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# A 2-D large area imaging system based on scintillating fibers

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In this paper we describe a new detection system for the tracking and measurement of the residual range, designed and developed with the aim of achieving real-time imaging and large detection areas with high space and time resolutions. The tracker has been designed and tested as a prototype, with a large 20 x 20 $cm^2$ area, consisting of two ribbons of scintillating fibers positioned in the classic bi-dimensional scheme. The prototype uses Saint Gobain, 500 μm multi-cladding BCF-12 scintillating fibers with square section. The track position information is extracted in an innovative way, using a reduced number of read-out channels.

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## 1. Introduction

Cutting edge research in the treatment of tumours has oriented towards hadron therapy, one of the most effective external radiotherapy techniques, that uses charge particle beams (protons and carbon ions) with up to 400 AMeV energy. Such beams make it possible to accurately release the required dose to control a cancerous mass, while at the same time leaving the surrounding healthy tissue almost totally untouched. If the maximum advantage is to be gained from the potential of these beams, this property must be accompanied by information on the stopping power of the particles used for 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].

The prefixed tasks are to design and build an imaging system for charged particles based on the consolidated principle of residual range measurement [2], taking advantage of new detection techniques. The aim is to use this system to achieve large detection areas (up to 40x40 $cm^2$), suitable for almost all medical physics applications, and high space (up to approximately 150 micron, calculated as strip pitch over $\sqrt{12}$) and time resolution (up to approximately 5 ns, considering about 1 ns for Sci-Fi and about 1 ns for photomultipliers) mainly employing scintillating fibers (Sci-Fi) for the trackers and the residual range measurement. We have developed prototypes that need accurate analysis. Preliminary tests with radioactive sources and cosmic rays have been carried out in this work. The test results will be useful for the optimization of the final detector.

## 2. Channel reduction system

Both the tracker and the residual range detector, use a read-out channel reduction architecture, which is suitable for imaging conditions, that is it reads a 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 [3], [4].

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 StripSet 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 identifies the $Strip_{hit}$ strip, hit by the particle following the formula (2.1).

$$Strip_{hit} = (i - 1) * n + j \qquad [2.1]$$

An X-Y strip detector consisting of 16 strips for each plane is shown in Figure 1 as an example of a two-dimensional strip detector where the channel reduction system is applied. In the classical 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. The position of the impact point, marked with a star, in the example is x = 11 and y = 6. The figure also shows the proposed read-out reduction system that allows the total number of channels to be reduced to only 16.

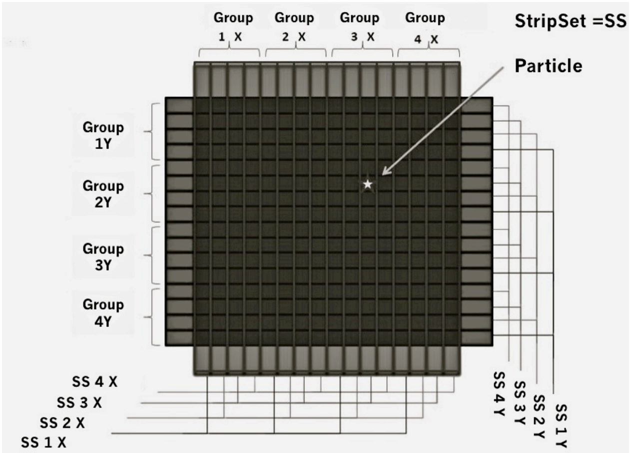


**Figure 1:** An example of the application of the channel reduction system.

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. Notice that, to reconstruct the point where the particle crosses the detector (event), it is necessary for it to release energy in both fiber planes. It is very interesting that when N is large the reduction factor becomes important, in sight of the goal of real time acquisition, and that the reduction foresees a coincidence between the ends of each strip, not present in a simple strip by strip read-out, which allows the spurious signals (noise, crosstalk and so on) to be automatically filtered.

