A Prototype Detector Array for Measurements in Laser Accelerated Charged Particle Beams

Radu A. Vasilache¹, Maria – Ana Popovici², Mihai Stratciuc³, Consuela Elena Matei⁴, Daniela Stroe⁵, Liviu Crăciun³, Mihai Radu³, Laura Ana Maria Niţă²

¹Canberra Packard Ltd., Bucharest, Romania; ²Bucharest Polytechnical University, Faculty of Applied Sciences, Bucharest, Romania; ³National Institute for R&D in Physics and Nuclear Engineering ”Horia Hulubei”, Bucharest – Măgurele, Romania; ⁴National Institute for Lasers, Plasma and Radiation Physics, Bucharest – Măgurele, Romania; ⁵Colţea Clinical Hospital, Bucharest, Romania

r.vasilache@cpce.net

Abstract. In all the future applications of the laser accelerated beams (as generated in the ELI and CETAL projects) in-beam dose measurements will be needed. The gold standard in dose measurement remain the ion chambers, but for the beams we intend to measure they do present some limitations given be the large number of corrections to be applied in order to calculate a correct dose from the measured charge. The ELIDOSE project is addressing these problems by proposing an array detector that would allow the simultaneous measurement of the recombination and polarity corrections, as well as of the dose – the QUADRO-fm (Quad Detector for RecOmbination factor measurement). The prototype detector consists of 4 identical ion chambers mounted together in a PMMA frame and the project analyses its response to various charged particle beams and the reciprocal influences of the chambers on each other. This reciprocal influences of the four chambers have been studied in well characterised therapy electron beams and conclusions regarding further developments have been drawn. The paper presents the characterisation of the proton and electron beams used in the experiment, as well as the dose measurements in the 5 MeV electron beams generated by a Siemens radiotherapy LINAC and the comparison with the FLUKA based simulations.

1. Introduction

Two important research projects – CETAL and ELI-NP were initiated in Romania, both aiming at physics with high power lasers. They both make use of PW class lasers (1 PW for CETAL and 10 PW for ELI-NP), with pulse widths in the range of some 20 fs and repetition rates of 0.1 Hz at the peak power. Both lasers have the capacity to generate pulses of accelerated particle beams with an estimated time width in the range of some tenths of picoseconds. Making use of these beams will require precise dosimetry but, due to the very short duration of the pulse, combined with the low repetition rate, the use of the ion chambers (which are still considered as the golden standard in dosimetry) is particularly difficult due to the high recombination corrections, which cannot be determined in the traditional way – as described, for instance, in the IAEA TRS 398 [1]. Under these circumstances, we propose to use an array detector with 4 ion chambers in a geometry described in the following paragraphs, one chamber being used for dose measurements, while the other 3 being used for simultaneous measurement of the recombination and polarity corrections. The acronym for the proposed array detector is the QUADRO-fm (Quad Detector for RecOmbination factor measurement). In order to evaluate the reciprocal
influences of the chambers, we will use a FLUKA [2], [3] simulation of the array. This paper presents the steps taken to characterise the available beams as well as the first dose measurements made with the array in a 5 MeV electron beam, compared to the results from the FLUKA simulations.

2. Method and materials

The dose measured with an ion chamber is given by [1]:

\[ D = M_{\text{uncorr}} k_{\text{elec}} k_{\text{Q}} k_{\text{TP}} k_{\text{S}} k_{\text{pol}} k_{r} \]  

(1)

where \( M_{\text{uncorr}} \) is the uncorrected indication of the dosemeter, \( k_{\text{elec}} \) is the calibration factor (Gy/C) at reference energy (usually Co\(^{60}\)), \( k_{\text{Q}} \) is the energy correction, \( k_{\text{TP}} \) is the air density correction, \( k_{\text{S}} \) is the ion recombination correction, \( k_{\text{pol}} \) is the bias polarity correction, \( k_{r} \) includes the rest of the corrections including (but not limited to) humidity and wall perturbation.

For the recombination correction in pulsed beams, the method recommended by IAEA TRS 398 [1] is the so-called two voltage methods, where the chamber is biased at two different voltages, and then the correction is given by:

\[ k_{S} = a_0 + a_1 \left( \frac{M_1}{M_2} \right) + a_2 \left( \frac{M_1}{M_2} \right)^2 \]  

(2)

where \( M_1 \) and \( M_2 \) are the dosimeter readings and voltage biases \( V_1 \) and, respectively, \( V_2 \). The parameters \( a_0, a_1 \) and \( a_2 \) are tabulated in TRS 398 for pulsed and pulsed scanned beams, vs. \( V_1/V_2 \). For the method to work best, the ratio between the two bias voltages must be at most 1/3. Also the polarity effect changes with the voltage, thus the readings should also be corrected for polarity effect, which brings us to the second factor of interest for our paper – the bias polarity correction, also known as polarity correction. This correction factor is known to be dependent on the energy and voltage bias and can be calculated with the formula given by the same IAEA TRS 398 [1]:

\[ k_{\text{pol}} = \frac{|M_1 + M_{-1}|}{2M} \]  

(3)

To avoid multiple measurements to determine the correction factors, an array detector with 4 chambers can be used, the drawing of the prototype QUADRO-fm detector is being presented in figure 1.

