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# QBeRT: an innovative instrument for Qualification of particle Beam in Real-Time

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Abstract: This paper describes an innovative beam diagnostic and monitoring system composed of a position sensitive detector and a residual range detector, based on scintillating optical fiber and on an innovative read-out strategy and reconstruction algorithm. The position sensitive detector consists of four layers of pre-aligned and juxtaposed scintillating fibres arranged to form two identical overlying and orthogonal planes. The 500 µm square section fibres are optically coupled to two Silicon Photomultiplier arrays using a channel reduction system patented by the Istituto Nazionale di Fisica Nucleare. The residual range detector is a stack of sixty parallel layers of the same fibres used in the position detector, each of which is optically coupled to a channel of Silicon Photomultiplier array by wavelength shifting fibres. The sensitive area of the two detectors is $9 \times 9$ cm$^2$. After being fully characterized at CATANA proton therapy facility, the performance of the prototypes was tested during last year also at TIFPA proton irradiation facility. The unique feature of these detectors is the possibility to work in imaging conditions (e.g. a particle at a time up to $10^6$ particles per second) and in therapy conditions up to $10^9$ particles per second. The combined use of the two detectors, in imaging conditions, as an example of application, allows the particle radiography of an object. In therapy conditions, in particular, the system measures the position, the profiles, the energy and the fluence of the beam.

Keywords: Beam-line instrumentation; Instrumentation for hadron therapy; Particle tracking detectors; Real-time monitoring.

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## Contents



# 1 Introduction

Hadron therapy is a growing field in treatment of tumours, because it is one of the most effective techniques of external radiation therapy which permits to destroy tumour target while leaving the surrounding healthy tissue almost intact. The high precision in hadrons dose deposition requires a real-time precise quality control of the beam parameters (position, profile, fluence, energy) together with the best possible knowledge of patient positioning.

QBeRT is a proton tracking system [1] which consists of a position sensitive detector (PSD) and a residual range detector (RRD) (see figure 1). Such kind of detectors are designed to achieve high resolution imaging, high resolution residual range measurement, large sensitive area and high rate beam compliance. The QBeRT system accomplishes all these tasks and, in addition, requires a low number of read-out channels, reducing the complexity of the electronic data acquisition (DAQ) chain, by means of a read-out channel reduction system patented by Istituto Nazionale di Fisica Nucleare (INFN). Both detectors, PSD and RRD, can be used in imaging conditions, with particle rate up to $10^6$ particles per second, and in therapy conditions (up to $10^9$ particle sec$^{-1}$). In therapy condition, the PSD works as profilometer, measuring the position, the profiles and the fluence of the beam. The combined use of the information coming from the PSD and from the RRD, permits to verify on-line the treatment plan. In imaging condition, the system could be used to realize a particle radiography which permits a real-time monitoring of the patient position in treatment room.

The design of both detectors is based on scintillating optical fibres (SciFi) with 500 µm nominal square section. The scintillation light is sent to Silicon Photomultiplier (SiPM) arrays, directly

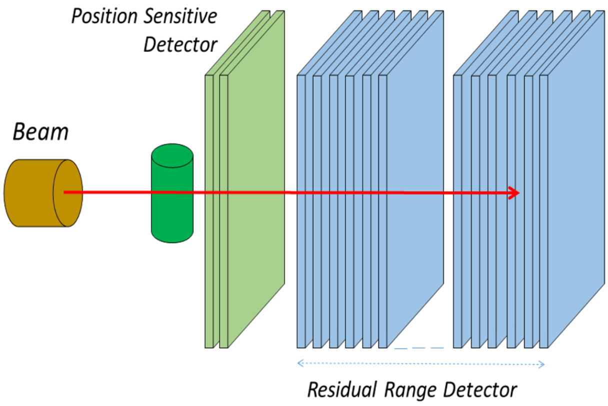



**Figure 1**. The layout of the QBeRT proton tracking system.

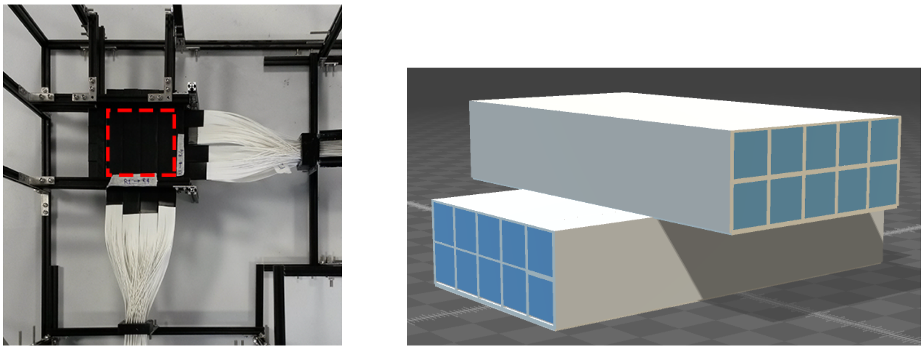
through the SciFi in the PSD or by means of wavelength shifting fibres in the RRD, to be converted into an electric signal. Both detectors use an electronic DAQ chain articulated in two main levels. The first level consists of the front-end boards which acquire the electric signal from the light sensor and operate the analogue-to-digital conversion. The signal from the front-end is sent to a read-out board with a National Instrument System on Module (SoM) for pre-analysis and filtering.

Because of the read-out channel reduction system applied in the PSD, the maximum measurable beam spot size is limited to about 2 cm, but the implemented architecture is thought to be modular and can be optimized for any specific requirement. It is possible to obtain a large area detector (up to $40 \times 40$ cm$^2$) covering a range up to 250 MeV protons with high spatial and range resolution (up to 150 µm and 170 µm, respectively).

## 2 The position sensitive detector

The PSD prototype has a sensitive area of $9 \times 9$ cm$^2$ consisting of two identical overlying and orthogonal planes, called the X and Y planes, each of which consists of two layers of pre-aligned and juxtaposed BCF-12 scintillating optical fibres, manufactured by Saint-Gobain Crystals. The SciFi have 500 µm nominal square section. In detail, each single layer comprises 160 fibres divided in four ribbons. The ribbons are optically isolated from each other by means of 220 µm thick black adhesive tape to eliminate cross-talk between adjacent ribbons and between the superimposed layers of fibres. Each fiber is coated with white extra mural absorber (EMA) [2] to remove the cross-talk between individual fibres. Particles crossing the PSD's sensitive area lose energy and produce scintillation light. A fraction of this light is channelled and travels along the fibre towards the photo-sensor. When a particle deposits enough energy in all four SciFi layers, his impact coordinates can be reconstructed. A front view of the detector is shown in figure 2.

QBeRT has 640 optical channels (four layers of 160 fibres each). The read-out channel reduction system [3] reduces this channel number without any data loss on position information and permits read-out in time coincidence drastically reducing the noise, without increasing the complexity of the system. In the prototype, read-out occurs in time coincidence between the two layers of fibres for each plane. With a classical read-out system 640 channels are used, whereas the



(a) (b)

**Figure 2**. Front view of the QBeRT detector during the assembly phase. The dashed red box highlights the sensitive area of the detector. (b) shows a sketch of the arrangement of the four layers.

channel reduction system can read the signal from the whole detector whit only 112 channels (less than a fifth). Each of the 56 optical channels per plane is optically coupled to one of the 64 channels of a SiPM array. For a detailed description of the read-out channel reduction system see ref. [4].

### 2.1 The PSD DAQ chain

As stated before, the electric signals from the SiPM are sent to an electronic acquisition chain organised in two main levels. The first level consists of the front-end electronics which operate the analog-to-digital conversion. The digital data output from the front-end is sent to the read-out board which hosts a SoM by National Instrument (NI) for decoding and filtering. This device is interfaced via gigabit Ethernet communication to a PC, for visualization and storage of the data in real time.

#### 2.1.1 The PSD front-end electronics

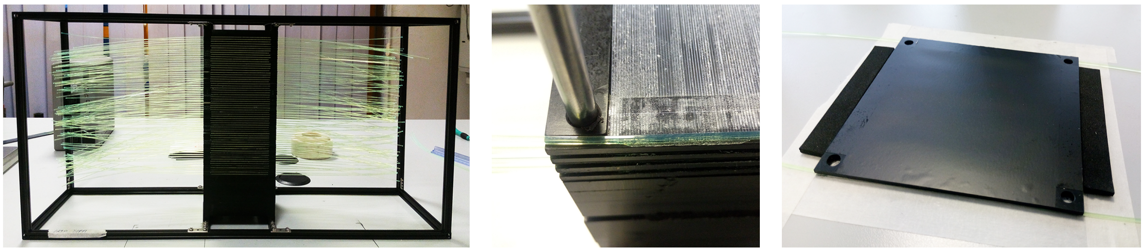
Two front-end boards, one for each X and Y direction, are required to acquire the light signal from the fibres. Each front-end board is equipped with a 64 channels SiPM array manufactured by Hamamatsu Photonics, mod.S13361-3050AE-08, with $3 \times 3$ mm$^2$ effective photosensitive area per channel. These custom designed boards amplify and filter the analog signals from each channel of the SiPM arrays and compare them to an individual threshold, remotely settable by a DAC, by means of an array of fast comparators. The individual threshold is necessary to compensate the non-perfect uniformity of the different SiPMs and optical coupling between SiPM and fibres. Each board provides a digital data bus of 56 bits which represents the status of the SiPM signals.

#### 2.1.2 The PSD Read-out and DAQ electronics

The digital data bus from the fast comparators array is acquired by the NI SoM on the read-out board. The SoM has a FPGA (Field programmable Gate Array) which samples the logic signal at high frequency, up to 250 MHz. This data is transferred to the SoM processor via Direct Memory Access (DMA). The processor applies real-time filtering algorithms and, after discarding the spurious events, reconstructs the impact point of the particles. The SoM's FPGA can be programmed via a graphical approach by means of the LabVIEW platform. The LabVIEW platform also manages the entire acquisition chain and data processing in real-time.

## 3 The residual range detector

The RRD prototype is a stack of 60 layers $9 \times 9\ \mathrm{cm}^2$ wide. Each layer is a ribbon of 180 BCF-12 SciFi with 500 µm nominal square section. A picture of the prototype during the assembly phases is shown in figure 3(a). The fibres, aligned, juxtaposed and oriented horizontally, are optically coupled at both ends of the ribbon to 1 mm square section wavelength shifting fibres (WLS), as shown in figure 3(b). To avoid optical cross-talk between adjacent RRD's layers which would degrade range resolution and therefore energy measurement, each layer is optically isolated from the others by means of 100 µm black adhesive film. This film is applied only on one side of the layer, as seen in figure 3(c). The SciFi used in the RRD are not coated with EMA because cross-talk between adjacent fibres in the same layer does not affect detector resolution.



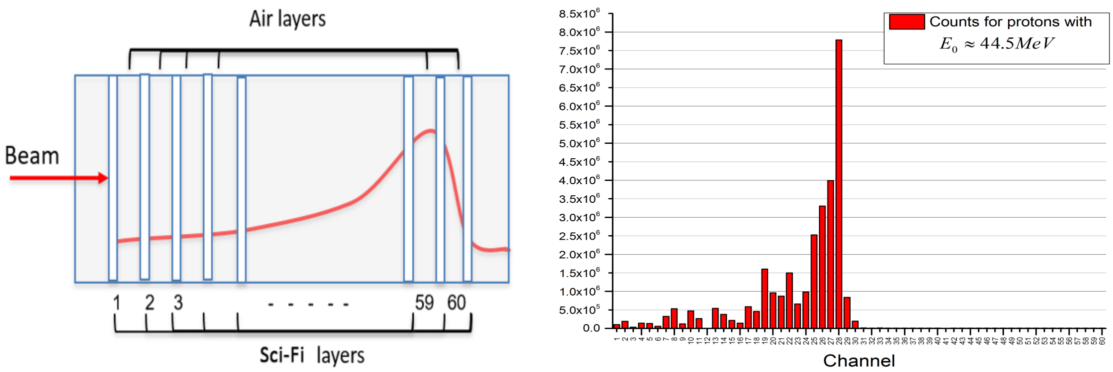
(a) (b) (c)

**Figure 3**. (a) Side view of the RRD prototype during assembly; (b), (c) different views of the RRD layers during assembly.

The scintillation light produced in each layer by the passage of the particle is sent through the WLS to a channel of a SiPM array to be converted into an electric signal. The SiPM array and the DAQ chain are identical to those used in the PSD described in section 2.1.

