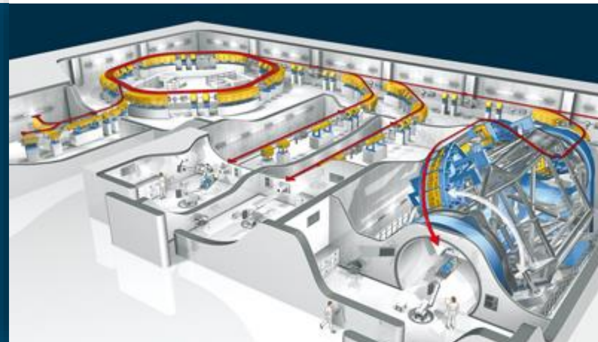
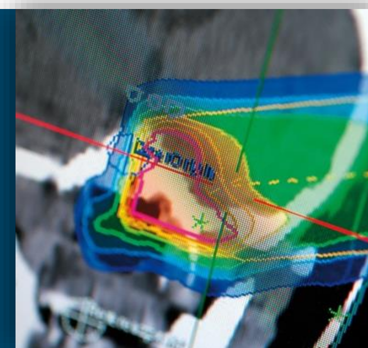
HEIDELBERG UNIVERSITY HOSPITAL
HIT Heidelberger Ionenstrahl-Therapiezentrum
dkfz. GERMAN CANCER RESEARCH CENTER IN THE HELMHOLTZ ASSOCIATION
GOETHE UNIVERSITÄT FRANKFURT AM MAIN





Development of a Scintillation Fiber Transverse Profile Monitor for Low-Intensity Ion Beams at HIT

DFG Deutsche Forschungsgemeinschaft

14.07.2022, Richard Hermann

Agenda

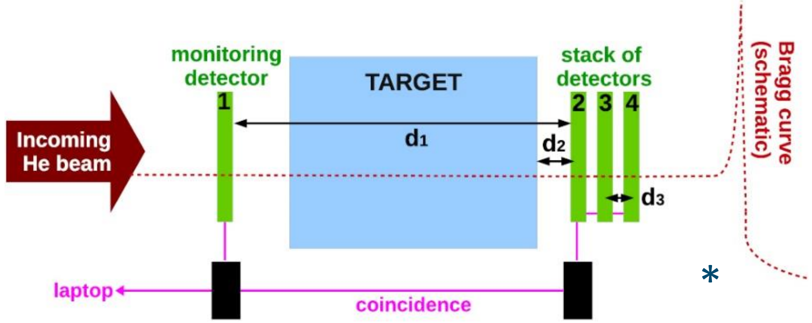
- Intro
- Prototype
- Experiments
- Conclusion & Outlook

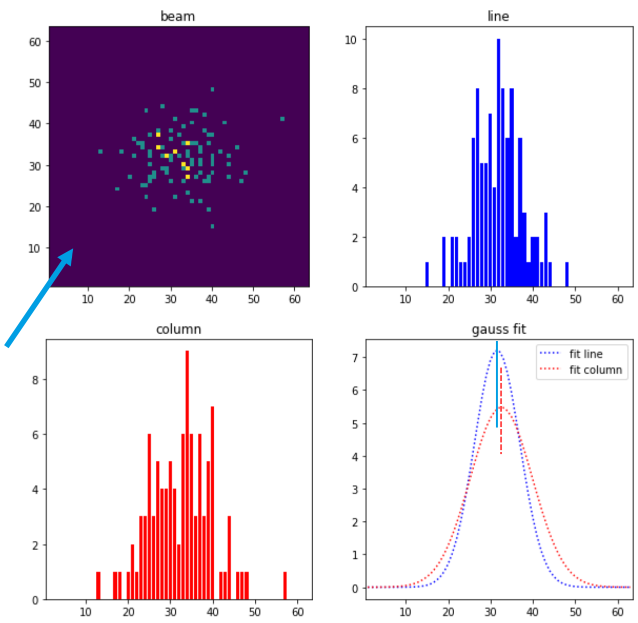
DFG Project

“Energy-painted ion radiography for precision radiotherapy“

- Helium Beam Radiography (Tim Gehrke)

  1. Smaller geometric uncertainties between CT and therapy.
  2. Tissue stopping power more precise.
  3. Smaller radiation dose.





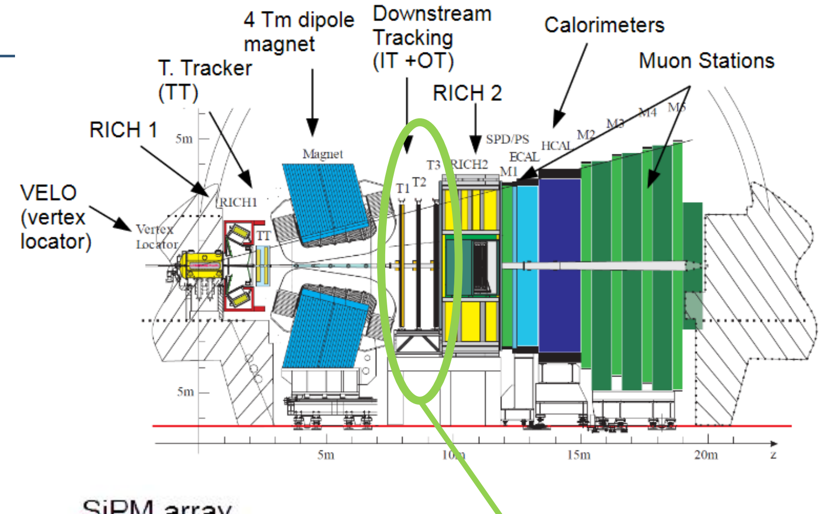
100 Ionen

Requirement:

- **Monitor for low intensity ion beams.** Beam pos. and shape not yet monitored for ≤ 10^5 pps (feedback missing)

*G. Aricò, T. Gehrke, J. Jakubek, R. Gallas, S. Berke, O. Jäkel, A. Mairani, A. Ferrari, M. Martišíková, *Investigation of mixed ion fields in the forward direction for 220.5 MeV/u helium ion beams: comparison between water and PMMA targets*, Physics in medicine and biology **62**, 8003 (2017).

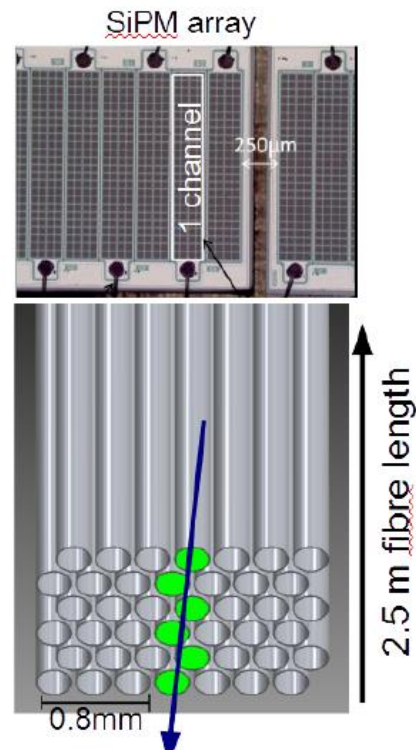
Idea from
LHCb Tracker @ Cern

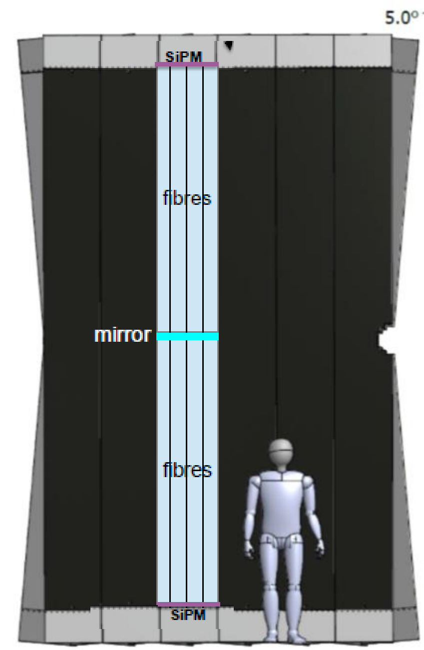


- LHCb fibers: 250µm x 3m, 6 layer, round (Kuraray SCSF-78MJ) (B. Leverington)

- 7.200 photons per MeV
  - 0,4 MeV/mm (@220 MeV/u He)
  - 5,4% trapping
  - 35% PDE* der SiPM**
  - 2x ~5% opt. coupling losses (air) *(R_s = 11.55% , R_p = 1.19%)*

→ ≈ 45 photo electrons / He-ion
(> 5 p.e. needed for S/N threshold)





+ 5% non-detected ions in on layer of round fibers.

***PDE: Photon Detection Efficiency **SiPM : Silicon Photomultiplier**

B. Leverington „The SciFi Tracker for the LHCb Upgrade", Vortrag 2014 in Neckarzimmern

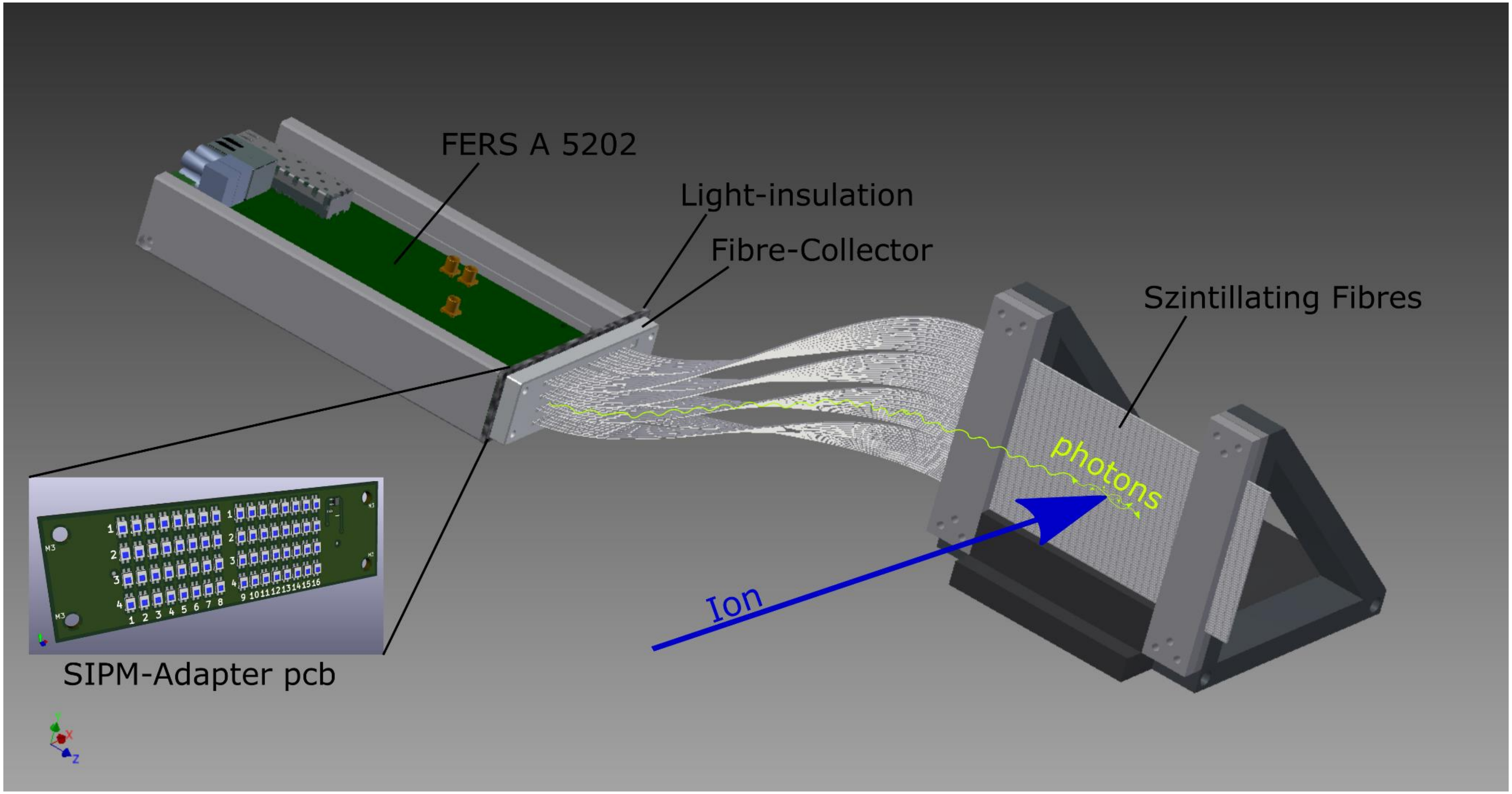
Profile monitor for low intensity ion beams
Advantages of LHCb inspired SciFi-Detector

- Highly-tested, radiation hard and cheap fibers
  - Low running/replacement costs: ion damage and aging only on fibers
  - Expensive electronics in safe distance to beam (≠ semiconductor det.)

