SiPMs for the SciFi Tracker at LHCb

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HighRR bi-weekly seminar

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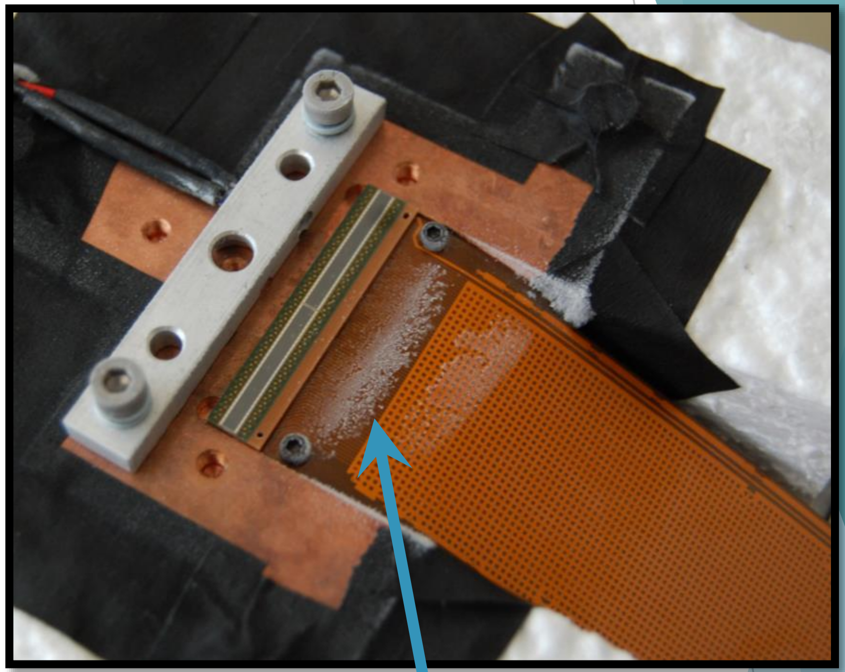
Outline

- introduction to the experiment
  - LHCb
  - Scintillating Fibre (SciFi) Tracker
- silicon photomultipliers
  - 128 channel arrays
  - irradiation damage
- neutron irradiation damage
  - dark count rates per channel
  - noise cluster rates
- efficiency and resolution (testbeam results)



spoiler ice on the cable

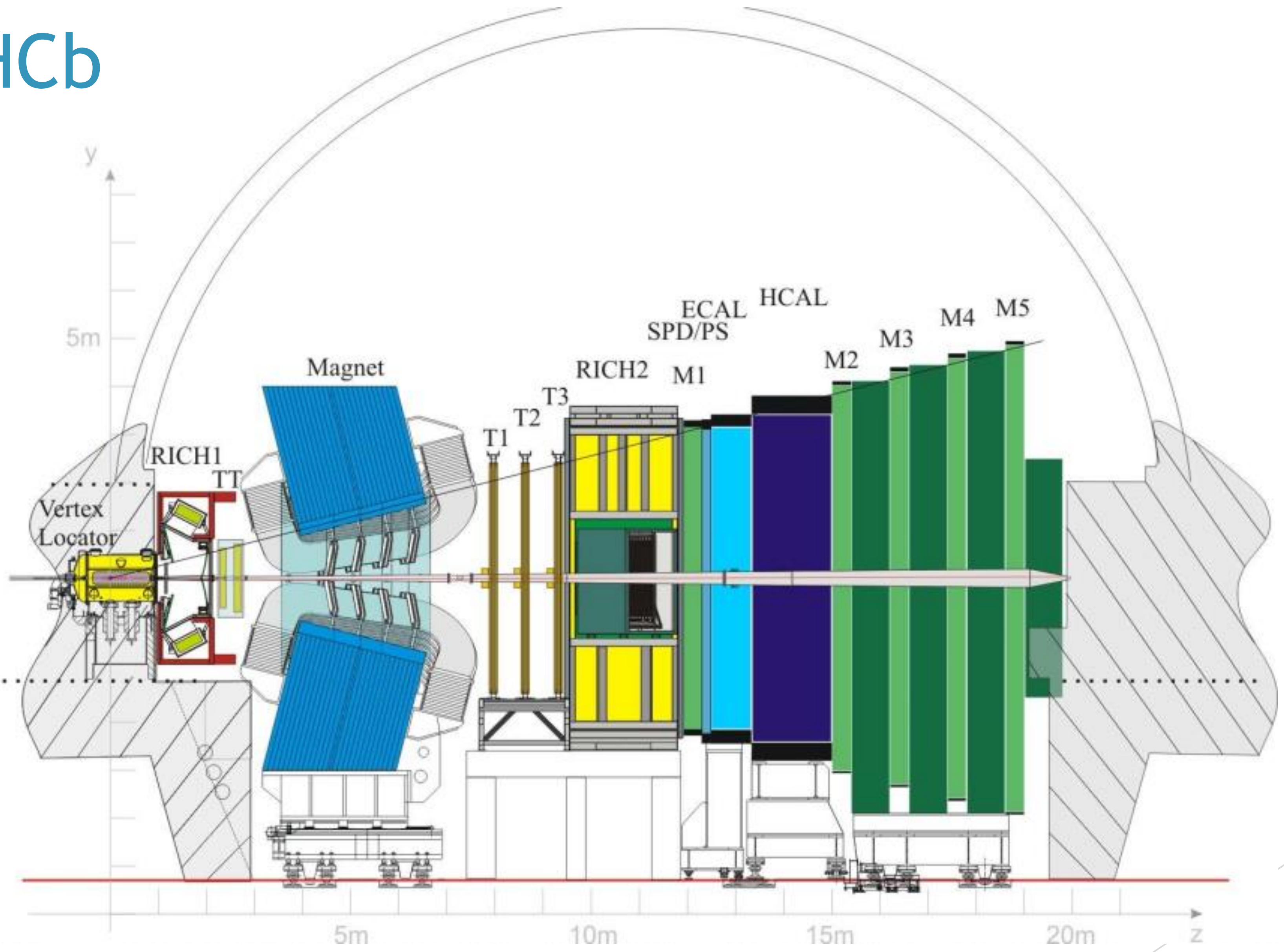
LHCb

- 1 out of 4 large experiments at the Large Hadron Collider
- 728 authors from 69 institutes in 16 countries (Jan. 2016)
- total >300 papers (Mar. 2016)

- mainly investigate decays of beauty- and charm hadrons
  - search for CP violation
  - rare decays
  - observation of tetra- and penta-quarks

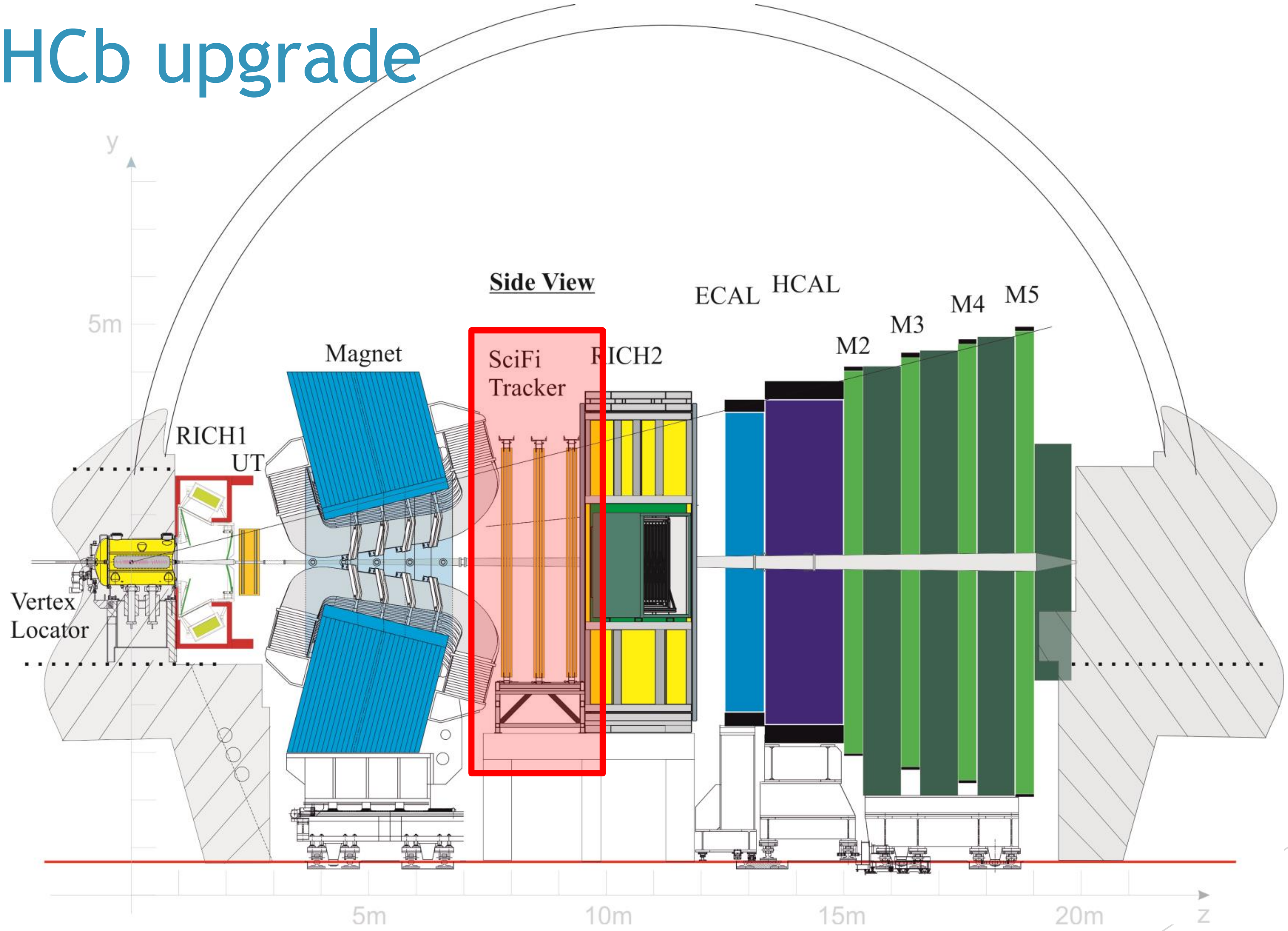
https://cds.cern.ch/record/1295244

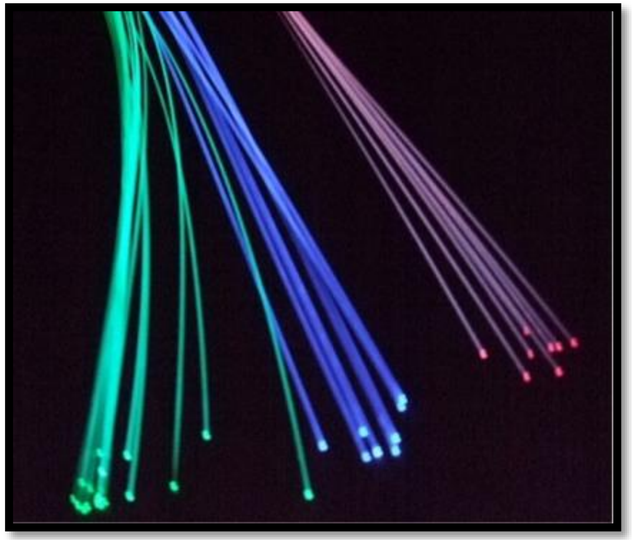
LHCb



y
5m
Magnet
RICH1
TT
Vertex
Locator
T1
T2
T3
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
5m
10m
15m
20m
z