## 3. OFFSET

This read-out channel reduction system has found an application in the design of a prototype particle detector named OFFSET, funded by the Istituto Nazionale di Fisica Nucleare. OFFSET (Optical Fiber Folded Scintillating Extended Tracker) is a large area detector, based on suitably folded Sci-Fi. It consists of two planes of Sci-Fi orthogonal to each other, called the X and Y planes. A prototype has been built. First results obtained on the efficiency and capabilities of the underlying idea are promising. The prototype uses Saint-Gobain [5], 500 μm multi-cladding BCF-12 Sci-Fi with square section to build the sensitive area of the detector. In these fibers, with a core in suitably doped polystyrene, the energy released by a crossing particle produces isotropically emitted light. Only a part of this light will be channelled into the fiber, which at this point will act as a guide. This light will flow in both directions along the fiber. These fibres come directly from the factory as a pre-glued, aligned ribbon. The ribbons are arranged in two layers and kept in position by pressure of from two square aluminium frames, delimitating the sensitive area of the detector in the prototype that is 20 x 20 $cm^2$.

### 3.1 Read-out channel minimization

In a classical read-out scenario, every Sci-Fi must be optically coupled to a light sensor read from a channel in the front-end electronics and acquired.

In the case of the 20x20 $cm^2$ prototype there are 400+400 channels meaning that a suitable read-out system in this case would be not only complex but would certainly suffer from high dead times.

The application of a read-out channel reduction consists in suitably coupling the Sci-Fi to larger standard (clear) optical fibers. The clear fibers are then coupled to light sensors.

We get a read-out channel compression dependent only on the relationship between sectional areas of the Sci-Fi and clear fibers. In the OFFSET module 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.

Figure 2 shows: (a) the scheme of optical coupling, (b) photographs of the Sci-Fi and clear fibers prepared for coupling and (c) a picture of the OFFSET detector.

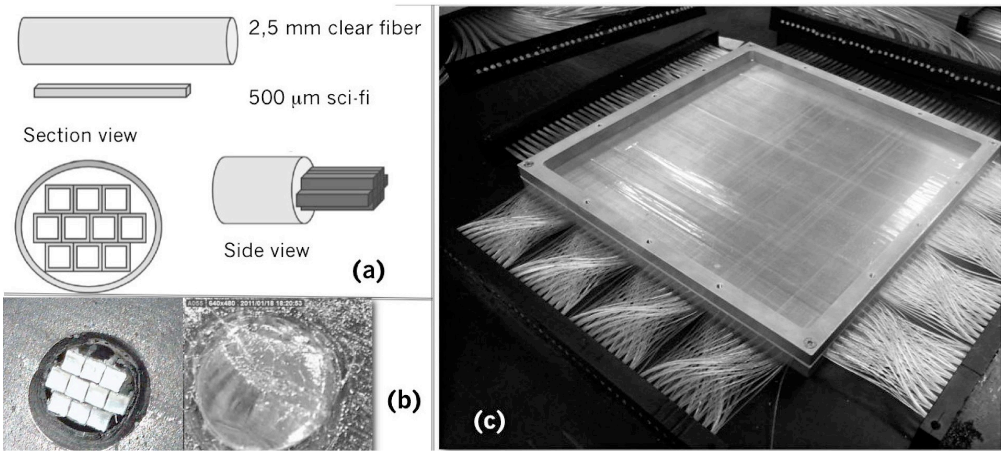


**Figure 2:** (a) The scheme of optical coupling, (b) photographs of the Sci-Fi and clear fiber prepared for coupling and (c) photograph of the OFFSET detector sensitive area.

### 3.2 Photo-sensor

A single multianode photomultiplier (PSPM) is used as a light sensor instead of having separate light sensors per clear fiber. The H9500 [6] PSPM Hamamatsu photomultiplier has 16x16 pixels, is very compact, 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 coupling is made by routing and fixing the Sci-Fi and clear fibers mechanically with optical gel. An alternative is optical glue but this bi-component resin requires several hours to set and gluing is irreversible. In any case the yield in terms of optical coupling is equivalent. The size of the clear fibers is constrained by the pixel size of the selected photomultiplier, about 2.8x2.8 $mm^2$, and even limits even the scale of reduction of the detector channels. Using photomultipliers with a larger pixel area or smaller Sci-Fi, the channel reduction increases significantly. For example, leaving the pixels unchanged and using 250 μm Sci-Fi, 45 Sci-Fi can be coupled to the same 2.5 mm clear fiber.

