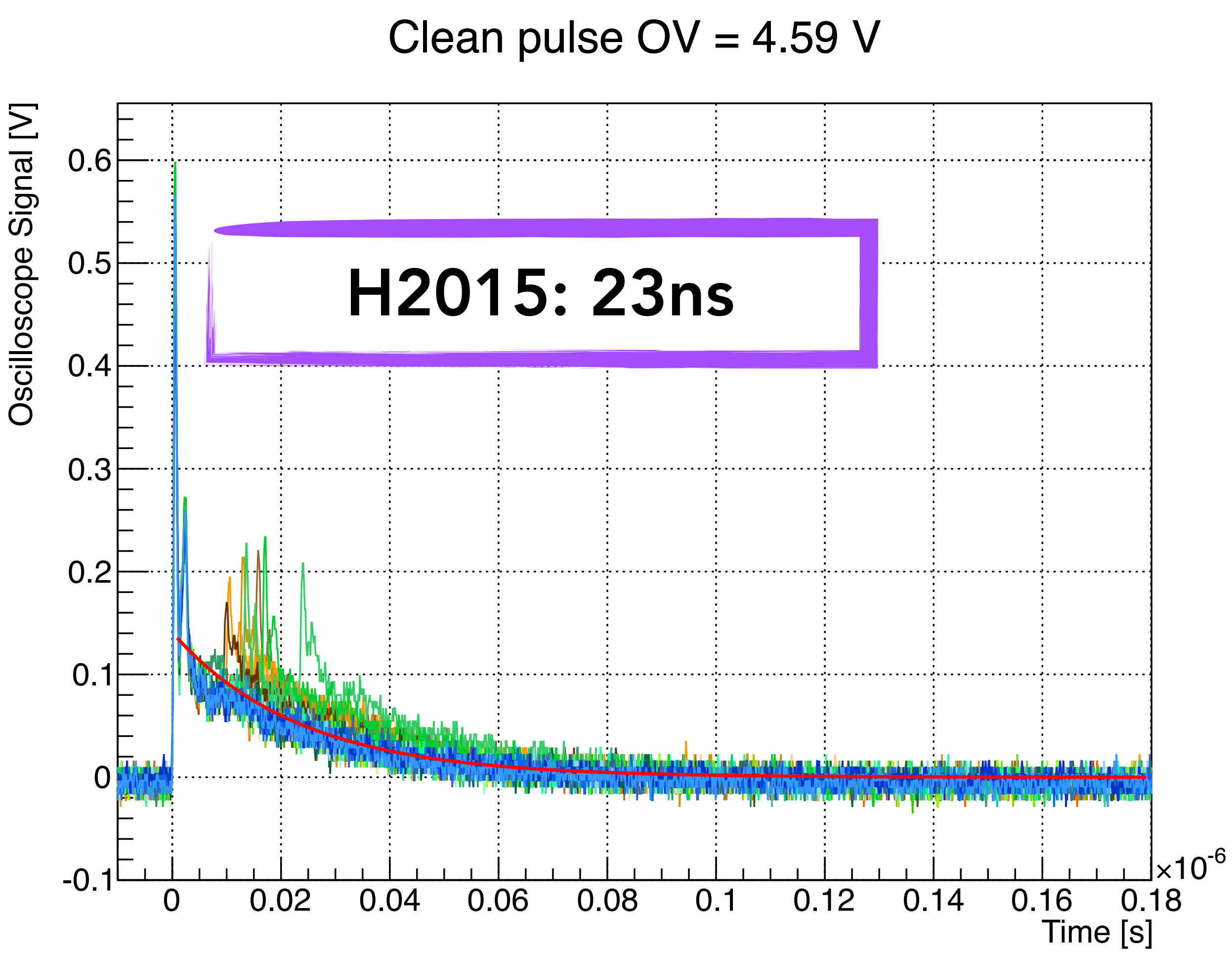


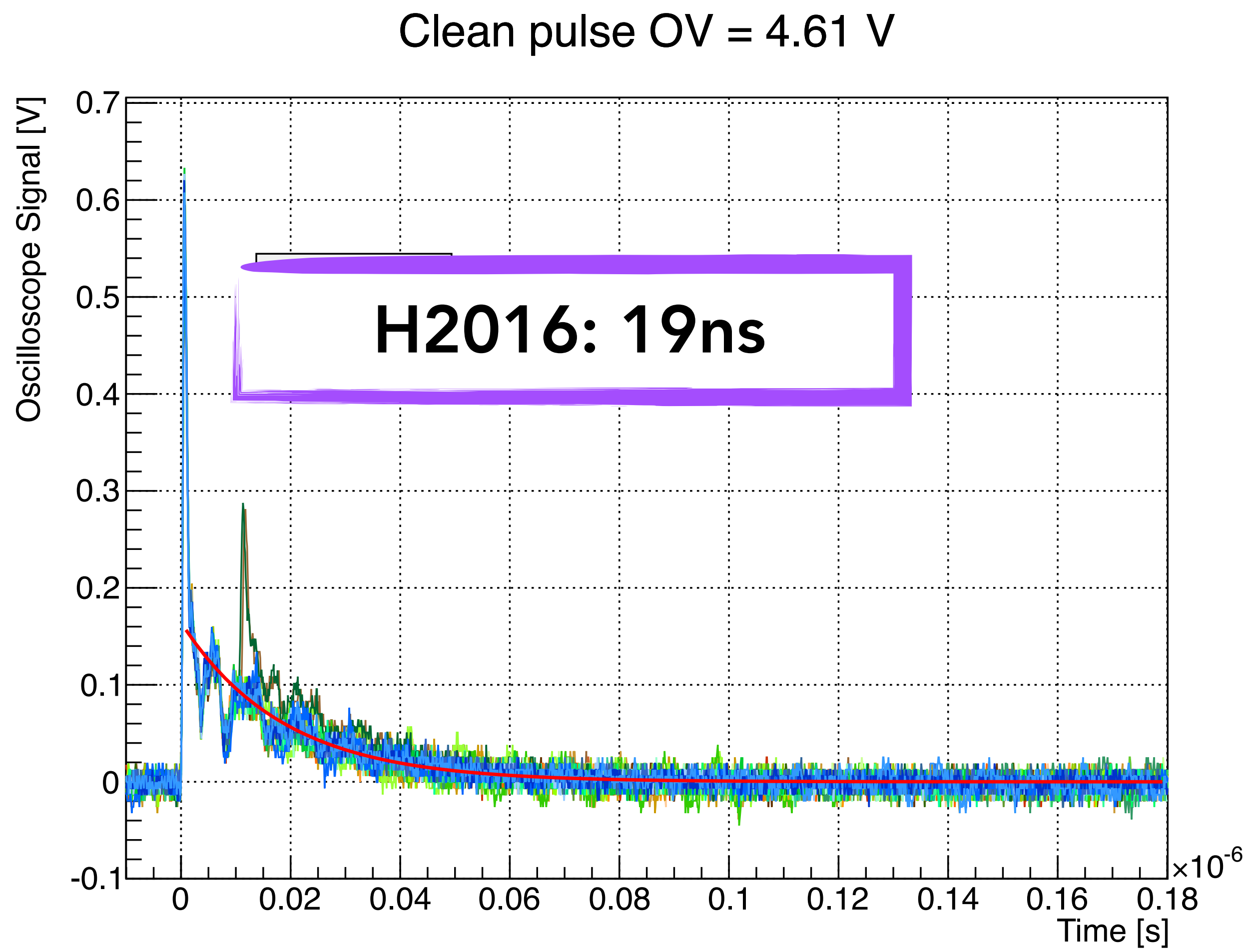


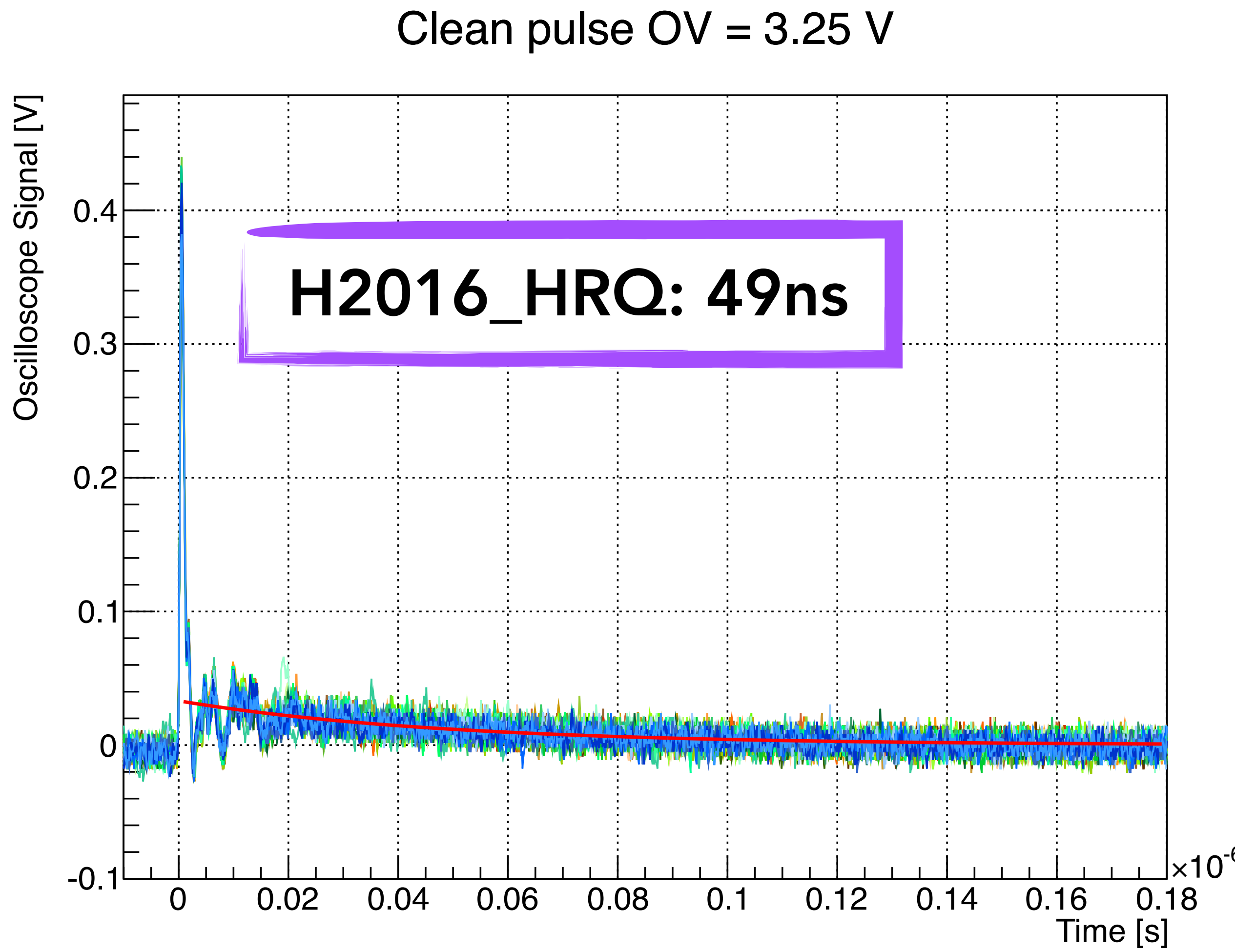
- $\tau_{H2016} \approx 21$ ns
- $\tau_{H2016\_HRQ} \approx 80$ ns
- @ -40°C R_Q increases of 6%
- We could choose different R_Q values



Slow decay time







detector type	$\tau_{recovery}$	τ_{slow}
H2015	31.02 ± 2.10 ns	29.41 ± 4.88 ns
H2016	20.83 ± 0.87 ns	20.65 ± 3.58 ns
H2016_HRQ	68.87 ± 2.08 ns	50.09 ± 4.07 ns

