The Scintillating Fibre Tracker for the LHCb Upgrade

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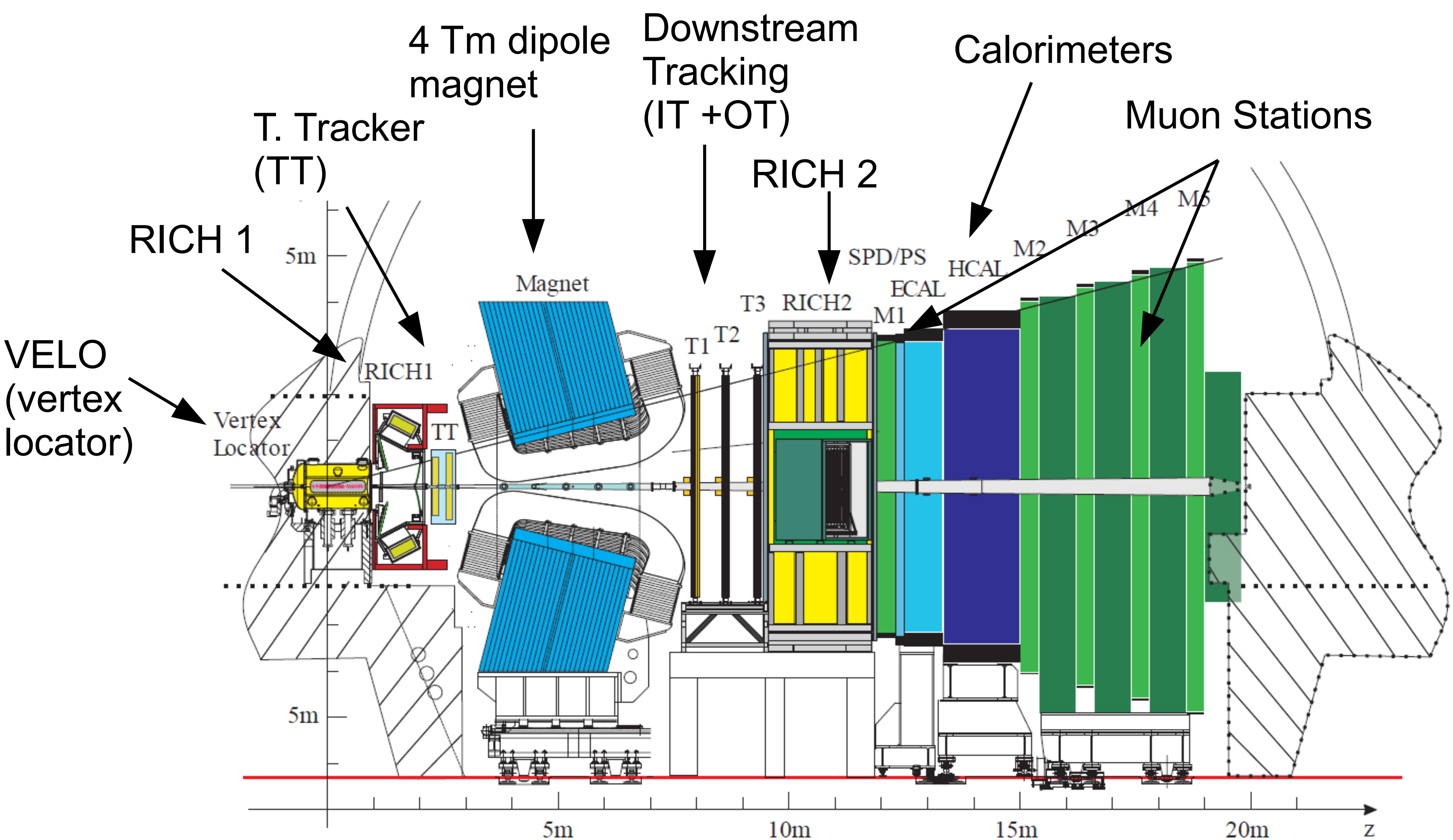
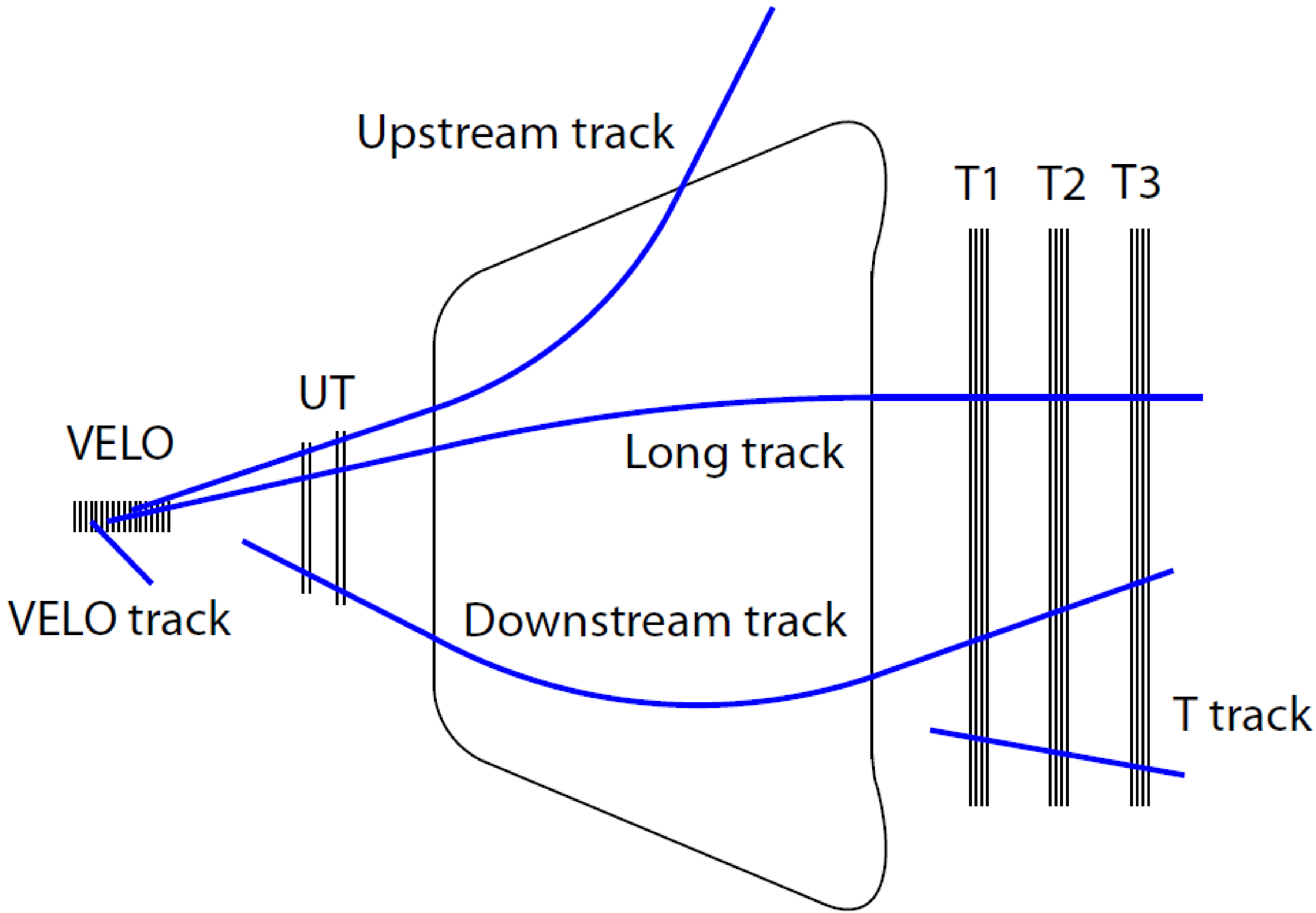
- Overview of the current LHCb and the LHCb Upgrade
- The SciFi Tracker
  - Scintillating Fibres
  - Fibre Mats and Modules
  - Silicon Photomultipliers in the SciFi
    - A little bit of electronics

- Single-arm forward spectrometer designed to search for new physics through measuring CP violation and rare decays of heavy flavor mesons



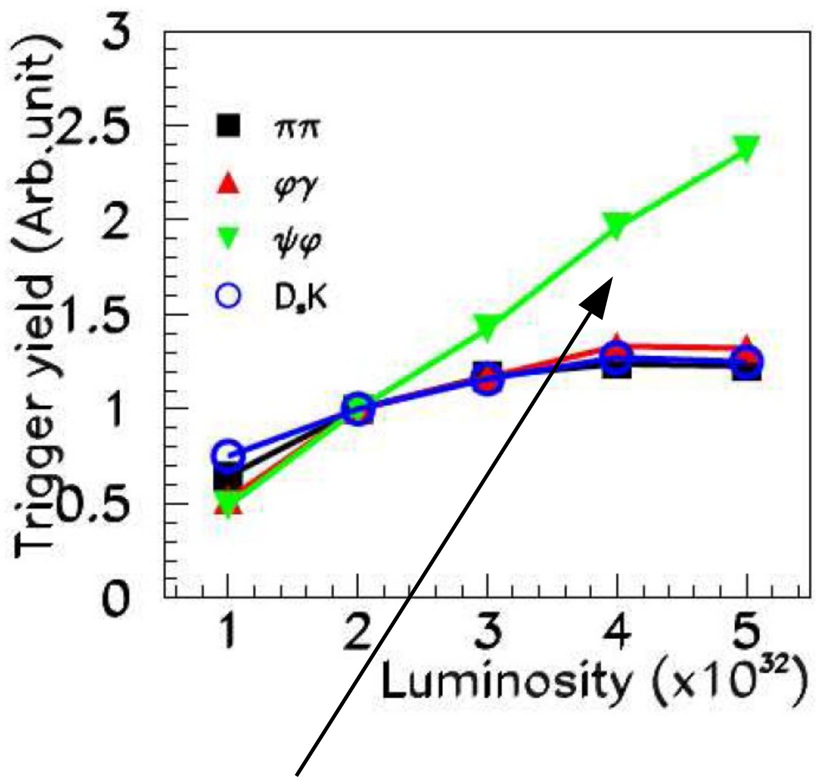

Upstream track
T1
T2
T3
UT
VELO
Long track
VELO track
Downstream track
T track

- Physic motivation:
  - Core flavour physics program to search for rare decays, such as $\mathbf{B^0_s \rightarrow \mu\mu}$ (Beyond the SM searches)
  - Evidence of matter-antimatter asymmetries in charm sector and B^0_s decays
  - Search for CP violation in charm sector
  - Constraints on γ(~4°) of the Unitarity Triangle

- Total data: 0.3 fb^{-1} (2010) + 1 fb^{-1} (2011) + 2fb^{-1} (2012) + 4-6 fb^{-1} (2015-17)
- Interactions per bunch crossing ν = 1.5
- Maximum Int. Luminosity of 4 x $10^{32} cm^{-2} s^{-1}$ (twice the design value)
- L0 hardware trigger with cuts on E_T and P_T in muon and calorimeters
- 1 MHz readout rate

- Physics:
  - Improved statistics would reduce uncertainties in some channels near to SM predictions (i.e. $B^0_s \rightarrow \mu\mu$ = 0.19; Theory = 0.3)
  - Improved sensitivities on β (0.8º → 0.3º) and γ (4 → 1º) in Unitarity Triangle
  - the sample sizes in most exclusive B and D final states will be far larger than those that will be collected elsewhere, for example at the upgraded e+e-B factories. The LHCb upgrade will have no serious competition in its study of B^0_s decays and CP violation. Also, charmed with charged tracks.
- LHCb-PUB-2013-015 ”Updated sensitivity projections for the LHCb Upgrade”

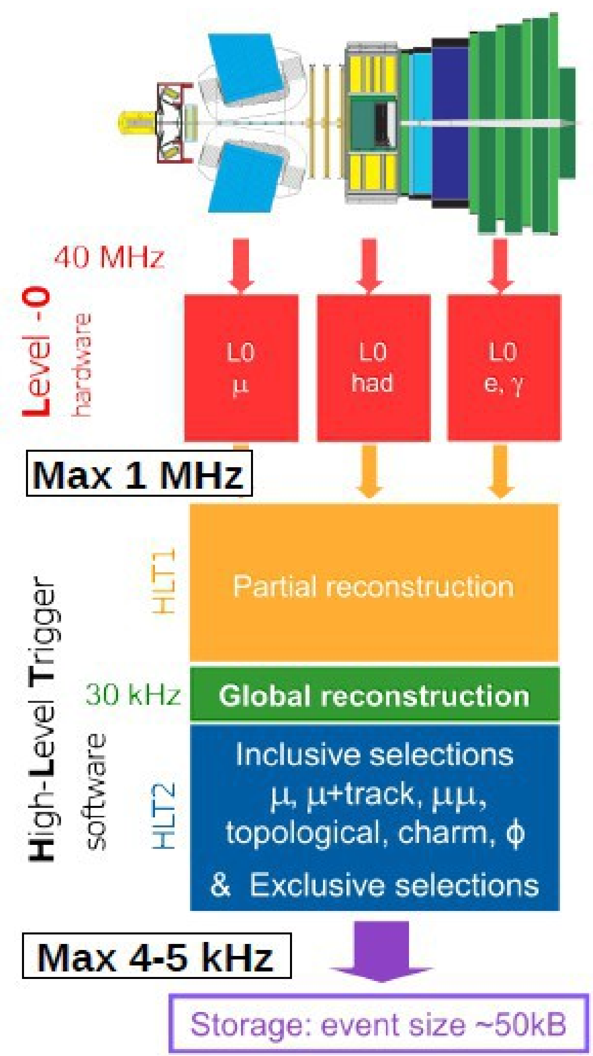
- It has been shown the detector could run up to a luminosity of 10^{33} $cm^{-2}s^{-1}$, but...
  - L0 hardware cut requires ever increasing E_T for hadrons, muons, electrons and photons
  - high efficiencies on dimuon events, but removes larger fraction of hadronic decays and B meson mass (signal)



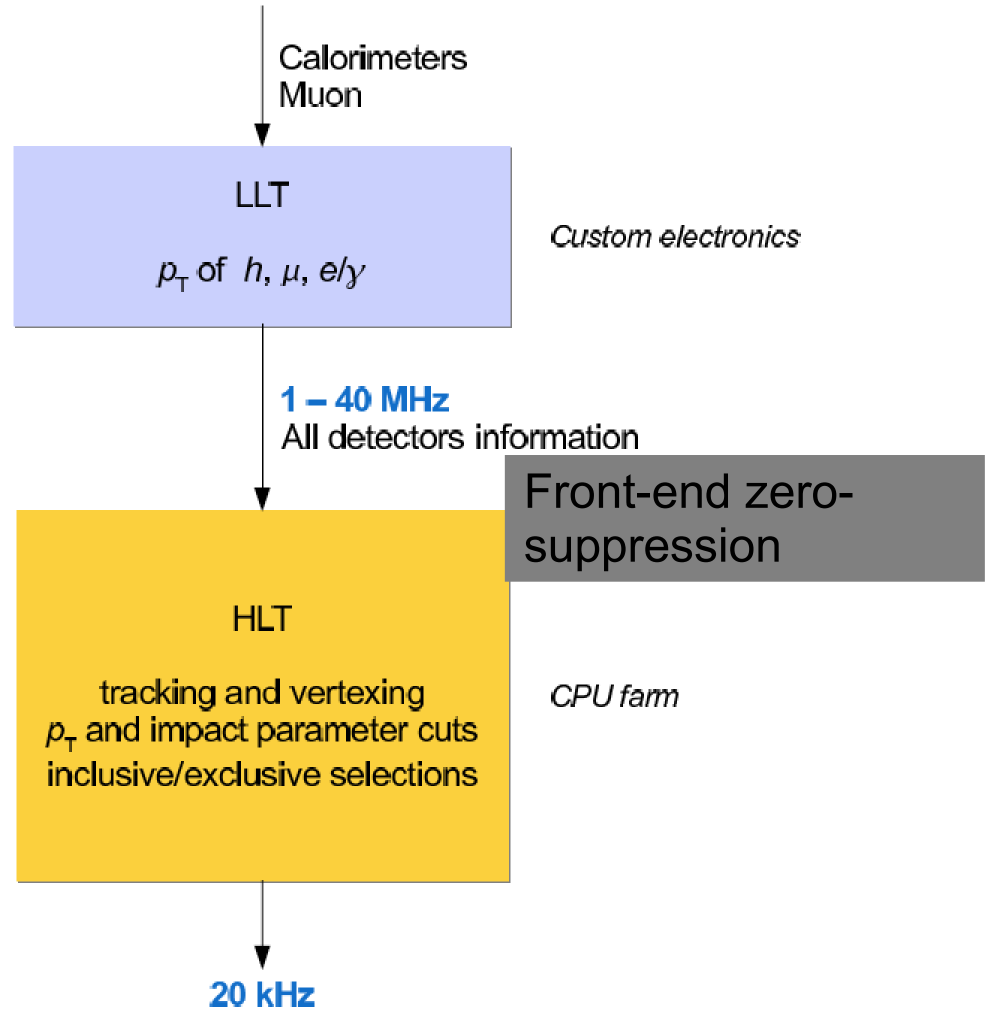
Saturation with L0-hardware trigger

- Remove the L0-hardware trigger, and replace with a flexible software trigger and analyse each event in a trigger system
  - Needs a fast tracking system for fast pattern recognition
  - the yield of hadronic B decays increases by up to a factor of 7-10 for the same LHC machine run-time. > factor 20 for heavy-flavour decays to hadronic final states
- Increased luminosity of 1 – 2 x 10^{33} $cm^{-2}s^{-1}$ (not tied to LHC luminosity upgrade);
- Interactions per bunch crossing ν = 3.6 – 7.2
- To accomplish this we must:
  - Upgrade all the front-end readout electronics from 1MHz to 40 MHz
  - Upgrades certain detectors to improve tracking and sustain the increased luminosity
- ~5 fb^{-1} / year after the upgrade in LS2(2018-19), 50 fb^{-1} total
- A full description of the LHCb Upgrade plans can be found in the Letter of Intent (LoI) (CERN-LHCC-2011-001) and the Framework-TDR (CERN-LHCC-2012-007); all detector TDRs have been submitted from Nov. 2013 to February 2014

Current Trigger Scheme



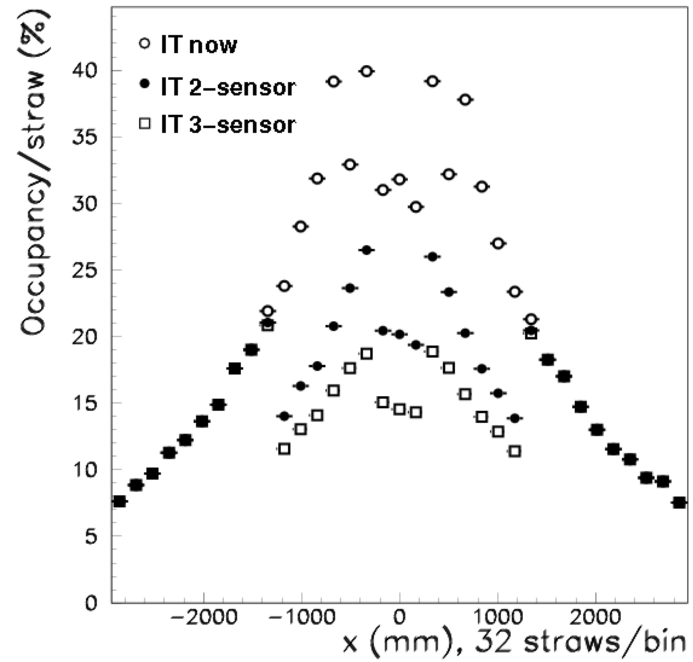
Upgrade Trigger Scheme

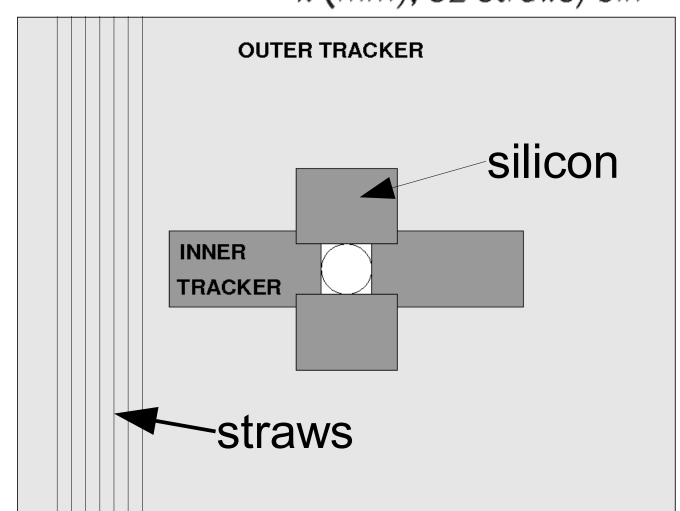


10 Gbits/s to the farm
- Event selection in the farm

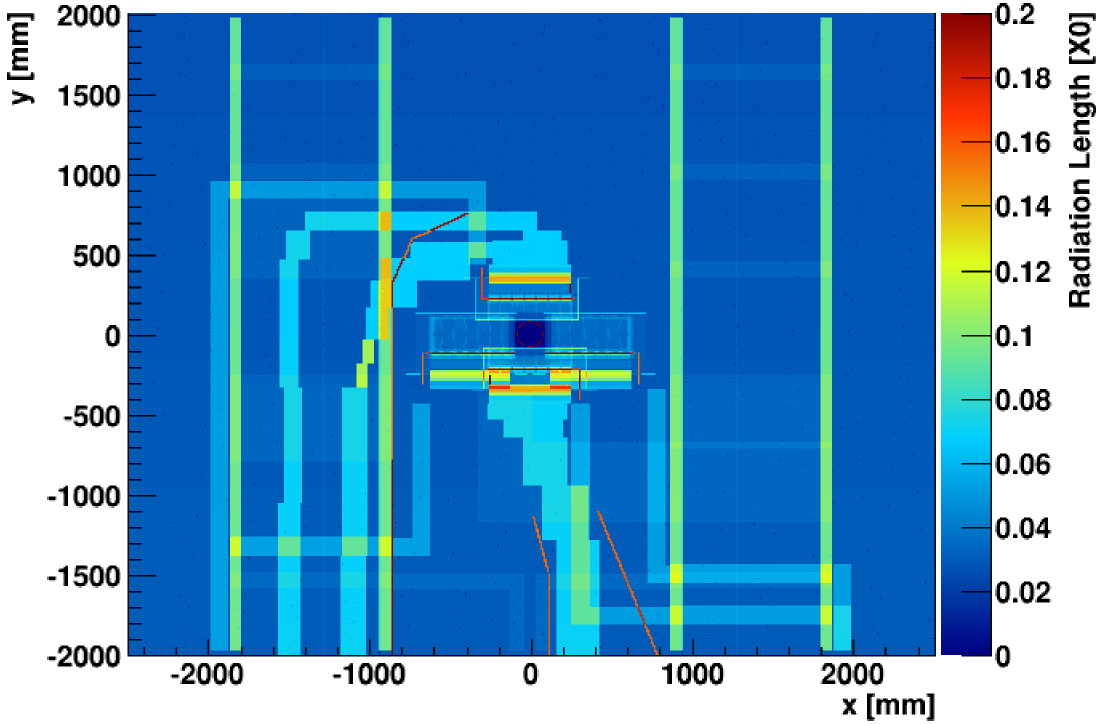
- **VeLo** → **VeLoPix** @ 40MHz
  - 55 x 55 um^2 pixels; The VELO reconstruction is fast enough to allow a full 3D pattern recognition in HLT.
- **TT** → **UT** (tracker) @ 40MHz
  - 4 planes of silicon strip detectors (X-U-V-X) at 5º; Improved small angle acceptance, less material (<4.5% X_0) .
- **RICH/PID** Upgrade
  - Replace integrated HPD(pixel) and readout electronics (1 MHz) with MA-PMT @ 40MHz; similar granularity.
  - Remove the aerogel from RICH-1 due to occupancy (sacrifice some low momentum resolution); only C4F10; RICH-2 stays as CF4.
- **Calorimeter** electronics → 40 MHz
  - Scintillating Pad Detector (SPD) and the Preshower (PRS), lead absorber will be removed. Lose some e/gamma PID power
- **Muon Stations**: Front-end is already 40MHz to L0 trigger; switch to LLT; Remove M1 station since it won't contribute, M2 – 5 remain.

- Replace with 40MHz front-end electronics
- Occupancy in the OT becomes too large due to secondaries from the IT structure (40% with current IT at 2x10^33cm-2s-1)
  - OT is 5mm straw drift tubes
  - OT can handle ~25% occupancy
- Either replace make the new IT larger (4x area) and reduce the OT (rebuild 96 5m straw modules)
- Reduce the IT detector material (lots of cables and cooling infrastructure in the acceptance)
- Averaged over the T-stations, a particle sees around 17.5% of a radiation length coming from the IT and OT material





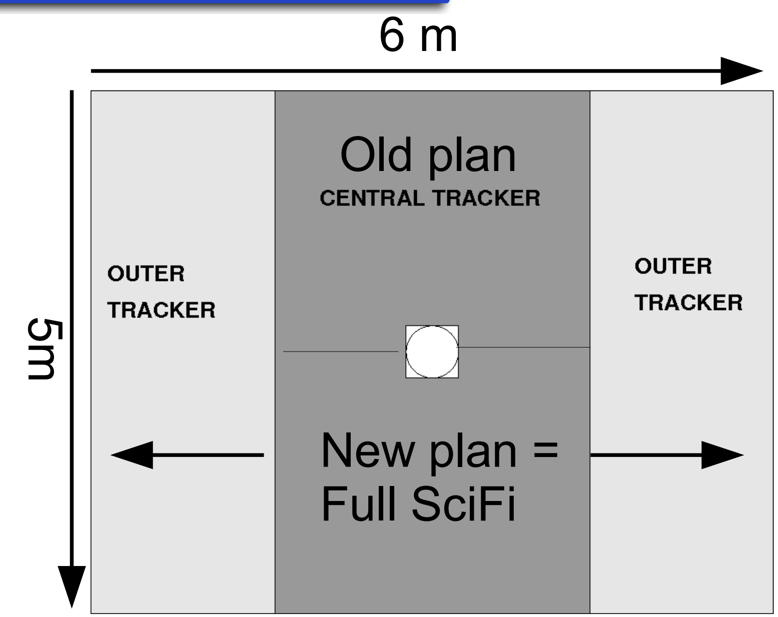
- Material in T1



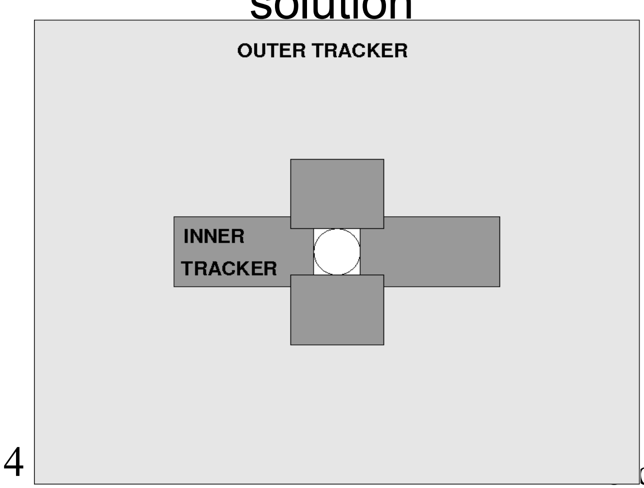
Particles averaged over eta and phi see 17.5% of X0 over 3 stations

- Replace with 40MHz front-end electronics
- Occupancy in the OT becomes too large due to secondaries from the IT structure (40% with current IT at 2x10^33cm-2s-1)
  - OT is 5mm straw drift tubes
  - OT can handle ~25% occupancy
- Either replace make the new IT larger (4x area) and reduce the OT (rebuild 96 5m straw modules)
- Reduce the IT detector material (lots of cables and cooling infrastructure in the acceptance)

- <u>OR</u> Replace everything with planes of thin scintillating fibres!

