

Design and Characterization of a Real Time, Large Area, High Spatial Resolution Particle Tracker Based on Scintillating Fibers

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Abstract- This paper presents the design flow of a detector for tracking charged particles together with the characterization techniques developed to extract the main design specifications. The goals for the final detector are to achieve real-time imaging, a large detection area and a high spatial resolution particularly suitable for medical imaging applications. The main concepts have been patented by the INFN. This paper describes the prototype tracker, which has a 20x20 cm² sensitive area consisting of two crossed ribbons of 500 μ m square scintillating fibers. The track position information is real-time extracted in an innovative way, using a reduced number of read-out channels to obtain a very large detection area but with moderate costs and complexity. The performance of the tracker has been investigated using β sources, cosmic rays, and a 62 MeV proton beam.

Keywords- Scintillating Fiber; Tracking Detector; Real-time

I. INTRODUCTION

Cutting edge research in the treatment of tumors is now oriented towards hadron therapy, one of the most effective external radiotherapy techniques, which uses charged particle beams (protons and carbon ions) with up to 400 AMeV energy. These beams make it possible to accurately release the dose required to control a cancerous mass, while at the same time leaving the surrounding healthy tissue almost totally untouched. The maximum advantage from using charged particle beams is reached when there is precise information regarding the stopping power of the particles used for the radiotherapy treatments. The direct use of this information, rather than that from X-ray tomography, leads to a more accurate evaluation of the distribution of the dose and can be used to verify the positioning of the patient.

Therefore, the availability of very accurate imaging systems is of fundamental importance [1]. Our task is to design and build an imaging system for charged particles based on the consolidated principle of residual range measurement [2] while at the same time taking advantage of new detection techniques. The aim is to use this system to achieve large detection areas (up to 30x30 cm²) suitable for almost all medical physics applications, and high spatial resolution (up to 150 microns) and time resolution (up to 2 ns). With this in mind, we have developed a prototype of an X - Y tracker, the OFFSET detector, mainly funded by the Istituto Nazionale di Fisica Nucleare (INFN), which has been accurately tested with radioactive sources, cosmic rays, and the 62 MeV proton beam available at the Laboratori Nazionali del Sud (LNS) CATANA proton therapy facility.

II. OFFSET

The OFFSET X - Y detector consists of two planes of scintillating fibers (Sci-Fi) orthogonal to each other. The sensitive 20x20 cm² area of the prototype was built employing 500 μ m square multi-cladding BCF-12 [3] Sci-Fi manufactured by Saint-Gobain. In these fibers, the energy released by a crossing particle produces an isotropic emission of light. Only a part of this light is channeled into the fiber [4], which at this point acts as a guide. This light flows in both directions along the fiber. The factory can deliver the fibers as a pre-glued, aligned, 400 fiber ribbon. We have arranged two ribbons in orthogonal layers, one above the other, kept in position by the pressure of two square aluminum frames, delimiting the sensitive area of the detector, as shown in Figure 1. In a classical read-out scenario, every Sci-Fi must be optically coupled to a light sensor, each of which is read from a channel in the front-end electronics. In the case of the 20x20 cm² prototype there are 400+400 channels, meaning that a suitable read-out system would be not only complex but would certainly suffer from high dead times.

A. Channel Reduction System

The OFFSET tracker uses a read-out channel reduction architecture that is suitable for imaging conditions. It detects one particle at a time. This architecture optimizes and reduces the number of read-out channels for a linear segmentation detector

and is an extremely modern version of previous applications [5, 6]. The operating principle of the channel reduction can be explained as follows. Let us consider a strip detector. Each strip is read from both ends but the meaning of the two signals is interpreted differently as a result of different groupings. At one end the strips are read together in groups of n contiguous strips, while at the other end the first strips of each group are grouped in *StripSet* (SS) 1, the second strips of each group in SS 2, and so on. A particle crossing one strip generates two signals at both ends.

Then we have a signal from the i^{th} group, and another from the j^{th} *StripSet* that uniquely identify the *Strip_{hit}*, hit by the particle according to Equation (1).

$$\text{Strip}_{\text{hit}} = (i - 1) * n + j \quad (1)$$

An X - Y strip detector consisting of 16 strips for each plane, shown in Figure 2, is an example of a two-dimensional strip detector where the channel reduction system is applied. In the classic scenario of a two-dimensional strip detector, there would be 16 read-out channels for the X direction and 16 for the Y direction, making a total of 32 channels. In the example the position of the impact point, marked with a star, is $x = 11$ and $y = 6$. Figure 2 also shows the proposed read-out reduction system that allows the total number of channels to be reduced to only 16. Using a simple mathematical treatment the optimized number of channels appears to be equal to $4\sqrt{N}$, where N is the total number of strips per layer, X or Y. It is very interesting that when N is large the reduction factor becomes significant, especially in real-time applications.

The bound coincidence between the ends of each strip, not present in a simple strip by strip read-out, allows spurious signals (noise, crosstalk, dark current, and so on) to be automatically filtered. It should be noted that to reconstruct the point where the particle crosses the detector (event), it is necessary for it to release energy in both planes. The application of a read-out channel reduction consists in suitably grouping and coupling the Sci-Fi to larger standard (clear) optical fibers. Each group of n Sci-Fi is coupled to a suitable clear fiber that is then pointed at a light sensor. The read-out channel reduction factor depends only on the relationship between the sectional areas of the Sci-Fi and of the clear fibers. Figure 3 shows: (a) the scheme of the optical coupling, (b) pictures of the Sci-Fi and clear fibers prepared for coupling.

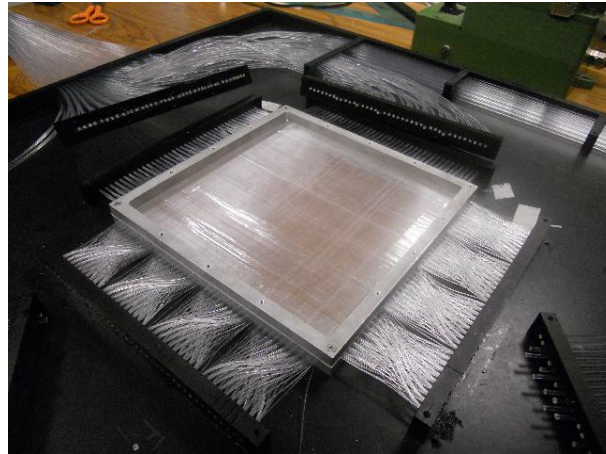


Fig. 1 The sensitive area of the OFFSET detector

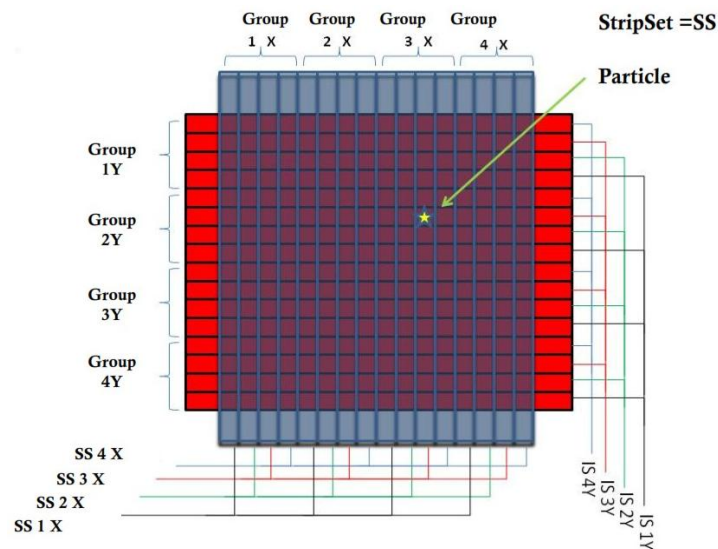


Fig. 2 An example of the application of the channel reduction system

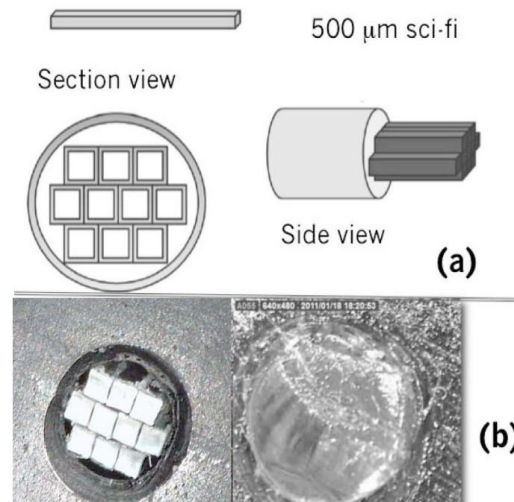


Fig. 3 (a) The optical coupling scheme, (b) photographs of the Sci-Fi and clear fiber prepared for coupling

In the OFFSET tracker, the application of the read-out channel reduction system led to a total of 160 channels, exactly one-fifth of those necessary without channel reduction.

