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Energy measurement of clinical proton beams with a telescope of Ultra-Fast Silicon Detectors

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Summary. — Within the MoveIT-project of the National Institute for Nuclear Physics (INFN), the University of Torino (UNITO) and INFN-Torino are developing a detector made of a telescope of two Ultra-Fast Silicon Detectors (UFSD) aligned along the beam direction to determine the energy of clinical proton beams from the measurement of the time-of-flight of single protons. Following the promising results obtained at the Centro Nazionale di Adroterapia Oncologica (CNAO, Pavia, Italy) with single pads, a second beam test was conducted at the Trento Proton Therapy Center (Italy) with dedicated UFSD sensors segmented in strips. The results obtained at Trento facility show that for 97 cm distance between sensors and for all the energies tested (chosen in the 62–227 MeV clinical range), the root mean square deviation between the measured beam energies with respect to the nominal ones corresponds to a range uncertainty < 1 mm in water, as clinically required.

1. – Introduction

Nowadays, the accuracy of the extracted beam energy in proton therapy treatments is guaranteed by safe checks of the accelerator settings and routine quality assurance

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measurements, but none of the current technologies allows to measure the energy of the beam during treatment [1]. The telescope system proposed by the University of Torino and INFN-Torino [2] exploits the high time resolution of the Ultra-Fast Silicon Detectors (UFSD) technology to measure the energy of clinical proton beams in a few seconds of irradiation, using Time of Flight (ToF) techniques. The energy is assessed using a telescope of two UFSDs sensors aligned with the beam at a fixed distance (fig. 1(a)). This work describes the results of the test performed at the Trento Proton Therapy Center cyclotron of the detector prototype, which was previously tested on the proton beam of the CNAO synchrotron [2].

2. – Methods

2˙1. *UFSD technology*. – The UFSDs are n-in-p silicon sensors with an internal moderate gain layer produced by implanting a highly doped p^+ under the n^{++} electrode [3]. The main benefit of UFSDs is to provide an enhanced signal with a fast rise time in thin detectors keeping the noise level at the same order of magnitude as the traditional silicon sensors with the same geometry. This advantage makes UFSDs a good choice for ToF measurement because of the time resolution of approximately 30 ps in 50 μm, signal duration of 1–2 ns, and good S/N separation [4]. Dedicated sensors for ToF measurements were manufactured by Fondazione Bruno Kessler (FBK, Trento, Italy, fig. 1(b)). They are segmented into 11 strips (10 with gain, 1 without gain), each one characterized by a sensitive area of 2.2 mm^2 (4 mm $\times$ 0.55 mm) and an interstrip pitch of 0.591 mm.

2˙2. *Experimental setup*. – The Trento proton beam is provided by a cyclotron which accelerates the beam to an energy of 228 MeV. Shortly after the cyclotron exit, a rotating degrader of different thicknesses and materials performs a coarse energy selection to reduce the beam energy reaching a minimum value of 70 MeV. The beam intensities at the extraction are ranging between 1 and 320 nA, modulated by a 50 percent duty-cycle square wave, with a 100 ms period [5]. In the beam test, two sensors were glued on high-voltage (HV) distribution boards aligned to the beam and positioned at three

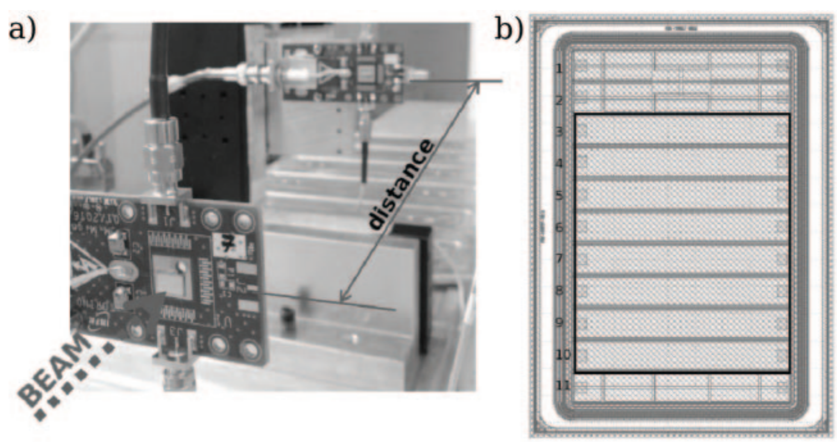

Fig. 1. – (a) Telescope of two UFSD strip sensors mounted on 2 channels high-voltage (HV) distribution boards fixed in the mechanical support; the distance between the two sensors in the telescope configuration has been changed (27, 67, and 97 cm). (b) Technical drawing of a UFSD segmented in 11 strips.