LHCb upgrade

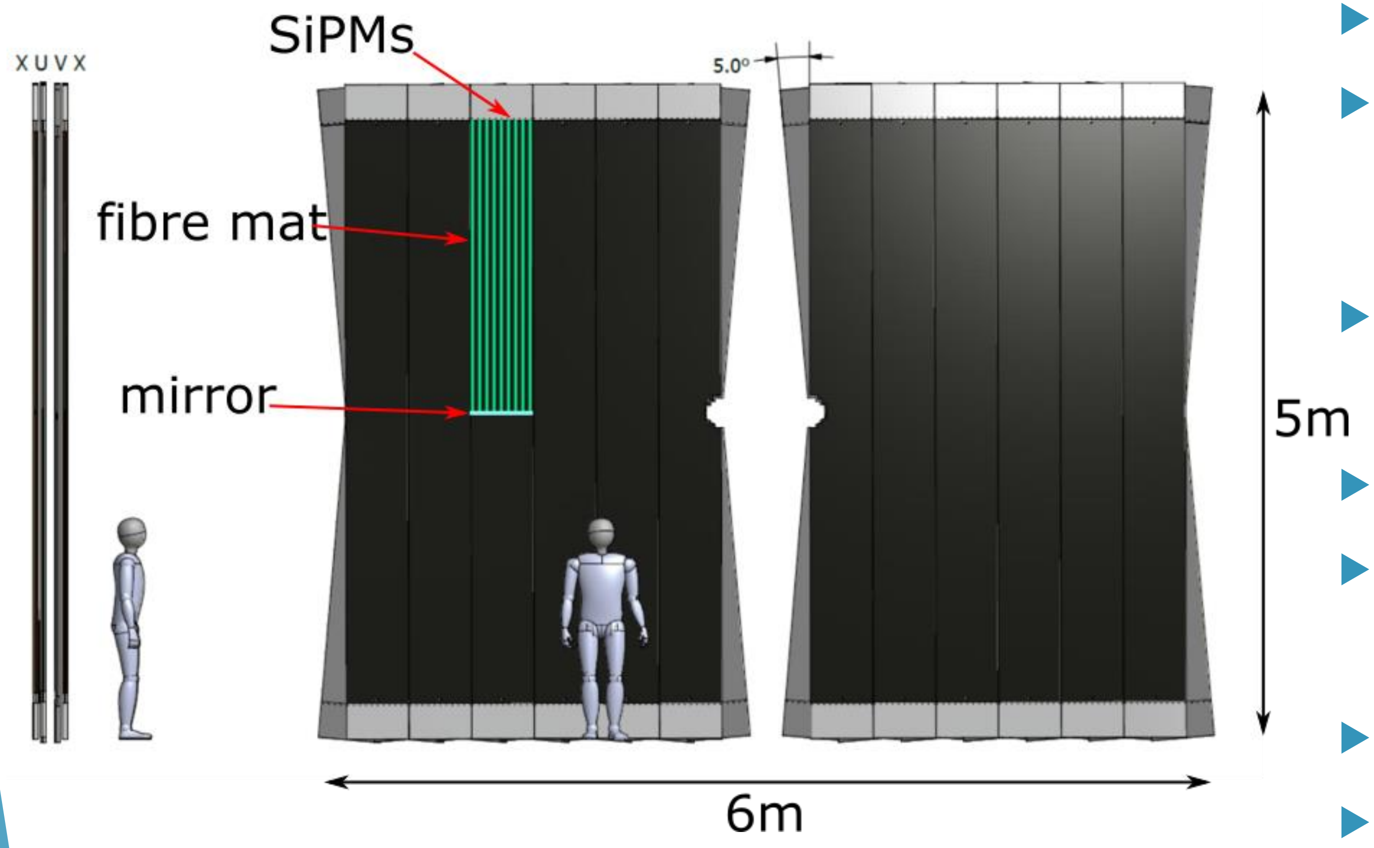




The Scintillating Fibre Tracker

upgrade of the downstream tracking stations during the next shutdown of the LHC in 2019/20

The Scintillating Fibre Tracker

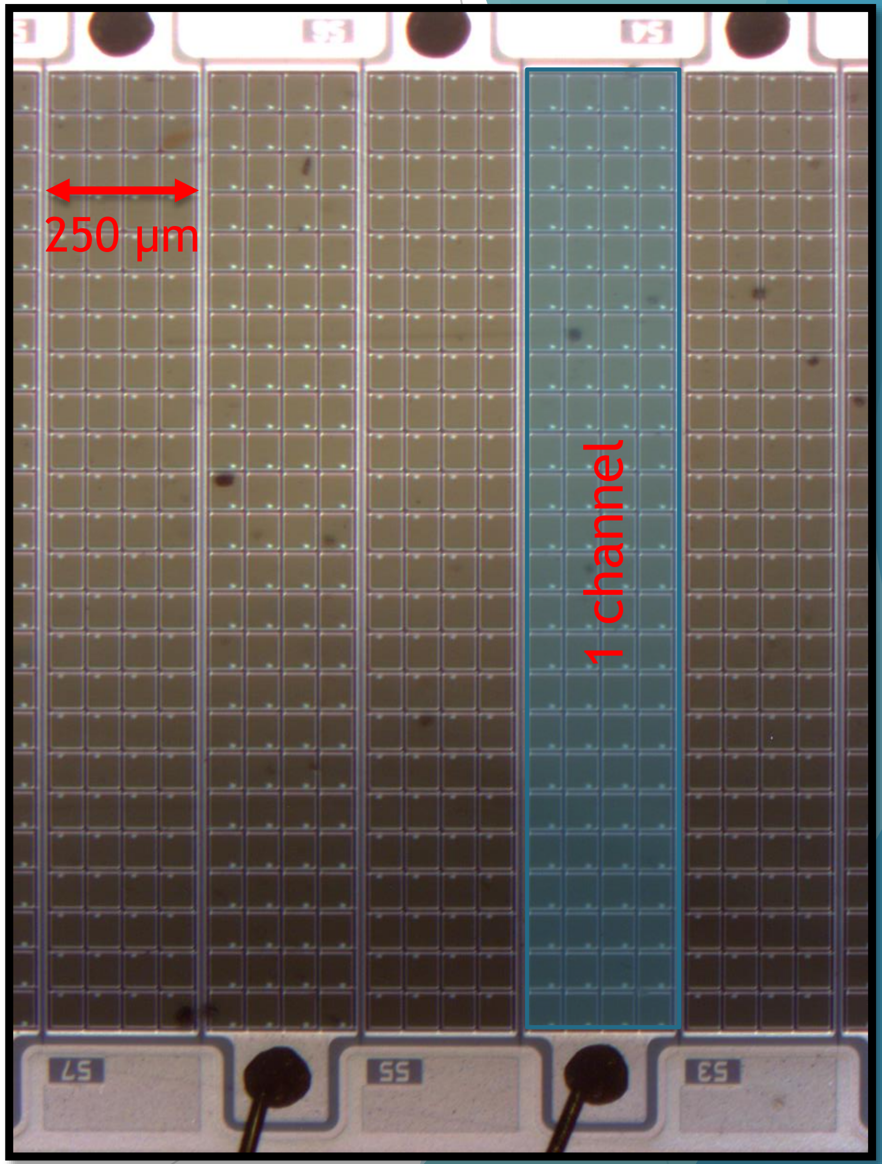


- 3 stations of each 4 layers
- cover a total area of 360m^2
  - **largest scintillating fibre tracker ever built**
- fibres are glued into mats
- resolution < 100µm (in x)
- radiation length < 1%/layer
- about 600.000 SiPM channels
- 40 MHz read-out (trigger-less at every BX)

The Scintillating Fibre Tracker

- SiPM channel size
  - 4 x 24 pixels à 57.5 x 62.5 µm²
  - 230 x 1 500 µm²
  - 128 channels per arrays → 325.9 x 1.5 mm²
- fibre dimensions
  - diameter 250 µm
  - length ~250 cm

