Radiation Hard Beam Profile Monitors for the North Experimental Beamlines CERN

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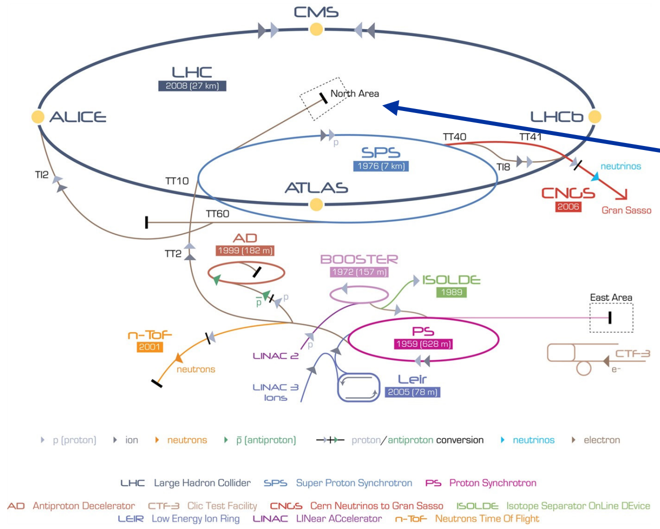
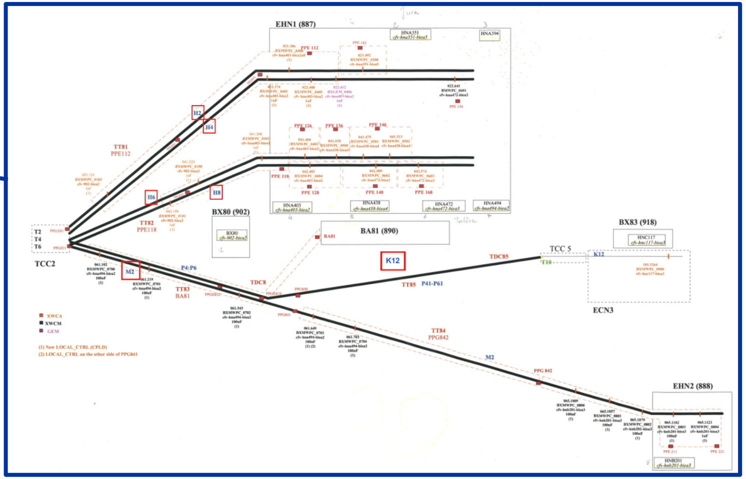
The North Experimental Area CERN





H2
H4
H6
H8

} Testbeam Areas & Experiments

K12 - NA62

M2 - COMPASS/AMBER

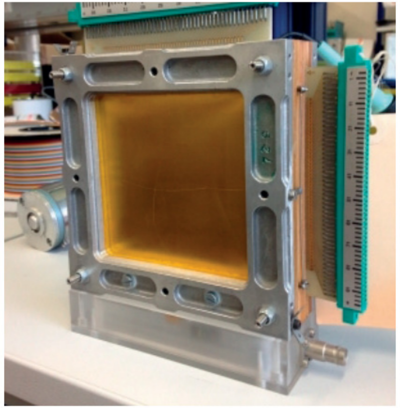
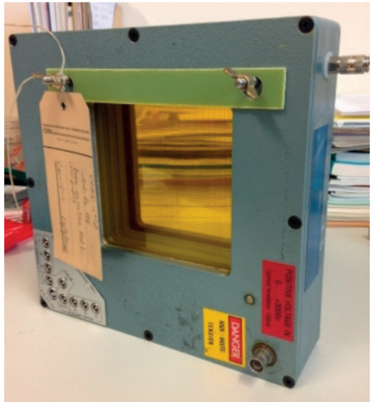
- The North Experimental Area started operation in **1978**
- It is the largest experimental area at CERN
- It has 6 beamlines totalling 5.8 km

- Intensity 10^3 - 10^{10} (future upgrades to 10^{11})
- Momentum 1 - 450 GeV/c
- Muons, electron, protons, mixed hadrons and heavy ions
- Secondary beams, slowly extracted (unbunched) over 4.8 s or 9.6 s

https://cds.cern.ch/record/2774716/files/CERN-ACC-NOTE-2021-0015-NA.pdf

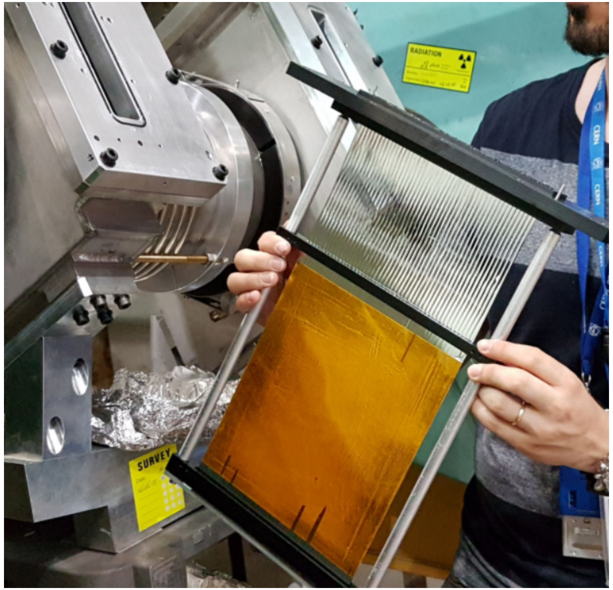
Beam Instrumentation in the North Experimental Area