Figure 1. Schematic drawing of the prototype array detector, consisting of 4 identical Advanced Markus\textsuperscript{TM} ion chambers, mounted in PMMA (above). Dimensions are given in millimetres.

It consists of four identical plane parallel chambers, type PTW Advanced Markus\textsuperscript{TM}, set up in two pairs, each pair allowing the measurement of the two correction factors – the recombination correction factor and the polarity correction, each of the four chambers having a different bias, at the values \( V_1 \), \( V_2 \), \(-V_1\) and \(-V_2\), respectively. The \( V_1 \) chamber will be considered as the reference chamber and will
also be used for dose measurement, whilst the other three chambers are meant to provide the values for the calculation of the correction factor.

One of the problems that needs to be addressed in this configuration is the reciprocal influence of the ion chambers, and therefore we have done FLUKA [2], [3] simulation of these reciprocal influences vs. the situation where we measure with a single chamber, placed in the centre of the beam. In the array prototype, the distance between the inner edges of the chamber is 3 mm, which makes the total area covered by the chambers to have the dimensions 63 x 63 mm.

2.1. Experimental setup for the initial measurements
In order to prepare FLUKA simulations, we needed to characterise the beams we intend to use in our experiments: the 3 MeV proton beam provided by the Tandetron™ accelerator, the 18 MeV beam from the TR19 Cyclotron from IFIN-HH, and the 5 MeV electron beam from the Mevatron Primus Siemens Linac from the Coltea Clinical Hospital. This was done using Gafchromic® EBT3 and HD-V2 films, read with an EPSON EXPRESSION 11000XL scanner and then the images were analysed with the PTW Mephysto Mcc software. The results of the beam profile analysis for each of the three beams is presented in figure 2. As it can be easily seen from, whilst the 10 x 10 cm electron beam is perfect for our experiment, the homogeneous sections in the two proton beams are only 8 mm (the 3 MeV beam) and, respectively, 20 mm in diameter (the 18 MeV beam) which makes them unsuitable, for the moment, for the irradiation of the array. The beams were used, however, for the initial fine tuning of the FLUKA simulation of the Markus chamber, with the results reported in [4].

![Figure 2. Beam profiles analysed with Mephysto mcc: a) 3 MeV protons, TandetronTM; b) 18 MeV protons, TR19 Cyclotron; c) 5 MeV electrons, Siemens Mevatron Primus.](image-url)

In order to evaluate correctly the dose, the energy of the beams had to be evaluated, too. The beam energy for the 3 MeV beam proton, at the entry point in the Markus chamber, has been estimated via FLUKA simulations, as reported in a previous paper [4].

For the 18 MeV beam we could measure the Bragg peak position using the setup from figure 3 a), in which we used a Gafchromic™ type EBT3 film sandwiched between two PMMA plates, each plate being 2 cm thick. The film was placed on the beam axis, parallel to the beam direction. As it can be seen from figure 3 b), the analysis of the percentage dose depth curve using the Bragg peak protocol of the Mephysto Mcc software shows the position of the Bragg peak at 1.31 cm and the range of the protons at 1.92 mm. This indicates an energy at the entry point in the Markus chamber of approximately 14 MeV.

Finally, the energy of the electron beam generated by Siemens Mevatron Primus LINAC was measured using a PTW MP3-M therapy beam analyzer and the IAEA TRS398 protocol from the software Mephysto Mcc.
Figure 3. Bragg peak analysis of the 18 MeV proton beam from the TR19 Cyclotron, performed with Mephysto mcc: a) photo of the experimental set-up, with the Gafchromic™ EBT3 film mounted between two PMMA plates, central parallel to the beam axis; b) PDD curve.

To estimate the cross-talk between chambers, the array was irradiated in the 10 x 10 cm electron beam, the beam being centred on the geometrical centre of the array, then the results obtained with the reference chamber from the array were compared with the measurement done with the same chamber, only in a single configuration, using the standard PMMA plate as a holder and the chamber placed on the axis of the beam.

