Dosimetric characterization with 62 MeV protons of a silicon segmented detector for 2D dose verifications in radiotherapy

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Abstract

Due to the features of the modern radiotherapy techniques, namely Intensity Modulated Radiation Therapy and proton-therapy, where high spatial dose gradient are often present, detectors to be employed for 2D dose verifications have to satisfy very narrow requirements. In particular they have to show high spatial resolution. In the framework of the European Integrated project MAESTRO (Methods and Advanced Equipment for Simulation and Treatment in Radio-Oncology, no. LSHC-CT-2004-503564), a dosimetric detector adequate for 2D pre-treatment dose verifications was developed. It is a modular detector, based on a monolithic silicon segmented sensor, with a n-type implantation on an epitaxial p-type layer. Each pixel element is 2×2 mm^2 and the distance center-to-center is 3 mm. The sensor is composed of 21×21 pixels. In this paper we report the dosimetric characterization of the system with a proton beam. The sensor was irradiated with 62 MeV protons for clinical treatments at INFN-LNS Catania. The studied parameters were repeatability of a same pixel, response linearity versus absorbed dose and dose rate and dependence on field size. The obtained results are promising since the performances are within the project specifications.

1. Introduction

The use of hadrons and in particular of protons in radiotherapy represents one of the major novelties in treating cancer. When crossing the matter, protons deposit most of their energy at the end of the range. As a

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result of proton dose-distribution characteristics, the radiation oncologist can increase the dose to the tumor while reducing the dose to surrounding normal tissues, which has the potential for fewer harmful side effects, and increased tumor control.

The specific features of highly conformal radiotherapy with proton beams require performing different dosimetry measurements, for which several detectors can be proposed. They can be point dosimeters, 2D or 3D dosimeters.

In the European Integrated project MAESTRO novel technologies in patient alignment, organ tracking, dose calculation and dose measurement are being developed. The aim of Maestro is to develop and validate in clinical conditions the advanced equipment needed in using new techniques. The development of clinical protocols is very important to evaluate the emerging results and to ensure that the new technologies will be clinically relevant and industrially viable. MAESTRO project is also involved in the assessment of requirements that detectors have to meet and in the determination of the protocols and procedures that should be followed for their clinical validation.

In the framework of this project a 2D silicon detector adequate for pre-treatment dose verifications was developed. In this work some parameters suitable for its dosimetric characterization have been measured, following the methodology and the procedures suggested by the project.

2. Materials and methods

A. The detector

A modular system based on a monolithic silicon segmented sensor for 2D pre-treatment dose verifications was designed. A detail description of the system is reported in Ref.s [1,2]. The main feature of the proposed device is the spatial resolution, which is the highest compared to all the commercially available 2D devices. A prototype has been assembled with a readout electronics made with discrete components [2]. The dosimetric characterization of the device with X ray beams has been reported in Ref. [3], while the dosimetric characterization with proton beams is described in this paper.

B. Protocol and Procedures

For clinical proton beams, the need for accurate dose distribution data, such as depth dose distributions and lateral dose profiles, is as great as for other radiation qualities used in radiation therapy.

Absolute and relative proton dosimetry are performed as recommended in protocols [4]. For absolute dosimetry, protocols suggest measurements with a cylindrical or plane parallel ion chamber and Laboratori Nazionali del Sud (LNS) INFN centre at Catania makes use of an Exradin T1 cylindrical ion chamber or of the PTW parallel plate Markus chamber [5-6].

In order to reach a level of accuracy on the measured dose which can be considered as acceptable for proton treatments, the 2D detector must satisfy a number of requirements. In this work measurements have been carried out in order to assess some of the dosimetric parameters, following the MAESTRO procedures. In particular, we have studied: the repeatability of the output of each pixel; the linearity of the response vs. absorbed dose; the output factors and the depth-dose distribution. The MAESTRO indications are the following: dose rate dependence <1%; response repeatability (i.e. short term precision) <0.5%; maximum deviation from linearity <1% in the dose range from 0.1 to 2000 cGy.

