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## Monitoring therapeutic proton beams with LGAD silicon detectors

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# 1 Monitoring therapeutic proton beams with LGAD 2 silicon detectors

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15 **ABSTRACT:** The University and the National Institute for Nuclear Physics of Torino are  
16 developing LGAD-based prototypes for beam monitoring in proton therapy. The direct  
17 measurement of single beam particles could overcome some features of currently used ionization  
18 chambers, such as slow charge collection and reduced sensitivity, which limit the implementation  
19 of advanced delivery techniques (e.g. rescanning). LGAD strip sensors have been designed and  
20 produced by Bruno Kessler Foundation (FBK, Trento) specifically for this project. A counter  
21 prototype to directly count individual protons at clinical fluence rates ( $10^6$ - $10^{10}$  protons/cm<sup>2</sup>·s)  
22 and a telescope system to measure the beam energy with time-of-flight (TOF) techniques are  
23 described. Tests of LGAD silicon strip sensors performed on synchrotron and cyclotron beams of  
24 therapeutic centers, using a pin-hole ionization chamber for the independent measurement of the  
25 particle flux, already showed the possibility to keep the counting error < 1 % up to a beam fluence  
26 rate of few  $10^8$  protons/cm<sup>2</sup>·s. The ongoing tests of counting sensors readout by a dedicated fast  
27 Charge Sensitive Amplifier chip are reported. The telescope system, made of two sensors at a  
28 distance up to 95 cm, allows measuring the beam energy in the clinical range (70-230 MeV) with  
29 a maximum deviation of 310 keV in respect to the nominal one, with an uncertainty of 500 keV,  
30 thus achieving the prescribed clinical accuracy of 1 mm in the range in water.

31 **KEYWORDS:** particle therapy, beam monitors, silicon detector

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## 45 1. Intro

46 Within the MoVeIT project, the University and the National Institute for Nuclear Physics of  
47 Torino are proposing the direct measurement of particles using LGAD-based innovative detectors  
48 for monitoring clinical proton beams [1,2]. This approach has the potential to overcome the limits  
49 of current beam monitors, such as slow charge collection times, thus supporting the future  
50 implementation of advanced and fast delivery techniques (e.g. fast rescanning modalities) in  
51 particle therapy. This contribution reports about the status of the project.

## 52 2. Materials and Methods

### 53 2.1 Thin LGAD silicon sensors

54 Ultra Fast Silicon Detectors (UFSD) are based on Low Gain Avalanche Detectors (LGAD)  
55 design, characterized by small thicknesses (typically  $\sim 50 \mu\text{m}$ ) and controlled low gain ( $\sim 10-30$ ),  
56 providing an enhanced signal in thin detectors with the same noise level of traditional silicon  
57 sensors of similar geometry, with very short time duration (ns), allowing particle counting, and  
58 excellent time resolution (ps), allowing beam energy measurement through TOF techniques [3].  
59 Thin planar UFSD prototypes were specifically designed and produced for the MoVeIT project  
60 by Bruno Kessler Foundation (FBK, Trento, Italy). Strip segmentation has been chosen for all  
61 structures (reported in Table 1) in order to reduce the expected particle rate per channel and the

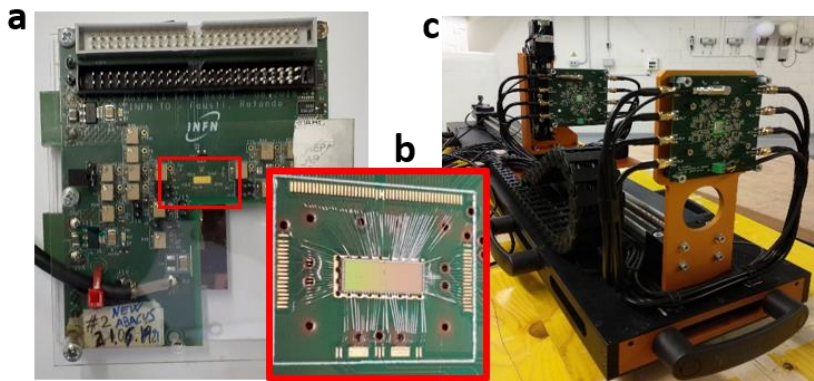
**Table 1.** Characteristics of the MoVeIT sensors for counting and timing purposes.

