SciFi Tracker Upgrades

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Outline

- Expected aging of the SciFi after Run 3 & 4
- Replacement and upgrade
- Upgrade the performance of the SciFi
  - Micro-lens enhancement of SiPMs
  - Thinner SciFi
  - Cryo-cooling
- Conclusion for Upgrade 1b, Upgrade II

SiPM aging

SiPM nominal design:

- Design luminosity $50fb^{-1}$
  - Neutron radiation: $6*10^{11}$ n_{eq}/cm^2
  - Charged: 50Gy, responsible for 15-20% of SiPM DCR increase after neutron shielding
- Fluka simulation with neutron shield yields the values for the most exposed regions in T1 and T3:
  - T1: $8.1*10^{11}$ n_{eq}/cm^2 ➔ $3.3*10^{11}$ n_{eq}/cm^2 (reduction of 2.5 after shielding)
  - T3: $14*10^{11}$ n_{eq}/cm^2 ➔ $4.2*10^{11}$ n_{eq}/cm^2 (reduction of 3.4 after shielding)
- Fluka simulation uncertainty for the absolute values of the neutron fluence is a factor 2

SiPM aging

SiPM after Run 3 of 40fb^{-1} :

- T1: 2.6*10^{11} n_{eq}/cm^2 (worst case 5.2*10^{11} n_{eq}/cm^2)
- T3: 3.3*10^{11} n_{eq}/cm^2 (worst case 6.6*10^{11} n_{eq}/cm^2)

SiPM after Run 3&4 of 80fb^{-1} :

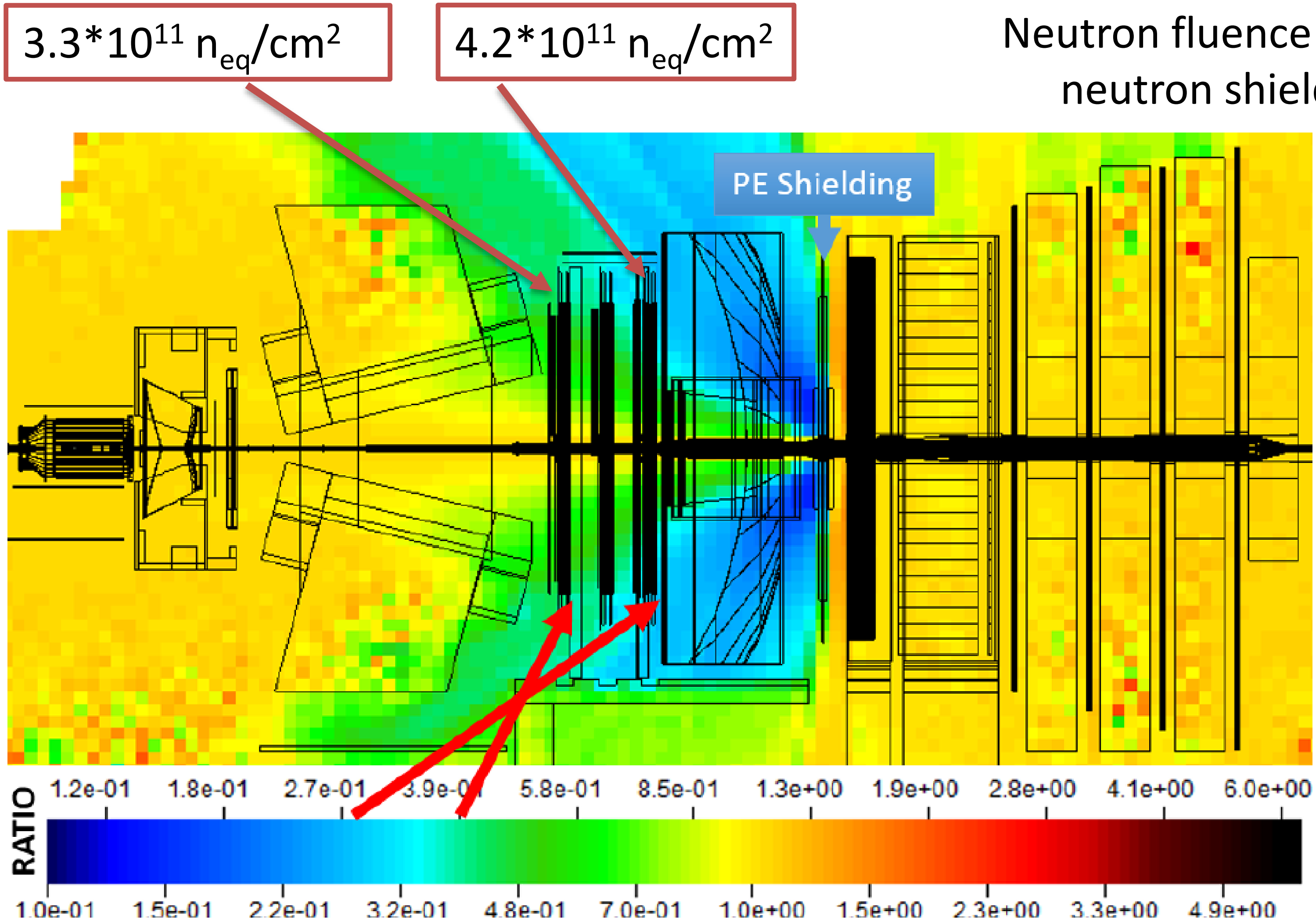
- T1: 5.2*10^{11} n_{eq}/cm^2 (worst case 10.4*10^{11} n_{eq}/cm^2)
- T3: 6.6*10^{11} n_{eq}/cm^2 (worst case 13.2*10^{11} n_{eq}/cm^2)

In red, values beyond the design fluence which is the limit of acceptable dark count rate (DCR) and has a consequence the noise cluster rate (NCR).

To maintain NCR<10MHz, the noise threshold cut has to be increased and the efficiency is dropping rapidly.

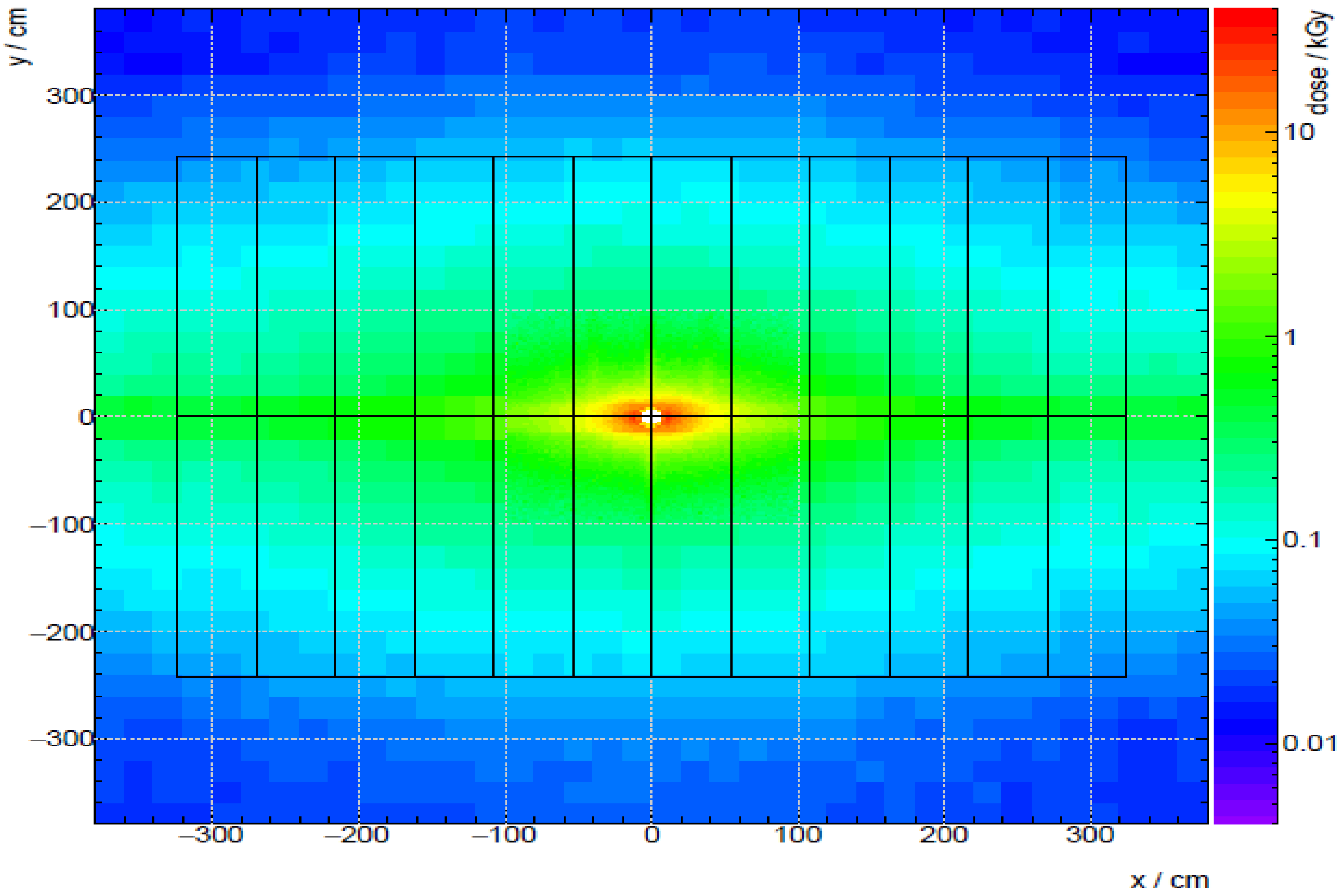
Neutron fluence is responsible for 80-85% of DCR increase of the SiPM after shielding

Neutron fluence with neutron shield.