- There are different devices that measure the beam profile and intensity
  - Scintillator paddles
  - Multi-Wire Proportional Chambers (MWPC)
  - Delay Wire Chambers (DWC)
  - Filament Scintillators (FISC)
- Many of them are as old as the North Area
- Expertise is lost and they are difficult to maintain
- **It's time to upgrade!**

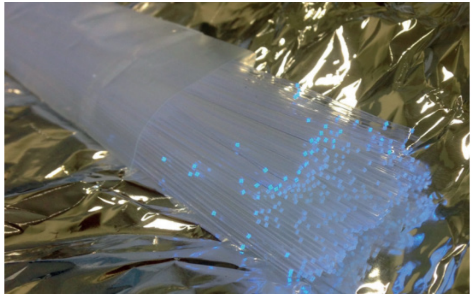




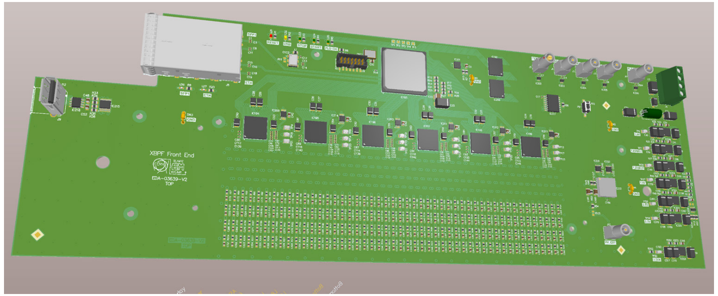

Detector descriptions given on page 27 of the pdf: https://jinst.sissa.it/jinst/theses/2018_JINST_TH_001.pdf

XBPF Scintillator Fibre Detector



- The XBPF is a scintillating fibre detector
- It was designed as a profile monitor for the East Experimental Area CERN
- It is readout using si-pms
- Suitable replacement profile monitor for the H2, H4, H6 & H8
- It is not suitable for the higher intensity lines K12 and M2
    - Scintillating fibres don’t have sufficient radiation hardness





New Radiation Hard Profile Monitor Requirements

- Active area of 20 cm x 20 cm
- A low as possible material budget 0.3% X0
- A spatial resolution of 1 mm
- Measure particle rates from **~10^4** to **~10^{11}** in the full energy range of 0.5 – 450 GeV/c
- Operational up to **2 MGy**, equivalent to a minimum of **8 years of operation**
- Operational in vacuum (10^{-3} mbar) and in air

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USER REQUIREMENT

User Requirements for XBPF Detectors in North Area Beamlines

ABSTRACT:

This document summarizes the needs of the users and the physics requirements for the XBPF detectors for all North Area Beamlines. It provides a set of user requirements and some technical details that may assist the implementation of these detectors.

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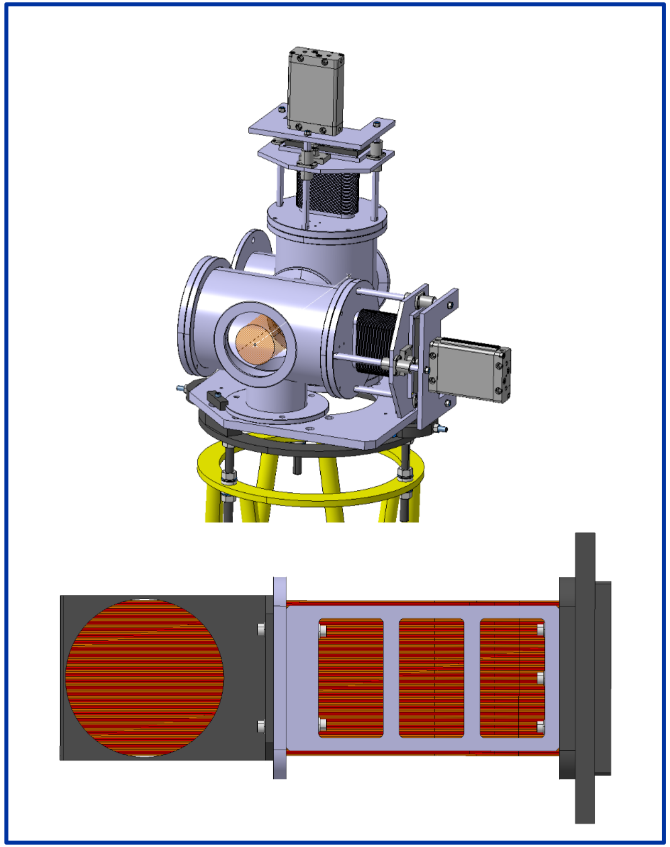
Initial Design Concepts

- Design a detector that has a similar silhouette to the XBPF
  - Easier for integration in the beamlines
    - Shared vacuum tank and motorisation designs
  - Reuse the XBPF si-pm readout board if possible
- A more radiation hard detection medium is needed
  - **Silica optical fibres**
  - Hollow core fibres
  - **Capillary fibres**
- Investigate alternative photodetectors