	Number of strips	Strip length	Strip area	Active thickness
Counting sensor (short)	20	1.5 cm	2.2 mm <sup>2</sup>	60 $\mu\text{m}$
Counting sensor (long)	30	3.0 cm	2.4 mm <sup>2</sup>	60 $\mu\text{m}$
Counting sensor (final)	144	2.6 cm	3.0 mm <sup>2</sup>	50 $\mu\text{m}$
Timing sensor	11	4.0 mm	2.2 mm <sup>2</sup>	55 $\mu\text{m}$

62 sensor capacitance. The final counting sensor, whose sensitive area ( $\sim 2.7 \times 2.7 \text{ cm}^2$ ) was defined  
63 to cover the clinical proton beam cross section characterized by a FWHM of  $\sim 1 \text{ cm}$  at the  
64 isocentre, is described in more details in the contribution of [4].

## 65 2.2 Counting

66 A dedicated fast Charge Sensitive Amplifier chip (ABACUS [5], Fig. 1a and 1b) with an  
67 area of  $2 \times 5 \text{ mm}^2$  and 24 channels has been designed to discriminate the expected signal pulses in  
68 a wide charge range (3-150 fC, corresponding to the energy released in silicon by clinical protons  
69 of 60-230 MeV) with a maximum dead-time of 10 ns to minimize pile-up counting inefficiencies  
70 at clinical fluence rates ( $10^6$ - $10^{10}$  protons/ $\text{cm}^2 \cdot \text{s}$ ).



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**Figure 1. a.** Test-board mounting a counting long strip readout by an Abacus chip, zoomed in **b.**  
**c.** Telescope system prototype for TOF measurements.

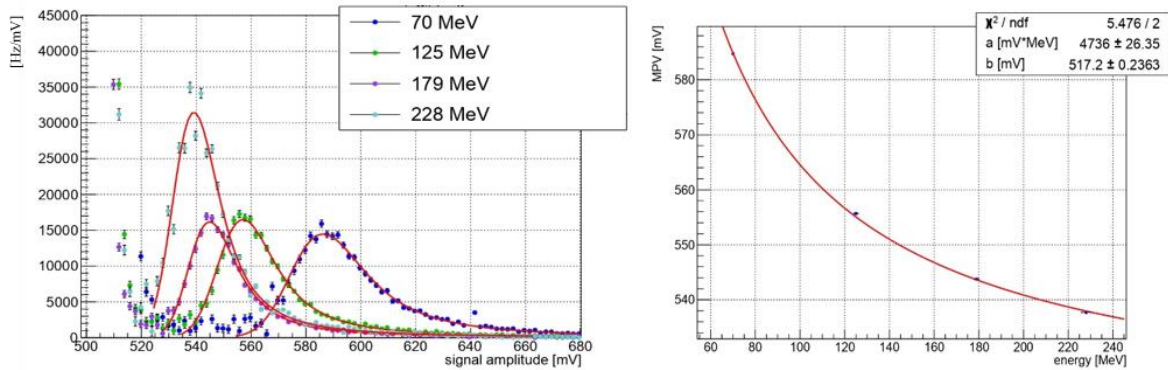
72 The outputs of the chip are sent to an FPGA for the pulse counting, and the FPGA is  
73 connected to a computer where a dedicated LabVIEW program controls and integrates the FPGA  
74 input-outputs, displays online the counting rate from each strip and stores the useful data. The  
75 same FPGA is also used to initialize the chip by setting the local DACs of the chip channels.

## 76 2.3 Timing

77 Timing sensors (Table 1), thinned down to a total thickness of  $70 \mu\text{m}$  to minimize the beam  
78 perturbation, are readout by dedicated boards with two stages of amplification optimized for time  
79 measurements with large signals (3-150 fC charge dynamic range) at high fluxes ( $10^9 \text{ p/cm}^2 \cdot \text{s}$ ).  
80 Signals generated by incoming protons are first amplified by the front-end electronics and then  
81 readout by a 16+1 channels digitizer (5 GS/s, 12 bits resolution) controlled by a PC with an 80  
82 MB/s optical link. A prototype of telescope made of two timing sensors aligned along the beam  
83 direction has been built (Fig. 1c). The first sensor is kept fixed at the isocenter of the beam  
84 distribution system, whereas the second sensor can be moved in the transversal plane (x-y) for the  
85 alignment of the telescope with the beam trajectory, and along the longitudinal direction (z axis)  
86 to vary the distance between the two sensors from 300 mm to 950 mm. An optical encoder ( $0.01 \mu\text{m}$   
87 resolution) provides the measurement of the position displacements of the second sensor.  
88 Starting from the measured time differences of coincident protons crossing the two detectors for  
89 different beam energies and distances between the sensors, the mean kinetic energy of the beam  
90 can be determined and finally the range in water, which is the clinically relevant parameter [6]. A  
91 self-calibration method, where only the measured mean time differences and the relative  
92 displacements are used as input parameters, has been implemented to remove the systematic