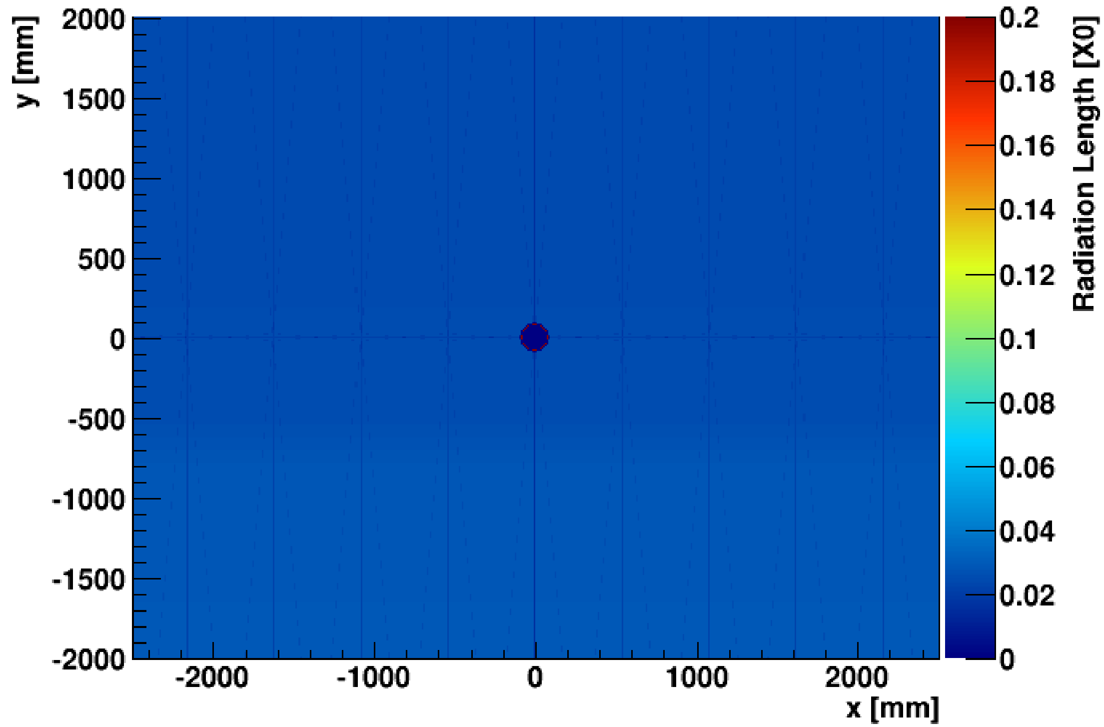


Large IT becomes backup solution



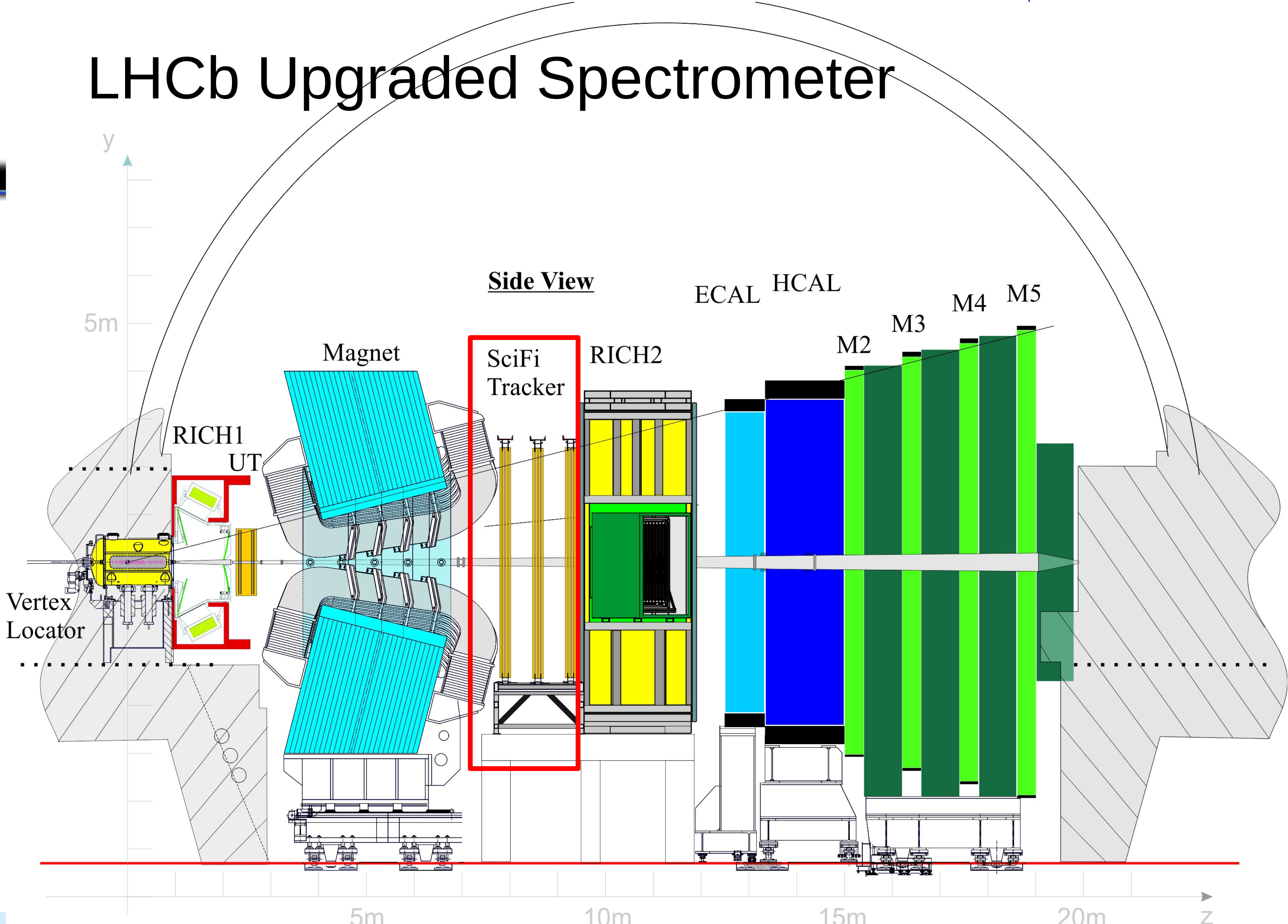
- SciFi material T1

A little too perfect, but close to reality



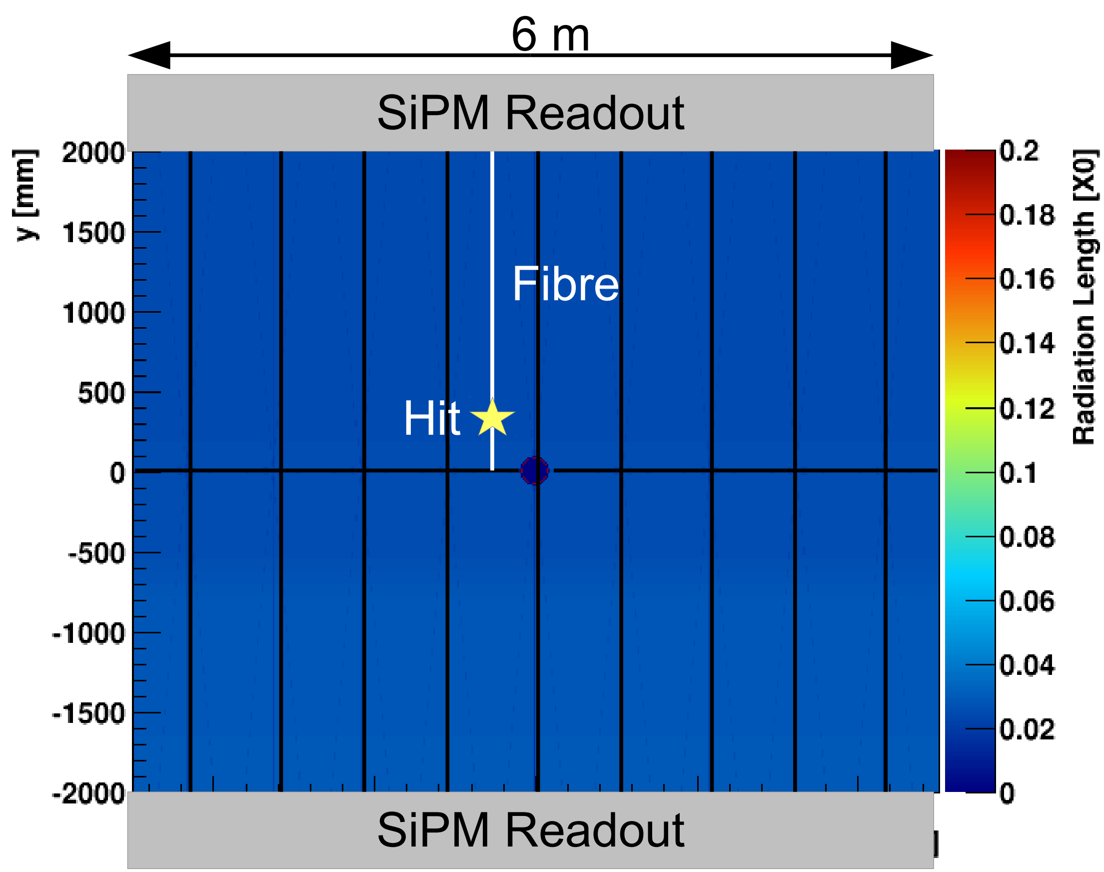
Particles averaged over eta and phi would see ~12% of X0 over 3 stations

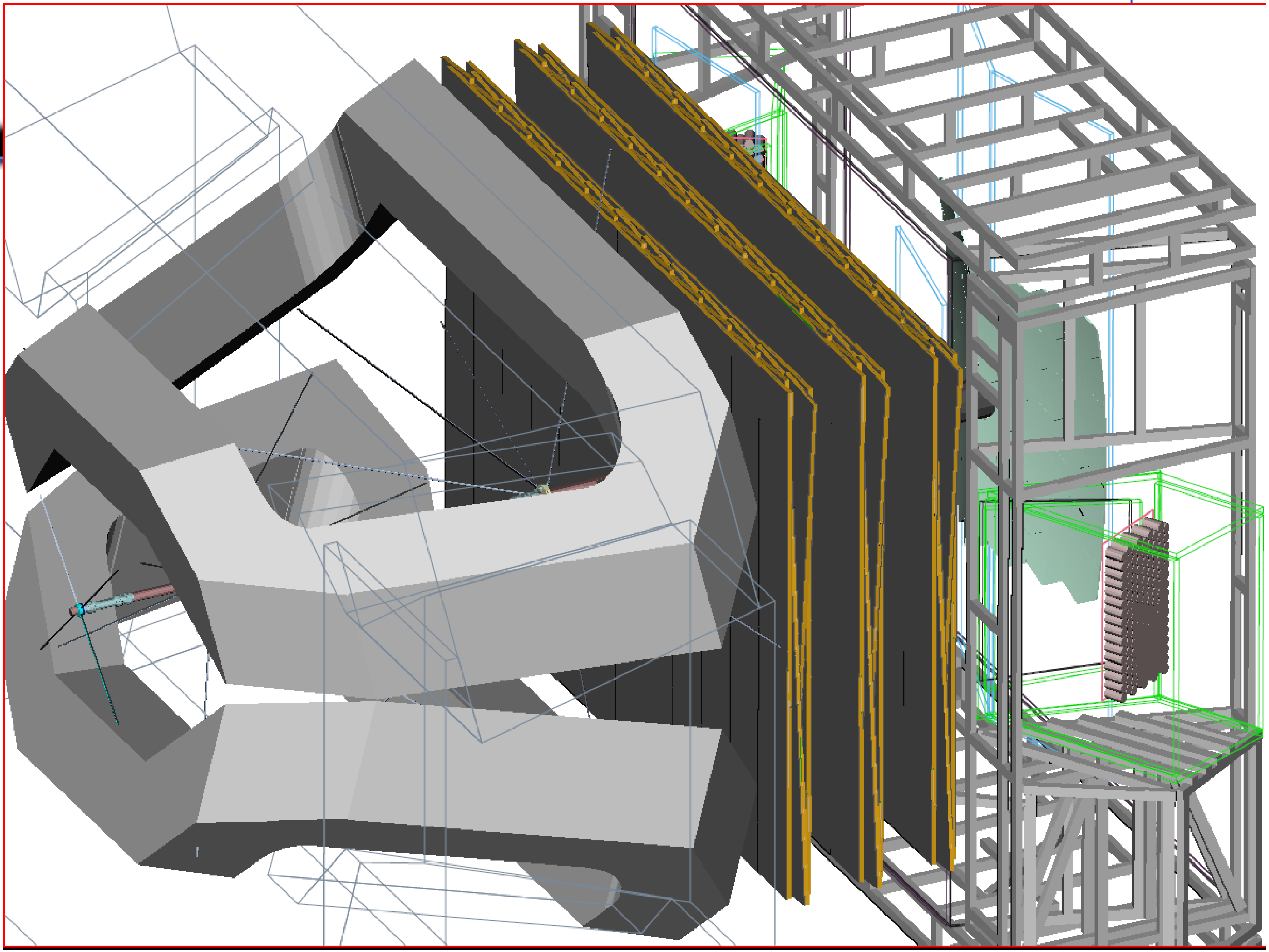
LHCb Upgraded Spectrometer



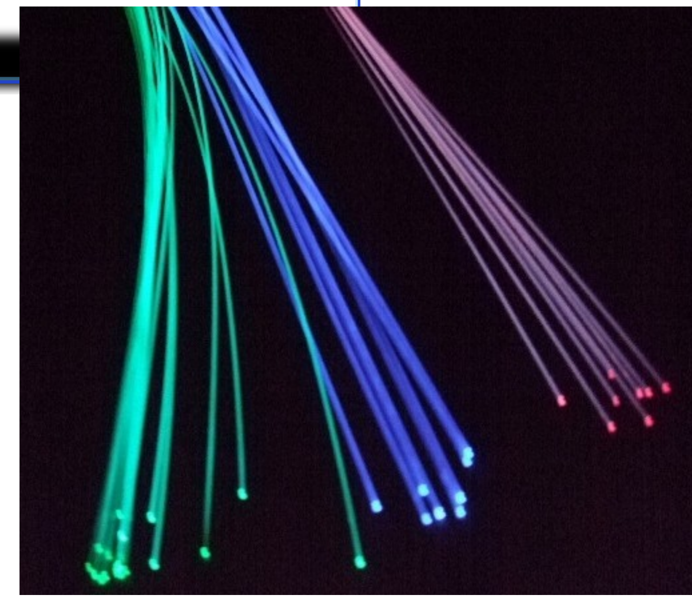
- Based on 2.5m long multilayer ribbons of 0.25mm diameter scintillating fibre with silicon photomultiplier readout
- Same X-U-V-X layer scheme as IT-OT; 12 layers total divided in 3 stations
- Reduced material budget (1 SciFi station <= 1 OT+IT station) evenly distributed
- Small fibre diameter and channel width (0.25mm) results in lower occupancy and good resolution
- ~65 um X-position resolution over the whole plane
  - OT = ~200um, IT~ 50um;
  - only needs to be <100 um in the middle
- A single fast detector covering 350m^2 with 560,000 readout channels (on-board hit position reconstruction)
- Requires developing new technology
  - no one has built a fibre tracker this large in this environment with this readout
  - **Not an off-the-shelf technology like silicon detectors**

- SciFi = fibre modules with SiPM readout

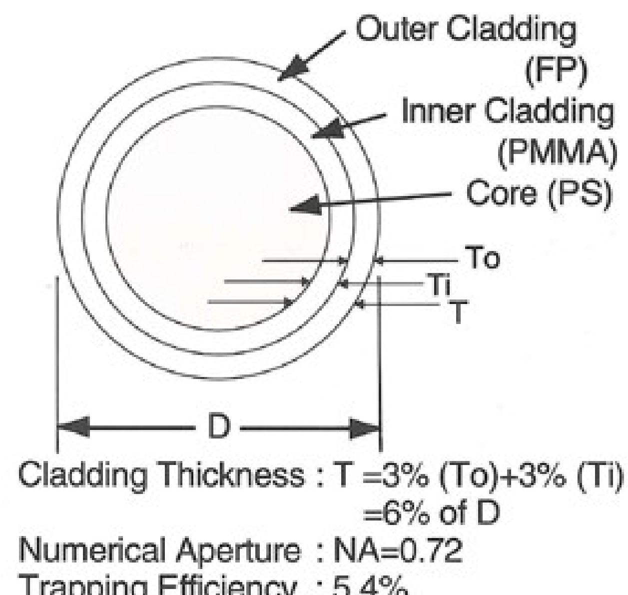




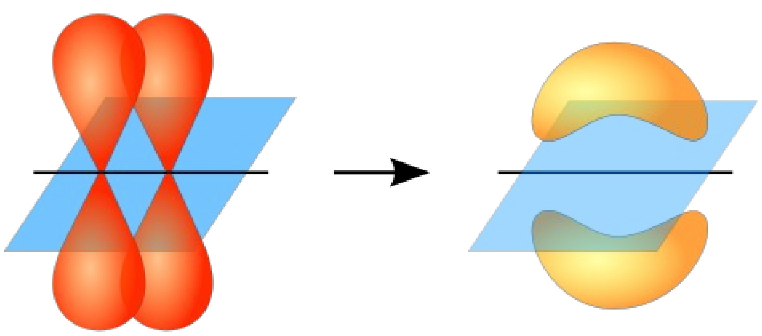
- Basic properties:
  - polystyrene core
  - Acrylic cladding (1 or 2) of lower indexes of refraction for light capture
  - Core doped with scintillating dyes for improved light yield and timing characteristics
  - 1-4m attenuation length
    - 3-4m for Kuraray SCSF-78MJ fibres
  - Signal decay time O(3-10 ns)
    - 2.8ns for Kuraray SCSF-78MJ fibres

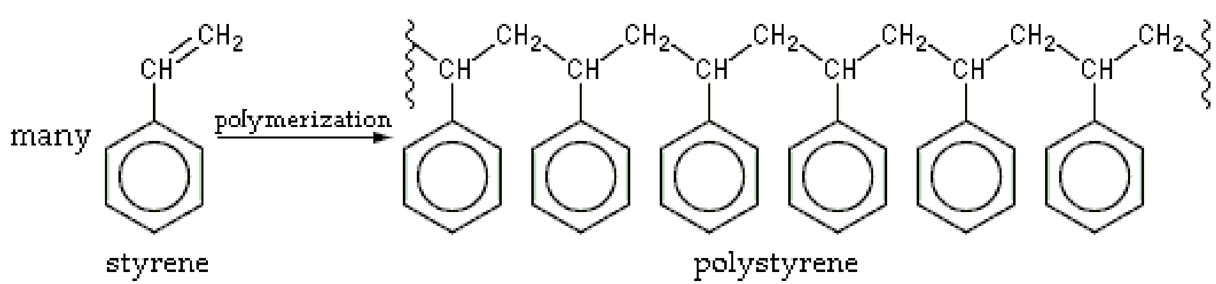


Images from Kuraray Co. Ltd.



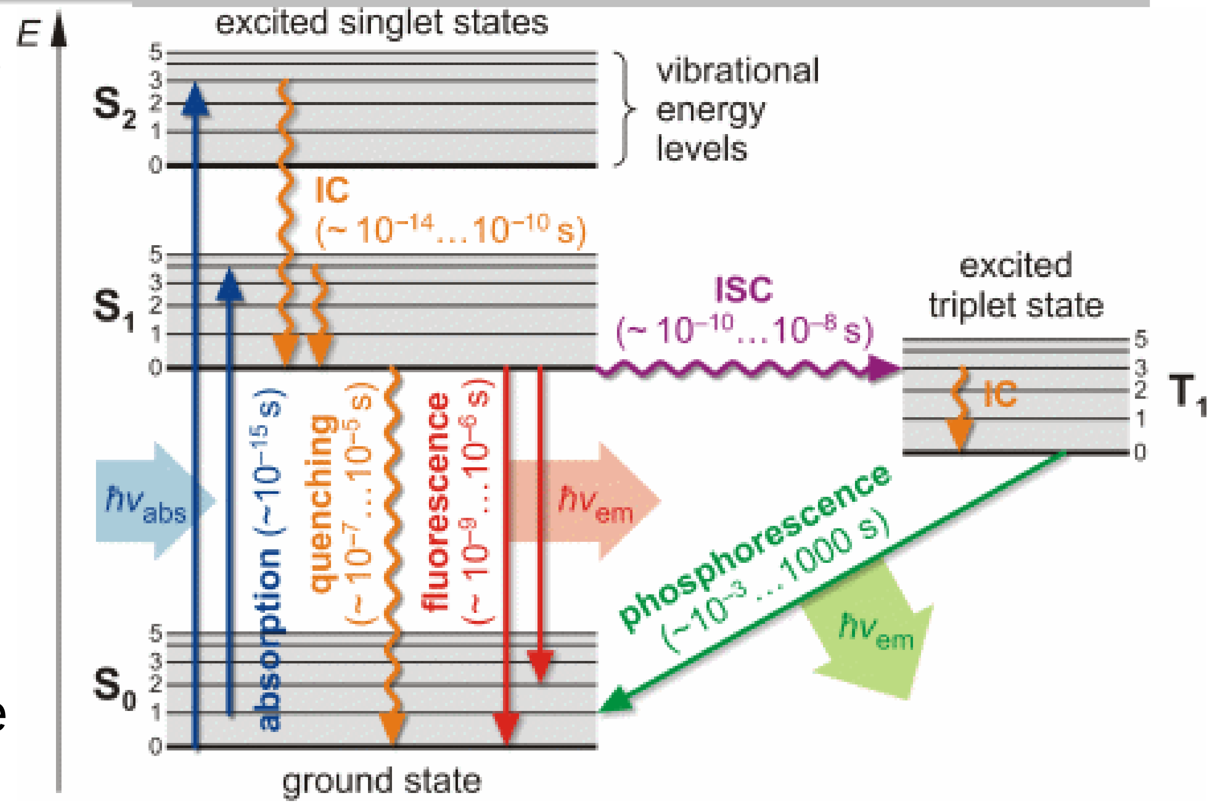
- Polystyrene, the base material of the fibre, is an organic scintillator
  - Scintillation light arises from Pi-orbitals of the benzene ring in aromatic polymers
  - Electrons are delocalised (weakly bonded)
- Charged particles leave ionization energy in the polystyrene base, exciting the electrons to higher energy states (few eV for first excitation)

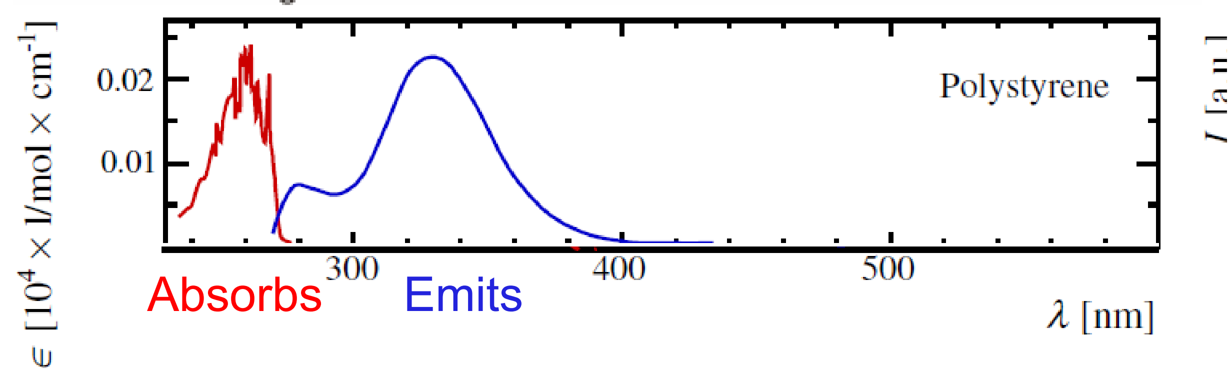




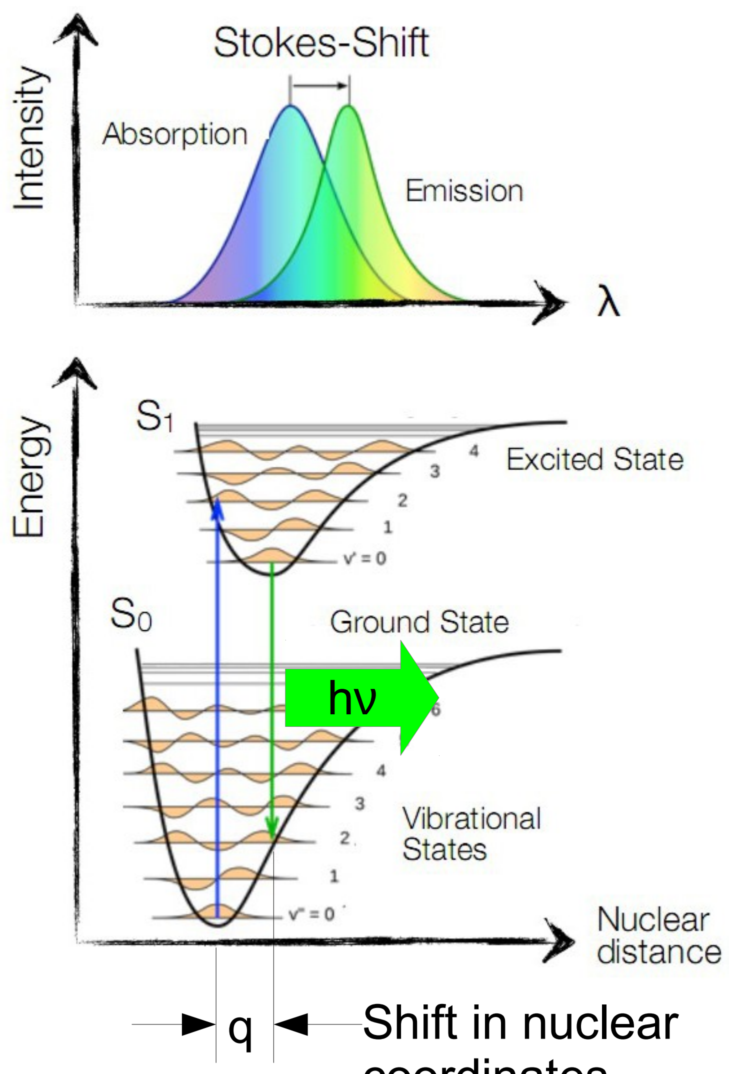
- However, the decay time for pure polystyrene is slow
  - τ =19.2 ns (500 ns radiative)
- Emits in the UV wavelength (~320nm) and is reabsorbed relatively quickly (<1cm)
- As a result of the **Franck-Condon principle** as well as inner non-radiative de-excitation (internal conversion), an increase of the wavelength of absorbed and emitted photon occurs (**Stokes shift**),
- Δλ = λem - λabs > 0