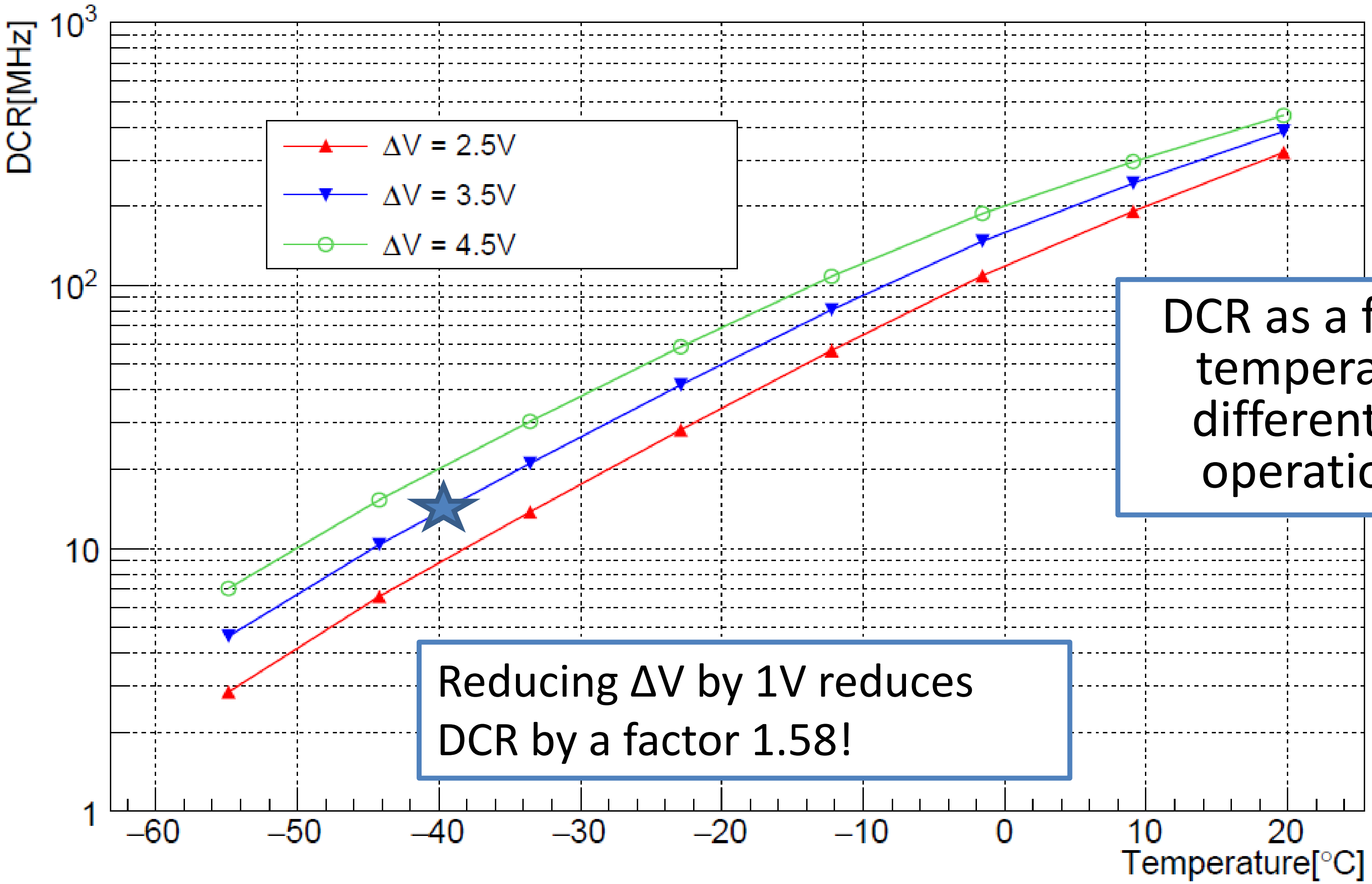
Dose due to charged tracks, makes up 15-20% of the DCR increase for the SiPMs

Decrease to the edge is slow



Radiation dose profile in the x-y plane

Irradiated detector with $6*10^{11}\ n_{eq}/cm^2$



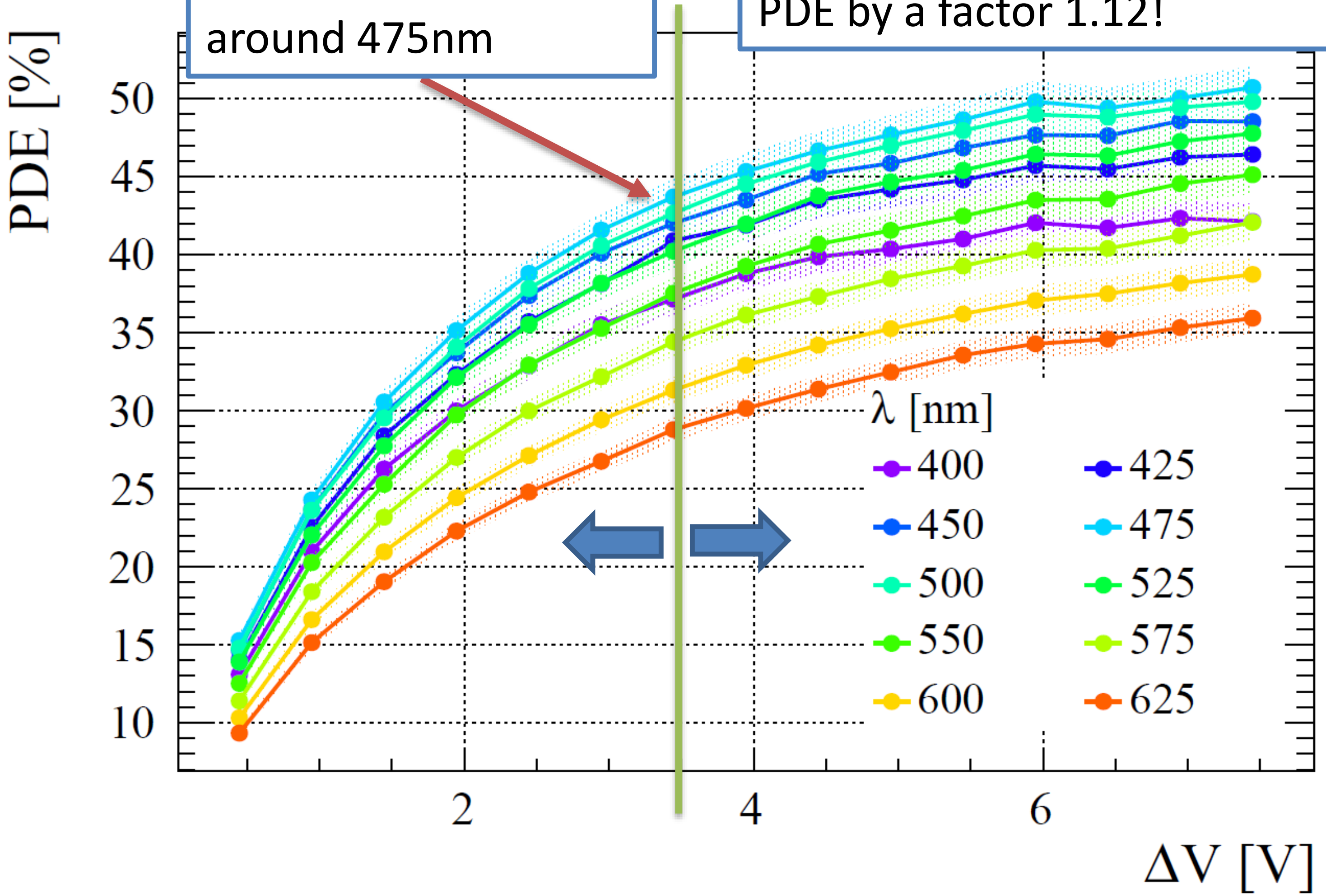
DCR as a function of temperature at 3 different possible operation points

Reducing ΔV by 1V reduces DCR by a factor 1.58!