Photo-detection efficiency

- The **photo detection efficiency:** ratio between the number of detected photons and the number of incident photons
- It is the product of three factors:
  - fill factor (dependent on the pixel size)
  - quantum efficiency (dependent on the wavelength)
  - avalanche probability (dependent on ΔV)
- The measurement is performed at different wavelengths and different over-voltages
- The PDE is obtained as a relative measurement, a calibrated photodiode being the reference:

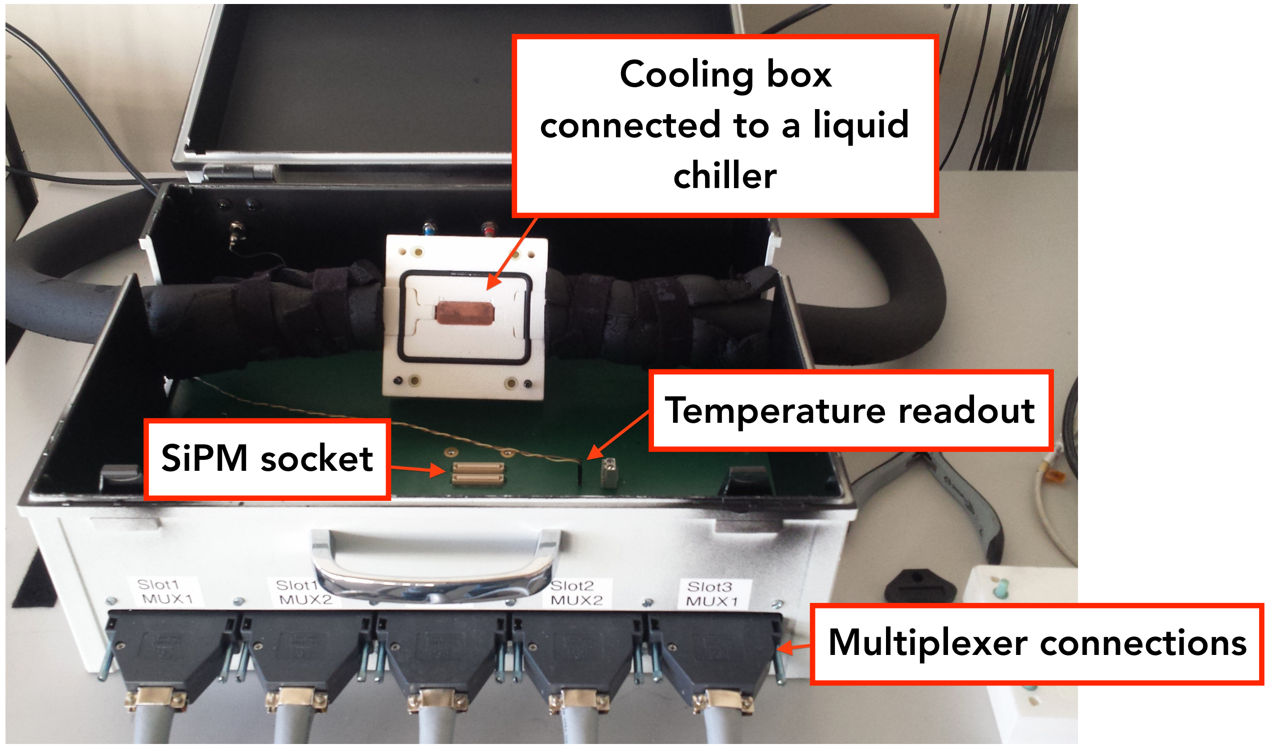
$$PDE_{rel} = QE_{PD} \cdot I_{SiPM}/I_{PD}$$

Overview

- Measurements done with Multiplexer setup:
  - 128 channel IV curves -> Dark count rate is calculated from the current

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

  - possibility to cool down to -50°C using a liquid chiller
  - temperature readout from temperature sensor (NTC) on the flex



Dead time

- Dead time is dependent on:
  - recovery time
  - DCR
  - average dead pixel is (with 65 ns of recovery time and 14 MHz DCR)