2.2. The geometry and beam parameters for the FLUKA simulation

The geometry of the Advanced Markus chamber used in the FLUKA simulation was the one described in the PTW chamber manual version D661.131.00/05. Also in the manuals are detailed the materials of the walls, electrodes and window. Figure 4 shows the FLUKA geometry for the QUADRO-fm detector used for the crosstalk calculations. The beam used in the simulations was a rectangular, homogeneous beam with 10 x 10 cm area centred on the geometrical centre of the array. FLUKA simulations were performed using the latest version of the code available at that time, FLUKA 2011.2x.3 [2], [3]. The transport thresholds for the electromagnetic shower particles were brought down to the lowest value: 1 keV for the charged particles, and 100 eV for the photons.

Delta rays were produced above 1 keV. Due to the small dimensions of the active region in the detectors, single scattering was activated (MULSOPT). The size of the electron step length was chosen such that 2% of the energy is lost for the detector materials - ten times smaller than the default (EMFFIX). This simulation setup led to a CPU time of 0.32 seconds/primary. The radiation source used in the simulation was Gaussian, 4.6 MeV average value, 0.78 MeV FWHM, full divergence angle 6°, field of 10 cm x 10 cm, placed at 0.5 cm in front of the detector [6].

Figure 4. FLUKA geometry for the array simulation, using the FLAIR code [5].

3. Results and discussion

The experimental measurements of the cross-talk influence on the dose values when the reference chamber is used in the array configuration is evaluated by the relative difference between the value returned by the reference chamber when mounted in the array and the value returned by the same chamber used in single configuration. Those differences are given in the table 1 below.
The difference between the single and array configuration is low for the experimental values and this can be attributed to the non-uniformity of the field, since the beam analysis revealed a flatness of 3.45%. The FLUKA simulation reveals a similar relative difference between the reference chamber and the central axis dose measured in single configuration (see table 2). The slight differences between the measurements and the simulations are due mainly to the fact that the radiation source used in the simulation does not entirely match the reality of the accelerator used, but is based on a generic LINAC of the same type, as described in [6].

Table 1. Comparison between the single configuration and the array configuration doses. The relative statistical errors for the FLUKA dose per primary computation are below 2.5%.

| D(Gy) measured in single configuration | D(Gy) measured in the array configuration | Experimental relative dose deviation (%) | FLUKA relative dose deviation (Ch. 1 in tab. 2, %) |
|--------------------------------------|----------------------------------------|------------------------------------------|-----------------------------------------------|
| 4.804 ± 0.05%                        | 4.733 ± 0.1%                           | 1.48%                                    | 2.097%                                        |

Table 2. Relative dose deviations, for each chamber in the array, as calculated with FLUKA vs. the central dose in single configuration.

| Channel | Relative dose deviation of each chamber in the array (%) | Statistical error for dose per primary computation (%) |
|---------|----------------------------------------------------------|-------------------------------------------------------|
| Channel 1 | 2.097%                                            | 2.5%                                                  |
| Channel 2 | 3.108%                                            | 2.2%                                                  |
| Channel 3 | 0.155%                                            | 2.4%                                                  |
| Channel 4 | -2.330%                                           | 2.8%                                                  |

In what concerns the recombination correction factor, table 3 below shows the difference between the single configuration and the array configuration.

Table 3. Relative dose deviations, for each chamber in the array, as calculated with FLUKA vs. the central dose in single configuration.

| k_s in single configuration | k_s in the array configuration | Relative k_s deviation (%) |
|-----------------------------|-------------------------------|---------------------------|
| 1.0027 ± 0.03%              | 1.0088 ± 0.01%                | 0.60%                     |

As expected, the recombination correction factors are very small, due to the fact that we had to perform the measurements in a continuous beam. The relative difference between the two methods is only 0.6%. The proposed correction method works very well in continuous beams however it has to be validated also for pulsed beams.

4. Conclusions
The initial measurements described in this paper allow us to conclude with enough confidence that the array detector described here can be successfully used for dose measurements in continuous electron beams. In order to check this behavior also in proton beams we will need to obtain wider 3 MeV and 18 MeV beams. For the measurements in pulsed beams a new experimental set-up is currently prepared, making use of the same beams but adding a chopper that will allow us to transform them into pulsed beams. Those results will be reported in further publications.
References

[1] IAEA TRS-398, Absorbed Dose Determination in External Beam Radiotherapy, IAEA Vienna, 2000

[2] A. Ferrari, P.R. Sala, A. Fassò, J. Ranft, FLUKA: a multi-particle transport code, CERN-2005-10, 2005, INFN/TC_05/11, SLAC-R-773

[3] T.T. Böhlen, F. Cerutti, M.P.W. Chin, A. