



# Simulation and measurement of particle detection with silica fibres as a function of impinging angle

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**Abstract:** Beam instrumentation in particle accelerators is necessary to ensure the quality of the circulating beams. Some of the transfer lines in the North Experimental Area at CERN transport beams of high intensity ( $10^9$  to  $10^{13}$  *particles/second*), which are slowly extracted during 4.8 or 9.8 seconds. The profile and position of these beams is measured at present with different types of secondary electron emission monitors that suffer from radiation damage due to the high beam intensities involved. We investigate the feasibility of a new beam profile monitor based on the detection of Cherenkov light in silica optic fibres, which would have the required radiation hardness and would be compatible with ultra-high vacuum. We have studied in the laboratory the detection of light from bare silica fibres coupled to photomultiplier tubes, by exciting them with a  $^{90}\text{Sr}$  radioactive source. We have performed measurements of the amount of particles detected as a function of the angle between the radioactive source and the fibre, for different fibre thicknesses, and we have compared the experimental data with GEANT4 simulations.

## Introduction.

The North Area at CERN has a very rich program of fixed target experiments, for example NA62, NA58, Compass and ToTem, as well as test beams facilities and many other experiments. The placement of North Area in the accelerator complex is shown with a red circle in Fig.1.

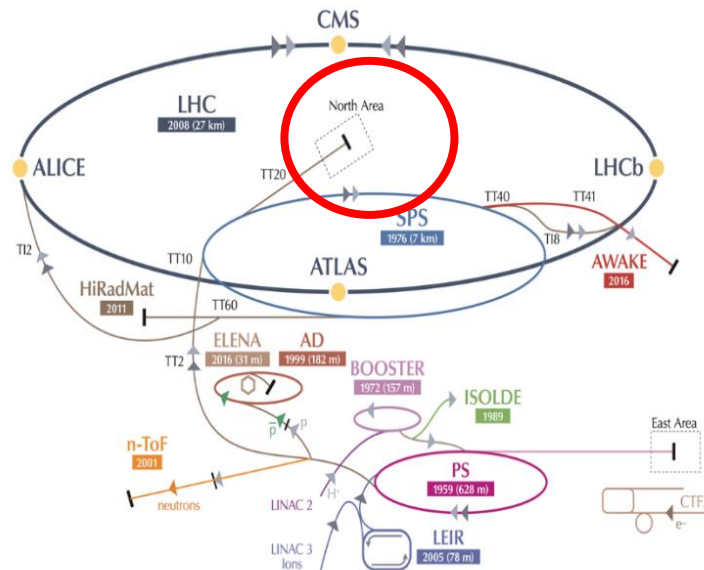


Figure 1. North Area placement in the scheme of CERN accelerator's complex.

The beams used by the North Area's fixed target experiments are composed of various types of secondary particles ( $\pi, K, \dots$ ), which are obtained from the collision of a proton beam from the SPS (Super Proton Synchrotron) with a primary target. SPS protons with an energy of 450 GeV are unbunched, slowly extracted during 4.8 or 9.6 seconds with a typical intensity of  $10^{13}$  *part/extraction*. These conditions set tight constraints for the beam instrumentation and make it a highly advanced engineering challenge.

Beam profile monitoring is necessary to ensure beam's quality before it collides with the targets. The fundamental requirements which the beam profile monitor should fulfill are the following:

1. **Radiation hardness**
2. **Low beam perturbation (scattering and energy loss)**
3. **Ultra-high vacuum compatibility**

Additional features, such as **low cost**, **fast response time** and **high precision**, are also important in any detector construction.

Being aware of the above restrictions, we propose a beam monitor based on **Cherenkov radiator fibres readout by photomultiplier tubes**, which could fulfill the expectations of a high quality beam monitoring system.

The basic features of the proposed design are:

1. **Radiation Hardness  $\geq MGy$**
2.  **$\frac{x}{x_0} = 44.47\ cm$**
3. **Ultra-high vacuum compatibility**
4. **Time resolution  $\sim ns$**
5. **Spatial resolution  $< 1mm$**
6. **Low cost**

**The aim of this work is to investigate the feasibility of the proposed Cherenkov fibre detector.**

### Physical phenomena in $SiO_2$

The emission of Cherenkov light occurs when a charged particle travels through matter with a speed exceeding the speed of light in that medium. Excited atoms in the medium emit photons in the visible spectrum (most likely in blue and violet), which are called Cherenkov photons. The first condition for the appearance of Cherenkov photons is described by Formula 1:

$$\beta > \frac{1}{n} \quad (1)$$

where  $n$  is the refractive index of the medium and  $\beta$  is the speed of the particle with respect to the speed of light in the vacuum.

Cherenkov photons are emitted within a characteristic angle  $\theta_{ch}$  that follows from Formula 2. Cherenkov angle  $\theta_{ch}$  is indicated in Fig 2.

$$\cos\theta_{ch} = \frac{1}{n\beta} \quad (2)$$

Table 1. shows two different Cherenkov angles calculated for 450 GeV protons and 1 MeV electrons in silica ( $SiO_2$ ). The latter particles can be obtained from a common  $^{90}Sr$  radioactive source.

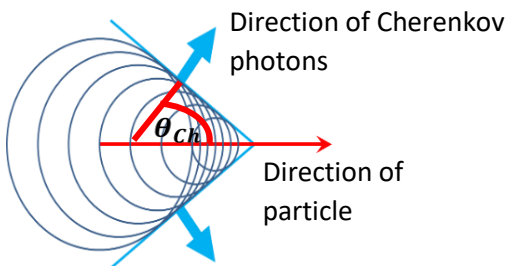


Figure 2. Cherenkov Angle

Table 1. Cherenkov Cone angle in  $SiO_2$  for given beams

| beam     | n    | E       | $\beta$ | $\theta_{cher}$ |
|----------|------|---------|---------|-----------------|
| <i>p</i> | 1.37 | 450 GeV | 1       | 47°             |
| <i>e</i> | 1.37 | 1 MeV   | 0.86    | 38°             |

## Application of $\text{SiO}_2$ optic fibres

At this point, it is very useful to note that the same medium that is used to produce the emission of Cherenkov light can be also used to propagate this light to a photodetector, given the condition that it is transparent to that light. Indeed, **silica optic fibres** make possible to trap the Cherenkov photons produced in the core and guide them to the photodetectors. Certain parameters, such as the refractive indexes of the core  $n_{\text{core}}$  and cladding  $n_{\text{cladding}}$  of the fibre, the particle's mass and the particle's energy, determine the valid range of angles between the fibre and the beam in which it is possible to measure Cherenkov photons at the end of the fibre.

Figure 3 shows how light propagation occurs in an optical fibre. In order to capture a photon, its incident angle,  $\theta_2$ , must be equal or higher than the Total Internal Reflection angle of the fibre  $\theta_{\text{TIR}} = \arcsin\left(\frac{n_2}{n_1}\right)$ .

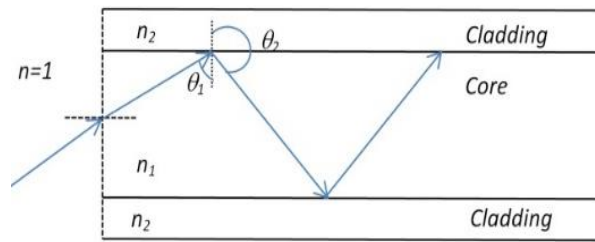


Figure 3. Light propagation in the optic fibre

In this application, we used optic fibres from Thorlabs [2], with  $n_{\text{cladding}} = 1.37$ ,  $n_{\text{core}} = 1.46$ , yielding  $\theta_{\text{TIR}} = 69^\circ$ .

**The aim of experimental part was to verify the detectability of Cherenkov Photons in Thorlabs Optic fibres of different diameter size.**

## Experimental setup.

In order to detect beta radiation with silica fibres, we used the following setup:

1. A ThorLabs Optic Fibre (60 cm length). We repeated the measurements for three core diameters:  $\varnothing = 1.5\text{mm} / 1\text{mm} / 0.4\text{mm}$
2. A Photomultiplier Hamamatsu H11934-200 [1]
3. A  $^{90}\text{Sr}$  radioactive source that emits  $\beta$  radiation
4. A Philips Scientific Constant Fraction Timing Discriminator 6915 [3] and a HAMEG Universal Counter HM8021-4[4]
5. A light-tight box, a protractor, a ruler

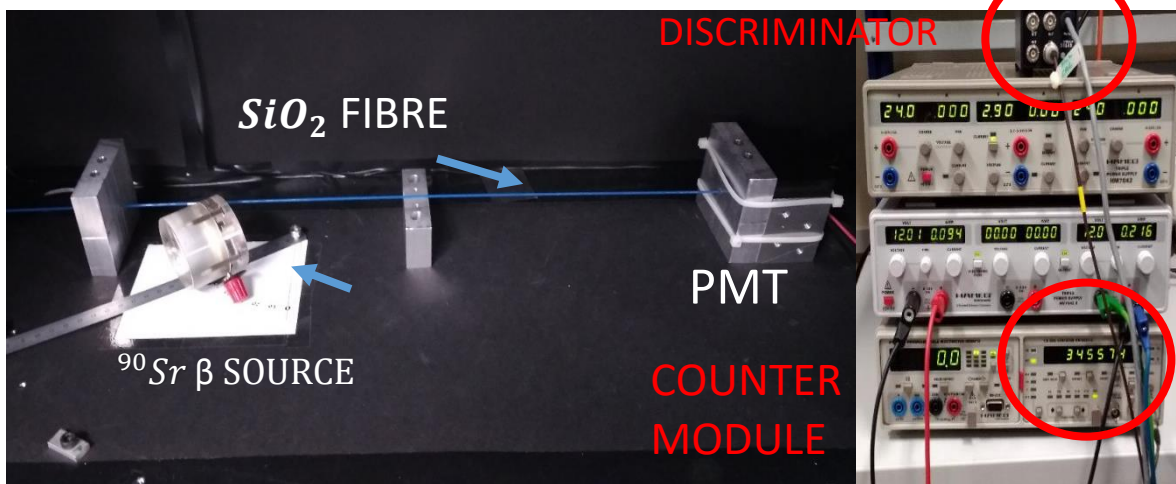


Figure 4. Experimental setup: the interior of the light-tight box is shown on the left part of the picture and the data acquisition system is shown on the right.

## Measurement methodology

The  $\beta$  – source and the silica fibre coupled to the PMT were standing inside a light-tight black box, as shown in Fig. 4. The angle  $\alpha$  drawn between the perpendicular to the fibre and the direction of radiation from the source was measured by a protractor and a ruler (See Fig.5). The discriminator and counter module that processed the signals were placed outside the black box.

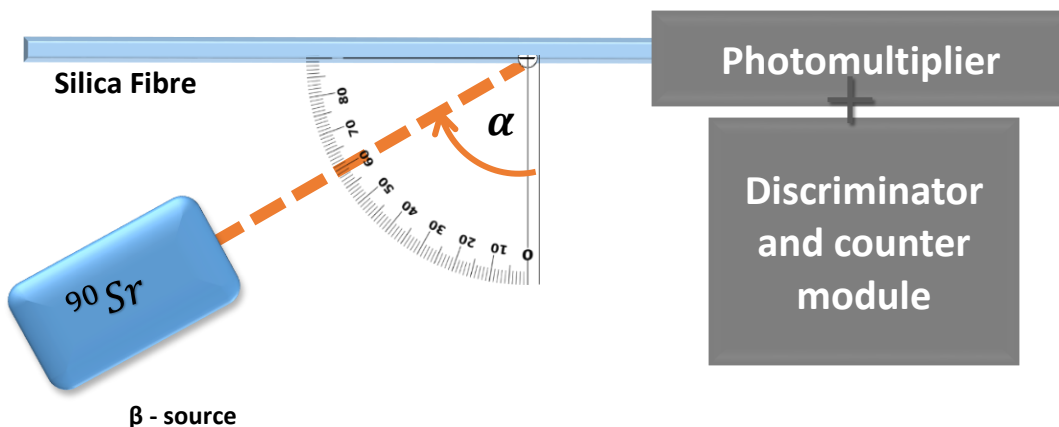


Figure 5. Experimental setup scheme

The discriminator's threshold was set for -30 mV, which seemed to optimize the signal-to-noise ratio of our setup. The output signal from the discriminator was sent to the counter module, which can register events at a maximum rate of 1.6 GHz [4]. For a given angular position of the radioactive source, we recorded the number of detected events by the counter module for 1 minute. To improve the statistics, we repeated 10 times the measurements for every angular position. Before and after each set of measurements, we also registered the baseline noise level of the PMT following the same procedure but without the radioactive source (10 x 1 min measurement).

The whole procedure can be summarized as follows:

1. Without radioactive source, measurement of the events registered by the counter module during 1 minute due to the background noise of the PMT. Repeat 10 times.
2. Place  $\beta$  – source 6 cm away from the fibre at a chosen angle.
3. Measurement of the events registered by the counter module in 1 min. Repeat 10 times.
4. Repeat measurement of the background noise of the PMT as described in point 1.
5. Calculate average of the data registered with the source and without the source.

### Monte Carlo Simulations in GEANT4

The experimental setup was simulated in detail with GEANT4, which is a software framework to simulate the interaction of radiation with matter [5]. The simulated setup consisted of a silica fibre (characterized as in the specifications of the manufacturer ThorLabs), and a pointlike source of electrons with the energy spectrum of  $^{90}\text{Sr}$ . We studied the angular emission and intensity of our radioactive source with another particle detector [6] in order to precisely characterize the particle emission in the simulation. We measured the emitted particle beam to be approximately Gaussian distributed with  $\mu = 0, \sigma = 8^\circ$  (See Error discussion and technical issues.). The measured intensity of the source was  $I = 125 * 10^3 (\pm 354) \text{ part/s}$ .

The simulation also takes into account the quantum efficiency of the PMT (Hamamatsu PMT 111934-200). The whole setup is placed in air, which can cause a significant scattering on the emitted beta particles. Fig. 6 shows a simulated event of 100 electrons shot to the fibre. The red lines are the tracks of the electrons emitted from the point-like source; the straight white cylinder is the silica fibre.

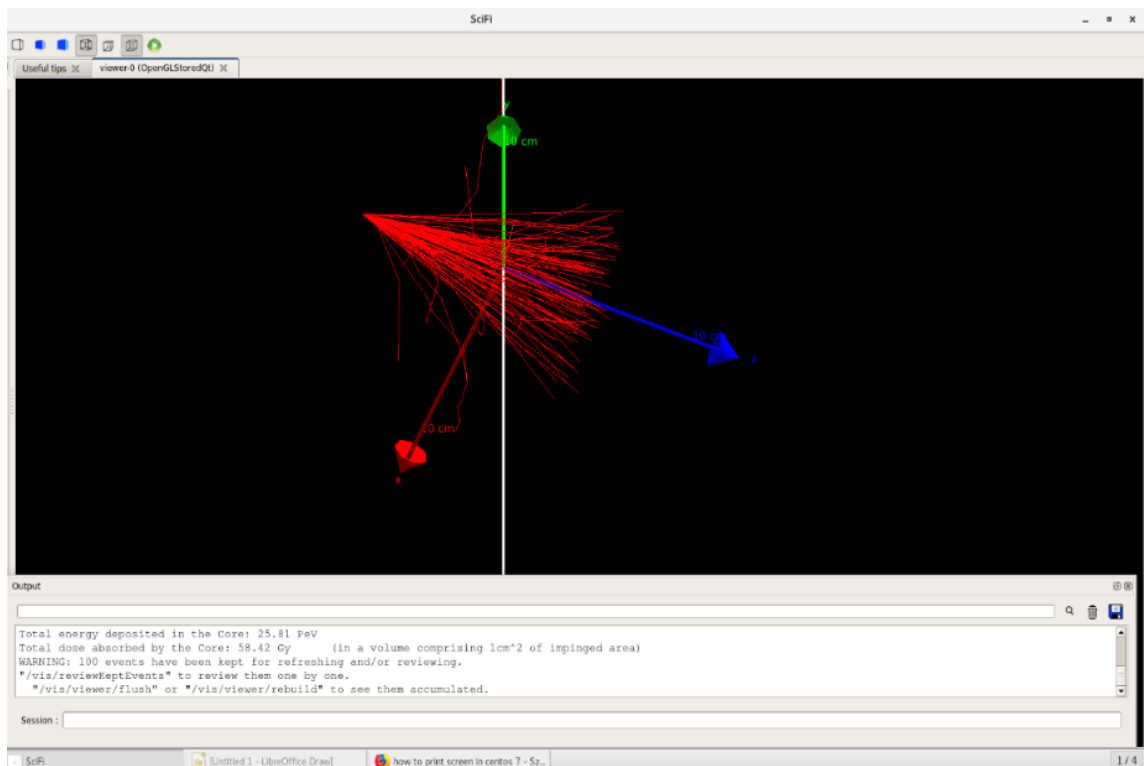


Figure 6. GEANT4 event display. The emitted electrons from the source are shown in red and the white cylinder is the silica fibre. The arrows indicate the coordinate reference system.

## Results

The outcome of the measurements of particle detection with silica fibres is presented in Fig.7 for the 3 different core diameters:  $\phi_1 = 1.5\text{ mm}$ ,  $\phi_2 = 1\text{ mm}$ ,  $\phi_3 = 0.4\text{ mm}$ . Analogously, Fig.8 shows the results of the simulated data. As aforementioned, the angle is equal to  $0^\circ$  when the electron beam is perpendicular to the fibre, and  $90^\circ$  when it is parallel. In the case of real data, the background of the PMT is subtracted from the total signal.

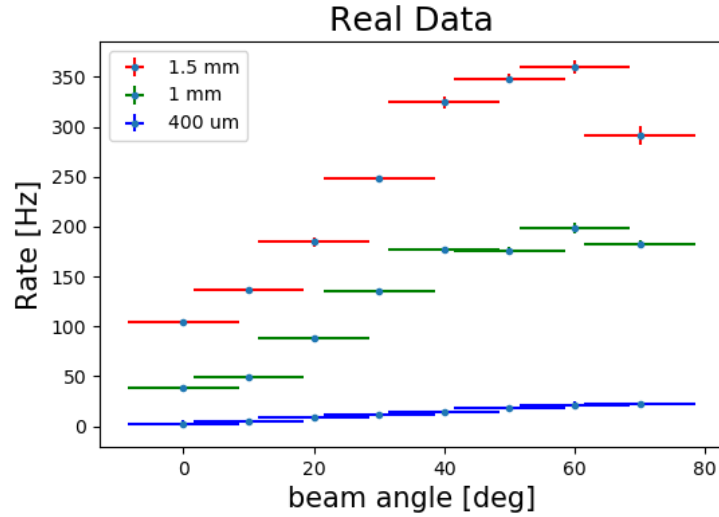


Figure 7. Event rate distribution in function of beam angle for different fibre core sizes. Real Data.

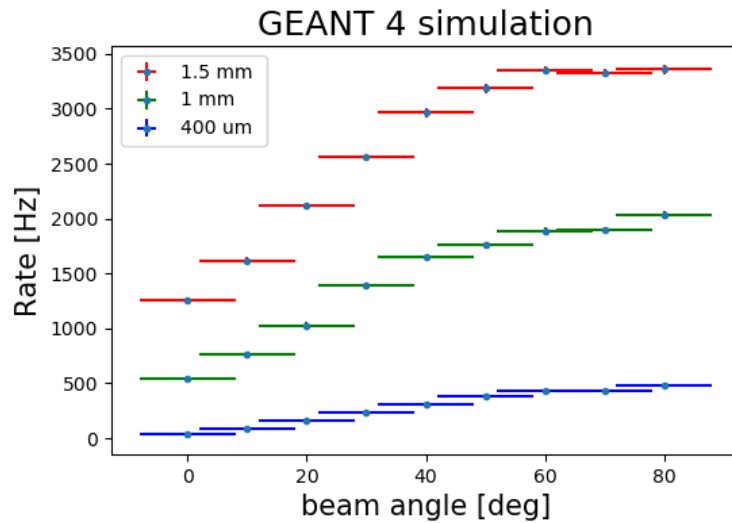


Figure 8. Event rate distribution in function of beam angle for different fibre core sizes. Simulated Data.

Figures 9-11. Present separately the comparisons of experimental and simulated data for each fibre size.

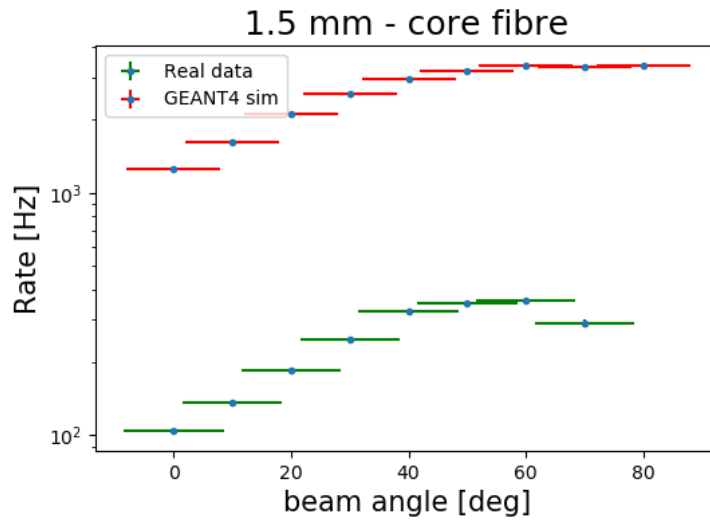


Figure 9. Comparison of simulated and experimental data for 1.5 mm core fibre

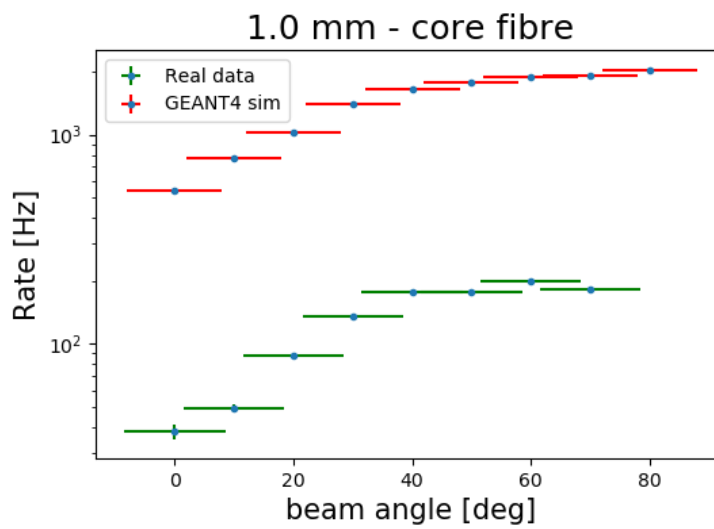


Figure 10. Comparison of simulated and experimental data for 1.0 mm core fibre



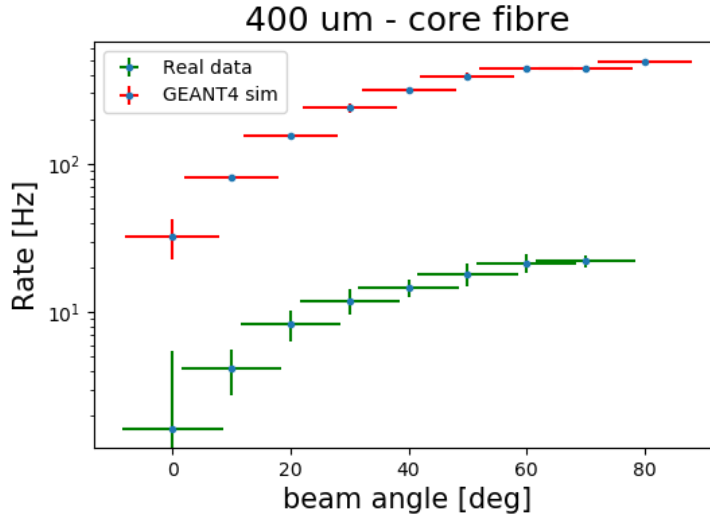


Figure 11. Comparison of simulated and experimental data for 400 um core fibre

The shape of the distributions of the experimental data agrees with the simulations, apart from the last point of 70 degree for measurement of fibre  $\varnothing = 1.5mm$  and  $\varnothing = 1 mm$  diameter. This angle's measurement was the most difficult to prepare, due to technical inconvenience (proximity of the fibre to the source). Although the sistematic error is already taken for account, we rather claim that this discrepancy is an experimental error.

The value of the measured event rate is about one order of magnitude lower than in the simulation. This could suggest that the **detection efficiency of the experimental setup is  $\sim 10\%$** . In fact, the simulation is not considering the lower detection efficiency of the experimental setup due to the threshold level of the discriminator, neither an eventual loss of photons in the boundary between the fibre and the PMT. In the simulation, **it is sufficient that a single photon arrives to the PMT to establish that a particle has been detected by the fibre.**

This study shows the technological challenge of detecting extremely low levels of light. The number of Cherenkov photons reaching the photodetector is very low, between **1 and 3 on average**. In our setup, a single Cherenkov photon can be at the level of the background noise (PMT noise, electrical noise or even light leak into the black-box) and they cannot be distinguished.