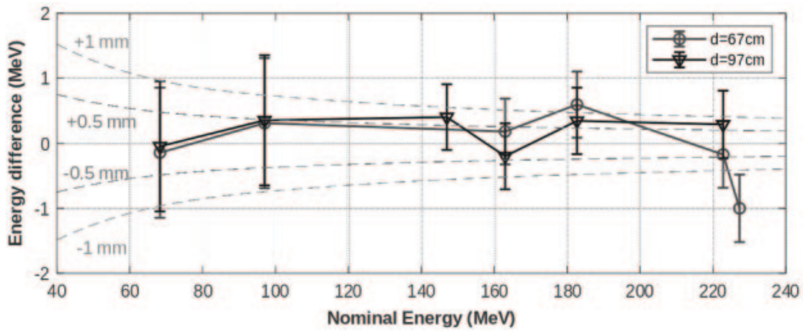

Fig. 2. – Deviations between the measured and nominal energy for different nominal energies at 2 distances between the sensors (67 cm (circles) and 97 cm (triangles)). The dashed lines represent the corresponding uncertainties in water range.

distances (27, 67, 97 cm $\pm$ 0.1 cm). Only 1 strip per sensor was readout. For each of these distances, the ToF were measured at 5−7 different beam energies between 68.3 to 227.3 MeV. These energies, retrieved from the PSTAR dataset(1) according to the water equivalent depths at the isocenter provided by the facility with 0.1 mm uncertainty [5], are considered as nominal energies. The detectors signals were amplified by a low-noise CIVIDEC (2) 40 dB current amplifier, and acquired through the high rate digitizer CAEN DT5742 (3) (5 GS/s, 12 bits resolution, 1 ADC = 0.2 mV, acquisition windows of 1024 samples, *i.e.*, 204.5 ns). A PC connected to the digitizer with 80 MB/s optical link was used to control the acquisition, collect the waveforms, and produce an asynchronous software trigger when the previous events were stored in memory.

2˙3. *Energy calculation procedure*. – The methodology is described in details in [2], and here briefly summarized. Figure 1(a) shows the experimental setup used in the beam test. The time of arrival of protons on each sensor is determined using the constant fraction discriminator algorithm (CFD), and the estimated Δt_{mean} is obtained as the average of the differences of the times of arrival of the same protons passing through the two sensors. Because of the systematic errors of the experimental setup (mainly due to the uncertainty on the distance between the sensors and the time offset given by the electronic chain), a proper calibration procedure is required. A Chi-square minimization procedure was used to calibrate the system [2], in terms of time offset and the distance between the sensors (free parameters), starting from *a priori* knowledge of several values of beam energies and taking into account the energy loss in the first sensor and in air.

3. – Results and discussion

The achieved difference between the energy measured with the ToF technique after calibration and the nominal energy is shown in fig. 2, where the large error bars are due to the precision of the water equivalent depth at the isocenter provided by the facility [5]. For the largest distance used (d = 97 cm) and for all considered beam energies in the

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(1) `http://physics.nist.gov/PhysRefData/Star/Text/PSTAR.html`.
(2) `https://cividec.at`.
(3) `https://www.caen.it/products/dt5742/`.

range from 68.3 to 227.3 MeV, a root mean square deviation of 341 keV and a maximum deviation of 402 keV (corresponding to an energy difference within the range uncertainty clinically acceptable of 1 mm) were obtained. For 67 cm, an uncertainty larger than 1 mm was found at the two highest energies, as previously obtained at CNAO [2]. These results are well in accordance with the expectations, since for a flight distance of 1 m between the sensors, the maximum error allowed on the ToF to obtain an energy error corresponding to 1 mm in water ranges from 80 ps at 60 MeV to 4 ps at 230 MeV, and these limits are more stringent for reduced distances [2]. The beam test was performed reading out only 1 strip per sensor. Moreover, data acquisition and performance were not optimized. Due to the unavoidable digitizer conversion time of 110 μs and the additional dead time due to data transfer and saving ($\sim$500 μs), only a small fraction (< 1 per mill) of the delivered particles were used for the analysis. Beam irradiation of less than 6 s (at therapeutic fluxes, $\sim$228 MeV proton beam energy, and at $\sim$1 m distance between sensors) was enough to collect a significant number of coincidences to keep the error on the ToF below the values needed to obtain the clinically required range uncertainty. Although further implementation (mainly focused on optimizing the acquisition chain) are still needed before application during patient tretments, in particular the use of a larger sensitive area will increase the statistics (8 strips, from strip 3–10 (fig. 1(b))) and will promote a rapid translation of the technology into a commercial device, useful for beam commissioning and quality control measurements.

4. – Conclusion

Using a detector prototype made of a telescope of two UFSD sensors to measure the beam energy of a therapeutic proton beam with ToF technique, a few hundred of keV of deviation from nominal energies were achieved for all energies for 97 cm distance between the sensors, corresponding to <1 mm range, as clinically required. The promising results obtained were independent of the beam delivery time structure (*i.e.*, synchrotron or cyclotron accelerator), demonstrating that UFSD could represent a viable option for new beam energy monitors, potentially able to measure online the beam energy during irradiation. A new experimental setup based on the readout of 8 strips together with a new movement stage to increase the positioning precision is almost ready for tests in the clinical environment.

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