### 3.1 The RRD operating principle

A charged particle crossing the RRD, passes through a number of layers related to its input energy, before stopping. The dose released in each layer increases with depth up to the Bragg peak, where the particles produce more scintillation light. This point corresponds roughly to the end of the particles' path in the detector, so, observing the layer in which the light signal is the highest, it is possible to detect their range. A schematic drawing of the RRD's operating principle is reported in figure 4, in comparison with an example of light signal's profile acquired with the RRD. A calibration of the detector permits to obtain a range-energy characteristic curve similar to $R_0 = \alpha E_0^p$ by witch it is possible to retrieve the input energy of the particles from the measured range. During the design phase, a series of prototype response simulations were carried out. The maximum measurable range was about 36 mm in polystyrene/PVC and this was enough to stop protons with 67 MeV input energy, but this value can be easily extended up to higher energies by placing a stack of calibrated water-equivalent range shifters between the beam exit and the RRD entry window.




(a) (b)

**Figure 4**. (a) Schematic drawing of a particle crossing the RRD. The red curve corresponds to the dose released in the detector; (b) example of signal acquired with the RRD for protons with 44.5 MeV input energy.

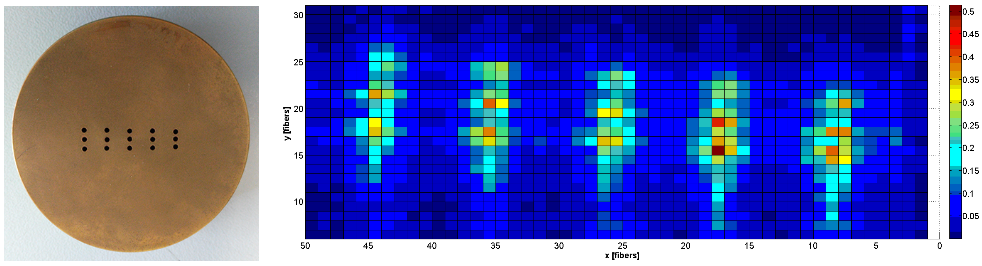
## 4 Experimental results

Measurements at CATANA (Centro di AdroTerapia e Applicazioni Nucleari Avanzate, Laboratori Nazionali del Sud, INFN, Catania, Italy) were carried out to fully characterize the performance of the prototypes, with protons up to 58 MeV at the output in treatment room. During last year, other measurements have taken place at TIFPA (Trento Institute for Fundamental Physics ad Applications, Italy) proton irradiation facility.

### 4.1 Characterization of the detectors

In order to measure the spatial resolution of the PSD, a calibrated brass collimator with 1 mm diameter holes whose spacing increased from 1.5 to 1.9 mm along a direction (figure 5(a)) was applied at the beam pipe exit in the treatment room at CATANA. An image of this collimator was acquired by the PSD working in imaging conditions, with a particle rate up to $10^6$ particles per second. The result of this acquisition is shown in figure 5(b). From data analysis, it is possible to estimate the holes centres and compare them with the projection of the collimator holes on the detector plane, as reported in figure 6. Then, the mean distances between the reconstructed centers and the collimator hole centres were calculated for each hole and the mean distance was about 130 µm, comparable with the (a priori) spatial resolution of the PSD, given by $500\,\mu\text{m}/\sqrt{12}$. The spatial resolution is an intrinsic characteristic of the detector, independent of the operation mode.

To perform a calibration of the RRD, we acquired several measures of the range varying the input energy of the particles. At CATANA facility, the proton beam energy can be passively modulated by placing a different calibrated range shifter prior to pipe. The energy of the particles at the beam pipe exit was calculated by means of Monte Carlo simulation. The Bragg peak position is not exactly at the real end of the particles' path but just prior. In this kind of application, it is an experimentally consolidated practice to assume that the particle range measurement is where the intensity of the Bragg peak signal is at 10% of its maximum value. This point coincides with the layer on the right of the Bragg peak (or the next layer compared to the incident beam direction). The results of this measurement are reported in figure 7 in comparison with the values of the range




(a) (b)

**Figure 5**. Image of a calibrated brass collimator with 1 mm diameter holes, whose spacing increased from 1.5 to 1.9 mm per direction.

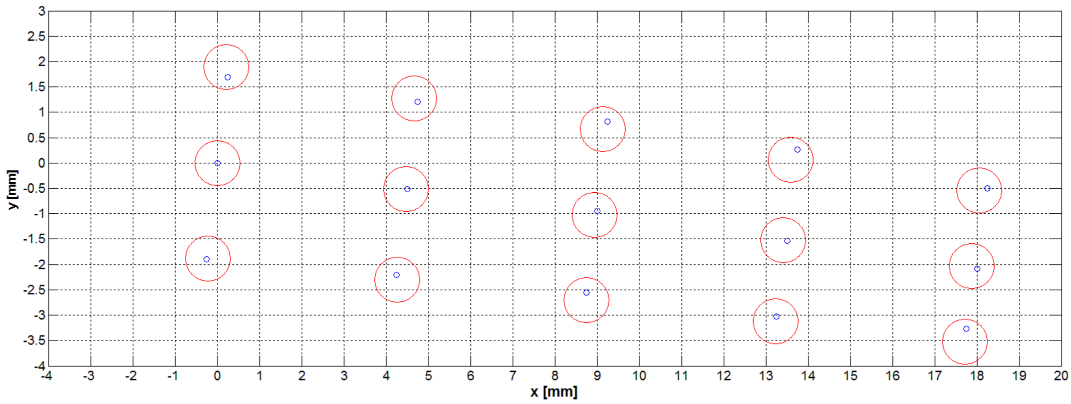



**Figure 6**. The red circles indicate the collimator hole projection on the tracker surface; the blue circles correspond to the hole centres reconstructed from the acquired image.

obtained from a Monte Carlo simulation of the response of the detector. Both data sets were fitted with the power law:

$$R = a + b\,E^{1.75}, \tag{4.1}$$

where $R$ is the range of the protons in the RRD, $E$ is the kinetic energy at the entrance of the RRD, $a$ and $b$ are free parameters of fit.

### 4.2 Beam profile measurement

In therapy conditions, up to $10^9$ particles per second, the PSD works as a profilometer measuring the size and the position of the beam spot. Because of the read-out channel reduction system, the beam profile can be reconstructed only when the beam spot size is lower or equal to the width of a ribbon (about 2 cm). A measure of the beam profile was performed at TIFPA. Here, the beam optics produces a reduction of the beam spot size with increasing energy of the particles. Therefore, the PSD works properly at high energies, as is possible to see in figure 8: (a) a beam with 202 MeV shows a FWHM smaller than 2 cm and by means of a calibration with a Gaussian fit it is possible to reconstruct the beam profile; (b) at lower energies, when the beam size exceeds the PSD specification, the profile and the position of the beam can't be reconstructed as well as before.