- Clear structure of detector system
  - Only a few components
  - No gas or vacuum necessary
  - No semiconductor creation necessary
  - No cooling necessary (works at RT)

- Usability
  - Scalability of detector channels and electronics
  - Readout electronics commercially available and comes with control software for first experiments

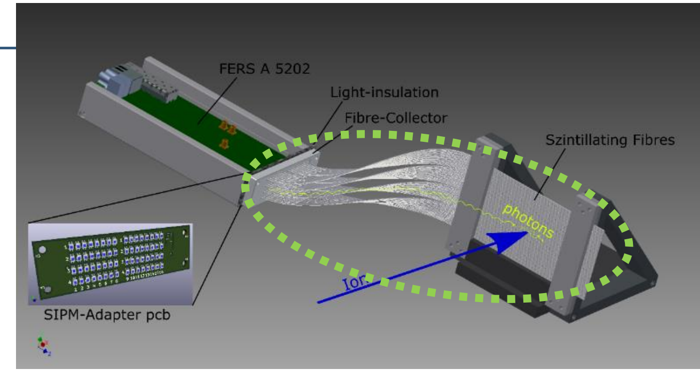
Prototype
Idea for first test setup



Readout inspired by IDEA Dual-Readout calorimeter - R. Santoro, INFN

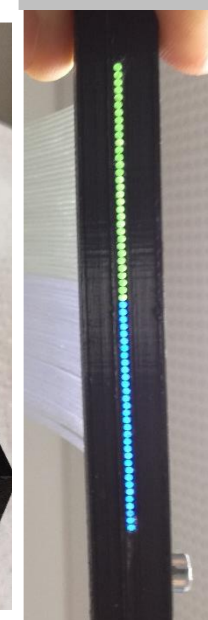
Scintillating fibers

Probes



- Cutted and polished by hand
- PI Heidelberg:
  gluing into 3D print and milling
- Kuraray SCSF-3HF multiclad
  - Radiation harder
  - 7ns decay, 530nm
- Kuraray SCSF-78 multiclad
  - Same as LHCb
  - 2.8ns decay, 450nm
- Radiation hardness:
  SCSF-3HF 20% loss where SCSF-78 has 60% loss *

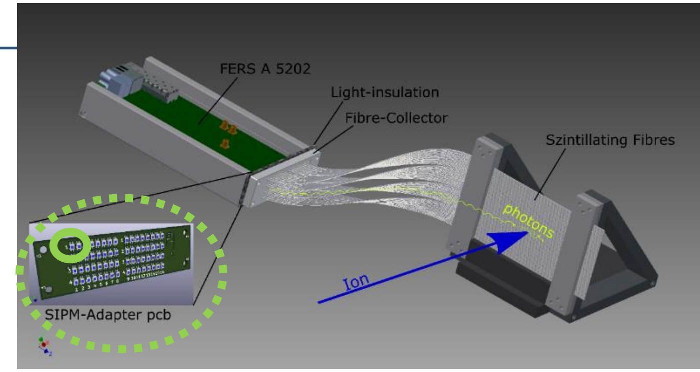
Kuraray 3HF multi clad



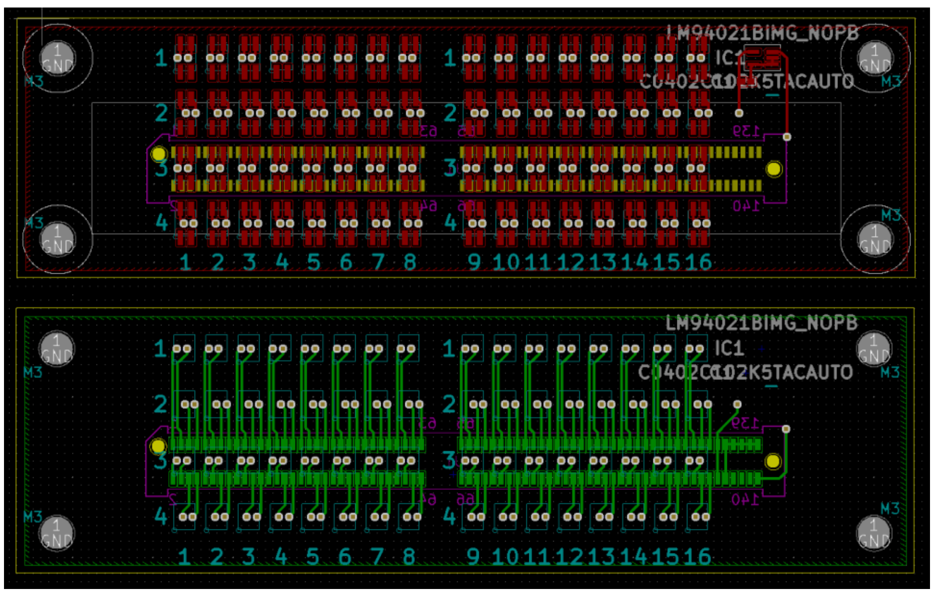
Kuraray 78 multi clad

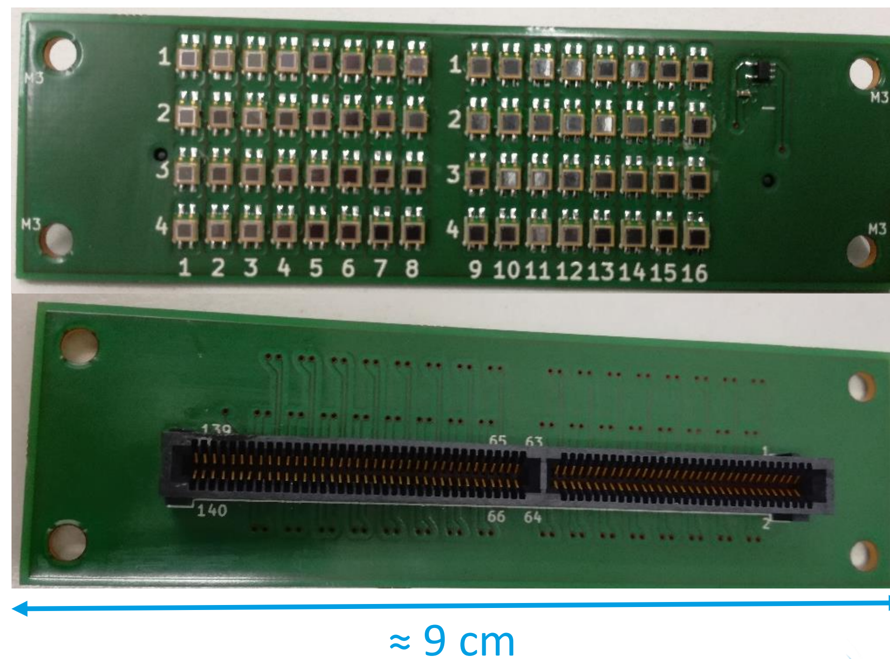
** Preliminary radiation damage analysis for the HIT beam profile monitor; M.Dziewiecki, B.Leverington, G.Meo; Heidelberg 13.02.2018*

Photomultiplier
SiPMs on PCB*

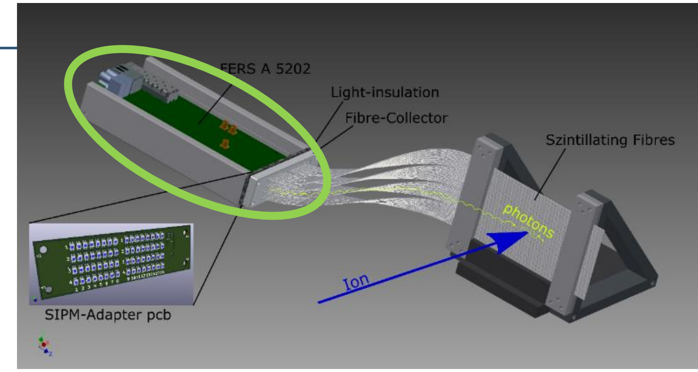


- MPPC** (S13360-1350PE)
  - 667 cells (50µm APDs) on 1,3x1,3mm² active area
  - Peak PDE at 450nm = scintillating fiber (SCSF-78)



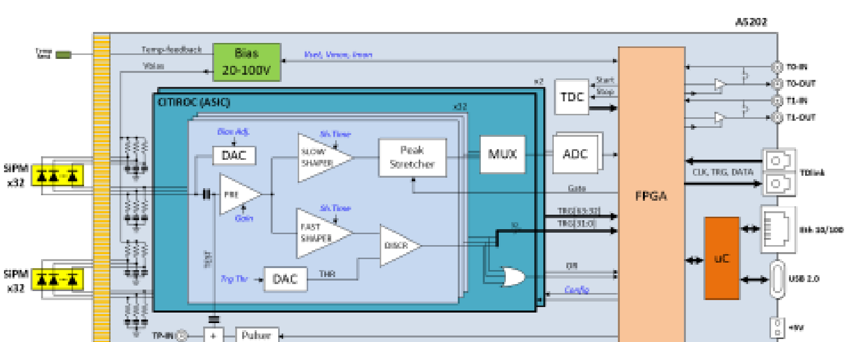


*PCB: Printed Ciruit Board
**MPPC: Multi-Pixel Photon Counter (by Hamamatsu)

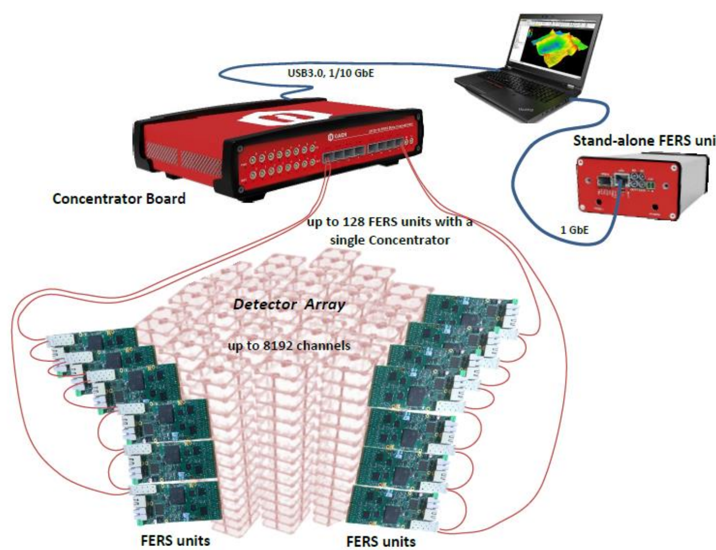


Electronics
Readout System

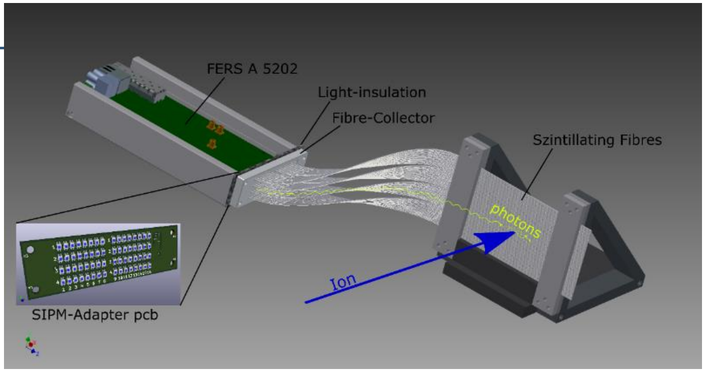
- CAEN FERS A5202
  [64 Channel CITIROC ASIC]

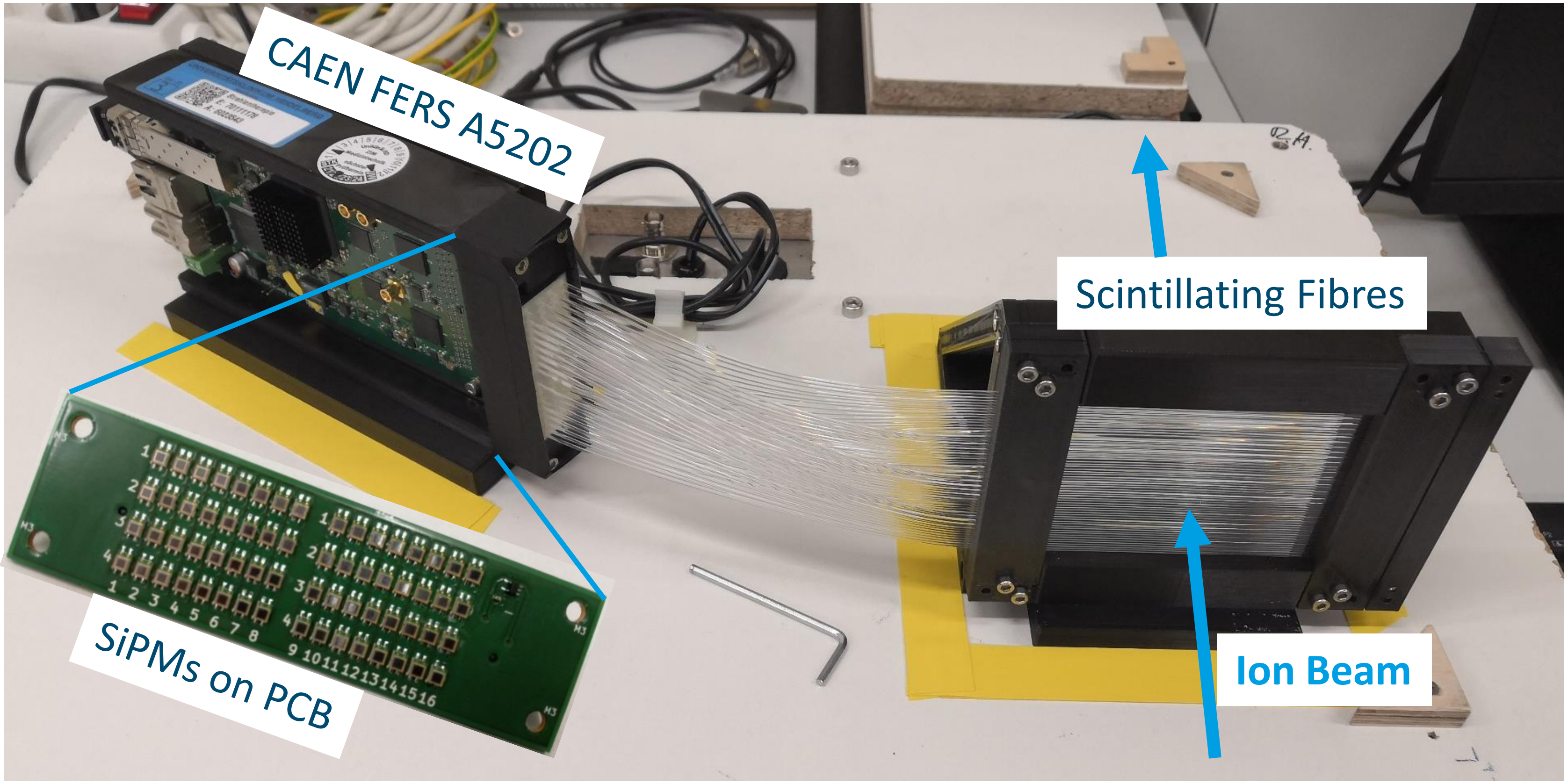


- *Future:* DT5215 (CAEN)
  combines several FERS boards



Prototype Setup
Realization

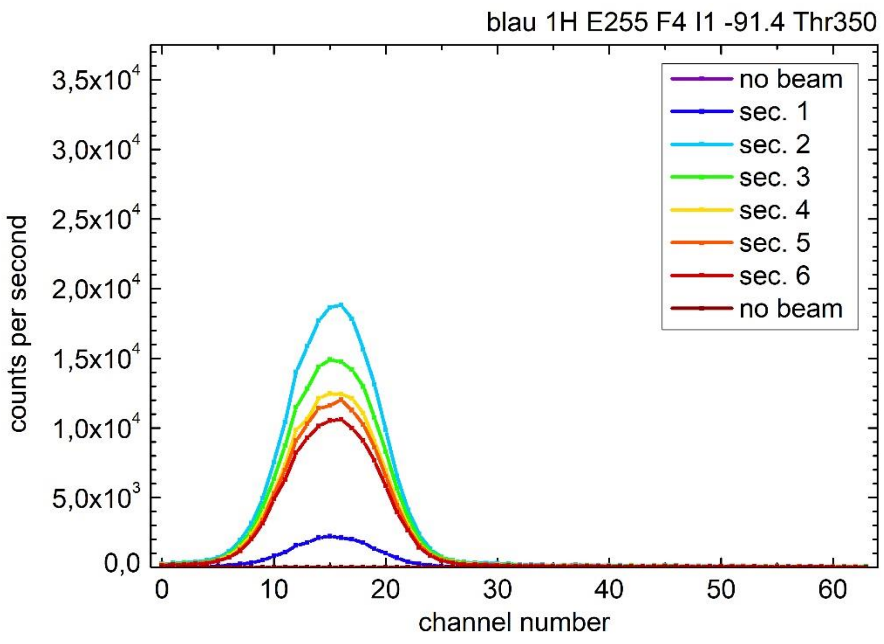




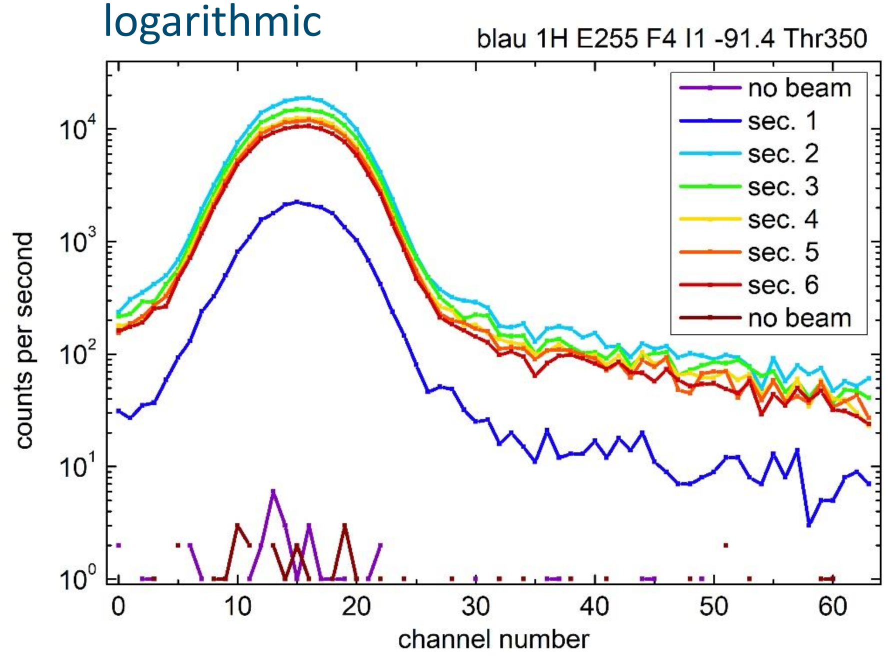
Measurements In Beam

1H, E#255, F#4, < I#1

- ≈ 100.000 ions/sec.
- Threshold 350 (a.u.) from staircase plot



logarithmic



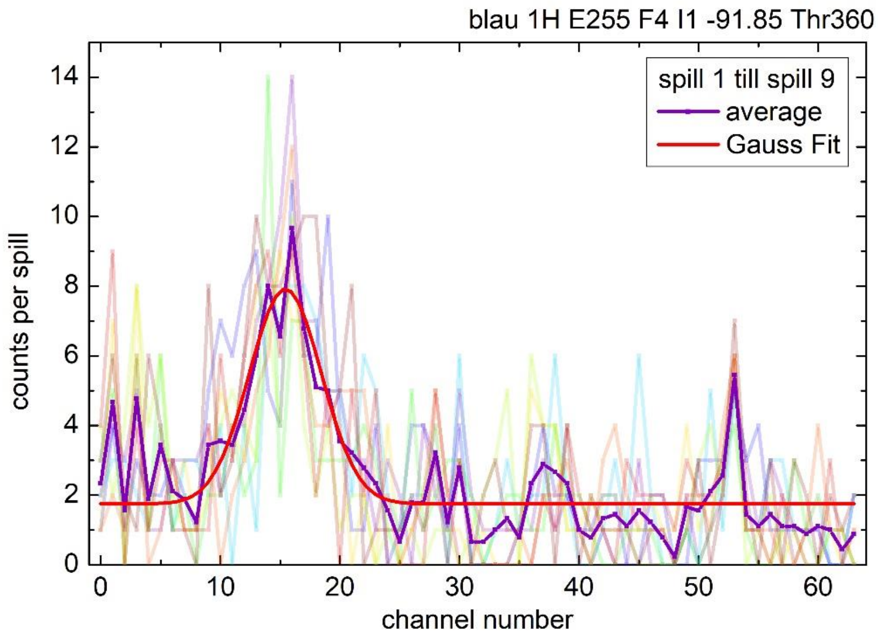
→ Signal to DCR: ≈ 20.000

→ Signal to Noise within beam: ≈ 50 - 100

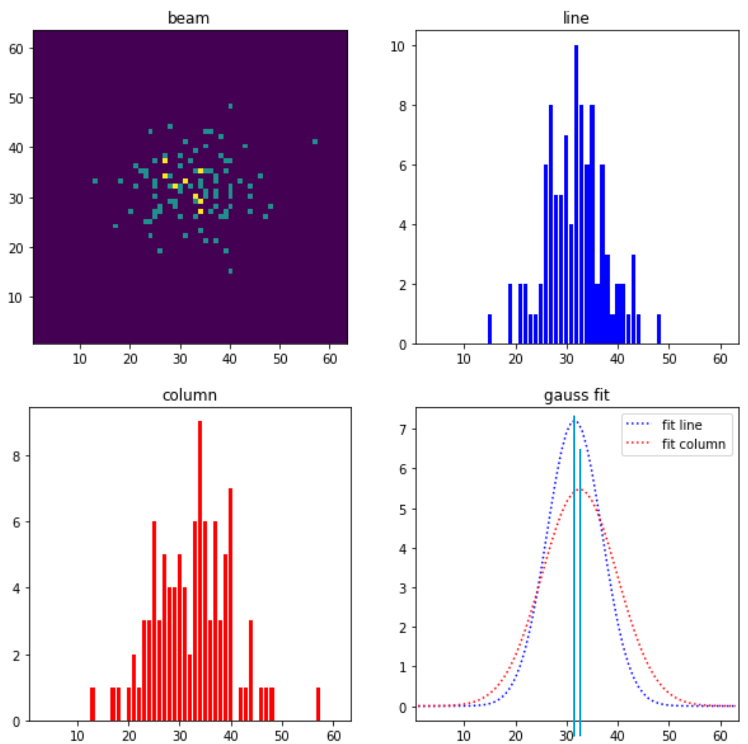
Proof of Principle: very low intensity beam

1H, E#255, F#4, << I#1

- Really low intensity: ≈ 8 ions/sec. (-> from TimePIX)



Simulation: 100 Ions



→ Edge of useful resolution reached.

→ Proof of principle ✓

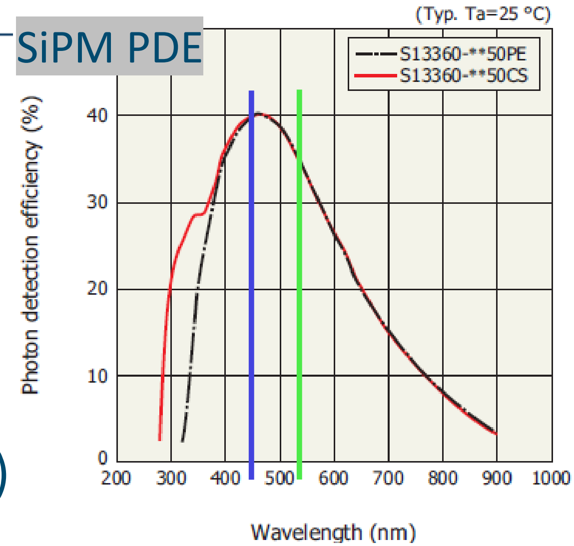
Measurements In Beam

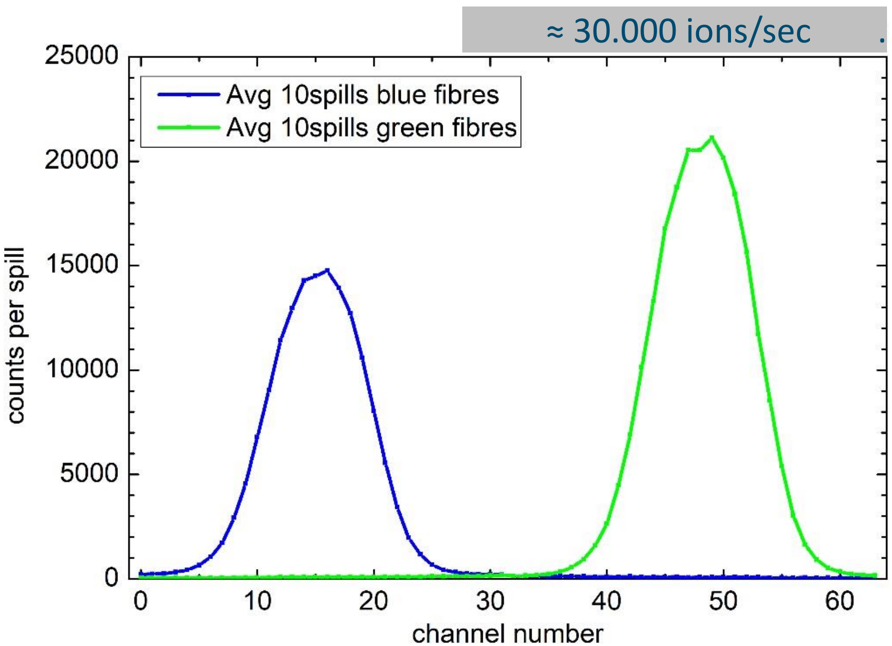
1H, E#255, F#4, < I#1

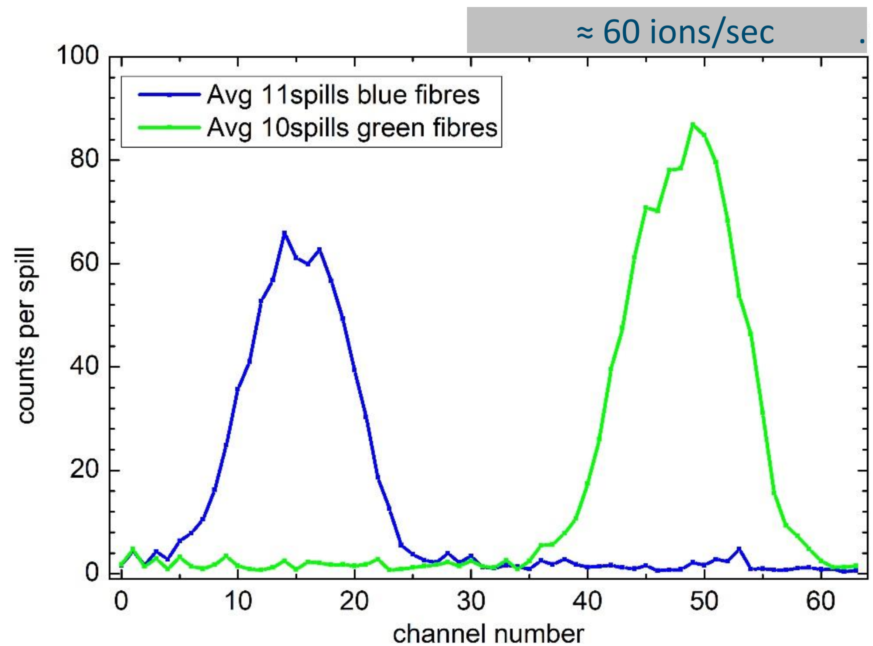
- Kuraray SCSF-78 (450nm, 8k phot./MeV*)

VS

- Kuraray SCSF-3HF (530nm, 7.1k phot./MeV*)







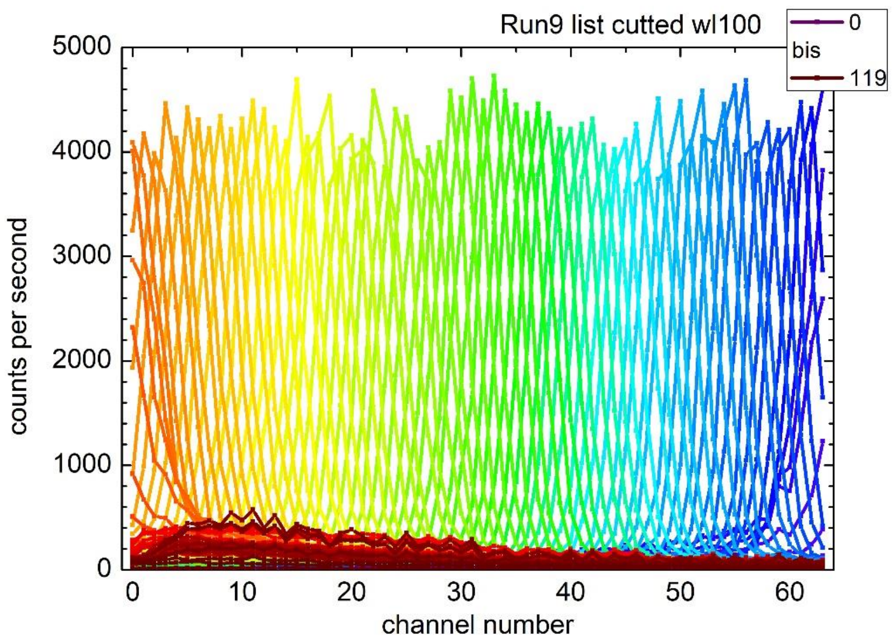
→ Fibre-SiPM combination seem to have better S/N in this application.

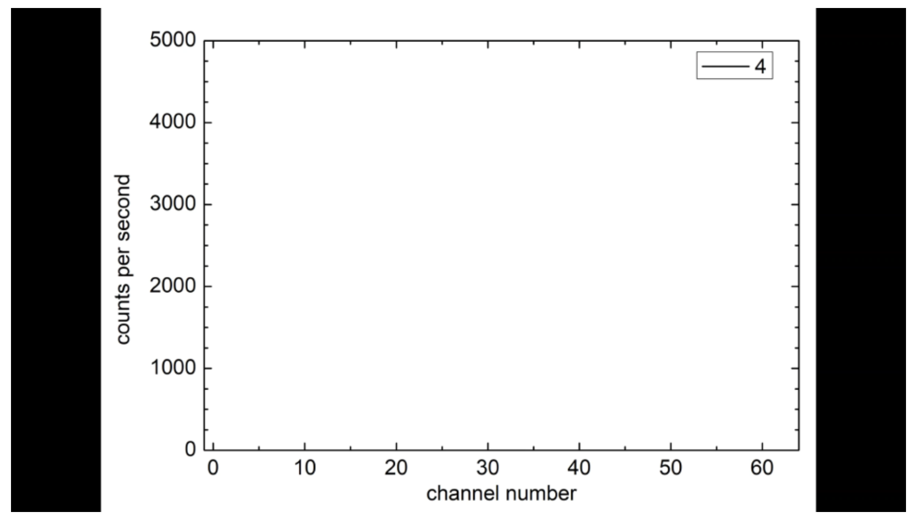
* From Saint-Gobain fibre product sheet. Values for Minimum Ionizing Particles (MIP), corrected for PMT sensitivity

Measurements In Beam

C12 Scan, 430 MeV/u, F 3.4mm, 20k ions/mm

- 100 steps in 1,2 sec (from -50mm till 50mm) → 2E6 ions/sec (≙ I#1)





- 10ms frames
- 8x slower than reality

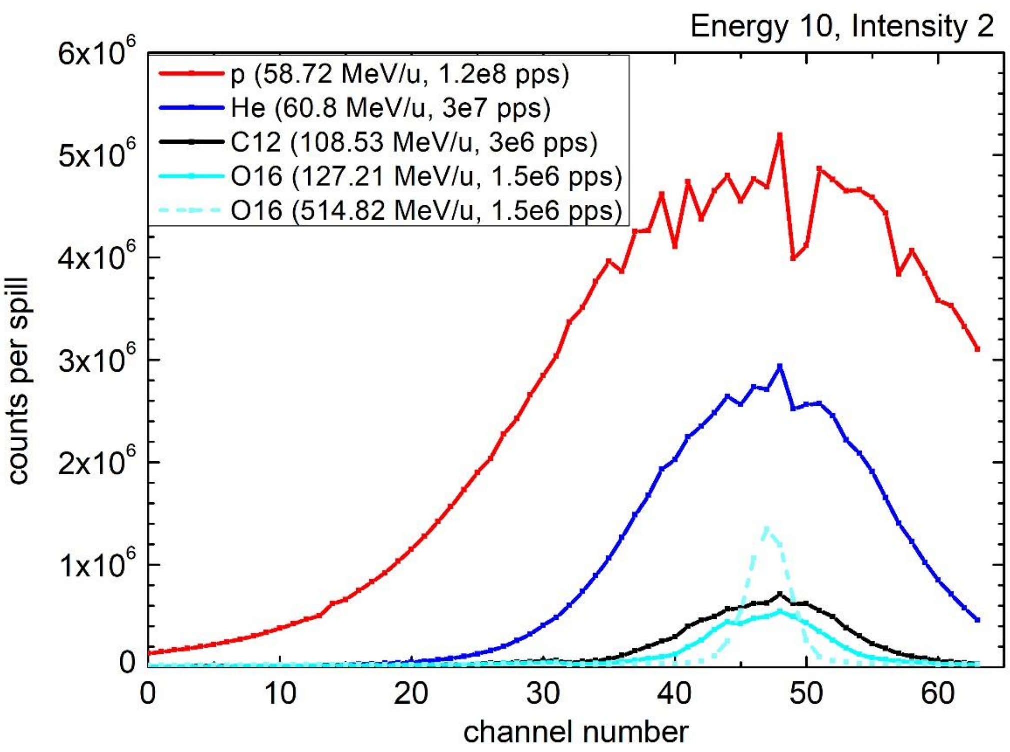
→ Position and width, movement and timing measurable.

→ If perfected, this can be used to define supply voltage corrections for SiPMs

Ion Comparison
All at E#10 and I#1

- I = 10mA was max.
- I > 1mA looses gaussian shape
- Over current only for wide (F > 1), high intensity proton beams.
- Anyway, data loss through jumped time windows

- Over a certain limit (roughly at 1e7 pps) SiPMs can't fully recharge before next hit.
  → Missing counts
  → non-gaussian form



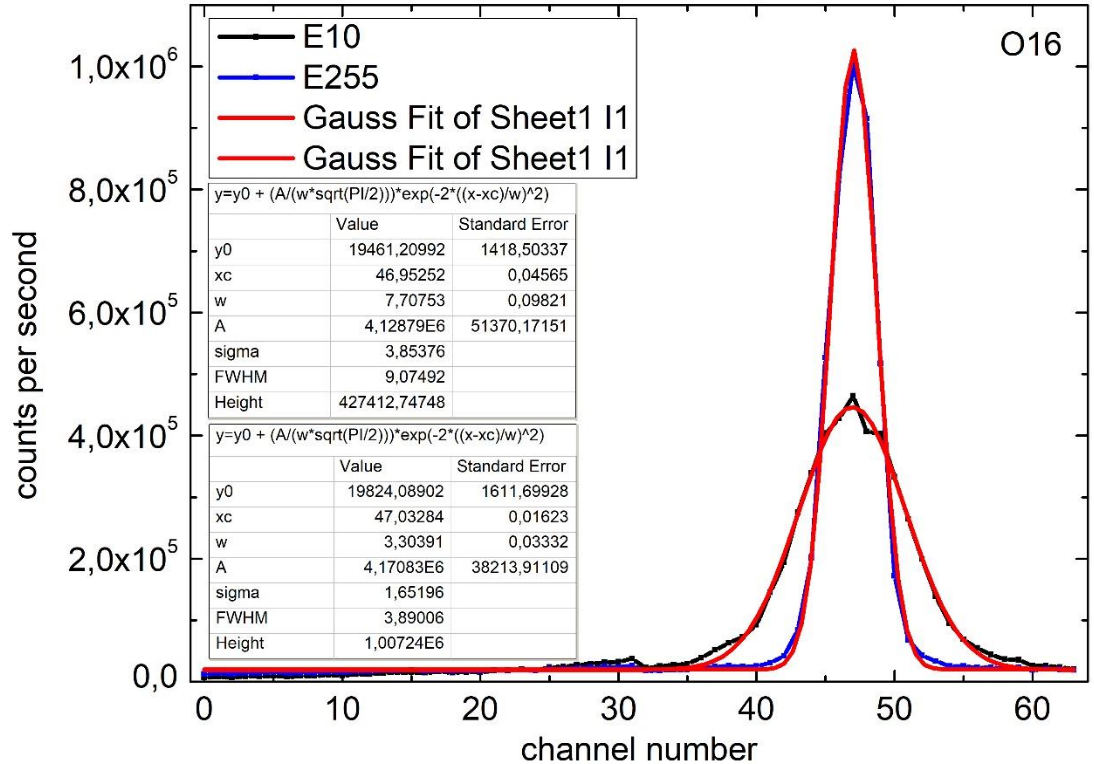
Energy comparison
Oxygen with E#10 and E#255 (1.5e6 pps)

- Higher Energy (same intensity)
  → smaller spot (=FWHM)

- Area A is the same
  difference: 0,01%

- y_0 = x ± ~8%
- xc = x ± ~0,1%
- w = x ± ~0,13%
- A = x ± ~0,12%

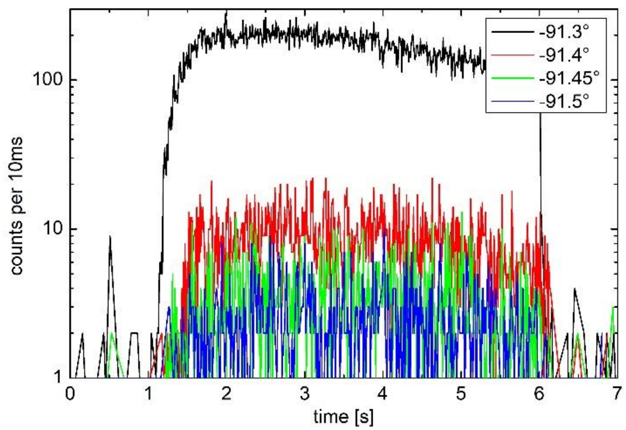
- W, FWHM, σ: Faktor /2,34
- Height: Faktor *2,34

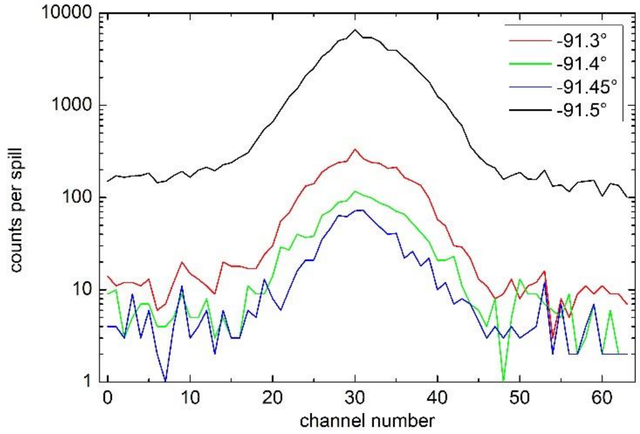


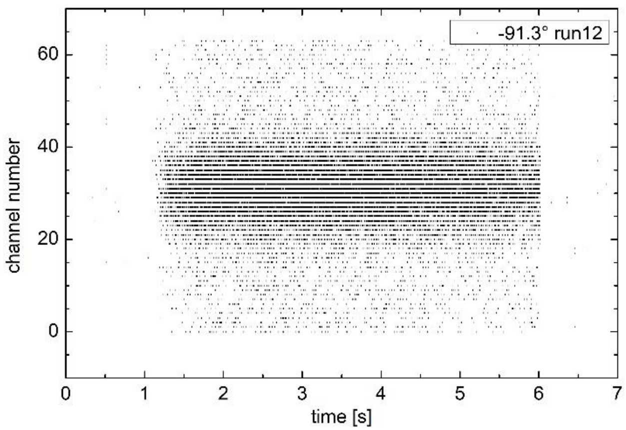
→ Intensity determinable by area A of the fit.

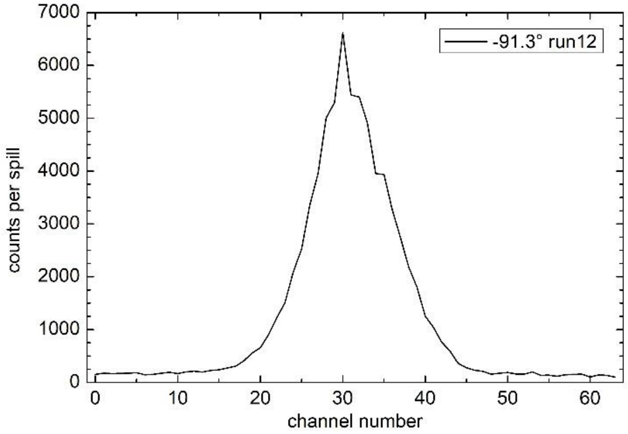
Timing Mode
Angle Comparison

C12 E255 F4 I1 -91.??°







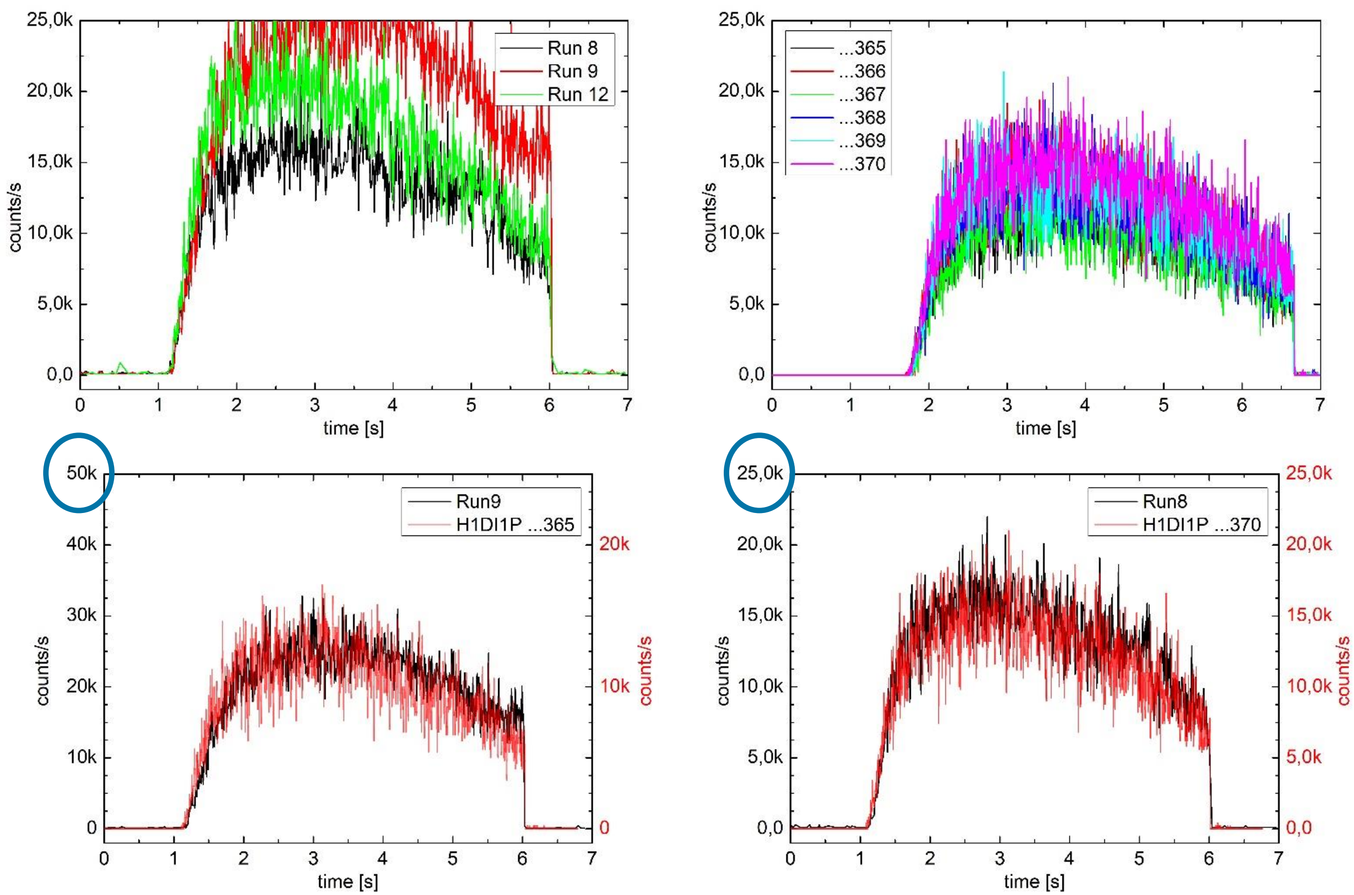


C12 E255 F4 I1 -91.3°

Timing Mode

Comparison with integrated scintillator

- “Run”:
  my detector
- “H1DI1P…”:
  integrated scintillator in accelerator



→ Spill form is really good comparable (except intensity fluctuations)

Conclusion

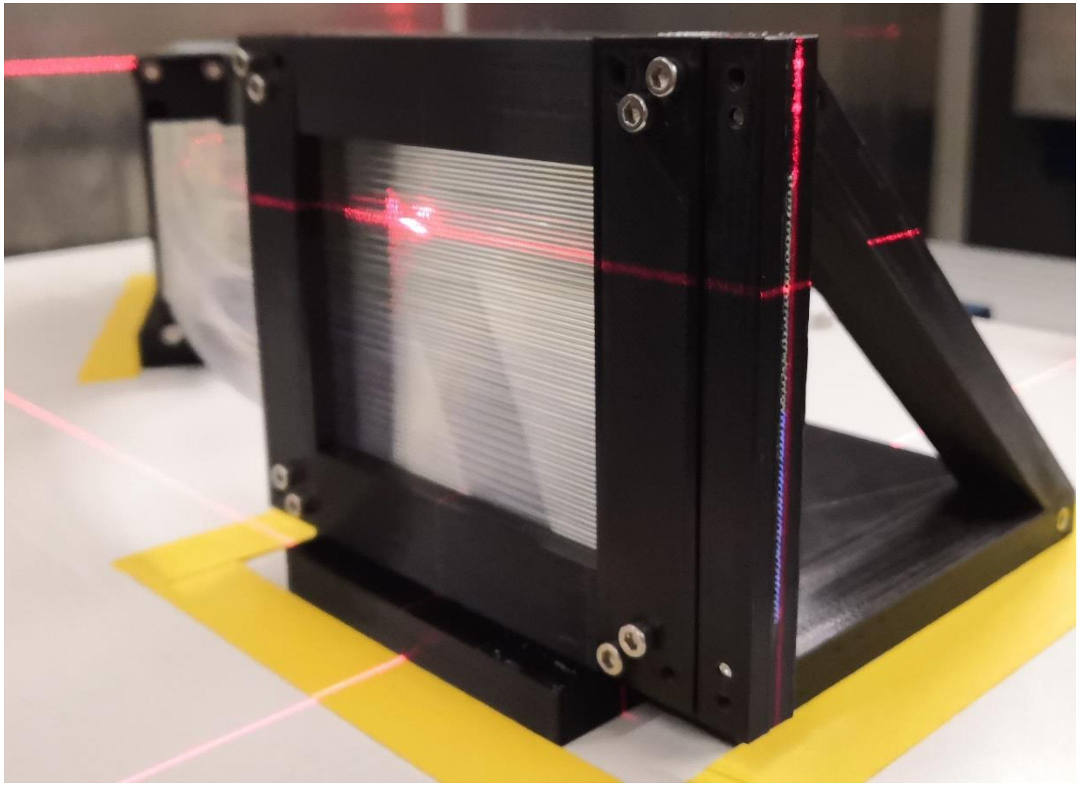
- Prototype successfully proven to measure:
  - Beam position and width
  - Intensity (spill form)
  - Tracking single ions (time stamp)

- Limits:
  - 1.8 MB data throughput, due to "how data is packed and transmitted in the links"
    - one full set of data takes 2776 bits (≈ 350 bytes)
  - Counting: Data loss, if too short time intervals, e.g <200µs resolution.
    Data loss, if to many ions/s, e.g >10^7 ions/s.
  - Timing: Data loss, if to many ions/s, e.g >5*10^4 ions/s.

Outlook

- More and more direct comparison to BAMS (HIT), Timepix (Tim) and SciFi-monitor (PI).
- Counting mode will be faster with Zero-Suppression
  (Caen promised program update within weeks)
- FERS A5202 & DT5215 for second detection layer are in order process and will be delivered in December & January
  - Concentrator Board and TDlink will allow data throughput of 60 MB/s (~170 000 events/s possible: 200µs -> ~6 µs time windows in counting)
  - Prototype extension: vertical plane & quadratic fibers.

End
Questions?



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Phys. Inst. HD
Blake Leverington
Sebastian Bachmann

Uni Frankfurt
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UK HD
Prof. Oliver Jäkel

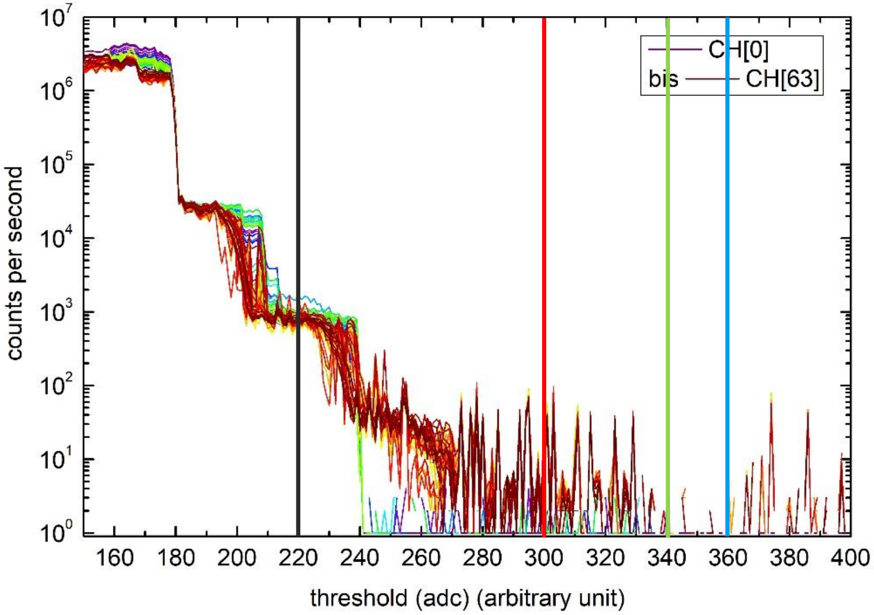
INFN
Romualdo Santoro

Appendix
Extra Slides

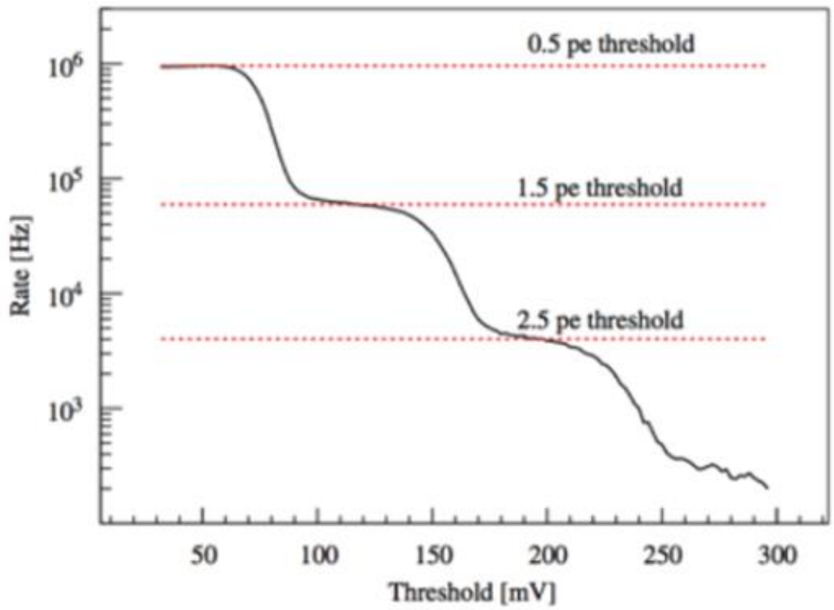
Dark Count Rate (DCR) measurement
Threshold Scan

- Different Threshold-Values: 220, 300, 340, 360 (arbitrary units)

S-curve / staircase plot



1 p.e. are due to **dark counts**
2 p.e., 3 p.e., etc. are due to **crosstalk**



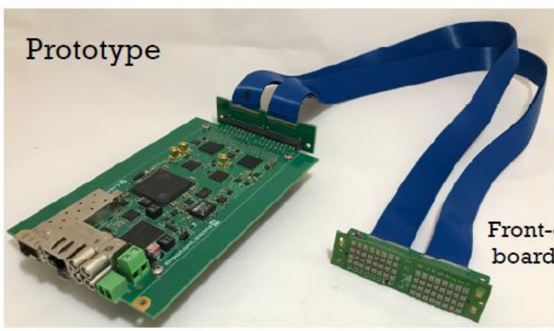
→ Threshold um 350 seems good

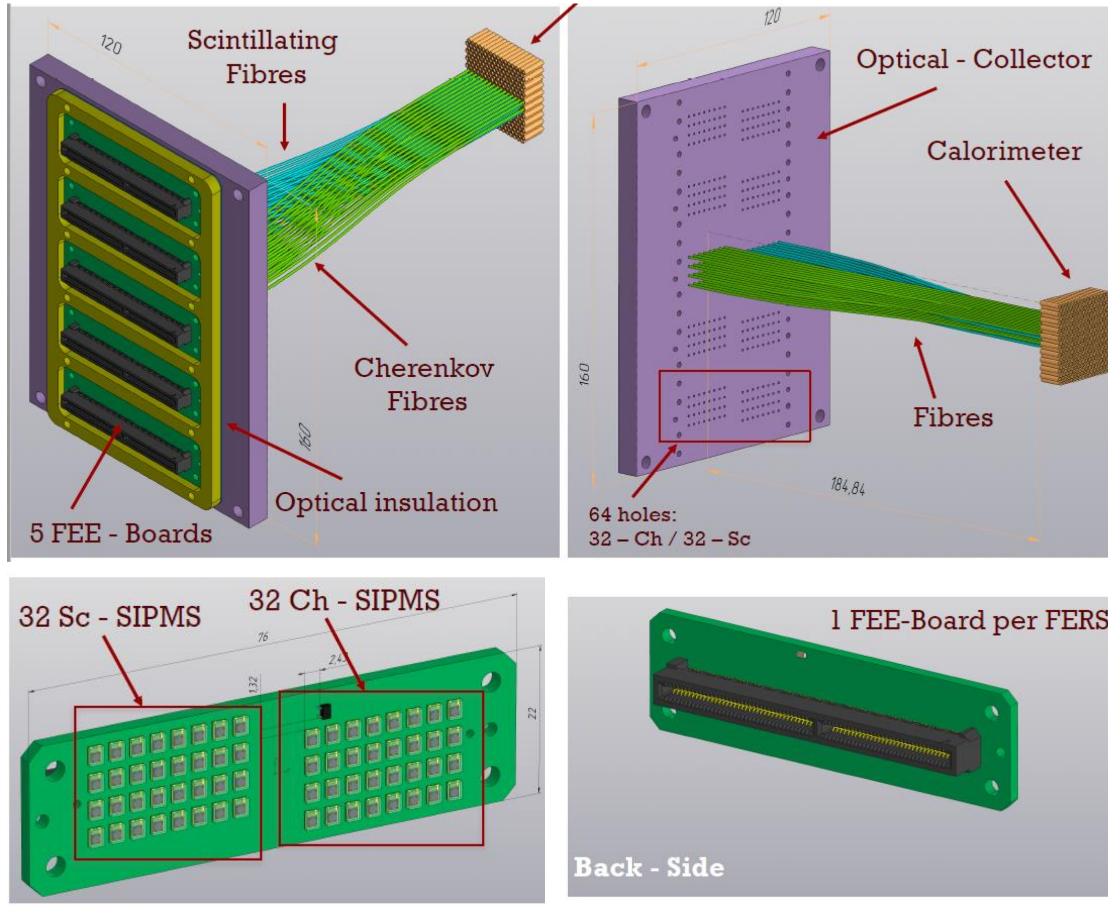
https://hub.hamamatsu.com/jp/en/technical-note/how-sipm-works/index.html

State of the Art
INFN – R.Santoro – INFN

IDEA Dual-Readout calorimeter collaboration
- R. Santoro (INFN)

Also:
SiPM + FERS A5202



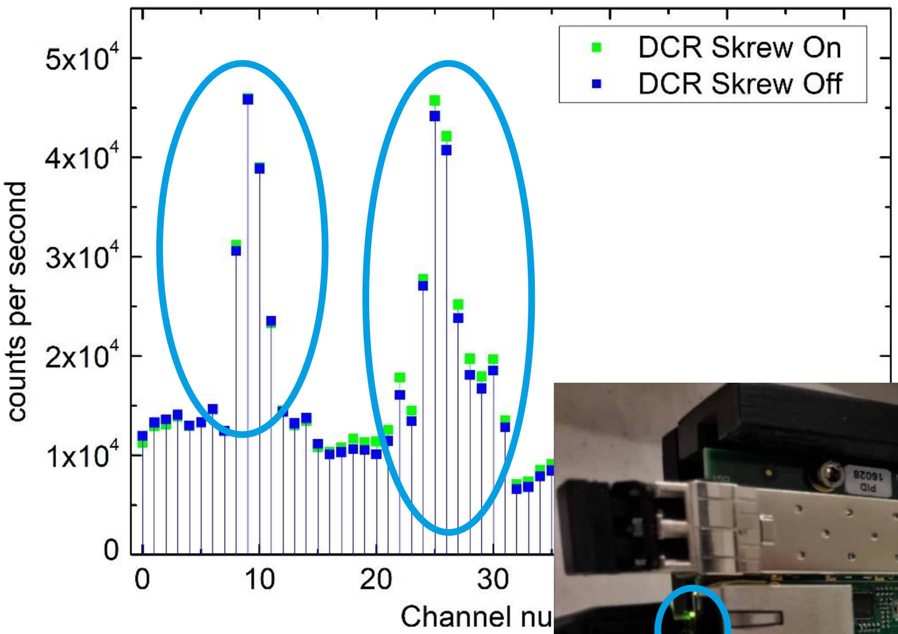


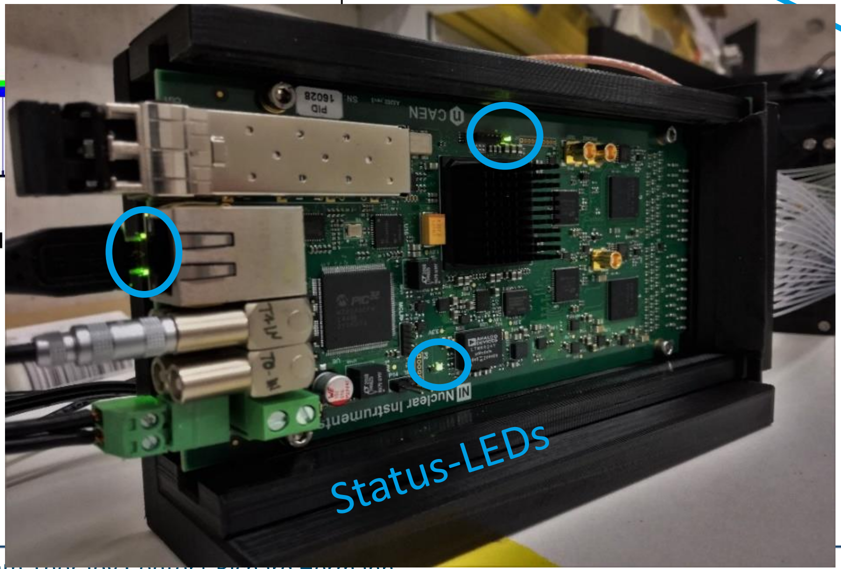
Romualdo Santoro, „IDEA DR Calorimeter: readout electronics“ , Univeristàdell’Insubria and INFN-MI, 2021

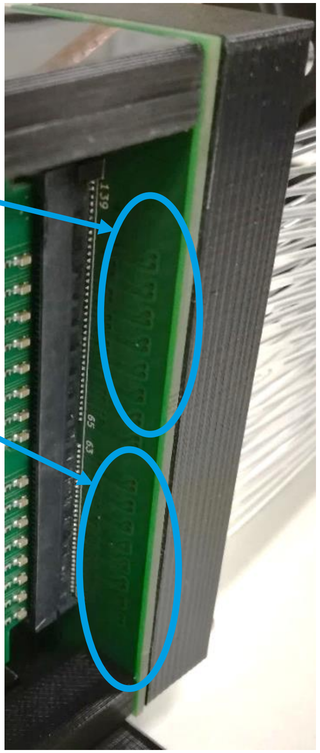
Dark Count Rate (DCR) measurement

Strange peaks

- Light leaks from behind through pcb through-holes.





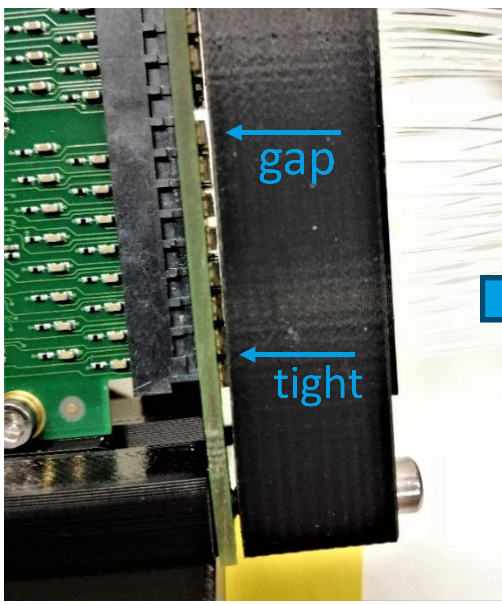


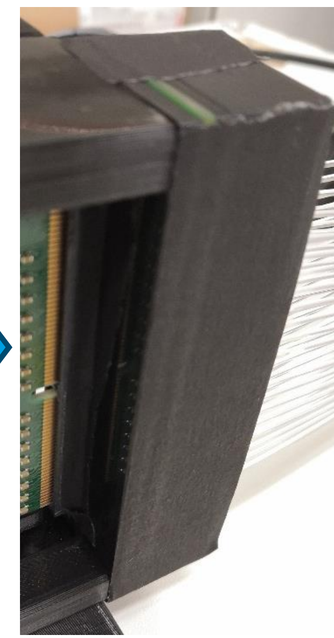
Dark Count Rate (DCR) measurement

Strange peaks

- Light leak through through-holes
- **And:** Gap on the side

→ 3D print for light protection

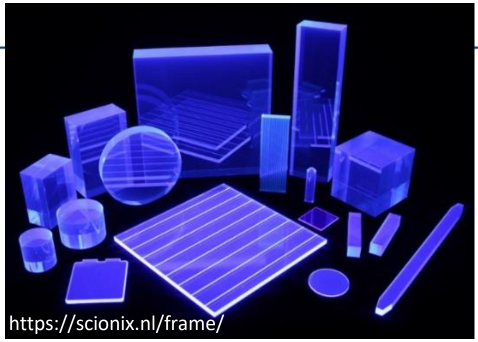




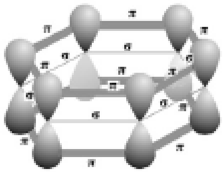
I

Szintillationsfasern

Scintillator
Organic



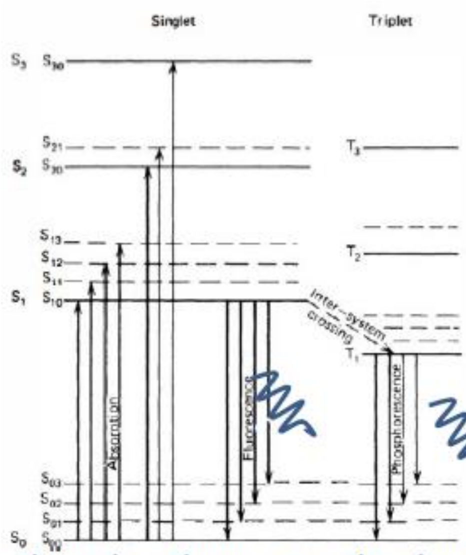
- **Scintillation**:
  Alternation of free valence electrons between molecular orbitals.
  Typical: Benzene ring circumferential e-



The π molecular orbital in benzene

- **Pro**: Fast (ns) - intensity determinable, magnetic field insensitive, fibres enable position measurements, (+ advantages slide 6)

- **Contra**: No energy measurement possible (non-linearity & saturation), defined radiation hardness and therefore defined lifetime – can't be refurbished



Absorption Fluorescence (fast) Phosphorescence (slow)

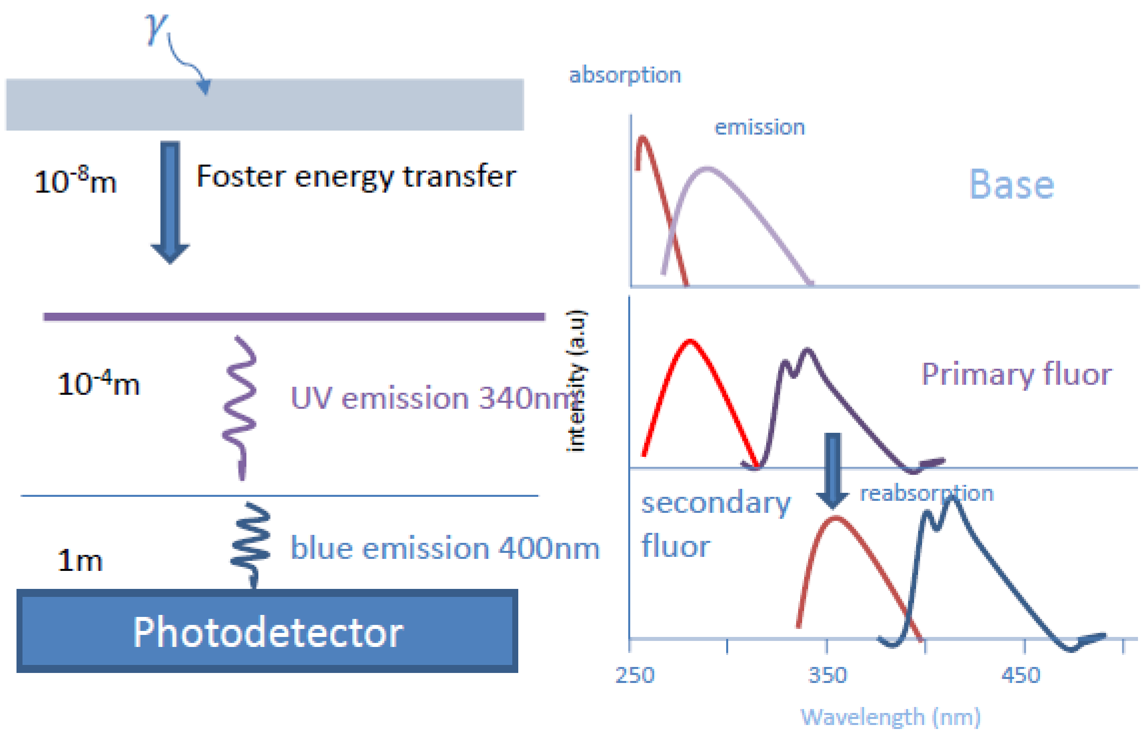
E. Auffray, „Scintillation Detectors", CERN, EP-CMX technoweek School 2021

Scintillator
Plastic scintillators and fibers

- Stokes-Shift:

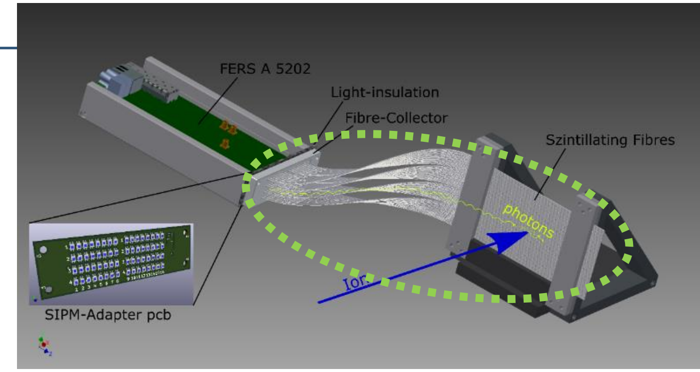
  Difference between maxima in absorption and emission.

  - Carrier medium
  - Primary scintillator
  - Wavelength shifter



1. Primary ionization => excitation of molecules in the base polymer
2. De-excitation of the base polymer [theoretically produces scintillation photons (~ 300 nm)] => Energy transfer directly to the fluor in a very short distance.
3. Primary fluor emits at a longer wavelength (~ 340 nm),
4. Absorbed by a secondary fluor
5. Secondary fluor emits in the visible (~ 400 nm)
6. Detect by photodetector

E. Auffray, „Scintillation Detectors", CERN, EP-CMX technoweek School 2021

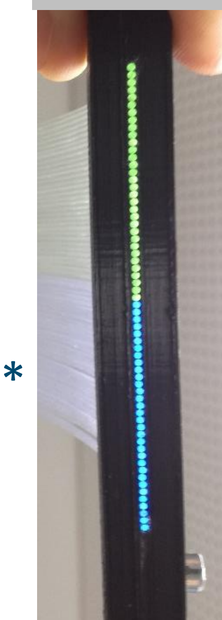


Scintillating fibers

Radiation hardness

- Kuraray SCSF-3HF multiclad
  - 3-hydroxyflavone
  - Smaller radiation damage than other fibers *
  - Lifetime & attenuation length also dependent on bending and on temperature of the fiber. *
  - annealing effect in days/weeks/months, total and none at all **
  - 20% loss where Kuraray SCSF-78 multiclad has 60% loss ***

Kuraray 3HF multi clad



Kuraray 78 multi clad

*Radiation damage in scintillating fibers -Preliminary literature study- ; Michael Moll, CERN, 15.10.2003
** A fiber detector radiation hardness test, J Bähr et al., Nuclear Instruments and Methods in Physics Research Vol 449, 11.08.2000
*** Preliminary radiation damage analysis for the HIT beam profile monitor; M.Dziewiecki, B.Leverington, G.Meo; Heidelberg 13.02.2018

Scintillating fibers
Cladding

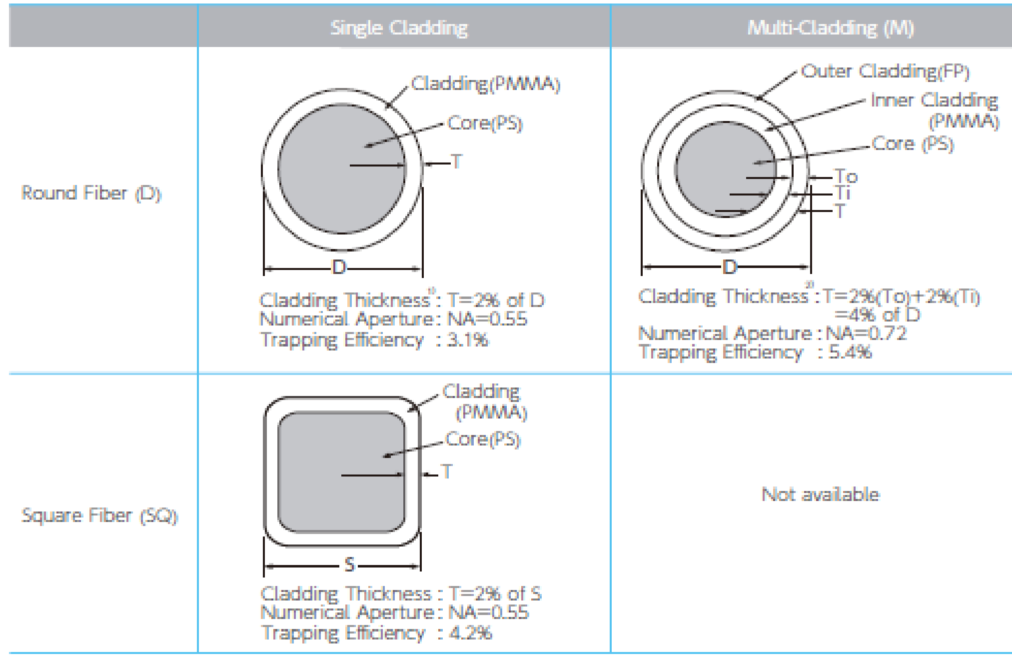
- E.g. Kuraray "polystyrene core (inner side) with a fluorescent agent and a methacrylate cladding (outer side)"

https://www.kuraray.com/products/psf

Materials

		Materials	Refractive index	Density (g/cm^3)	No. of atom per cm^3
Core		Polystylene(PS)	n_D=1.59	1.05	C: 4.9×10^{22} H: 4.9×10^{22}
Cladding	for single cladding inner for multi-cladding	Polymethylmethacrylate (PMMA)	n_D=1.49	1.19	C: 3.6×10^{22} H: 5.7×10^{22} O: 1.4×10^{22}
	outer for multi-cladding	Fluorinated polymer (FP)	n_D=1.42	1.43	

Cross-section and Cladding Thickness

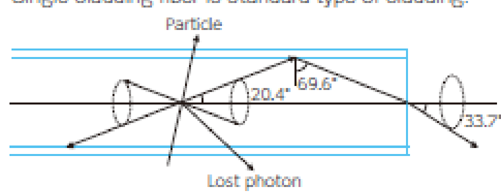


1) In some cases, cladding thickness T is 3% of D. 2) In some cases, cladding thickness T is 6% of D, To and Ti are both 3% of D.

Cladding and Transmission Mechanism

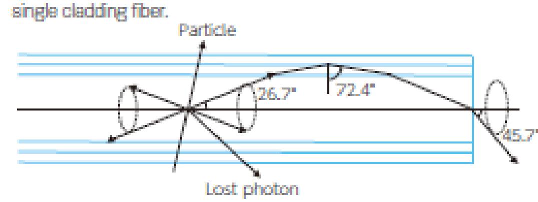
Single cladding

Single cladding fiber is standard type of cladding.



Multi-cladding

Multi-cladding fiber(M) has higher light yield than single cladding fiber because of large trapping efficiency. Clear-PS fiber of this cladding has extremely higher NA than conventional PMMA or PS fiber, and very useful as light guide fiber. Multi-cladding fiber has long attenuation length equal to single cladding fiber.



II

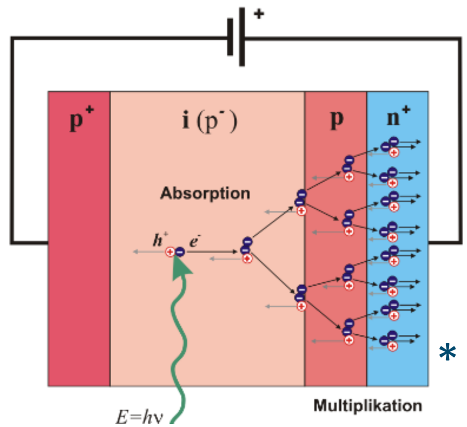
SiPM

Photomultiplier

Silicon Photomultiplier (SiPMs)

- APDs: 50 x 50 µm²

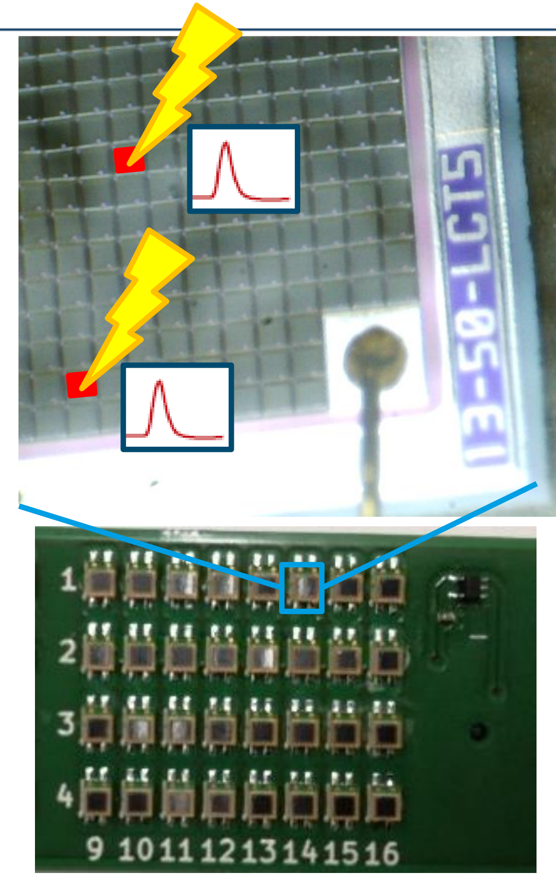
  Avalanche-Photodiode: Semiconductor equivalent of a photomultiplier.

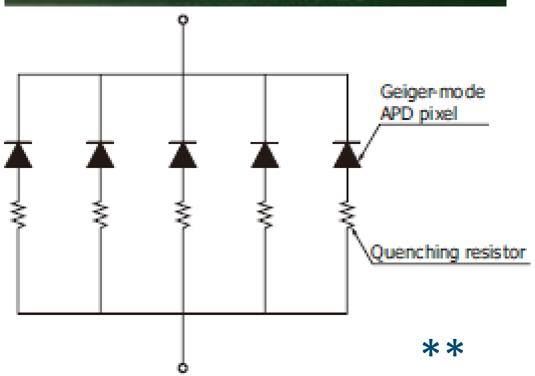


- SiPM:
  50µm APDs on 1,3x1,3mm² active area
  = 667 pixels

- **Pro**: Fast (ns) - intensity determinable, magnetic field insensitive; (+ advantages slide 6)

- **Contra**: No energy measurement possible (Geiger-Mode), radiation damage – aging

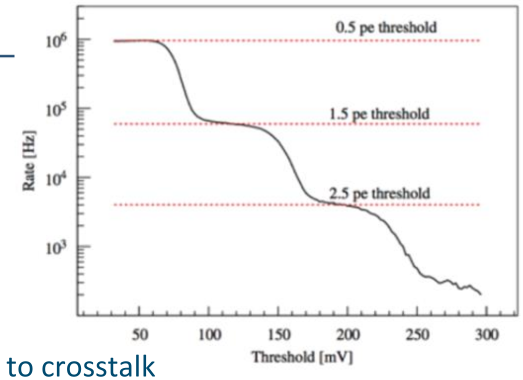




*Von Kirnehkrib - Eigenes Werk, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=17725203

**Hamamatsu, MPPC Technical Note Cat. No. KAPD9008E01 Apr. 2021 DN

Detector principal
SiPM (Silicon-Photomultiplier)



- The primary waveforms (1 p.e.) are due to dark counts; whereas, 2 p.e., 3 p.e., etc. are due to crosstalk

Optical crosstalk in a SiPM

Optical crosstalk occurs when a primary discharge (avalanche) in a microcell triggers secondary discharges in one or more adjacent microcells. The secondary discharge may be nearly simultaneous with the primary (direct or prompt crosstalk) or delayed by several 10's of ns (delayed crosstalk). Optical crosstalk is an example of a correlated noise: it can be present only if a primary discharge is present. The primary discharge can be due to 1) absorption of a photon, 2) thermal generation of a charge carrier in the multiplication region, 3) injection of a charge carrier, thermally generated outside of the avalanche region, into the avalanche region, or 4) crosstalk-induced secondary discharge becoming the primary discharge for subsequent crosstalk events. If not corrected for, crosstalk makes the output signal higher than that implied by the amount of the incident light.

Mechanism

The figure below depicts the mechanism for the prompt (P-CT), delayed (D-CT), and no (No-CT) crosstalk. The primary avalanche in the middle pixel creates three representative photons. One of them moves directly to the avalanche region of the microcell on the right and triggers a simultaneous secondary avalanche there. This is a direct or prompt crosstalk (P-CT). The other photon creates a charge carrier in the vicinity of the avalanche region of the microcell on the left. The charge carrier diffuses to the avalanche region, triggering a secondary avalanche that is delayed with respect to the primary. This is a delayed crosstalk (D-CT). The third photon leaves the SiPM; no crosstalk occurs (No-CT). The majority of photons produced by the primary discharge does not produce crosstalk.

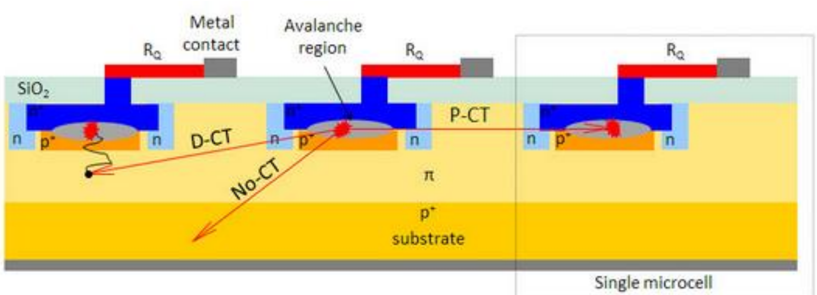
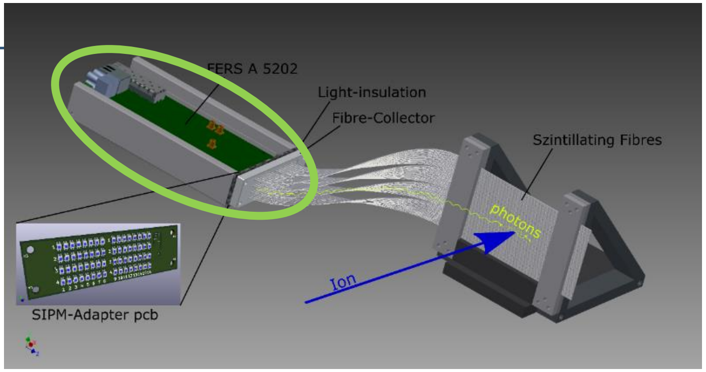


Figure 11. This diagram depicts the mechanism for the prompt (P-CT), delayed (D-CT), and no (No-CT) crosstalk. (It also shows a typical structure of a SiPM, but it does not correspond to the actual structure of the Hamamatsu product.)

https://hub.hamamatsu.com/jp/en/technical-note/how-sipm-works/index.html

III

FERS



Electronics
The CAEN FERS

- Measurement Modes:
  - Counting Mode
    no dead time (except saturation), max. 20Mcps/channel
  - Timing Mode
    TOA (25-bit), dynamic range ~16,78ms (2^25 *0.5ns)
  - Time Stamped Spectroscopy:
    TOA (16-bit) + TOT (9-bit), dynamic range ~32,77µs
  - Spectroscopy Mode
    Amplitude conversion by 13-bit ADC (~10µs dead time)
- Data Throughput: 1.8 MB/s *(due to data packaging → 200µs time windows)*

User Manual UM7945, A5202/DT5202; 64-Channel Citiroc-1A Unit for FERS-5200; Rev. 2 - September 9th, 2021

Readout

FERS A5202 (CAEN)

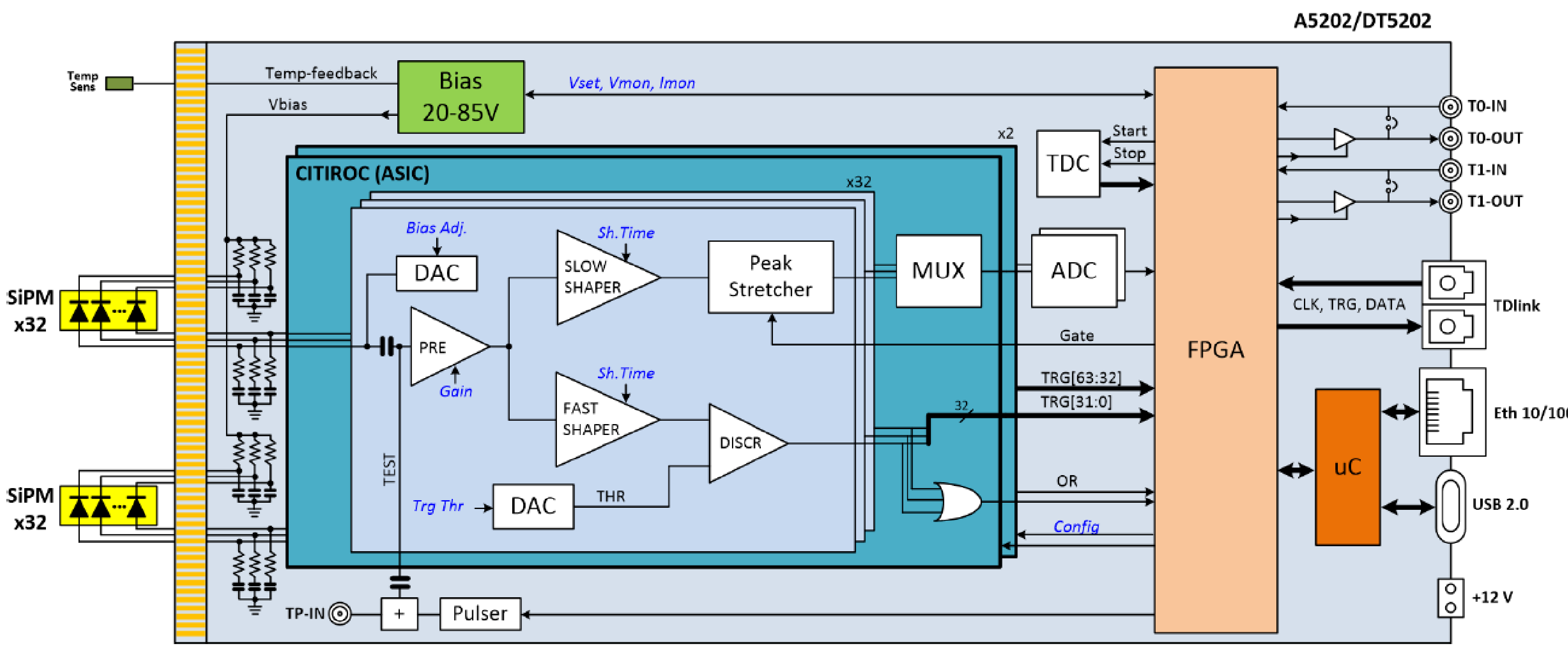


Fig. 7.1: Simplified block diagram of the A5202/DT5202 FERS-5200 unit.