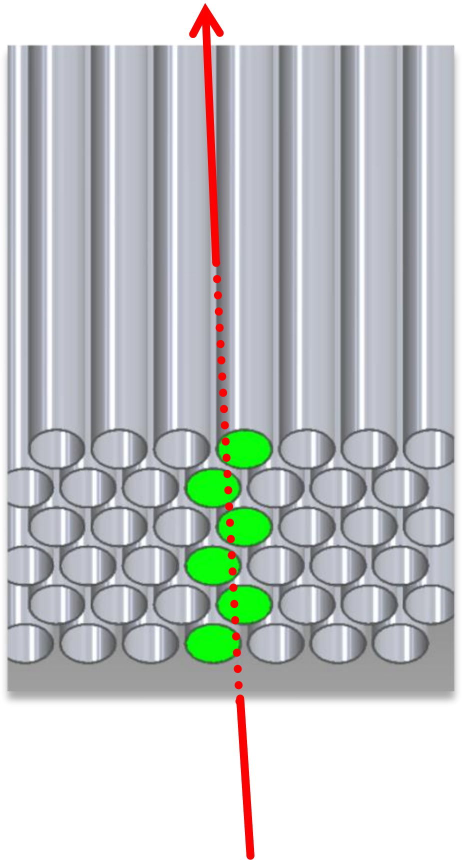
SiPM array

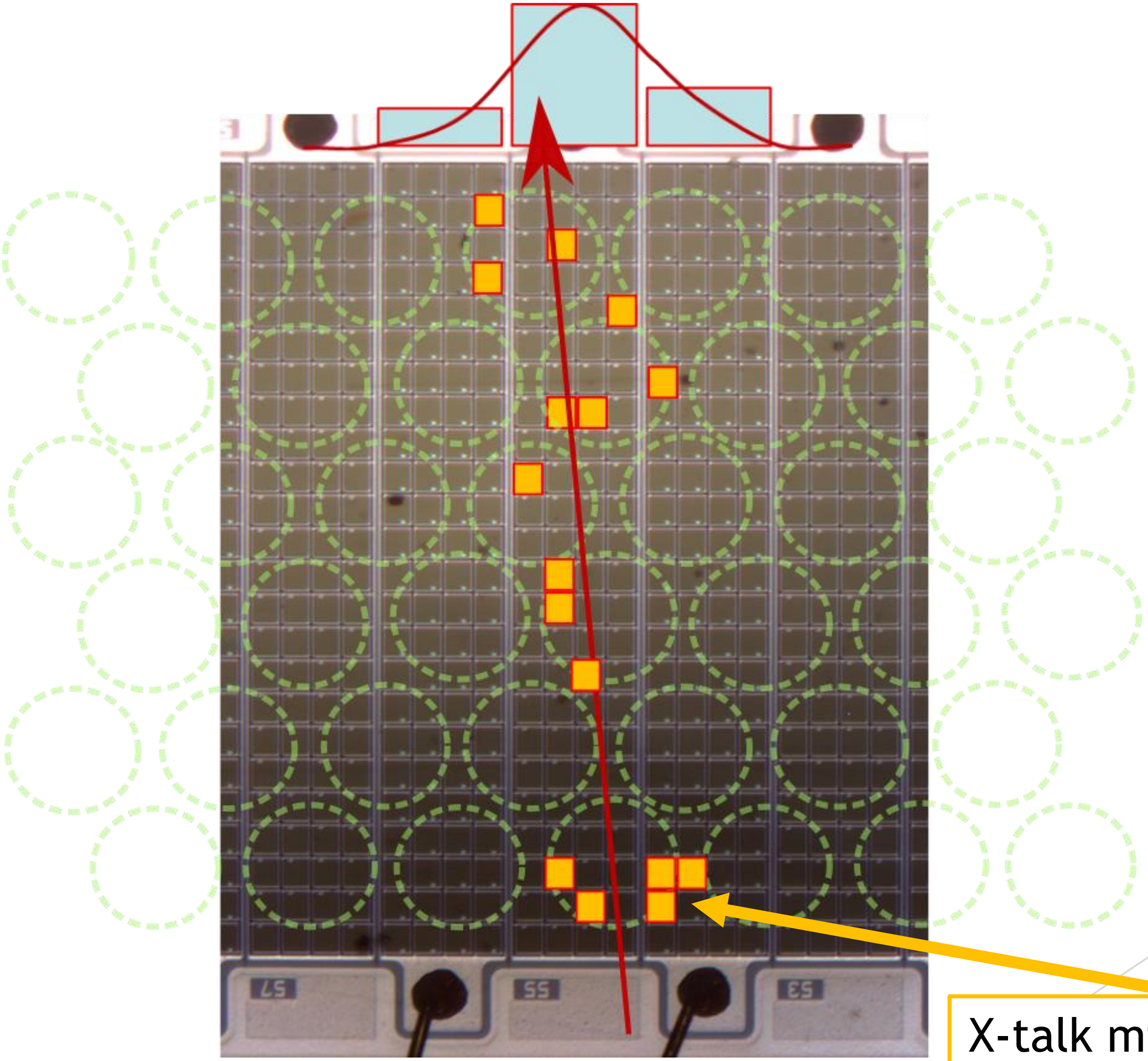


mat cross-section

The Scintillating Fibre Tracker

traversing charged particle





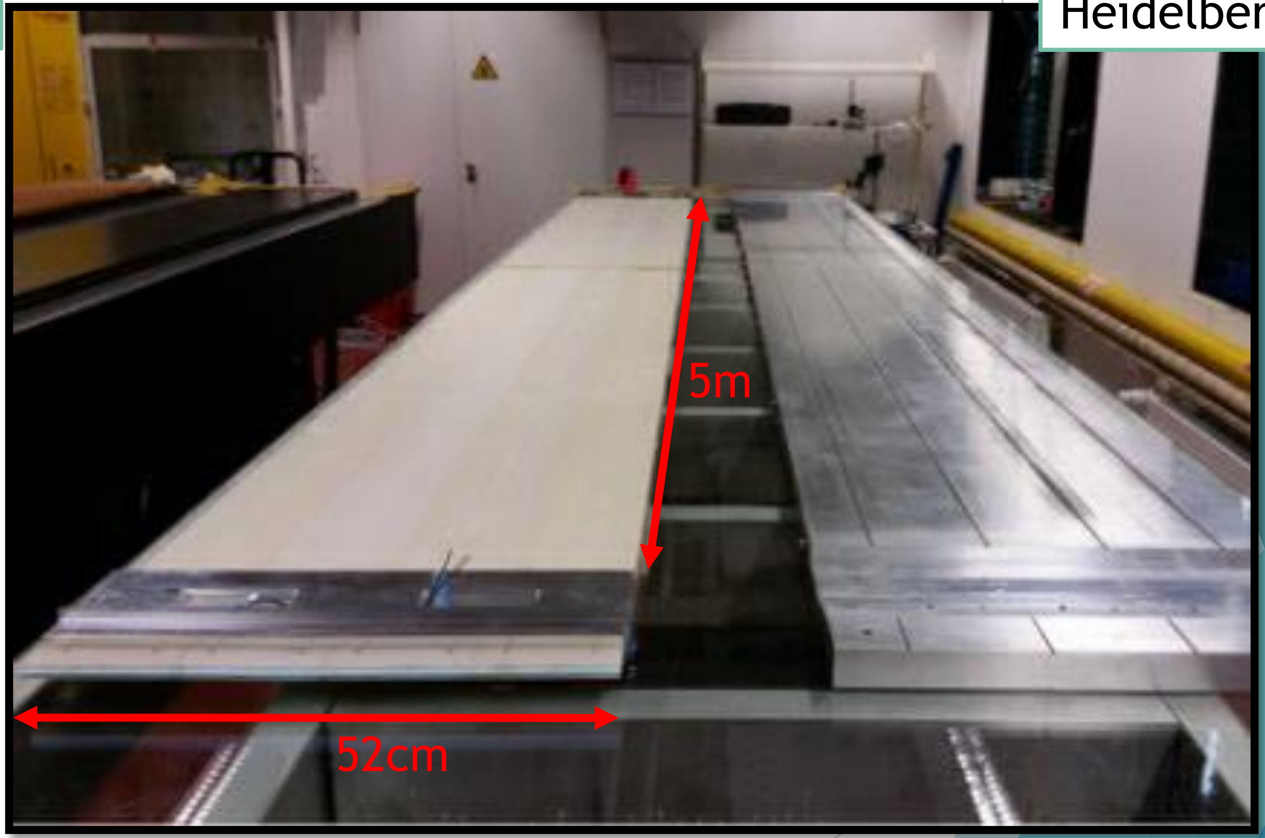
X-talk might trigger neighbor channels

Fibre mat production

Dortmund et al.

Janine Müller

Heidelberg



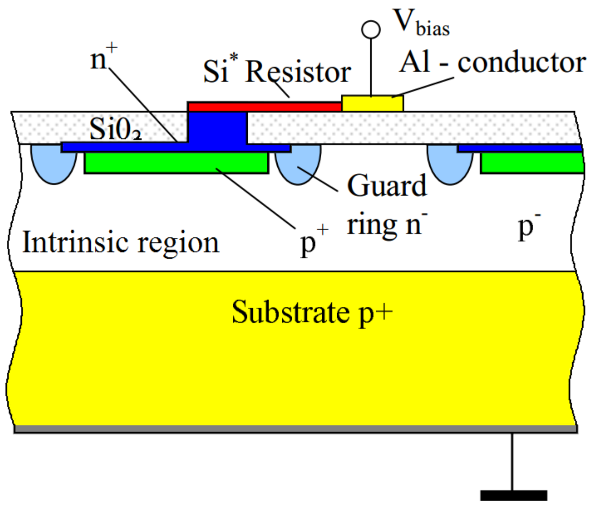
Sebastian Bachmann

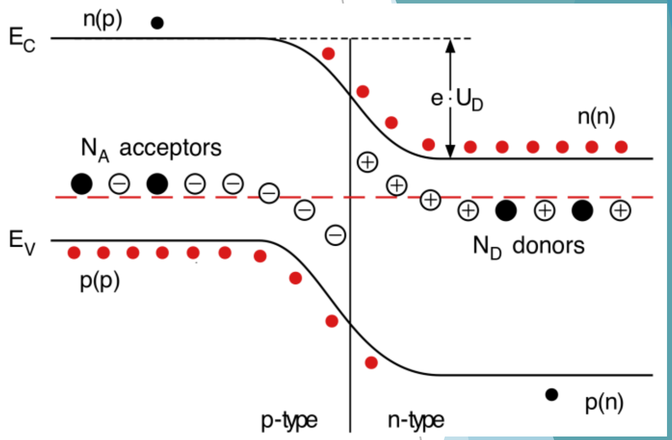
silicon photomultipliers

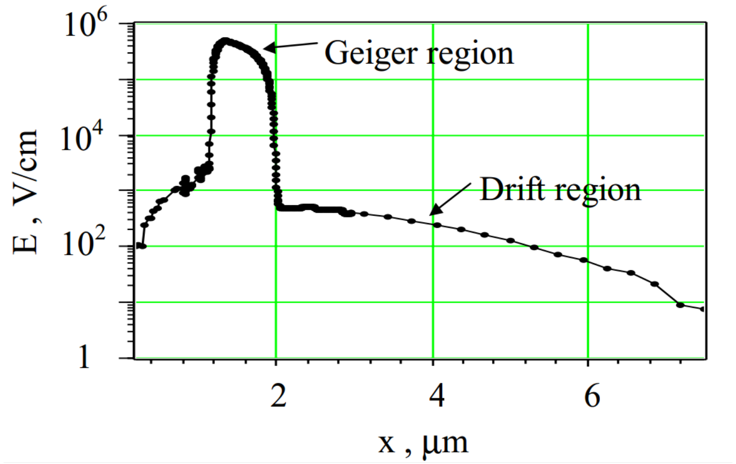
pixelated single photon detectors

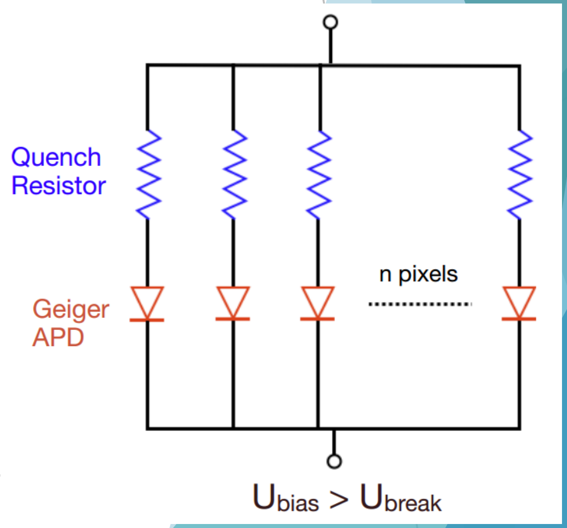
working principle of SiPMs

- etched into silicon substrate
- each pixel is a p-n-junction
- operated in reverse bias Geiger mode
- incoming photons create e-h-pairs
- discharge of pixel via e-h-avalanche
- avalanche stopped via quench resistor





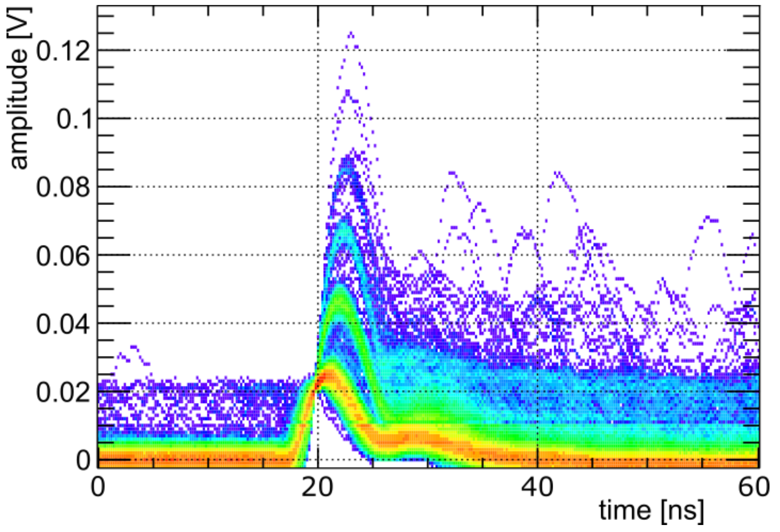




Demtröder EX3, Buzhan et al. (2001), HCSC Neckarzimmern (2014)