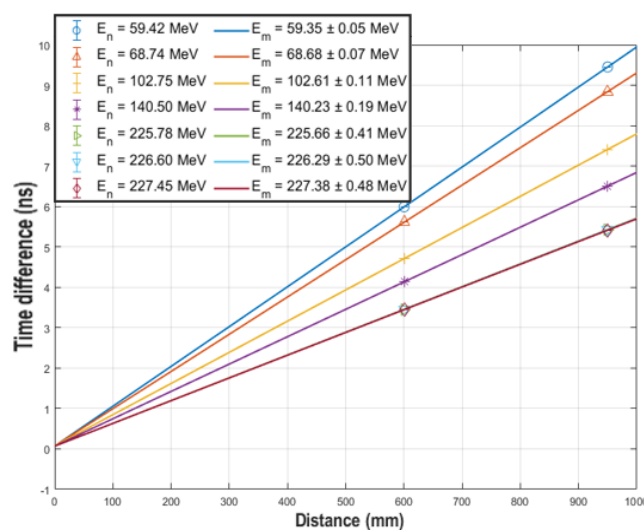
93 errors due to the experimental setup, independently from any a priori knowledge of the beam  
 94 parameters (the method is object of the Italian Patent Application No. 102021000025190).

95 **3. Results**



**Figure 2.** *Left.* Signal amplitude distribution obtained from 1 chip channel fitted with convolution of Landau and Gaussian (red curves) for 4 beam energies. *Right.* Most Probable Values (MPV) vs energies.

96  
 97 Tests of LGAD silicon sensors performed on synchrotron and cyclotron beams of therapeutic  
 98 centers, using a pin-hole ionization chamber for the independent measurement of the particle flux,  
 99 showed the possibility to keep the counting error  $< 1\%$  up to a beam fluence rates of few  $10^8$   
 100  $\text{p}/\text{cm}^2 \cdot \text{s}$  [2]. Algorithms based on logical combinations of signals from two independent detector  
 101 channels under the same radiation field are being developed for count-loss correction at fluence  
 102 rates up to  $10^{10} \text{p}/\text{cm}^2 \cdot \text{s}$  [7]. To characterize the counting prototype (sensor + asic), threshold scans  
 103 (rate as a function of the threshold voltage set in the leading-edge discriminator of each channel)  
 104 have been acquired with different proton beam energies (70-228 MeV) at the Trento Proton  
 105 Therapy Center. The signal amplitude distribution of one channel, obtained through the discrete  
 106 derivative of the threshold scan, is shown in Fig. 2. The Most Probable Values, obtained by fitting  
 107 the amplitude distributions with the convolution of a Landau and a Gaussian, vs the beam energy



**Figure 3.** Time difference vs distance for two distances (600 and 950 mm) between the sensors of the telescope and 7 beam energies. The legend shows the nominal energy ( $E_N$ , retrieved from the Bragg peak positions measured by CNAO using a Peakfinder water column with a maximum deviation within  $\pm 0.15$  mm) and the measured energy ( $E_M$ ).

108 reproduce the mean energy loss per unit path length described by the Bethe Bloch formula, as  
109 expected (Fig. 2).

110 For TOF measurements, the self-calibration method allowed defining the time offsets  
111 between different combinations of strips in sensor 1 and sensor 2. These time-offsets were used  
112 to correct the time-of-arrival differences of protons crossing sensor 1 and sensor 2 of the  
113 telescope, for different beam energies and 2 distances between the sensors (Fig. 3) at CNAO  
114 (Pavia). A maximum deviation of 310 keV between nominal and measured energies, obtained  
115 from the linear interpolation of time differences vs distance, have been observed with a  
116 uncertainty of 0.5 MeV on the measured energy, thus achieving the prescribed clinical accuracy  
117 of 1 mm in the range in water (Fig. 3).

#### 118 **4. Conclusion**

119 This contribution reports about the status of the development of two prototypes, based on  
120 the UFSD technology, for online monitoring of clinical proton beams: the first one to directly  
121 count individual protons and the second to measure the beam energy with time-of-flight (TOF)  
122 techniques. The final counting prototype, featuring a  $2.7 \times 2.7$  cm<sup>2</sup> sensor with 144 strips and its  
123 custom readout will be tested in the next months, while the promising results of the telescope  
124 system suggests its future use in beam quality control procedures.

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