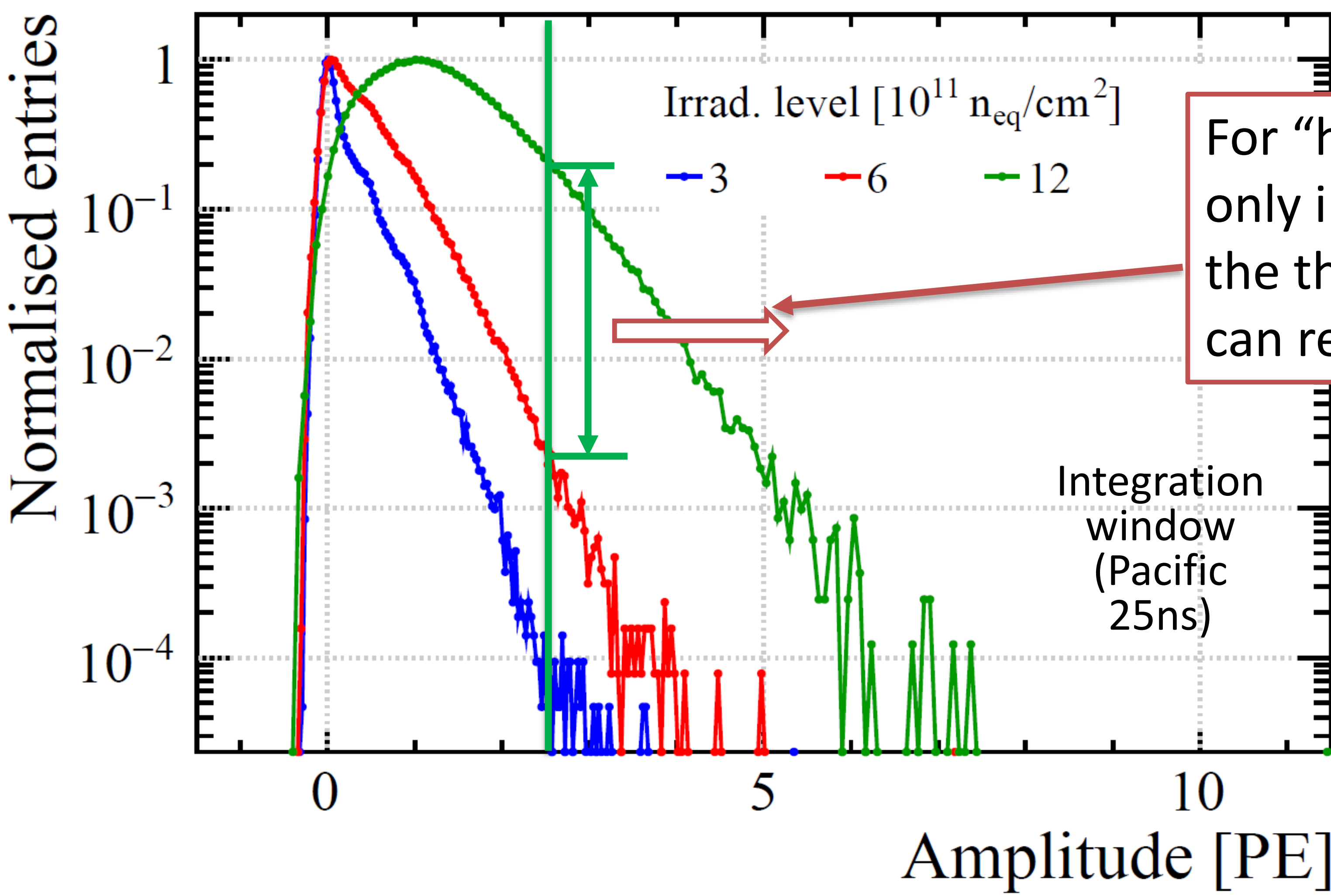
PDE as a function of over-voltage

Light emitted by the SciFi is centered around 475nm

Reducing ΔV by 1V reduces PDE by a factor 1.12!

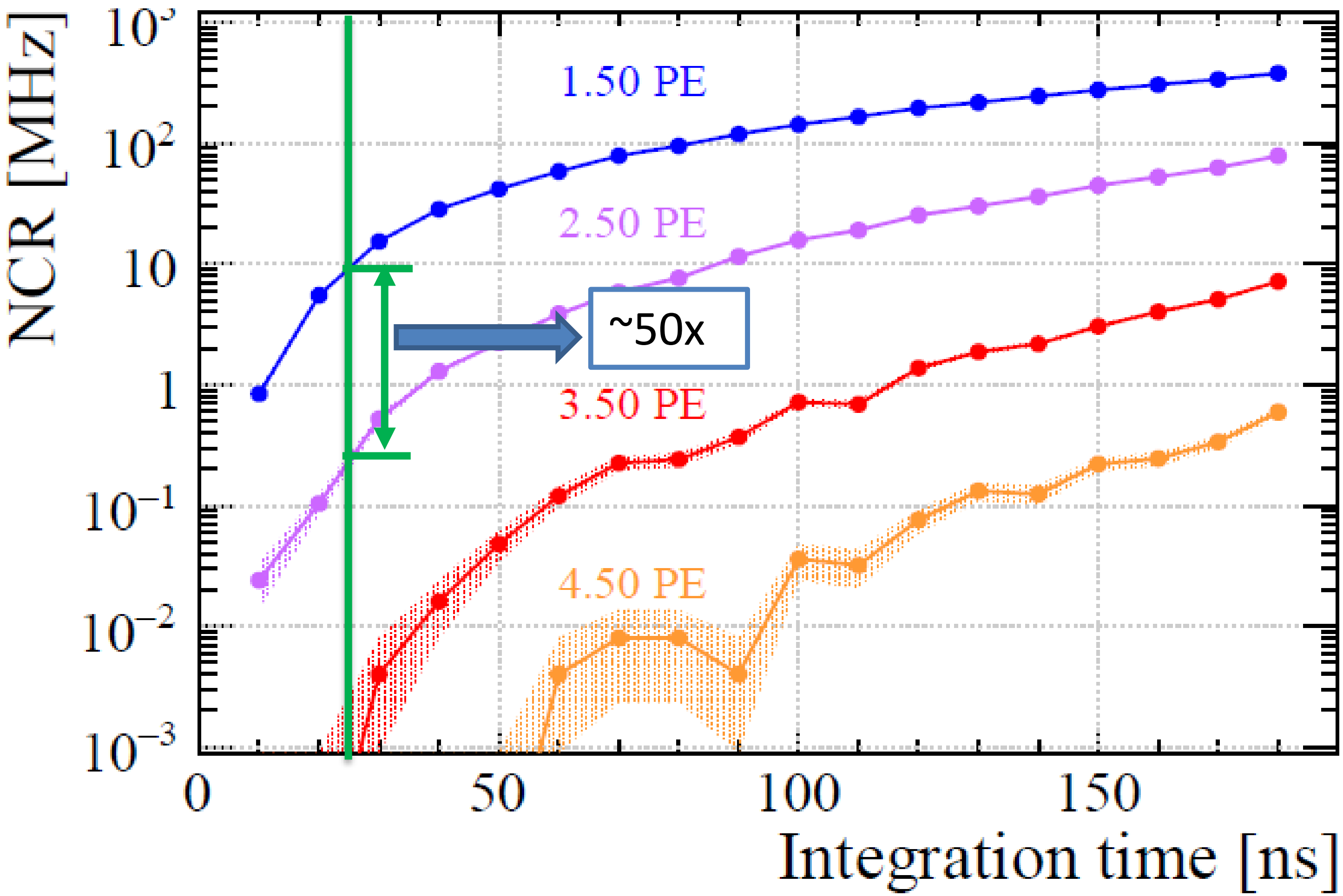


Noise cluster rate (NCR) expected for the current SciFi



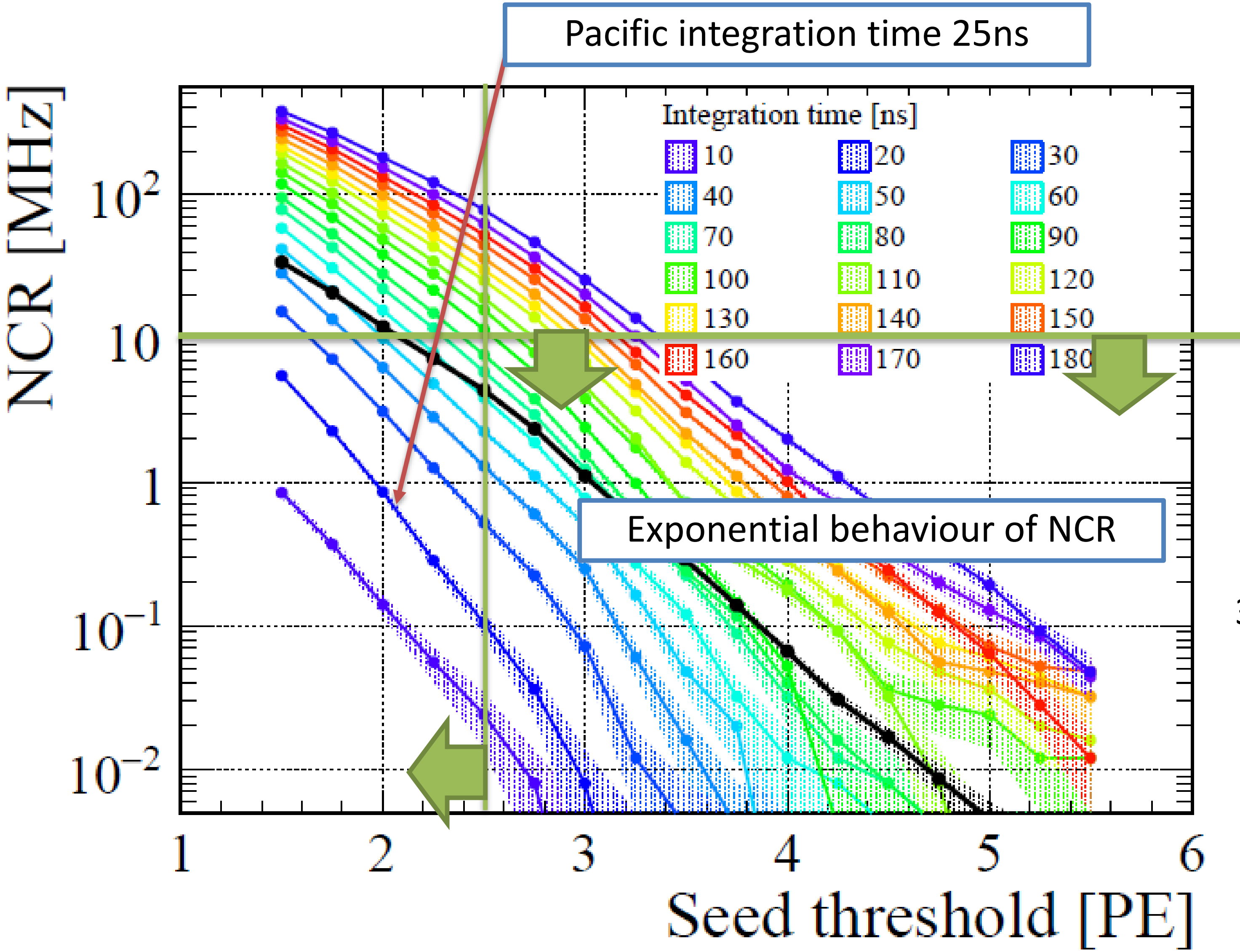
For "high" DCR only increasing the threshold can reduce NCR.

Noise cluster rate for different seed thresholds



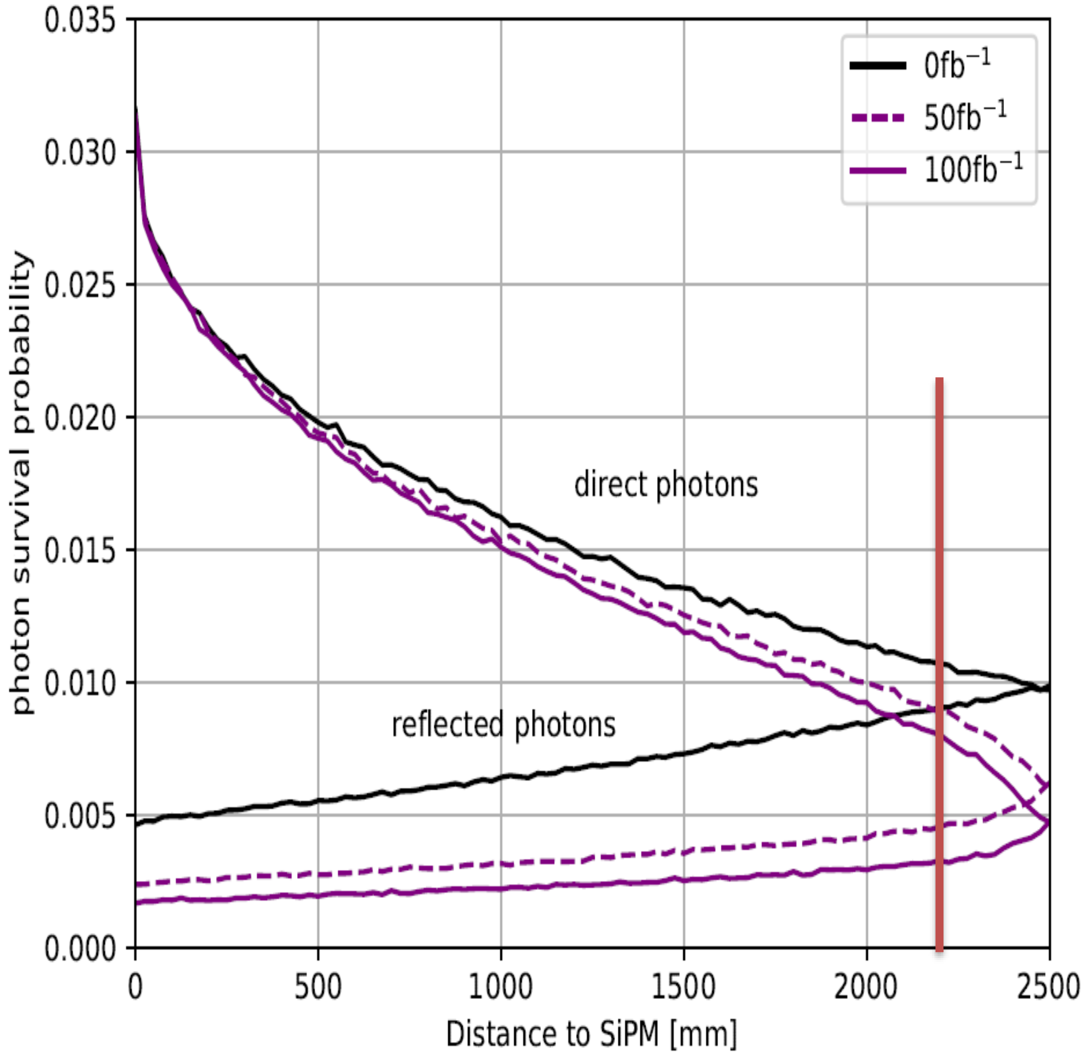
Integration window (Pacific 25ns)

Noise cluster rate expected for the current SciFi



Irradiated detector to $3*10^{11}$ n_{eq}/cm^2

Radiation damage of the fibre results in lower photon survival probability



Linear law model ratios:

$$\frac{LY_{50fb^{-1}}}{LY_0} = \frac{12\text{PE}}{18\text{PE}} = 67\%$$

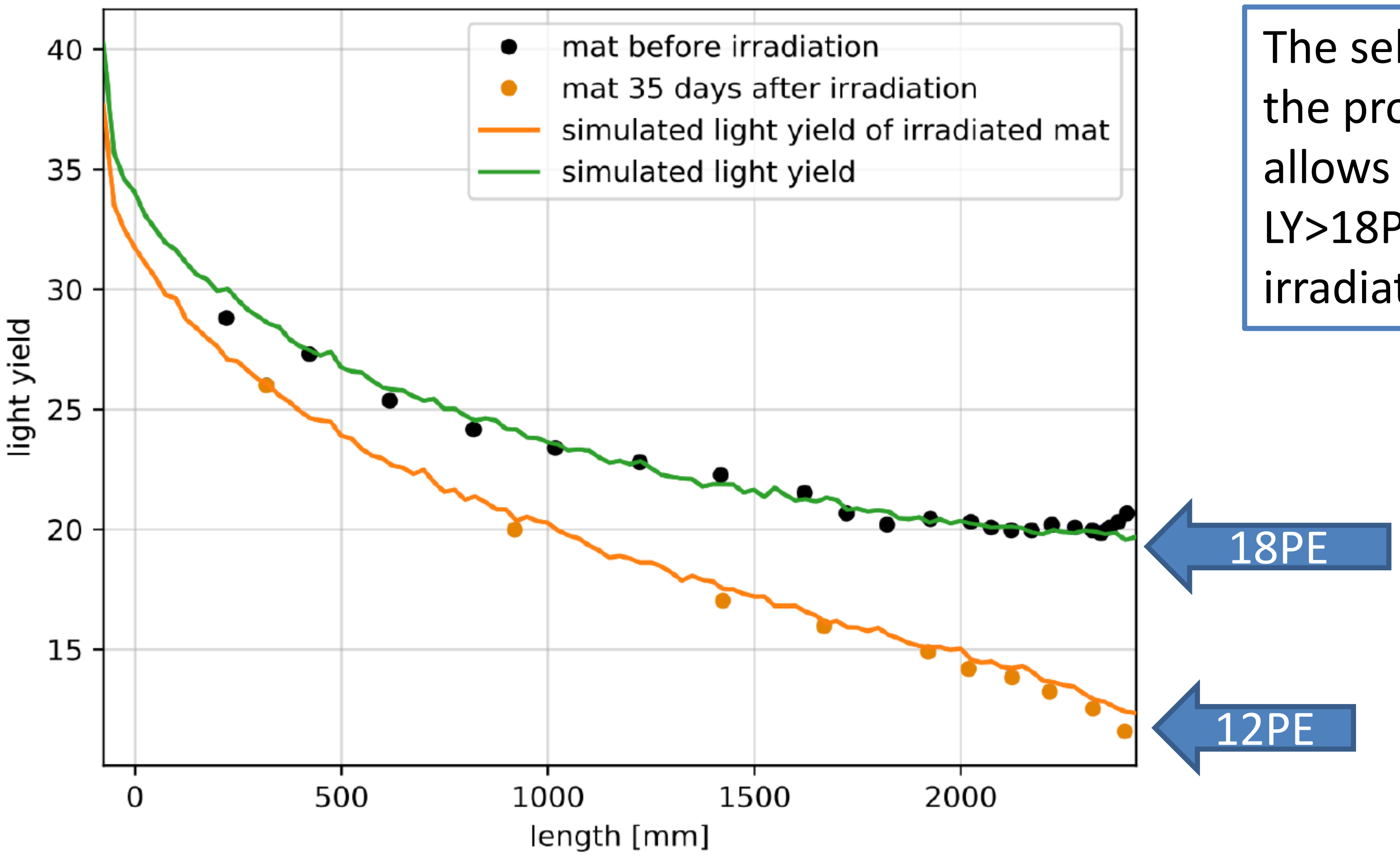
$$\frac{LY_{100fb^{-1}}}{LY_0} = \frac{8.5\text{PE}}{18\text{PE}} = 47\%$$