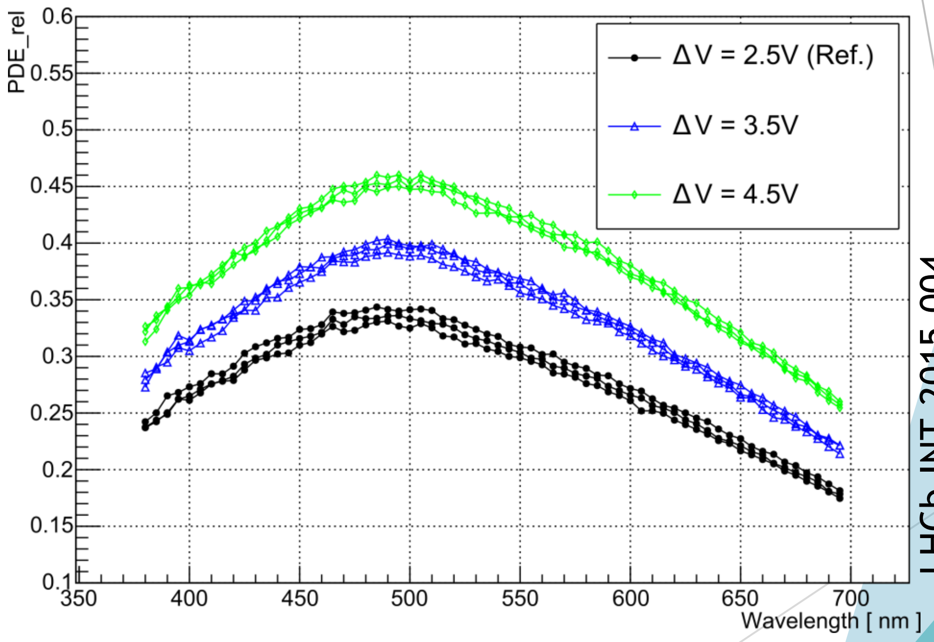
silicon photomultipliers

- HighRR : **high** resolution & **high** rate
  50-100 µm 40MHz
- high PDE (≈40% @ 500nm @ 3.5V_{OV})
- allows detection of single photons



relative measurement of the

photo detection efficiency for Ham2014



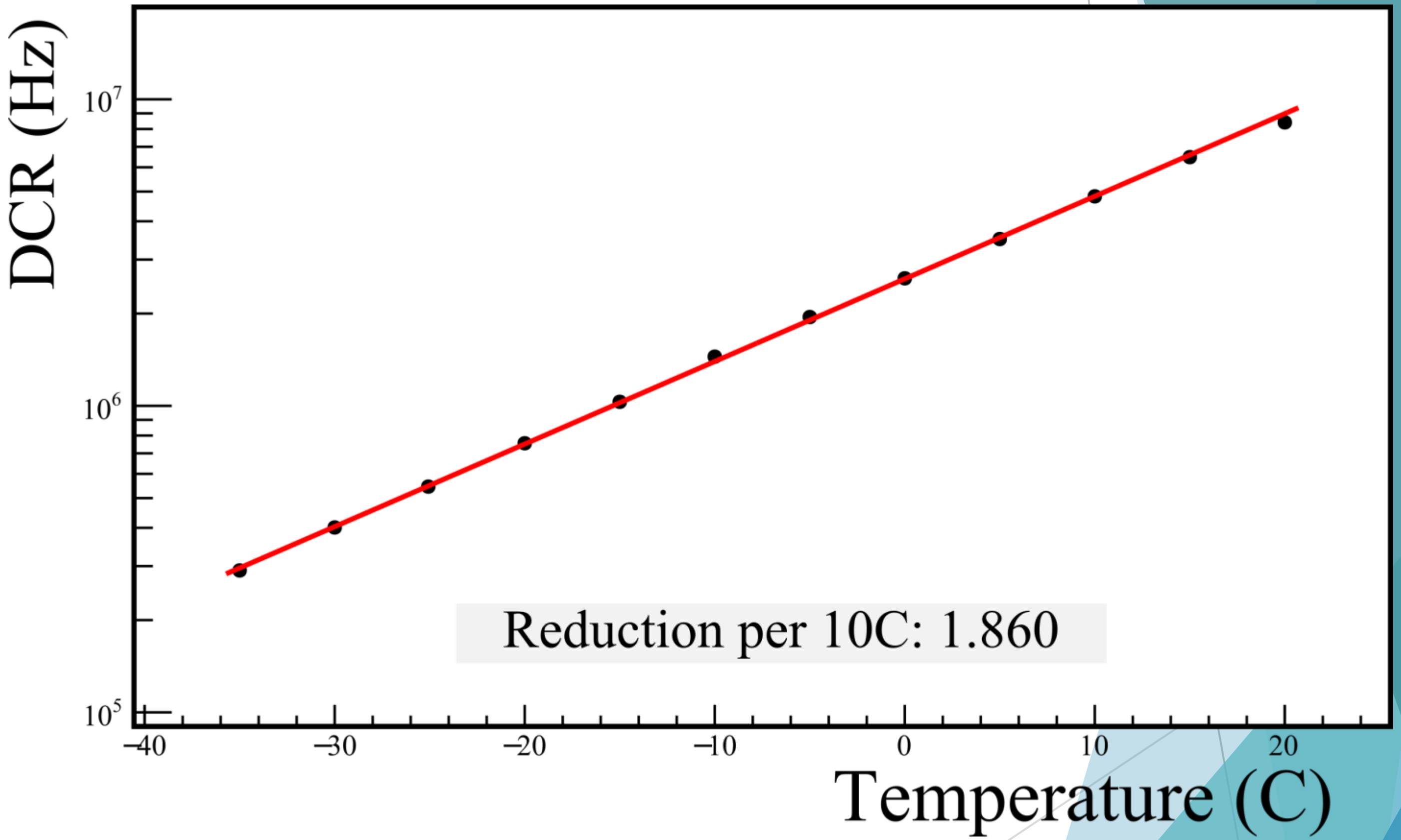
LHCb-INT-2015-004

thermal noise in SiPMs

- creation of e-h-pair due to thermal excitation
- ‚thermal signal' is identical to ‚single photon signal'
- **dark count rate (DCR)**

  pixel fire rate per area in absence of light

- DCR depends exponentially on (ambient) temperature
- higher signal amplitude due to pixel x-talk



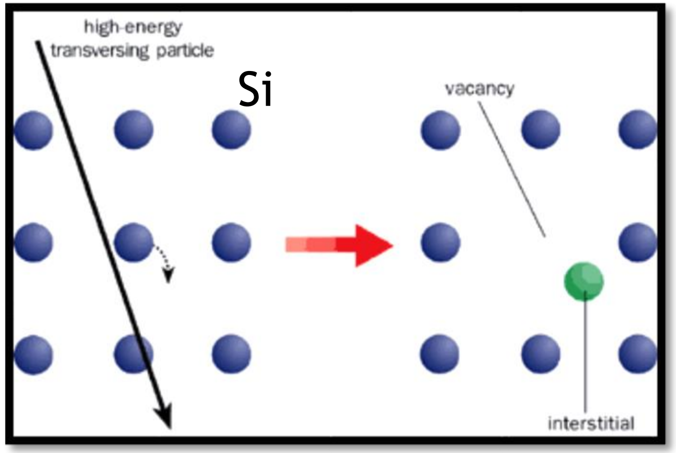
→ operate SiPMs at T = -40°C
(lower limit due to thermal stress on fibres)

neutron irradiation damage inside SiPMs

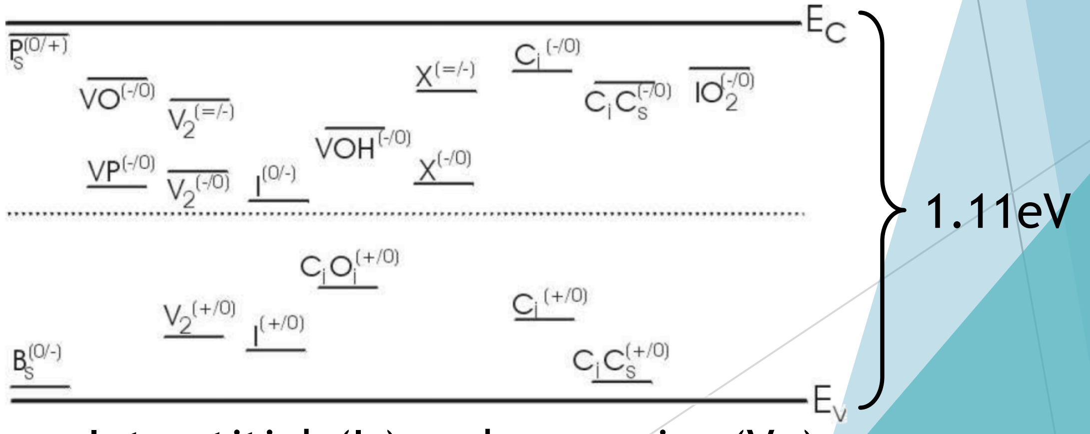
- displacement of Si atoms in the crystal‘s lattice due to neutron scattering
- damage in silicon bulk (not on surface)
- **vacancy**

  removed atom at lattice knot
- **insterstital**

  additional atom in between knots
- additional energy levels in bandgap increases probability of electron excitement into conduction band
  → increase of DCR



Radiation defects in the bandgap of Si

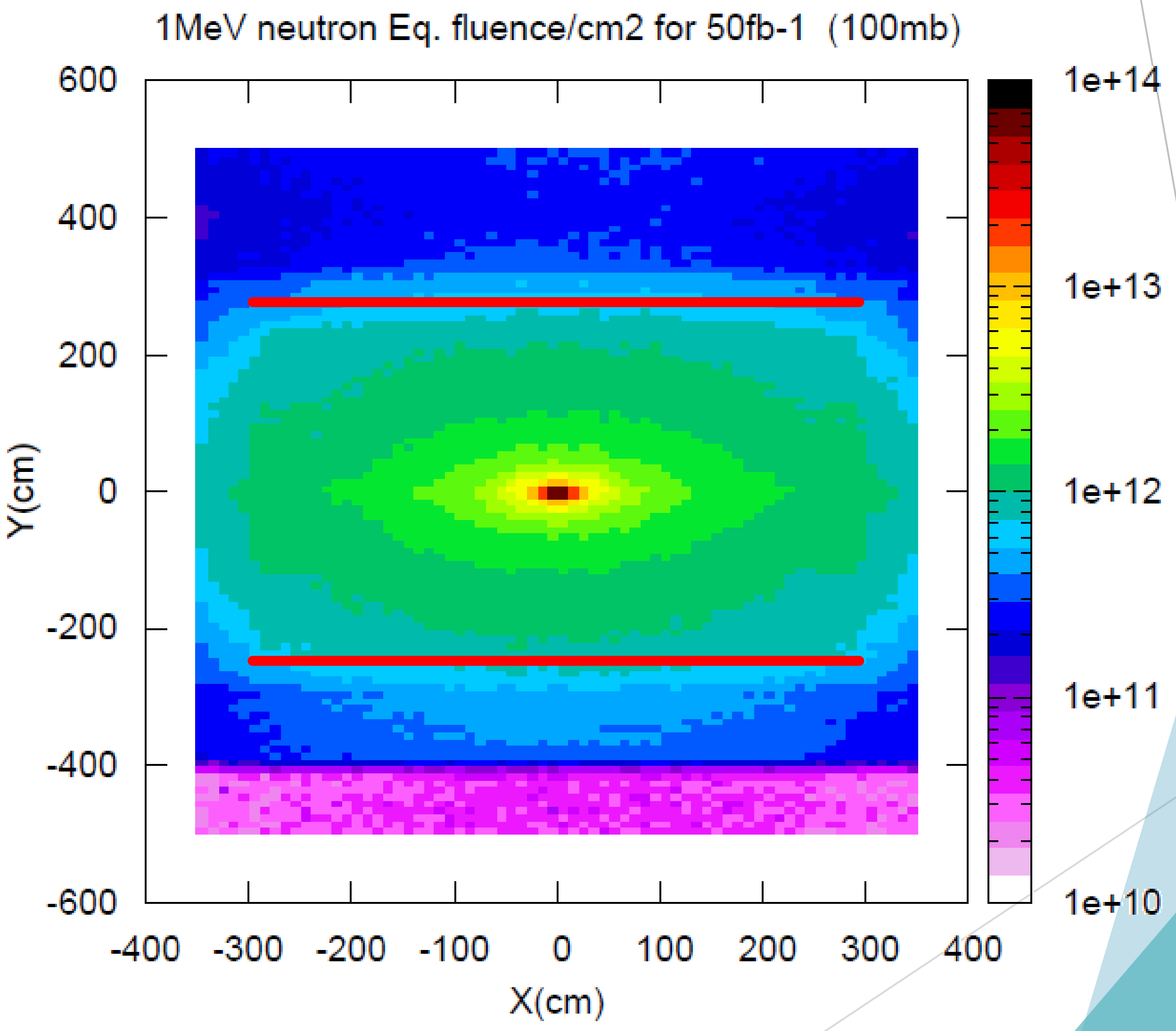


Interstitials(I-) and vacancies (V+)