### 3.3 Front-end electronics

It is clear that, at this point, it is possible to propagate the light through clear fibers to the distance required, in the case of the OFFSET module about a meter, to the PSPM photocathode pixels.

The architecture of the front-end is simple and very fast. The PSPM is socketed on a front-end board. Each of the 160 PSPM anode signals is seen by one of the four inputs of a Maxim-Dallas MAX964 fast comparator. A 100ns monostable board follows the comparators. The front-end electronics information is acquired by simple digital acquisition electronics for subsequent pre-analysis, filtering and fast storage on a PC. The board has four output connectors fitting the data acquisition interface cable requirements.

The PSPM anodes have different gain values. The selected 160 channels of the PSPM have a less than 6 % rms spread of the gain values.

The threshold chosen for the anode signal comparators is 1/3 of the single photoelectron mean peak amplitude. Anodic resistance for all channels was chosen as a compromise between excellent value, the amplitude of the signal and its frequency spectrum and the timing characteristics of the anodic voltage signal [7].

### 3.4 Data acquisition

The data acquisition board used to characterize the OFFSET module is a real-time FPGA PXI-7813R [8] made by National Instruments. The firmware and the software for data acquisition, analysis, display and control was developed in the LabView software platform. This board has 160 digital input/output and performs sampling up to 40 MHz and supports real-time analysis and DMA transfer to mass storage. 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.

## 5. Preliminary tests

The design of the OFFSET module started with a simulation campaign in order to evaluate the detector architecture from its response to different stimulus: cosmic rays, beta sources and proton beams at different energies. The GEANT4 simulations [9] of the Sci-Fi are not determinant because of a lack of information about submillimiter size Sci-Fi. The dopant concentration is different and this specification affects the scintillation light yield and the attenuation length. However, scientific literature [10], [11] provides some essential reference points needed for the design of the detector. The best way is to directly measure the selected Sci-Fi, coupled to the selected photo-sensor, to find, for example, the maximum size limits that the detector can reach. The OFFSET module is well below these limits.

The OFFSET module has been tested and characterized using two different sources: cosmic rays and β sources. The use of β sources is very useful because it allows an image to be produced in the worst possible conditions, that is with low linear energy transfer particles, and to bench test the detector without the limitations of an accelerator room. Furthermore the first prototype of the detector has also been tested under proton beam in the CATANA [12] facility at the LNS in Catania but, at the time, the data acquisition system was not definitive so, although the results are very encouraging, they are not conclusive.

The sampling frequency of the present read-out board is 40 MHz and the comparator output has been stretched by the use of a monostable board. This is not the final solution and the monostable board has been mounted as a mezzanine to the front-end board. The best solution is to use a higher-performance read-out board, which reads the comparator output directly. The minimum signal that can be acquired in this way is lower than in the present set-up, as foreseen in the detector design. This means that, with new read-out electronics, the measured efficiency of the detector would be about 90%, taking into account of the dead area of the Sci-Fi multicladding.

In figure 3 an image of the final detector is shown (a) with the cover open cover and (b) with cover closed. The overall size of the detector, including the mechanical structure is 70x100 $cm^2$. In (a) the sensitive 20x20 $cm^2$ area, made of Sci-Fi and the routed clear fibers, which guide the scintillation light to the PSPM, are visible.

