CERN

A scintillating fibre beam profile monitor for the experimental areas at CERN

High Resolution and High Rate Detectors Bi-Weekly Seminar – 30th November 2016 – Heidelberg

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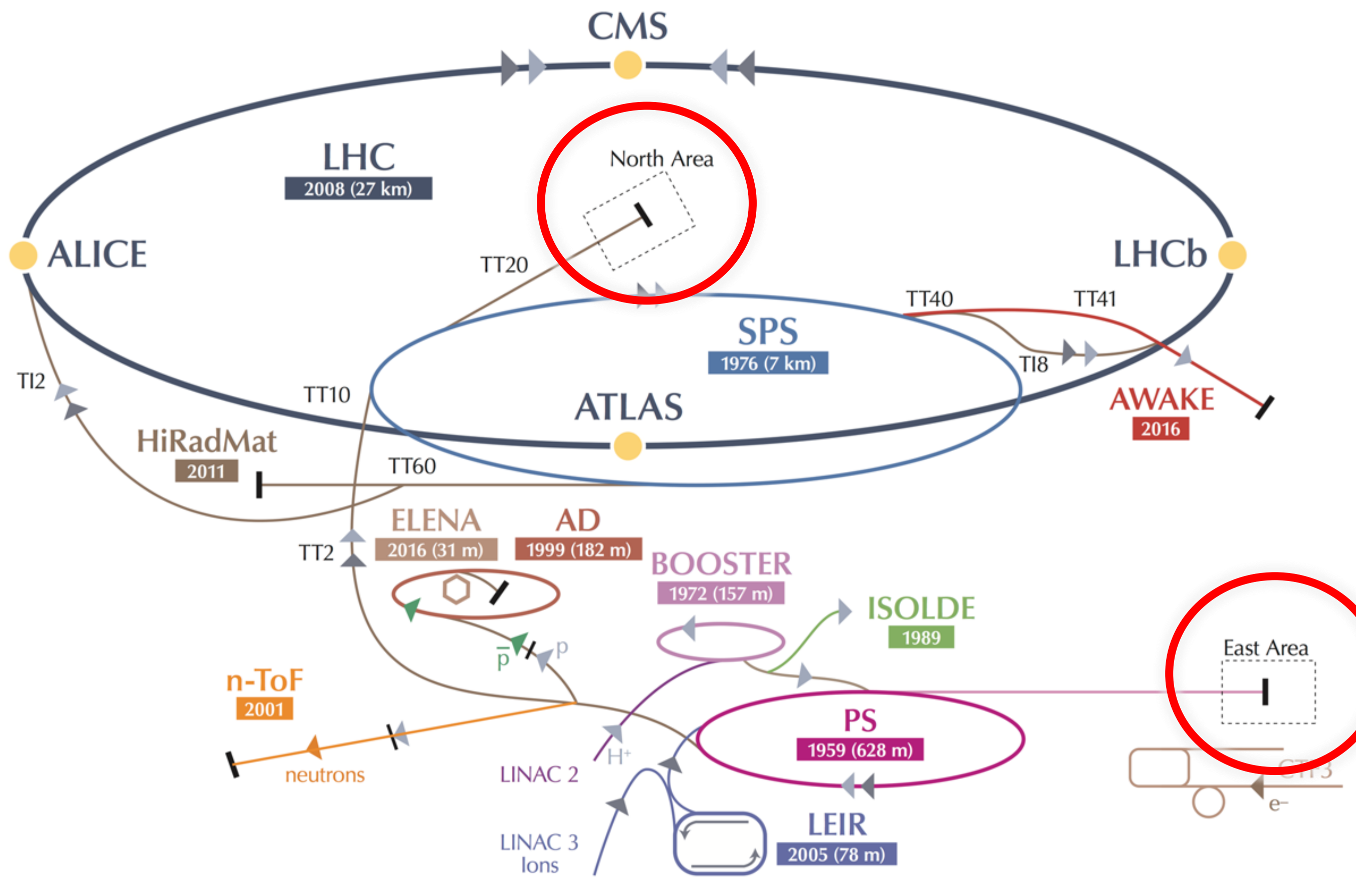
Outline

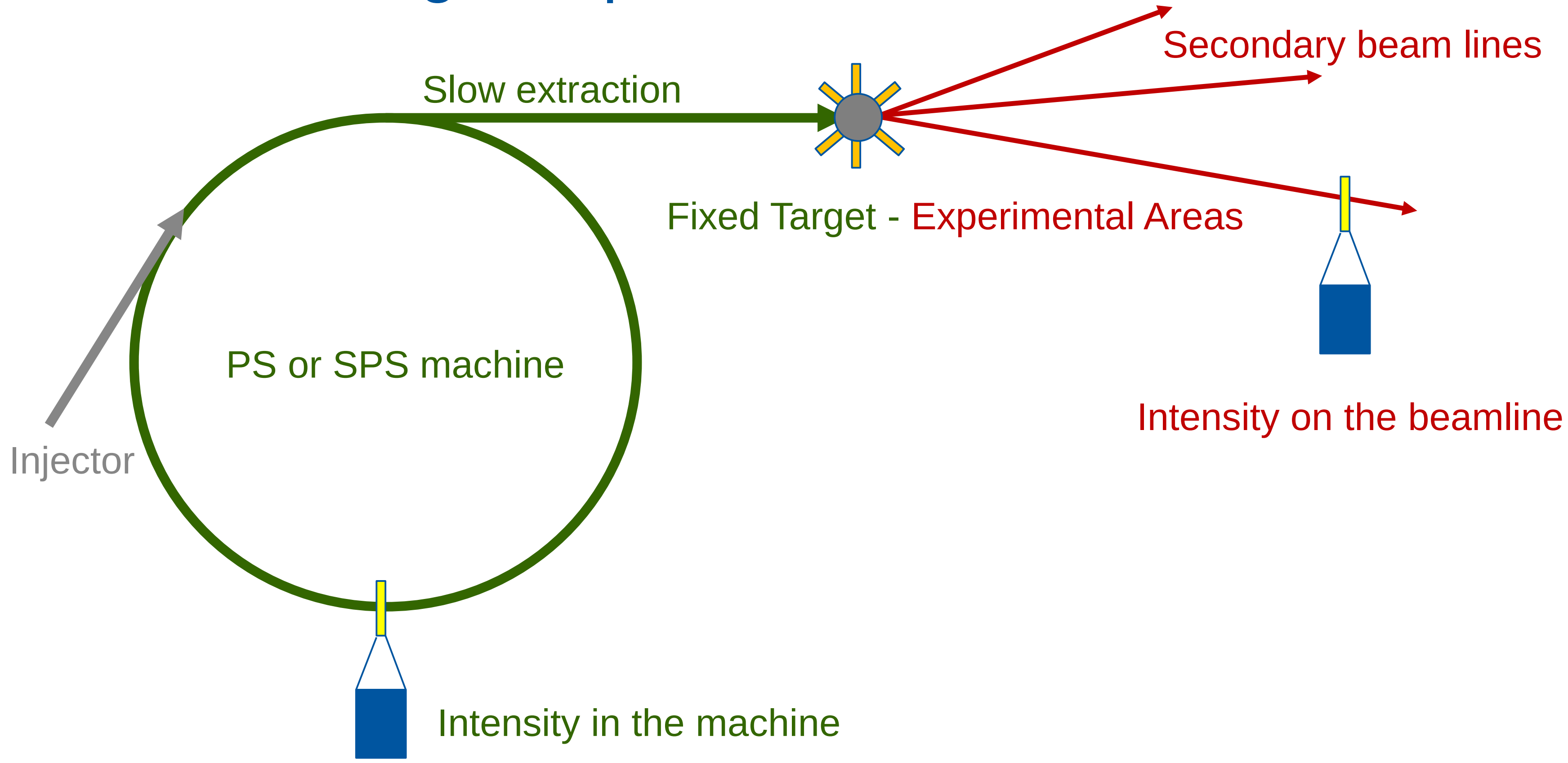
1. Introduction
2. Scintillating fibres
3. Photodetectors & readout electronics
4. First prototype
5. XBPF
6. Time-Of-Flight

1. Introduction: the experimental areas



- A big number of experiments use the experimental areas
- 41% of PS protons: 1.65×10^{19} protons

The fixed target experiments



- 1 A = 6.241×10^{18} elementary charge (e.c.) / second.
- SPS machine: 2.2×10^{12} e.c. / 22 us = 10^{17} e.c./s = 16 mA
- SPS experimental areas: 100,000 (e.c.) / sec = 16×10^{-12} mA !

Wide range of particles, energies and intensities

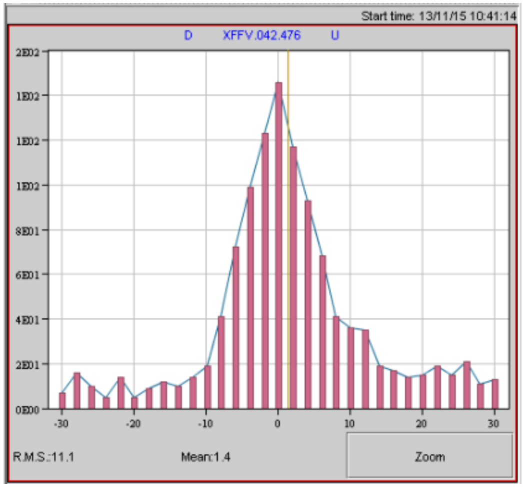
		Momentum (GeV/c)	Max. Intensity per burst
Primary	p+	350	10^7
Secondary	π+ / π-	10 – 200	10^7 – 10^8
	e+ / e-	10 – 150	10^6
	Pb ions	10 – 400	10^7
	µ	5 – 200	10^5
	Other hadrons in lower intensities (Ks, p-)		
Terciary	e+ / e-	1 – 9	10^4 – 10^5
	π+ / π-	1 – 9	10^4 – 10^5

Requires different instrumentation than the machines → closer to physics experiments

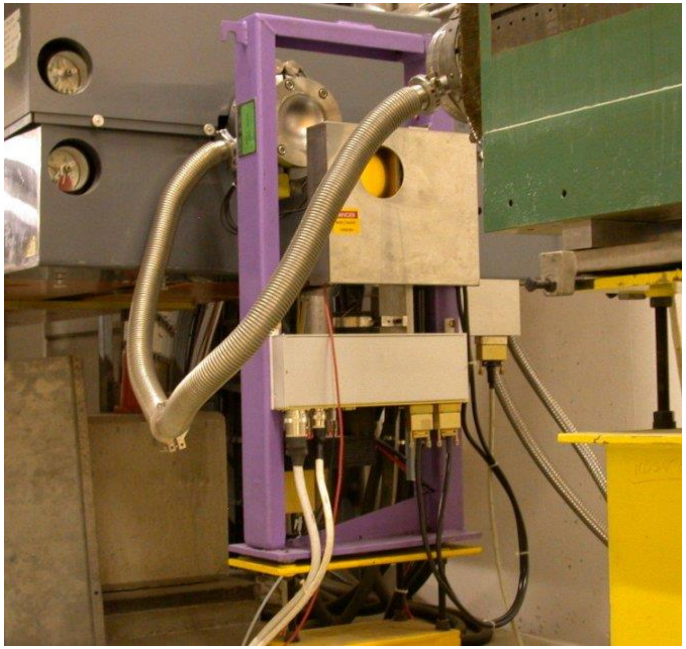
Beam profile monitors for the experimental areas

Current profile detectors:

- Multi-wire analogue chambers
- Delay wire chambers
- Finger scintillator scanner (FISC)
- GEMs



A FISC profile



Multi-wire analog chamber

These detectors have done a fantastic work for many years.

But new challenges, like the extension of EHN1, demand new solutions.