Blake Leverington - DPG 2015

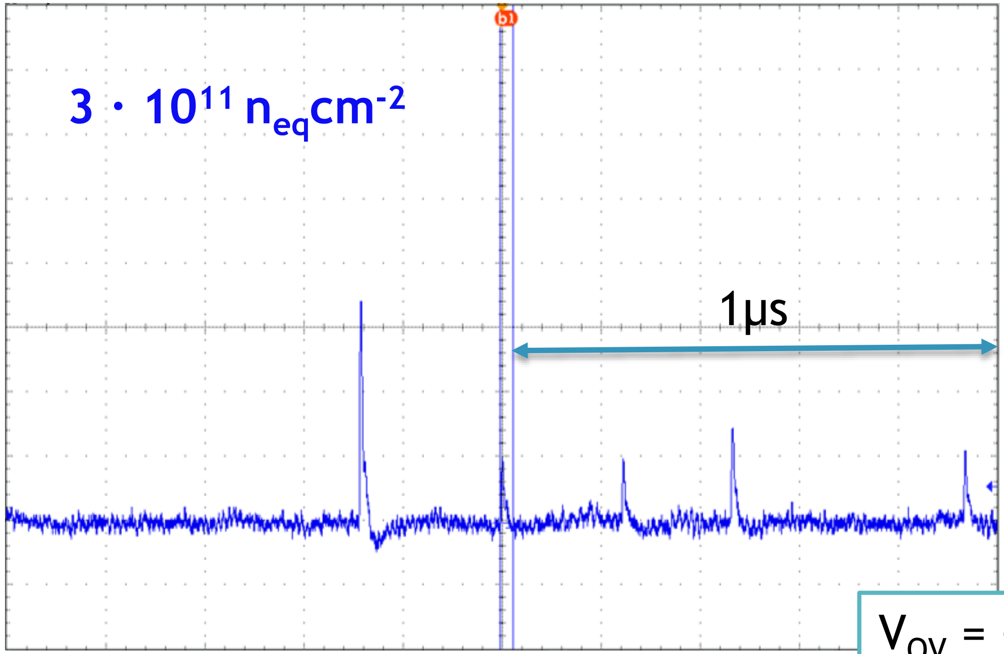
radioactive environment at LHCb

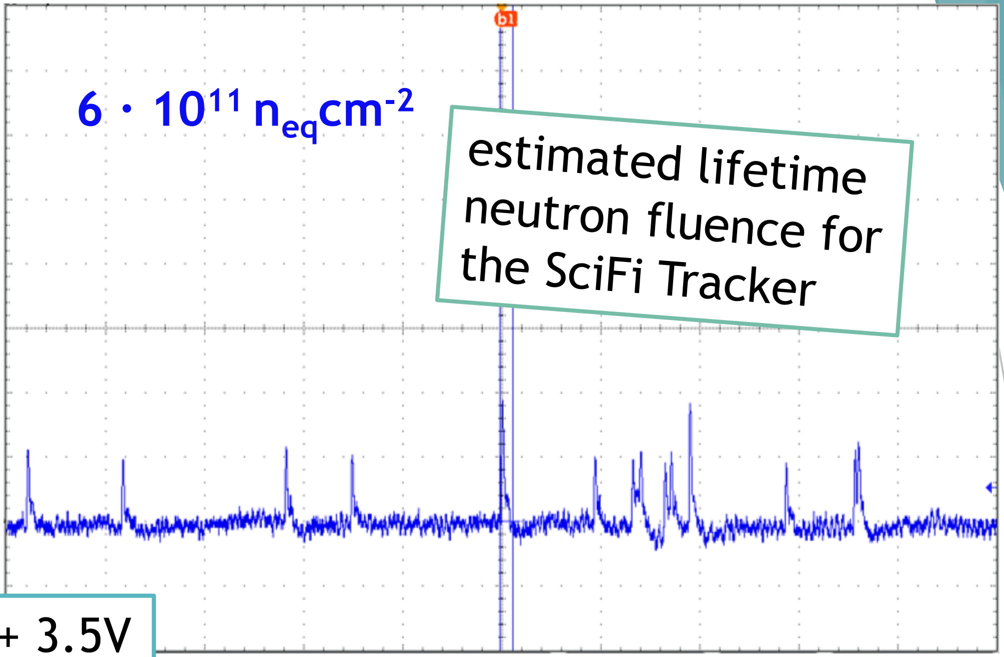
- expected neutron fluence with PE shielding:
  - **$6 \cdot 10^{11}\, n_{eq} cm^{-2}$**
- source of HE neutrons: backscattering from CALO
- damage mostly neutrons
- NIEL* damage is normalized to 1MeV neutron damage
- no damage from thermal neutrons observed



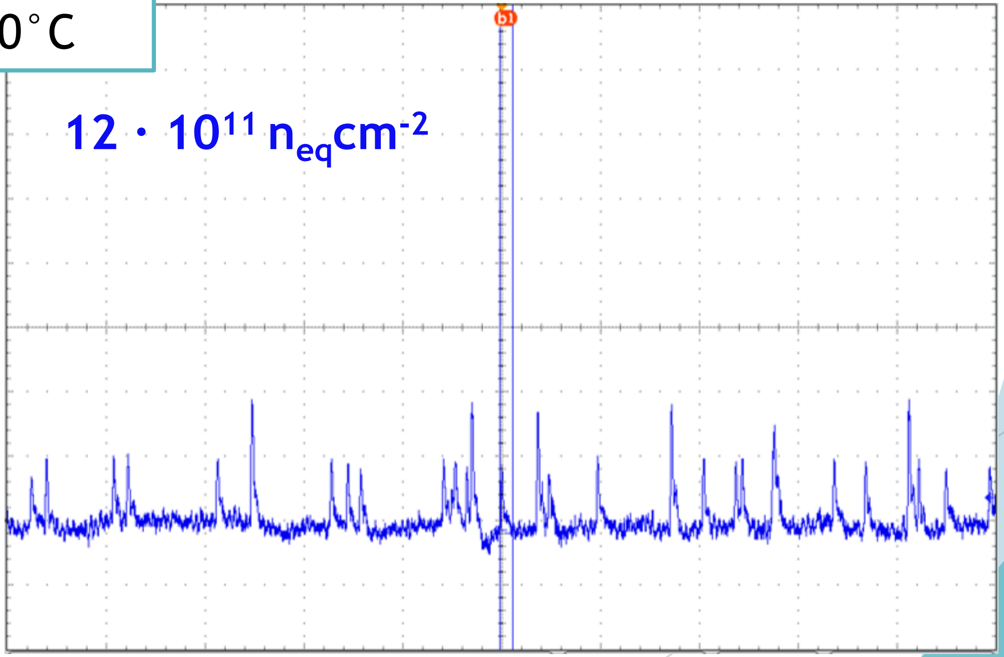
(*): NIEL = non-ionizing energy loss

dark count rate (DCR)