C. The experimental setup

Figure 1: CATANA proton beam line

The detector was irradiated with 62 MeV proton therapeutic beam line of the CATANA [6-7] equipment at the LNS. Collimators were used in front of the detector to focus the beam. Repeatability, linearity, and depth dose measurements were performed using the collimator of 25mm diameter, while for output factor measurements collimators with diameter ranging from 25mm to 8mm were used. Figure 1 shows the CATANA beam line while figure 2 shows the experimental set up used during the beam test.

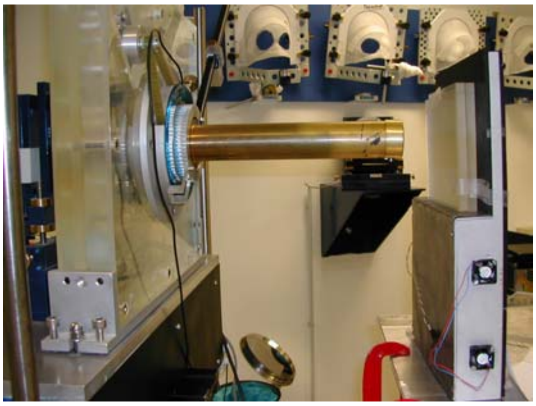

Figure 2: Proton experimental setup. During the beam test the 441 channels silicon module was set in vertical position. Some slabs of PMMA were placed between the sensor box (on the right) and the beam collimator (on the left).

3. Results

As an example in figures 3 and 4 the dose distribution in the transverse plane and the corresponding profiles along x and y directions are shown, in the case of a 20 mm diameter circular beam.

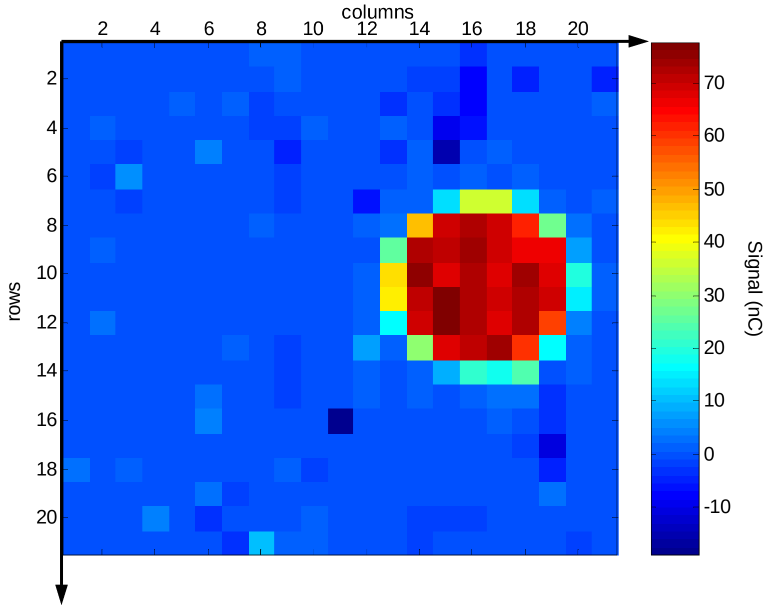

Figure 3: Charge generated in the pixel matrix by a 20mm diameter circular field, the pitch size is 3mm. Delivered dose is D=…

