Accurate Profile Measurement of the Low Intensity Secondary Beams in the CERN Experimental Areas

LPHE Seminar – 30/04/2018 – EPFL
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Outline

1. Introduction
2. First Prototype
3. Beam Tests of the First Prototype
4. Instrumentation for the Neutrino Platform
5. Beam Tests of the XBPF
6. Cosmic setup
7. Conclusions
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Objective of the thesis work:

*Develop a new monitor, as well as the associated electronics, in order to accurately determine the beam position and profile for the lowest intensity beams that are delivered to the CERN Experimental Areas.*
What are the experimental areas?
Experimental Areas

- Injector
- PS or SPS machine
- Slow extraction
- Fixed Target
- Secondary beam lines
- Beam monitor
- Large number of experiments and researchers: R&D in physics, particle detectors and accelerators technology, among others. Well known by LPHE researchers.

- The EA utilise ~41% of the protons produced at CERN.

- Wide variety of beams: different particle types, intensities, and energies.
ProtoDUNE: Neutrino detectors consisting in ~700 tons of liquid Argon
- Very low energy beams
- Very low rate
- Large beam spot size
Monitors in the experimental areas:
- Multi-wire analogue chambers
- Delay wire chambers (DWC)
- Finger scintillator scanner (FISC)

These detectors have greatly performed for decades.

However:
- They are ageing.
- They cannot fulfil the requirements of the Neutrino Platform, particularly individual particle detection and active area size.
Requirements of the new instrumentation:

- Individual particle detection.
- High detection efficiency: > 90%.
- Spatial resolution: 0.5 or 1 mm.
- Maximum beam intensity: \( \sim 10^7 \) particles/second/mm\(^2\).
- Wide dynamic range: 0.5 GeV to 450 GeV.
- Minimise material budget: < 0.5% radiation thickness (x/X0).
- Two detector sizes: 10cm x 10cm and 20cm x 20cm.
- Moderate radiation hard: \( \sim \)kGy.
- Operation in vacuum.
- Robust and easy to maintain.
- Reasonable cost.
Review of most common tracking technologies: GEM, Micromegas, Semiconductors, and Scintillating Fibres
GEM

Main physical processes:
- Gas ionisation.
- Avalanche.

Micromegas

Disadvantages:
- Sparks (especially at high rates).
Semiconductor Detectors

"Solid state ionisation chamber":
Semiconductor ionisation + drift.
Low gain → sensitive electronics.

Advantage: high performance.
Disadvantages:
- Expensive
- Cooling needed.

Scintillating Fibres

Working principle:
Excitation of atoms → scintillation (light).
Light trapping + photodetector.

Advantage: non expensive material.
Disadvantage: production can be cumbersome.
Qualitative comparison of the four tracking technologies reviewed:

<table>
<thead>
<tr>
<th></th>
<th>Efficiency &amp; Resolution</th>
<th>Material budget</th>
<th>Active area</th>
<th>Vacuum integration</th>
<th>Maintenance &amp; Cost</th>
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</thead>
<tbody>
<tr>
<td>GEM</td>
<td></td>
<td></td>
<td><img src="checkmark.png" alt="Green Check" /></td>
<td><img src="x_mark.png" alt="Red X" /></td>
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<tr>
<td>μMegas</td>
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<td>Semiconductors</td>
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<td><img src="x_mark.png" alt="Red X" /></td>
<td><img src="x_mark.png" alt="Red X" /></td>
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<td>SciFi</td>
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7. Conclusions
- Pixelated readout → every ‘fibre – photodetector’ pair is a channel.
- Fibres in vacuum, photodetector in air → Monitor integrated in vacuum.
- One plane of 64 packed square fibres of 1mm → profile reconstruction over 64mm.

- Mirror on one end to increase light collection.
- The number of particles/channel is counted → profile and intensity measurement.
Choice of Scintillating Fibre

• Square cross-section → good beam coverage with a single or double layer design.

• Two thicknesses investigated: 0.5mm and 1mm.

• Two main manufacturers reviewed: Saint-Gobain and Kuraray.

Small setups to characterise the signal from different fibres → Measurements done in LPHE.
Choice of photodetector and electronics

Two options:
- Silicon Photomultipliers (SiPM)
- Multi Anode-Photomultipliers (MA-PMT)

SiPM favoured for a first prototype.

SiPM: ✔ efficiency, ✔ new technology, ✔ low cost, ✗ noise
MA-PMT: ✔ low noise, ✗ gain uniformity, ✗ crosstalk

Three brands of SiPM studied in the laboratory.

Readout electronics:
CITIROC ASIC chosen for SiPM signal readout.
Other electronics investigated (STiC and NINO), but CITIROC features: configurability, SiPM gain trimming, signal discrimination, charge reading, low cost, and simplicity.

<table>
<thead>
<tr>
<th>SiPM model</th>
<th>DCR (kHz)</th>
<th>Crosstalk (%)</th>
<th>$V_{ov}$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu S13360-1350</td>
<td>26.3 ± 4.2$^1$</td>
<td>0.8 ± 0.4</td>
<td>3</td>
</tr>
<tr>
<td>Ketek PM1150TS</td>
<td>142.0 ± 6.6$^2$</td>
<td>3.9 ± 1.3</td>
<td>2.5</td>
</tr>
<tr>
<td>SensL MicroFC-10050</td>
<td>48.5 ± 7.7$^3$</td>
<td>6.6 ± 2.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

$^1$ Active area: 1.3 mm × 1.3 mm.
$^2$ Active area: 1.2 mm × 1.2 mm.
$^3$ Active area: 1 mm × 1 mm.
First prototype built in the workshops of LPHE

The array of fibres hanging upside down for glue drying

Polishing of the fibres on the mirror end
Fibre connector after polishing

PCB board housing the 32 SiPM. The alignment to the fibre connector is guaranteed by precision dowel pins.
The SiPM board connected to the CITIROC board

The prototype mounted and being tested in the lab. The VME counters are in the lower part of the table
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Beam tests in the North Area
SciFi intensity

Scintillator Paddle intensity

FISC

DWC

Today 9-19 setting up LHC Pb cycle in parallel with NA physics
Profile analysis of 180 GeV/c proton/pion beams of three different intensities

- **SciFi**: performed well in all intensities.
- **DWC**: had troubles with high intensities.
- **FISC**: could not resolve low intensity beams.

*Intensity = 3.4 × 10^4 particles/second*

*Intensity = 8.2 × 10^4 particles/second*

*Intensity = 6.5 × 10^5 particles/second*

The SciFi performed well in all intensities; the DWC had troubles with high intensities; the FISC could not resolve low intensity beams.
Measurements with lead ion beams

SciFi profiles were wider than the DWC.

Believed to be optical crosstalk between the fibres, caused by the large energy deposition of lead ions.

Possible solution: aluminium coating of the fibres.

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Beam instrumentation for the Neutrino Platform: XBPF

Specific requirements:
- 200mm X 200mm active area
- Individual particle detection
- 1mm spatial resolution
- High efficiency > 90%
- Fibre multiplicity information
- Use White Rabbit for common time reference
- Vacuum integrated
- Detector size constraint

Two versions of the detector with different functions.

XBPF:
- Beam profile
- Momentum spectrometer

XSCINT
- Trigger generation
- Time-of-flight
Fibres chosen: Kuraray, 1mm thickness.
Different functions in the beam line

**Trigger + ToF: 1 XSCINT**

**Spectrometer + Profile: 4 XBPF**

**Profile + Trigger + ToF: 2 XBPF - 1 XSCINT**
- Trigger generation for the beam instrumentation and the neutrino experiments.
- Dataflow from front end to back end via optical link.
- Single event time-stamping with White Rabbit (special low latency network for high-performance time transfer).
Front End Board

New development that features:

- 192 SiPM aligned to the XBPF fibres.
- Hamamatsu C11204 power supply for SiPM.
- 6 CITIROC ASIC.
- Xilinx FPGA Artix 7.
- SFP module with Gbit transceiver.
Back End Board: VFC

Digital acquisition VME board developed in the Beam Instrumentation group at CERN.

It performs the following functions:

- Decode Gbit stream from Front End.
- Create event structure.
- Send control data to Front End.
- Incorporates White Rabbit receiver for event time-stamping.
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Fighting against the clock

Two weeks of accelerator time booked for us: from 20 November to 4 December 2017.

The fibre assemblies were ready at the beginning of October.

The vacuum tanks arrived in the middle of October.

The front end boards were ready for testing at the beginning of November.

Next beam time available would be May 2018 (with much luck...).
But we did it!!

Large efforts were done in the last quarter of 2017 in order to be ready for the beam tests.

Even the Time-of-Flight system was working!
Vacuum tests

$10^{-3}$ mbar achieved

(North Area requirement)
Debugging in the laboratory
First profile of a Sr90 source obtained locally (via USB) in the laboratory
First profile of a Sr90 source obtained remotely via the VFC (optical link) in the laboratory
Installation of the monitors in the T10 beam line of the East Area

(24 November)
Layout of the T10 setup

One XBPF and one XSCINT per tank

*DWC = Delay Wire Chamber for beam profile reconstruction
*SCINT = Scintillator paddles for beam intensity measurement
Upstream monitor, close to a DWC and a Scintillator Paddle

Downstream monitor
14m further away
XBPF front end board installed on top of the fibres

Control room: VME crate with the VFC board and the Time-of-Flight TDC

All the electronics have the same time reference provided via White Rabbit.
VFC data has particle-by-particle information containing:

- Status of 192 fibres: hit / not-hit.
- Timestamp
Preliminary results of the East Area tests

The first analysed data sets showed an overall good performance with:
- Efficiency higher than 90%
- Fibre crosstalk lower than 3%

However, the analysis is long and hard and is still ongoing. There are some phenomena that have to be understood.

Example of analysis plots:
Profiles of a -6 GeV/c pion beam of $I=1.5 \times 10^5$ particles

Local acquisition of the XBPF

Delay Wire Chamber

Horizontal profile (upstream XBPF: 1m away from DWC)

Vertical profile (downstream XBPF: 14m away from DWC)
Trigger efficiency measurement

XSCINT detection efficiency = 94.0 ± 0.1%
What about the time of flight?
Time-of-flight principle

Secondary beams are composed of many particles not identified

\[ \Delta t = t_2 - t_1 = \frac{L}{pc^2} \left( \sqrt{m^2c^4 + p^2c^2} \right) \]

The time resolution of our system limits our ability to identify particles.
TDC used: SVEC FMC-TDC

Mezzanine board mounted in the SVEC VME carrier.

Incorporates ACAM Time-to-digital converter.

Fully compatible with White-Rabbit.

81 ps time resolution (1 sigma).

Constant Fraction Discriminator used: CAEN N842

NIM module quickly available and easy to use.

400ps time walk.

NIM output → signals need TTL conversion for compatibility with TDC.
Time-of-Flight performance in the East Area tests

Time resolution of 900ps: allows distinguishing beam composition at low momenta.
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Cosmic setup

Sandwich of 2 XSCINT and 1 XBPF.

Excellent way of measuring the performance of the detector.

Generates data uninterruptedly → people for protoDUNE DAQ working on integration can access real data from cosmics.

No time pressure as in the accelerators → scan on various parameters to investigate the performance of the detector.
Example measurement with the SiPM overvoltage = 3V, preamp value 16 (x 12.8), discriminator’s threshold to 3.5 photons:
Files found:
[0] discrit235-16h-55V-tfs-preamp16.root
[1] discrit-235_22h_55V-tfs_preamp32.root

Select file to analyse.
File number: 0
Processing... It may take a while.
FCN=1060.41 FROM MIGRAD  STATUS=CONVERGED  72 CALLS  73 TOTAL
EDM=6.63322e-11 STRATEGY= 1  ERROR MATRIX ACCURATE

EXT PARAMETER      STEP    FIRST
   NO.  NAME      VALUE    ERROR    SIZE    DERIVATIVE
  1  Constant  1.89157e+03  5.20245e+00 6.39478e-02    2.53174e-06
  2      Mean  9.57010e+01  1.20373e-01 1.91437e-03   -4.48382e-05
  3     Sigma  4.92137e+01  1.13751e-01 1.02237e-05  1.05713e-02

Processed events:  182625
Detected events:   173620  90850    87485
Efficiency:        94.74%  52.51%  50.56%
Total multiplicity: 20.87%  44.67%  51.09%
Multiplicity 2:    17.15%  46.96%  52.99%
Multiplicity 3:    2.28%  35.67%  44.70%
Higher Mult:      1.45%  31.71%  38.58%
Adjacent fibres:  19.02%  45.67%  52.20%

Analysis of the aluminised and uncoated fibres as individual detectors:

<table>
<thead>
<tr>
<th></th>
<th>Aluminised</th>
<th>Uncoated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total multiplicity</td>
<td>17.76%</td>
<td>21.09%</td>
</tr>
<tr>
<td>Multiplicity 2</td>
<td>15.34%</td>
<td>17.97%</td>
</tr>
<tr>
<td>Multiplicity 3</td>
<td>1.55%</td>
<td>2.02%</td>
</tr>
<tr>
<td>Higher Mult</td>
<td>0.87%</td>
<td>1.10%</td>
</tr>
<tr>
<td>Adjacent fibres</td>
<td>16.54%</td>
<td>19.64%</td>
</tr>
</tbody>
</table>

Gaussian fit of the profile:
Mean = 95.70; Sigma = 49.21

Output file name: discrit235-16h-55V-tfs-preamp16.analysis.txt
Plots saved in PNG format

Elapsed time: 1.00s

root [1]
Distance between two activated fibres

- Aluminised
- Uncoated

Number of events vs Distance in #fibres

Entries: 29671
Beam profile reconstructed with events of multiplicity 2 and 3

Number of events

Fibre number

Multiplicity 2
Multiplicity 3

Entries 59342
Monte Carlo simulation of the cosmic setup

- Recreates geometry of the setup.
- Generates data file identical to XBPF monitor, so it can be analysed identically.
- Uses random generator to create cosmic’s tracks.

Straight tracks are originated at a fixed altitude, with an arbitrary x0 and an arbitrary angle distribution according to $\cos^2\theta$. 
Simulation data analysed:

The high multiplicity is due to real particles crossing 2 fibres due to their angle!

The optical crosstalk for the uncoated fibres is <3%.
For the aluminised fibres <1%.
Time-of-flight improvements are also being investigated:

- Use of better cables.
- Constant Fraction Discriminators with less walk time.
- Constant Fraction Discriminators with direct TTL output to avoid logic conversion.

<700ps achieved in the cosmic test bench with good quality cables (50m)
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Conclusions

• A SciFi monitor based on a pixelated readout, and integrated in vacuum, performs better than the present monitors under secondary beams.

• It is also capable of extending the functionalities with the Time-of-Flight at low momenta.

• It shows limitations with Pb-ions that are believed to come from crosstalk → still under investigation.

• The cost of the SciFi monitor is lower than the present detectors and its maintenance is simpler (no gas, no HV).

• The expected lifespan of the monitor is long, several years. In case of failure, the modular design would allow for an easy replacement of the faulty component.
Final remark

This simple and cost-effective development could extend its application to other fields outside particle physics, such as: radioprotection, management of radioactive waste, medicine, or even industrial applications in which it is necessary to track charged particles.
Thank you very much for your attention!
Backup slides
Additionally, the measurements done with the fibres were used to tune a Geant4 simulation.

Saint-Gobain can produce square multi-clad fibres → improved light trapping.


The choice for the first prototype: Saint-Gobain fibres, 1mm thickness → guarantee a clear signal to reconstruct the beam profile.