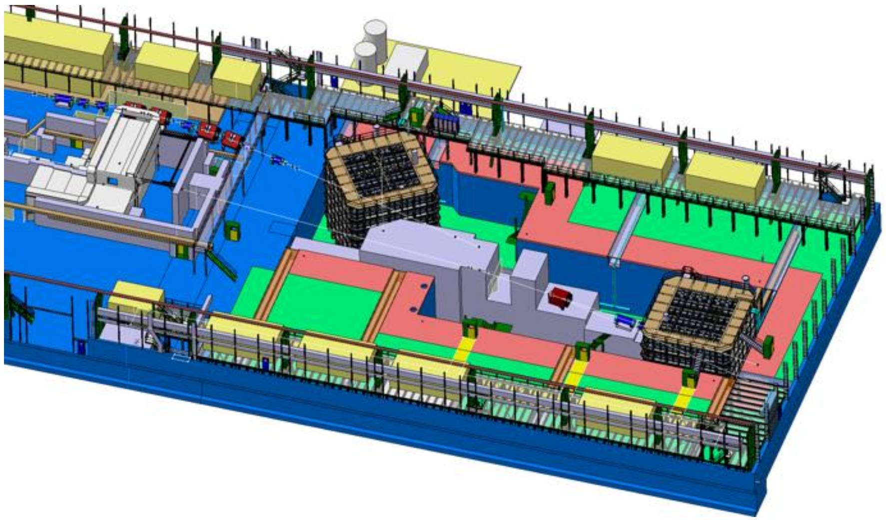
EHN1 extension: The CERN Neutrino Platform

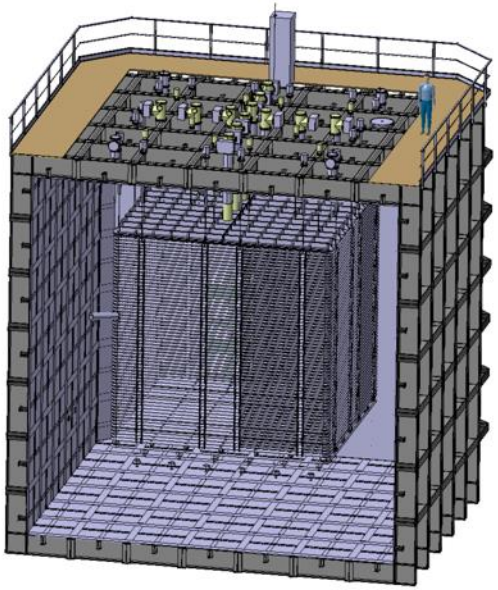
Mission:

- Provide charged beams and test space to neutrino community → North Area extension
- R&D to demonstrate large-scale LAr technology (cryostats, cryogenics, detectors)
- Construction of first cryostat for DUNE
- Support neutrino experiments in US and Japan (e.g. BabyMIND: muon spectrometer for WAGASCI experiment at JPARC)

These new beam lines will have the following characteristics:

- The energy can go down to 500 MeV and the intensities can lower to 10^2 particles / spill
- Large beam profile → need monitors of 200 mm × 200 mm
- Require individual particle counting



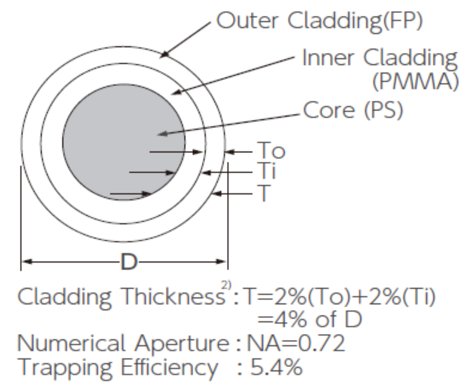


2. Scintillating fibres

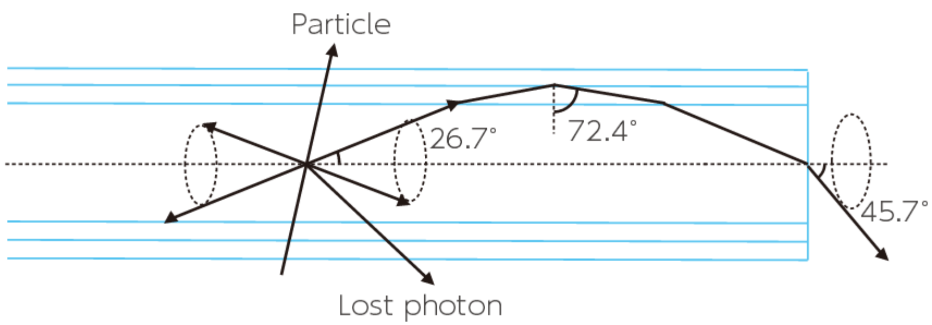
The features of a good beam monitor for the EA are close to those of a “tracker” detector:

- Low material budget x/X_0
- Precise spatial and time information
- Good rate capability
- Radiation hardness

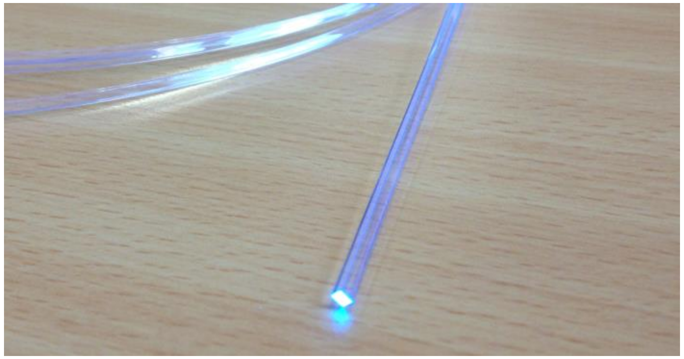
} Get precise information of the passage of the particle whilst minimising the perturbation.



Scintillating fibres (SciFi) cover these requirements



- They produce ~8000 photons/MeV deposited
- Very fast rise and decay times: ~1-2 ns
- Wavelength emission peak: ~420 nm (visible blue) → matches PMT
- Long attenuation length for emitted light: between 3-4 m
- Long radiation length: low perturbation of the beam
- Moderate radiation damage: from tens of kGy absorbed doses
- Affordable cost and easily replaceable

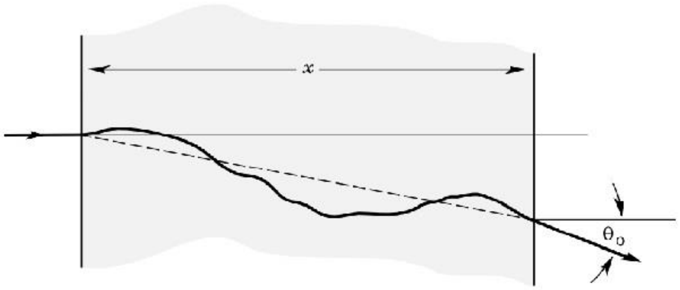


Study of the beam perturbation: radiation length

The radiation length (X_0) is related to the multiple scattering produced by a material

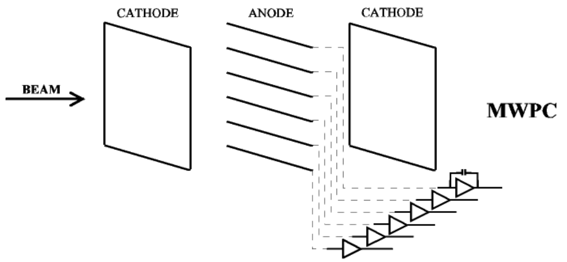
$$\theta_0 = \frac{13.6 MeV}{\beta c p} Z \sqrt{\frac{x}{X_0}}$$

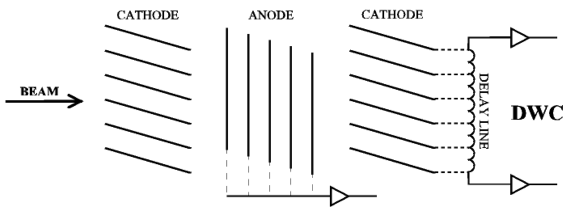
Where θ_0 is the RMS of the scattering angle distribution, x is the thickness of the material, p the particle momentum, βc its speed and Z its charge



We can calculate the X_0 for the different detectors and compare them

Detector	x/X_0 (%)
MWPC	0.34
DWC	0.25
SciFi 1 mm	0.47
SciFi 0.5 mm	0.24



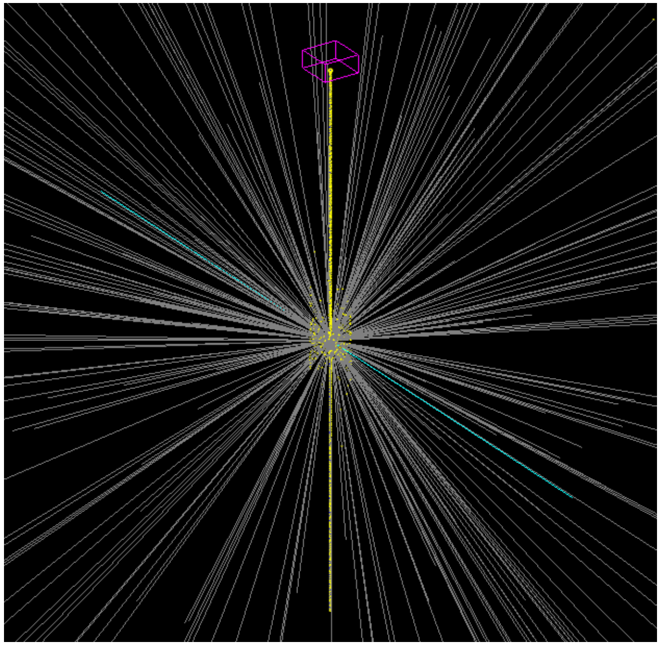


Theoretically a SciFi monitor could be as good as the Delay Wire Chambers in terms of beam scattering.

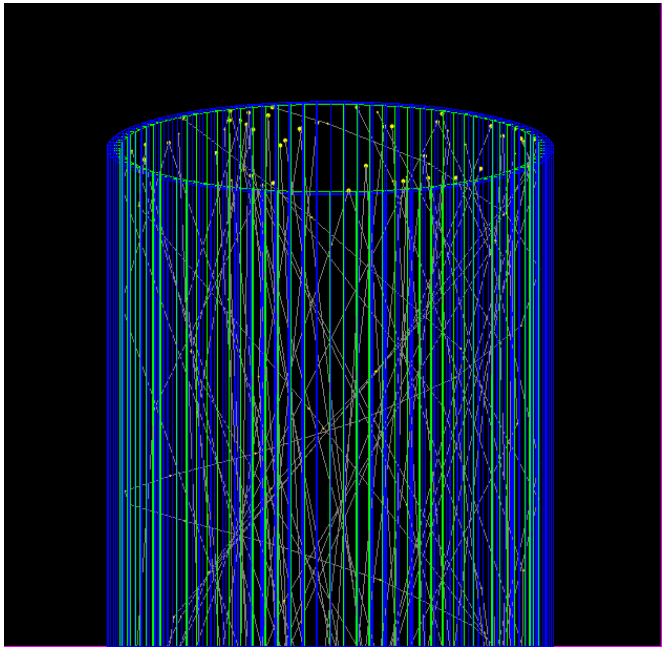
A great advantage of the SciFi is that they can work in vacuum.

Geant4 simulations

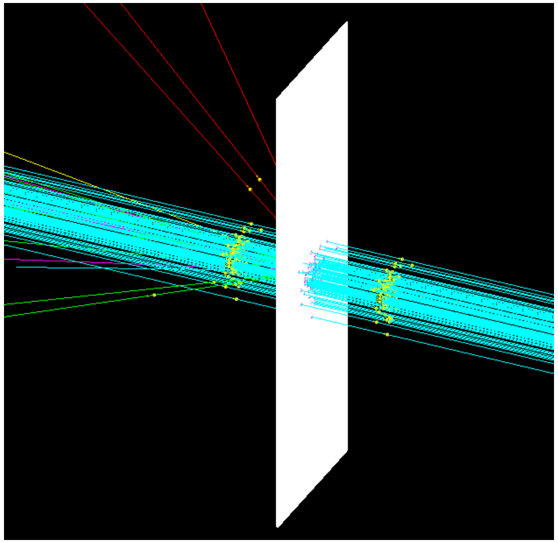
They help us to understand and quantify the physics processes: light production, transport and absorption.
We can easily predict the scattering of the detector and the absorbed dose for a wide variety of particles and energies.



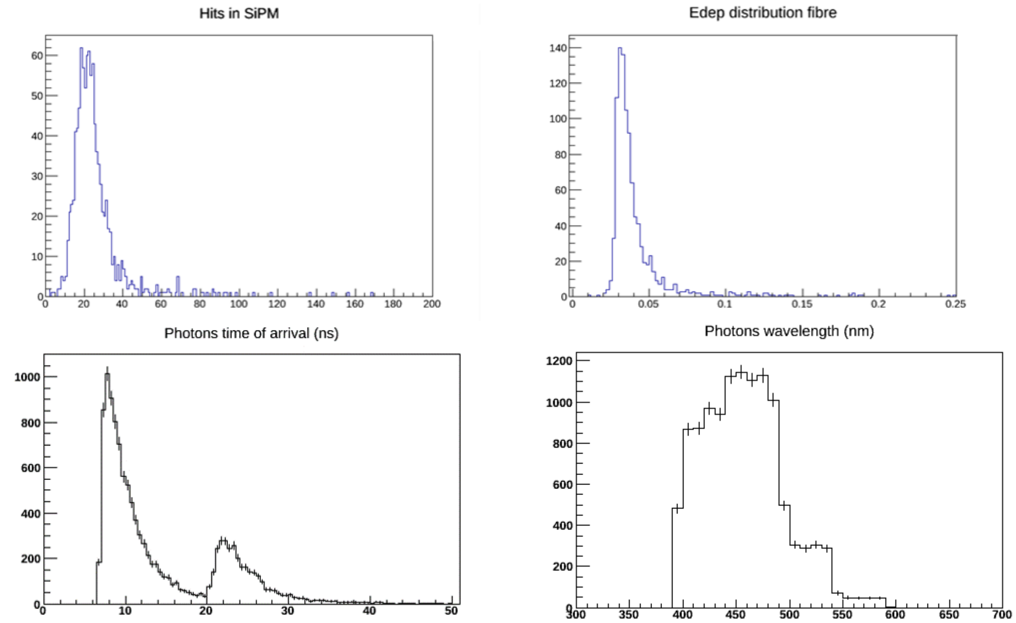
100 GeV proton hitting a 250um round fibre



Closer look to the absorption of photons in the photodetector



Example of secondary particles produced in the interaction with a Gaussian beam of 100 GeV protons



Example of some of the information given by Geant4

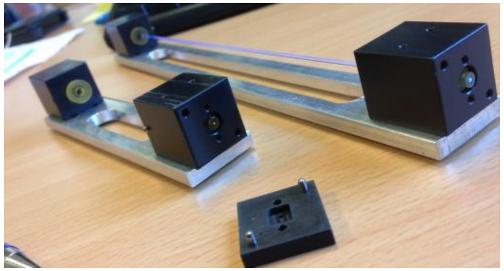
We can also calculate the absorbed dose to estimate the life expectancy of the fibres:

- For an SPS extraction of 10^8 MIPs (minimum ionising particle), the absorbed dose per fibre is ~100mGy.
- Fibres show damage from 10kGray absorbed dose → they could bear 10^5 extractions → they can survive years before showing radiation damage.