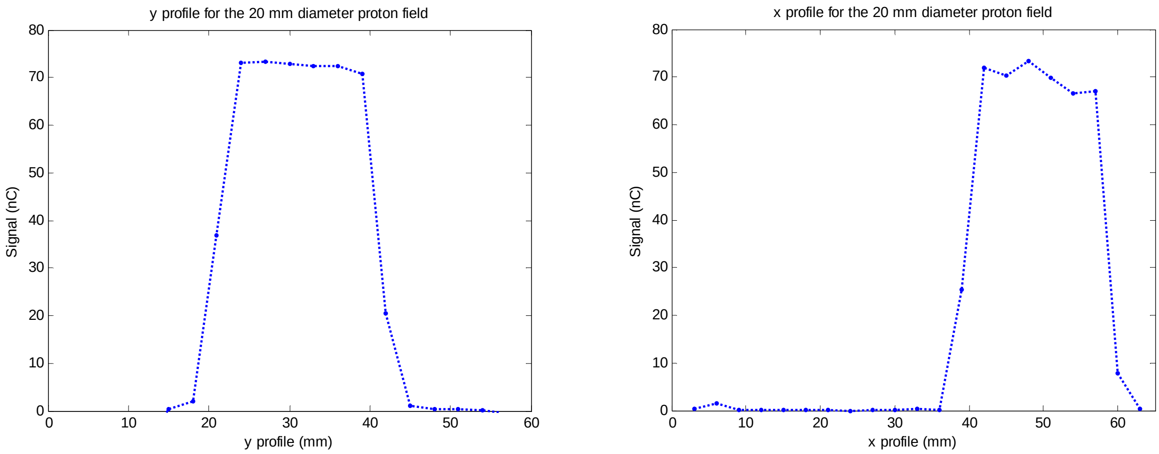

Figure 4: a) Dose profile along the x-axis (raw no. 10?) for a 20 mm diameter proton beam; b) Profile along the y-axis (column no. 16?) for a 20 mm diameter proton beam.

A. *Repeatability*

Repeatability was measured by irradiating several times the detector with a fixed dose D at constant dose rate. Measurements were performed for different dose rates, in the range from 0.18 up to 14 Gy/min. The output voltage $v_n(t)$ of each channel (n = 1…441) is generated by integrating the pixel current $i_n(t)$ with a capacitance C = 1.0 nF. $v_n(t)$ values are sampled by an analog data acquisition board (DAQ) with period $T \cong 0.2$ s: $v_{nm}=v_n(m \cdot T)$, m= 0,1,2… Capacitors are discharged after these readings, so that the charge integrated during a period T is $q_{nm} = C \cdot v_{nm}$.

Several acquisitions q_{nm} are performed during each irradiation j, and they are summed to obtain the response Q_{nj} of each channel to the dose D: $Q_{nj} = \Sigma(q_{nm}-q_n^0)$, q_n^0 being the dark signal measured when the beam is switched off. The sum is extended to the values sampled during the irradiation interval j.

Repeatability is expressed, for each channel, by the standard deviation of the output for the Q_{nj} irradiations: $\sigma_n = \sigma(Q_{nj})$. In table 1 the mean repeatability $\sigma = <\sigma_n>$, averaged on the channels and measured with different dose rates is displayed. $N_{0,5}$ is the percentage of channels with $\sigma_n < 0.5\%$.

Dose rate (Gy/min)	**Repeatability**		**Linearity**	
	σ% (%)	**$N_{0.5}$ (%)**	**d (%)**	**N_1 (%)**
0.18	0.8	58	---	---
2.5	0.2	100	1	57
6.8	0.2	100	---	---
14	0.5	70	1	65

Table 1. Summary of repeatability and linearity tests with different proton dose rates.

B. *Linearity*

Linearity was studied by measuring the response of each detector channel Q_{nj} to different values of the absorbed dose D_j, at constant dose rate. The sensitivity S_n of each pixel and the maximum deviation from linearity d_n are then determined by a linear fit in the sense of minimum χ^2.

In figure 5 as an example, for the central pixel of the detector, the signal as a function of the dose in the range 20-5000 cGy is shown for two very different dose rate values: 2,5 Gy/min and 14 Gy/min at half Spread Out Bragg Peak. The linearity at low dose rate was investigated in the range 0,2-5 Gy while at the maximum dose rate the dose range was 1- 50 Gy. All the channels behave in the same way, showing a good linearity of the response with the absorbed dose. The maximum deviation from linearity $d=<d_n>$ averaged on all pixels and the number of channels N_1 with maximum deviation d_n lower that 1% are reported in table 1.