Jabolinski Diagram





- **Franck-Condon principle**
  - electronic transitions (excitation) are very rapid compared to motions of the nuclei of the molecule (τ =fs)
  - The probability that the molecule can end up in any particular vibrational level is proportional to the square of the (vertical) overlap of the vibrational wavefunctions of the original and final state.
  - electron configuration of the excited state may result in a shift of the equilibrium position of the nuclei constituting the molecule
  - In the electronic excited state molecules quickly relax to the lowest vibrational level $S_{1,n} \rightarrow S_{1,0}$ (τ = ps), and from there can decay to the lowest electronic state via photon emission $S_{1,0} \rightarrow S_{0,n}$(τ = ns).
  - transitions between vibrational sublevels ν=0 and ν=2 and ν=1→ν=0 are favoured over ν=0→ν=0



- Polystyrene (PS) alone also has terrible radiative quantum efficiency. The rate of **R**adiative and **N**on-**R**adiative (quenching) transfer for polystyrene is

$$q_R = \frac{k_R}{k_R + k_{NR}} = 0.038$$

$$k_R = 1.98 \times 10^6 s^{-1}$$

$$k_{NR} = 5.02 \times 10^7 s^{-1}$$

$$\tau_{PS} = \frac{1}{k_R + k_{NR}} = 19.2\, ns$$

J. PHYS. B (PROC. PHYS. SOC.), 1968, SER. 2, VOL. 1. PRINTED IN GREAT BRITAIN

Energy transfer in organic systems
VI. Fluorescence response functions and scintillation pulse shapes

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MS. received 29th April 1968

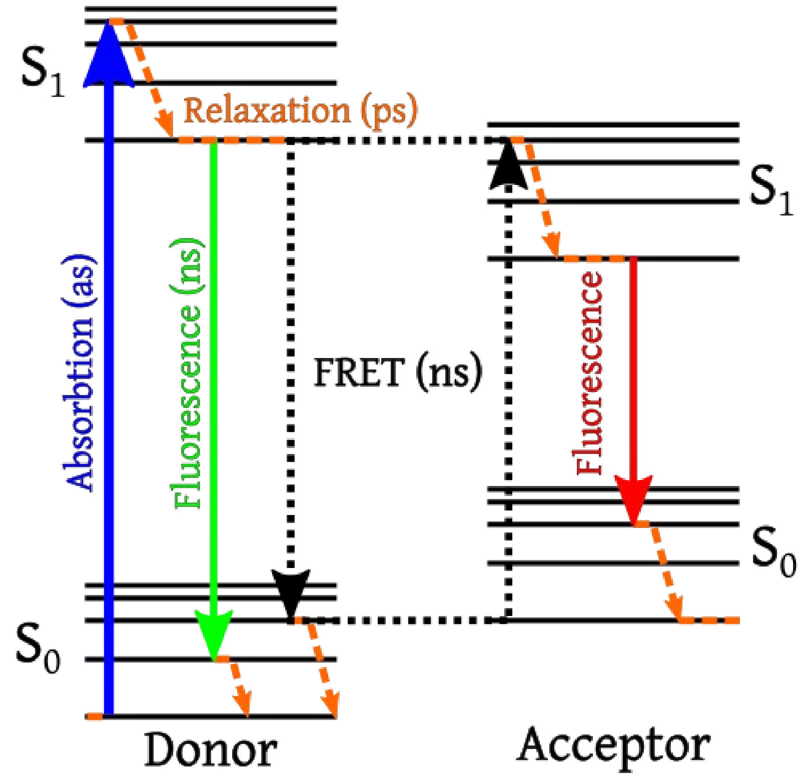
Zwischenmolekulare Energiewanderung und Fluoreszenz

Von Th. Förster

- However, one can add one or more additional solutes (organic scintillators) to compete for the energy transfer via **Förster Resonance Energy Transfer** (FRET)
- nonradiative dipole–dipole coupling between donor and acceptor molecule
- Transfer rate and efficiency is concentration dependent (maximize)

$$c \approx 10^{-3} \rightarrow 10^{-1} \, mol/l$$

$$k_T \approx 10^{9} \rightarrow 10^{10} \, l \, mol^{-1} \, sec^{-1}$$

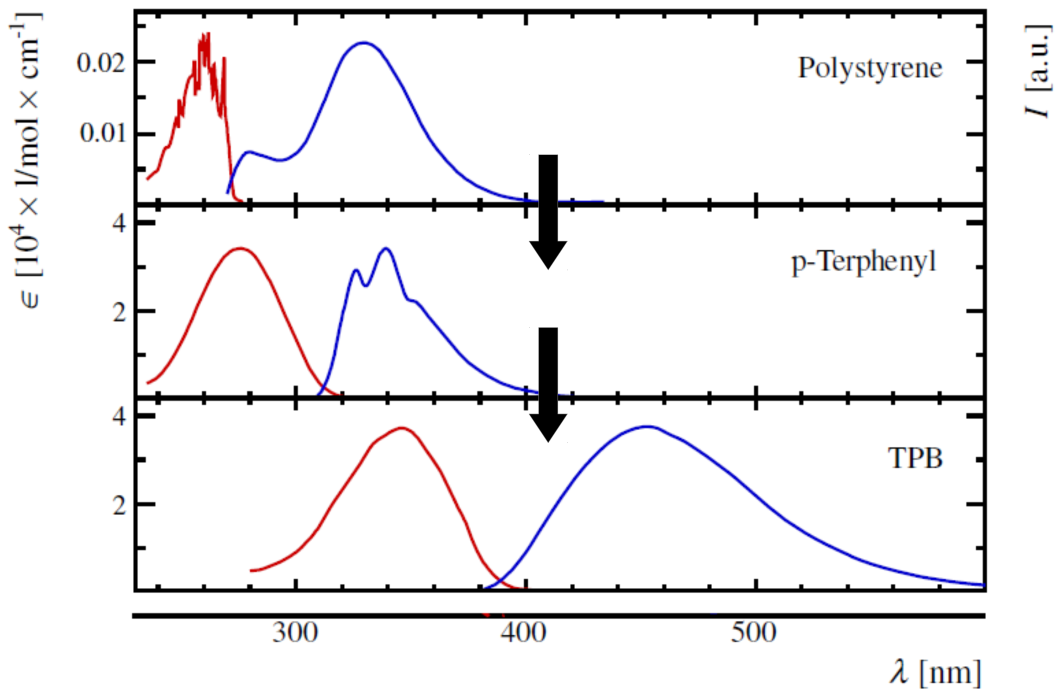


$$q_T = \frac{k_T c}{k_R + k_{NR} + k_T c} \Rightarrow 1 \qquad q_T = \frac{1}{1 + (\frac{r}{R_0})^6}$$

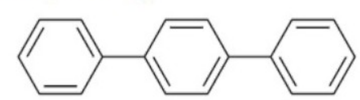
R_0 = few nm

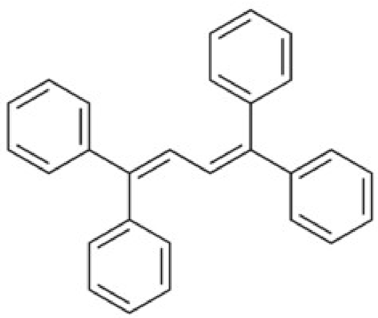
$$\tau_{PS} = \frac{1}{k_R + k_{NR} + k_T c}$$

- By choosing the correct scintillators and maximizing the concentrations (without introducing self-absorption)
  - achieve excellent quantum efficiency (light yield) for radiative and non-radiative transfers
  - Signal is the fluorescence decay time of your last scintillator dye (2.8 ns for TPB)
  - longer attenuation length due to longer wavelengths
  - Matches photodetector q.e. better



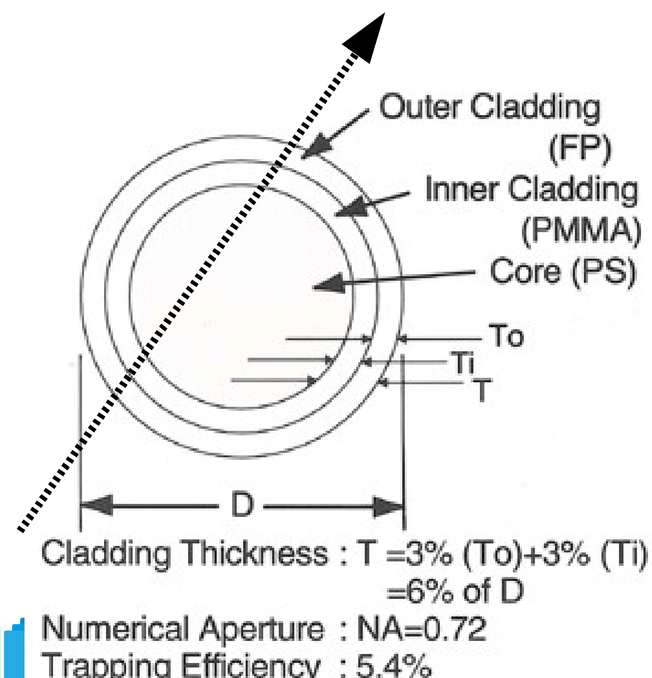
p-Terphenyl

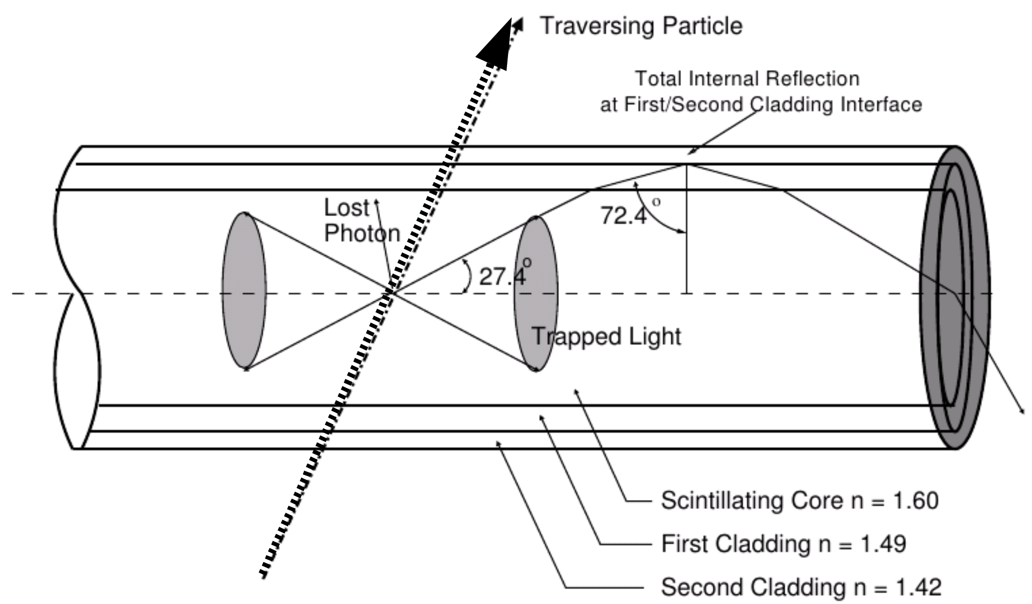




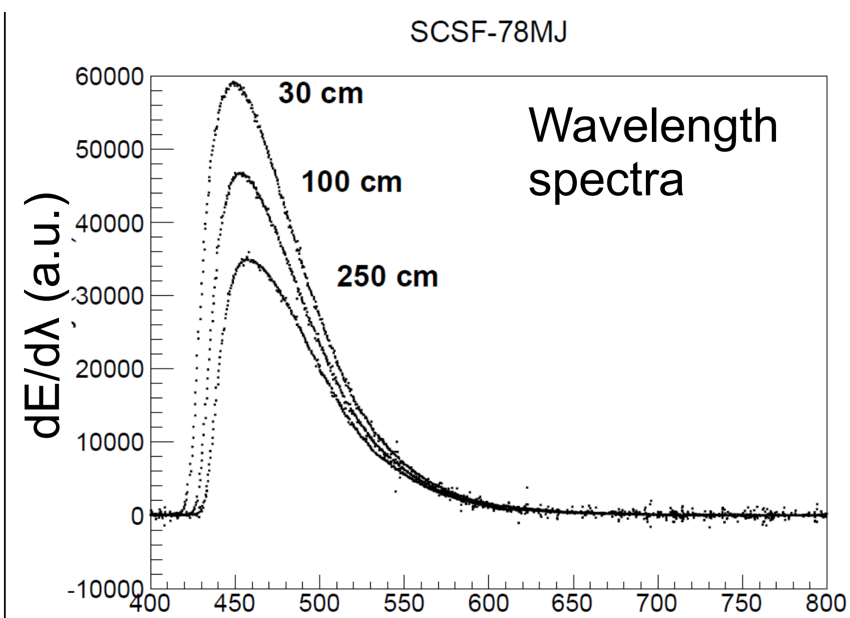
1,1,4,4-Tetraphenyl-1,3-butadiene

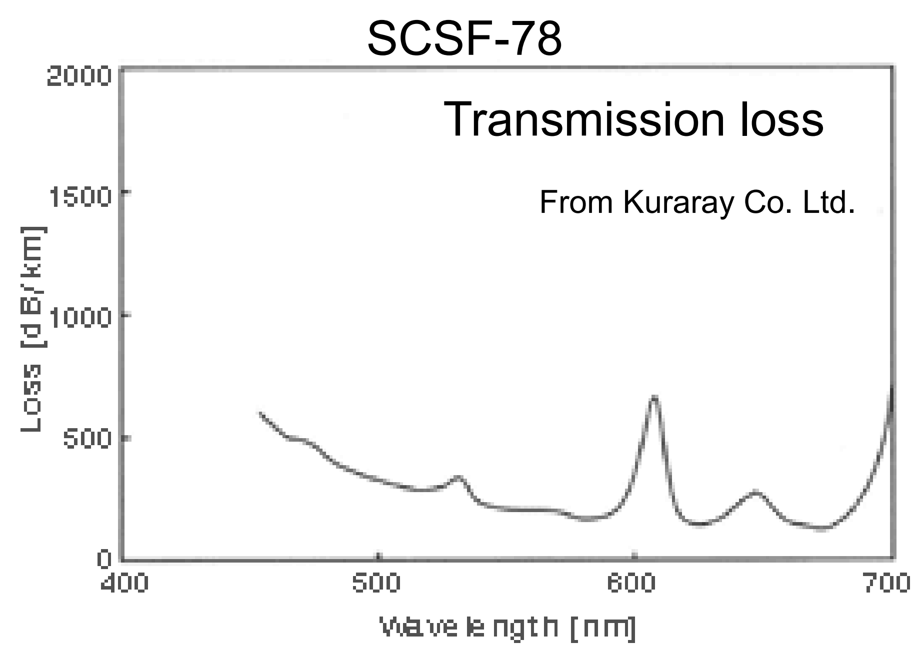
- dE/dx for a MIP is 0.2 MeV/mm of PS
- Scintillator produces ~8000 photons/MeV
- 300 photons in 4π produced for avg MIP crossing of 0.25mm fibre
- 5.35% captured (total internal reflection) in one direction
- If detection efficiency of ~30% = a few photons detected (@0cm)





- Parrameters affecting attenuation of signal over length
  - Helical and meridional path modes (θ, φ affect number of bounces from cladding interface and total path length)
  - Imperfections in cladding and core increase attenuation
  - Rayleigh scattering (wavelength dependence)
  - Absorption bands in polystyrene
  - Angular acceptance of detector

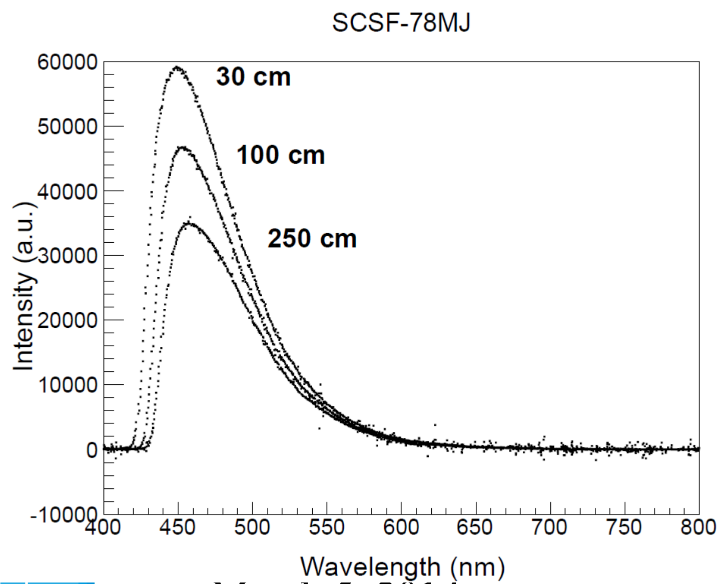


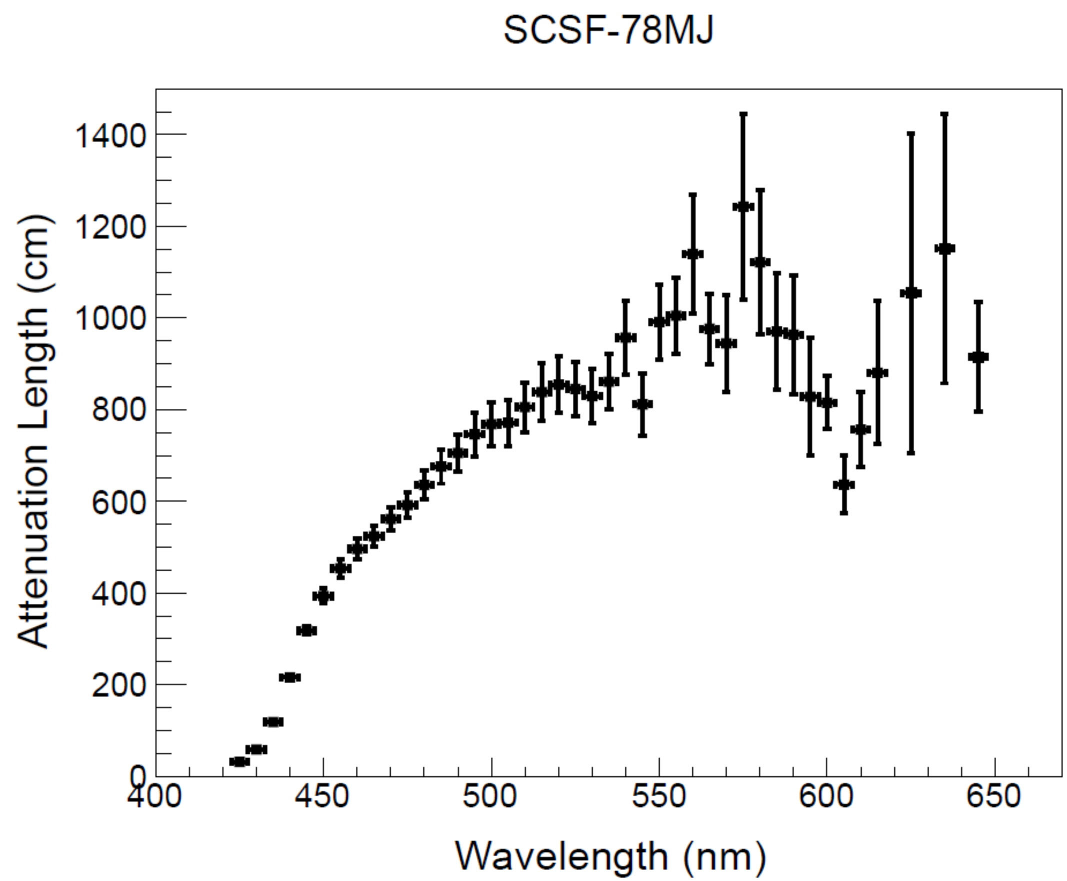


- Data is typically fit to a single or double exponential; integrated over multiple effects

$$I(x) = I_0\left(Ae^{-x/\Lambda_{short}} + (1-A)e^{-x/\Lambda_{long}}\right)$$

$$\Lambda_{short} \sim few\,cm$$
$$\Lambda_{long} \sim 350\,cm$$





Damage

- Different radicals are produced in the polystyrene matrix under ionizing radiation (few eV)
- Radicals are absorption centers which reduce the transmission of scintillation light
- Some radicals are unstable (R+R→X), some react with oxygen ($R+O_2$->RO_2), some are permanent damage
- Diffusion of oxygen plays an important roll in formation and annealing (**dose rate and diffusion effects**)
- Half lives of hours and weeks depending on temp and O_2

W. Busjan et al. / Nucl. Instr. and Meth. in Phys. Res. B 152 (1999) 89–104

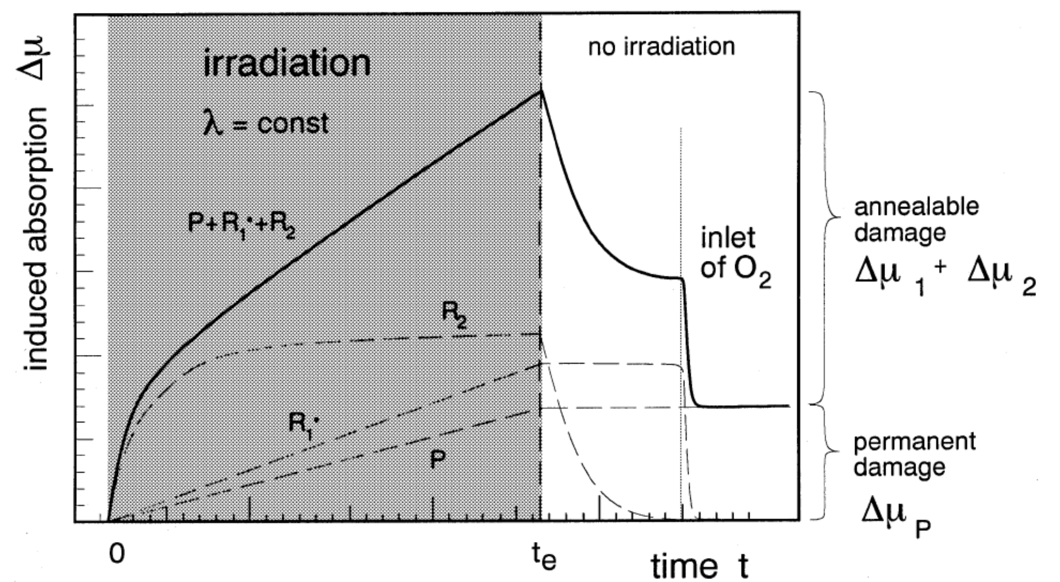
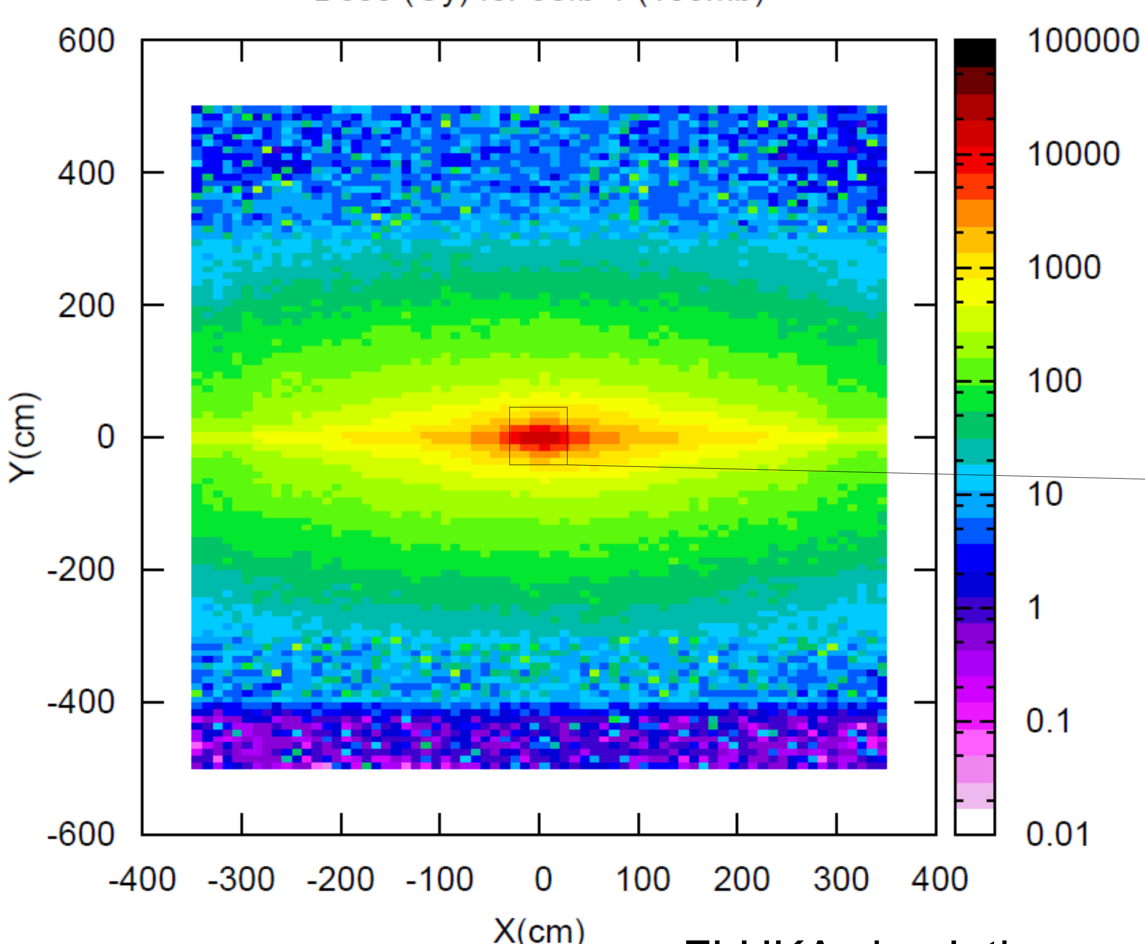
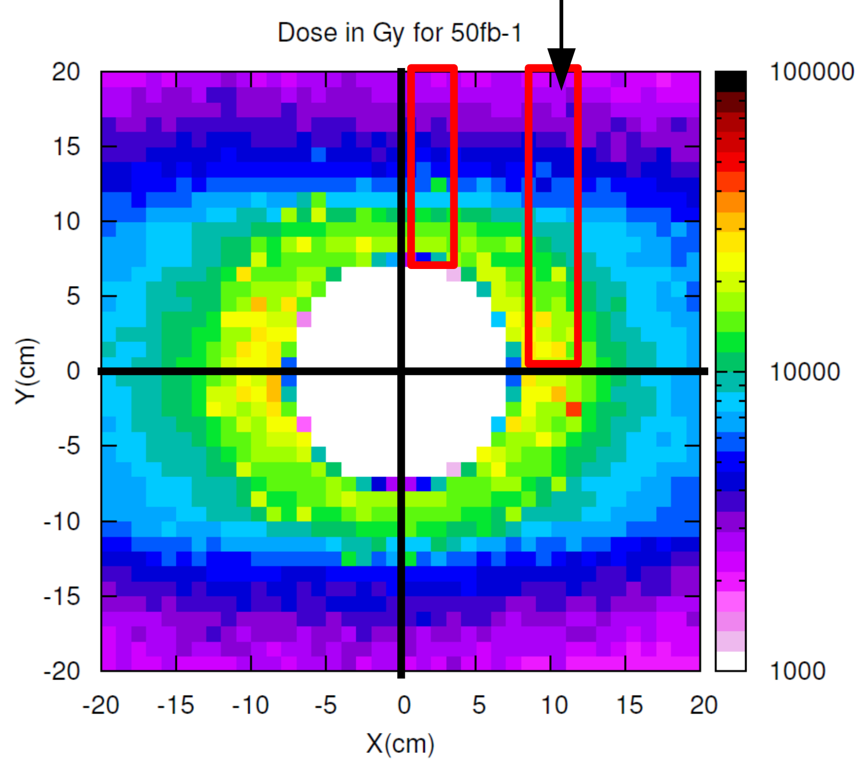


Fig. 2. The additional absorption $\Delta\mu$ induced in the scintillator BCF-12 during irradiation in argon atmosphere. The stable absorption centers P are responsible for the permanent damage $\Delta\mu_P$, while the annealable damage $(\Delta\mu_1 + \Delta\mu_2)$ is caused by $R_1\cdot$ and R_2. Rapid annealing occurs after inlet of oxygen.

Expected ionizing dose for LHCb Upgrade

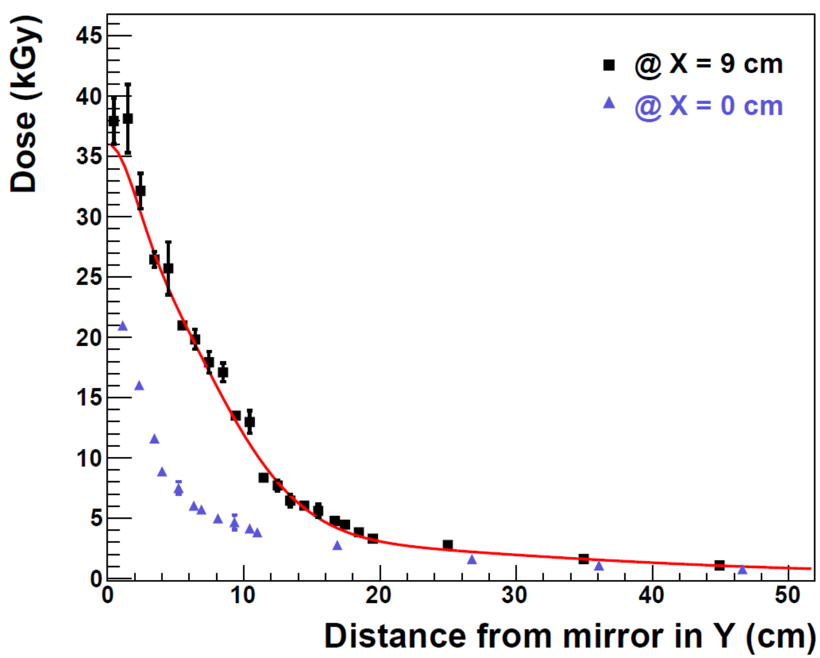


Longest signal path through the worst radiation (x=9cm)

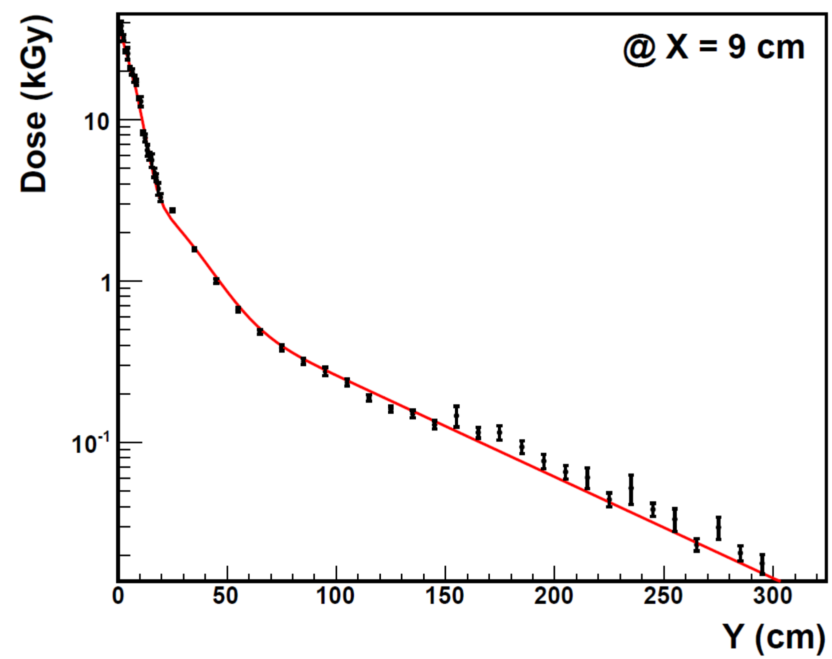


FLUKA simulations

Linear Y-axis, inner 50cm



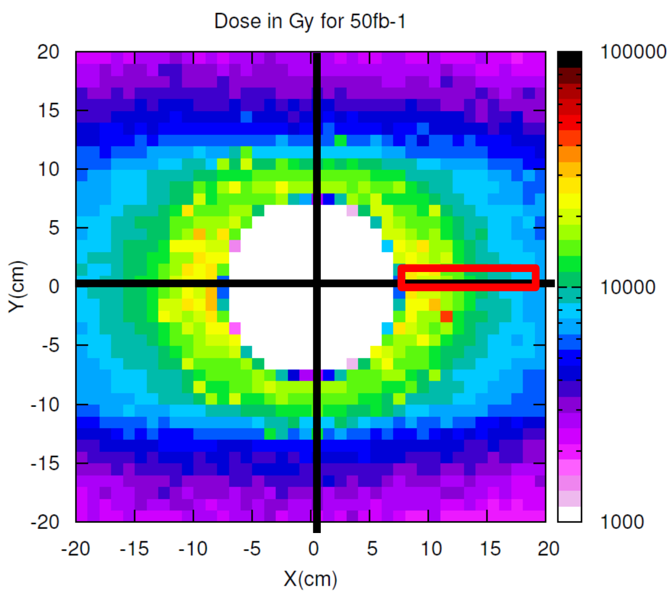
Log Y-axis, full 300cm

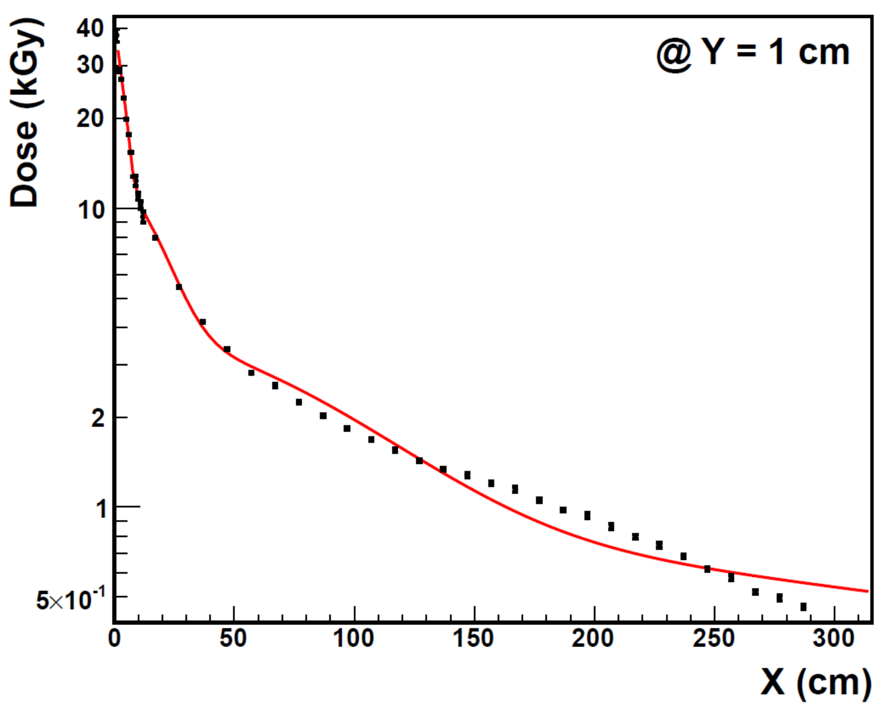


I've taken the Gy/collision numbers from Neus and Matthias, multiplied by 5 x 10^15 collisions (50fb^-1@100mb) → 37.5 kGy at peak.

Damage

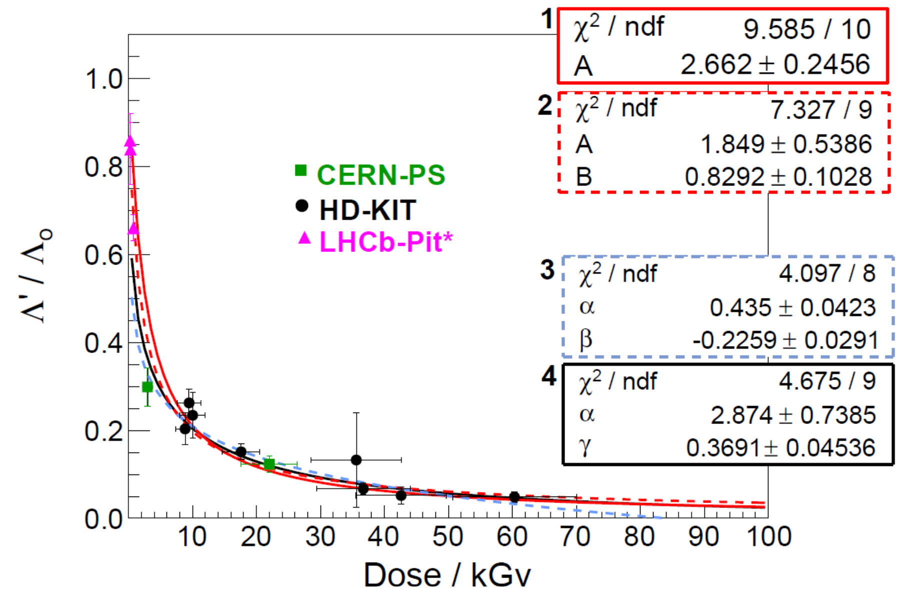
- Dose along x in the y=0 plane

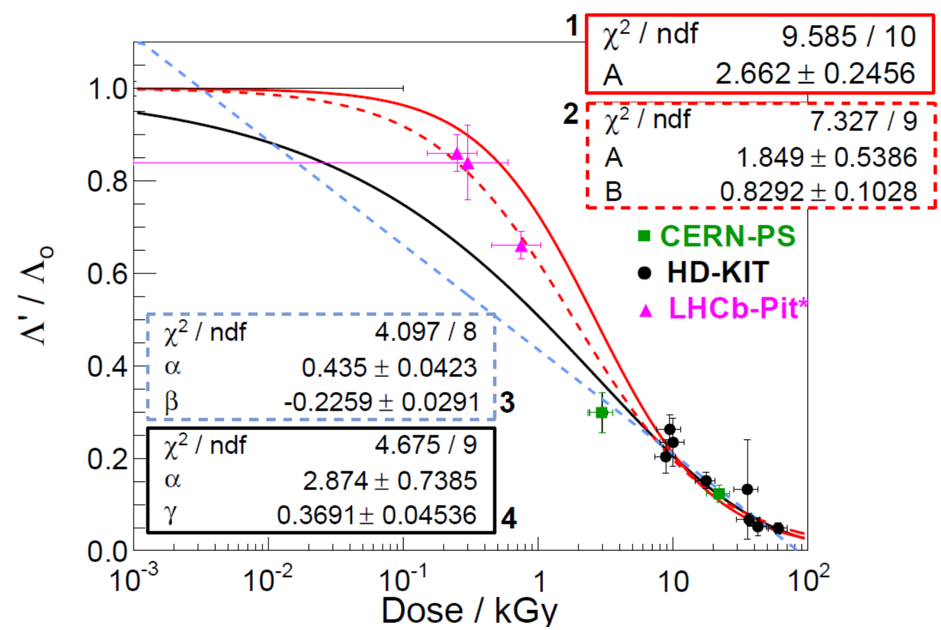




Damage

- Two separate measurements with 24 GeV/c protons and 23 MeV protons plus an unreliable *in situ* measurement
- Measurements taken 1 day – 1week after irradiation
- Will likely require measurements of fibre mats in their final construction at similar dose rates to the LHCb Upgrade to make accurate predictions
- Damage to the attenuation length goes almost logarithmically with dose i.e. **rapid damage at low dose**





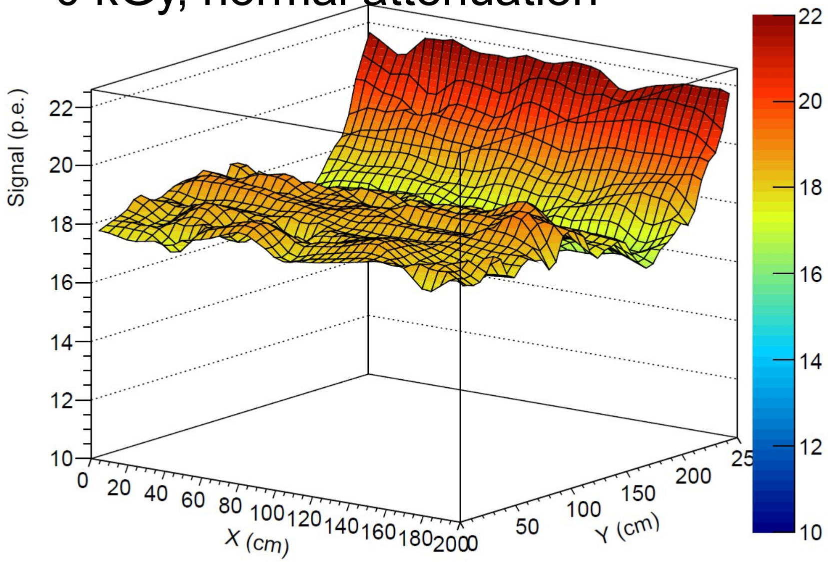
Damage

- Expected photoelectron yields

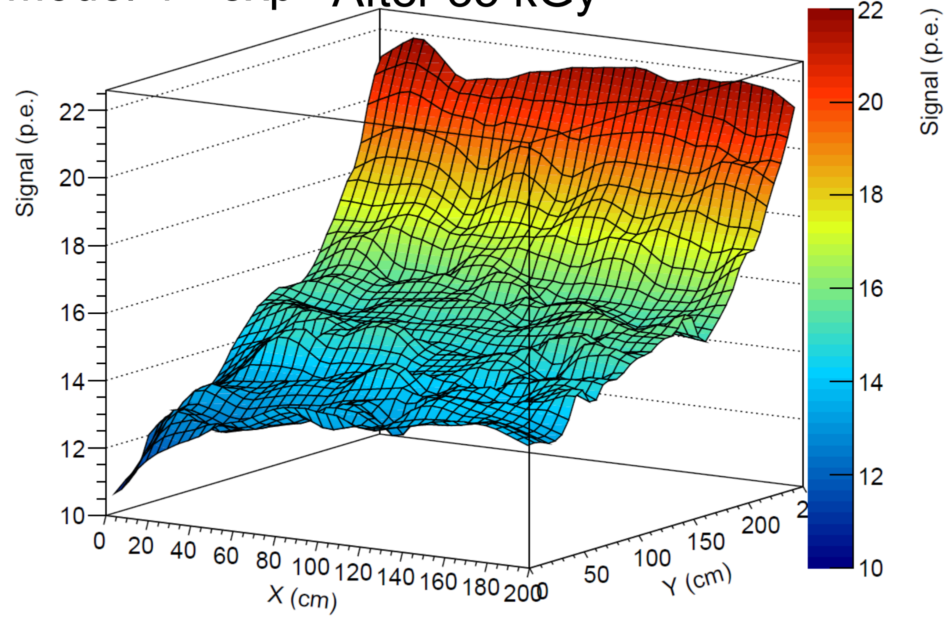
Table 1.9: Expected light yield in photons (PE) at different locations in the detector before and after irradiation. The base for this table is a light yield of non-irradiated fibres with six layers at the mirror of 20.7 PE. The attenuation of the light from the mirror to the detector is 32%. A 40% signal loss is assumed near the mirror in the irradiated region and the radiation has a smaller 10–20% effect in the outer region.

6-layer region inside ± 0.5m				5-layer region outside ± 0.5m			
Non-irradiated		Irradiated (up to 35 kGy)		Non-irradiated		Irradiated (up to 35 kGy)	
Mirror	Detector	Mirror	Detector	Mirror	Detector	Mirror	Detector
20.7	27.3	12.4	16.4	17.3	22.8	14 – 16	22.8

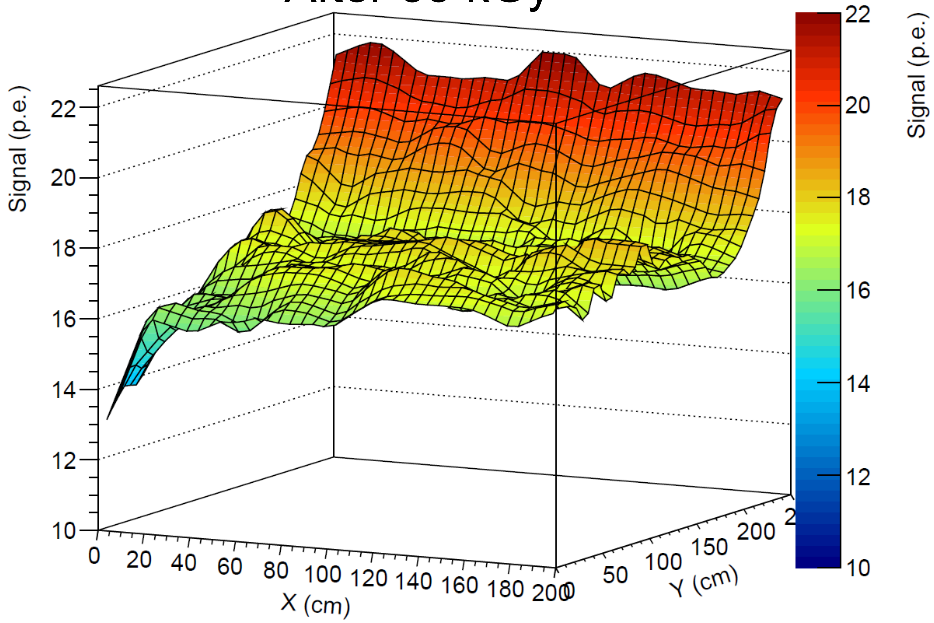
0 kGy, normal attenuation



Model 4 - exp After 35 kGy

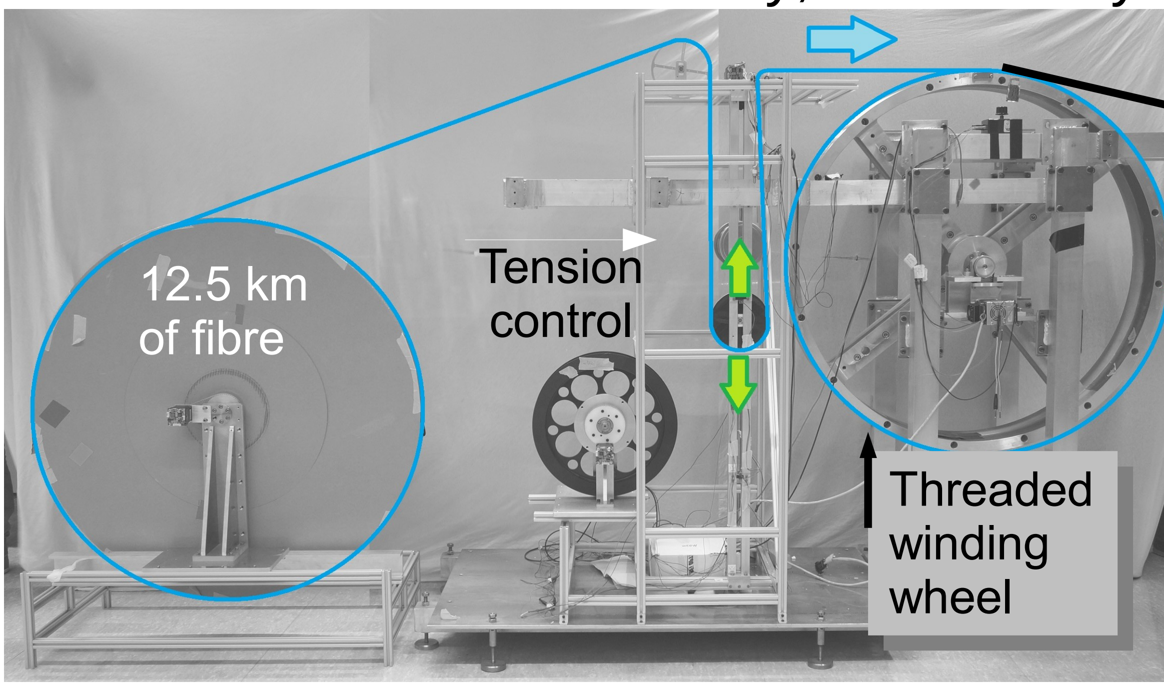


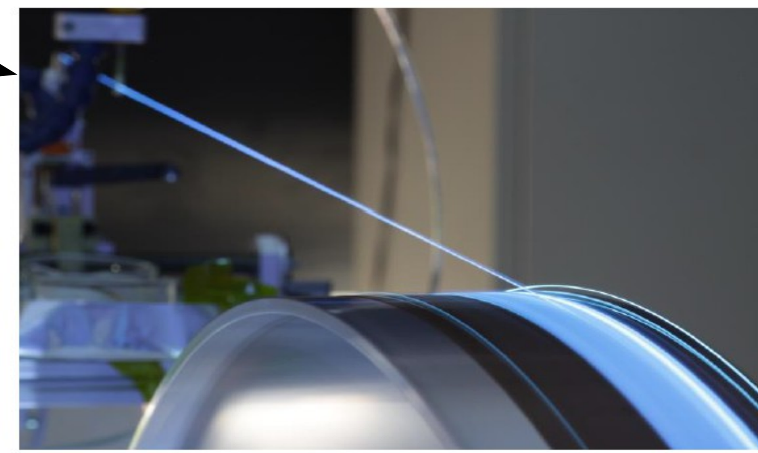
Model 1 - linear After 35 kGy



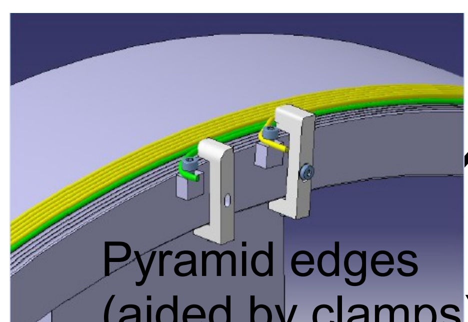
- Signals are integrated over 25ns; 85% mirroring included @y=0cm. Assumes 5-layer fibre mats.
- Signal over most of the detector is affected by low dose (<1kGy) dependence (10-20% signal loss)
- Most of the tracks are near (x=0,y=0) in high radiation (30-40% signal loss)

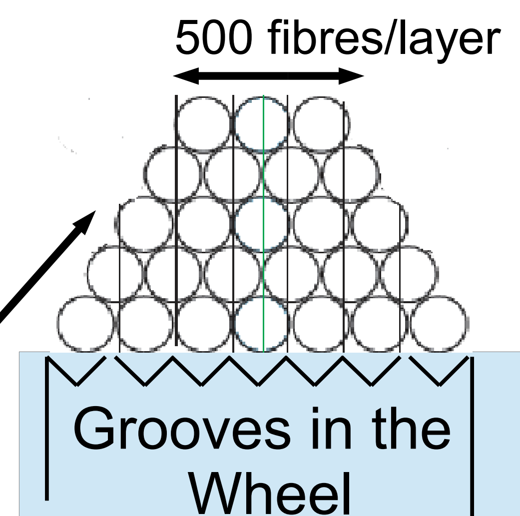
- After attenuation, a single fibre does not produce enough light for 99% detection efficiency; we need layers of fibre





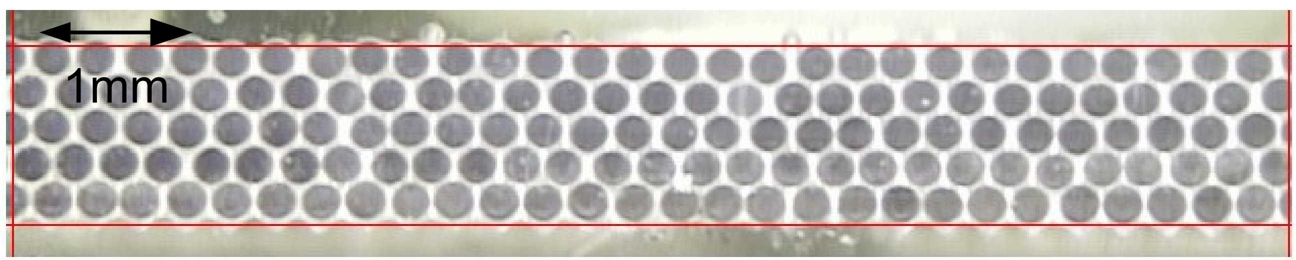
- Need about 7km of fibre for one 250cm long mat, 14cm wide, with 5 layers.
- 10,000 km in total ...

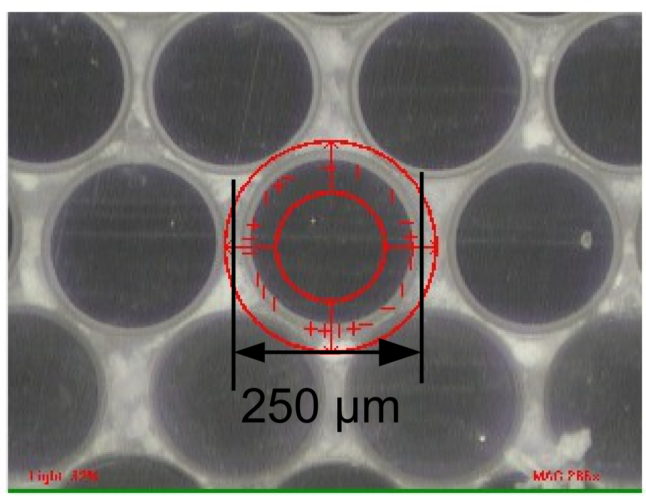


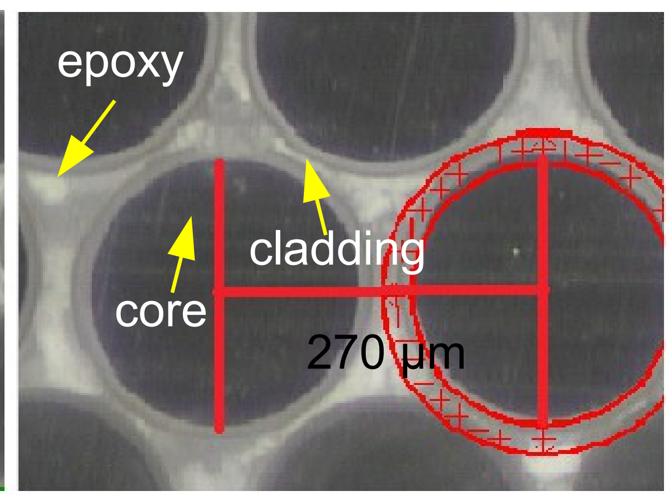


- Epoxy/Glue is mixed with Titanium Dioxide (opaque, diffuse) to block inter-fibre crosstalk
- Fibres have glue added during winding
- Measure the interfibre alignment with pattern recognition software

Finished 5 layer mat

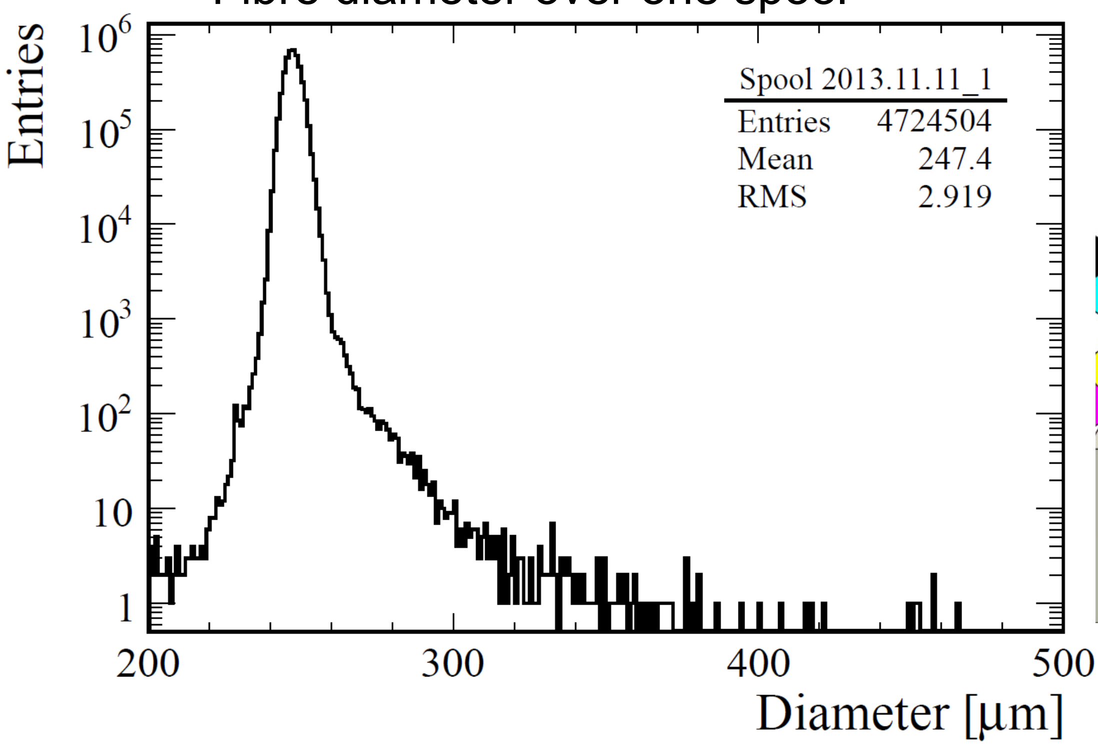




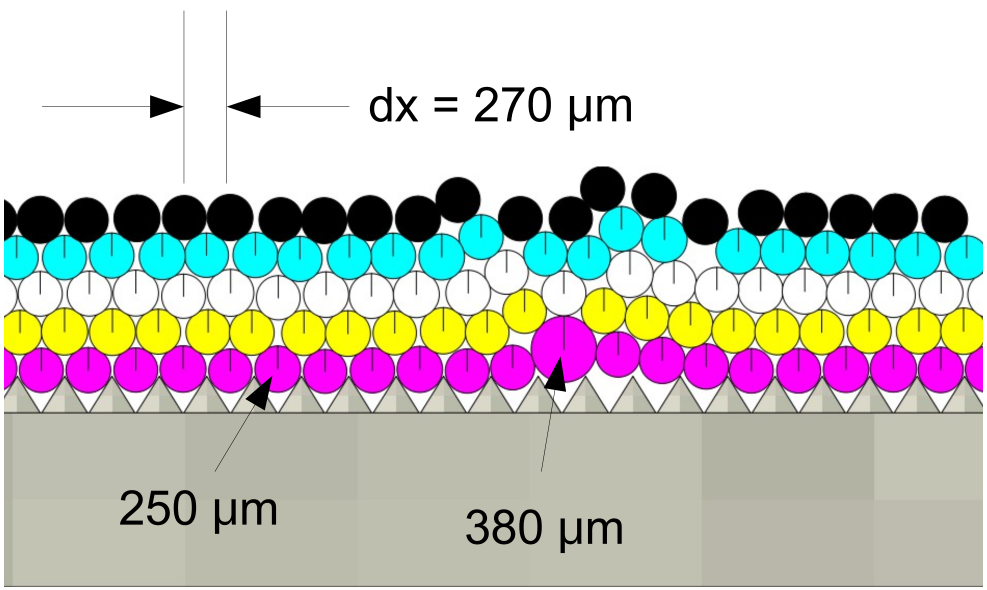


- Defects of the fibre can be created during the extrusion process making “blobs”
- Blobs ruin the packing of the fibre matrix and alignment

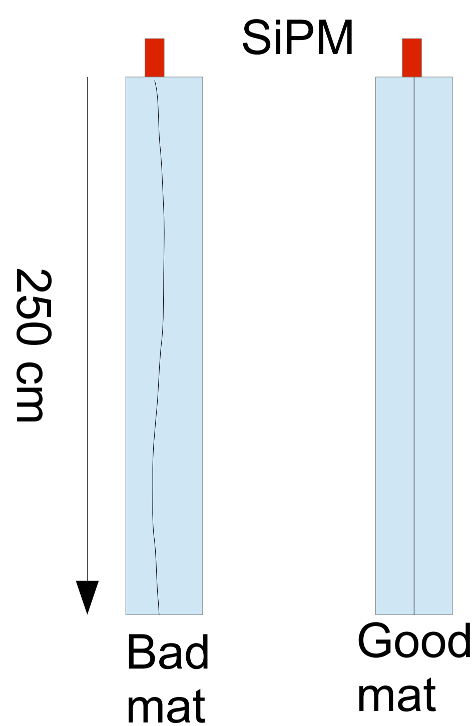
Fibre diameter over one spool

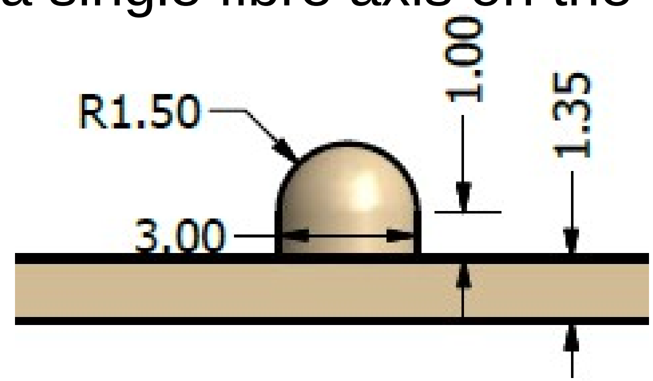


For a good mat
rms(dx) = 8-15 μm

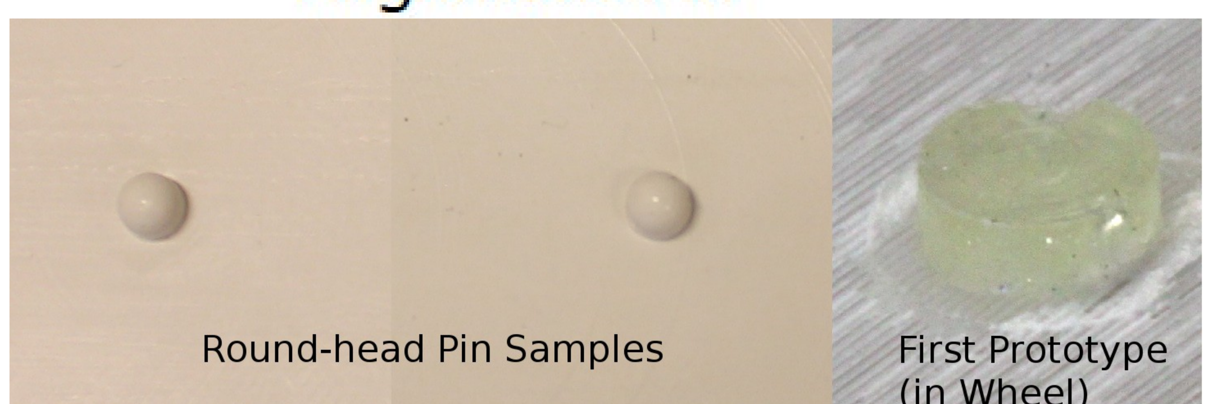


- Straightness over the mat length should be better than the required detector resolution of <100 μm
- Pins are bonded to the fibre mat on the wheel as part of winding (alignment holes follow a single fibre axis on the wheel)

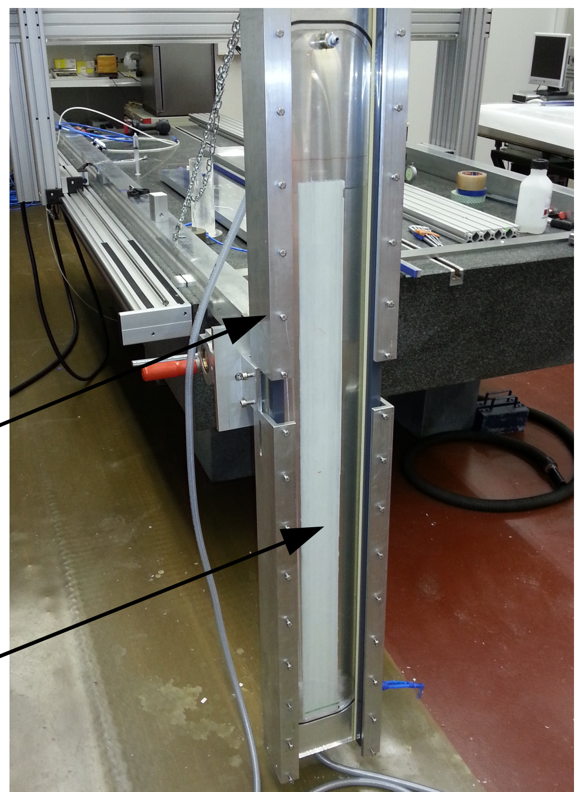




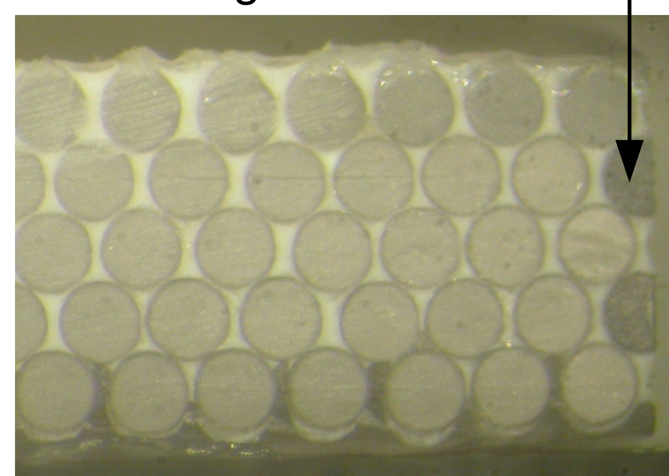
Alignment Pin

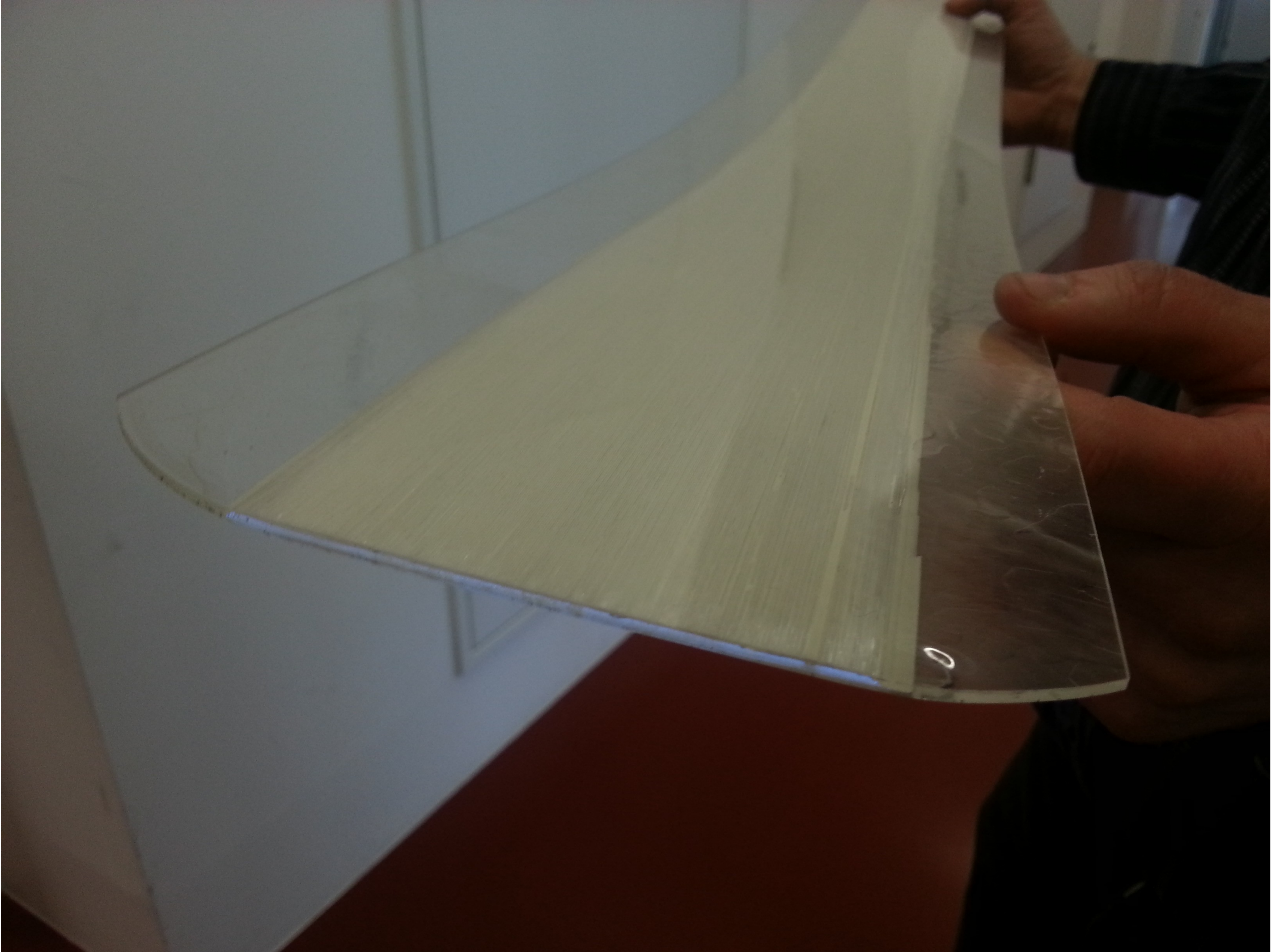


- Mats need to be cut on each side and end to fit together precisely and have maximum optical transmission (precision cuts of 100 um tolerance over 2.5m are difficult).
- Flat face surfaces are rough and the mats are prone to splitting between the fibre lengths; requires casting



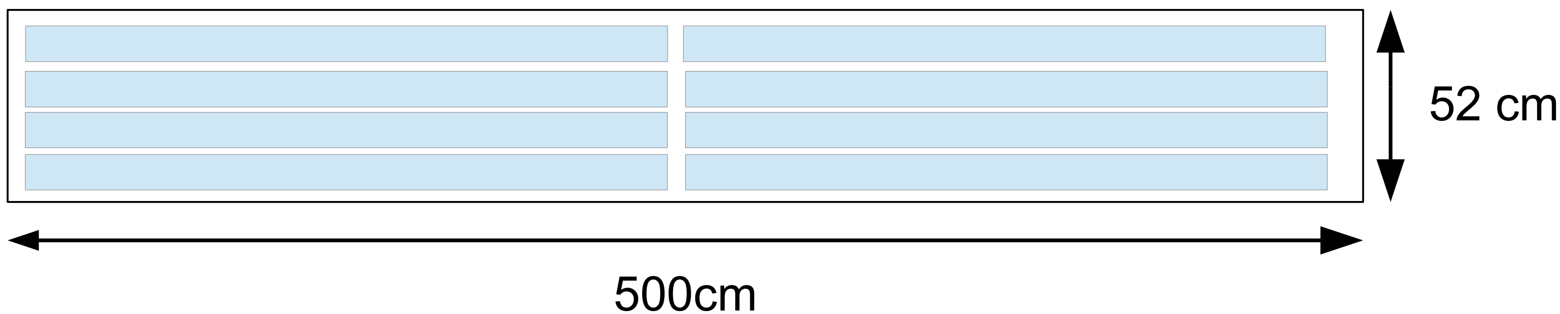
Cutting will create dead fibres on the edges



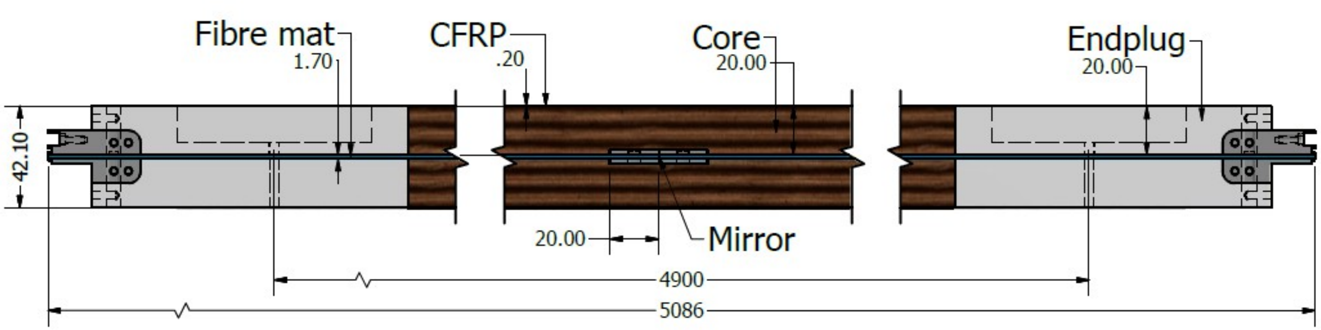


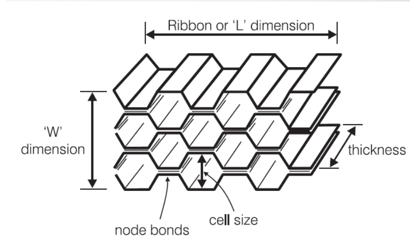
- The fibre mats need to be assembled into an object that can be mounted and placed in the LHCb pit: **a module**

8 mats aligned on a precision table



- Bond a carbon fibre + core structure to make a strong rigid object
  - Precision in time in z-direction better than 300 micron

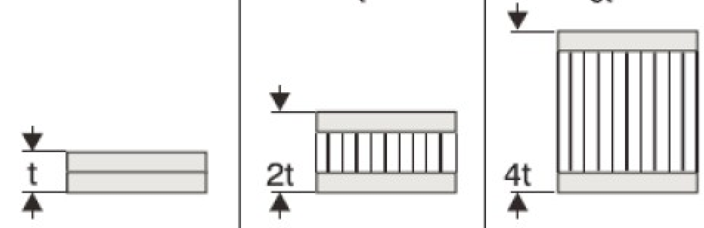




- Material budget (multiple scattering and nuclear interactions)

Material	Thickness(µm)	Layers	X_0(cm)	X/X_0 (%)
Core(N/A/D)	20000	2	1750/689/1050	0.229/0.580/0.381
CF skin	200	2	23.3	0.172
Panel glue	75	4	36.1	0.083
Fibre mat	1350	1	33.2	0.407
Casting glue	175	2	36.1	0.097
Total	4220			0.99/1.34/1.14

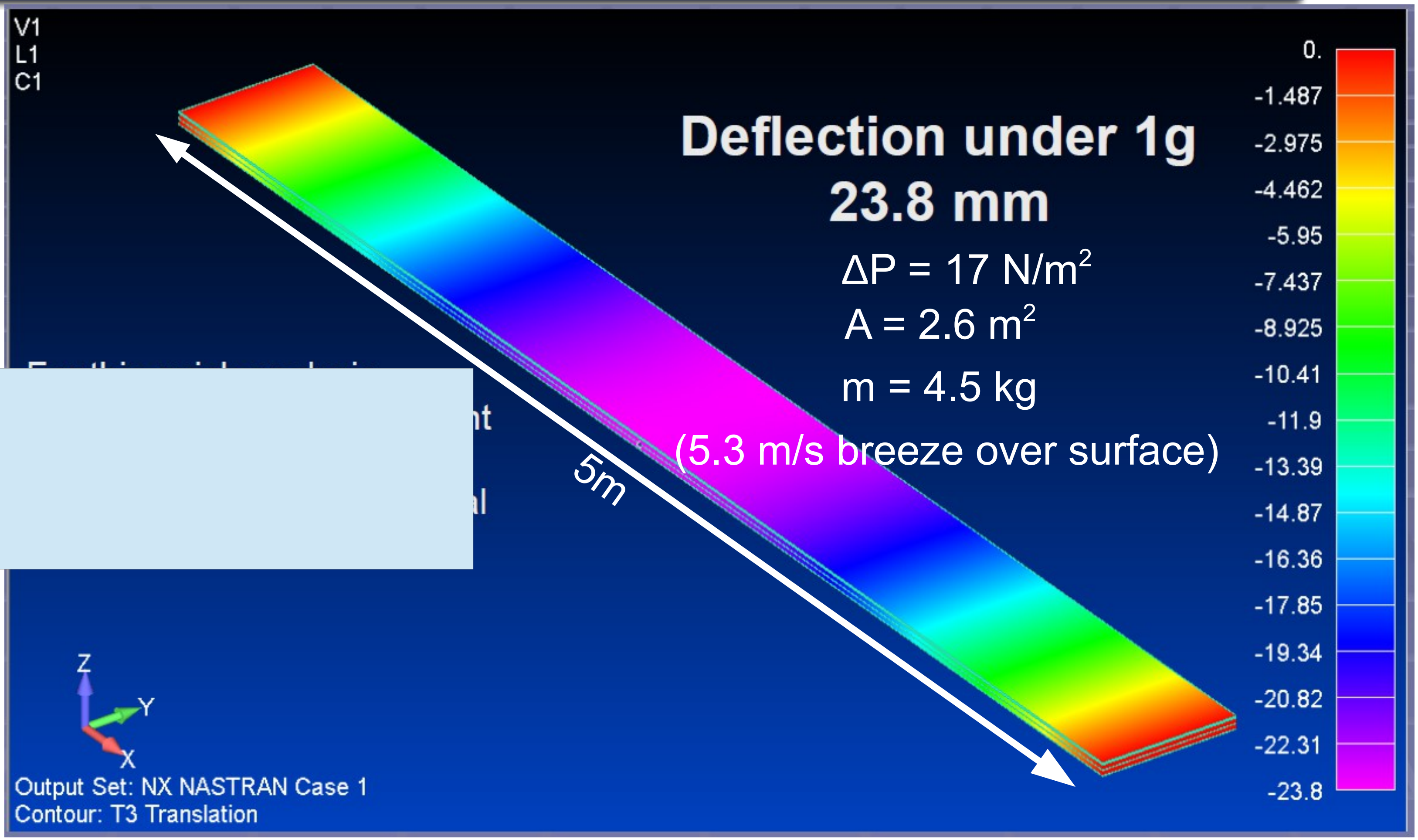
- With sandwich structures, maximize the separation of the carbon fibre skins
- Cores should be low mass, incompressible, cheap, fire resistance machinable
- Materials:
  - Honeycombs (Metal, Plastic, Paper, Wood)
    - **Nomex 24 kg/m3**
  - Plastics, Foam Materials
    - **Airex R82-60, Divinycell F40**
  - Balsa Wood



	Solid Material	Core Thickness t	Core Thickness 3t
Stiffness	1.0	7.0	37.0
Flexural Strength	1.0	3.5	9.2

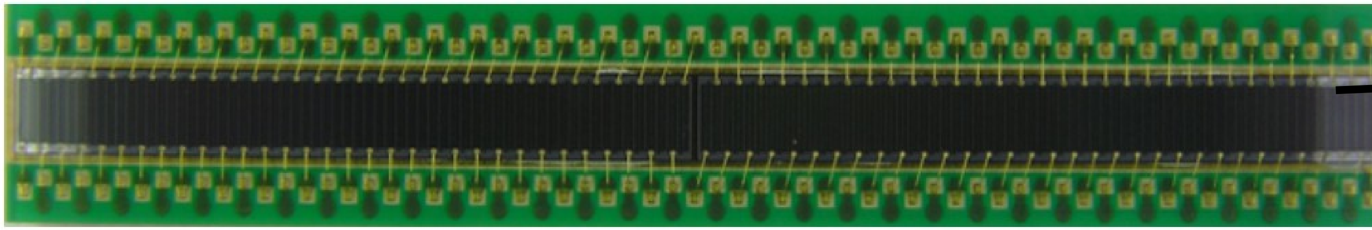
Flexural Stiffness $I_{Beam} = t^3/12$

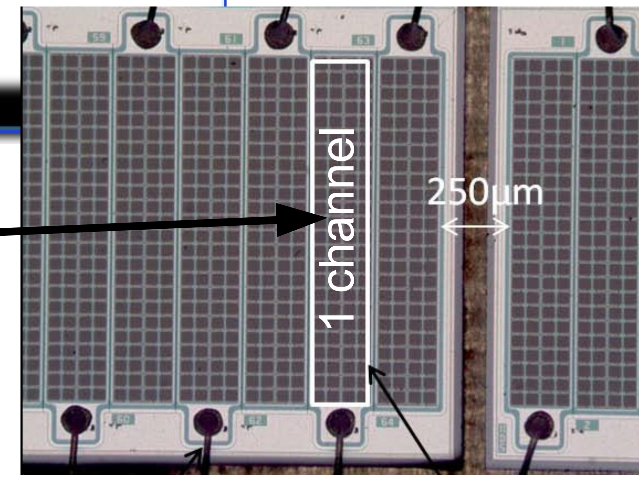
Flexural Strength $W_{Beam} = t^2/6$



A dummy SciFi module has a Young's modulus of 1.73GPa compared to the OT which is 1.24GPa.