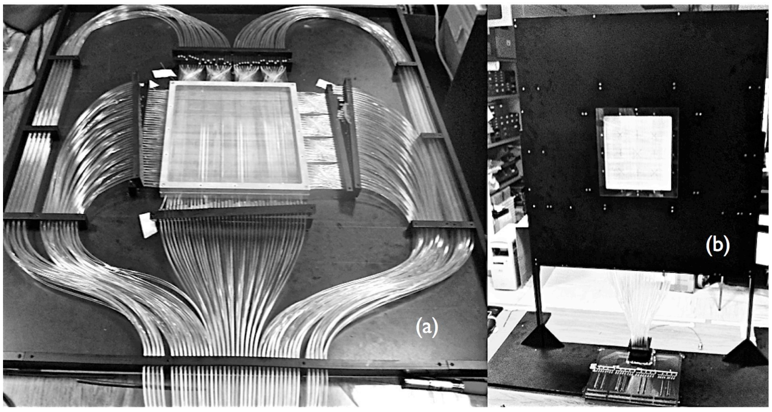


**Figure 3:** (a) A picture of the OFFSET module with open cover, (b) a picture of the complete OFFSET module.

In figure 4 is shown a real time image of a $^{90}Sr$ $\beta$ source realized acquired using OFFSET. In figure 4 (a) there is the 2D image of the beta source, with a diameter of 2 cm. In figure 4 (b) there is a histogram of the same image. The fact that some lines are missing is clearly visible. 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. Furthermore, in the front-end board three electronic channels malfunctioned due to errors in the PCB design and caused the lack of three ribbon of ten Sci-Fi, as clearly visible in figure 4.

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. Notice 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.

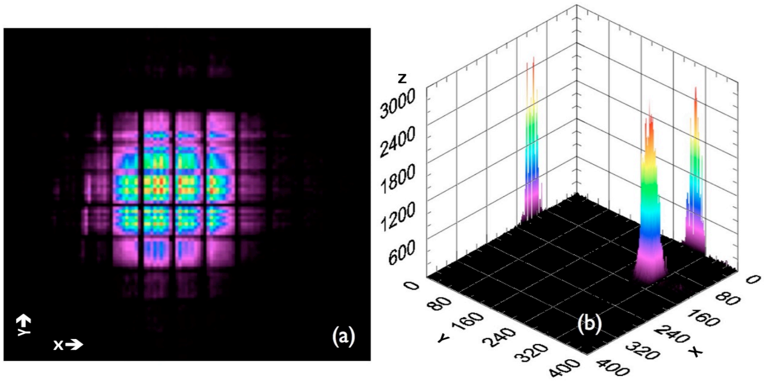


**Figure 4:** Real time image (a) and histogram (b) of $^{90}Sr$ beta source acquired by the OFFSET module. X and Y coordinates are expressed in Sci-Fi unit, 500 μm size, and Z coordinate is the number of events recorded for each specific X and Y coordinate.

In figure 5 the image of the cosmic rays acquired in 47 hours relative to the entire active area of the detector can be seen. Three groups of Sci-Fi, ten Sci-Fi each, are absent in the image. This is due to the failure of the relative front-end channels and can be easily repaired. Some vertical and horizontal lines are missing, as can be clearly seen, for the same reason as given in the case of the test with beta sources.

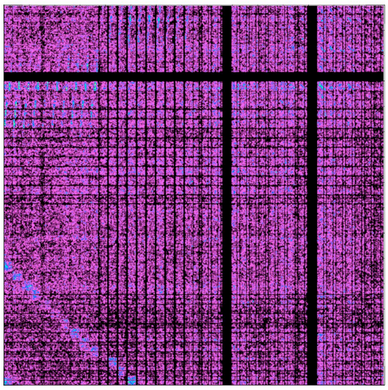

**Figure 5:** Image of cosmic rays acquired by the OFFSET module.

It is possible to use this information to calibrate the detector, taking into account of the different gains of the PSPM channel, the different optical couplings between the Sci-Fi and clear fibers and between the clear fiber and PSPM photo-cathode pixels.

## 6. Conclusions

The first prototype of the OFFSET module has been designed and tested with beta sources and cosmic rays. It demonstrates the great advantages of the read-out channel reduction system applied to a large detector with a high space resolution, employing submillimiter Sci-Fi and the functionality of the architecture. However, a complete characterization will only be possible with a final data acquisition setup. Possible alternative implementations are now being developed in order to reduce the overall size and to improve the imaging performances also in view of an extension of the size of the sensitive area to 40x40 $cm^2$. The use of smaller size, 250 μm Sci-Fi is under study. These fibers have higher dopant concentration and, then, higher light yield, but also lower attenuation length and recent developments of the read-out electronics demonstrated an increased efficiency. Accurate tests under beam of the detectors will be carried out before the end of 2011. Future work foresees the development of a device for the measurement of particle residual range. It will be essentially a hodoscope made by scintillating fiber ribbons, which employing the channel reduction technique is capable of real time measurement of particle residual range with very high space resolution.

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