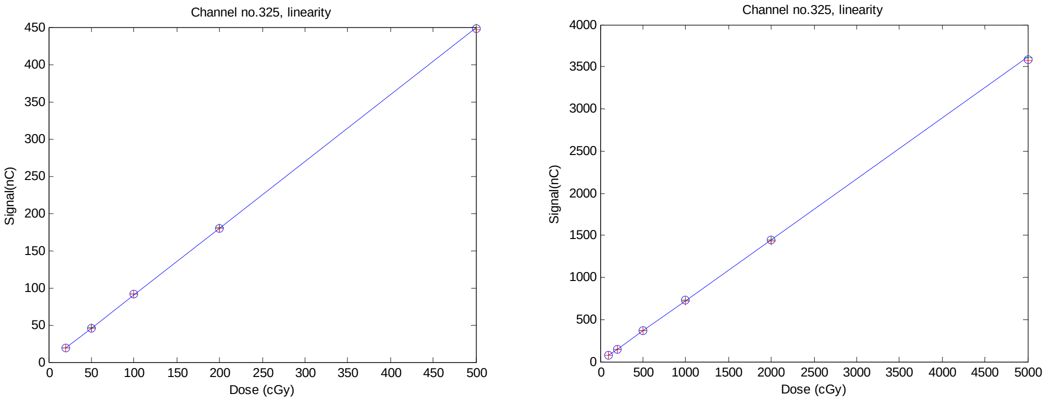

Figure 5: For a pixel of the detector, the signal as a function of the absorbed dose in the range 20- 5000 cGy is shown as an example for a) dose rate equal to 14 Gy/min and b) equal to 2.5 Gy/min. The dots are the experimental points, while the line is the linear fit.

A slight difference (percentage?) between the values of the sensitivity obtained with these two data sets was observed. Anyhow further experiments are planned in order to study the dependence of the sensitivity on the dose rate. In fact, the measurement conditions were totally different in the two cases: in the first the absorbed dose range was 0.2-5 Gy with a very low dose rate, while in the second the absorbed dose range was 1-50 Gy with the highest possible dose rate.

The sensitivity corresponding to the dose rate used in clinical treatments (4,9 Gy/min at half Spread Out Bragg Peak) is S= 0.75 nC/cGy.

C. *Output factors*

The output factors are defined as the ratio between the signal Q_j for a field of given dimension (the diameter d_j in our measurements) and the signal Q_0 for a reference field delivering the same dose. In our experiment the reference field was a circular field of 25mm diameter.

$$OF_d = Q_j / Q_0$$

In figure 6 the measured output factors for the central pixel are plotted and compared with those measured at LNS using different detectors like TLD, GAF, Markus ionization chamber and a Scanditronix diode. Since during our measurement session no precise system for detector alignment was available, we have not been able to perform a measurement with th smallest field (d=5mm).

Output factor measured by our dosimeter are in agreement with those obtained by other dosimeters, within the uncertainty determined by manual device positioning in these small fields.

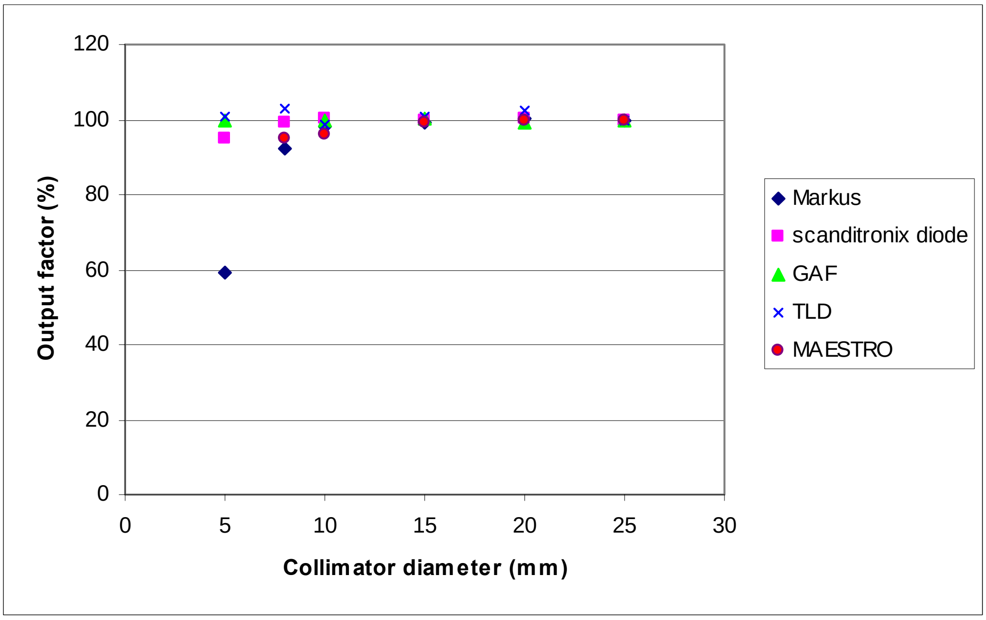

Figure 6: Output factors normalized to 25 mm diameter circle field. The red points are measured with MAESTRO prototype.