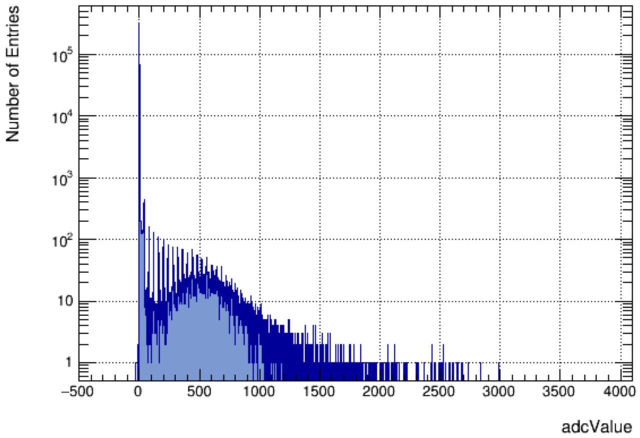
The simulations were fine tuned with real measurements from an electron beam → next slide

Electron gun measurements

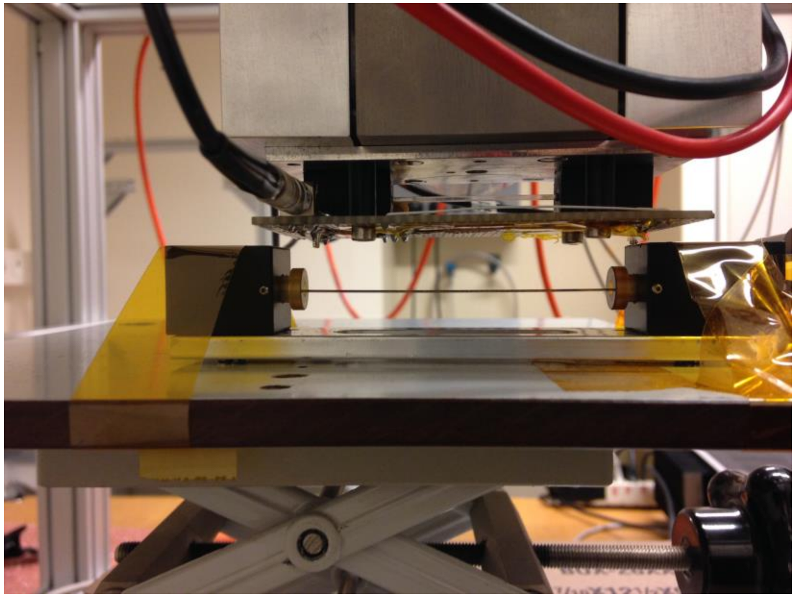
We designed a small experiment to measure the light produced by different fibres by using a low rate electron gun that generates a monochromatic beam of 1 MeV electrons.



Fibre support with holder for SiPM



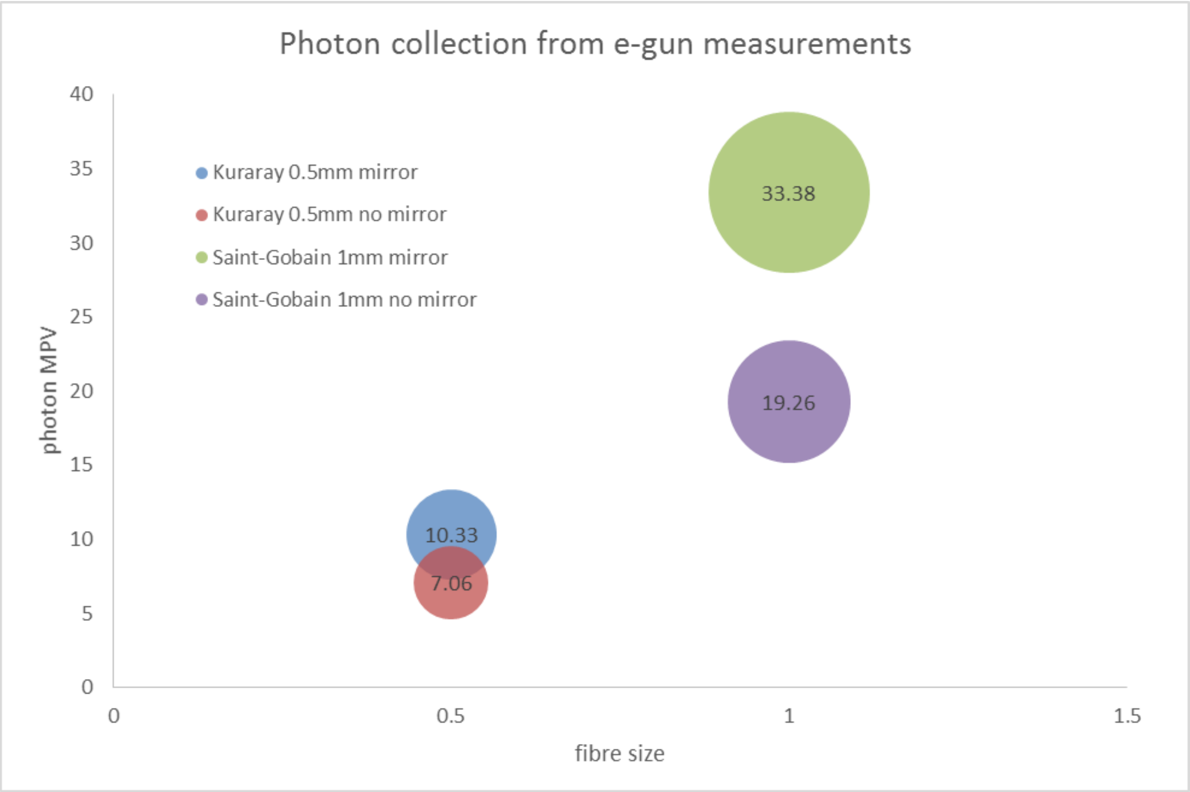
Integrated charge histogram where the individual photo peaks can be identified.



Close look to the e-gun and the scintillating fibre

Square fibres of 0.5mm and 1mm thickness were studied with and without a mirror glued to one end.

The light is detected with a 1mm^2 Hamamatsu MPPC read by a VATA64 chip.



Summary of light yield for different fibre setups

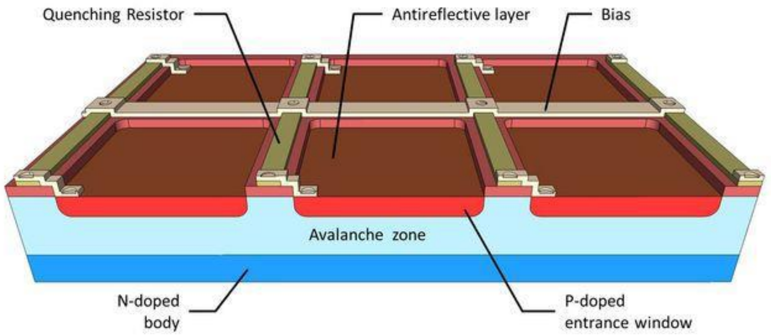
The histograms of the integrated charge are fitted to a Landau distribution and the MPV is calculated

3. Photo detectors

The best existing solutions to read multiple scintillating fibres are:

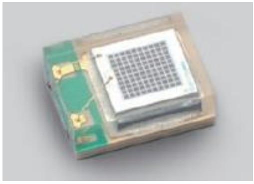
- Silicon photomultipliers (SiPM or MPPC)
- Multi-Anode photomultipliers (MA-PMT)

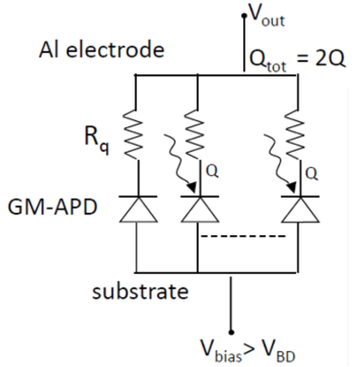
Silicon photomultipliers: matrix of avalanche photodiodes connected in parallel



Advantages:

- High gain: 10^6
- High detection efficiency: 40% at 450 nm
- Fast rise time: <1ns
- Low jitter → timing applications
- Compact size
- Low voltage
- Cost potentially low
- Insensitive to magnetic fields
- New technology: further development foreseen





Drawbacks:

- High dark count rate at room temperature: $100 kHz/mm^2$
- Crosstalk
- Need cooling for some applications

Multi-Anode PMT: matrix of PMT sharing a common cathode.

Stacks of micro machined perforated metal sheets act as independent dynode channels. Multiple anodes receive the e^- avalanches.

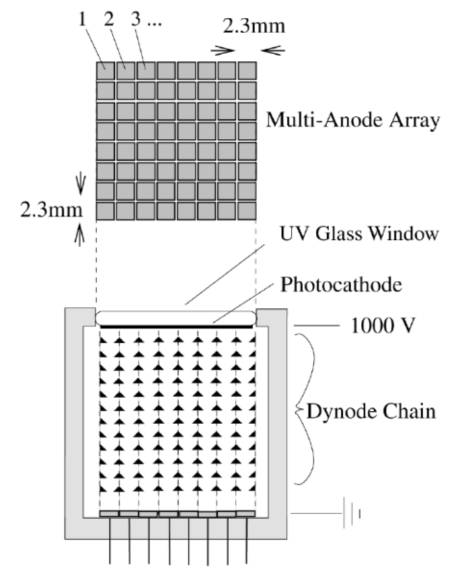
Advantages:

- High gain: 10^6.
- High quantum efficiency: ~40% at 420 nm.
- Fast rise time: <1ns.
- Low dark count rate: few Hz.
- Compact size.

Drawbacks:

- Gain uniformity between channels: can be a factor 3.
- Cross-talk between channels.
- Sensitive to magnetic fields.

At the moment, the price per channel is more competitive for SiPM and even further low in cost is foreseen.



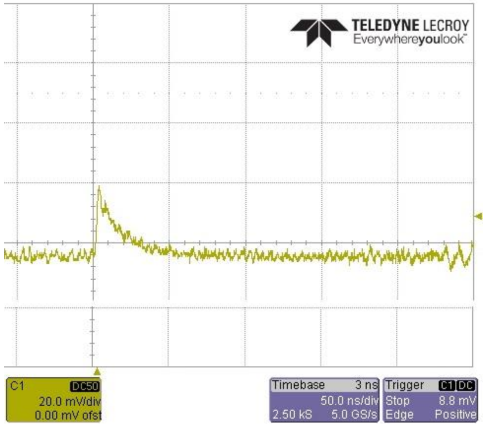
64-Channel MaPMT:
Hamamatsu R7600-03-M64

After thorough investigation, we favoured SiPM for a first prototype.

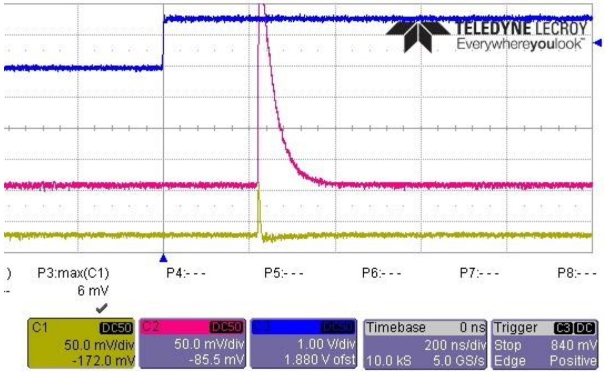
Three brands of SiPM studied in the lab: Hamamatsu, Ketek and SensL.

Hamamatsu MPPC S13360-1350: best overall performance. High gain, low crosstalk, high PDE.
SensL MicroFC-SMTPA-10035: fast channel gives ultra fast signal ~1-2 ns, but lower gain 10^5.

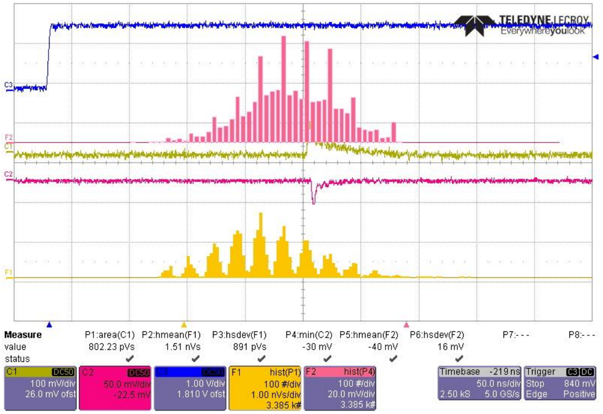
We have also studied the performance of the Hamamatsu MA-PMT H7546-300 and compared it to the SiPM.



Typical MPPC signal after ×20 amplification



MPPC in pink and SensL in yellow both excited by a LED



MPPC signal in yellow with charge histogram and MA-PMT signal in pink with pulse height distribution

Readout electronics

We investigated several commercial ASIC availables.

<ins>CITIROC</ins>: an analogue front-end ASIC made by Omega Microelectronics (CNRS-IN2P3-Ecole Polytechnique)

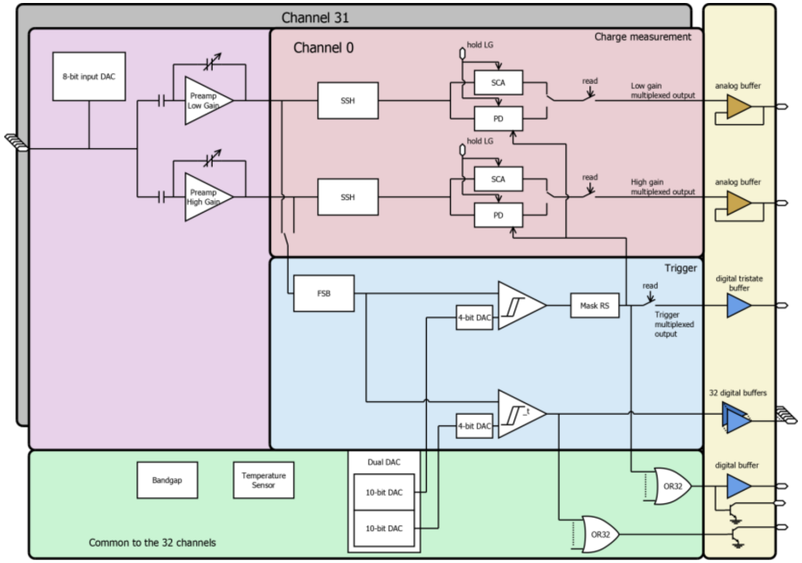
- 32 channels with adjustable SiPM voltage
- Variable slow shapers, track & hold and peak detector for charge measurement
- Variable fast shaper and discriminators for trigger
- Low-power consumption

<ins>NINO</ins>: An ultrafast and low-power front-end amplifier and discriminator ASIC. Developed ALICE ToF system.

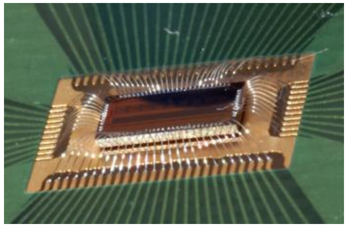
- 8 channel differential input/output
- Fast amplifier with less than 1 ns peaking time
- Charge measurement by Time-Over-Threshold

<ins>STiC</ins>: Readout ASIC for SiPM designed to provide very high timing resolution for time-of-flight.

- 64 channels differential/single-ended with adjustable SiPM voltage
- Two thresholds: energy & timing
- TDC timing resolution 20ps
- Serial link 160Mbit/s LVDS



CITIROC's Block diagram



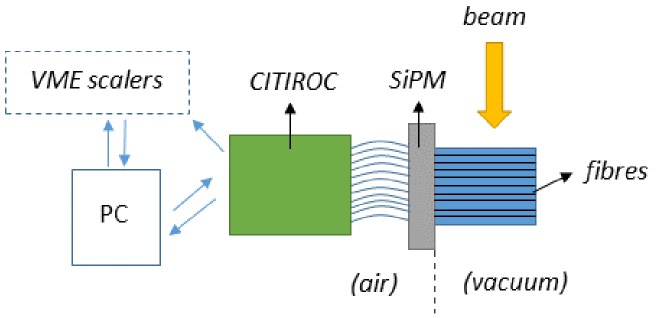
NINO chip

STiC ASIC

4. First prototype

A first prototype was successfully tested in the H8 beam line of the North Area at CERN:

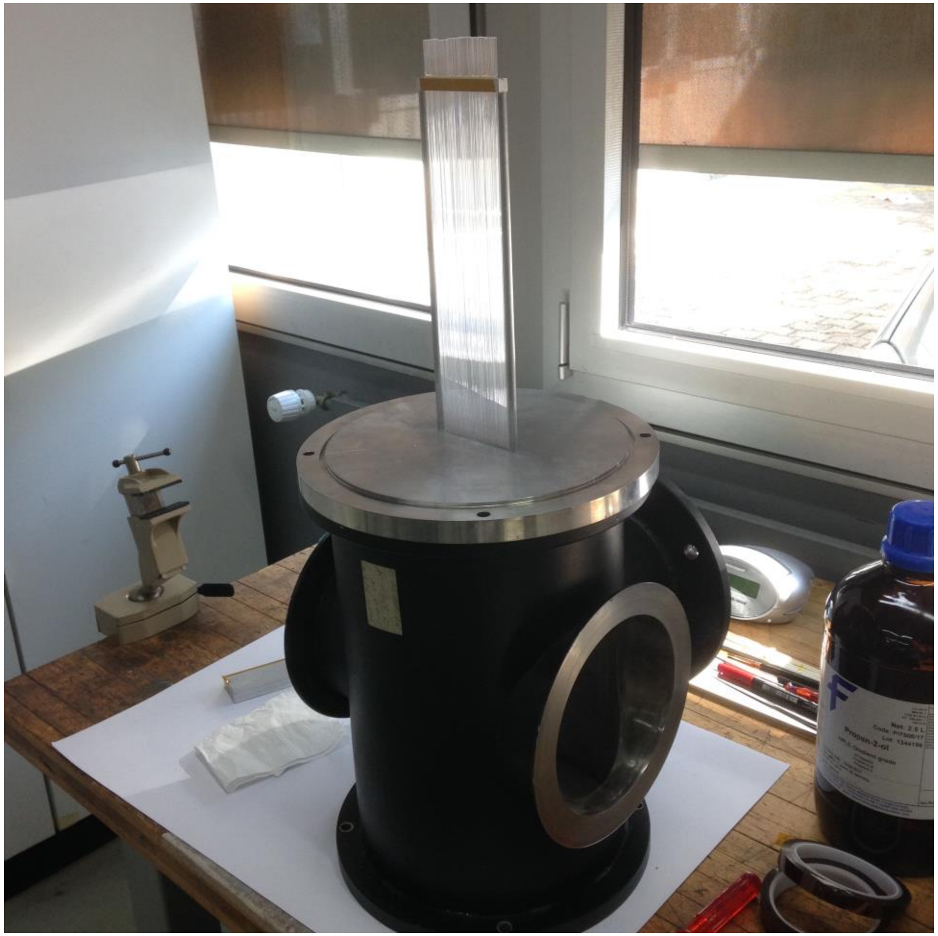
- Only one plane composed of 64 square fibres of 1mm thickness and no space between them → covered 64mm of the vertical profile.
- Fibres Saint-Gobain BCF12, 1mm square, multi-cladding. No treatment to avoid cross-talk.
- Used aluminium mirror on one end to increase light collection.
- Read 1 every 2 fibres for simplicity on electronics acquisition → spatial resolution of 2mm.
- Hamamatsu MPPC S13360-1350 as photo detector.
- Used CITIROC evaluation board for electronics readout: 32 channels.
- VME scaler modules for the data acquisition → only profile and intensity measurements.
- Integrated in the vacuum tank of the FISC → fibres in vacuum, MPPC in air.



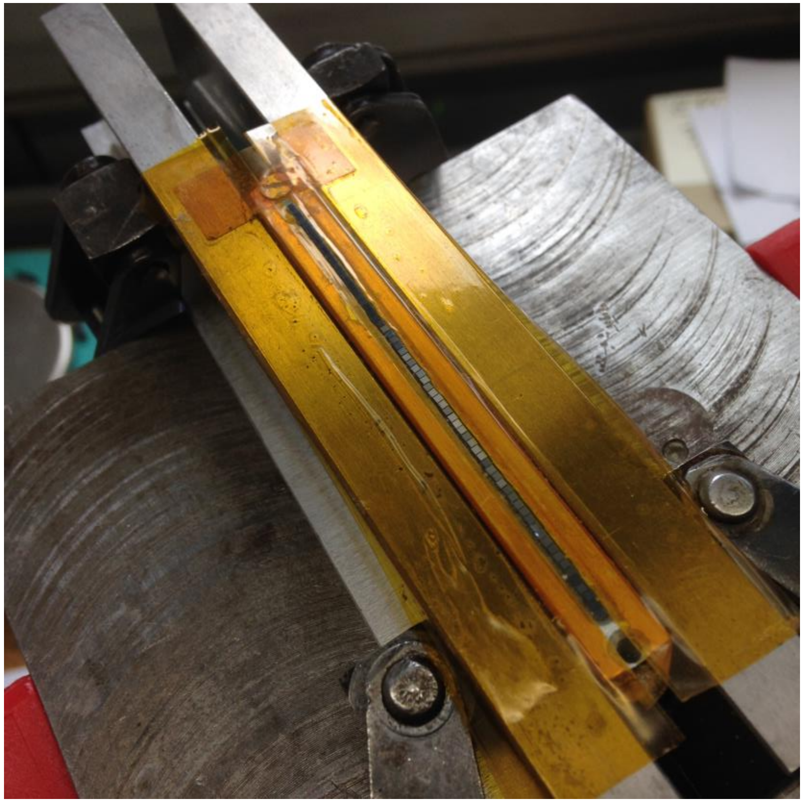
It monitored different Z=1 beams (electrons, pions, protons…) with momentums from 20 GeV/c to 180 GeV/c and intensities from 10^3 to 10^6 particles/spill. It also monitored Pb(82,208) ions.

The FISC vacuum tank

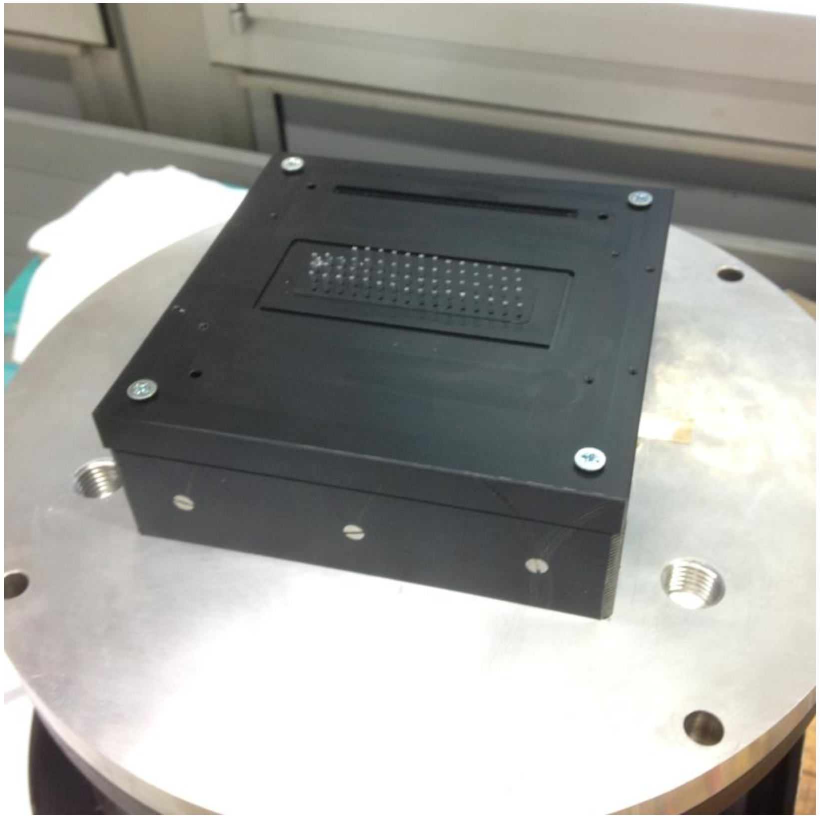
The fibres used: Saint-Gobain BCF12, 1mm square, multi-cladding



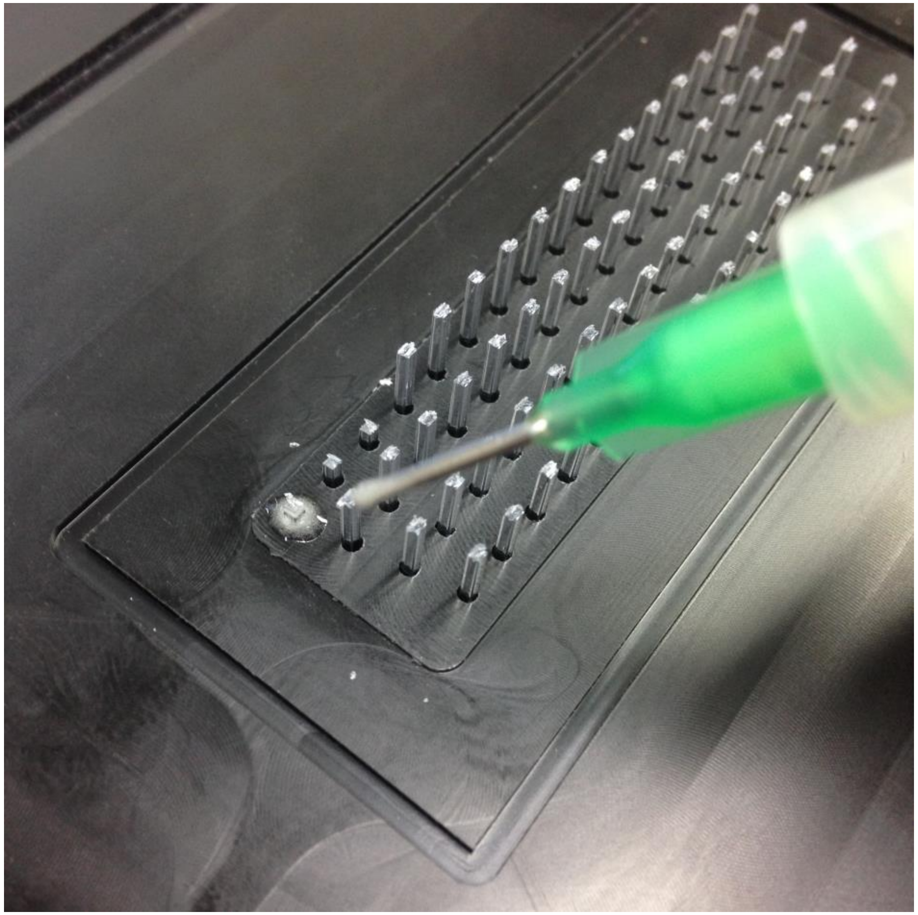
The array of fibres hanging upside-down for glue drying



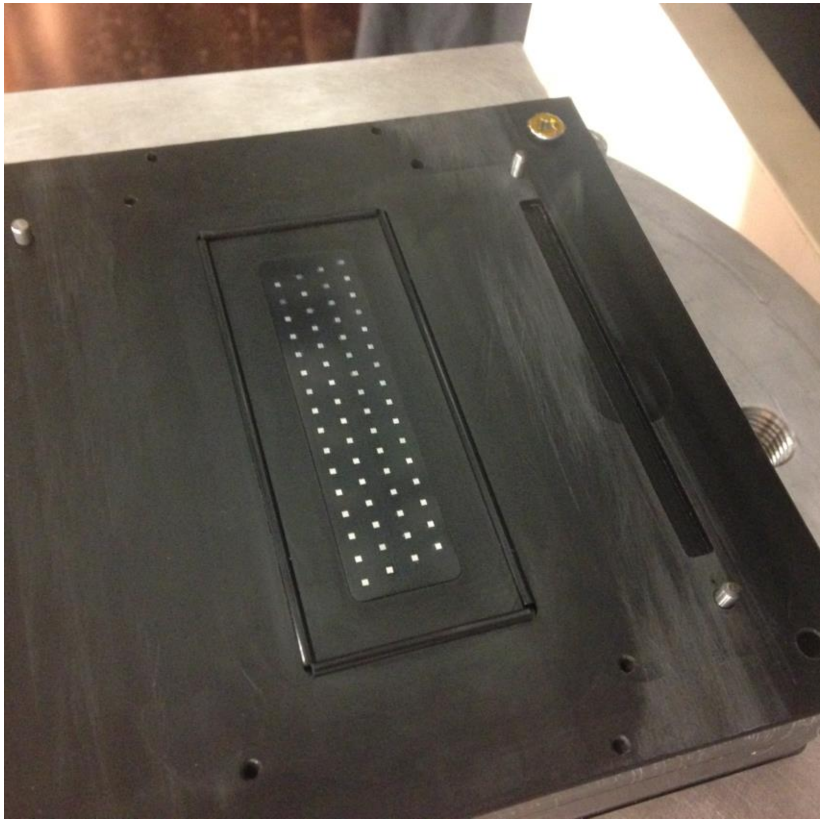
Polishing the fibres on the mirror end



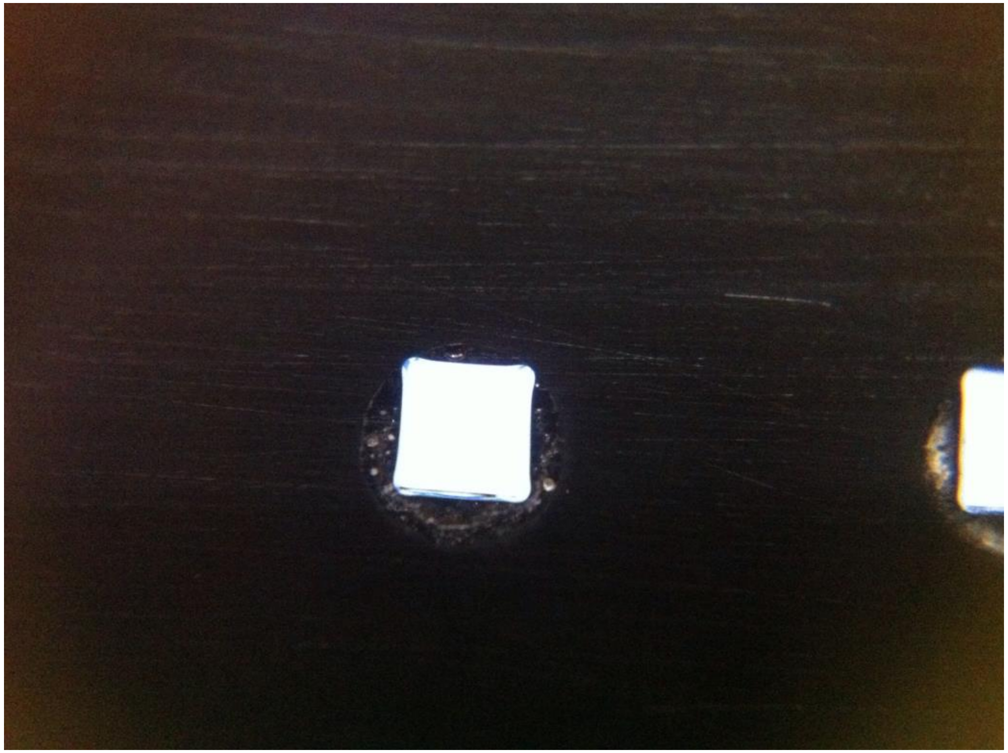
Fibres on the support where the SiPM are coupled



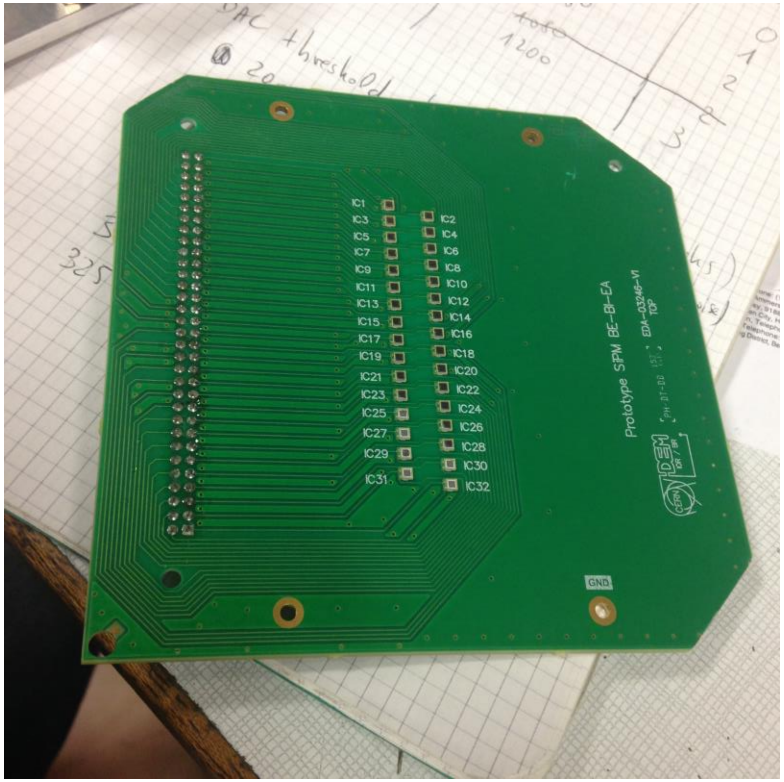
Gluing of the fibres



Fibre connector after polishing.

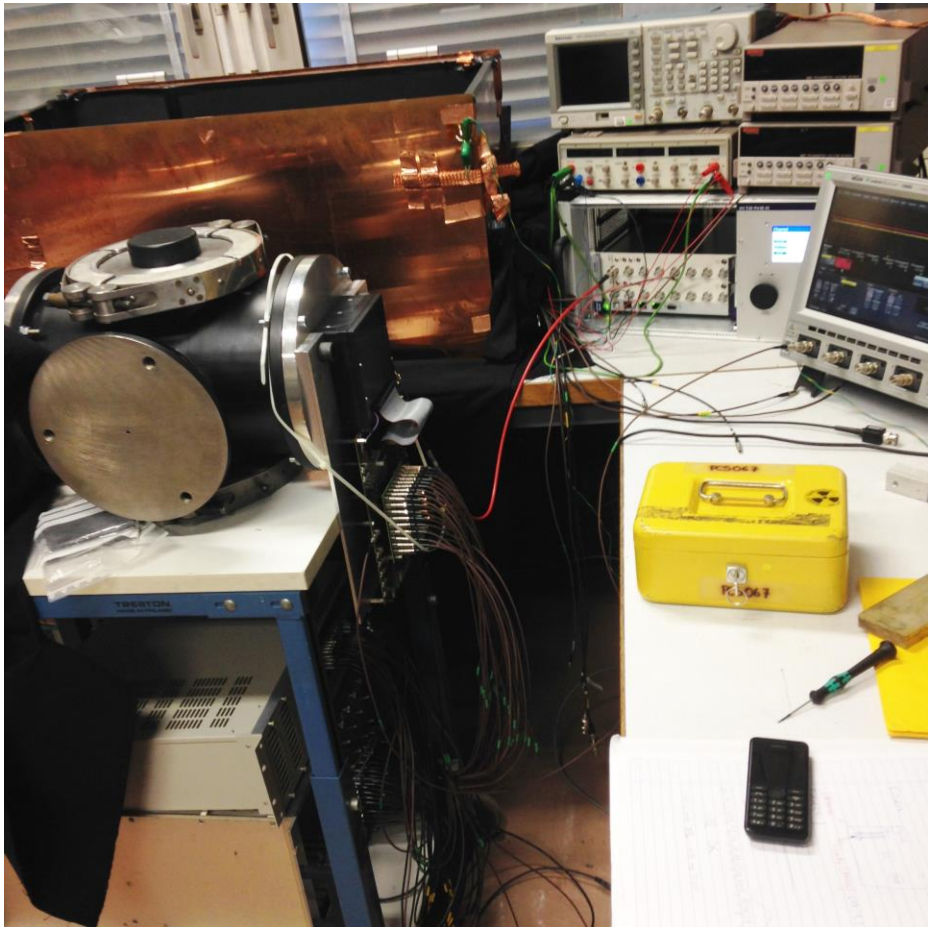


Microscope image of one fibre on the connector.
We can appreciate air bubbles in the glue, the round corners of the square fibre and even the outer cladding of the fibres.

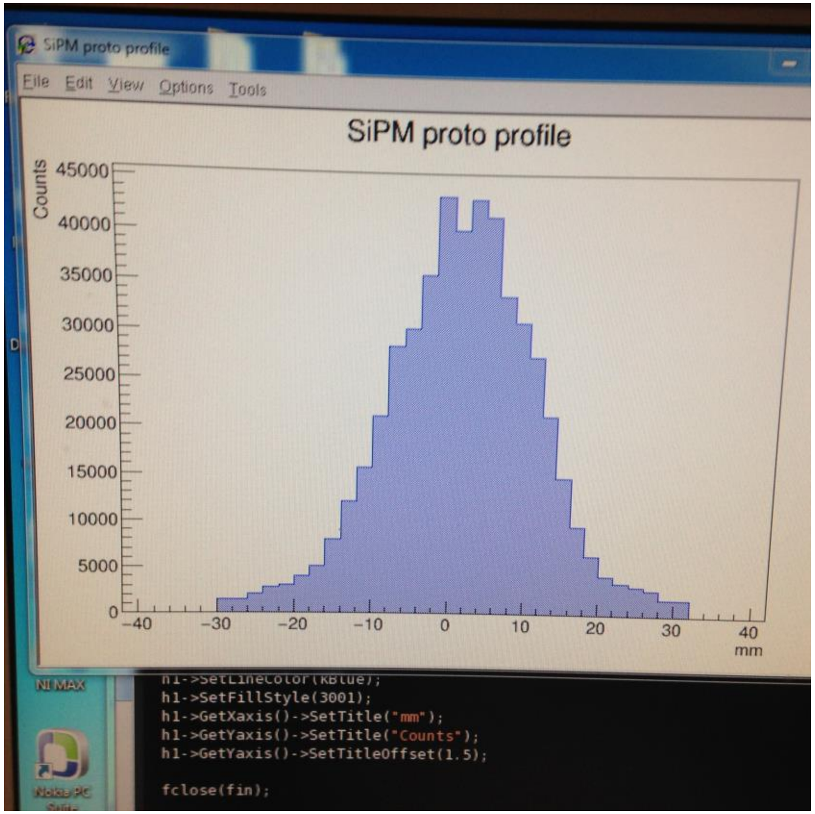


PCB board housing the 32 Hamamatsu MPPC.
It is precisely aligned to the fibre connector

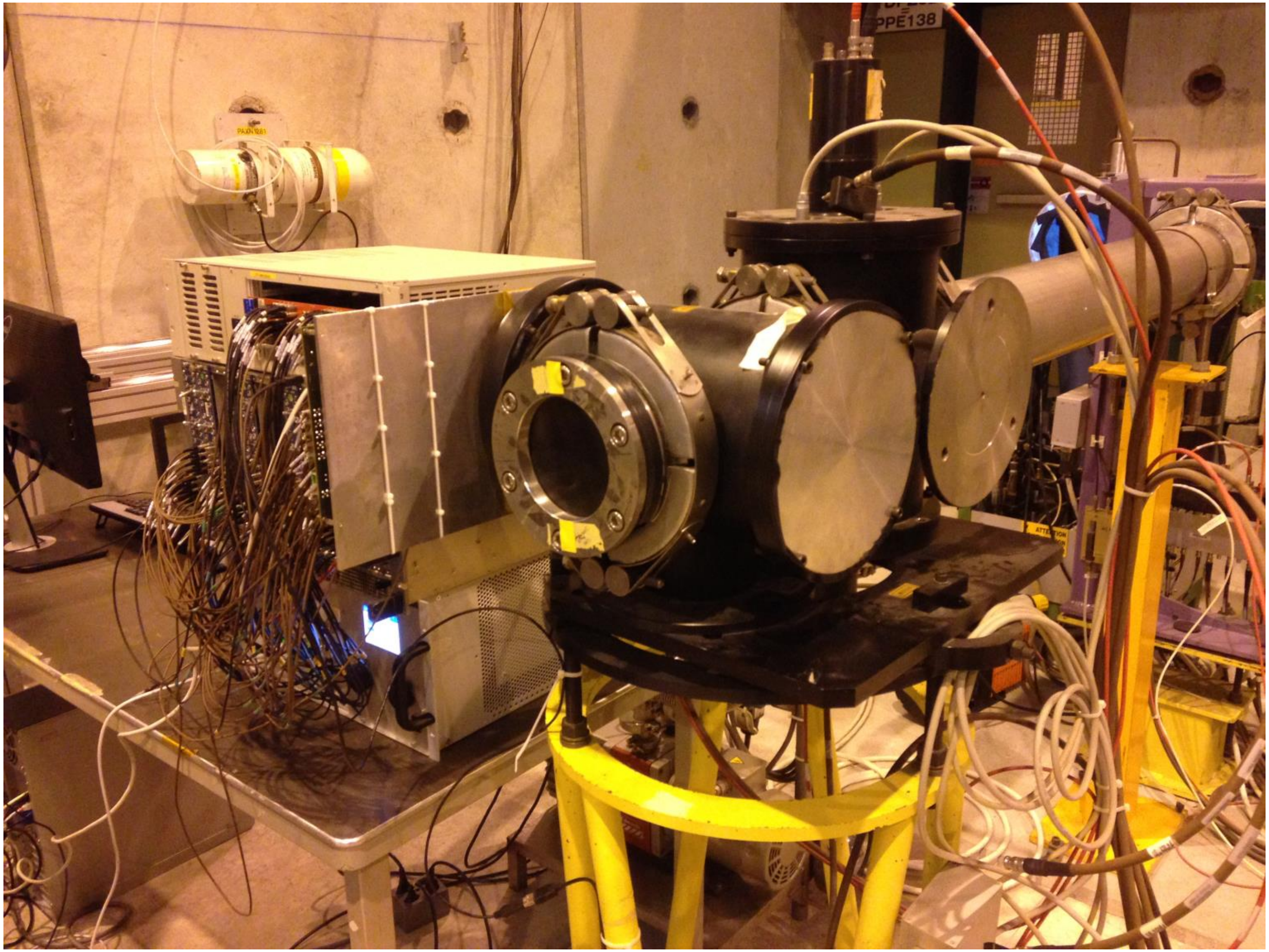
The MPPC board plugged onto the CITIROC board



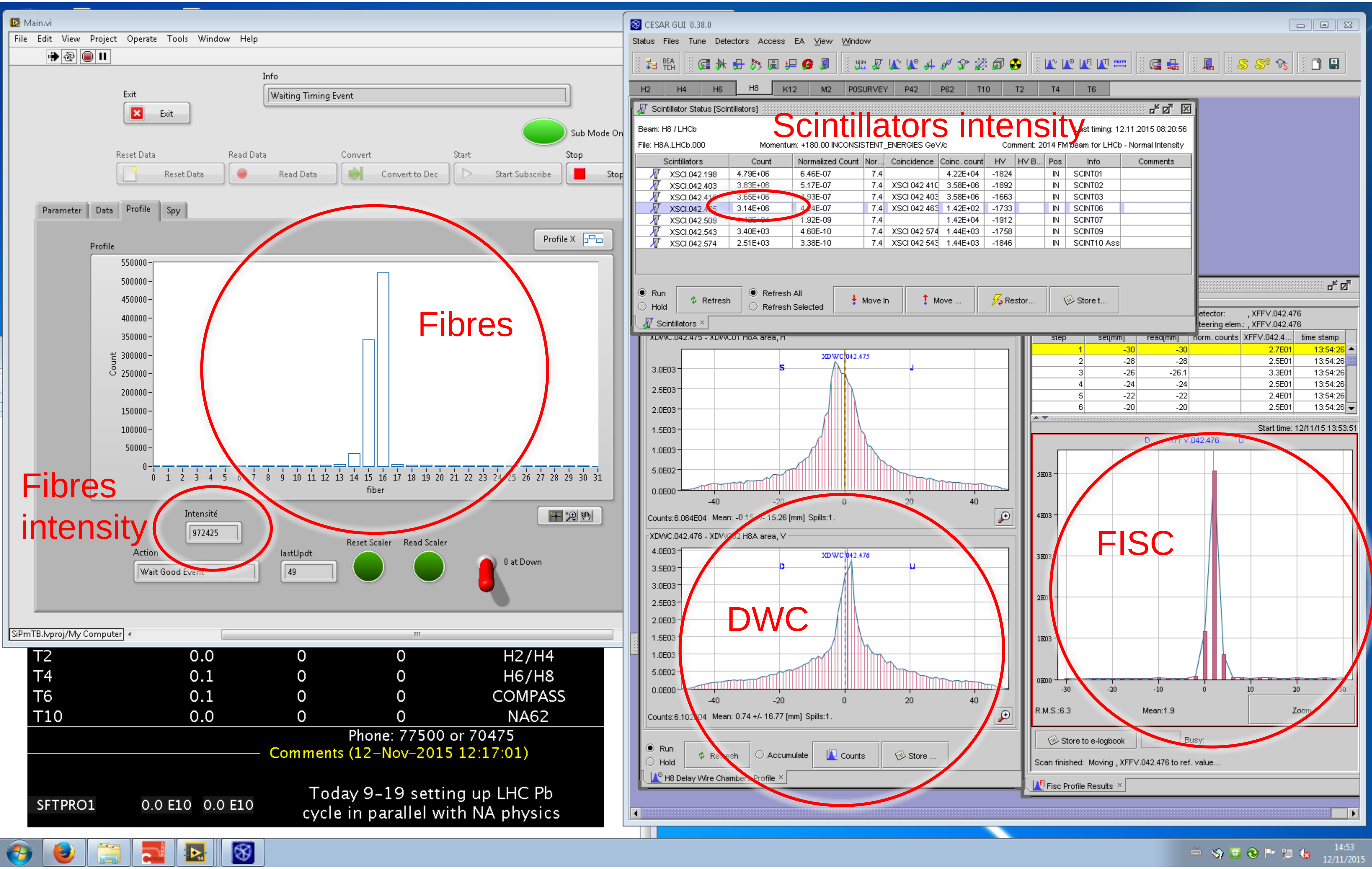
The detector being tested in the lab.



First profile taken with a ^{90}Sr source!



The SciFi monitor installed in H8: the vacuum tank in the centre houses the fibres, while the SiPM and the electronics stay on the outside (left of the figure).


Scintillators intensity
Fibres
Fibres intensity
DWC
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Scintillator Status [Scintillators]
Beam: H8 / LHCb
File: H8A.LHCb.000
Intensité
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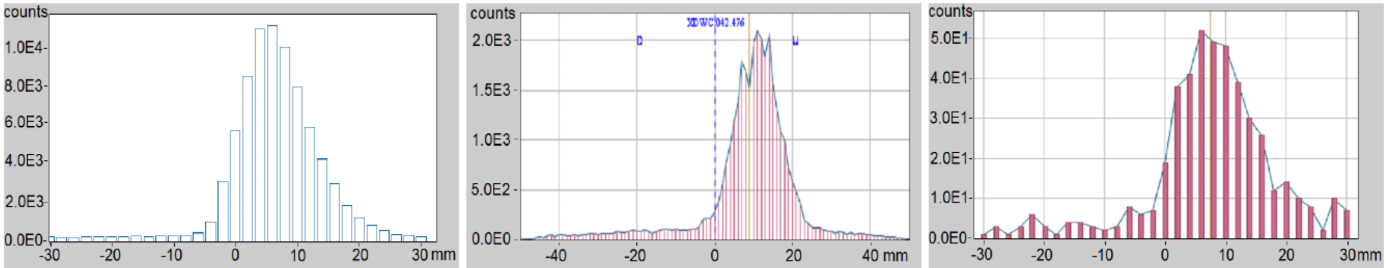
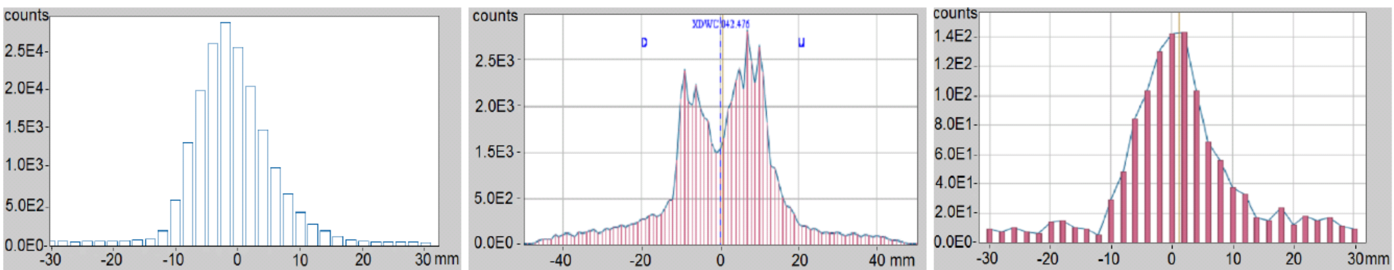
Profile
fiber
Count
T2 0.0 0 0 H2/H4
T4 0.1 0 0 H6/H8
T6 0.1 0 0 COMPASS
T10 0.0 0 0 NA62
Phone: 77500 or 70475
Comments (12-Nov-2015 12:17:01)
SFTPRO1 0.0 E10 0.0 E10
Today 9-19 setting up LHC Pb cycle in parallel with NA physics
H8 Delay Wire Chambers Profile
Fisc Profile Results

Profile analysis of 180 GeV/c proton/pion beams

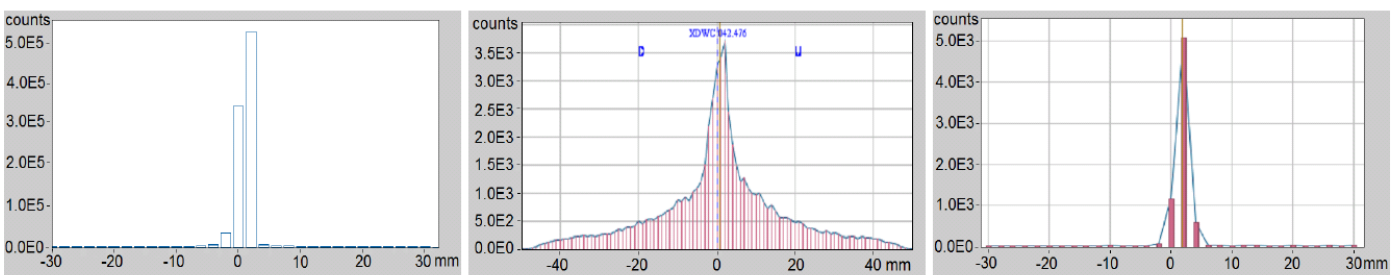
SciFi *DWC* *FISC*



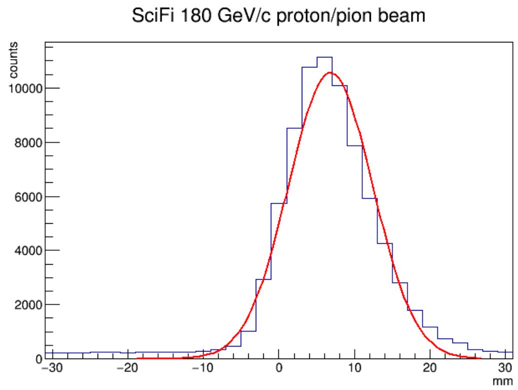
Intensity = 3.4×10^4 particles/second

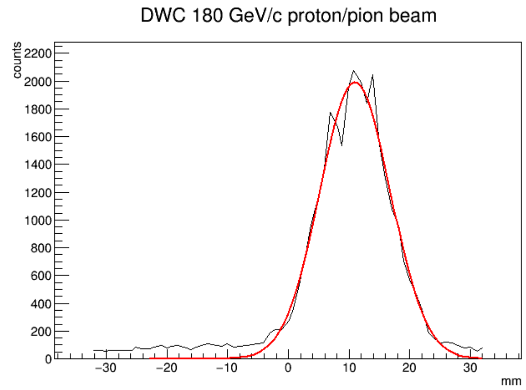


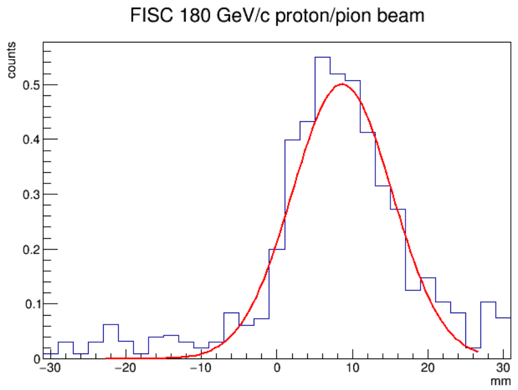
Intensity = 8.2×10^4 particles/second



Intensity = 6.5×10^5 particles/second







Intensity(particles/s)	σ(mm) **SciFi**	σ(mm) **DWC**	σ(mm) **FISC**
3.4×10^4	5.6	5.8	6.6
8.2×10^4	5.4	11.2	6.2
6.5×10^5	0.9	4.0	1.1

The SciFi performed better than the other monitors in all intensities!

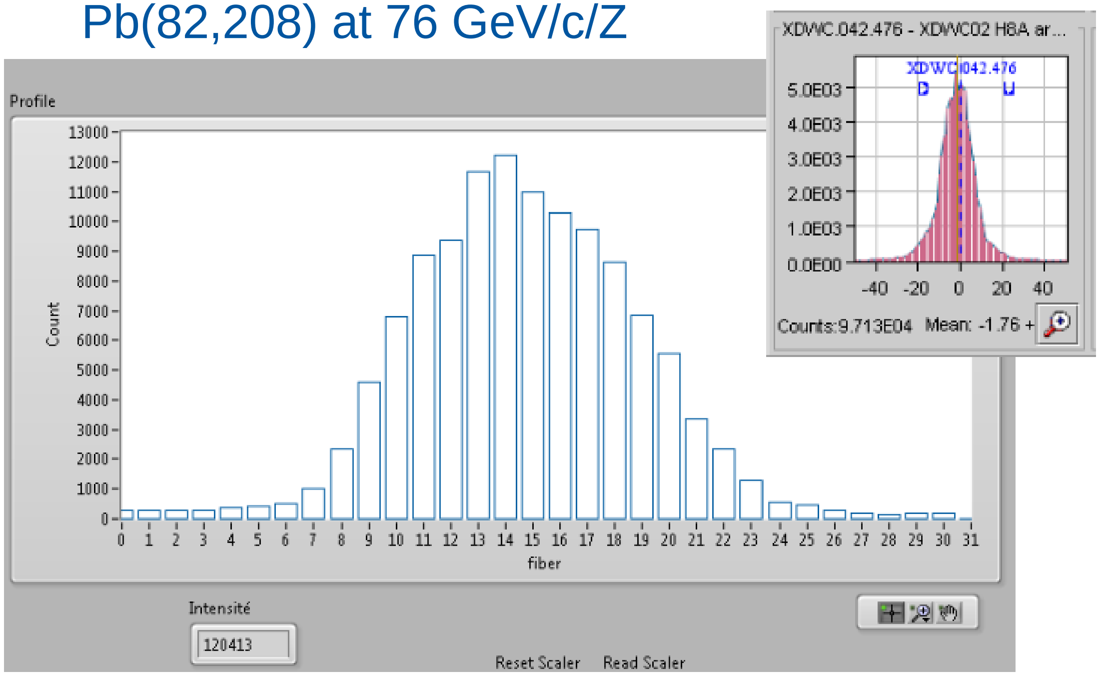
Lead ions

Pb(82,208) ions deposit ~4 times of magnitude more energy than the Z=1 beams (dE/dx is proportional to Z^2):

- The photo detectors were saturated
- The cross talk between fibres, which for Z=1 beams was negligible, became a problem
- Absorbed doses of Gray can be reached within a day → the life length of the fibres is shorten

Pb(82,208) at 76 GeV/c/Z

DWC



Fibres

The wider profile in the fibres can be due to cross-talk: primary UV photons escaping from a fibre and exciting neighbouring fibres.

It could be eliminated with a surface treatment of the fibres, for example an aluminium coating.

5. XBPF

Name given to the new monitor designed for the CERN Neutrino Platform.

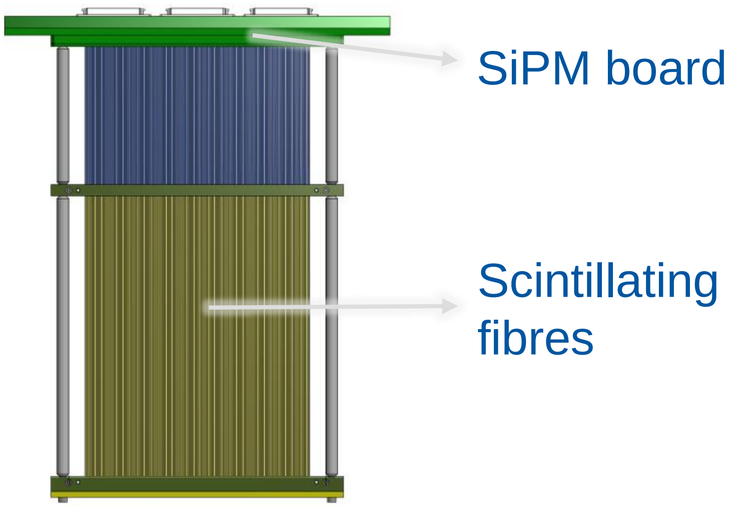
The new beam lines will host the WA105 and ProtoDUNE experiments.

These experiments are neutrino detectors based in large liquid Argon tanks of ~1,000 cubic metres

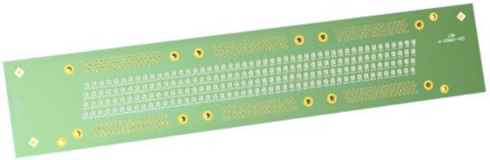
The new beam lines operate at very low intensities (10^2 particles / second), low energies (0.5 to 12 GeV) and require instrumentation with a big active area (200mm x 200mm) → The current BI monitors do not fulfill these requirements.

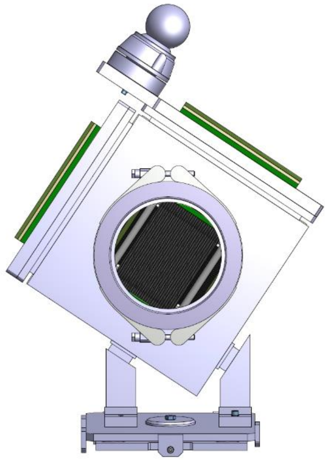
26 detectors have to be produced for 2018. We aim for a fully working prototype in June 2017.

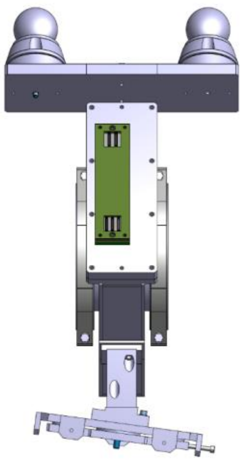
The new proposed instrumentation is based on scintillating fibres read out with silicon photomultipliers.

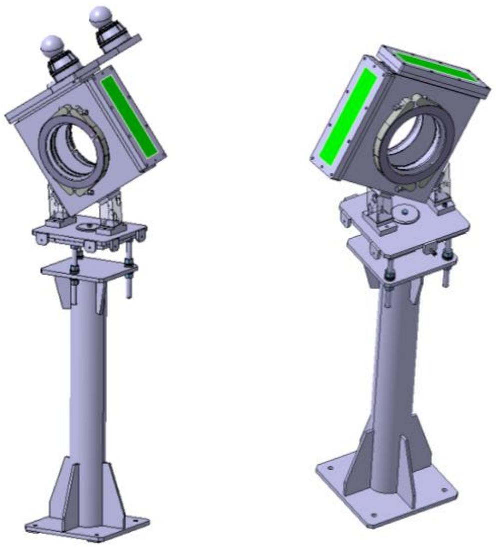


- One layer of 1mm square fibres.
- 200 channels.
- Individual MPPC for every fibre.



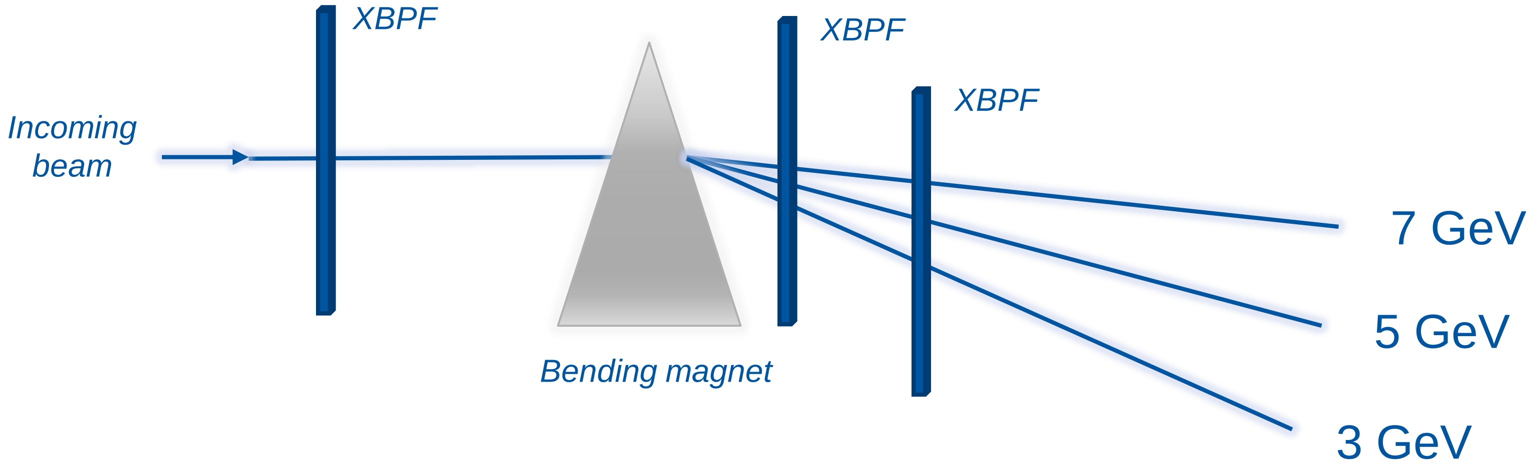




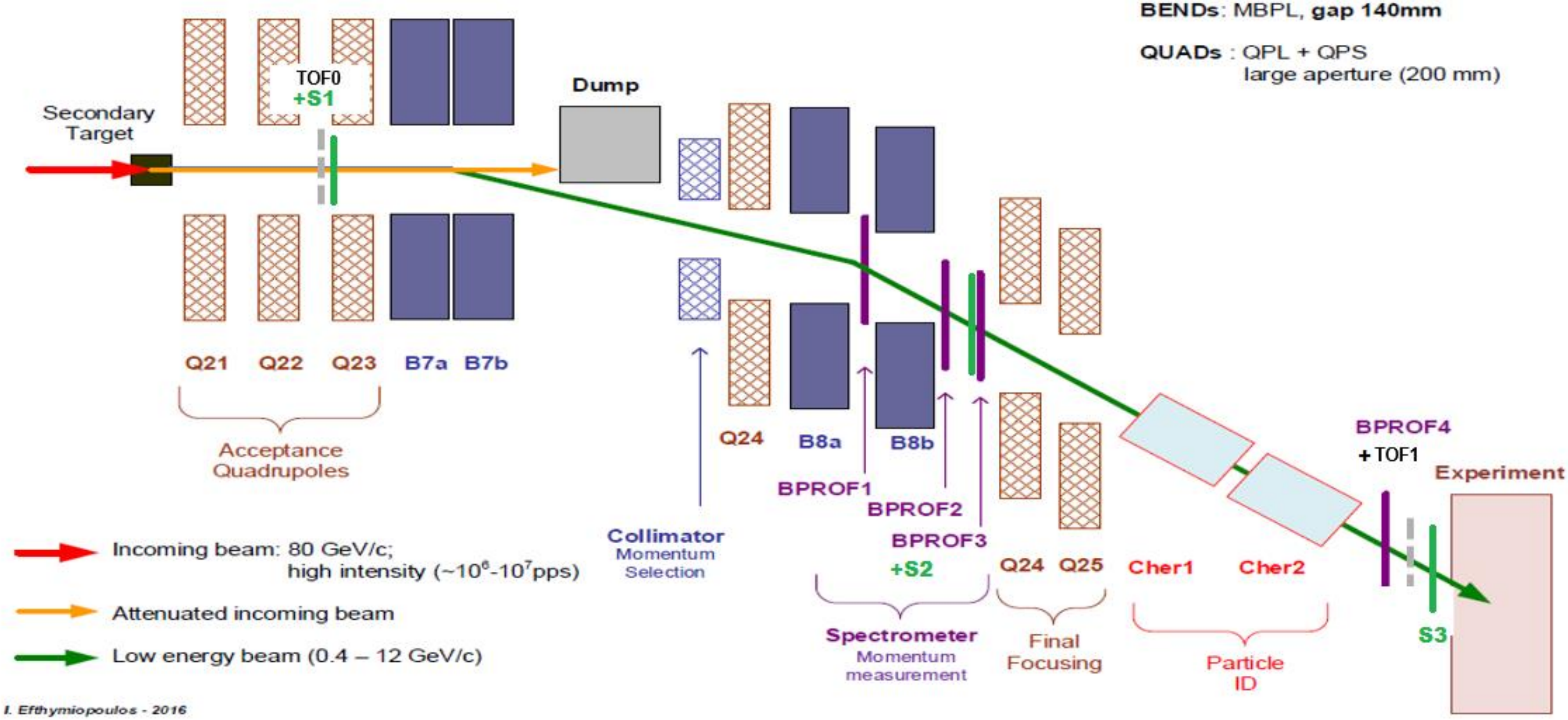


The monitor will perform several functions:

- profile measurement
- magnetic spectrometer
- trigger for the experiments
- time-of-flight

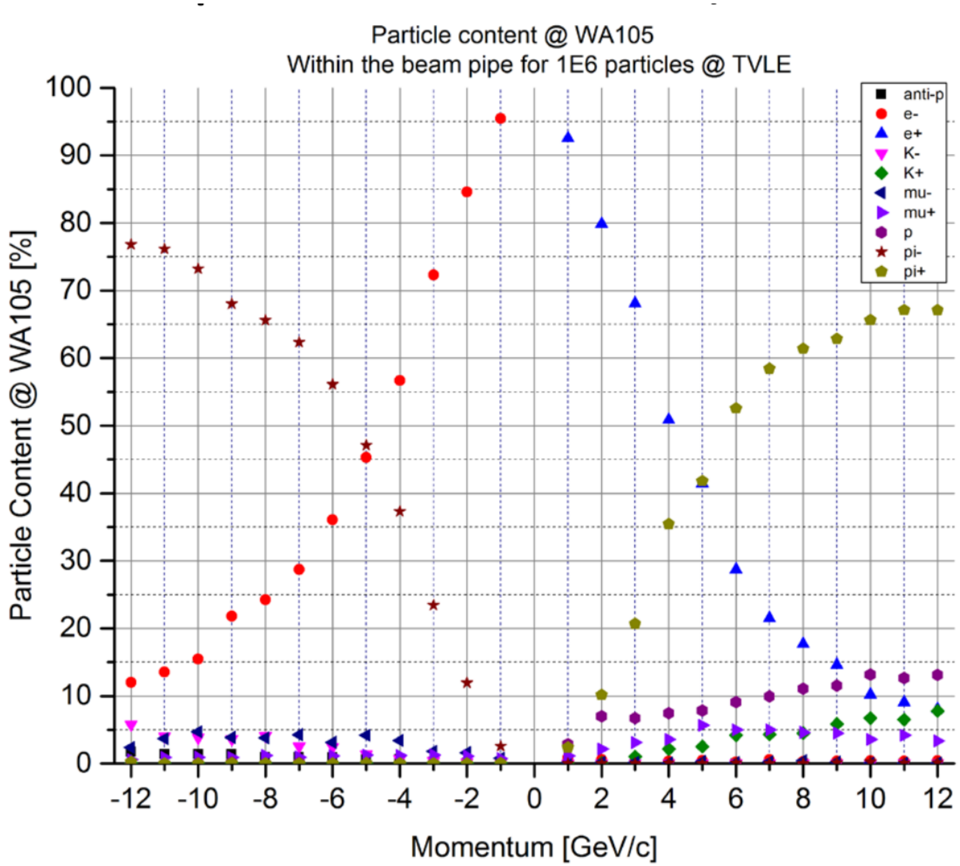


EHN1 Extension - H2 VLE Beam
Schematic Layout



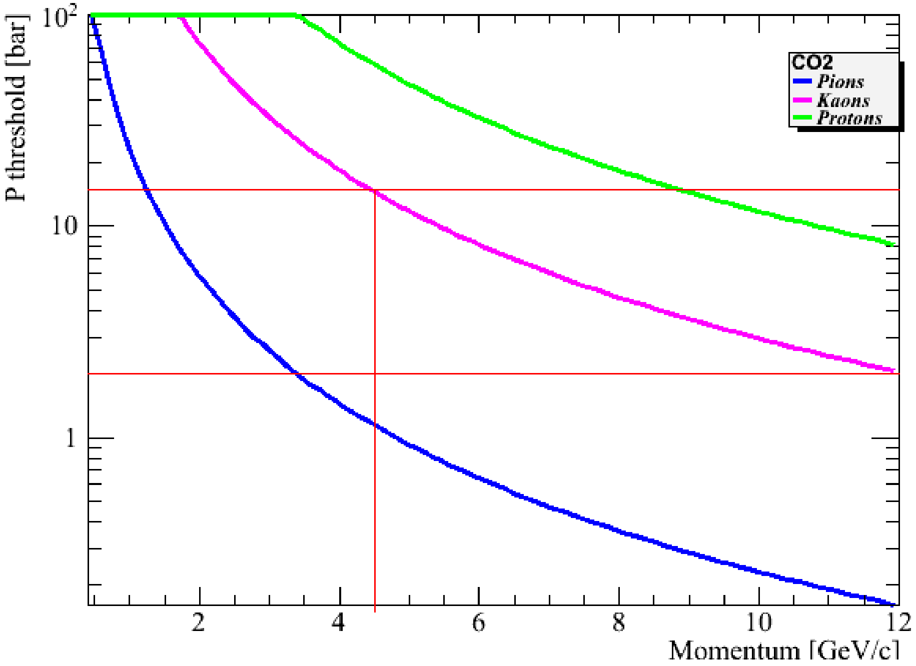
6.Time-of-Flight

Due to the nature of a secondary beam, it will have mixture of different particles. One of the requisites of the new instrumentation is to provide particle identification.



Two methods for particle identification:

- Cherenkov counters: useful for momenta above 4 GeV/c

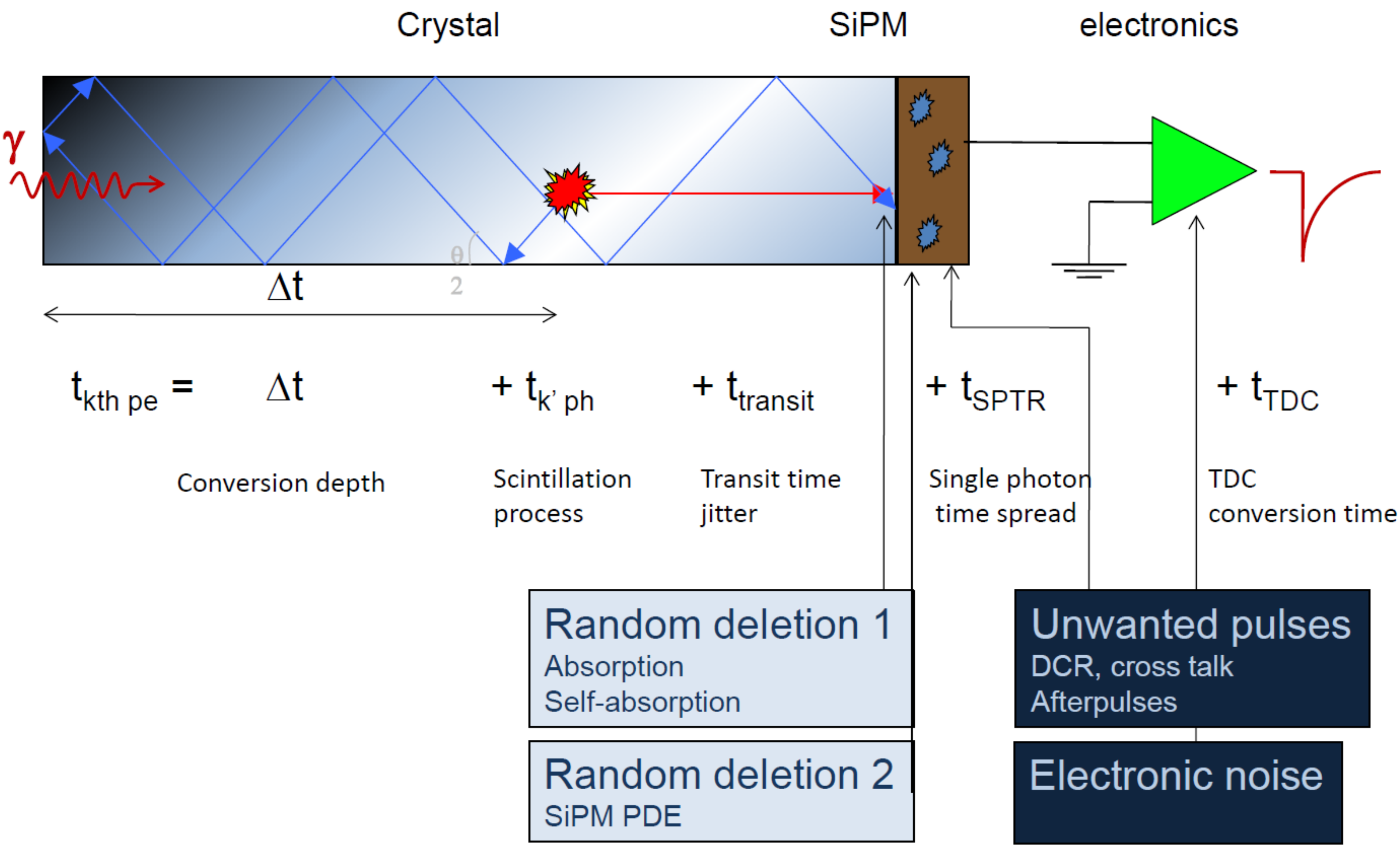


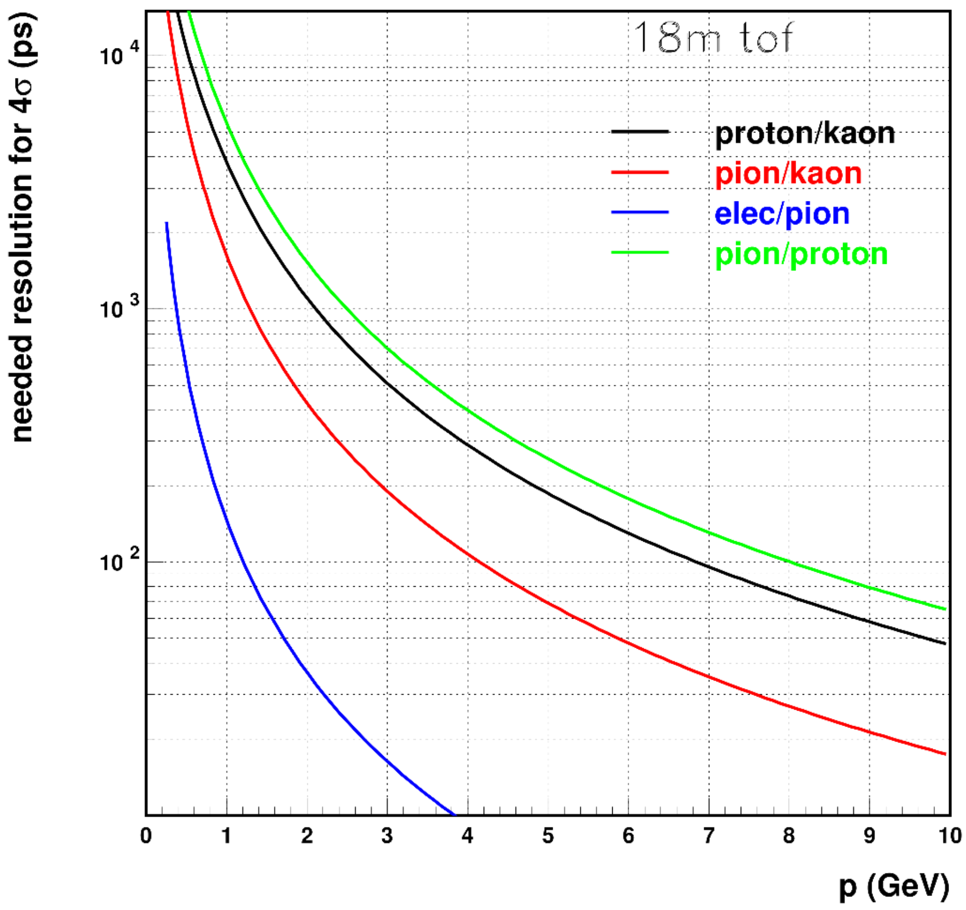
- Time-of-Flight: for lower momenta

Time-of-flight principle

$$\Delta t = t_2 - t_1 = \frac{L}{pc^2}\left(\sqrt{m_2^2c^4 + p^2c^2} - \sqrt{m_1^2c^4 + p^2c^2}\right)$$

The time resolution of your system fixes the particle identification


Crystal
SiPM
electronics
γ
Δt
θ
2
$t_{kth\ pe} = \Delta t + t_{k'\ ph} + t_{transit} + t_{SPTR} + t_{TDC}$
Conversion depth
Scintillation process
Transit time jitter
Single photon time spread
TDC conversion time
Random deletion 1
Absorption
Self-absorption
Random deletion 2
SiPM PDE
Unwanted pulses
DCR, cross talk
Afterpulses
Electronic noise



Our idea is to use the STiC as readout electronics of the SiPM.

We believe that sub-ns time resolution can be achieved with a combination of:

- 1mm fibres (high photon yield)
- Hamamatsu 13360 (low jitter)
- STiC: specialized ToF ASIC

Other experiments like Mu3e have already achieved similar resolutions.

I hope that you have enjoyed!

Time for questions?