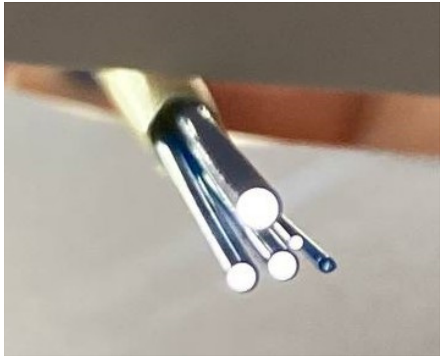


New XBPF motorisation design

Fibre Options

Traditional Silica Optical Fibres

- Silica Fibres propagate light via total internal reflection
- A well known phenomenon is the production of Cherenkov light in silica fibres when charged particles pass through
  - Often at CERN this is a unwanted source of background
  - For this application maybe it can be the signal
- Pros:
  - Fibres are cheap and are available in a variety of diameters
  - Silica glass known to be more radiation tolerant than plastics
- Cons:
  - Chrekenov signal is smaller than a scintillation signal
  - Light is produced at an angle, may need to tilt detector relative to beamline
    - Complicates the installation



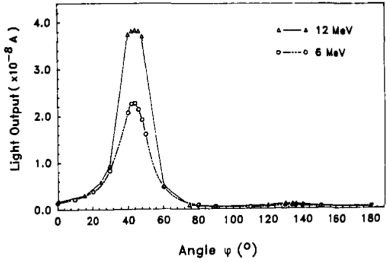
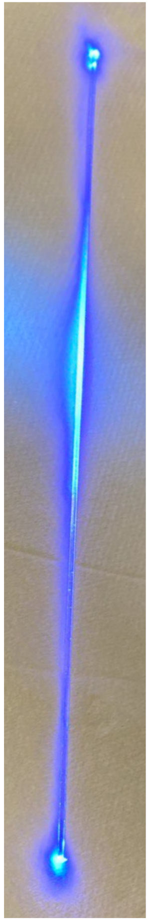


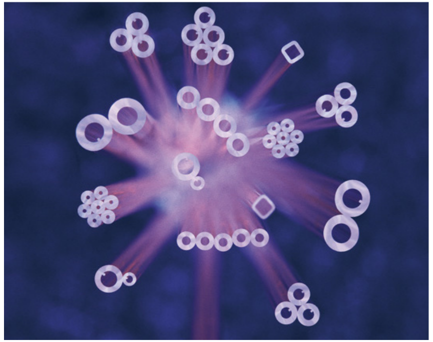
Figure 3. Radiation-induced light intensity measured from fibreoptic bundle light pipe in the geometry shown in figure 2. Electron beam energies: 6 and 12 MeV.

https://iopscience.iop.org/article/10.1088/0031-9155/37/4/007/pdf

Capillary Fibres

- Capillaries are small tubes of quartz glass with a hollow core
- They propagate light via total internal reflection if you fill them with a material with a higher refractive index than glass
- One option is to fill them with liquid scintillator
- Pros:
  - Liquid scintillator should have a higher radiation tolerance than solid scintillators
  - The glass might discolor with radiation damage but only needs to maintain a lower refractive index than the liquid scintillator
  - Both materials are relatively cheap and capillaries come in a variety of sizes
- Cons:
  - They are difficult to fill and are very fragile
  - Liquid scintillator is a “dangerous” material





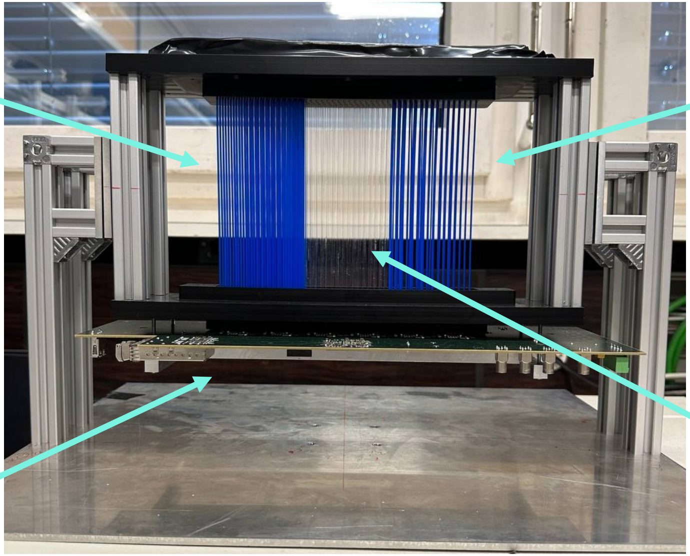
Beam Tests

M2 Beamline North Area CERN

M2 Prototype

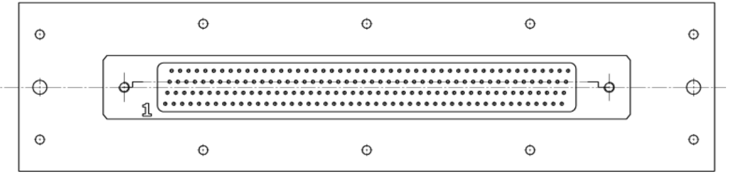
Silica Optical Fibre 1000 µm

Silica Optical Fibre 600 µm



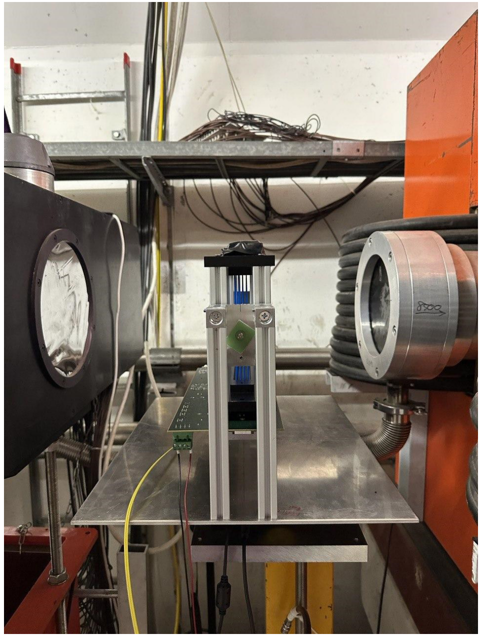
XBPF SiPM Readout Board

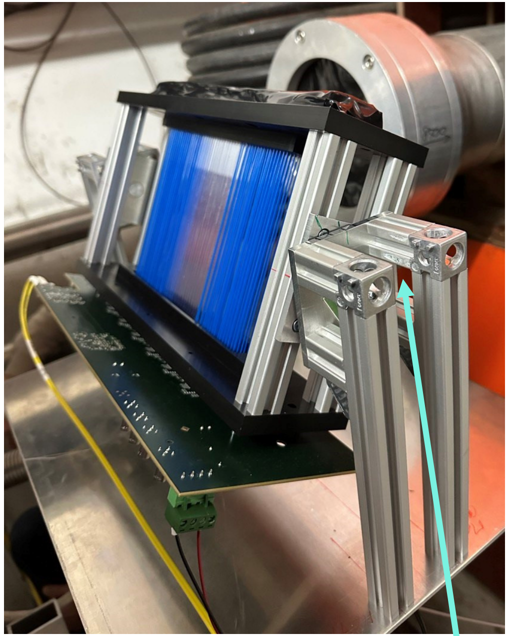
EJ-309 Filled Capillaries



Fibre Layout

M2 Prototype Installation and Beam Conditions

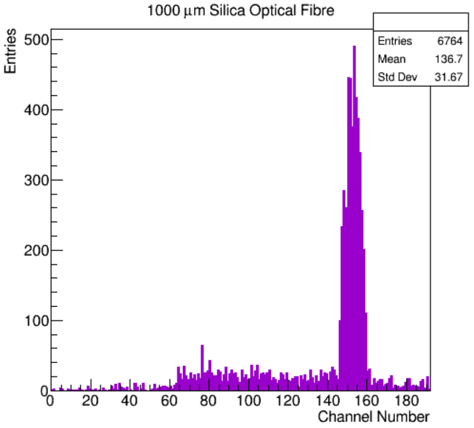


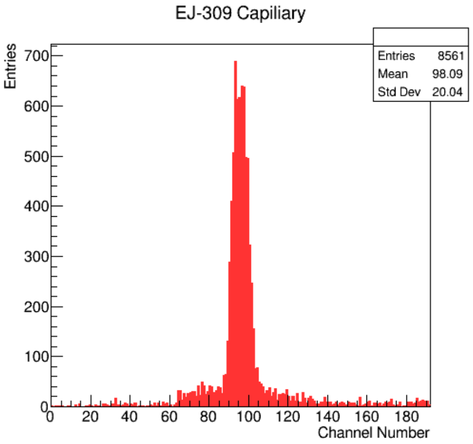


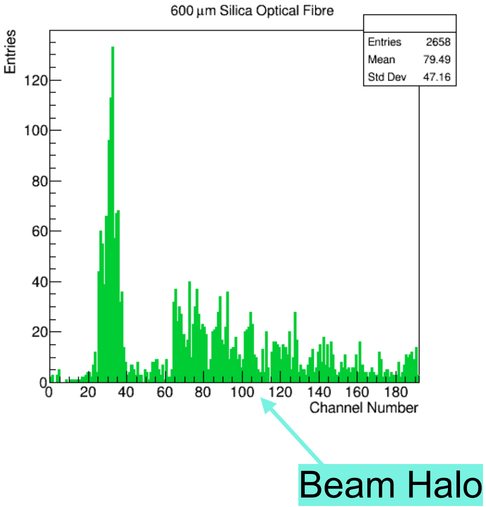
- First installed in April 2023:
    - Rate was ~3×10^5 particles per spill
    - 190 GeV hadrons

Preliminary Results

- **Prototype was tilted 45° relative to beam due to insufficient signal in silica fibres at 0°**



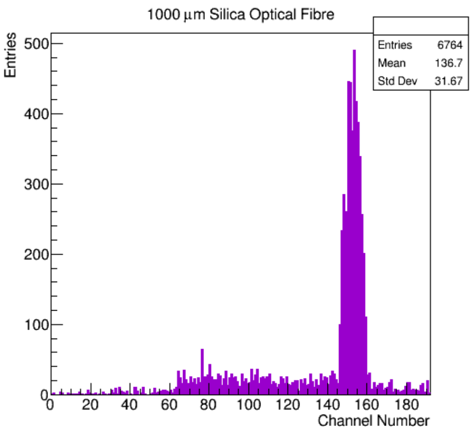


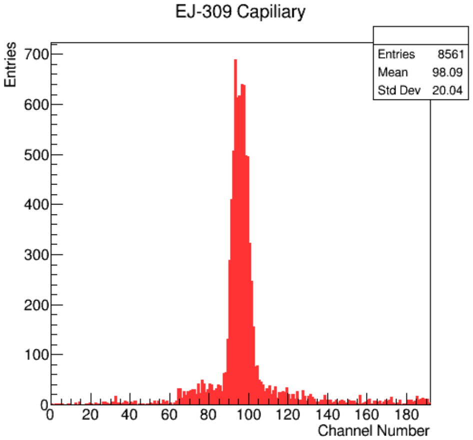


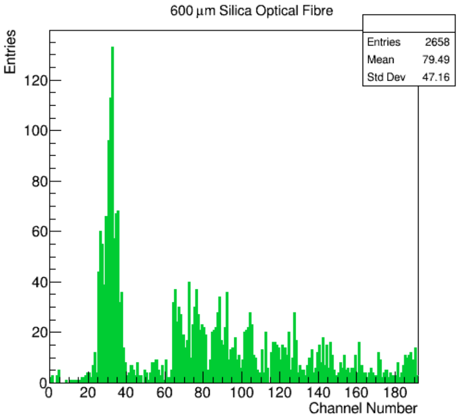
- Example profiles for single particle spills
- Higher signal measured in the capillaries compared to silica fibres
- Higher signal measured in the 1000 μm silica fibres compared to 600 μm silica fibres

Preliminary Results

- **Prototype was tilted 45° relative to beam due to insufficient signal in silica fibres at 0°**





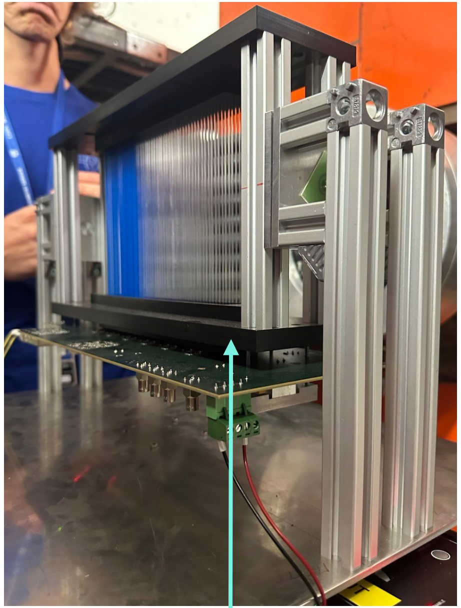


Fibre Type	Profile σ	Efficiency %
1000 µm	3.50 ± 0.03	46.4
EJ-309 Capillary	3.92 ± 0.04	64.8
600 µm	3.57 ± 0.01	15.1

- Wider beam profile measured in the capillaries compared to silica fibres
  - Mostly likely due to cross talk
- Efficiency higher in capillaries as expected due to higher light yeilds

M2 Prototype - Quartz Rods

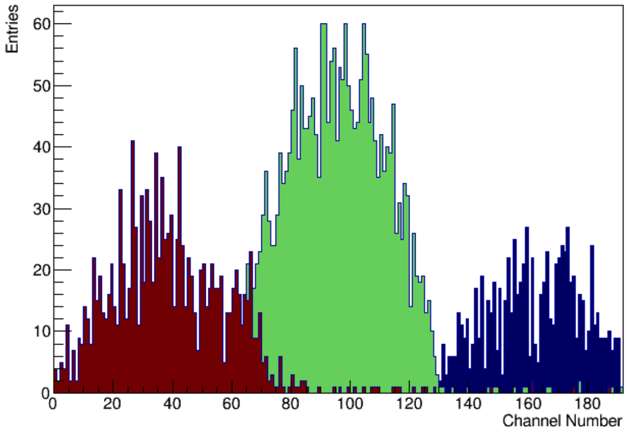
- **600 µm silica fibres replaced by 1 mm quartz rods**



Quartz Silica Rods

- For the second installation in August 2023, we replaced the 600 µm silica fibres with 1000 µm quartz glass rods
- Removing the cladding and jacket increases the refractive index gradient
- Hopefully increasing light yield and trapping efficiency

Preliminary Results at 45°



Silica Quartz Rods 1000 µm

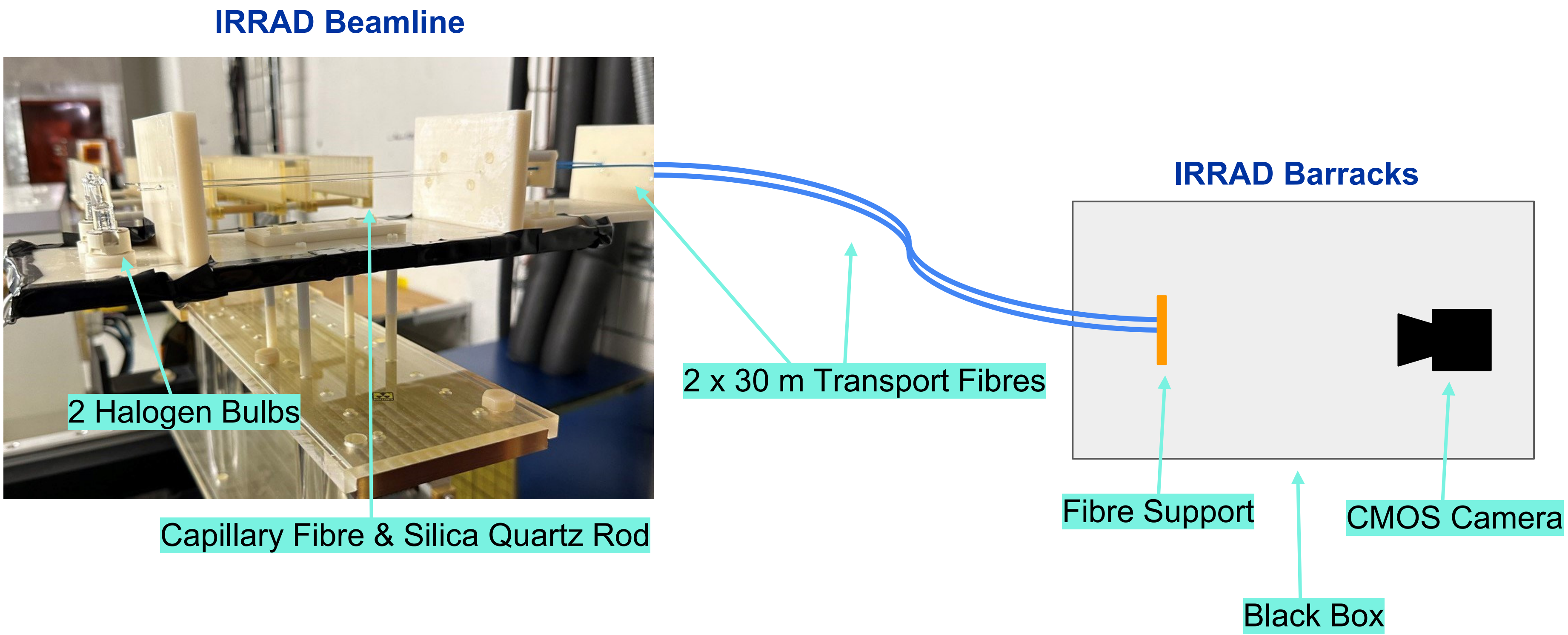
EJ-309 Filled Capillaries

Silica Optical Fibre 1000 µm

- Rate was ~8×10^6 particles per spill
- Large Muon Beam
- Quartz rods have slight higher signal compared to 1000 µm silica fibres
- **Analysis ongoing**

IRRAD

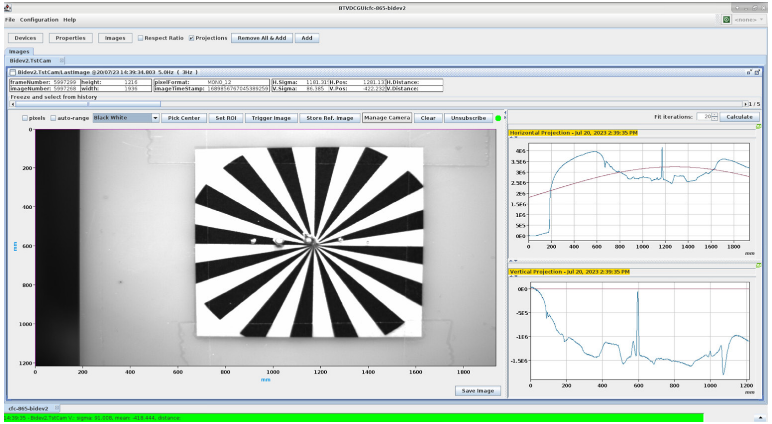
IRRAD Setup

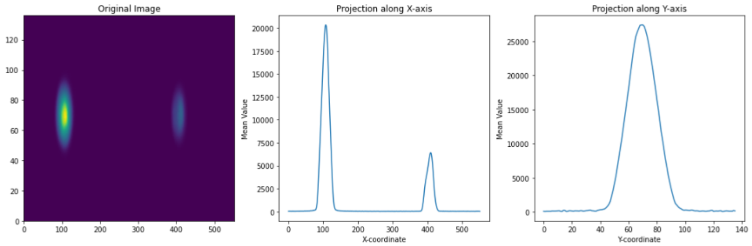


A black box is placed over the setup in the beamline

CMOS Camera Readout in the Barracks

- Two images are taken:
    - Before the beam arrives the bulbs are flashed
    - When there is beam
- This allows us to measure the **light transmission** and the **light yield**
- The variable plotted is the integral of the individual fibre spots
- Optical filters on both fibres to avoid saturation

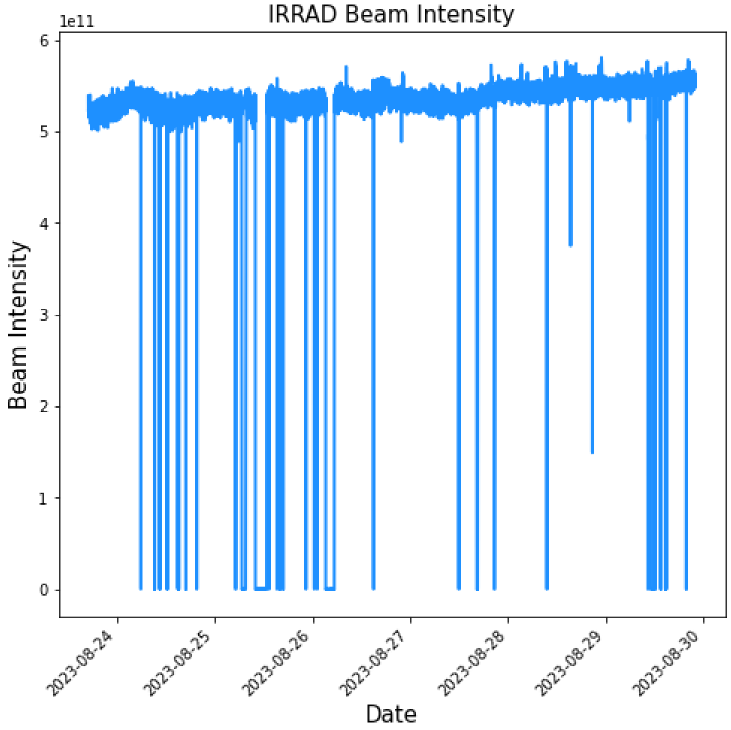




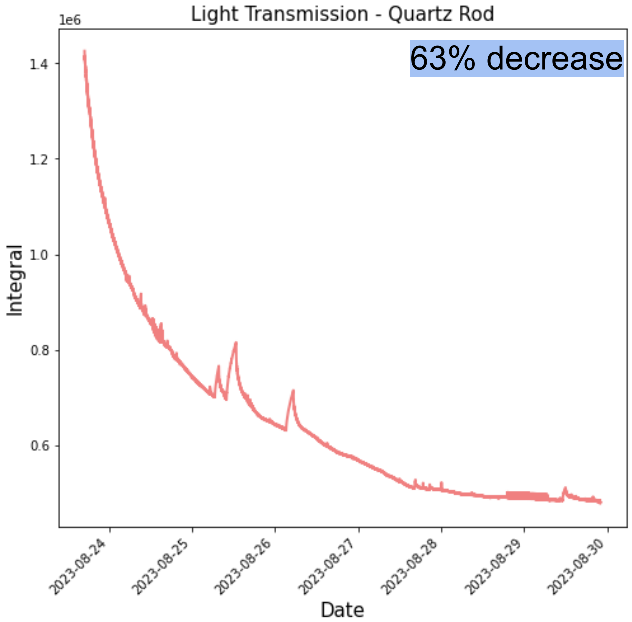
Example when bulb is flashed

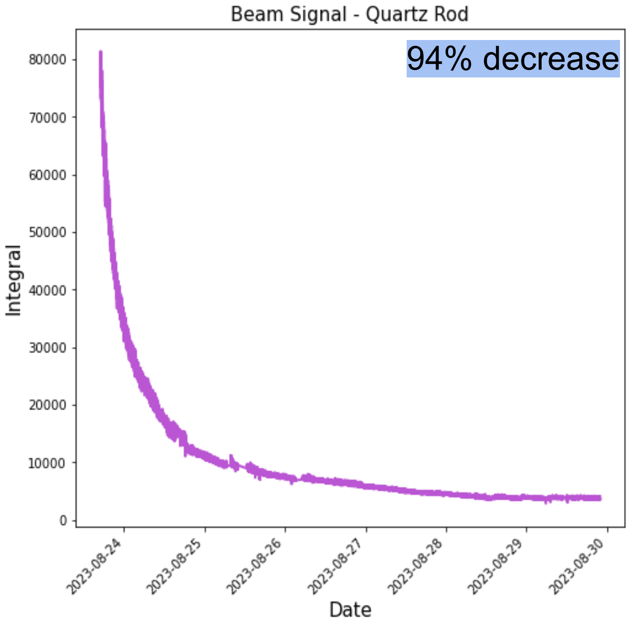
IRRAD Beam Conditions

- IRRAD is a proton irradiation facility at CERN
- Proton beam of momentum 24 GeV/c
- maximum intensity ~5x10^{11} particles per spill
- Spill length of ~400 ms
- We installed at IRRAD for 1 week in August 2023
- Total dose was 2.85 MGy over an area of 10x10 mm^2
- Only a few periods of no beam



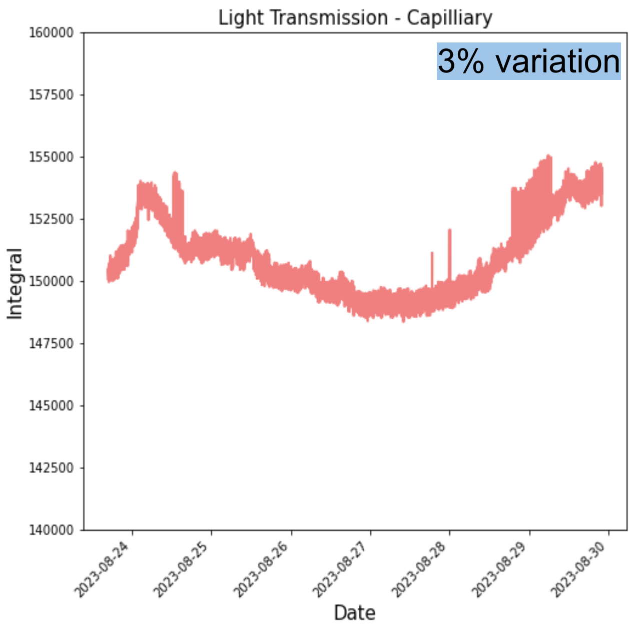
Preliminary Results - Quartz Rod Results

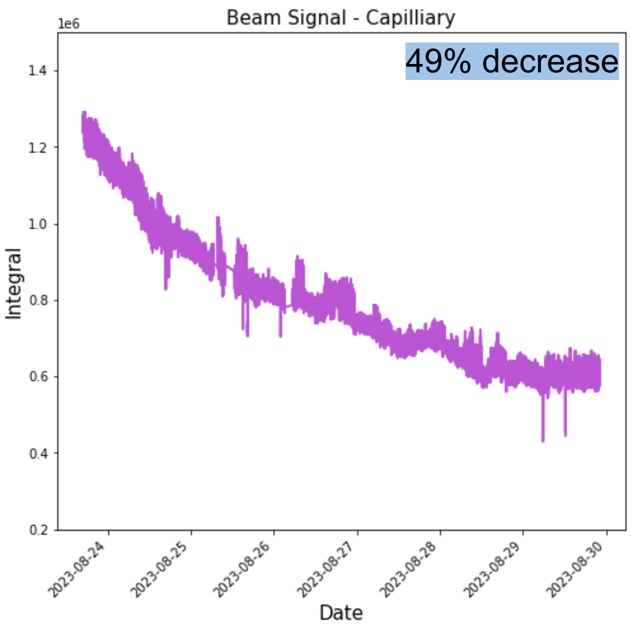




- Larger decrease in light yield compared to light transmission
- Bulb has wide range of wavelengths compared to the UV Cherenkov photons
- Periods of annealing when there is no beam

Preliminary Results - EJ-309 Capillary Results





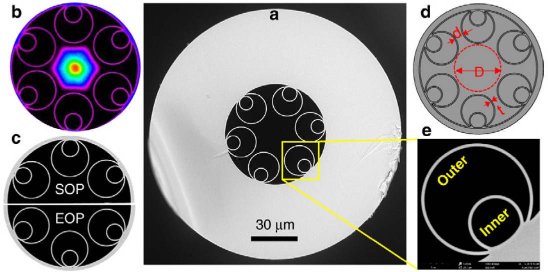
- Decrease in light yield but negligible change in light transmission
- Comparable to results we have seen in literature

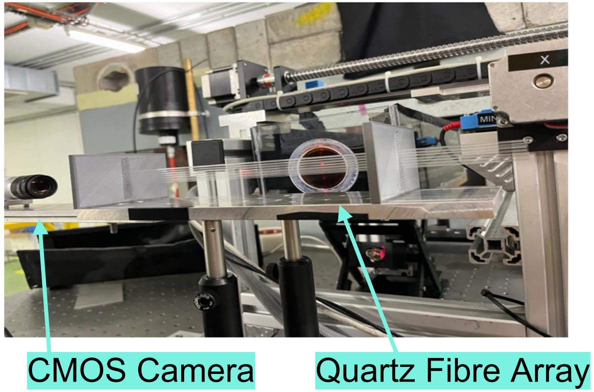
https://www.sciencedirect.com/science/article/abs/pii/0969806X9390061X#! https://pos.sissa.it/282/935/

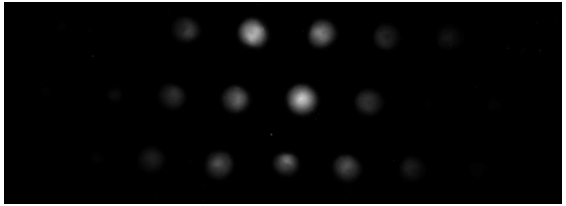
Future Plans
&
Conclusions

Future Plans

- Reinstall the M2 prototype to check for saturation at higher beam intensities
- Test hollow core fibres filled with scintillation gases
- Continued collaboration with colleagues working on FLASH therapy applications
    - FLASH radiotherapy will use very high energy electrons (VHEE) in milliseconds to treat cancers
    - At the moment, there is no clear candidate for a beam profile monitor
    - One of our fibre candidates may be suitable
        - Monitor must be able to measure charges from 10pC to 40nC
        - Spatial resolution <1 mm
    - Currently tested silica optical fibre and quartz rods







A Novel Fibre Optic Monitor for VHEE UHDR Beam Monitoring: First Tests at CLEAR (ipac23.org)

Conclusions

- An R&D effort is ongoing to find a radiation hard active medium, based on fibre optics, that would be suitable for a new radiation hard beam profile monitor
- Silica Optical fibres, quartz rods and EJ-309 capillaries have been tested in the M2 beam line up to $x10^6$ particles per spill
  - Capillaries have the highest light yield
  - Silica fibres and quartz rods are required to be tilted to 45 degrees for signal to be seen
  - Higher intensity beams are needed to check that saturation is not reached
- A EJ-309 capillary fibre and silica quartz rod were tested at IRRAD up 2.85 MGy
  - The capillary was found to have a larger light yield and greater radiation tolerance than the silica quartz rod
- Hollow core fibres filled with a scintillation gas will be tested later this year
- In parallel, the fibre candidates are being tested for their use in FLASH therapy applications
  - Results of these tests will be presented at the **FLASH Radiotherapy and Particle Therapy (FRPT)** Conference in Toronto in December 2023

Thank You

https://home.cern/