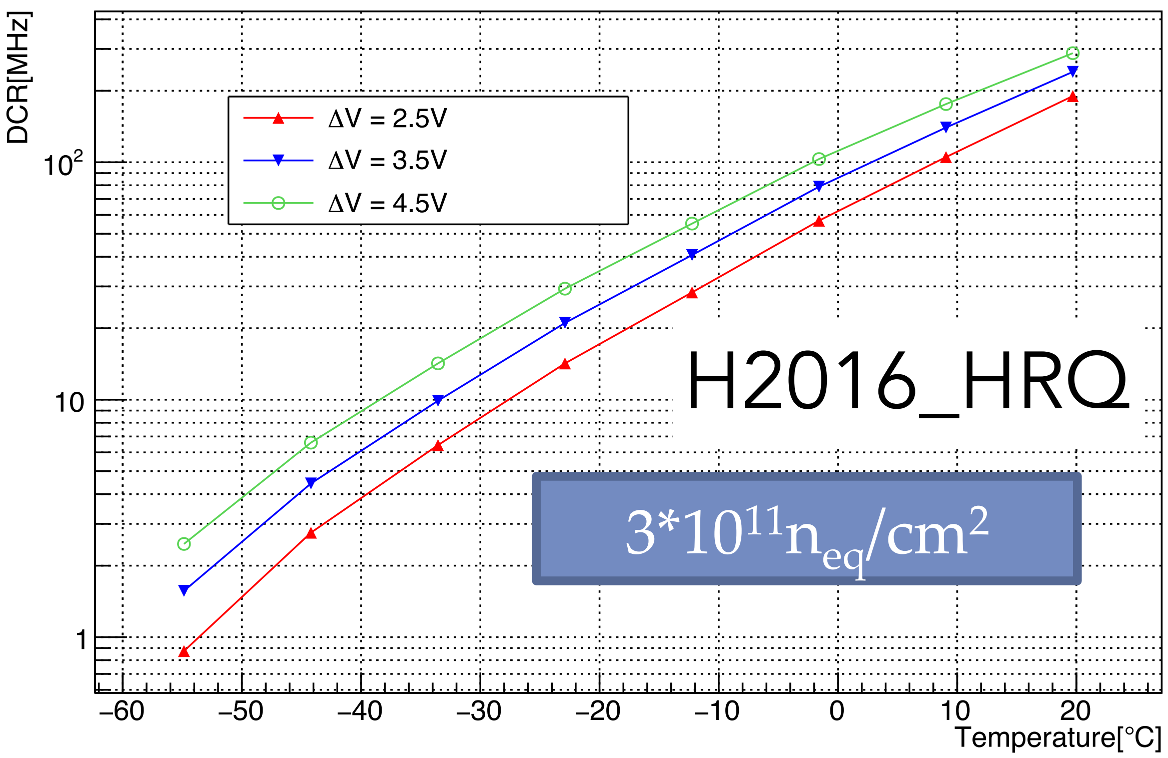
$$N_{\text{pix\_av\_dead}} = \frac{f_{\text{sig}} + f_{\text{DCR}}}{f_{\text{recovery}}} \sim 1.7$$