D. *Depth dose measurements*

The presence of a Bragg Peak in the stopping power profile permits to irradiate selectively tumors sparing the surrounding normal tissues. The full width half maximum of a typical Bragg Peak is usually of the order of 1 mm, a value completely insufficient to cover a tumor region (of the order of 20 mm for the case of the eye melanoma). In order to form a homogeneous dose distribution within the tumor volume, individual pristine beams have to be added up. Most proton therapy facilities are currently using a broad beam modulation technique where a spread-out Bragg peak (SOBP) is generated by a set of absorbers having different thickness.

In this experiment, the detector was used to measure the SOBP. The signal was obtained by averaging on all pixels inside a beam with 25mm diameter. Depth of measurement is determined by the total thickness of PMMA slabs stacked in front of the silicon module. In this way we were able to reproduce the clinical CATANA spread out Bragg peak (figure 7). The red points are the MAESTRO measurements while the blue line is the peak measured with a diode embedded in the modulator. There is a good agreement between MAESTRO and CATANA data, especially in the distal region of the SOBP. At this stage it is a qualitative test, but this measurement is important since it takes into account at the same time the dependence of the detector response on dose rate, energy and radiation LET.

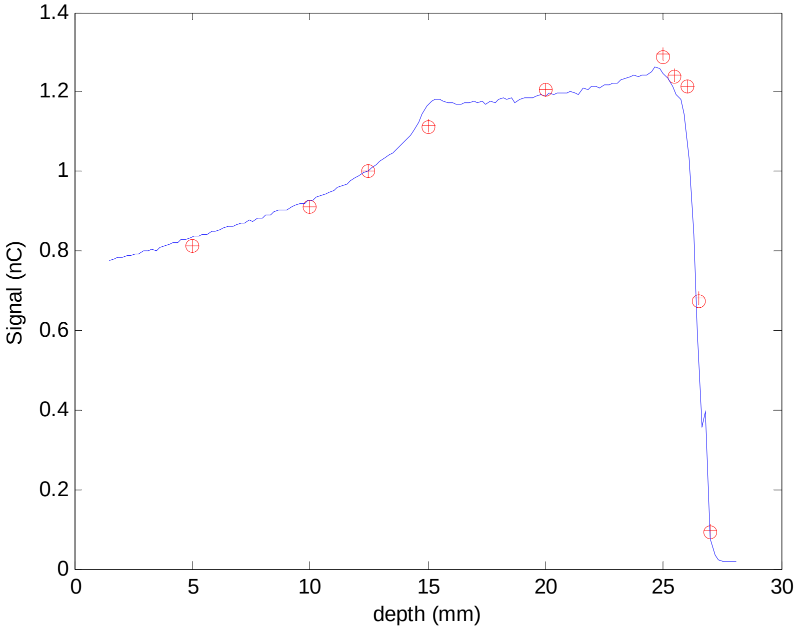

Figure 7: Clinical Spread out Bragg peak: red points are MAESTRO measurements; blue line is from CATANA measurements (multiplied by an arbitrary factor).

Conclusions

We designed and manufactured a modular system based on a monolithic silicon segmented sensor for 2D dose verifications in X-rays and proton therapy. The dosimetric characterization of the system presented in this paper refers to experiments performed with the CATANA clinical proton beam. Some of the pre-clinical tests prescribed by the MAESTRO protocol have been carried out and the results confirm that the detector exhibits performance within the project specifications. Repeatability tests were performed at different dose rates and the results are inside MAESTRO indication but at the lowest dose rate. The output factors are in good agreement whit those measured with ionization chamber, single diode or film, within the uncertainty determined by manual system allignment.. The measured Spread Out Bragg Peak shows a good agreement with the one measured with a single diode and the detector shows also a good linearity in the range 20-5000 cGy. In the final configuration nine silicon modules will be assembled together to cover an area closes to 20×20 cm^2. Connected to a new integrated electronics the full system should be assembled and tested during 2008. The new electronics is also expected to further improve the detector performances.

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