Nevertheless, a high detection efficiency is not desired for a beam monitor, which works with intensities up to  $10^{13}$  particles/sec, since there is no read-out technology available to handle these high frequencies and such **a large number of recorded particles is not needed to reconstruct the profile and position of a particle beam.**

## Error discussion and technical issues.

### $\beta$ Source Characteristic

In order to characterize the emission properties of the  $^{90}\text{Sr}$  radioactive source, we measured it with a XPBF detector [6], with the following results:

- Intensity: 125 000 ( $\pm 354$ ) part/s
- Gaussian spatial distribution with  $\sigma = 8^\circ$  in 2D plane

Those parameters were fed into the GEANT4 simulation. The energy distribution of the source was described by a double gauss with:  $E_{mean1} = 1.069 \text{ MeV}$ ,  $\sigma_1 = 0.505 \text{ MeV}$ ,

$$E_{mean2} = 0.280 \text{ MeV}, \sigma_2 = 0.106 \text{ MeV}.$$

### Experimental systematic uncertainty

There is an uncertainty in the angle position that depends on the aforementioned angular spread of the electrons ( $\sigma = 8^\circ$ ) and the precision of the instrument used to measure the angular position, which is  $\delta = \pm 5^\circ$ . Therefore, the systematic error was calculated according to the Formula 3 [7]:

$$d\alpha = \sqrt{\left(\frac{\delta}{\sqrt{3}}\right)^2 + (\sigma)^2} = \sqrt{\left(\frac{5^\circ}{\sqrt{3}}\right)^2 + (8^\circ)^2} = 8.5^\circ \quad (3)$$

### Statistical uncertainty

Both experimental measurements and simulations have been repeated 10 times for each angular position. These 10 repetitions were averaged to obtain the event rate and the standard deviation was taken as the systematic error.

In the case of the experimental data, **the event rate measured without the radioactive source is subtracted from the measured rate with the source (equivalent to signal minus background)**. The error bar in this case is evaluated according to the rule of uncertainty propagation (Formula 4):

$$\delta_{sig-bck} = \sqrt{(\delta_{signal})^2 + (\delta_{bck})^2} \quad (4)$$

In case of the simulated data the statistical error bar comes from the standard deviation of the mean value.

### Polishing procedure and handling the fibre.

In order to prepare the setup, it was necessary to learn how couple efficiently the fibre with the PMT. By trial and error, we evaluated how to cut the fibre properly and how to ensure a high quality surface at the edge. The best method seems to be, firstly, cut the fibre with a standard cutting tool (a cleaving approach brings out a similar result, but it is more complicated) and secondly, polish the fibre with sandpapers of different granularity. Following the above steps result in a high quality, smooth edge of the fibre. This improves light propagation to the photomultiplier and avoids the use of optical connector. Figure 12 shows the comparison of an unpolished and a polished edge of a silica fibre.

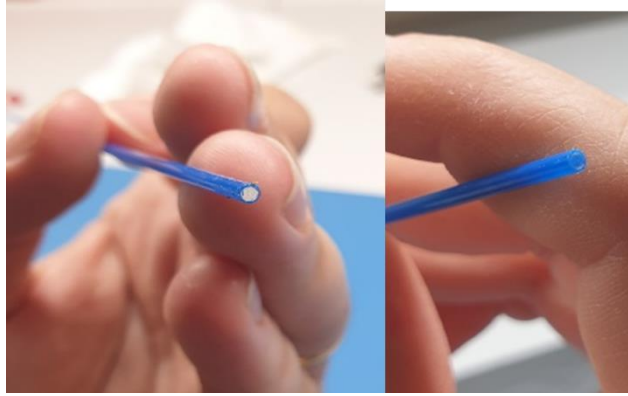


Figure 12. Comparison of an unpolished (left) and polished (right) silica fibre.

## Conclusions

We have investigated the detection of charged particles in commercial silica fibres by reading-out the Cherenkov light created by the particles as they cross the fibre. We measured the number of particles detected as a function of the angle at which they impinge on the fibre and we repeated these measurements for 3 different size of fibres. We compared the experimental data with simulations performed in GEANT4. The measured data is in agreement with the simulations, which motivates further investigations of a new beam profile monitor based on silica optical fibres.

We suggested to carry out a simulation of proton beam for the same experimental setup.

## References

All links available last time 8/10/2019

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