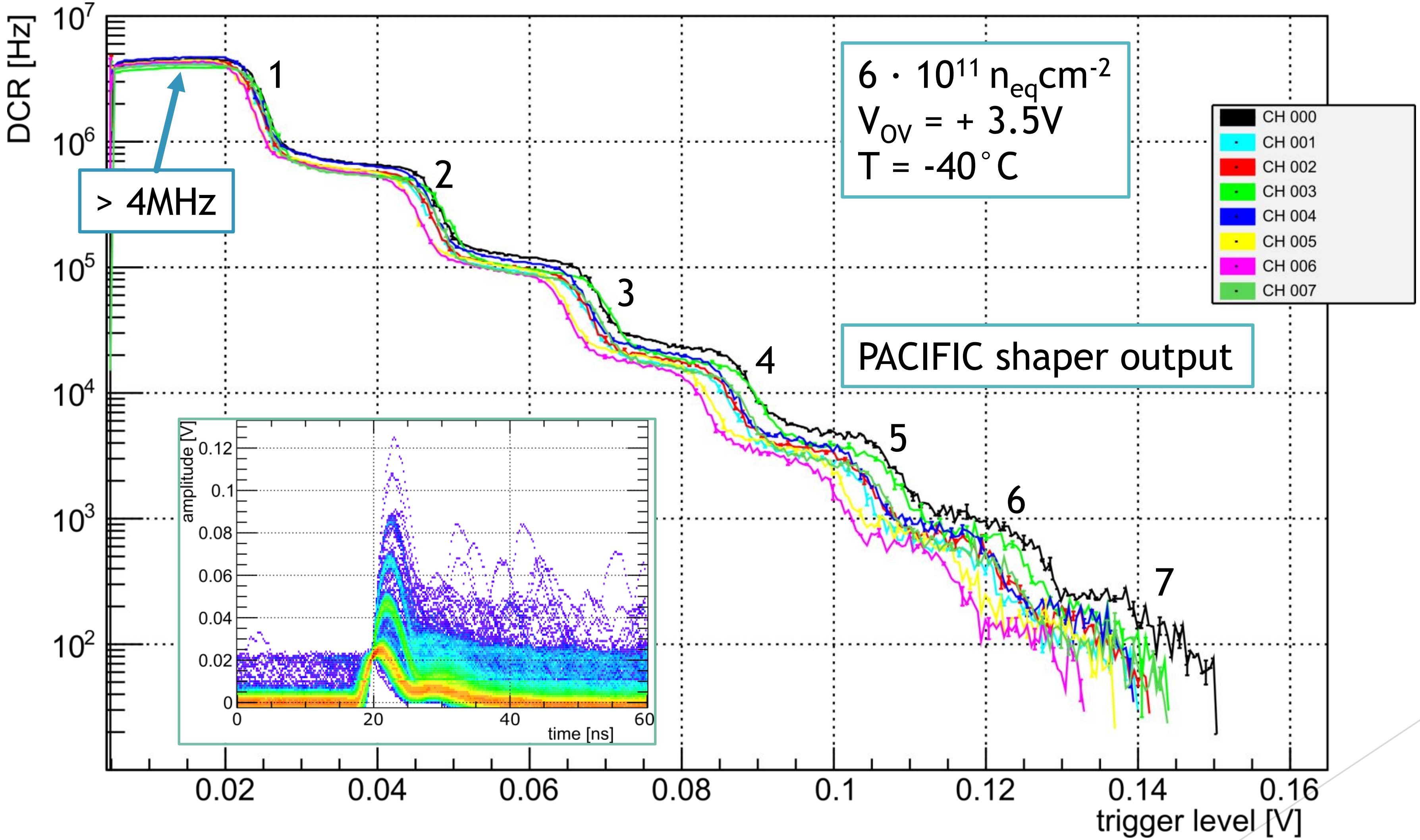


V_{OV} = + 3.5V
T = -40°C

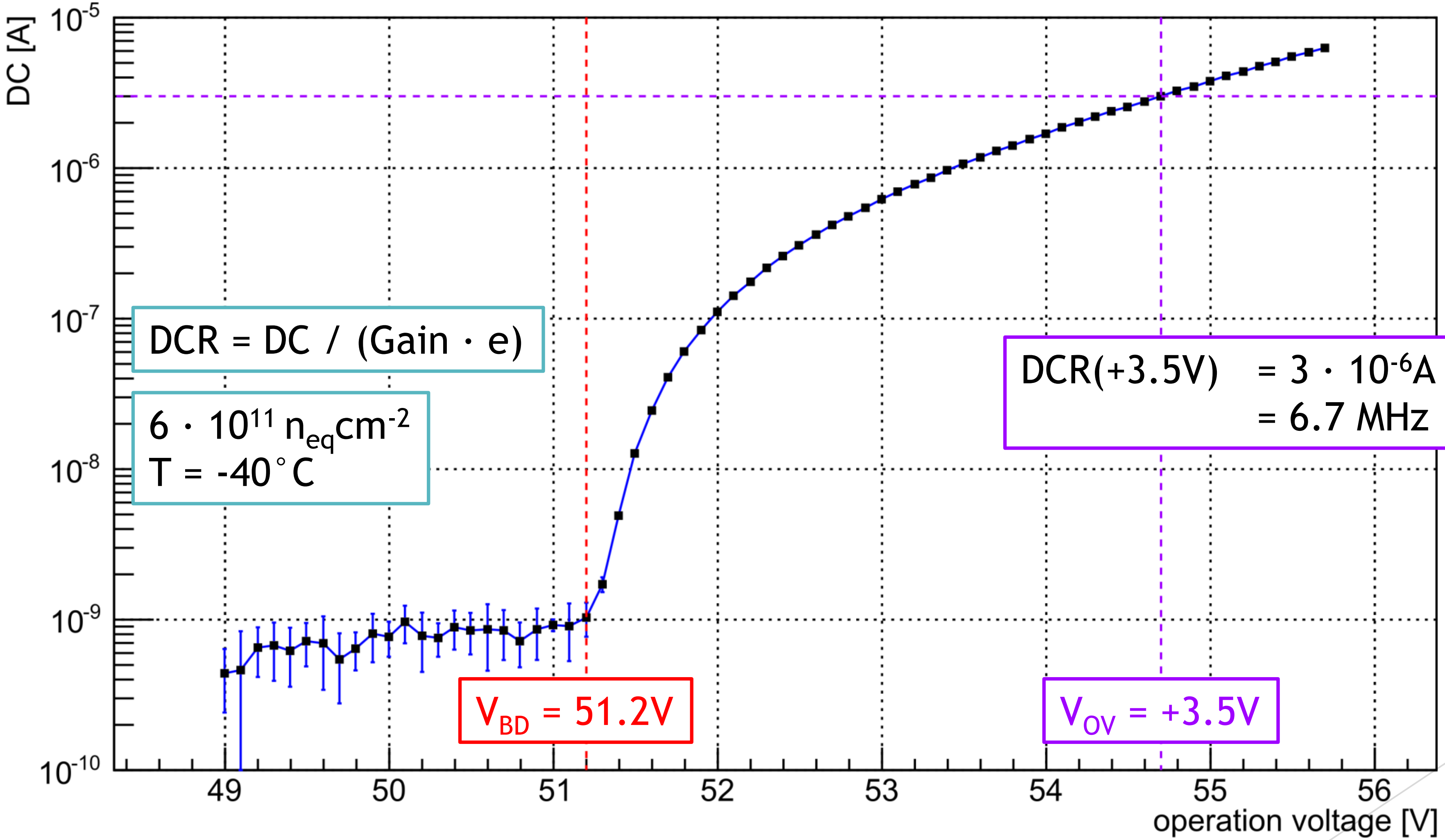


- irradiation at reactor in Mainz
- increase of DCR is directly visible
- in the following I introduce three methods to determine the DCR
- DCR always per SiPM channel
- compare to 40 MHz read-out