Readout

FERS A5202 (CAEN)

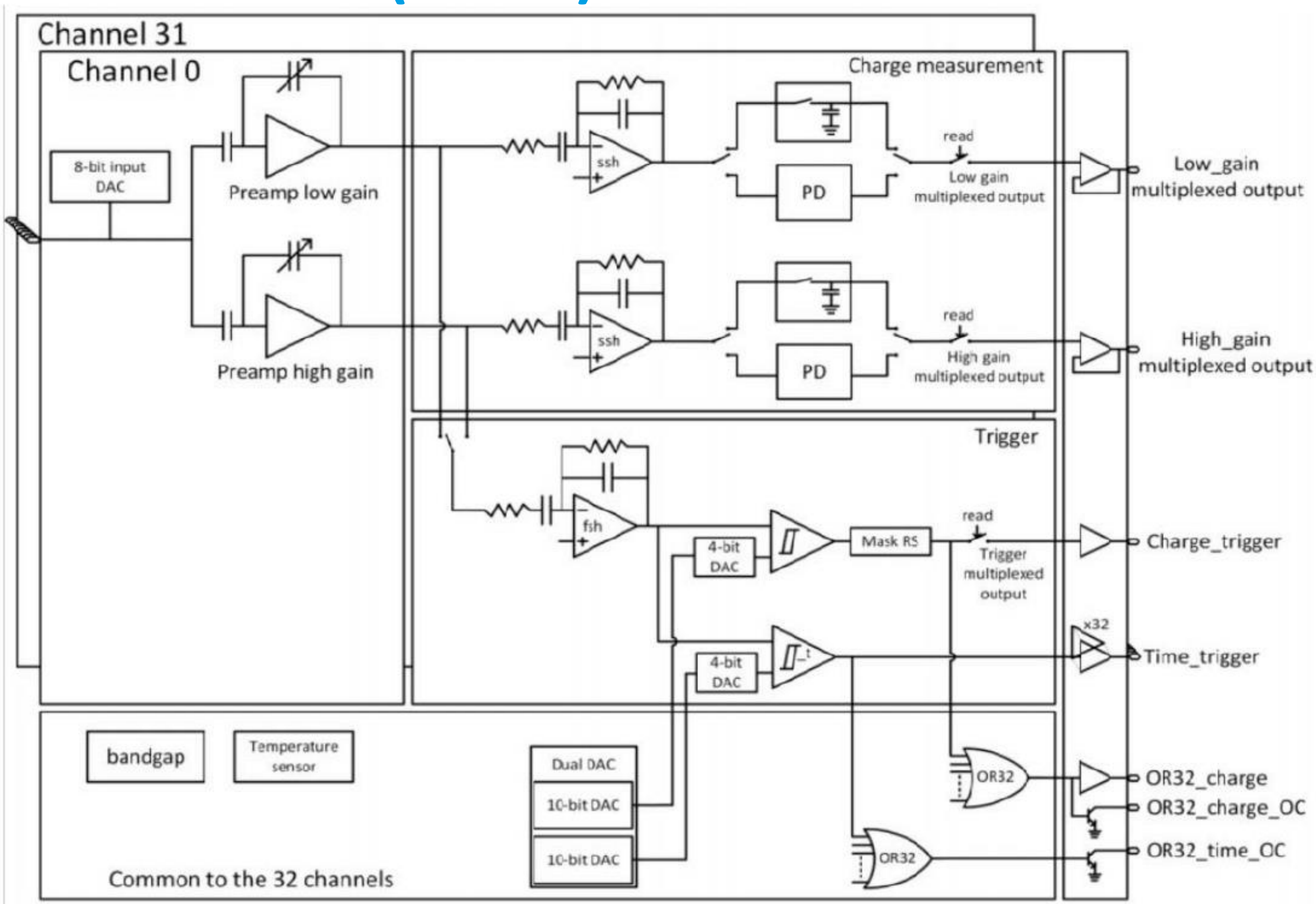


Fig. 7.2: Citiroc-1A block scheme.

User Manual UM7945, A5202/DT5202; 64-Channel Citiroc-1A Unit for FERS-5200; Rev. 2 - September 9th, 2021

Readout
FERS A5202 (CAEN)

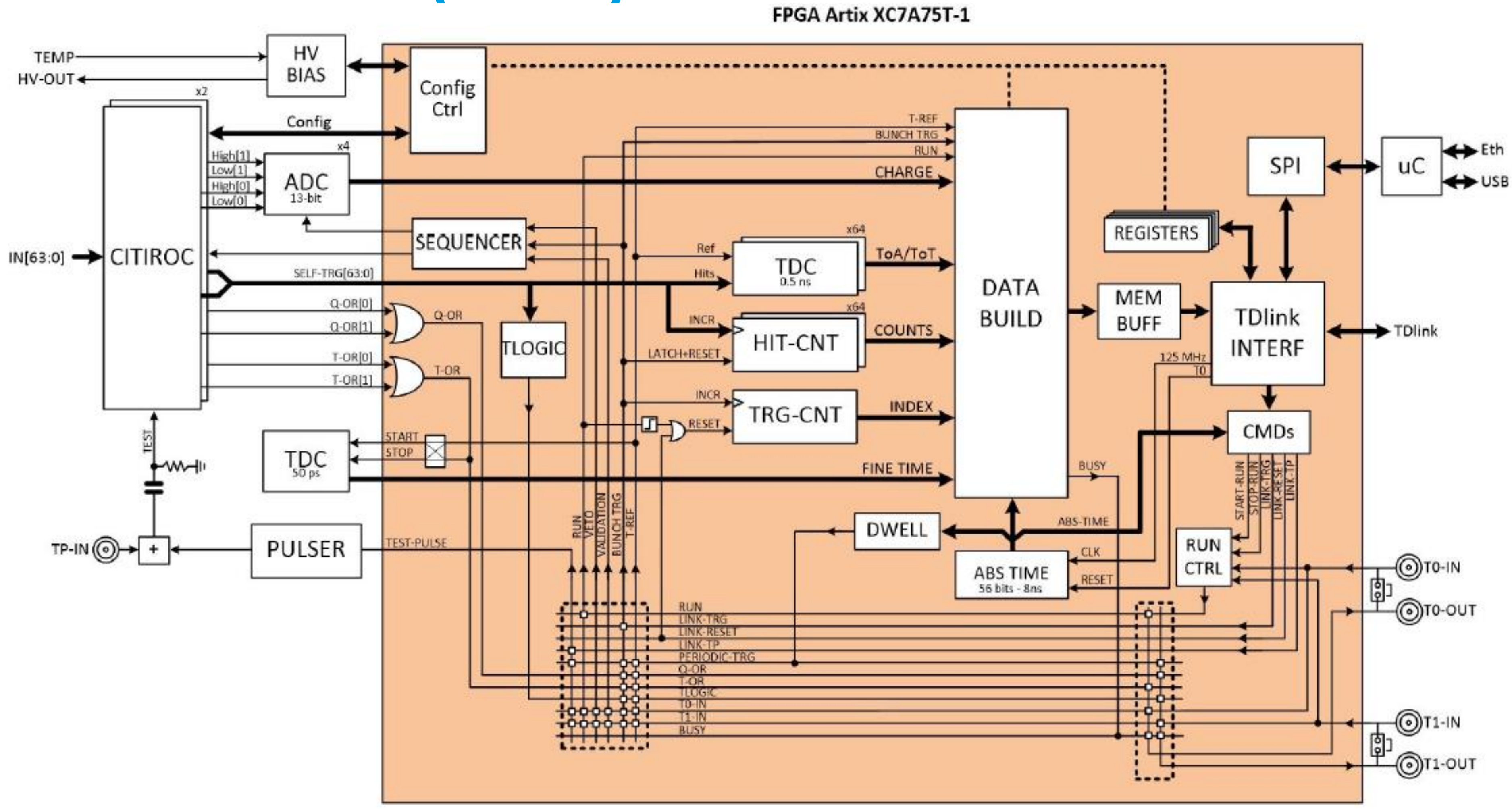


Fig. 7.8: FPGA block diagram.

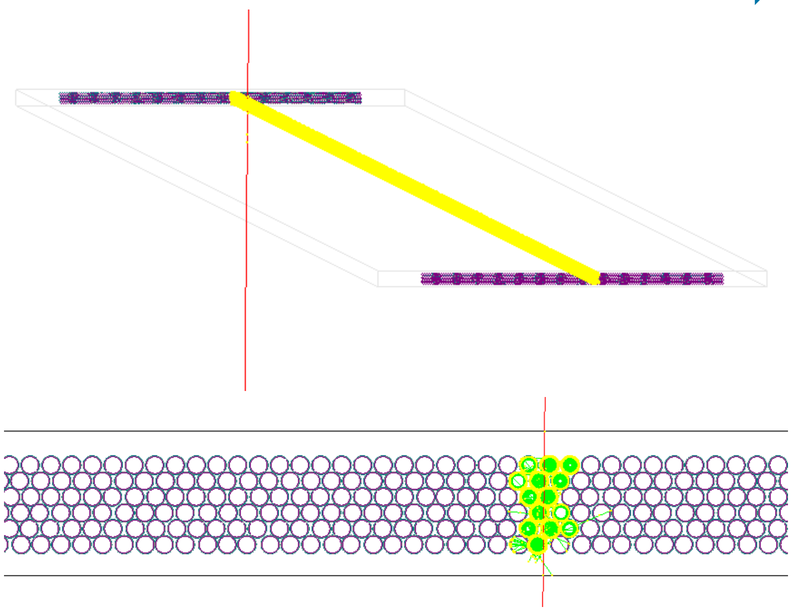
User Manual UM7945, A5202/DT5202; 64-Channel Citiroc-1A Unit for FERS-5200; Rev. 2 - September 9th, 2021

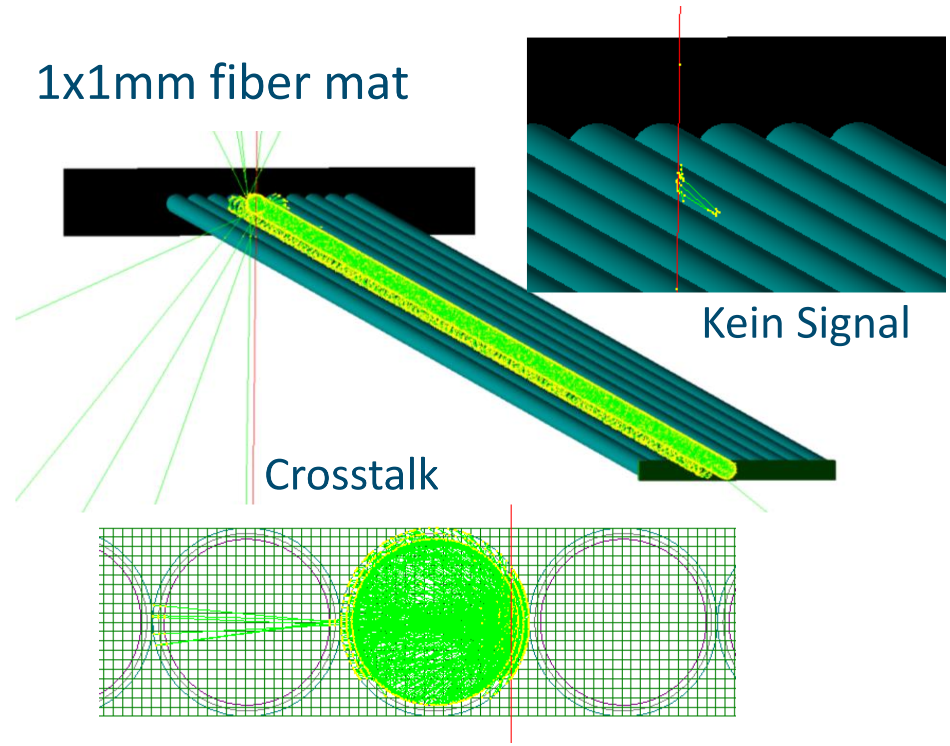
IV
Simulation

Sideproject – Simulation Geant4
LHCb-tracker Simulation adapted

- Only first adaptions: size, material, readout cells

6x250µm fiber mat → 1x1mm fiber mat





- **BUT** Output file/-plots not yet useable (e.g. pixels not correctly assigned)