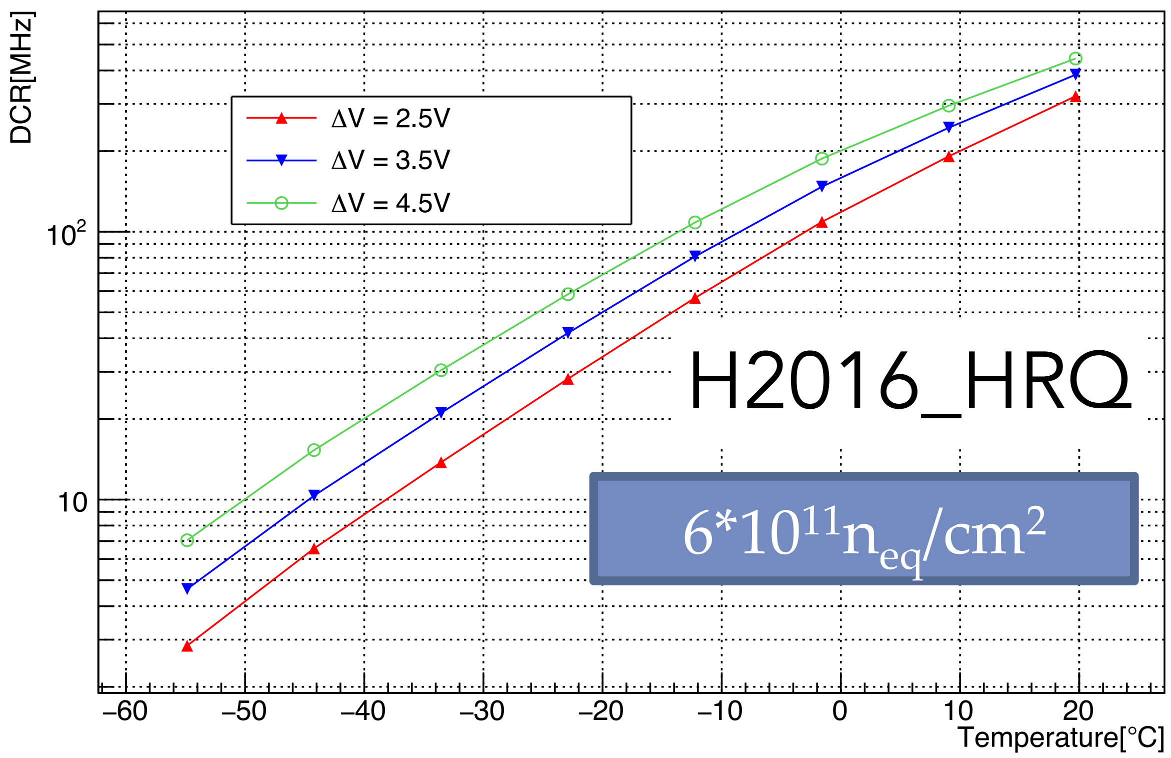
  - detector inefficiency due to the dead time in the worst case is given by

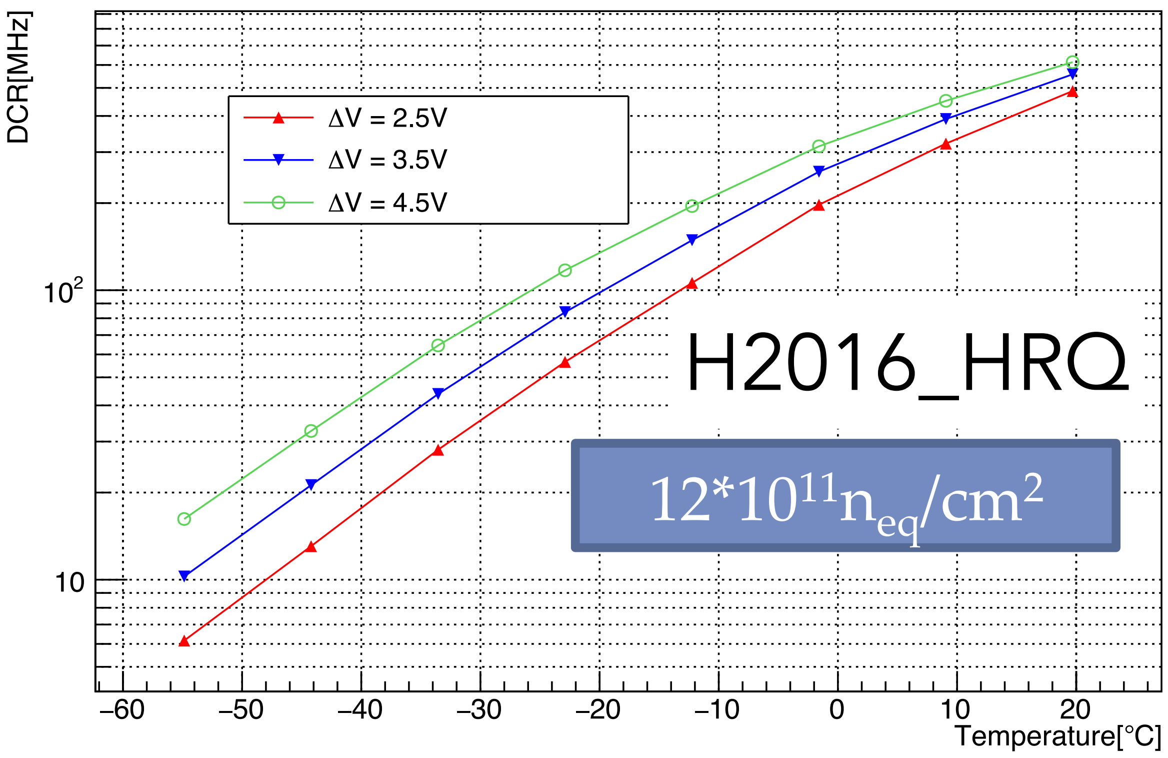
$$\epsilon_{\text{ineff}} = \frac{N_{\text{pix\_av\_dead}}}{N_{\text{pix\_total}}} \sim 1.6\%$$