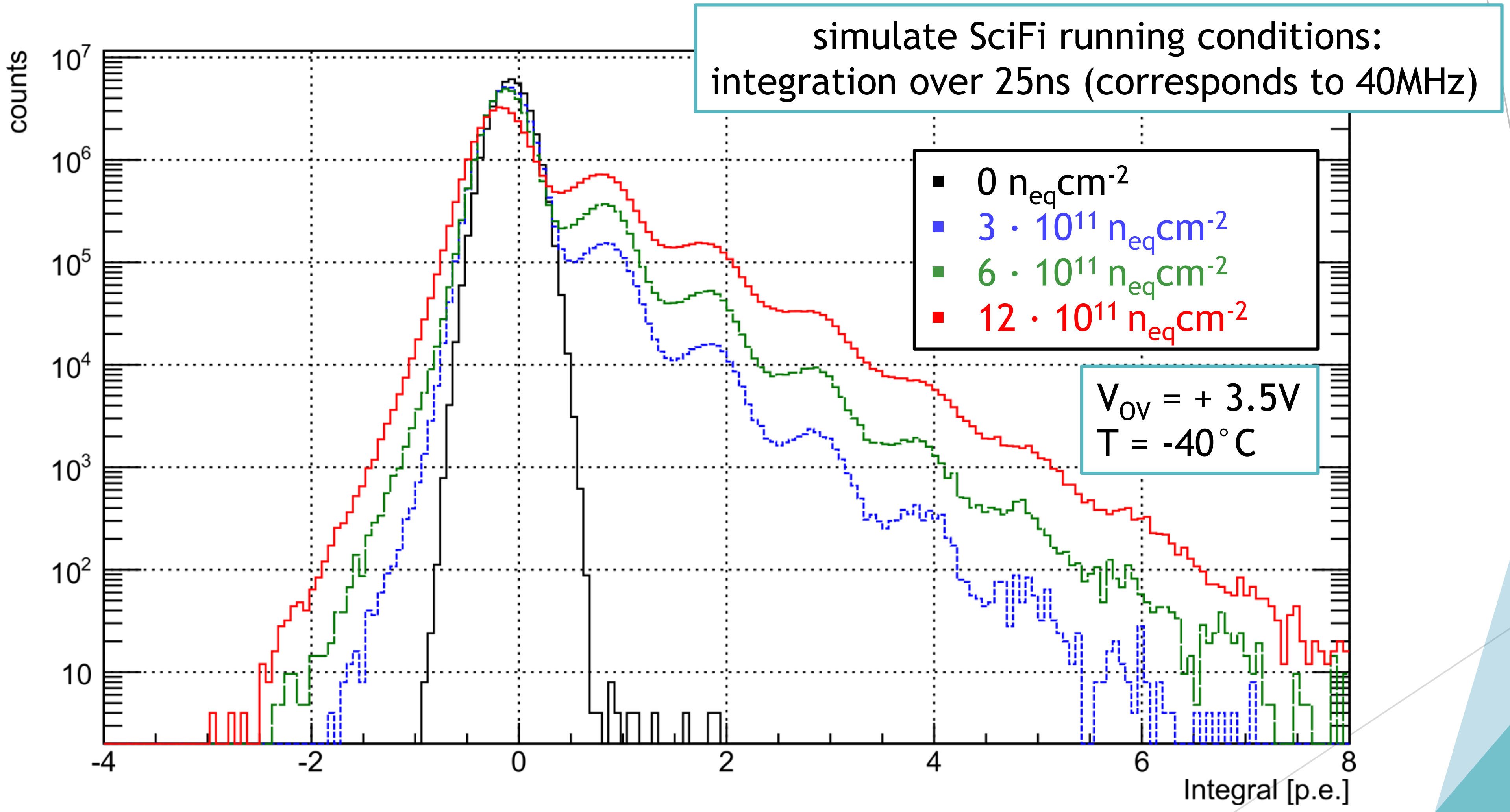
DCR trigger scans



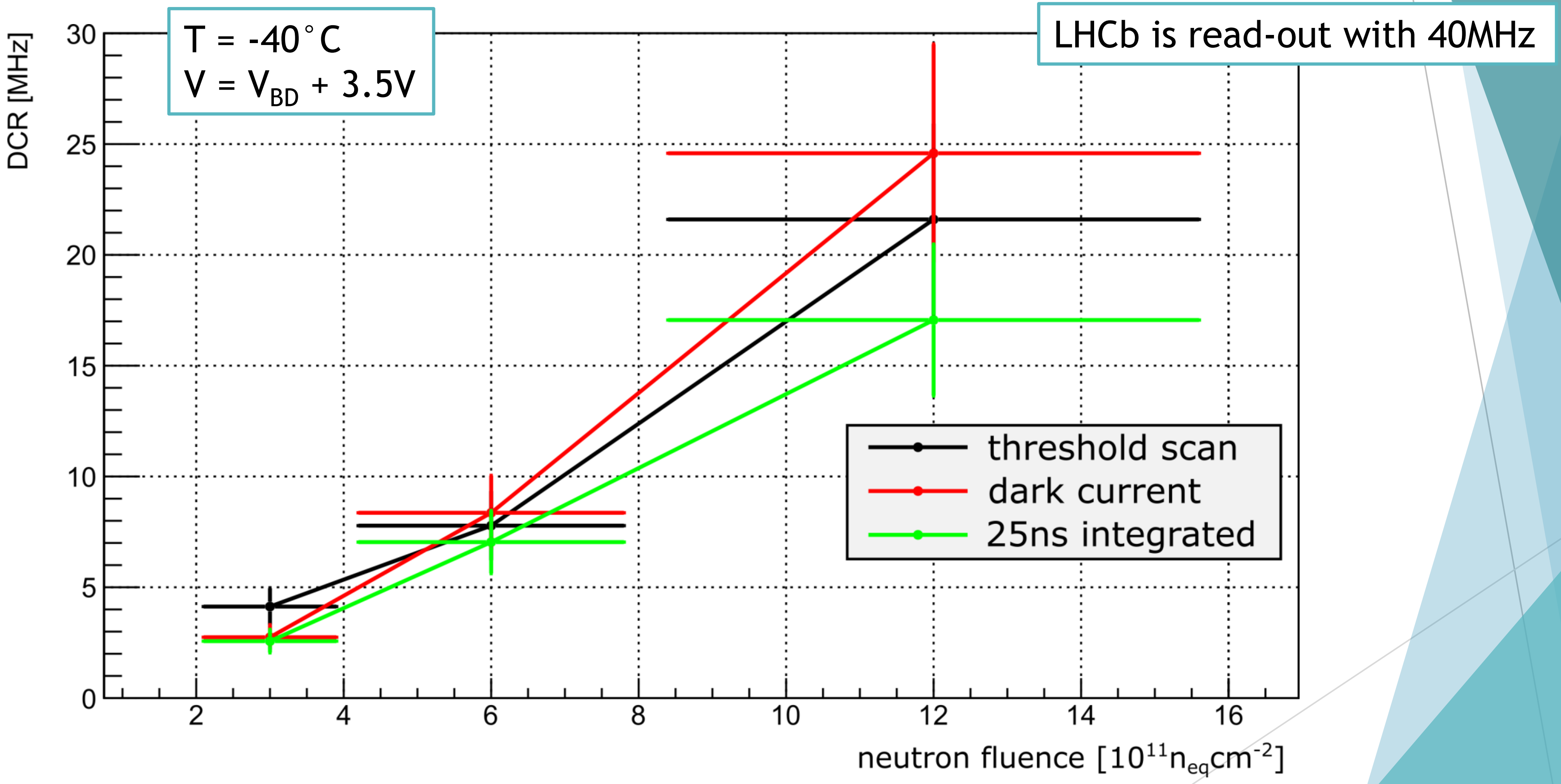
DCR from IV curves



25ns integrated DCR spectrum



resulting DCR values

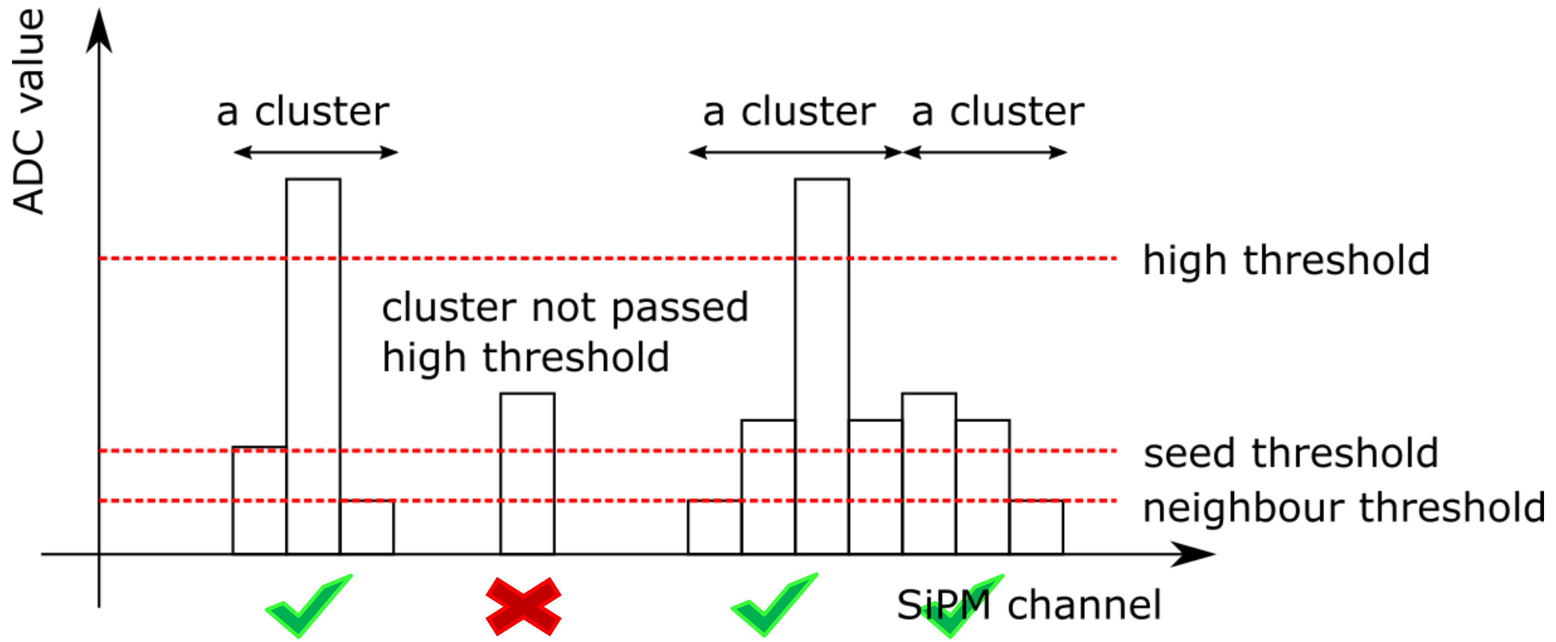


noise cluster rate (NCR)

rate of clusters per 128 channel array after $6 \cdot 10^{11}\, n_{eq}cm^{-2}$

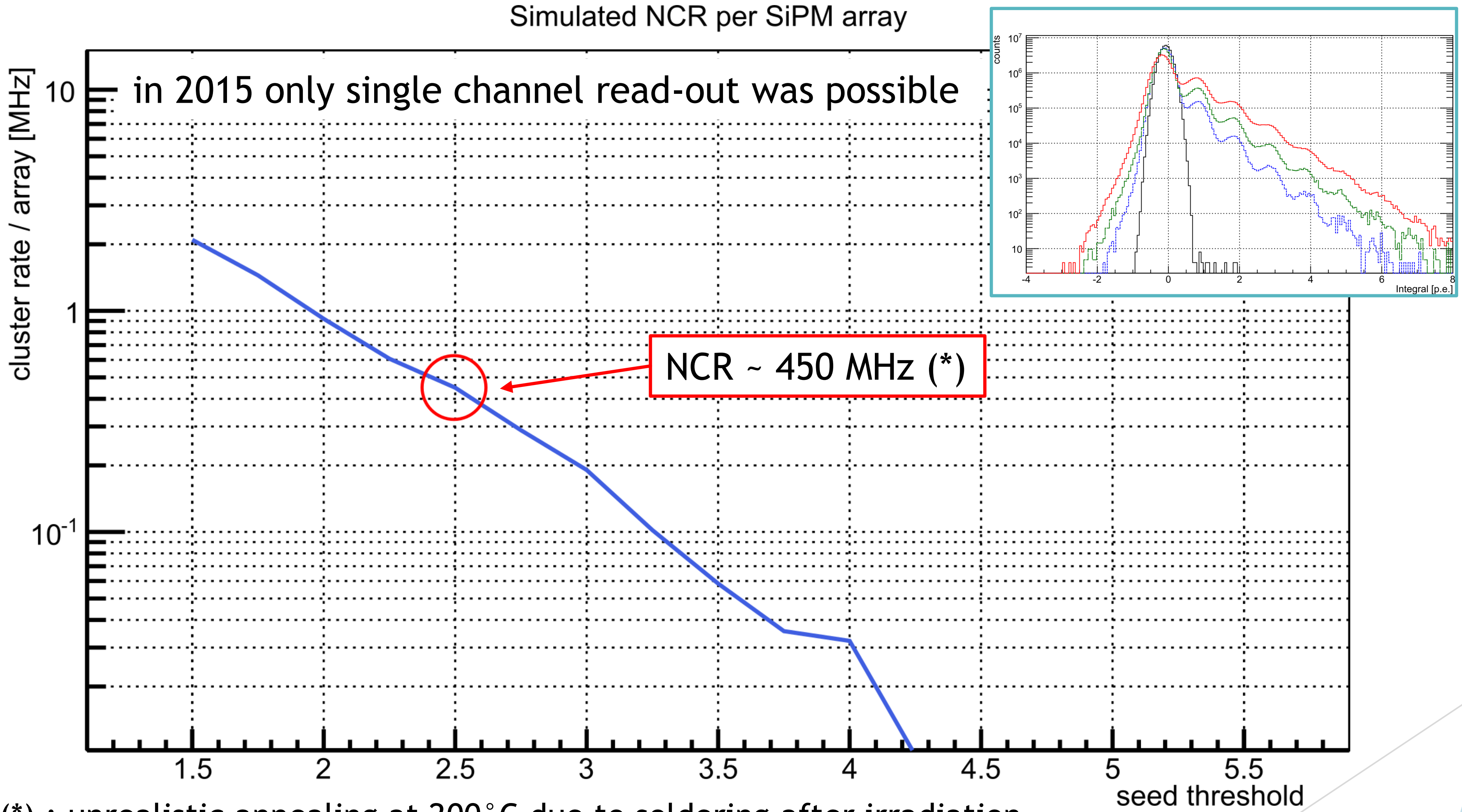
T = -40°C V_{OV} = +3.5V

cluster algorithm



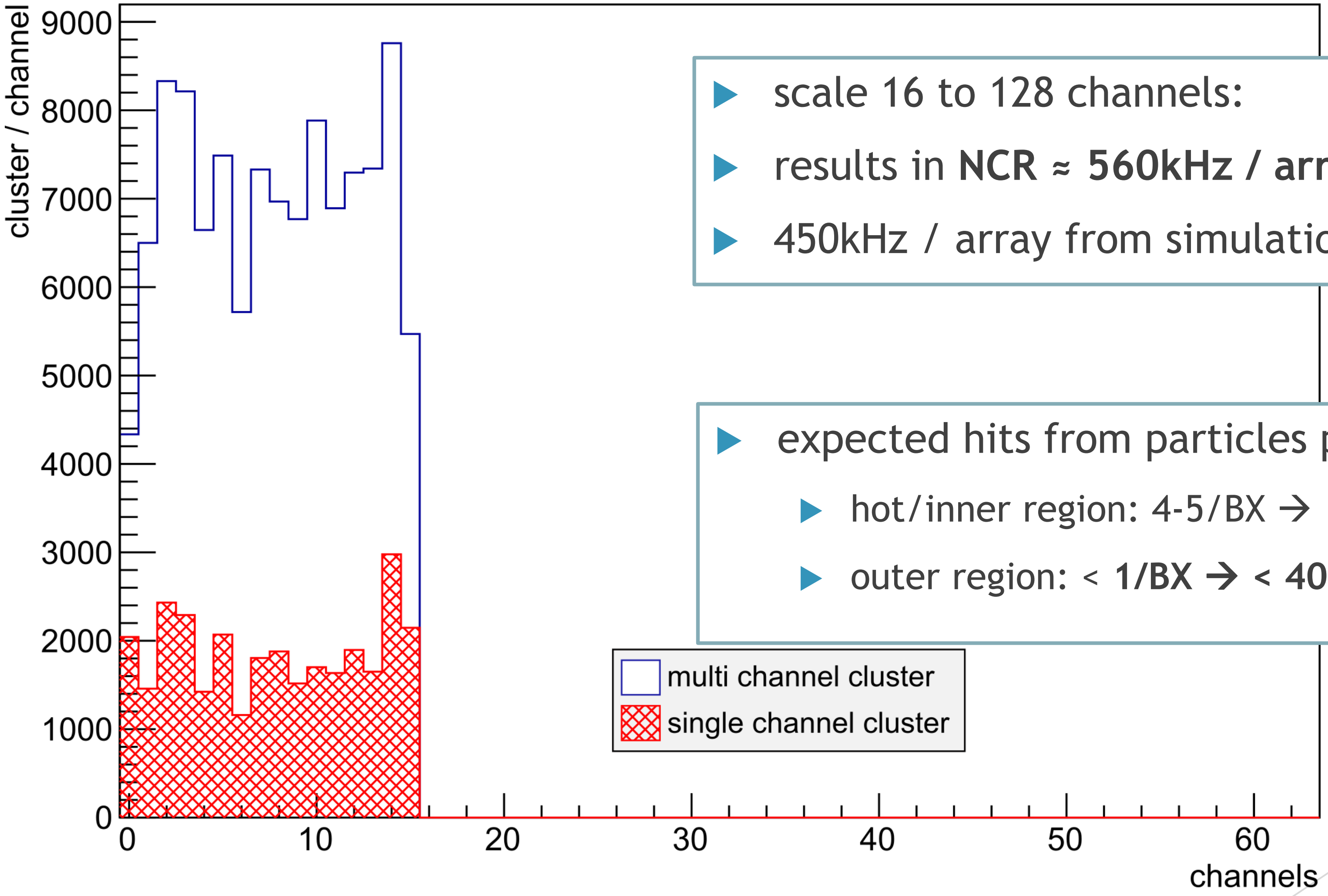
- use charge weighted mean of cluster to get hit position for particle tracking
- clustering of channels suppresses noise, because:
  - noise appears uncorrelated in channels
  - higher thresholds suppress small noise signals