B. Photosensor

A single multianode photomultiplier (PSPM) is used as a light sensor instead of having separate light sensors for each separate clear fiber. We have chosen the 16x16 pixels H9500 PSPM Hamamatsu photomultiplier [7]. It needs only one high voltage power supply and provides an additional signal, called the dynode, which is connected to all the last dynodes of each PSPM channel.

In the detector, 10 Sci-Fi are coupled to a single clear fiber. The light from the scintillating fibers propagates through the clear ones to the distance required, which in the case of the OFFSET tracker is about a meter, to reach the PSPM photocathode pixels. The coupling is made by routing and fixing the Sci-Fi and clear fibers mechanically with optical gel. The size of the clear fibers is constrained by the pixel size of the selected photomultiplier, about $2.8 \times 2.8 \text{ mm}^2$, which limits the scale of reduction of the detector channels. Using photomultipliers with a larger pixel area or smaller Sci-Fi, the channel reduction could increase significantly.

C. Front-end Electronics

The front-end electronics is simple and very fast. The PSPM is socketed onto the front-end board. We have chosen the anodic resistance for all channels as a compromise between the amplitude and the timing characteristics of the anodic voltage signal [8]. A fast comparator that feeds a monostable reads each of the 160 PSPM anode signals. The threshold chosen for the anode signal comparators is about 1/3 of the single photoelectron mean peak amplitude.

D. Data Acquisition

The front-end electronics information is acquired by simple digital acquisition electronics for subsequent pre-analysis, filtering, and fast storage on a PC. Logic signals from the front-end board are fed into a data acquisition module, a real-time FPGA PXI-7813R [9], via four output connectors fitting the data acquisition interface cable requirements. This module has 160 digital inputs/outputs and performs sampling up to 40 MHz and supports real-time analysis and DMA transfer to mass storage. Given this sampling frequency, the comparator output has been stretched up to 100 ns by the monostable in the front-end board in order to have at least three samples for each event. This choice limits the maximum rate to no more than 10M particle/sec. Using a higher performance read-out module, it would be possible to attain up to 100M particle/sec, which is the maximum rate allowed by the photomultiplier output signal characteristics. A real-time module, the PXIe-8102, is interfaced to the PXI-7813R through the PXI bus. A solid state hard disk is used to store data. The PXIe-1062Q crate hosts the PXI-7813R, the real-time module, and the hard disk, and has gigabit Ethernet communication to the acquisition PC. We have developed the firmware and the software for the OFFSET tracker data acquisition, analysis, display, and control, using the LabView software platform. The electronic devices mentioned in this section are manufactured by National Instruments.

E. The Overall Detector

Figure 4 shows two pictures of the final detector. In (a), with the cover open, the sensitive $20 \times 20 \text{ cm}^2$ area made of Sci-Fi and the routed clear fibers, which guide the scintillation light to the PSPM, are visible. In (b), with the cover closed, the front-end board is seen. The overall size of the detector, including the mechanical structure, is $70 \times 100 \text{ cm}^2$.

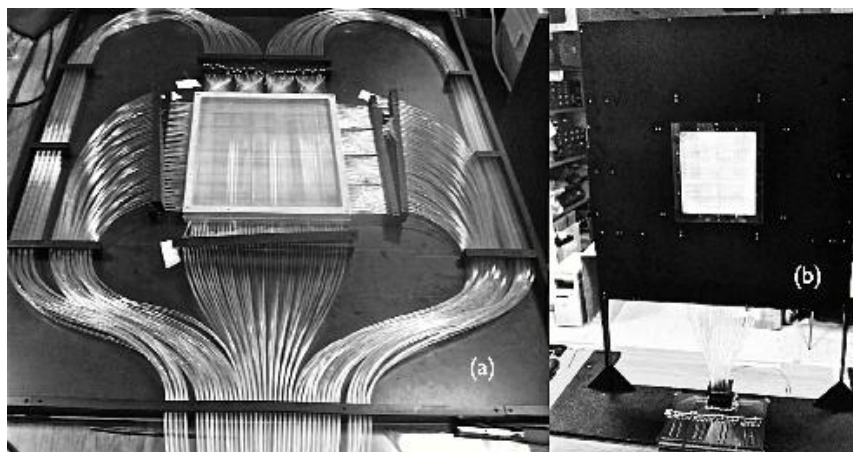


Fig. 4 (a) The OFFSET tracker with open cover, (b) the complete OFFSET tracker

III. THE SCINTILLATING FIBER

A measurement campaign was performed on selected scintillating fibers (Sci-Fi) for the OFFSET detector [10]. The fibers used are the 500 μm square multi-clad BCF-12 produced by Saint-Gobain (SG) [3].

A. Light Generation and Transmission Properties in Sci-Fi

Considering the fibers from the point of view of their use in particle detection, we characterized them with regard to the attenuation of light over the distance traveled by the light from its point of production to the end of the fiber, optically coupled to a photo-sensor. The manufacturer supplies a range of catalog specifications for all types of Sci-Fi with a diameter of one millimeter. It is not possible to extrapolate the characteristics for different Sci-Fi diameters or other cross-sections with a different shape. In particular, with respect to the thicker Sci-Fis, the sub-millimeter Sci-Fis have a higher dopant concentration, which is responsible for a larger production of scintillation light, with respect to the thicker Sci-Fis. The higher dopant concentration is used to increase the light yield of the Sci-Fis but also influence their light attenuation performance. The manufacturer does not give the dopant concentration, and furthermore, this can slightly change from one stock of fibers to another. This is the main reason why a precise characterization of the Sci-Fis is necessary before any application. The system used by SG to measure the attenuation length, for example, is to record the actual output of a bialkali photomultiplier, optically coupled to a Sci-Fi, in response to a ^{90}Sr beta source placed at varying distances along the fiber, from one to three meters, from the photomultiplier.

The attenuation length of an optical fiber is defined as the distance at which the intensity of light travelling along the fiber, is reduced to $1/e$ of its initial intensity. From scientific literature [11, 12], the attenuation length function is the sum of two exponential terms, and in this case, we can define two attenuation lengths acting in two distinct intervals of the distance traveled by light along the fiber. Furthermore, the attenuation length is a function of the wavelength.

In this work we will consider only the integral attenuation length, convolution of the response of the Sci-Fi and the quantum efficiency of the selected photomultiplier (PMT).

It should be noted that by definition the input light is generally considered as travelling along the fiber axis direction. In the case of scintillation light, this condition is not fulfilled because the light is produced isotropically inside the fiber, and therefore, only a fraction of the scintillation light is channeled into the fiber after a characteristic distance. Therefore, the transmission properties for scintillation light and injected light must be quite different.

B. Attenuation Length

In the first survey, the attenuation length function was extrapolated by projecting a pulsed laser beam of about 400 nm wavelength coaxially at one end of a ribbon of 8 Sci-Fi and using a bolometer to measure the amount of light collected at the other end. This measurement was made starting with a one-meter long Sci-Fi ribbon and repeated, shortening the length of the ribbon by cutting it each time, while trying to preserve the same conditions.

In this way, each measurement is the average of the results on the individual Sci-Fis, both in terms of the parameter dispersion of fibers and of the repeatability and uniformity of the ribbon cutting and lapping procedure.