  - Assuming 4 clusters per 128 channels with 16PE in average every 30MHz bunch crossing that gives a signal frequency of 15 MHz

DCR as a function of T for 3 different ΔV

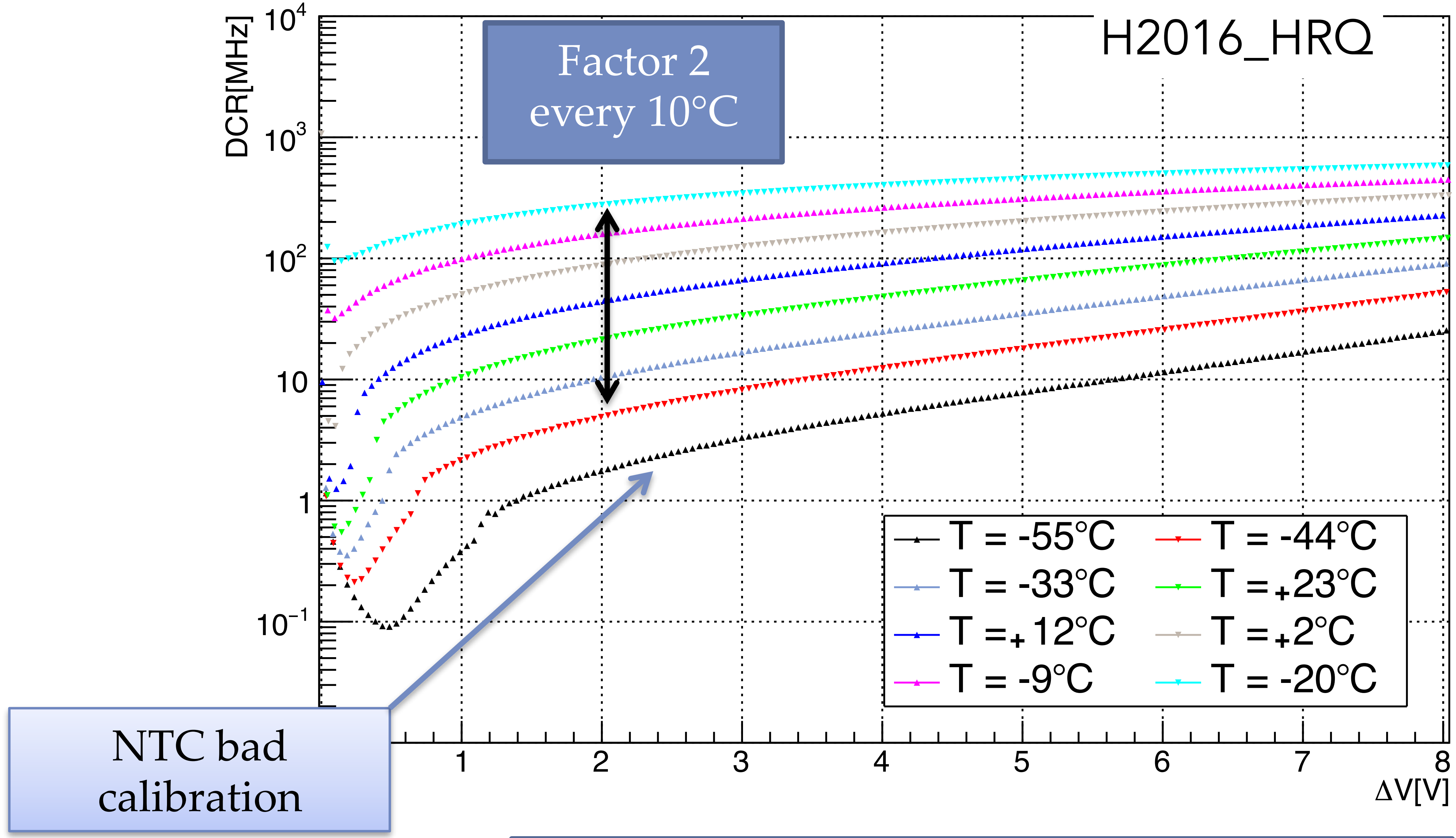






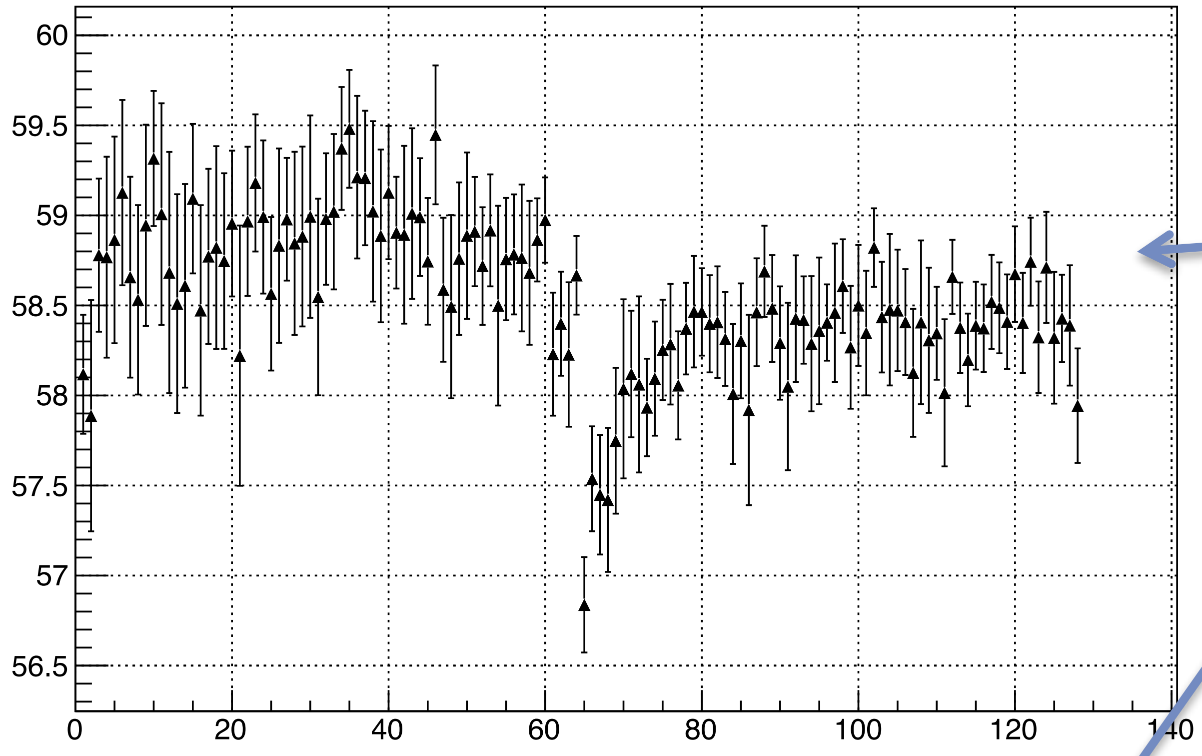
- At high T, pixel saturation appears
- At low T, NTC calibration is less precise

Temperature dependence and $T_{1/2}$



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

Temperature coefficient



- T_{coef} is 59.0 mV/K ± 2 mV/K
- T_{coef} follows the V_{BD} patterns
- Little or no correlation between V_{BD} and T_{coef}