Simulation of NCR in 128CH array



(*) : unrealistic annealing at 200°C due to soldering after irradiation

cluster distribution along 16 channels



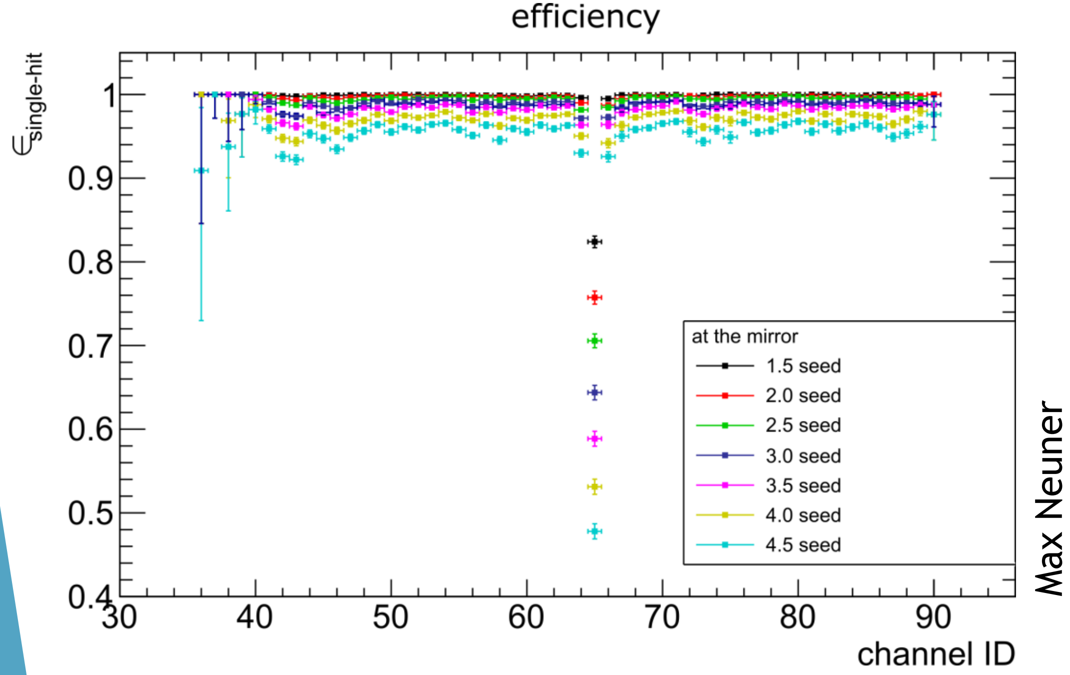
- scale 16 to 128 channels:
- results in **NCR ≈ 560kHz / array**
- 450kHz / array from simulation

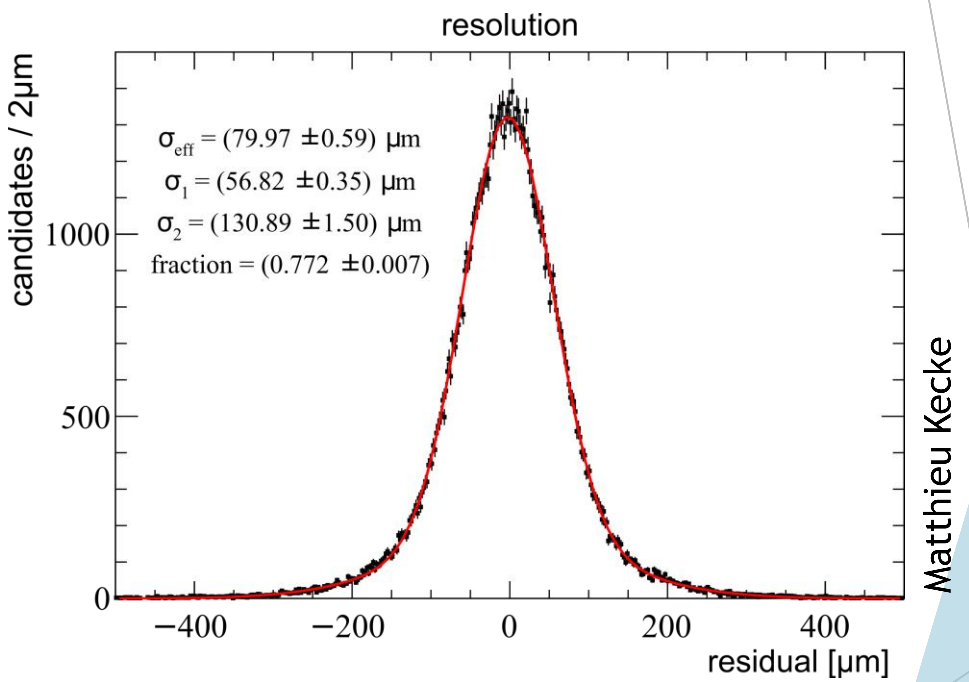
ongoing work!

- expected hits from particles per array:
  - hot/inner region: 4-5/BX → **160-200MHz**
  - outer region: < **1/BX → < 40MHz**

Efficiency and resolution of SciFi

testbeam results from November 2015





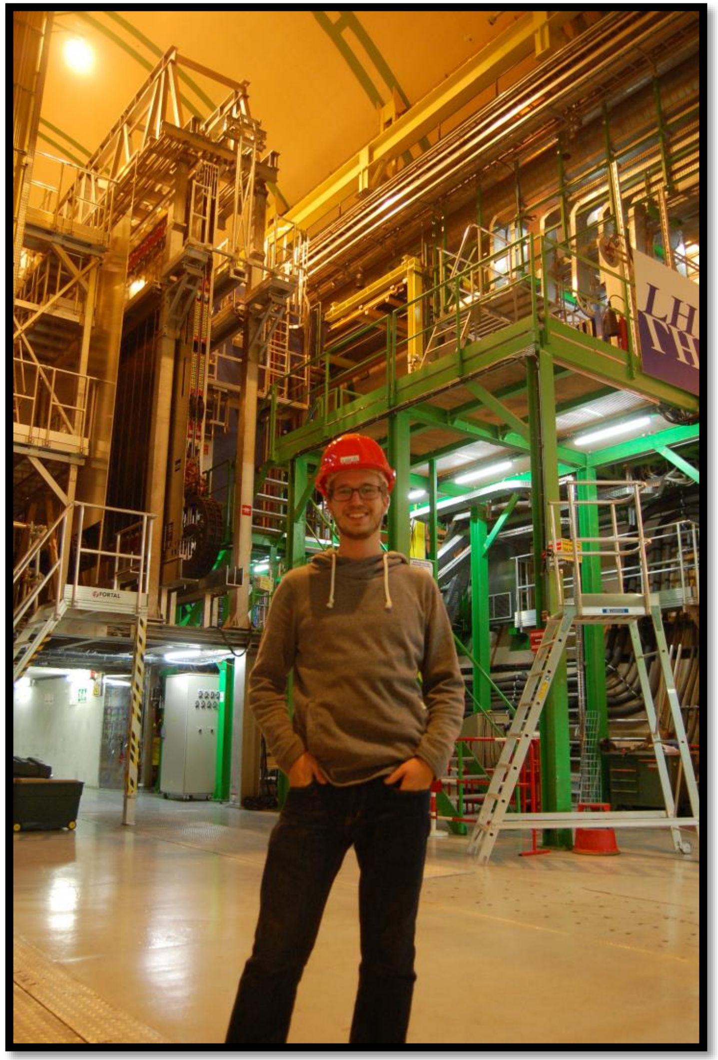
- single hit efficiency > 99% ✔
- resolution < 100µm ✔

Conclusion & Outlook

- thermal noise in SiPM arrays due to neutron irradiation is a hot topic for particle detectors in hadron colliders
- detectors are still functional after irradiation
- still single photon sensitive
  - after $12 \cdot 10^{11}\, n_{eq}cm^{-2}$, thanks to fast readout, cooling and annealing
- DCR per channel increases linearly with the neutron fluence
- After $6 \cdot 10^{11}\, n_{eq}cm^{-2}$ at $T = -40^{\circ}C$ and $V_{OV} = 3.5V$
  - single channel DCR: **6-8 MHz** (area = $1.5mm \cdot 250\mu m = 0.375mm^2$)
  - NCR per 128 channel array: **3 MHz** at threshold set (1.5, 2.5, 4.5) with realistic annealing
- clustering at FEE is important to reduce total bandwidth to acceptable level
- Hamamatsu 2015 came back last week from irradiation facility

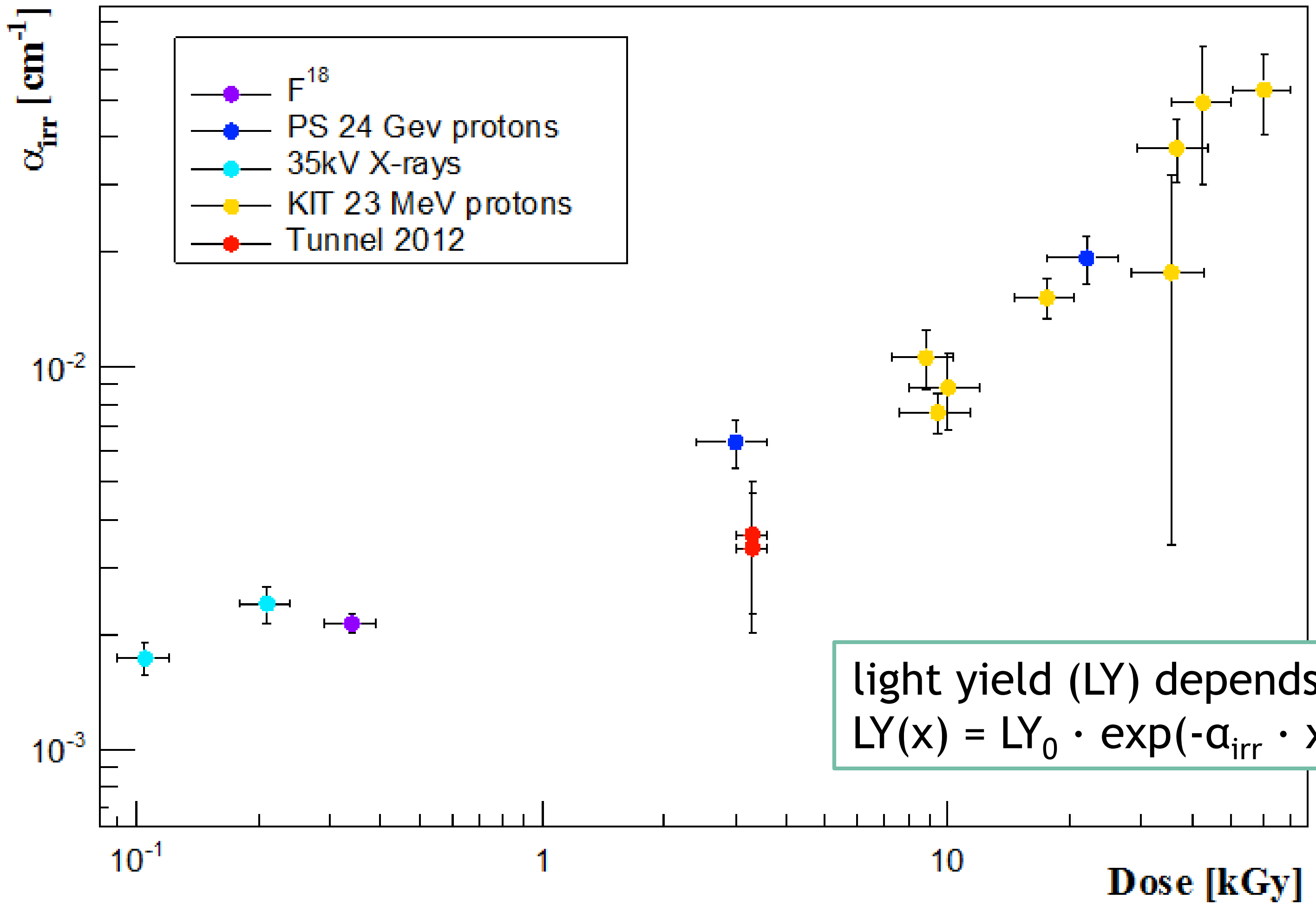
Thank you

… for your attention!



Backup

irradiation damage to fibres



light yield (LY) depends on the attenuation length:
$LY(x) = LY_0 \cdot \exp(-\alpha_{irr} \cdot x)$

SciFi Internal

Fibre emission spectrum