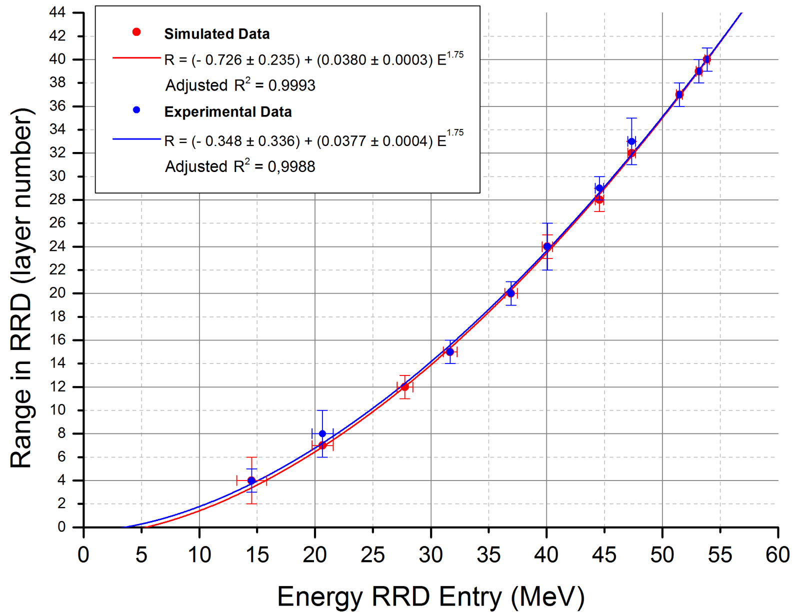



**Figure 7**. Comparison between the experiment and simulation data of the residual range with their respective fit.

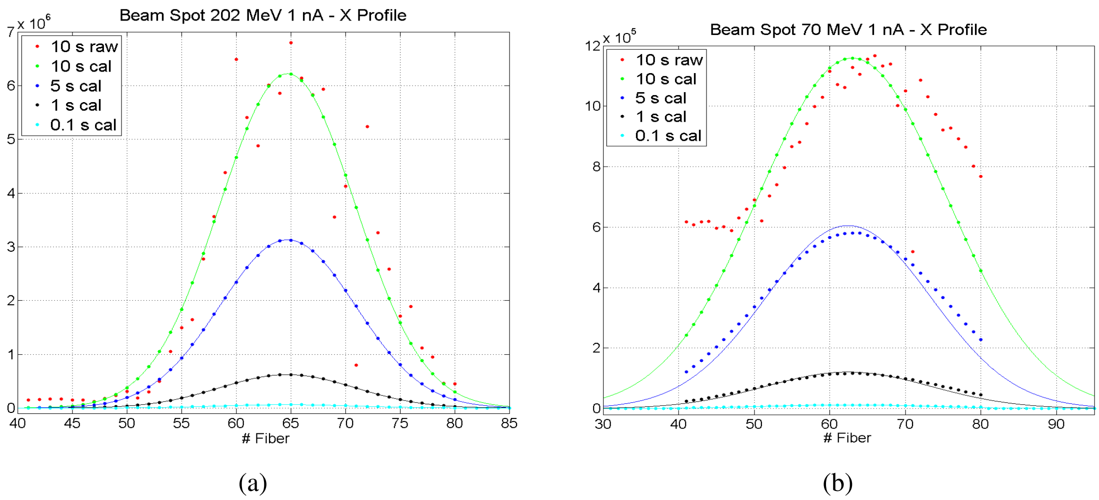



**Figure 8**. Examples of profiles at 202 MeV and 70 MeV before and after calibration by means of Gaussian fit of raw data.

The variation of the beam spot size as a function of the energy at TIFPA is shown in figure 9. Here the measured beam spot size as the sigma of the Gaussian fit is reported as a function of the energy. It is clearly visible that for energies higher than about 160 MeV the values measured by the PSD are very close to those measured with Lynx dosimeter by IBA-Dosimetry, Schwarzenbruck, Germany. In this energy range, the beam spot is contained into a ribbon and the PSD can reconstruct correctly the beam profile. Because the position of the beam spot is obtained as the centroid of a Gaussian fit, also this measure can be carried out properly in the same energy range.

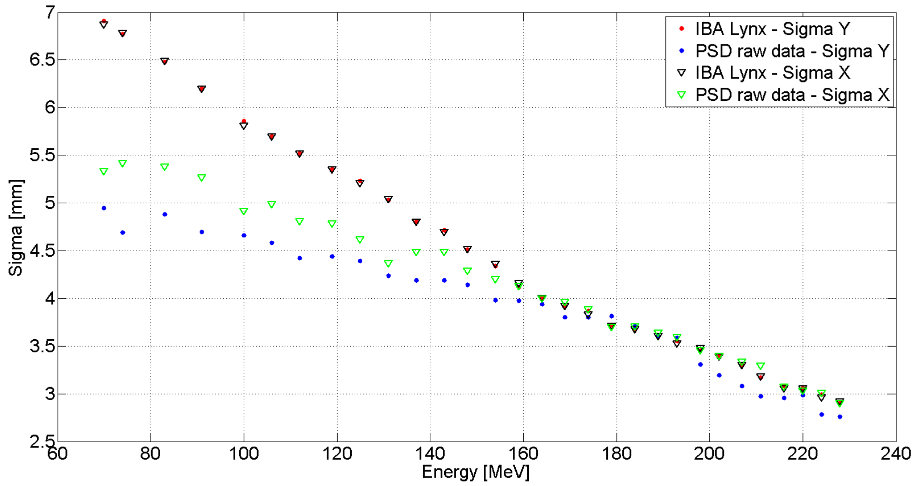



**Figure 9**. Comparison of measured beam spot size with the PSD and with Lynx by IBA as the sigma of the Gaussian fit of the beam profile.

### 4.3 Fluence measurement

The PSD performs a fluence measurement by counting each particle that crosses the sensitive area of the detector up to a rate of $10^8$ particles per fiber. A typical pencil beam spot covers at least ten fibres, so in principle, the maximum measurable fluence is about $10^9$ particles per second. Figure 10 shows a preliminary comparison between the sum of the total counts per second for each fiber covered by the beam spot and the integral of particles per second on the spot as measured by an ionization chamber (miniQ-Strip, Ionization Chamber for Quality Assurance by DeTecTor, Devices and Technologies Torino). As can be seen from the zoomed panel, when particles' rate exceeds $10^7$ particles per second the PSD undergoes saturation effect. This saturation effect is due to AC coupling of the SiPM signals which produces a baseline shifting depending on the signal amplitude and frequency for each channel. The integral measure of the fluence is shared among different fibres, so the frequency of the signal for each channel depends on the size of the spot. At the same time, at high energies, the particles transfer less energy in the fibres lowering the signal amplitude. The resulting effect is a compression of the measured fluence. A simple solution could be reading the ribbons at one end by coupling them with WLS fibres. The efficiency of the optical coupling between scintillating fibres and WLS reduces the signal amplitude and frequency by a factor that can be restored by a calibration of the detector. This solution will be tested during the next test at TIFPA that is planned for next months.

## 5 Conclusions

This paper describes the current status of the development of an innovative system for Qualification of particle Beam in Realt-Time (QBeRT). It is composed of a position sensitive detector and a residual range detector based on scintillating optical fibres and on an innovative read-out strategy and reconstruction algorithm. The performance of the prototypes was fully characterized at CATANA

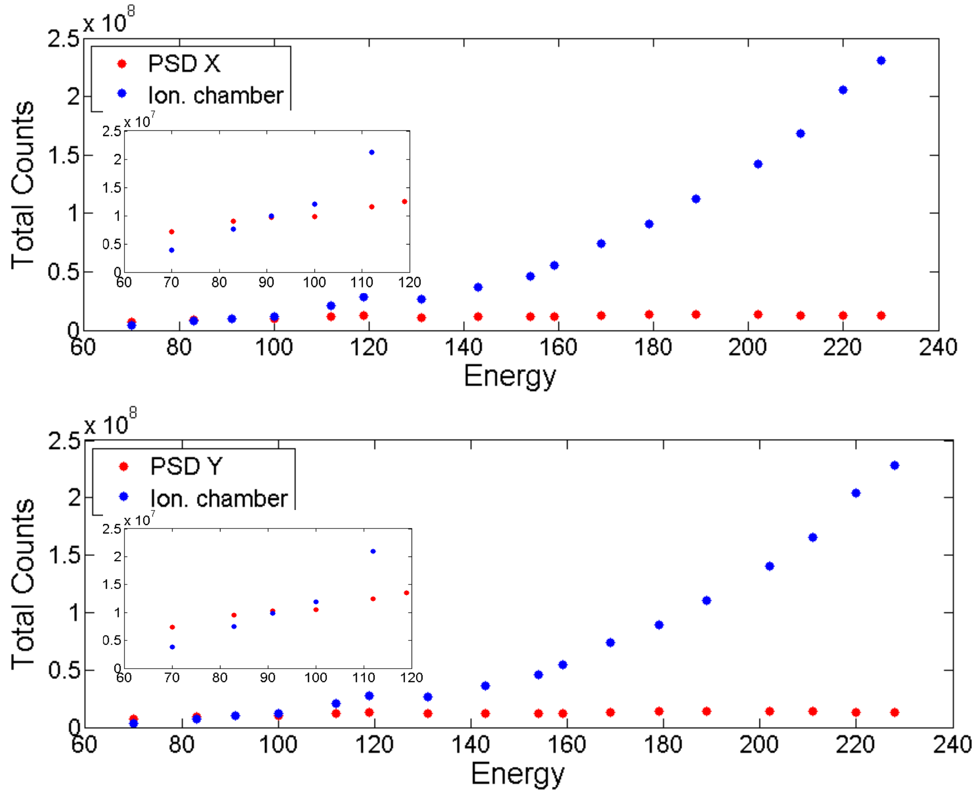



**Figure 10**. Red dot: fluence measured with the PSD; blue dot: fluence measured with an ionization chamber. The top panel refers to X direction and the bottom panel to Y direction.

proton therapy facility (November 2015) with protons up to 58 MeV, and a measurement campaign has taken place at TIFPA proton irradiation facility (June 2016), with protons up to 228 MeV. The beam tests have demonstrated that the system is ready to be used in treatment room both in imaging condition (particle rate up to $10^6$ particles/sec) and in therapy condition for beam profile measurement. A solution for fluence measurement with a particle rate up to $10^9$ particles per second is under study and will be experimentally verified as soon as possible.

## References

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