Power law model ratios:

$$\frac{LY_{50fb^{-1}}}{LY_0} = \frac{10\text{PE}}{18\text{PE}} = 56\%$$

$$\frac{LY_{100fb^{-1}}}{LY_0} = \frac{6.7\text{PE}}{18\text{PE}} = 38\%$$

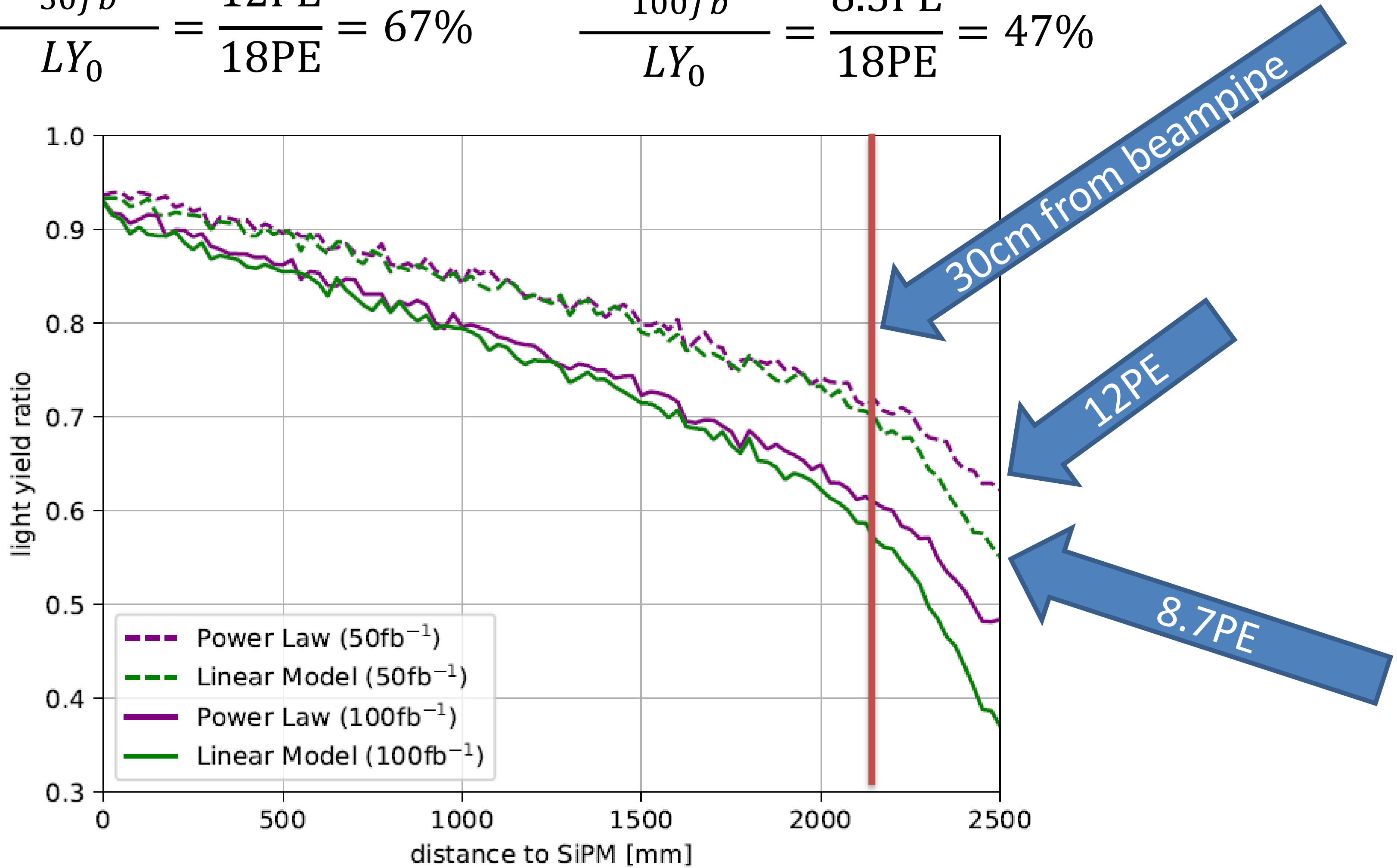
Radiation damage reduces the LY



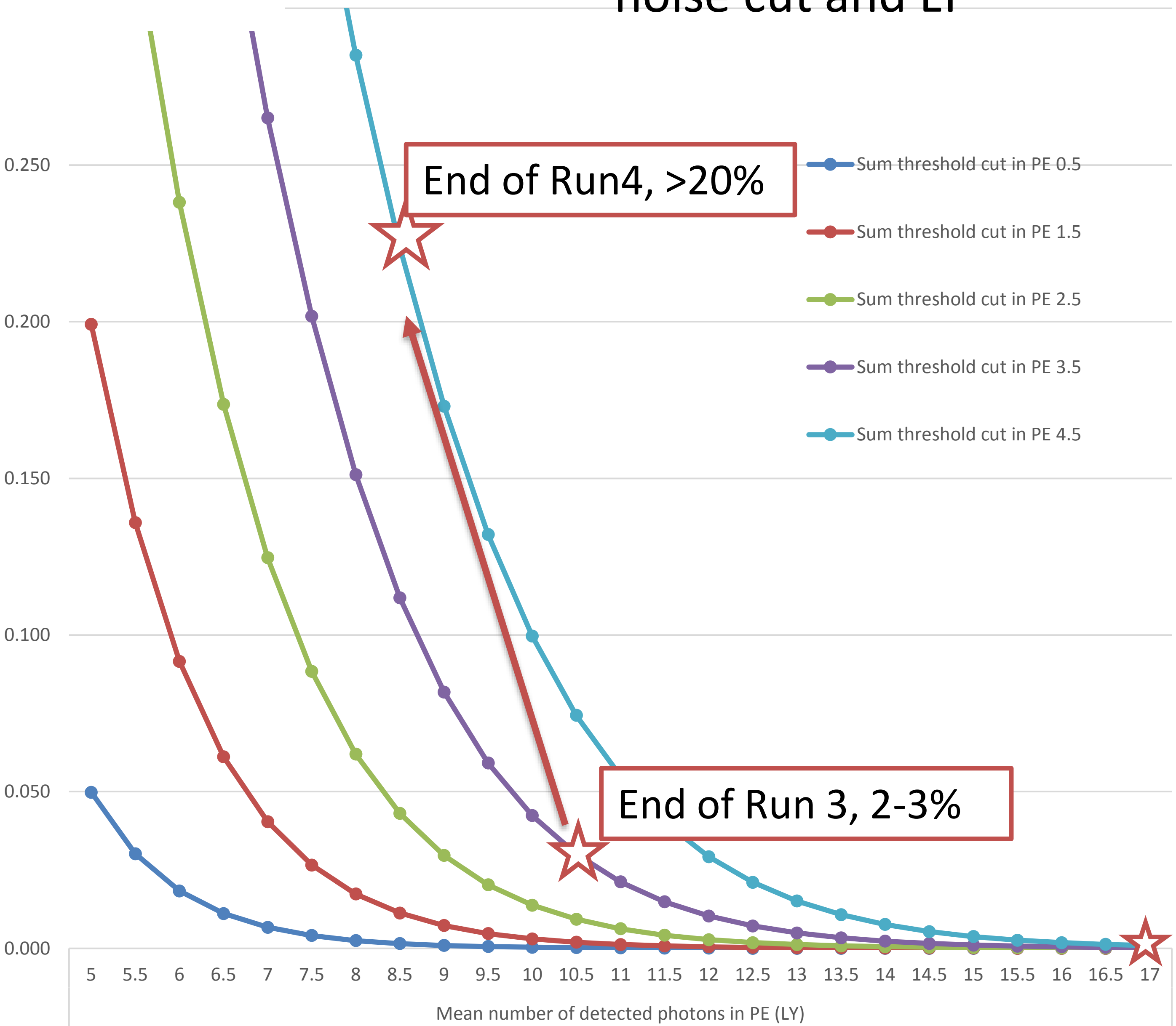
The selection at the production allows to obtain LY>18PE before irradiation

Cutting or "not using" 30cm of the inner-most part of the module

$$\frac{LY_{50fb^{-1}}}{LY_0} = \frac{12\text{PE}}{18\text{PE}} = 67\% \qquad \frac{LY_{100fb^{-1}}}{LY_0} = \frac{8.5\text{PE}}{18\text{PE}} = 47\%$$



Inefficiency as a function of noise cut and LY



Micro-lens enhanced SiPMs

Goal 1: Reduce pixel size without loosing light to reduce:

- optical x-talk
- gain and therefore bias current and self heating
- recovery time (dead time) and after-pulsing
- DCR for irradiated devices

Goal 2: Improve sensitivity (PDE)

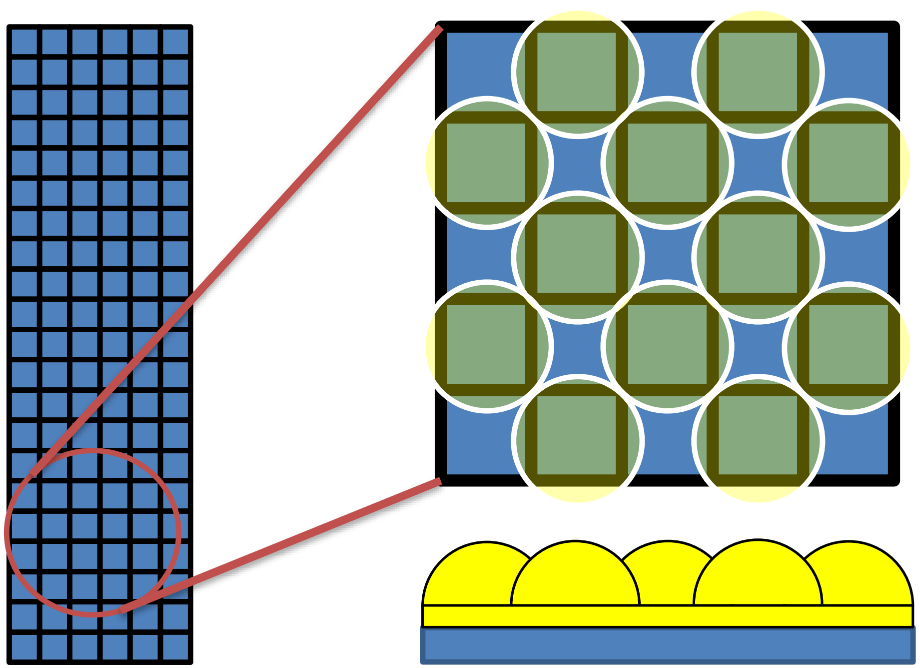
- use micro-lenses to focus light in the center of the pixel avoiding dead and low-field region

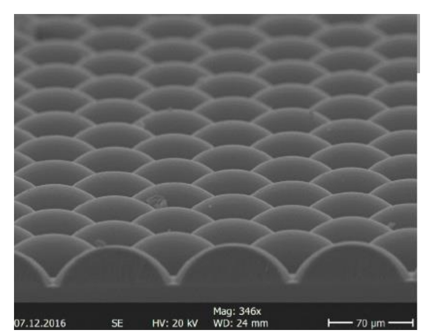
Pro:

- Expected improvement of the LY is larger than 20%
- Same detector geometry and package size as current SiPM array

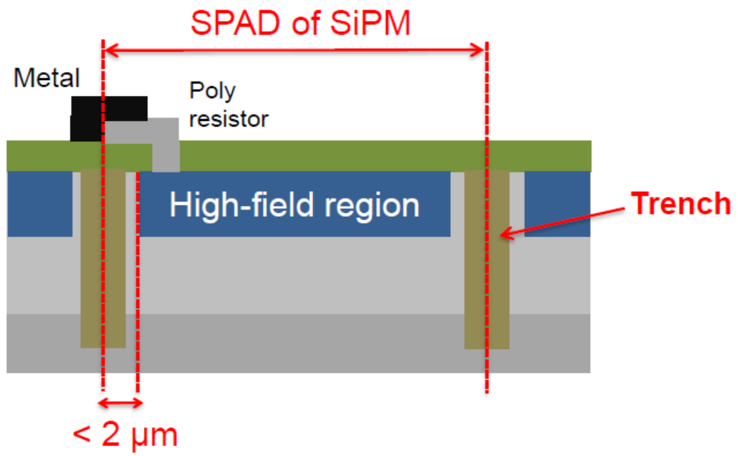
Cons:

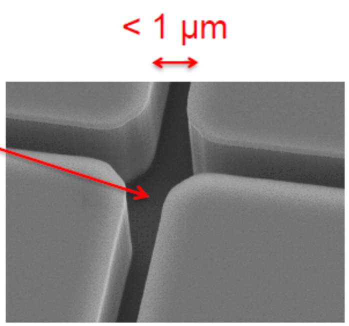
- High cost for micro-lenses and through silicon via (TSV) package
- No cleaning possible anymore

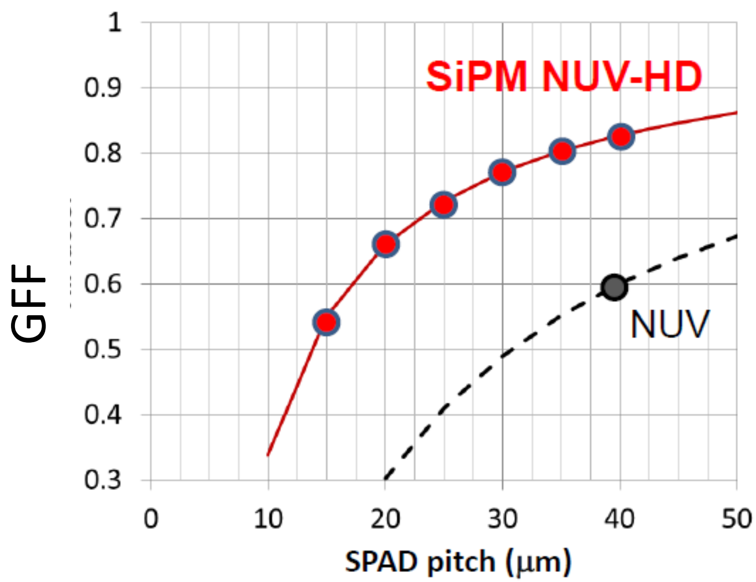




Higher GFF technology between 2017 and now







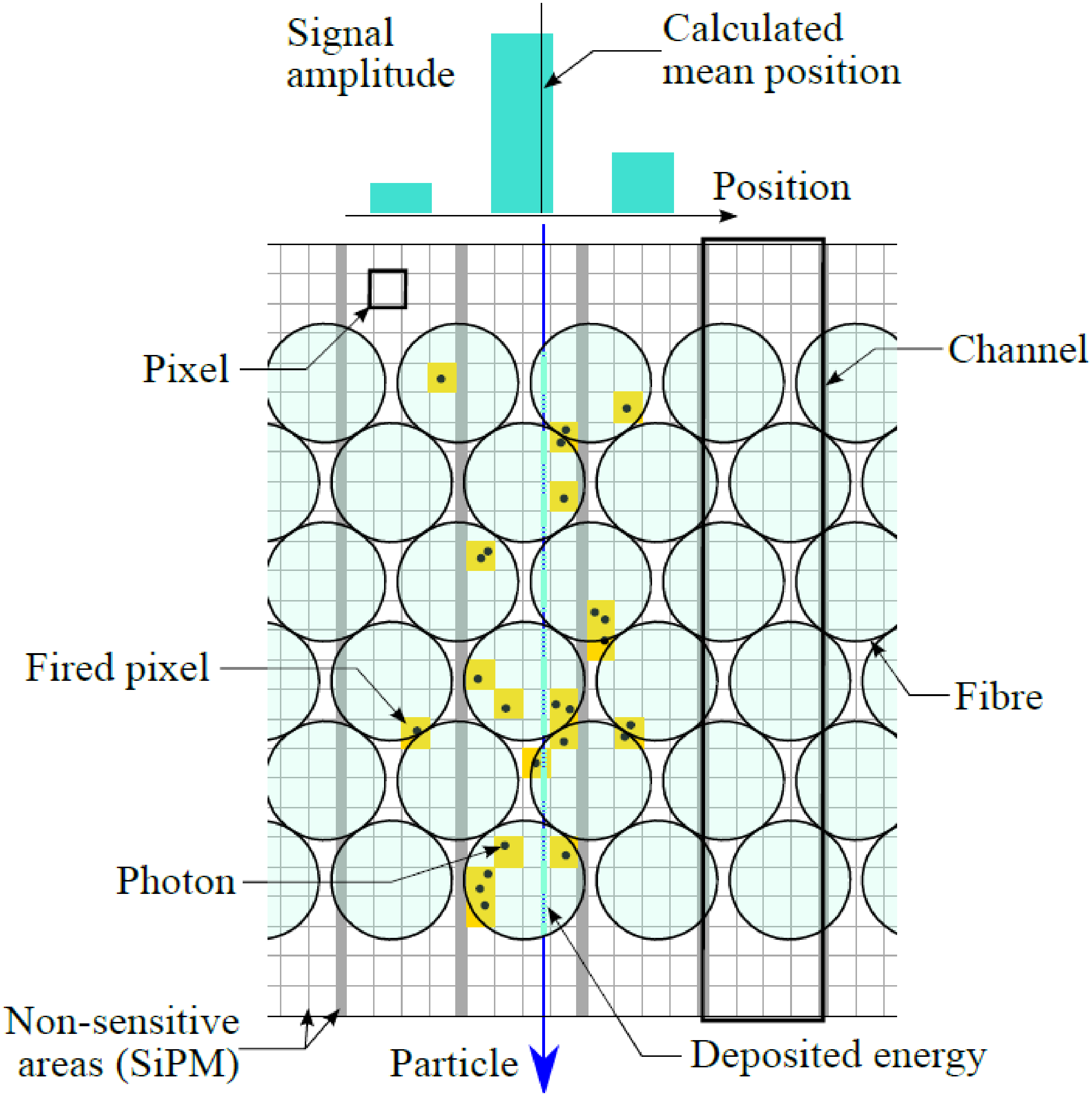
Implementation example from FBK: High geometrical fill factor (GFF) due to thin trenches, NUV-HD has 20% higher GFF than the previous NUV design.

Comparison with H2017:

GFF=70% for H2017 62x57.5µm^2 vs
GFF>80% for FBK 40x40µm^2

EPFL

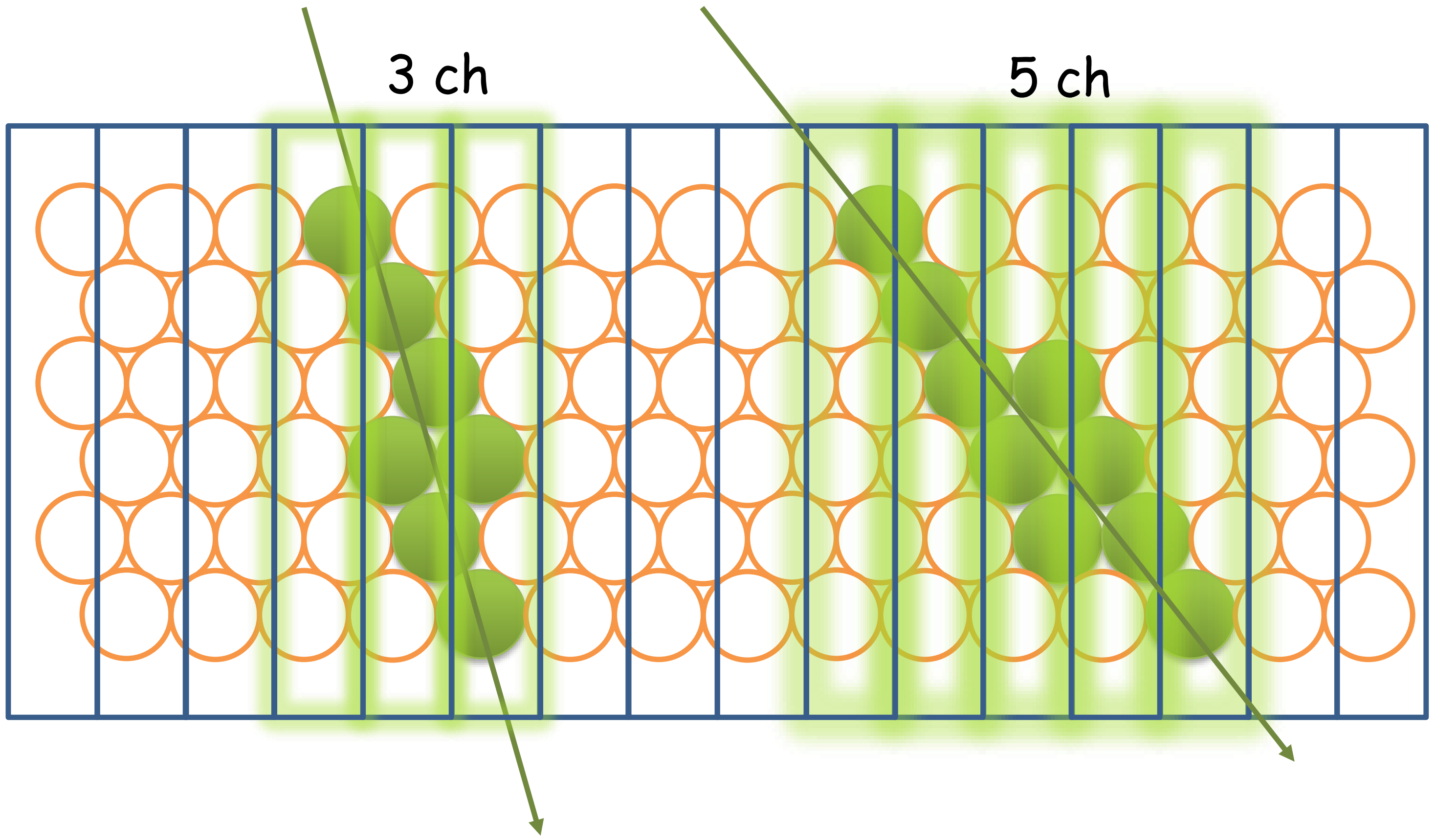
Reducing occupancy



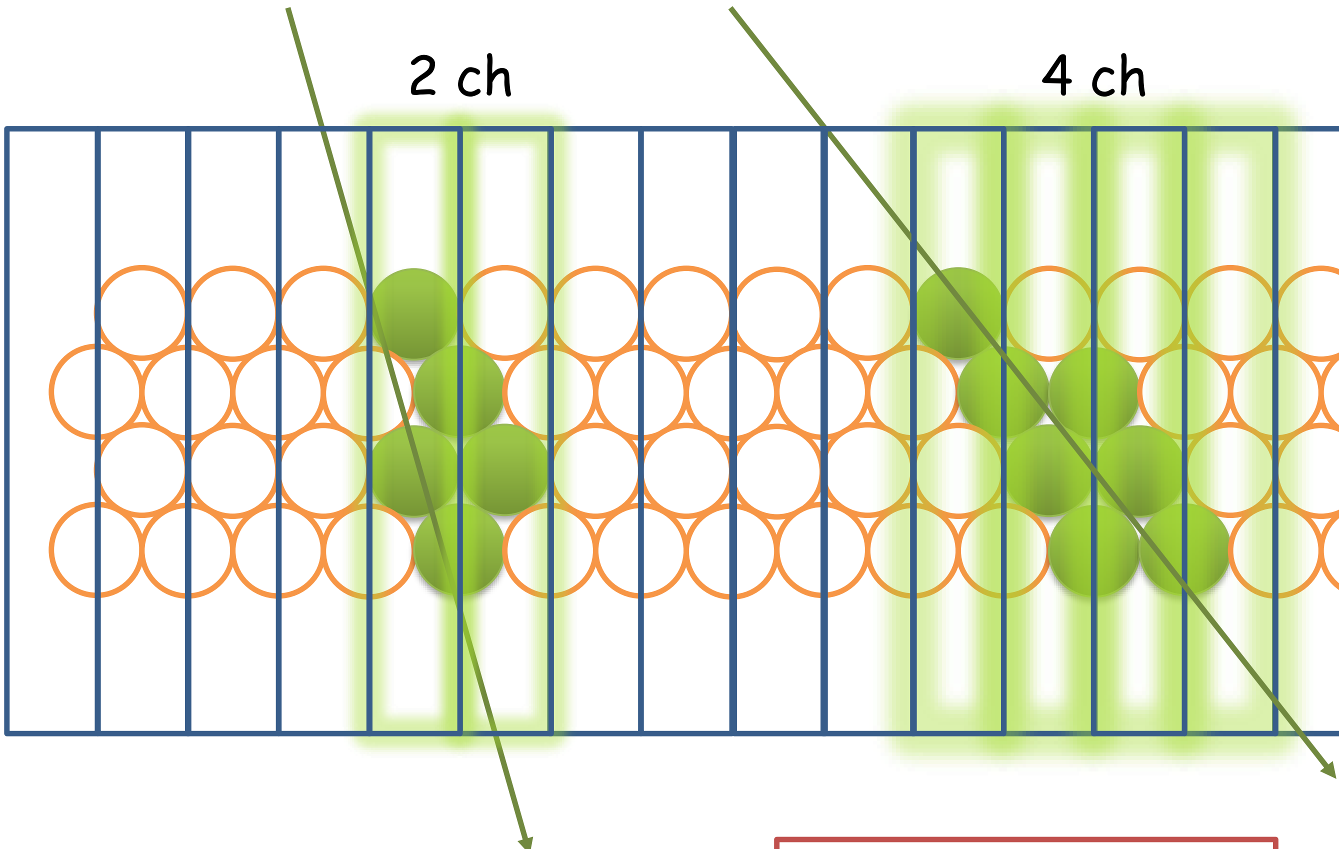
Typical cluster for an orthogonal track has a size of 3 channels.

Maximum occupancy depends not only on the number of tracks per linear distance but also on the cluster size.

Reducing occupancy

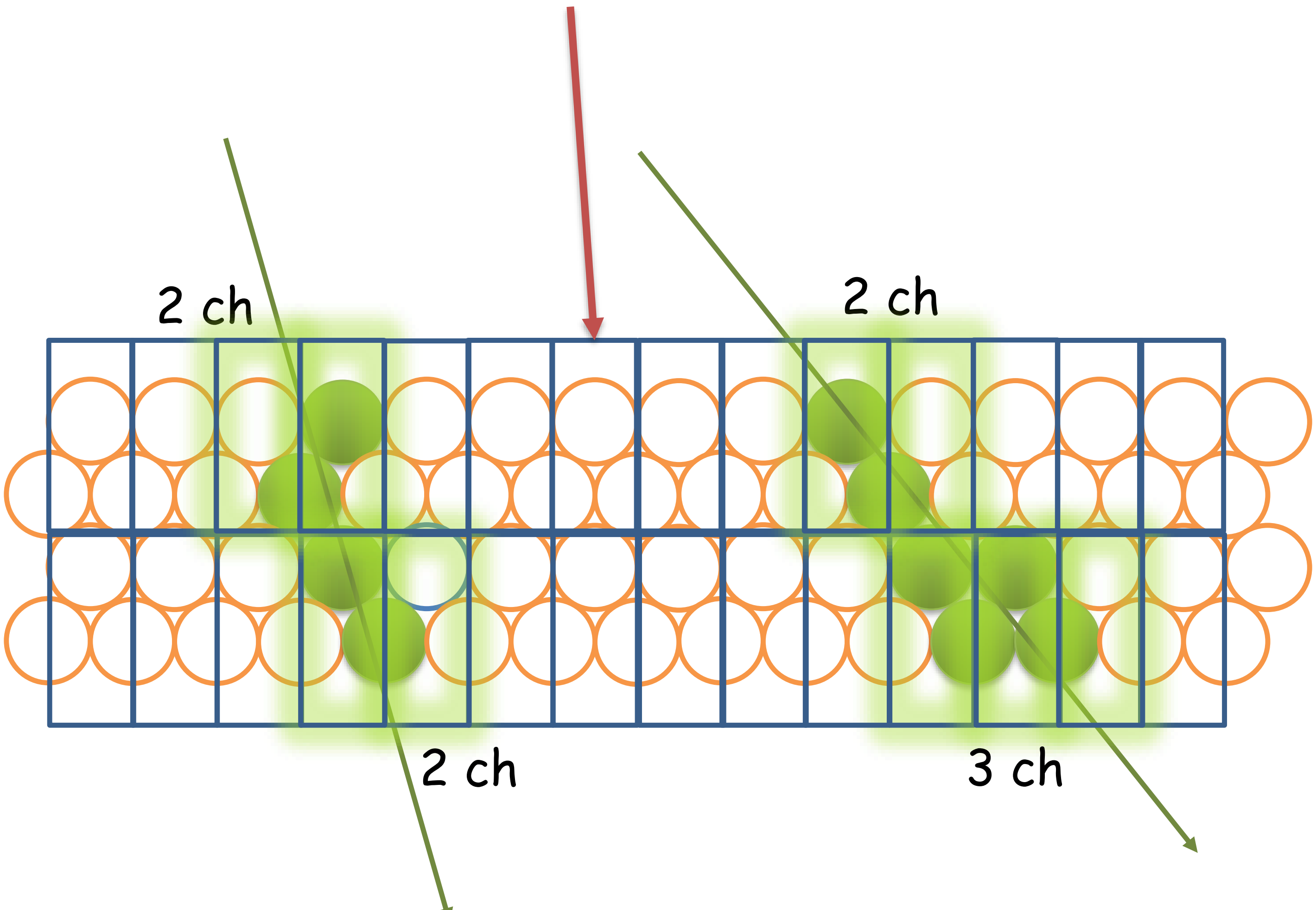


Reducing occupancy with thinner SciFi mats (less layers = less signal)



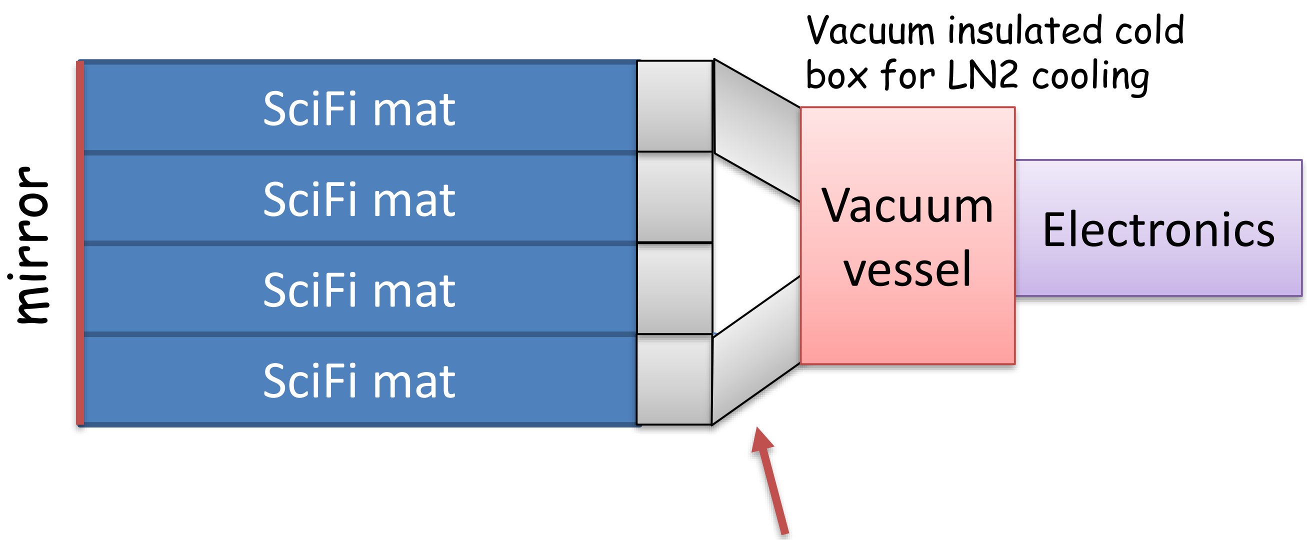
Less light, this can work with cryogenic cooling!

Reducing occupancy with thinner SciFi mats and or segmenting channels in height



Requires 2x the number of channels, this will be simulated for evaluation.

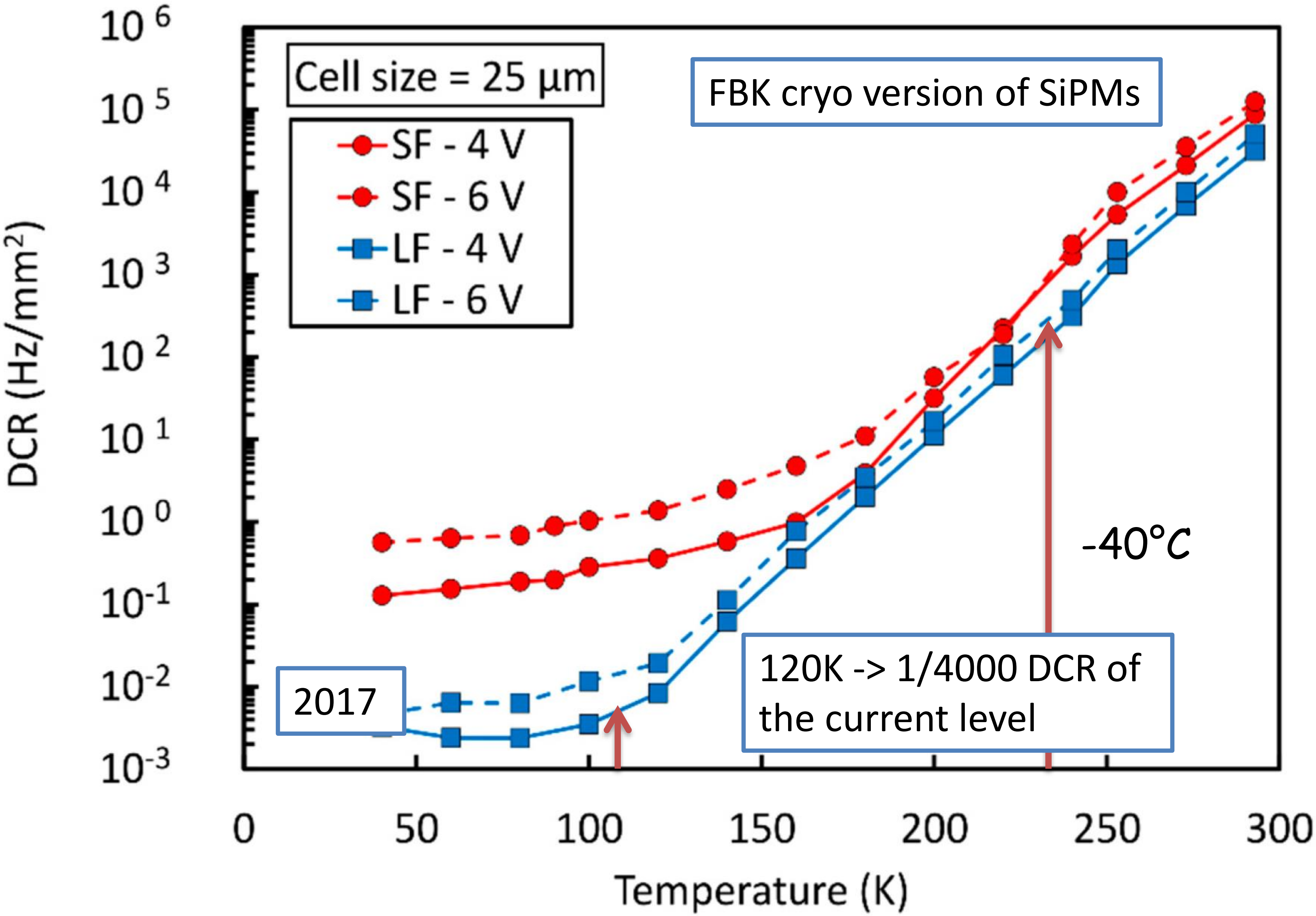
Reducing noise drastically with cryogenic cooling (LN2) in a vacuum chamber



Note:

- Flexible interface with clear fibre, expected light loss <15%
- Total width of vacuum vessel allows space between modules. Sufficient space for services for the Si-pixel detector is available
- Vacuum feedthrough with clear fibres

Reducing noise drastically with cryogenic cooling (LN2) in a vacuum chamber



Reducing noise drastically with cryogenic cooling (LN2) in a vacuum chamber

Noise reduction for FBK SiPMs optimized for cryogenic operation:

- pessimistic assumption for noise reduction slope (10K instead of 8K for a factor 2)
- Limited range of valid slope
- Upgrade II conditions, 10 x radiation level $6*10^{12}$ n_{eq}/cm^2 of current Upgrade
- 5x higher DCR than Hamamatsu for the same neutron fluence

⇒ Cryocooling allows to reduce DCR to a level of $5*10^7$ Hz per SiPM array
⇒ Noise cut is as low as 1.5PE producing less NCR than for the current detector

Cryogenic cooling is currently the only solution to operate the SciFi tracker beyond Run 4! It can compensate for the reduction of LY due to the fibre irradiation.

Conclusion

- Large uncertainties for radiation level simulated by Fluka (Factor 2), neutron shield and neutron fluence.
- Uncertainties for efficiency are large when the LY is close to 10 photons, steep rise
- Uncertainties in LY from the fibre module at large irradiation level, annealing and aging of scintillator

We need to operate the detector to gain detailed knowledge

Upgrade 1b:

Optimistic scenario:

- Replace the 12 0° central modules (6 layers) with Si-pixel + SciFi modules.
- Keep fibre modules with 5° angles without exchange of fibres
- Replace SiPMs for all 24 central modules after Run 3 (avoid 80fb^{-1} of radiation for central SiPMs)
- Develop and produce advanced micro-lens enhanced SiPMs for this replacement

Pessimistic scenario:

- All replacements needed for the optimistic case plus replacing also the 5° central fibre modules

Upgrade 2:

- Replace all modules and SiPMs
- Replace cooling with cryogenic LN2 cooling and develop a clear fibre interface

EPFL and Upgrade 1b,2

- Development of radiation optimized SiPMs
  - Study optical focusing system on pixels with micro-lens to increase overall PDE.
  - Study more radiation hard SiPM implementations (silicon structures) and the use of smaller pixels (Hamamatsu, Ketek, FBK, SensL, …).
- Development of a clear fibre interface required for cryogenic cooling (vacuum feedthrough) and to reduce SciFi length for segmented readout.
- Development of fast, high light yield, green fibres to reduce light transport loss (radiation) with possible application in LHCb SciFi Upgrade 1b or II.

Backup S/N

- Reduced hit detection efficiency is the "aging" effect of the SciFi and is directly coupled to the S/N ratio.
- For 50 fb^{-1} a reduction of efficiency of 1-2% is expected. Precise numbers are difficult to obtain before a few years of operation.