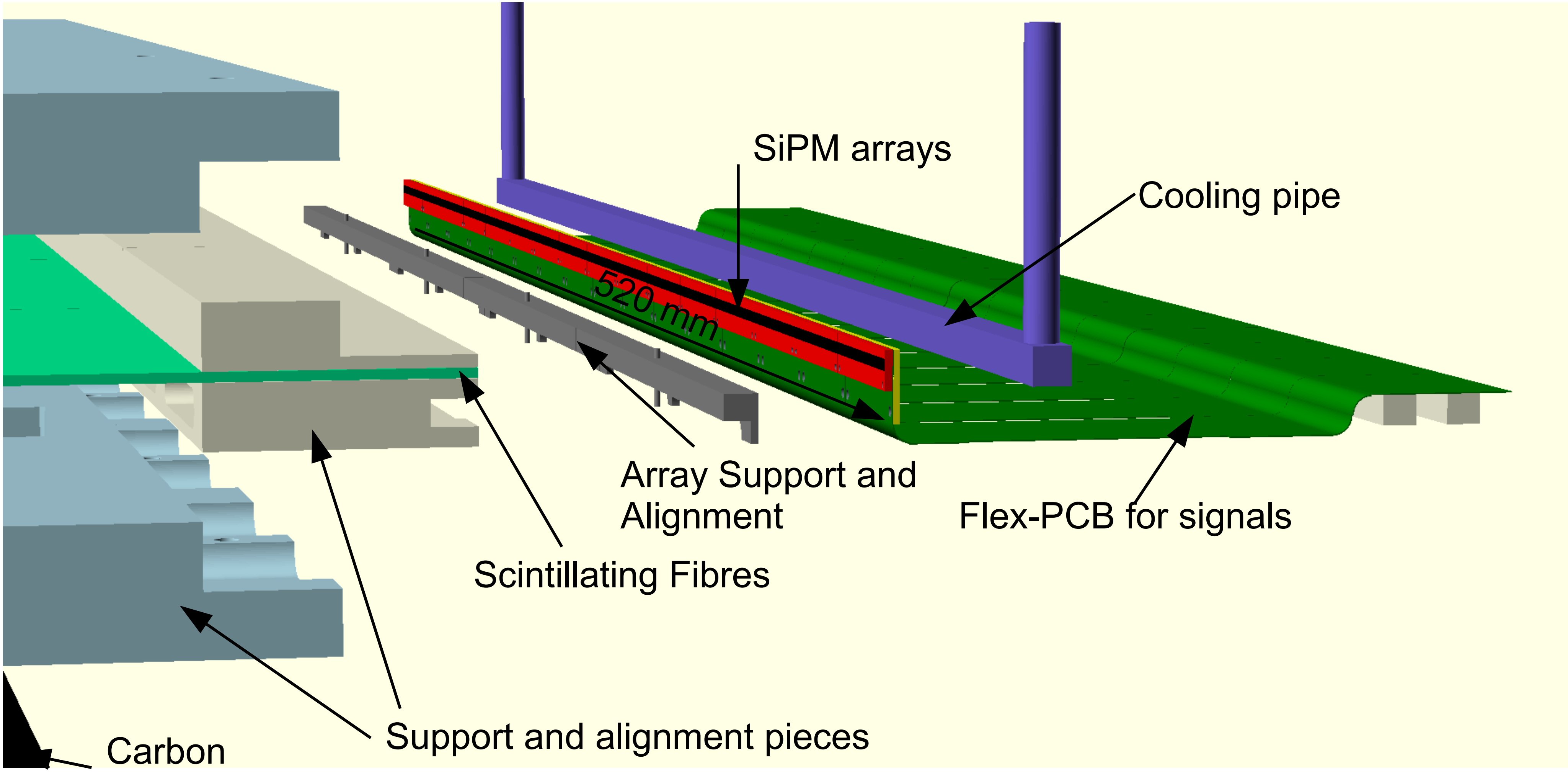
Break here.



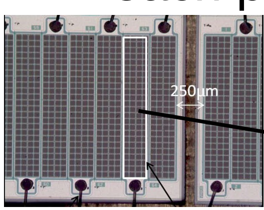


- Basic Properties:
  - provide high photon detection efficiency (PDE) over a large wavelength range that matches the fibres
  - Immune to magnetic fields
  - Low operating voltage <100V compared to 2kV for PMTs
  - high reliability due to its simple mechanical construction
  - a high density multi-channel package to match fibre granularity
  - sufficiently low cost to allow the construction of a large area tracking device (560,000 channels)

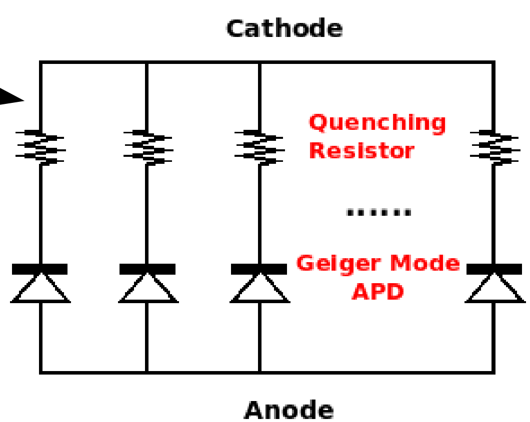
- SiPM arrays for the fibre tracker

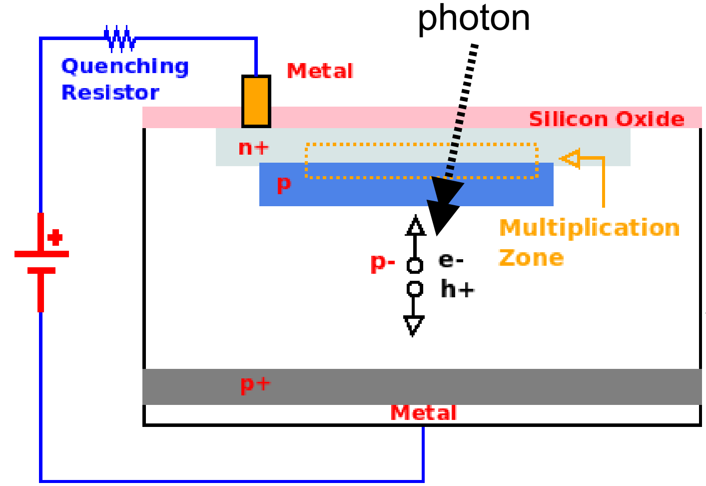


- The SiPM pixel is an avalanche photodiode operated in Geiger mode (reverse-biased photodiode operated above its breakdown voltage)
- A photon hits the depleted zone and creates an electron-hole-pair
- Generated carriers will drift to the multiplication zone and then trigger the Geiger mode avalanche process
- a single electron/hole-pair can trigger an avalanche of electrons and holes producing a charge gain of 10^5 – 10^6.
- A fired pixel is insensitive to additional pixels (binary mode). Same signal for each pixel

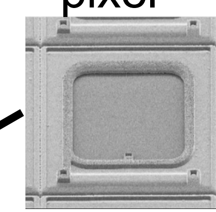


1 channel of a SiPM array

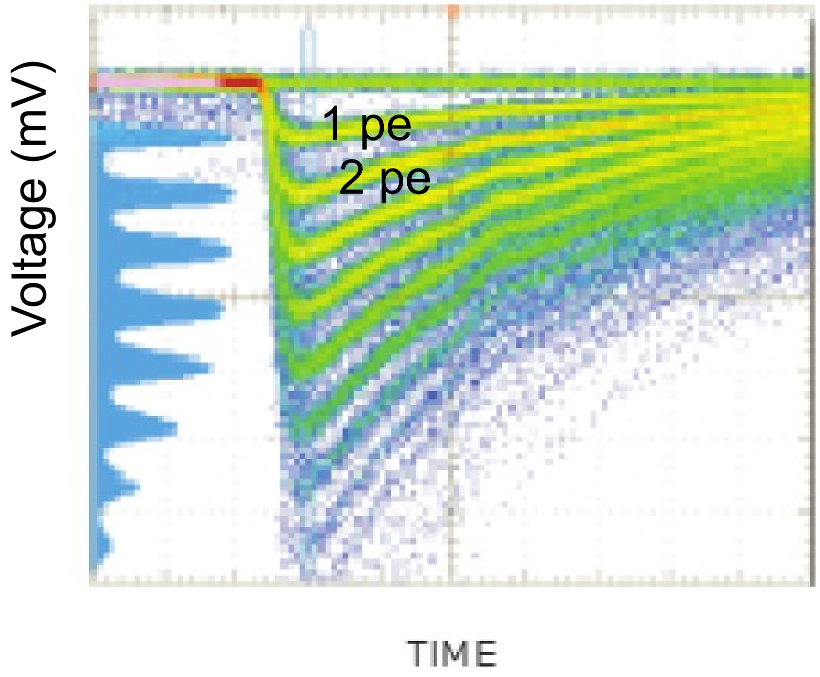


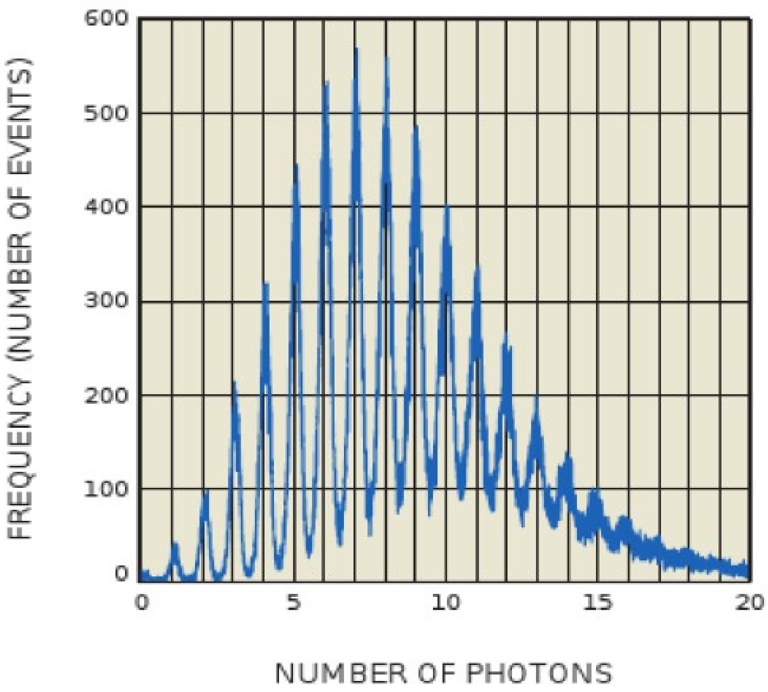


Each pixel

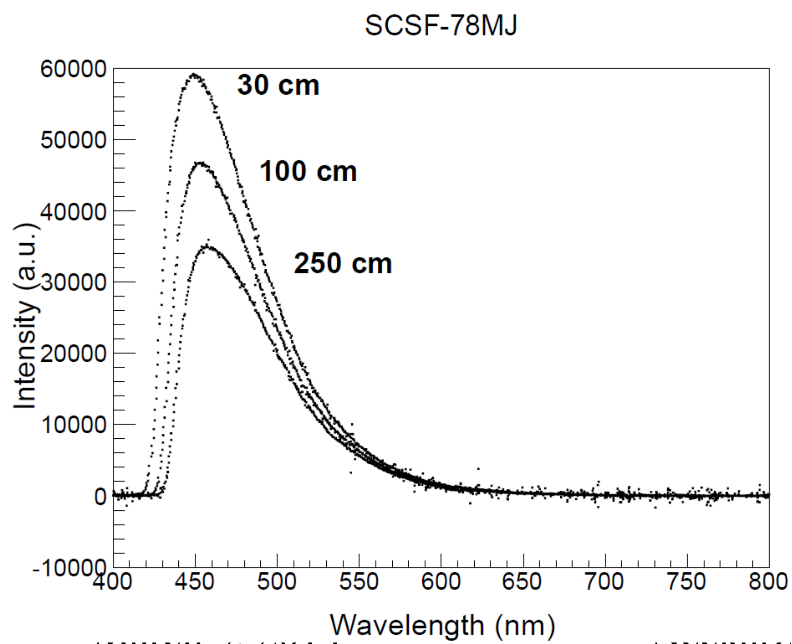


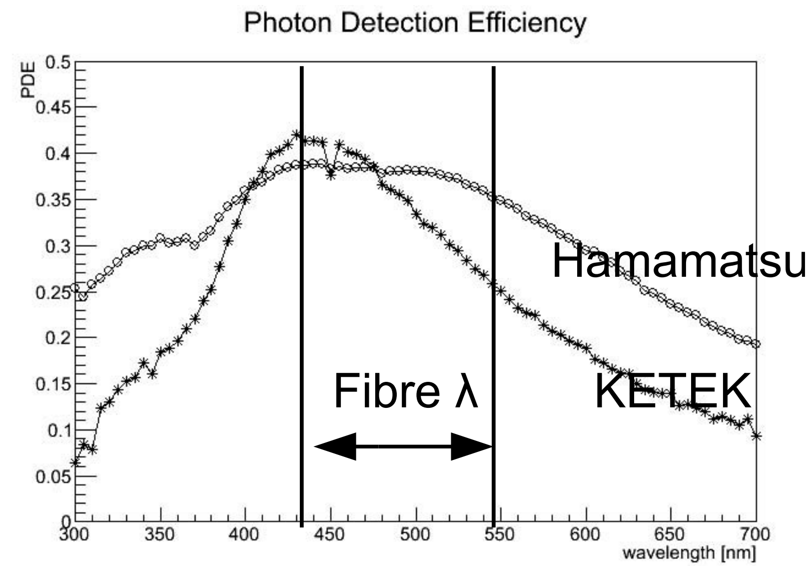
- Typically, it is quite easy to distinguish signals from individual photons with a SiPM
- Photoelectron counting is great for calorimetry... OK for tracking



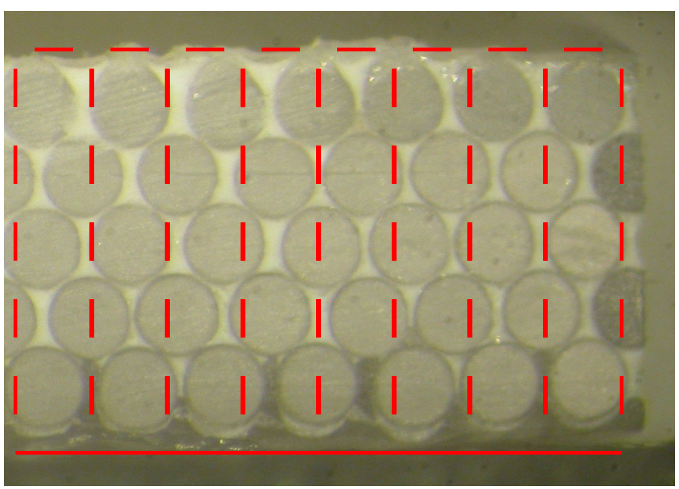


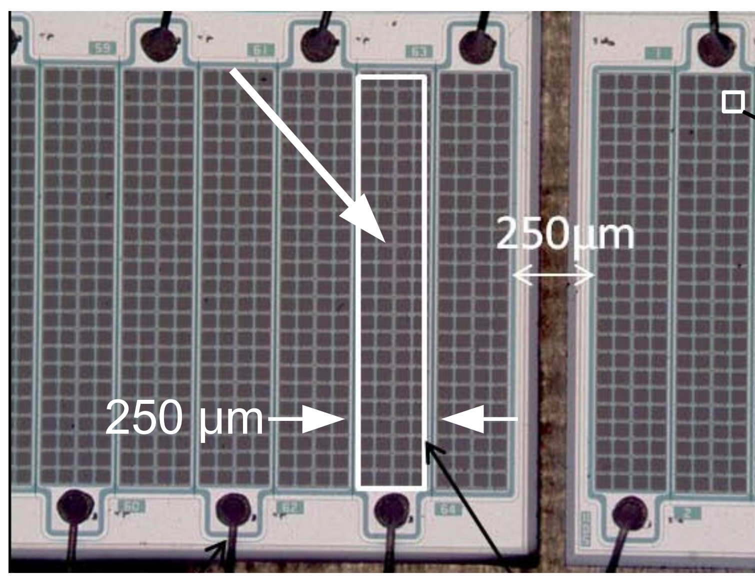
- Photon detection efficiency (PDE) depends on
  - Geometrical efficiency (active area/total area of pixels) (50-85%)
  - Quantum efficiency to convert photon to electron/hole pair (~85% for silicon), wavelength dependence, depth of layers
  - Reflectivity of surface (surface coatings)
  - Avalanche probability (bias voltage dep.)



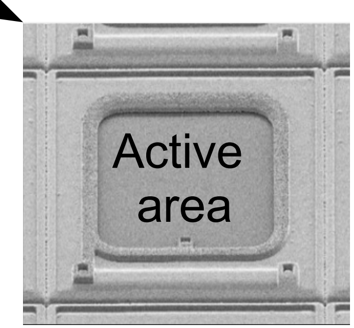


- SiPM channel width approximately matches the fibre spacing and diameter (not matched 1-to-1)
- Particle track angle and fibre overlap will produce “clusters” of 1-4 channels



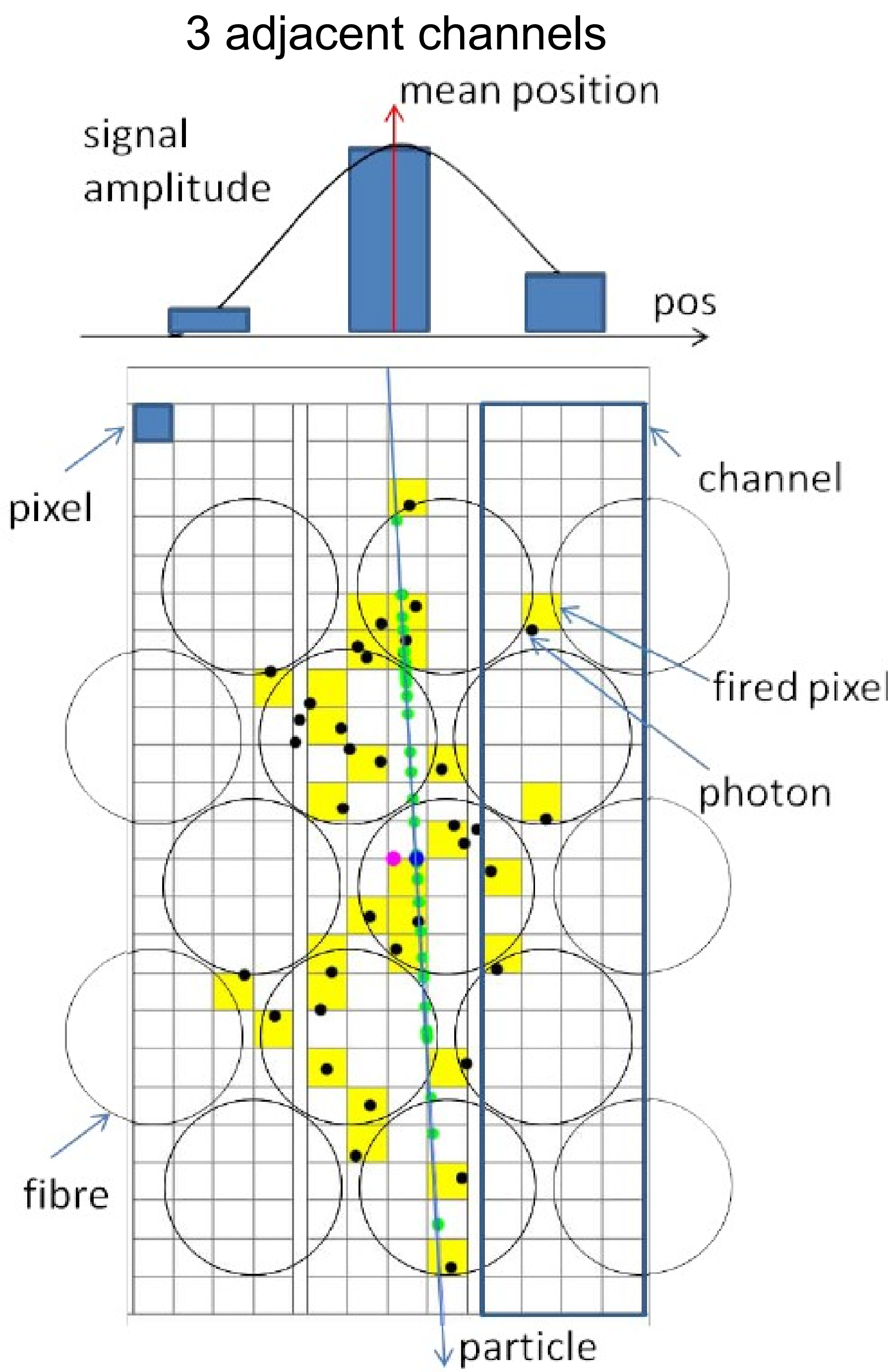


1 channel ~ 88 pixels



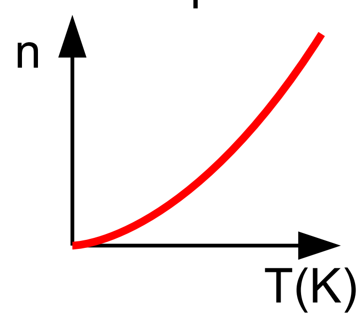
1 pixel

- Particle track angle and fibre/channel overlap will produce “clusters” of 1-4 channels
- Track position is determined by the centroid of the clusters (analog or digital)
- A signal cluster in the SciFi Tracker will see 12-24 photo-electrons (photons converted to avalanche signals)
- Binomial distribution (σ(n)~sqrt(N)) with tails from dE/dx
- Hit efficiency requires clusters to have n.p.e. > threshold cuts to suppress noisy channels

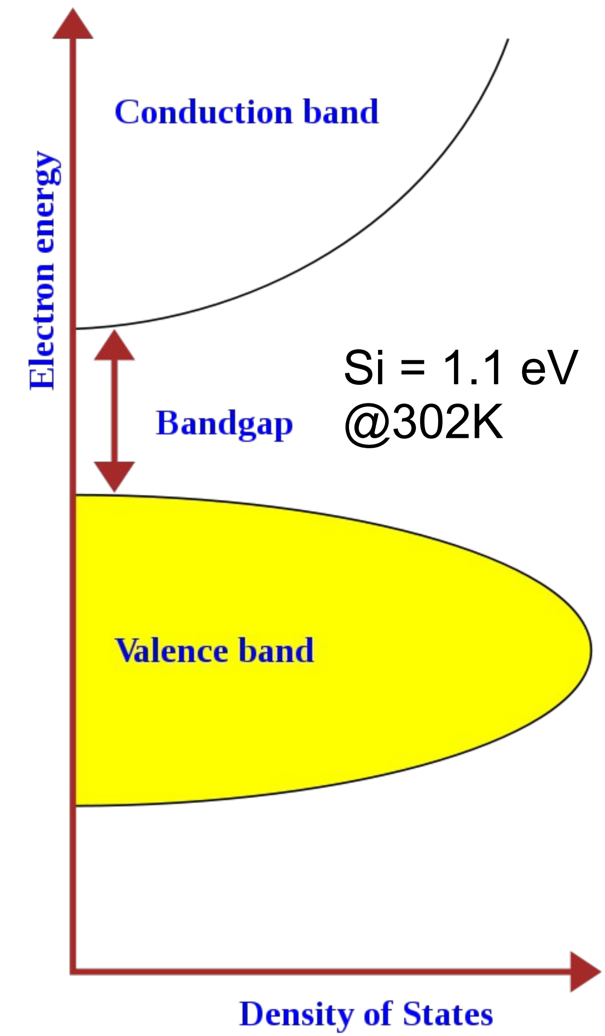


- Noise
  - Typically 0.1-0.5 MHz/mm^2 in standard SiPM silicon for signal > 0.5 p.e.
  - From thermal excitations of single electrons into the conduction band causing avalanches
- Electrons in the conduction band increase with temperature

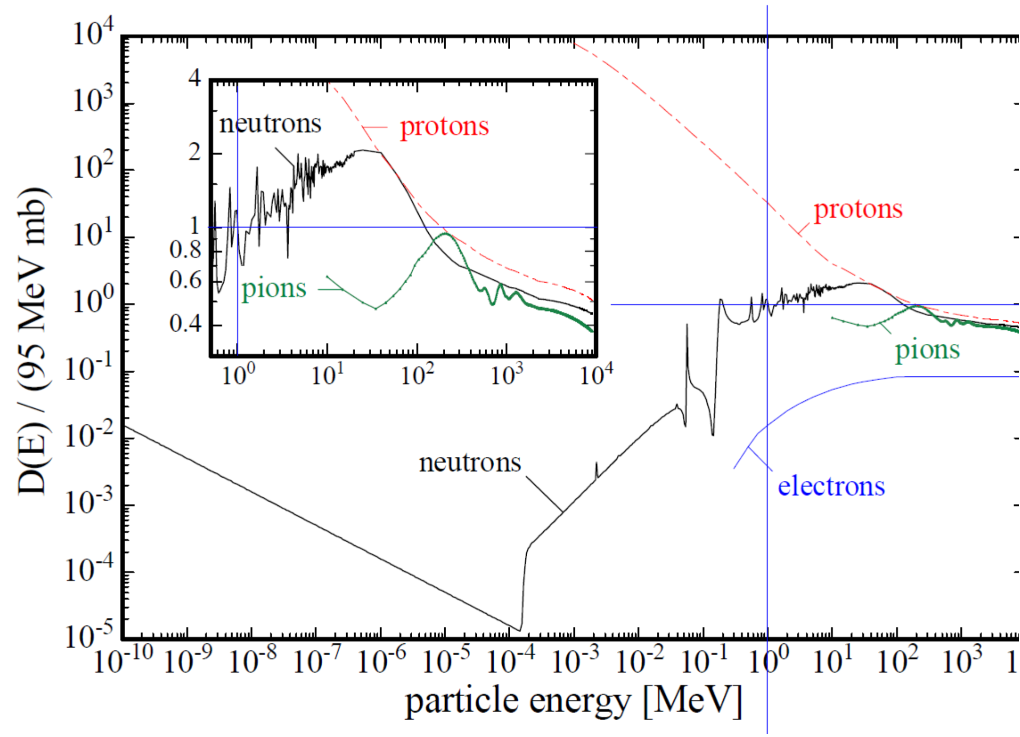
$$n \propto (k_B T)^{3/2} \exp\left(-\frac{E_C - E_F}{k_B T}\right)$$



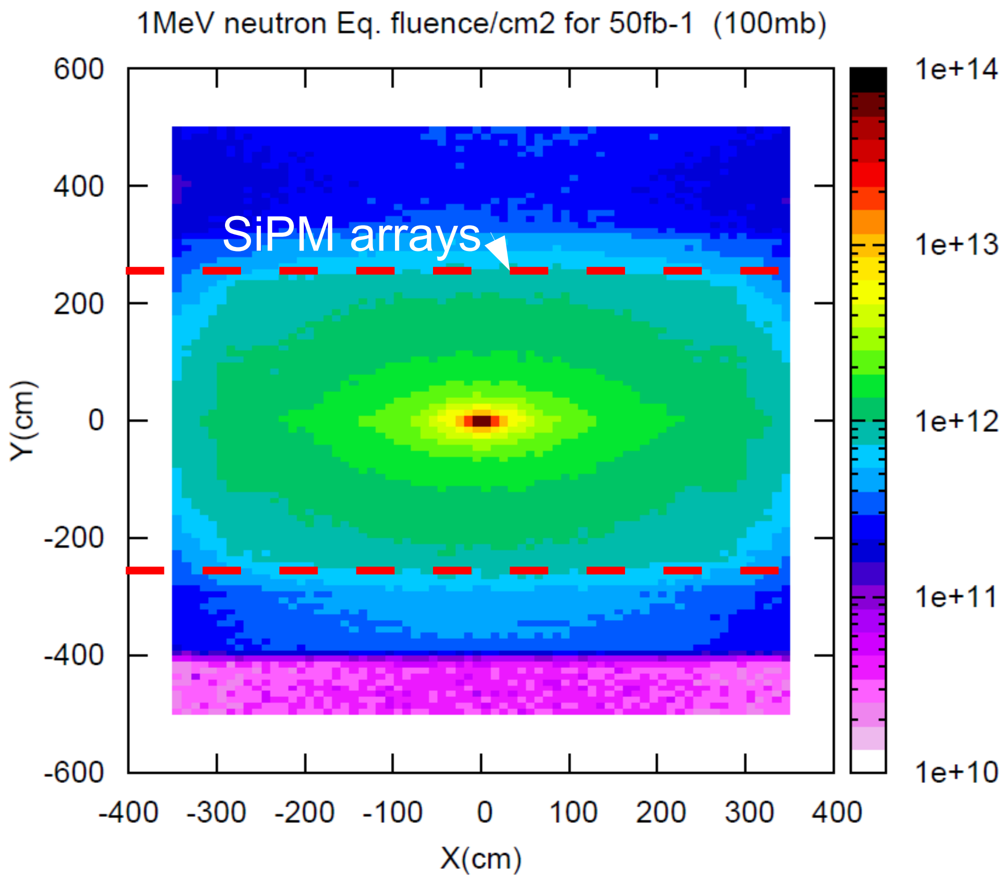
- for every 10K decrease in temperature, a factor of ~2 reduction in noise has been observed
- After-pulsing is also a minor issue, but we won't talk about it here (trapped charges that are delayed τ~100ns)



- Radiation will cause defects in the silicon
  - non-ionizing energy loss (NIEL) for charged particles is mainly due to the Coulomb interaction
  - neutrons interact mainly via elastic scattering with the nucleus.
  - Damage is energy and particle-type dependent
- A displacement threshold energy of about E=20eV can knock out a silicon atom from its lattice site.
  - By this effect an interstitial (I+) and a vacancy (V-) are created (Frenkel pair)
  - Higher energies can create clusters of defects from cascades.