In dark conditions, the background level was recorded before turning on the laser beam to take each new measurement. A 10 MHz laser pulse frequency was chosen to fit the input dynamic range of the bolometer. The Sci-Fi ribbon was gradually shortened down to 10 cm. Figure 5 shows the power measured by the bolometer, normalized to its maximum value, for each fiber length.

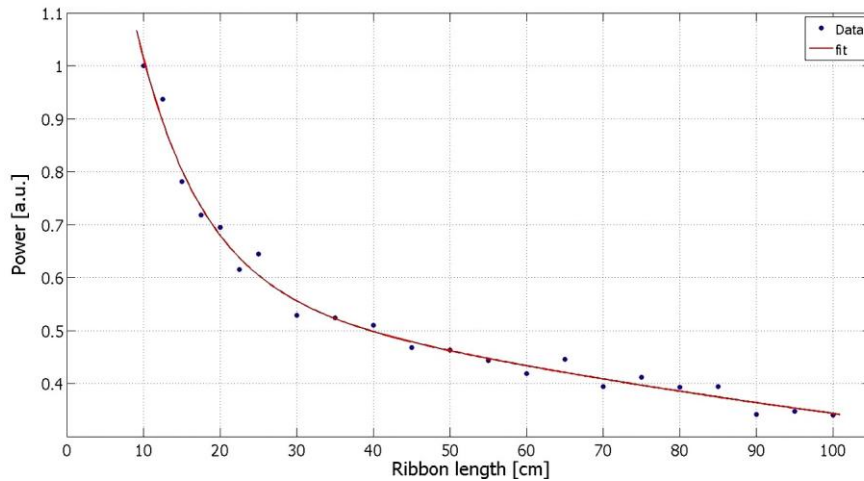


Fig. 5 Plot of the data and best fit relative to attenuation length measurement by coaxial laser injection

Fitting the data by double exponential function in (2), we obtained the parameters reported in Table 1.

$$y(x) = ae^{-\frac{x}{\lambda_1}} + be^{-\frac{x}{\lambda_2}} \quad (2)$$

TABLE 1 EXTRAPOLATED PARAMETERS: CUT FIBER

Parameters	Value
a	1,417
c	0,6107
λ_1	8,52 cm
λ_2	173,55 cm

C. Characterization by Cosmic Muons

An innovative system for the characterization of Sci-Fi has been developed in order to measure the attenuation length of the Sci-Fi when the light is produced by scintillation.

The system does not require the use of a source or particle beam as it uses the flow of secondary cosmic rays, mostly muons, which hit the Earth's surface. In effect, this measurement differs from the previous one because only a small fraction of the light generated isotropically by cosmic rays is channeled into the fiber. The system developed consists of two PMTs anchored to the floor with photocathodes placed in a coaxial position.

A four Sci-Fi ribbon was fixed on a horizontal plane, then optical grease was used to optically couple the edges to two identical PMTs having the same gain. Their signals were sent to two ADCs through two electronic lines with the same characteristics.

The spectra resulting from the acquisition of the PMT charge signals in coincidence, related only to the cosmic ray events, were then compared with the results of a Monte Carlo simulation.

D. Optical Coupling

A preliminary step to determine the asymmetry between the two channels, called Left and Right, mainly related to the different optical coupling or different quality of the ribbon-cutting procedure, was carried out with an intense UV laser beam illuminating the center of the ribbon, recording the average relationship between the charge measured by the two chains, PMTs and data acquisition electronics. The PMTs and the electronic chains were accurately characterized before the measurement. The two Thorn-EMI 9816B PMTs, were set to about the same gain ($\approx 2,4 \times 10^7$). After absorption, UV laser light produced scintillating light in the Sci-Fi.

The measurement was repeated by reversing only the channels of the acquisition system to eliminate offset and any differences in gain and sensitivity of the two channels. Figure 6 shows the charge spectra obtained with laser light for the Right (a) and the Left side (b).

Each of the figures shows the results obtained by reversing the A and B electronics and acquisition channels. In effect, the results, which take into account the differences of the various parameters, are essentially the same, showing a deviation of less than 2%. The laser light is injected perpendicularly into the center of the ribbon, and therefore, the light is attenuated along the fibers by the same amount in each direction. It follows that the relationship between the centroids of the spectra of the Left and

Right PMTs is the ratio between the different attenuations due to the optical coupling between the PMT and fiber ribbon, taking into account the differences between the PMT and electronic channels.

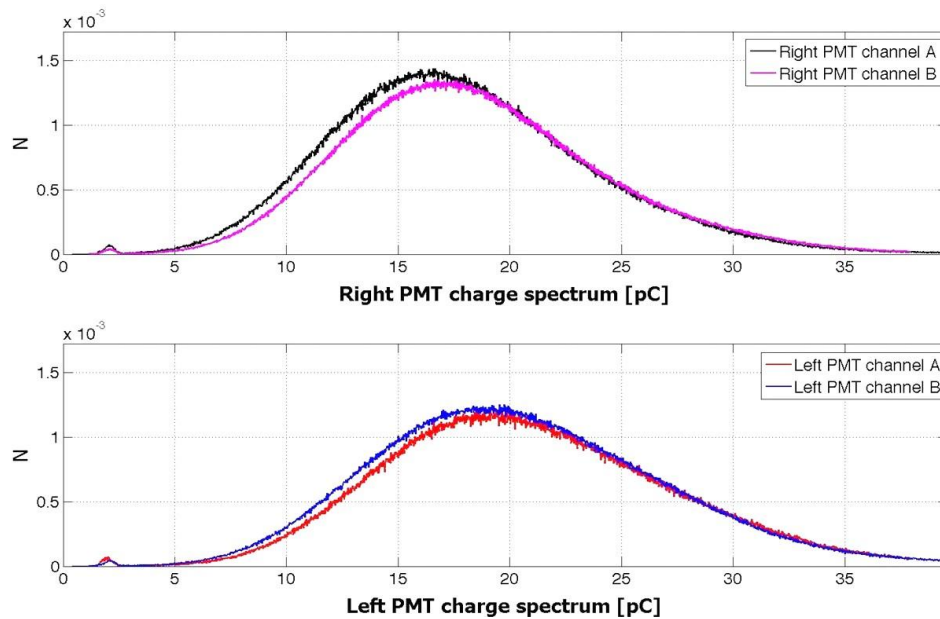


Fig. 6 Charge spectra for the Right PMT (top) and for the Left PMT (bottom) obtained injecting the UV laser into the center of the fiber ribbon and reversing the electronic chains

E. Measurement by Cosmic Muons

Once the system was characterized and calibrated, data acquisition was performed for events induced by cosmic rays crossing the Sci-Fi ribbon. It took a few days to achieve a number of events sufficient for the purposes of the measurement. The area exposed to the cosmic rays was 2 mm x 49 cm and the expected event rate was about 0.2 Hz.

Figure 7 shows the ADC spectra obtained by cosmic muons for the two channels, in both the acquired and smoothed versions. Using the QDC calibration data and the electronic characteristics of the two channels it is possible to obtain the charge that comes from each of the PMT anodes.

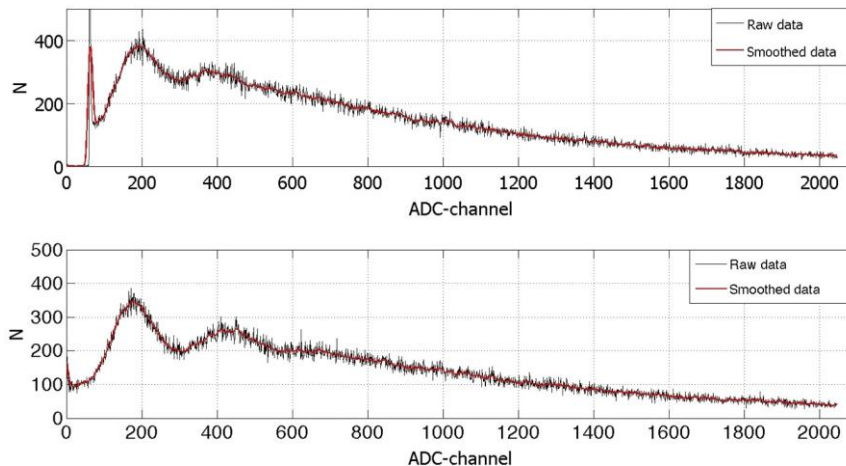


Fig. 7 Spectra of the Left PMT (top) and Right PMT (bottom) acquired under cosmic rays, raw data (black) and smoothed (red) data

F. Monte Carlo Simulation

An essential starting point for simulating the response of the fiber ribbon to the passage of muons is the modeling of the flow and the interaction of the cosmic rays with these fibers.

Especially when dealing with very short distances from the impact point of the cosmic muons, we expect very different results. The first phase consists in modeling the flow of cosmic rays on a surface consisting of a Sci-Fi ribbon placed parallel to the Earth's surface. The energy and angular distributions of cosmic rays at different altitudes are well-known in literature [13]. Thus, a code was designed to generate muons, all of which are assumed to be of high energy, and therefore, from the point of view of the fibers, minimum ionizing particles. The angular distribution follows the $\cos^2\theta$ function, where θ is the zenith angle,

while the distribution is uniform in space and for the other angles.

For each generated muon, the code calculates the isotropically produced light and propagates a fixed portion of it, related to the efficiency of light trapping, along the Sci-Fi in the two opposite directions. In relation to the point of impact, it is clear that the light will travel different distances in the two directions and, therefore, the light attenuation will act differently in the two cases.

The code finds a coincidence between the two signals, verifying that the two PMTs output signals simultaneously pass the same threshold. It takes into account the difference in optical coupling measured in the previous section, the quantum efficiency of the two photocathodes, the calibration of the two ADCs and the response of the two PMTs. Then it is possible to calculate the charge spectra with the number of events required for the two channels.

G. Comparison of Simulation and Measurement Results

At this point, it is possible to compare the measured and simulated charge spectra, in order to derive the λ_1 , λ_2 , a and c parameters of a double-exponential Function (2), which can describe the light transmission in the Sci-Fis under these conditions. The determination of the optimal values for the parameters is the result of a successive approximation procedure that ends when the difference between the two spectra reaches the minimum value.

The result of this process leads to the values listed in Table 2. Given that the light is not injected parallel to the fiber axis, the physical process is quite different, and obviously, the values of the two tables are not equal. From the results obtained through the use of cosmic rays, the attenuation coefficient of scintillation light produced inside the fiber at the passage of muons was obtained. Taking into account the angular distribution by which the particles reach the Earth's surface, the length of the path within the Sci-Fi is not constant, so it is not possible to obtain a suitable match between the intensity of light produced by the cosmic ray at the incidence in the fiber.

TABLE 2 EXTRAPOLATED PARAMETERS: COSMIC RAY SOURCE

Parameters	Value
a	1
c	1
λ_1	17 cm
λ_2	36 cm

Figure 8 shows the simulated and measured charge spectra for the two PMTs. In the figure, the charge value relative to a single photo-electron (pe), two pes, three pes and the charge threshold used for coincidence are also marked. For transmission, the simulated spectra uses the Expression (1) with the parameters in Table 2.

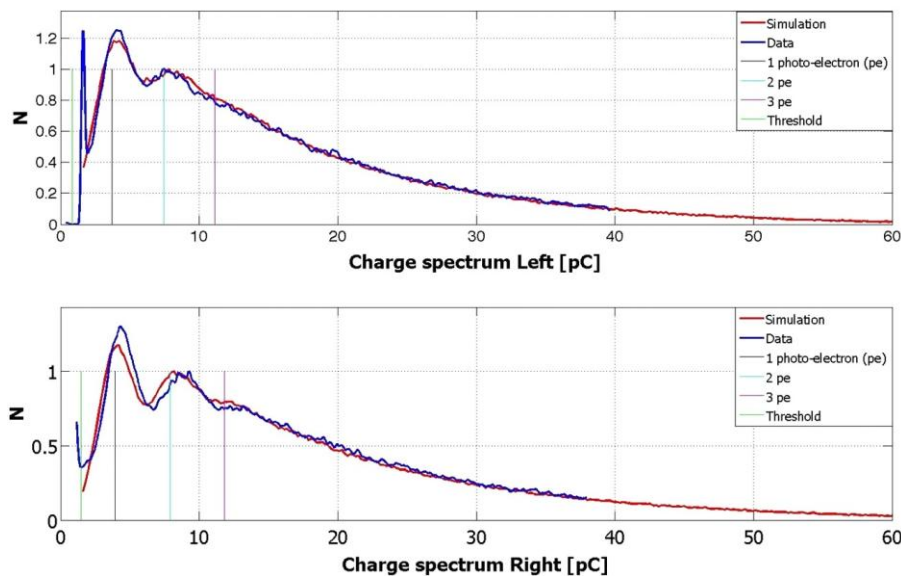


Fig. 8 Charge spectra of the Left (top) and Right PMT (bottom) acquired under cosmic rays. The blue line is the measured spectrum. The red line is the simulation output spectrum

H. Measurement with UV Light

A widely-used method for the characterization of the Sci-Fi is to move a particle source along the fiber and to measure the light at its ends.

We designed a different measuring apparatus in which the scintillation was produced by incident particles perpendicular to

the Sci-Fi ribbon, thus ensuring a constant amount of isotropic light, regardless of the entry point of the particle in the scintillator. We used a UV laser beam controlled by a pulse generator which, passing through a collimator, hits a ribbon consisting of four 500 μm square Sci-Fis in a very small area, i.e. only 3 mm. Figure 9 shows the experimental set-up, schematic view and picture. Two PMTs are optically coupled to the opposite edges of a Sci-Fi ribbon. The light source is mounted on a slide.

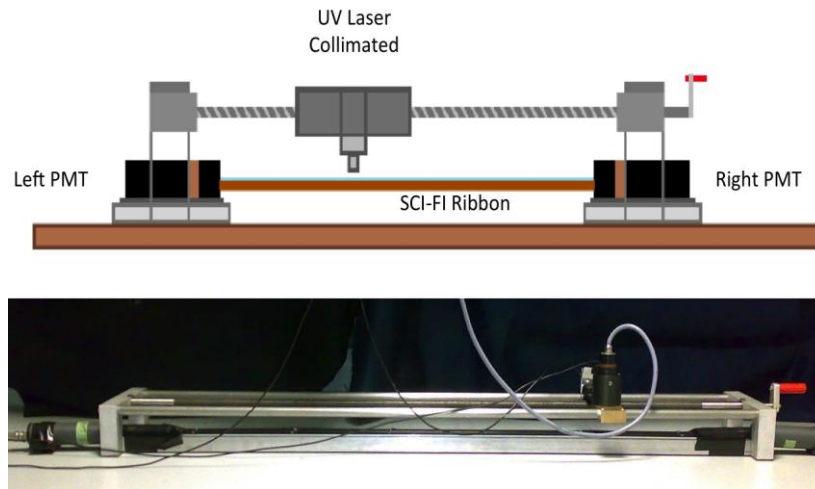


Fig. 9 Schematic view and picture of the experimental set-up

The block diagram of the data acquisition system employed for the measurement is shown in Figure 10. The electronic chains for the two PMTs are the same as for cosmic ray measurement.

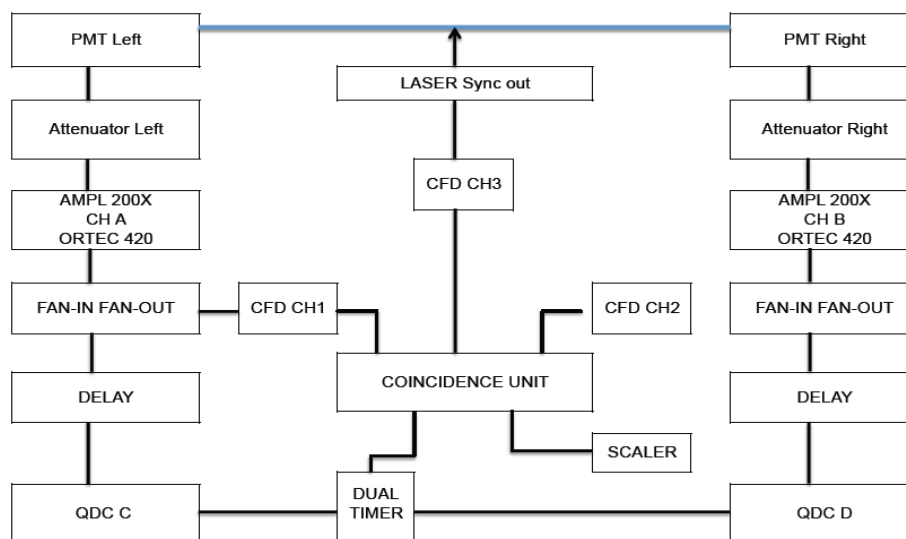


Fig. 10 Block diagram of the data acquisition system

The acquisition of the input signal is controlled by a trigger signal whose duration is the time window of measurement (GATE). This signal, leaving the Connections Unit, is present only if the pulses from the PMTs coincide with the sync-out signal of the laser. The combination of attenuator and amplifier modules at the output of the PMTs is used to fit their signal charge with the input dynamic range of the two QDCs.

I. Comparison of the Results

These three measurements are not actually comparable for reasons relating to the mechanism of light production. In the first case, light is injected at one end of the fiber ribbon and read at the opposite end, after the cut and lap procedure. In the second case, we measured the portion of light produced by cosmic muons channeled into the fiber and produced by particles that release energy in the scintillator in a completely random way. It can be seen from Figure 7 and Figure 8 that a large part of the spectra came from a single pe. In other terms the light in the fiber is quite feeble. In the last case the scintillation light is produced by a UV laser beam positioned perpendicularly with respect to the fiber with almost constant intensity. The different mechanisms of production and propagation of light in the three cases explain the different results regarding the attenuation length measurement. Figure 11 shows a plot of the three attenuation length functions derived.

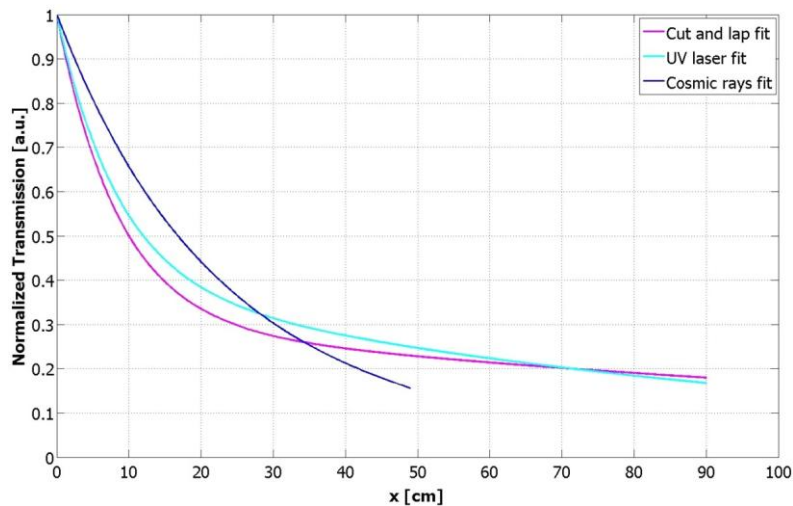


Fig. 11 Plot of the three normalized attenuation length functions derived. In violet, the attenuation length for the cut and lap quality control, with coaxial light ignition. In blue, the attenuation length function obtained by cosmic rays. In cyan, the attenuation length function obtained by UV laser

The fit parameters for the three measurements are summarized in Table 3. The parameters refer to (2).

TABLE 3 SUMMARY OF THE FIT PARAMETERS

Technique	Parameters	Value
Cut and lap	a	1,346
	c	0,58
	λ_1	8,5 cm
	λ_2	1,74 m
Cosmic rays	a	1
	c	1
	λ_1	17 cm
	λ_2	36 cm
UV laser	a	1
	c	0,65
	λ_1	8,52 cm
	λ_2	1,05 cm

J. Monte Carlo Simulation of the Response of Fibers to Protons

The simulation software was adapted to meet the case of protons that pass through the fiber ribbon perpendicularly.

It is possible to repeat the same calculations with the revised simulator, even if the data to be compared are insufficient and only qualitative. In any case, the parameters derived for the scintillating fibers remain unchanged. The only change is the scintillation light produced which is greater with protons than with muons. This result was provided by simulations with GEANT4. Note that, in the case of the proton beam the simulated trace length is not very different and it plays an important role in the efficiency of the scintillating fiber. The spectrum of energy deposited on fibers by 62 MeV protons is shown in Figure 12. Note that the average energy released in these conditions by the particles is about 546 KeV.

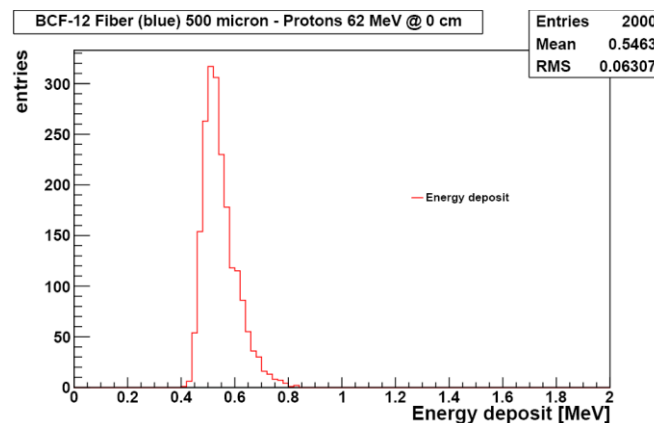


Fig. 12 GEANT4 simulation of protons passing through the fiber ribbon perpendicularly; Spectrum of energy released by 62 MeV protons on the BCF-12 fibers

A simulation of the same type was carried out with 250 MeV protons considering the specific requirements of the detector. In this case, the average energy released, according to the simulation, is 408 KeV, therefore lower than the 62 MeV protons. Given this situation the paper continues by considering the context of the 250 MeV protons as representing the condition in which the scintillation light is lower.

When using fiber ribbons of the type previously considered to build the detector, not all of the tape forms part of the sensitive area. A part of the tape is used for optical coupling. The simulation takes account of this by generating protons only on the sensitive area, as shown in blue in Figure 13. In any case, when calculating the attenuation of the scintillation light from the scintillating fibers, the entire length of the tape must be considered including both the yellow and blue areas as shown in Figure 13.

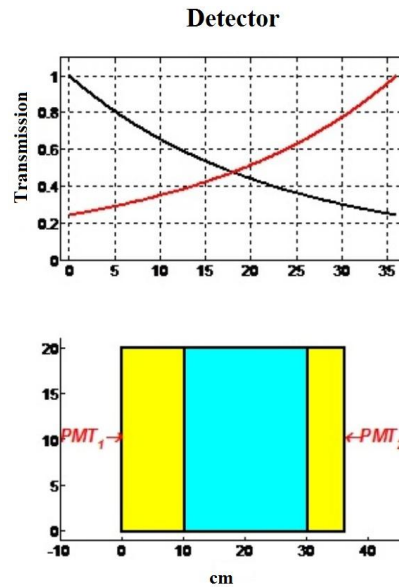


Fig. 13 Transmission and sensitive area in the detector 20x20 cm²

By varying only the part concerning the generation of events, it is possible to extract and display results similar to those achieved with cosmic muons. Important differences are, however, the light produced, the direction of the incident particles, and therefore, the length of the traces through the fibers. The expected output spectra from the two photomultipliers are shown in Figure 14. The distribution of these, compared with the muon spectra, shown in Figure 8, highlights the fact that although the parameters have remained the same, the light produced is much greater. As can be observed, there are no highlighted single or double photoelectron peaks.

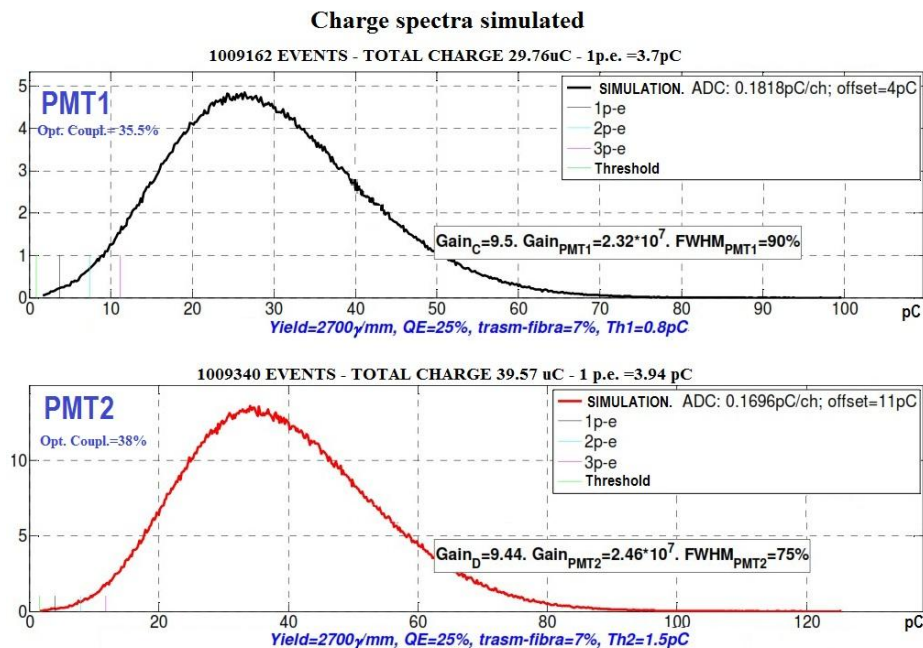


Fig. 14 Spectra simulated of the output to the two photomultipliers

The distribution of photoelectrons detected by the two photomultipliers for the protons is plotted in Figure 15, which shows that the responses of the two photomultipliers cannot be superimposed. The peak of the distribution of the photomultiplier called PMT₁ has moved further to the left, indicating that less photoelectrons are detected. This effect is most certainly due to the different distances at which the sensitive photomultipliers have been placed to simulate the needs of real techniques, as shown in Figure 13. The small difference between the two spectra is due to the gain difference and optical coupling between the two channels.

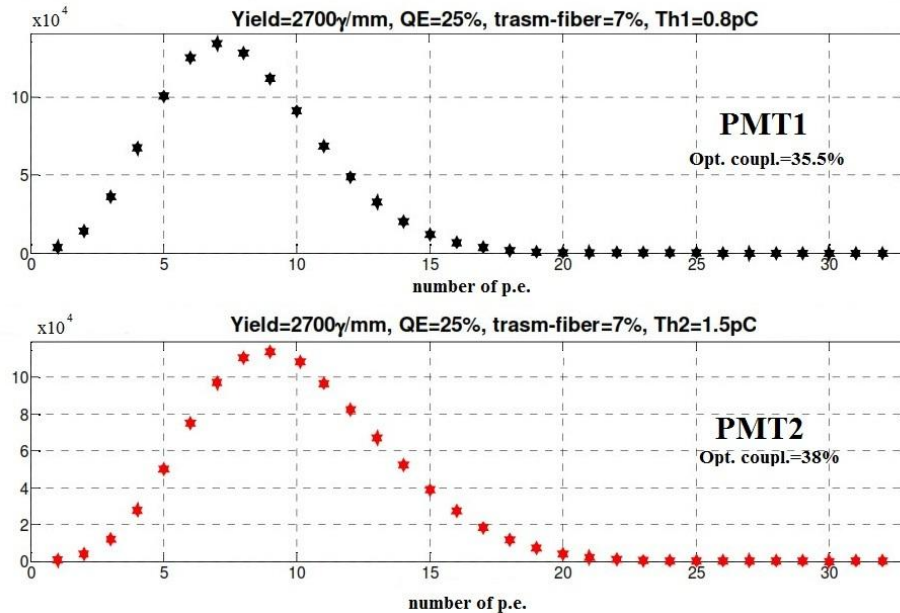


Fig. 15 Spectra of the expected output from the two photomultipliers in number of photoelectrons

Figure 16 shows the average number of photoelectrons detected by the two PMTs as a function of the proton impact position on the fiber measured, starting from PMT₁. In this case the average number of photoelectrons detected by the two PMTs is superior to that of the muons. Figure 16 also shows the number of simulated PMT signals in coincidence for a given threshold, and an average detection efficiency of 99.9%. Note that the parameters shown in the figure are unchanged as compared to the previous case.

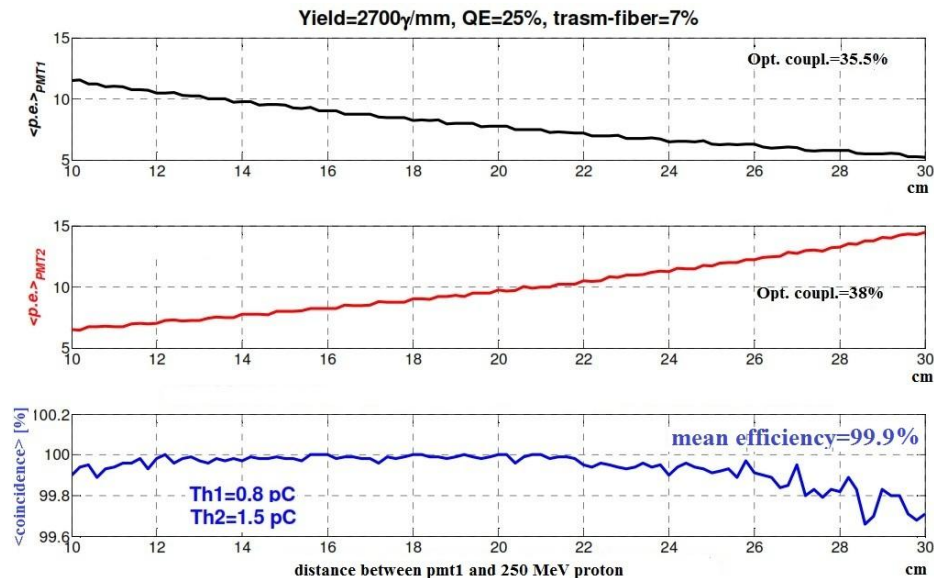


Fig. 16 Photoelectrons produced as a function of the position of impact for the two PMTs and detection efficiency

The results are, therefore, that in the case of 250 MeV protons, the detection efficiency increases only the events related to the sensitive area and the central ribbon. As in the previous case regarding muons, events related to the extreme zones of the belt are more likely to produce non-coincidence between the two photomultipliers, and then to be lost in the acquisition phase. In these conditions, however, the average efficiency occurs almost constantly throughout the ribbon.

If we consider a detector consisting of two superimposed planes of fibers oriented perpendicularly to each other, we can

deduce that the detection efficiency is the total square of the one previously mentioned. Since this is 99.9%, this suggests that the efficiency of the detector remains completely unchanged.

It is evident that it is possible to design a detector with the services requested in advance/to advance specifications. It should however be noted that given that the OFFSET detector is subject to loss of scintillation light due to the optical couplings, multianode super bialkali photomultipliers with high quantum efficiency could be employed to ensure good detection efficiency margins. A simulation using a photomultiplier with a QE equal to 35%, is shown in Figure 17. It can be noted that the average number of photoelectrons detected by two photomultipliers, to vary the impact position on the fiber of the protons, is greater than the previous case, although its media of detection efficiency is similar to the previous case for muons on scintillating fibers, and the function that expresses the coincidence has an almost constant value of 100%.

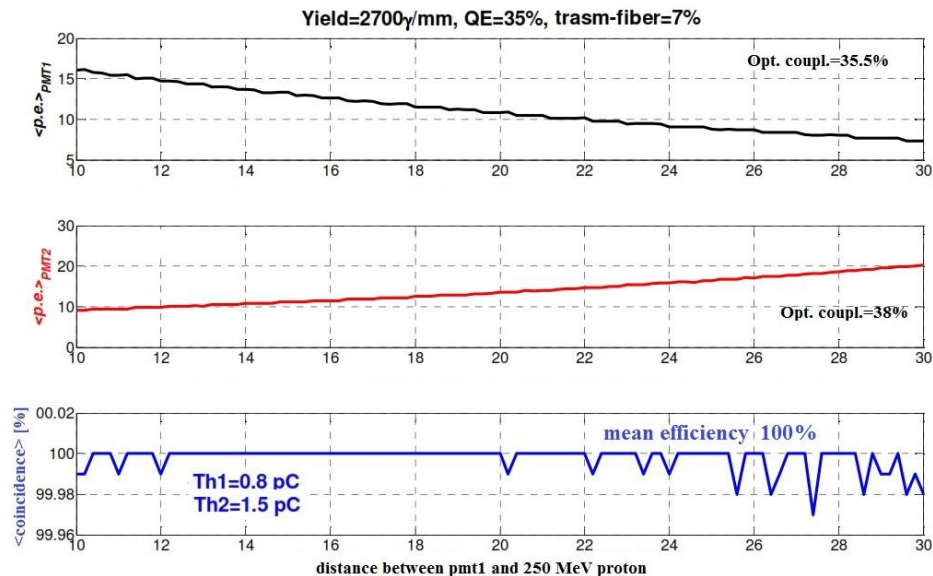


Fig. 17 Simulation similar to Figure 15 adopting photomultipliers with a QE of 35%

It should be remembered that these results were obtained for 250 MeV protons and that this is an unfavorable condition as compared to the use of 62 MeV protons.

K. Attenuation Length

The main conclusion is that the different scintillation light production mechanisms determine different integral attenuation length functions.

Two exponential law components may be distinguished: one short and one long. The short component is responsible for the limitation in the use of fibers more than one meter long.

IV. OFFSET TESTS

The design of the OFFSET tracker started with a simulation study in order to evaluate the detector architecture on the basis of its response to different stimuli: cosmic rays, beta sources, and proton beams at different energies. Nevertheless, the GEANT4 simulations [14] of submillimeter Sci-Fi were not decisive, due to a lack of sufficient factory information. However, the scientific literature [12, 15] provides some essential reference points for the design of the detector. The best way is to directly measure the selected Sci-Fi coupled to the selected photo-sensor in order to find, for example, the maximum size limits that the detector can reach. The OFFSET tracker is well below these limits. The OFFSET was submitted to several tests using both the β sources and a beam.

A. Test Using β Sources and Cosmic Rays

We have preliminarily tested the OFFSET using two different sources: β sources and cosmic rays. The use of β sources is very useful because it allows an image to be produced in the worst possible conditions, i.e., with low linear energy transfer particles, and also to bench test the detector without the limitations of an accelerator room. Figure 18 shows a real-time image of a ^{90}Sr β source with a 2 cm diameter. In Figure 18(a) there is a 2D image of the source, while Figure 18(b) is a histogram of the same image. Some lines are clearly missing. These lines correspond to the tenth fiber of each Sci-Fi group and indicate a worse optical coupling than in the other groups. This is due to the Sci-Fi routing procedure and can be easily corrected. One important test is the detection of cosmic rays because they are minimum ionizing particles (MIP) and represent a diffused source of low energy transfer particles. It should be noted that the 250 MeV proton beam used for medical imaging is equivalent to about 2 MIP. The image provides additional information: first, the level of uniformity in the detector response;

second, the level of efficiency of the detector. Figure 19 shows the image of the cosmic rays acquired in 47 hours, relative to the entire active area of the detector. Three groups of Sci-Fi, ten Sci-Fi each, are absent in the image. This is due to the failure of their front-end channels and can be easily repaired. Some vertical and horizontal lines are missing for the same reason as given in the case of the test using beta sources.

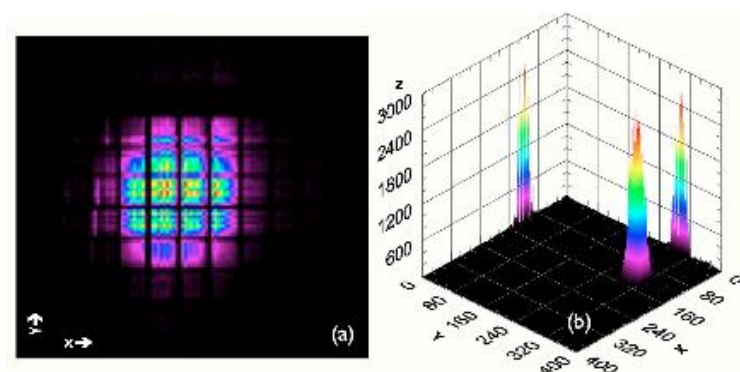


Fig. 18 Real-time image (a) and histogram (b) of ^{90}Sr beta source acquired by the OFFSET tracker

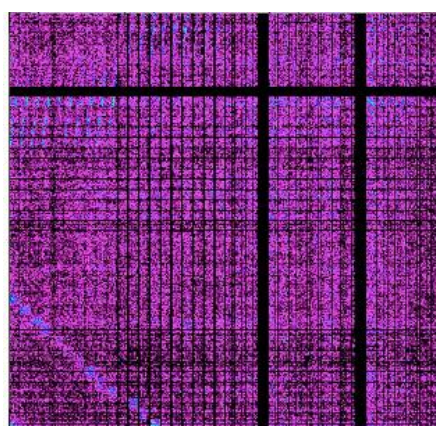


Fig. 19 Image of cosmic rays acquired by the OFFSET tracker

B. Test with 62 MeV Protons

The paper presents a characterization technique for selected. In order to determine the detection efficiency of the prototype, we measured the rate rCFD of the particles that crossed the scintillating collimator. The prototype of the detector has also been tested with a 62 MeV proton beam in the CATANA [16] facility at the LNS in Catania.

Before measuring, the CATANA staff performed a beam profile characterization along the X and Y directions employing calibrated diodes. The result is shown in Figure 20. In order to perform a precise calibration of the detector, a gafchromic EBT [17] film was fixed to the portion of the sensitive area crossed by the proton beam. Using the beam profile characterization, we have calibrated the gafchromic film. Figure 21 shows a sketch and a picture of the experimental setup.

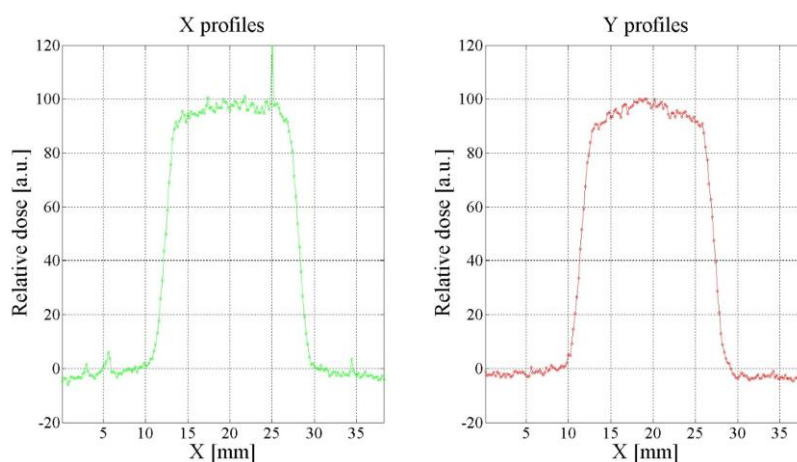


Fig. 20 Beam profile characterization

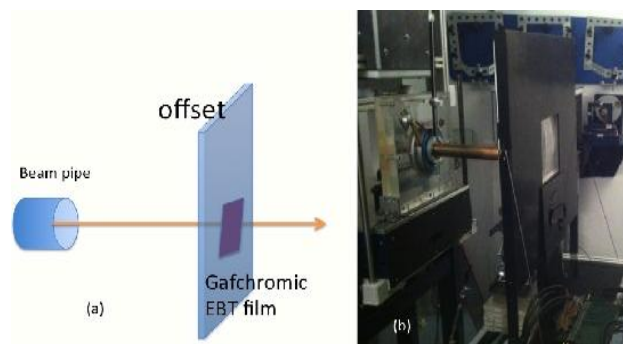


Fig. 21 Drawing (a) and picture (b) of the experimental setup inside the CATANA hadrotherapy facility

A long run, up to about 1.2 Gy, was performed using a 1.5 cm diameter hole calibrated collimator. The comparison between the standard beam profile and the measurements with OFFSET allowed the imaging performances of the tracker to be extracted. During this run, an image of the beam was recorded in real-time every minute. The calibrated gafchromic EBT film was digitized by a scanner and the final dose distribution was used to calibrate the region of the sensitive area of the tracker intersected by the beam. The calibration was performed by summing, pixel to pixel, all the images acquired, based on the reasonable assumption that any non-uniformity in the pixel response in the sensitive area was time invariant. This lack of uniformity is mainly due to the different optical couplings between the fibers and the PSPM and the non-uniformity of the PSPM photo cathode gain.

Figure 22 shows the results of the test. Starting from the gafchromic EBT film image and the raw sum of all the images acquired with the hole collimator, a calibration matrix was obtained. Once calculated, the calibration matrix was then applied to each image acquired. After calibration, each one-minute frame was analysed in order to perform a beam profile characterization over time. Figure 23 shows this result. To evaluate the effectiveness of the calibration, another long run, up to about 1.6 Gy, was performed using a patient eye collimator. The same calibration matrix produced using the beam spot was used to correct the patient eye collimator image and the results are shown in Figure 24. In this image, it is possible to see where the dashed circle representing the calibration area of interest ends and how it influences the patient eye collimator image.

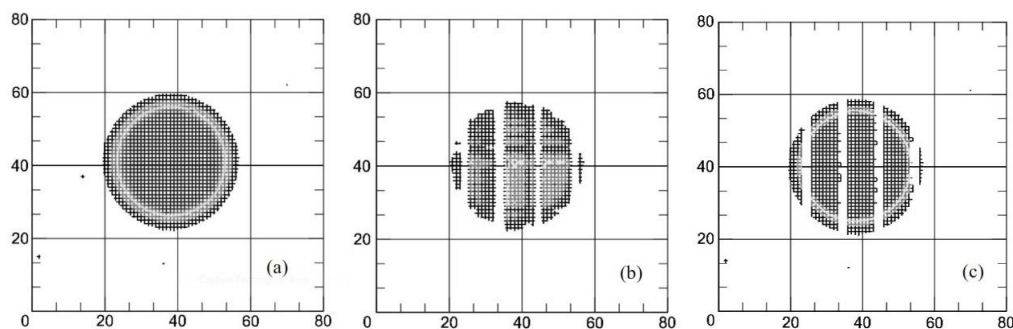


Fig. 22 (a) The gafchromic EBT film image; (b) the raw sum of all the images with OFFSET; (c) the corresponding image, calibrated. Axes are in fiber units (500 μm)

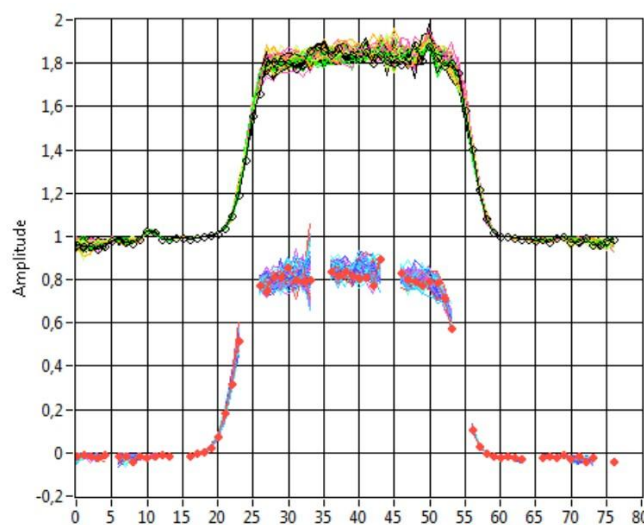


Fig. 23 X and Y beam profile monitored during time by OFFSET

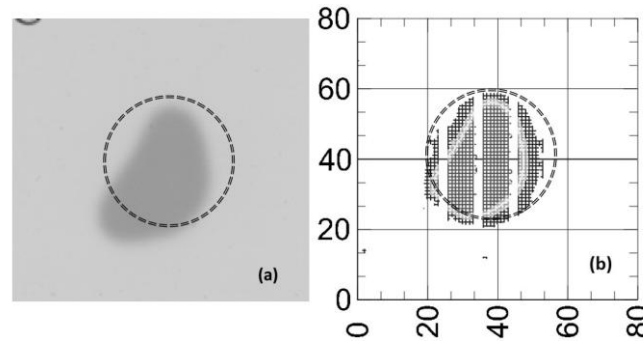


Fig. 24 (a) The gafchromic EBT film image; (b) the patient eye collimator image, calibrated. Axes are in fiber units (500 μm)

C. Efficiency

In order to determine the detection efficiency of the prototype, we measured the rate r_{CFD} of the particles that crossed the scintillating collimator area, about 70 kparticle/sec, mainly due to the light produced in the scintillating fibers. The measurement was made using the dynode signal of the PSPM connected to the input of a SensL CFD [18]. The PSPM dark rate of about 100 Hz is negligible. During the run time, we used this CFD to measure the total number N_{CFD} of particles that crossed the scintillating part of this selected area. We counted the total number N_{Tr} of tracks recorded by the detector read-out in the same interval of time. As can be seen in Figure 21b, some events were missing due to the lack of some vertical and horizontal lines. We have estimated the number N_{Te} of tracks in these lines to be the average of the neighbouring pixels. In this way, the total number N_{Ti} of tracks can be evaluated as the sum $N_{Tr} + N_{Te}$. Then the capability of OFFSET to detect tracks in its sensitive area is expressed by the ratio N_{Ti}/N_{CFD} , which was calculated as about 80%. In effect, the sensitive area of the detector is affected by the multi-cladding of the fiber. So the rate r_{CFD} does not take into account the particles impinging on the cladding area. In an X - Y square detector of size L that utilizes square fibers of thickness t_f having a multi-cladding t_m thick, the real sensitive area can be calculated as

$$S_a = \left[1 - 4 \frac{t_c}{t_f} \left(1 - \frac{t_c}{t_f} \right) \right] L^2 \quad (3)$$

Then the geometric efficiency is:

$$\eta_G = 1 - 4 \frac{t_c}{t_f} \left(1 - \frac{t_c}{t_f} \right) \quad (4)$$

The fiber used has a t_c of 6% of t_f , and then η_G can be evaluated as about 77.44%. Then the rate r_{Coll} of the particles crossing the collimator area is

$$r_{Coll} = r_{CFD} \cdot \eta_G \quad (5)$$

With all the detector channels working, we would have about 0.8×0.7744 , that is, 62% efficiency, which is the maximum value obtainable given the size of the dead area of the Sci-Fi caused by the multi-cladding.

V. CONCLUSIONS

The paper presents a characterization technique for selected scintillating fibers to extract the main design specifications. The first prototype of the OFFSET tracker was designed and tested with beta sources, cosmic rays, and a proton beam. It has the great advantage of a read-out channel reduction system applied to a large area detector with a high spatial resolution, employing submillimeter Sci-Fi, and a functional architecture. A complete characterization was carried out and the results are presented. A new version of the detector is now under construction in order to reduce its overall size and to improve its imaging performance with a view to extending the size of the sensitive area to $30 \times 30 \text{ cm}^2$. The main results regarding the system architecture have been used to demonstrate the technique, which has been patented by the Istituto Nazionale di Fisica Nucleare (INFN) [19].

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