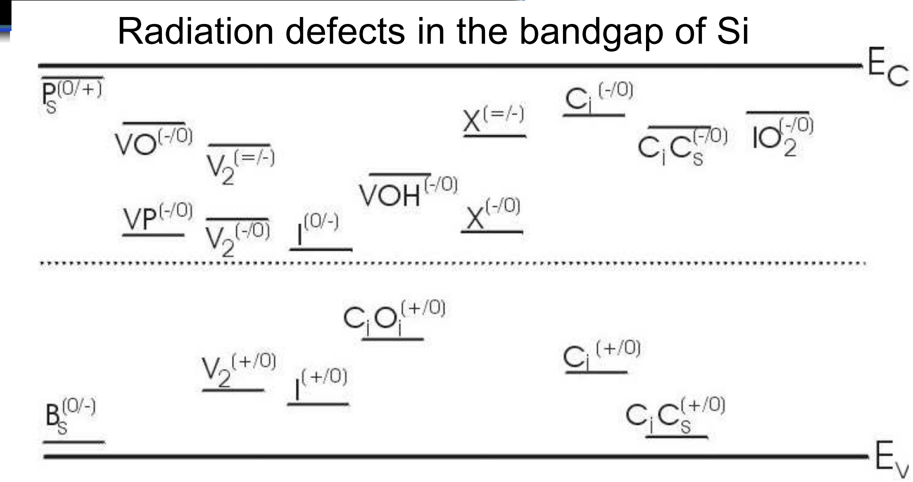


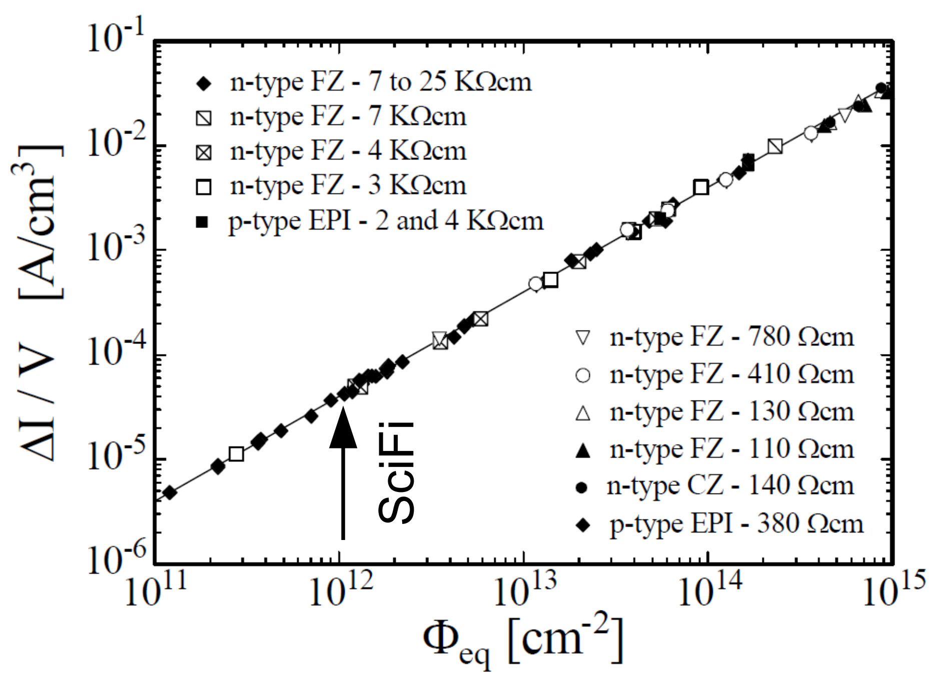
- 1.3 x 1012 neq/cm2 are expected for the central SiPMs at T3 (0.9x1012 @ T1)
- Mainly due to back scatter from calorimeters
- Possibility of shielding to reduce the neutron fluence by a factor of 2



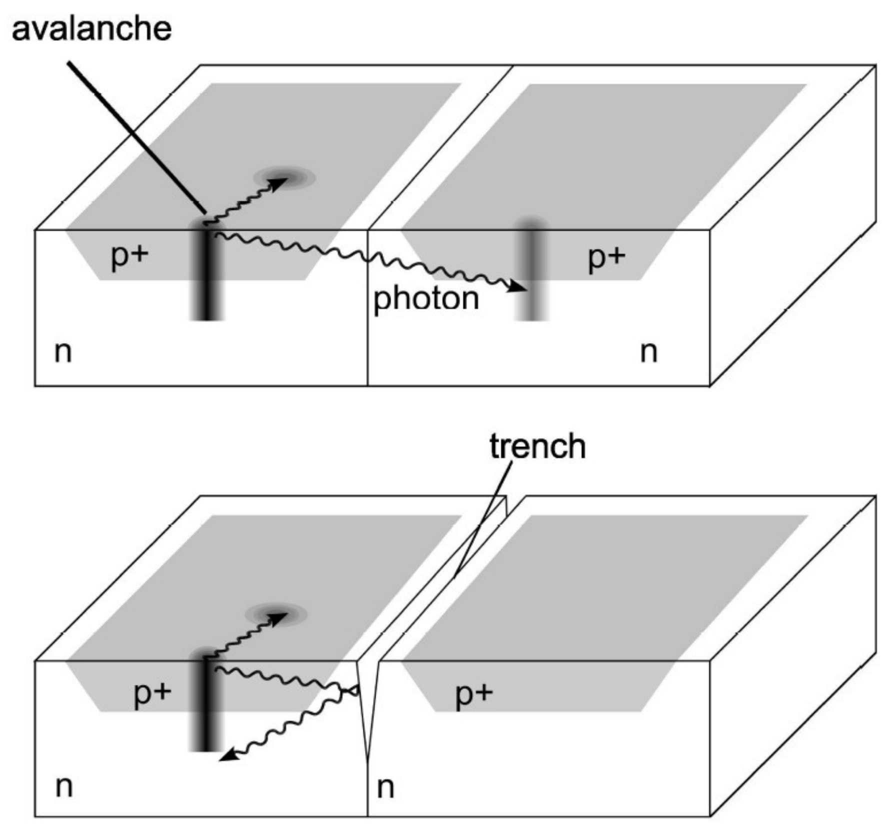
Damage

- These defects modify the electrical properties of the silicon
  - Introduces intermediate states in the band-gap region
- Damage is linear with the 1 MeV neutron equivalent fluence ($1.3\times10^{12}/cm^2$ for SciFi)
- Results in an increase of the leakage (dark) current in a reverse biased detector like the SiPM
- **Annealing**
  - Defects are mobile at certain temperatures
  - Defects can be removed or reduced by increasing temperature (~60C)
  - Planned for 40C cycles in the SciFi

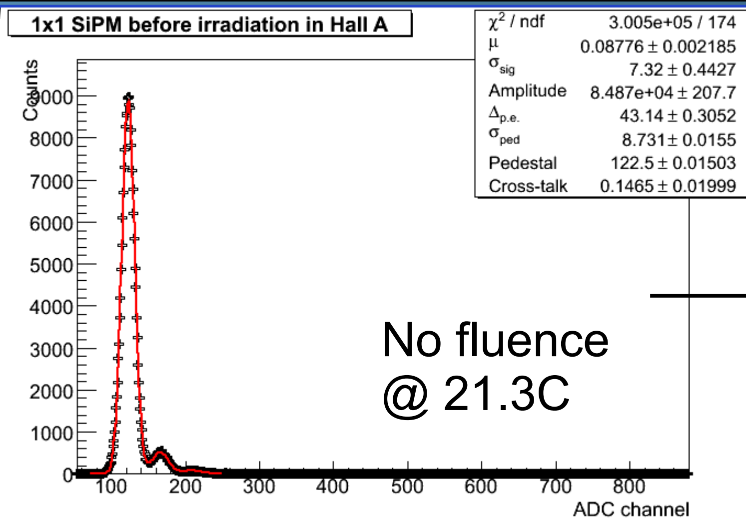




- Crosstalk: photons are generated by the charge avalanche
  - Direct: these photons enter an adjacent pixel causing it to fire
  - Indirect: absorbed in a sub-layer and re-emited into an adjacent pixel
- Has the appearance of increasing the signal amplitude
- A bigger problem when you have additional noise
  - 1 photoelectron from noise becomes 2+ with crosstalk
  - Looks like a weak signal!
  - High rates begin to look like track clusters
- Crosstalk can be reduced with trenches
  - 21% → 7% (bias voltage dependent)

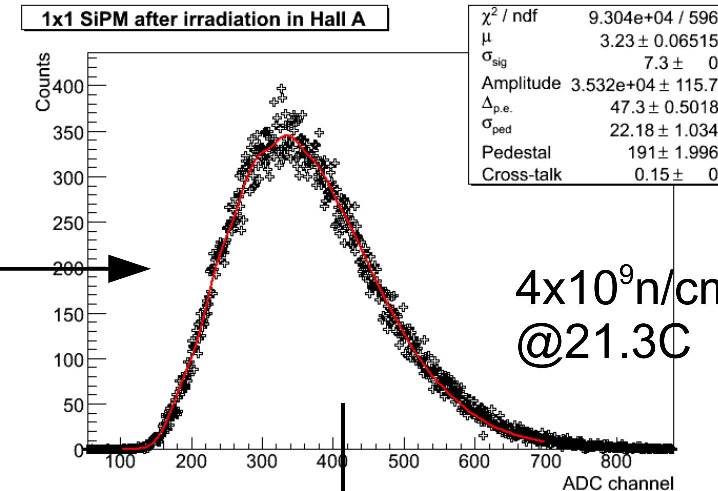


Damage



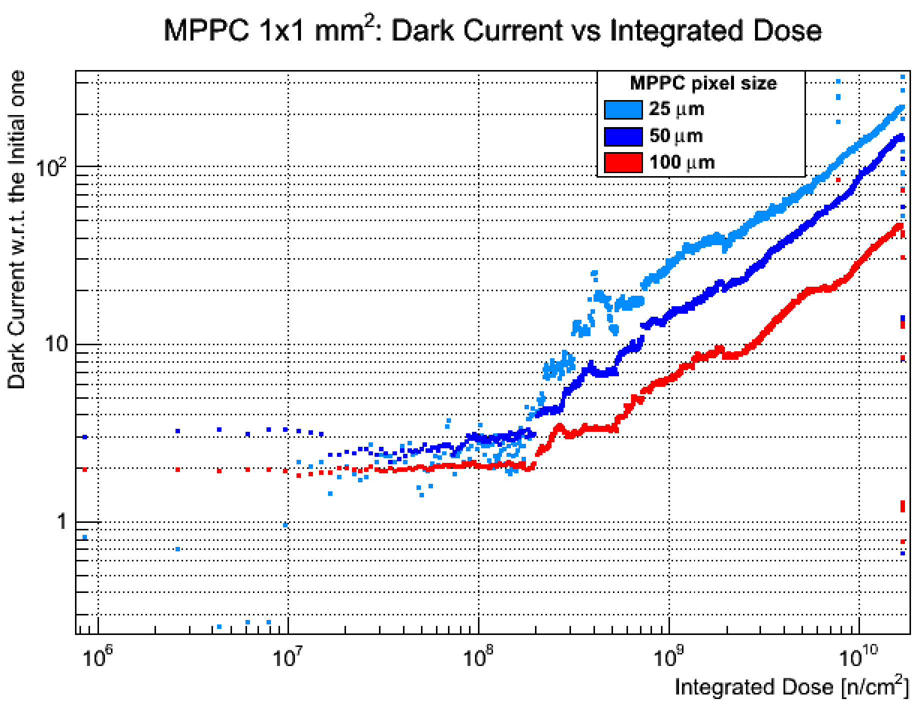
No fluence
@ 21.3C

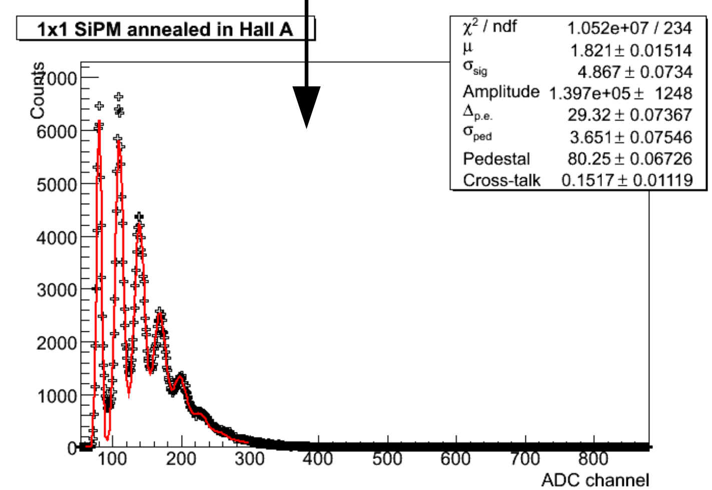
irradiated



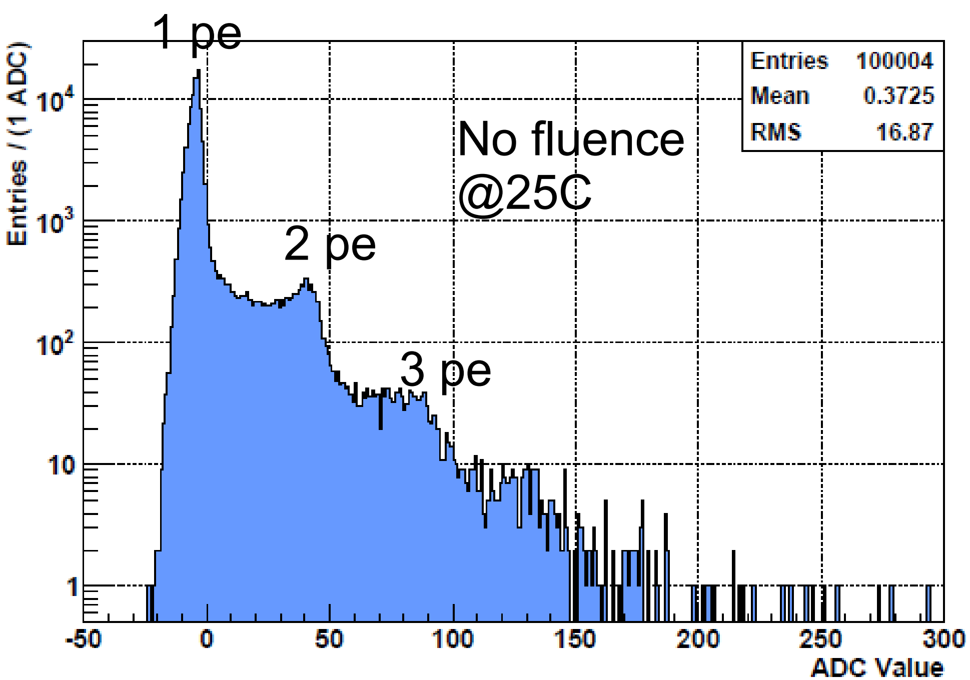
$4\times10^9 n/cm^2$
@21.3C

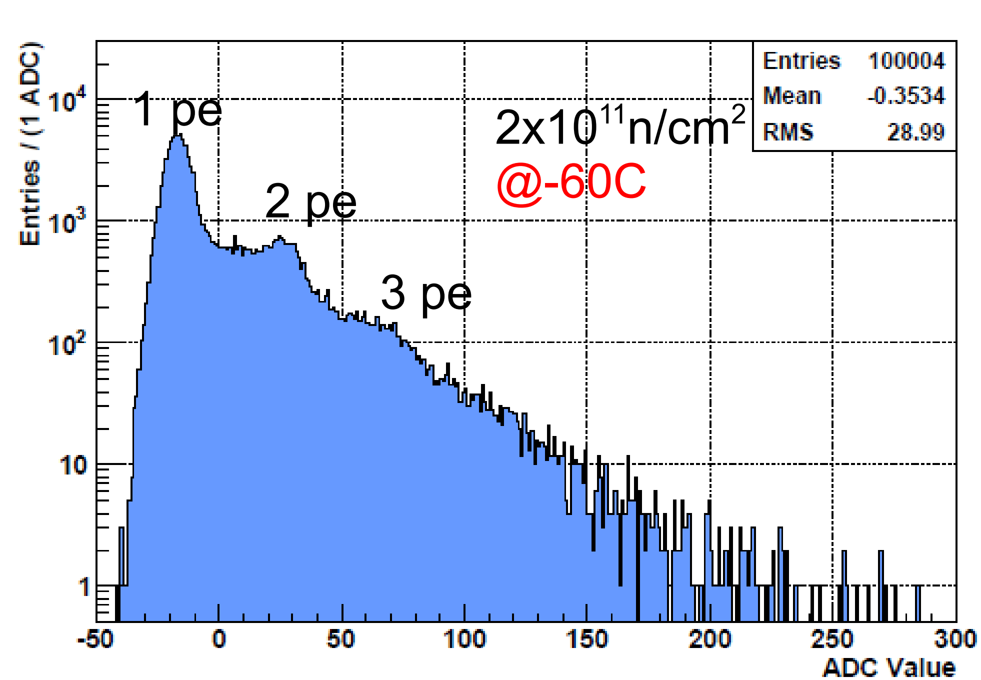
annealed





- Dark noise signal before and after irradiation





- Without cross talk, 2pe noise is only about 2% of 1pe

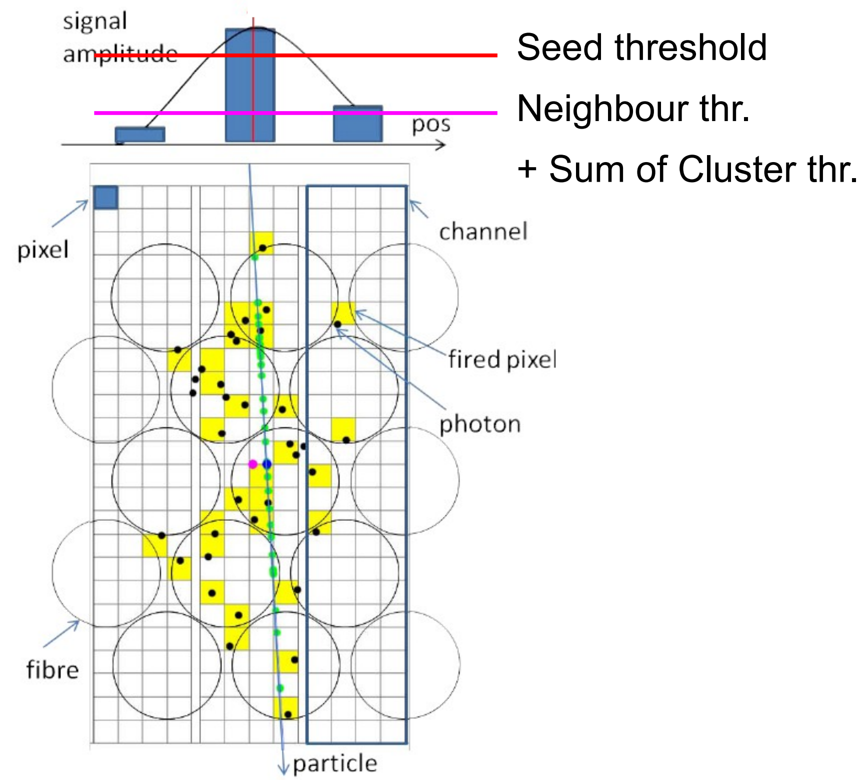
- Analog or digital clustering → Cluster finding and Noise rejection algorithms
- First find Cluster Seeds (signals>~2.5 p.e.)
- Secondly, add neighbours if they exceed the Neighbour Threshold (>~1.5 p.e.)
- Thirdly, the sum of the cluster must exceed the Cluster Threshold (>~4.5)

Analog: $$\overline{X} = \frac{\sum_{i=1}^{N} X_i C_i}{\sum_{i=1}^{N} C_i}$$ σ_x = 55 μm

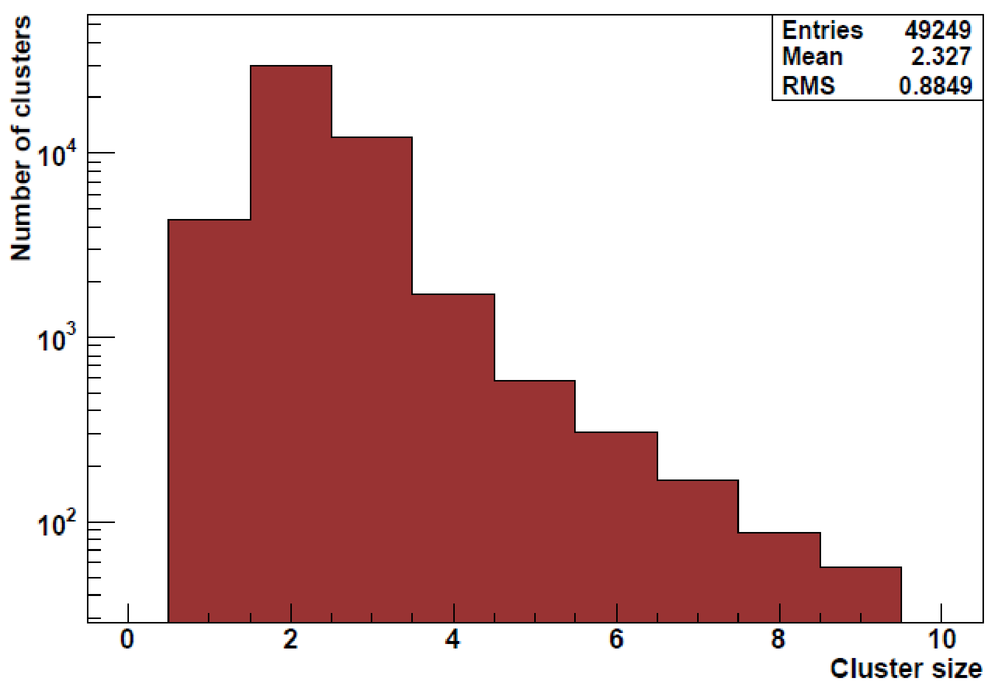
Charge weighted

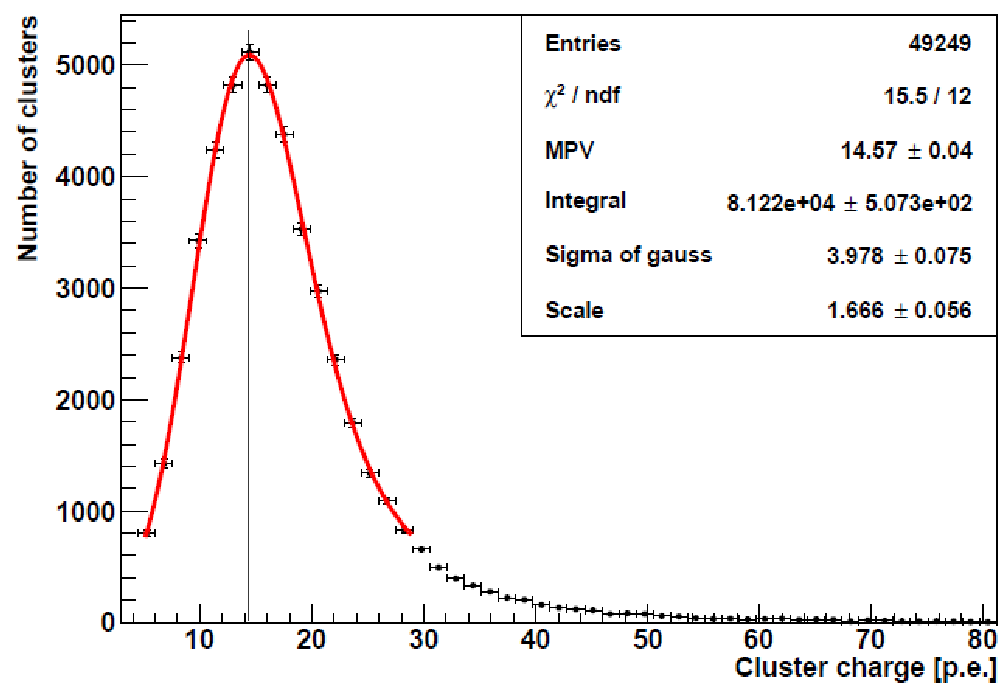
Digital: $$\overline{X} = \frac{\sum_{i=1}^{N} X_i}{N}$$ σ_x = 65 μm

$$\sigma_{square} = \frac{250\,\mu m}{\sqrt{12}} = 72\,\mu m$$

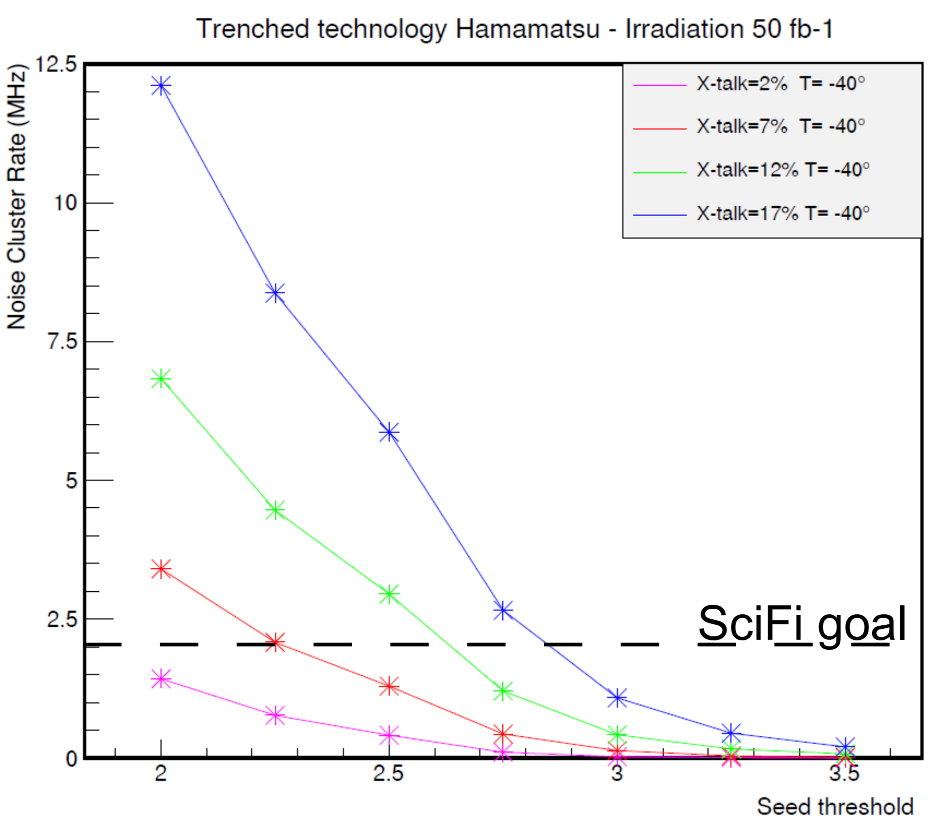


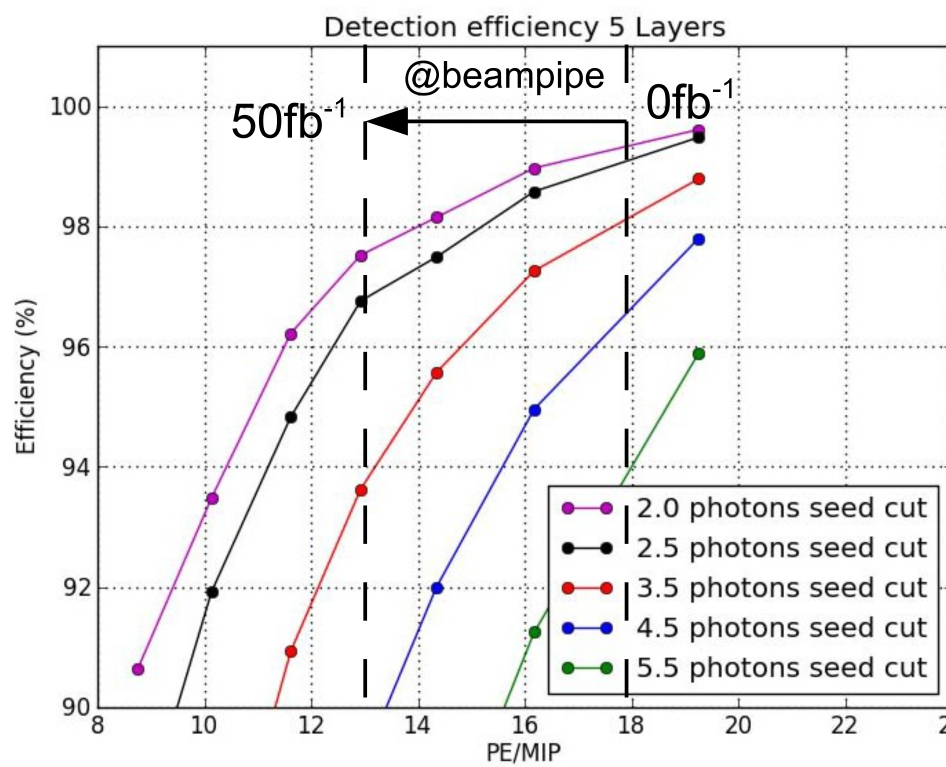
- Signal cluster results from a cosmic ray test stand (un-irradiated):
  - Single channel clusters contribute 9% of the total
  - 2 ch = 60%;
  - 3 ch = 25%;
  - 4 ch= 3%; >4 ch = 2.6%

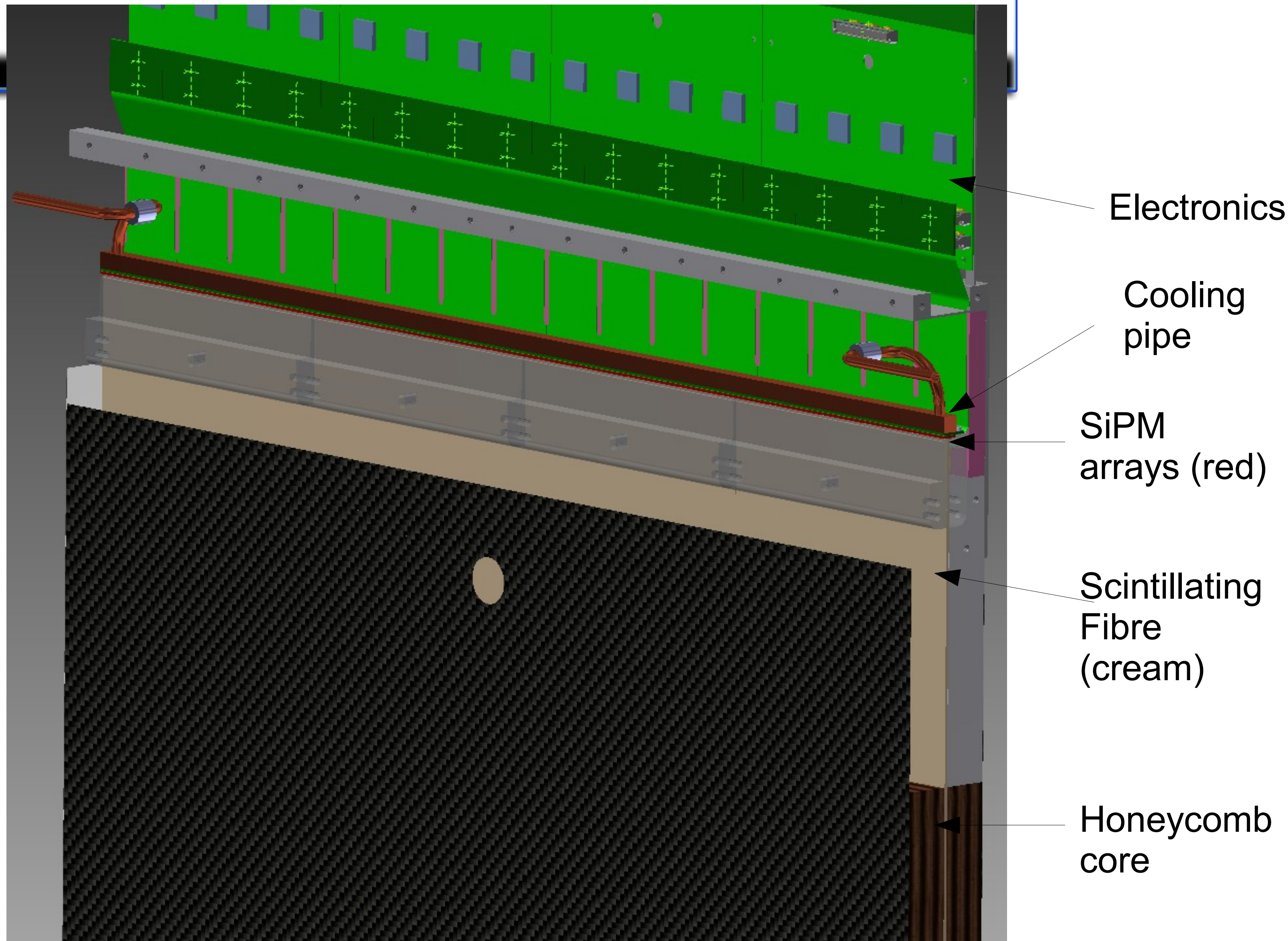




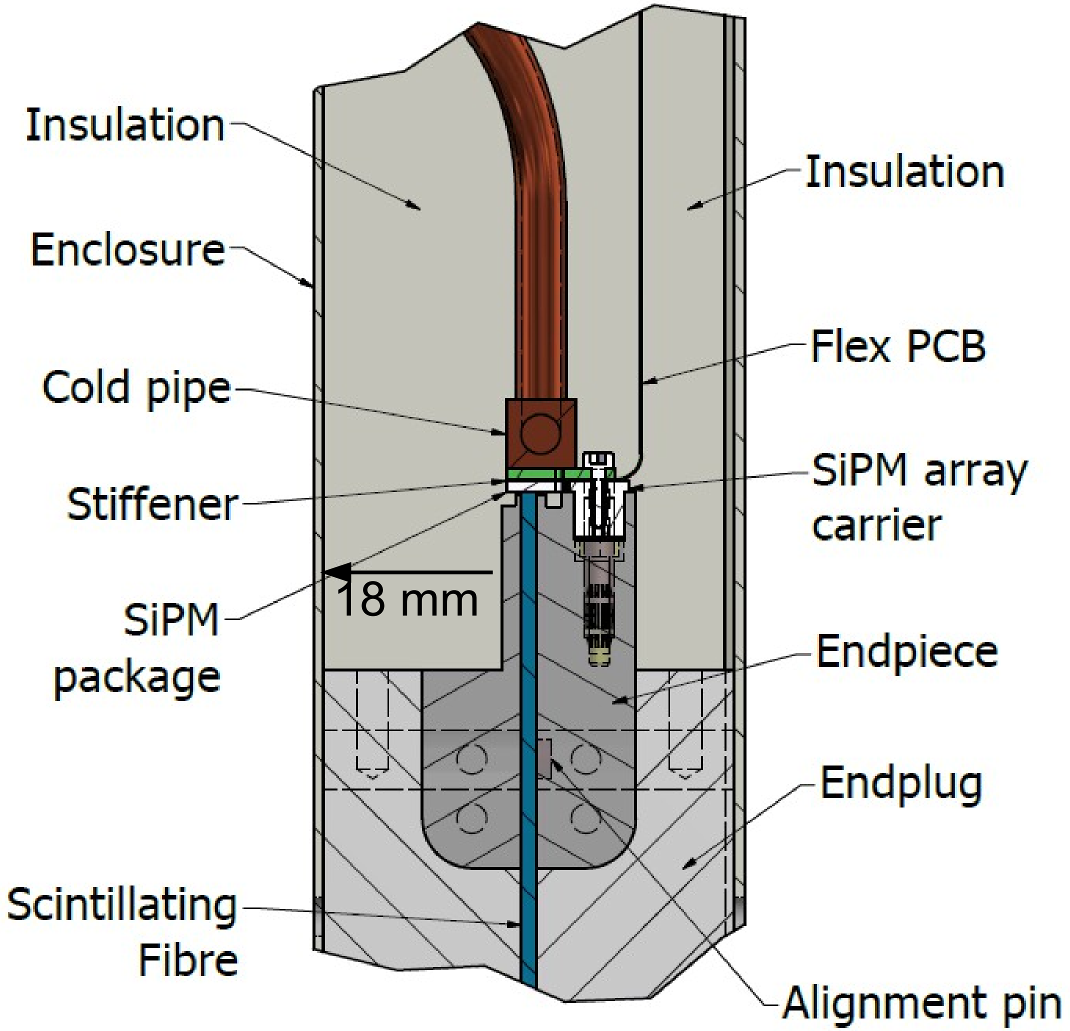
- We want a higher threshold to exclude noise contributions but a low threshold to retain signal, resolution and hit efficiency
- Excessive noise clusters will degrade tracking






Electronics
Cooling pipe
SiPM arrays (red)
Scintillating Fibre (cream)
Honeycomb core

- Single phase liquid cooling
- Compact space
- <20 W thermal load per module
- SiPMs produce little to no heat; box dominated by parasitic heat load
- Issues with condensation and frost need to be dealt with



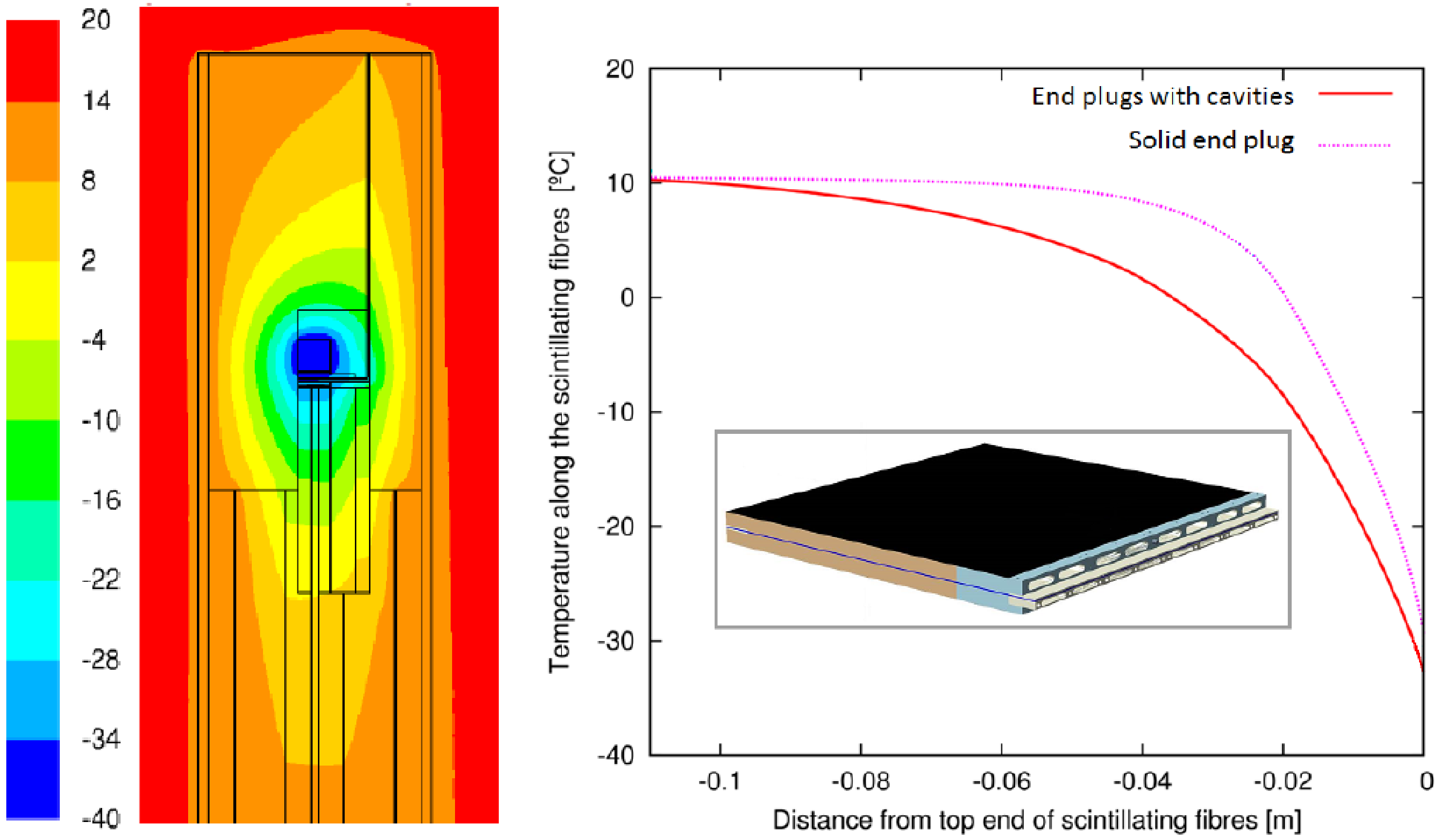
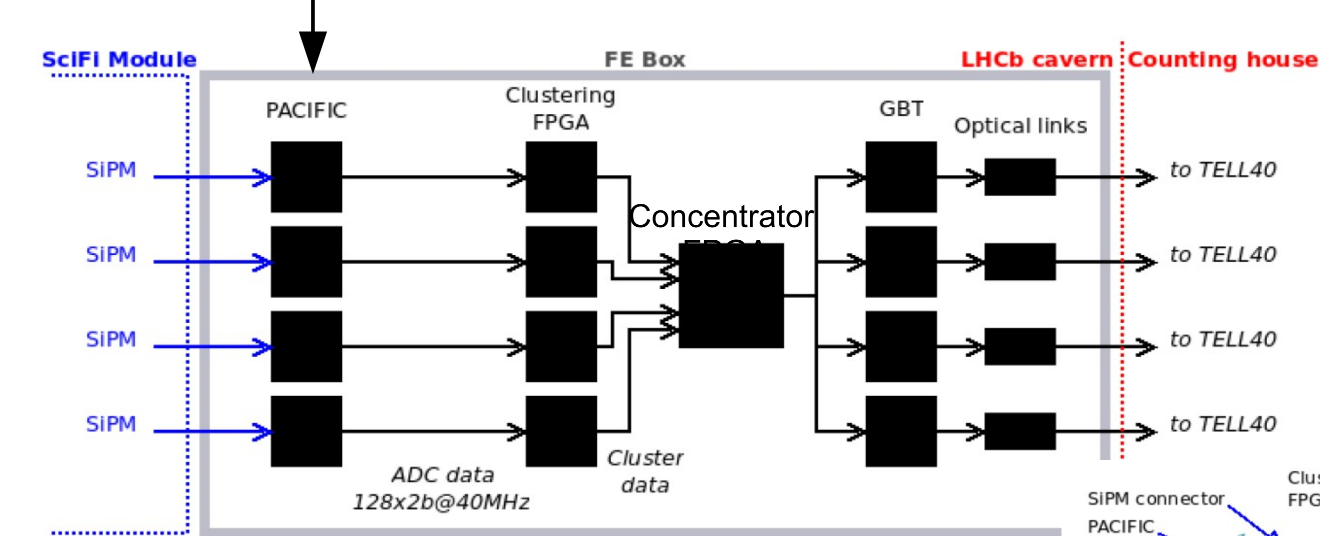
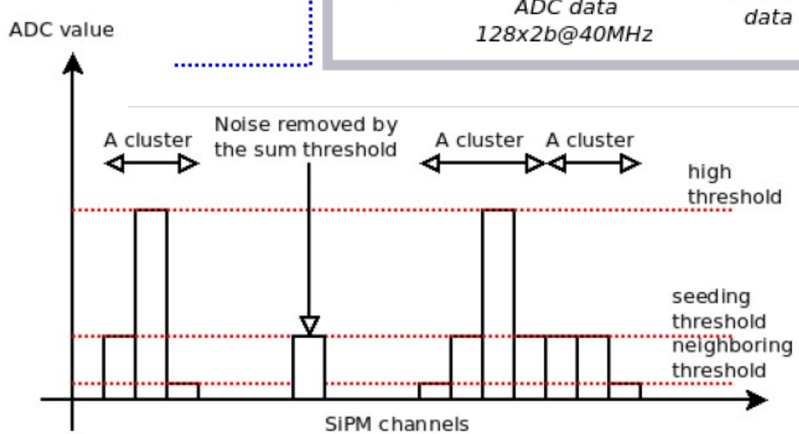


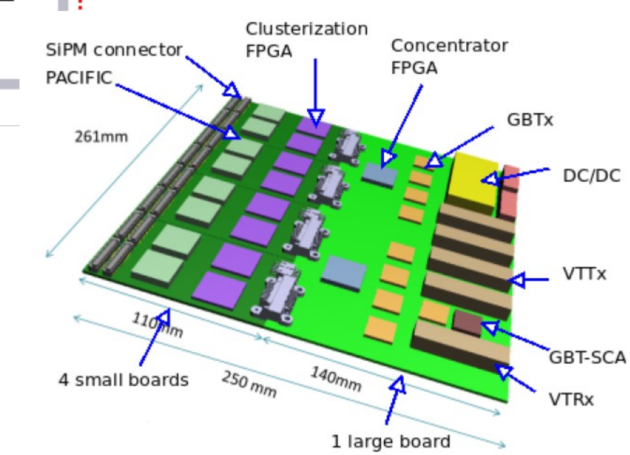
Figure 1.46: An ANSYS thermal simulation of a simplified SiPM compartment of the Read-out Box. Left: The temperature distribution around the SiPM array. Right: fibre temperature profiles as function of the position along the mat with and without cavities in the end-plugs (position 0 corresponds to the contact between the mat and the SiPM, position –0.11 corresponds to the bottom of the end-plug). A detail of a simulated module is shown in the insert.

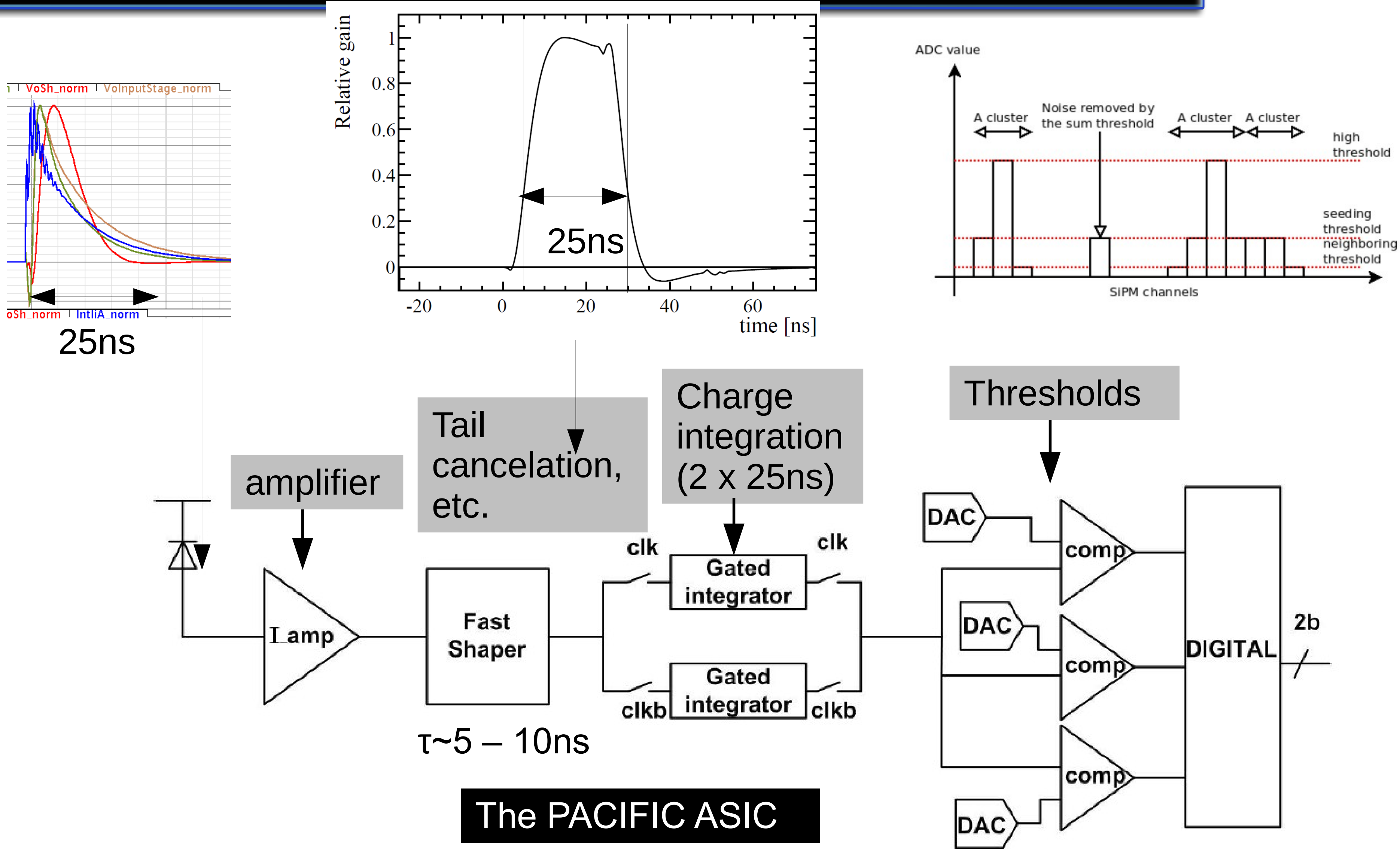
- Digitizes the SiPM signals and forms the clusters and hit positions

Amplification, Shaping, Integrating Digitization (ASIC)








VoSh_norm
VoInputStage_norm
oSh_norm
IntIA_norm
25ns
Relative gain
1
0.8
0.6
0.4
0.2
0
-20
0
20
40
60
time [ns]
25ns
ADC value
A cluster
Noise removed by the sum threshold
A cluster
A cluster
high threshold
seeding threshold
neighboring threshold
SiPM channels
amplifier
Tail cancelation, etc.
Charge integration (2 x 25ns)
Thresholds
I_amp
Fast Shaper
τ~5 – 10ns
clk
Gated integrator
clk
clkb
Gated integrator
clkb
DAC
comp
DAC
comp
DAC
comp
DIGITAL
2b
The PACIFIC ASIC

- End.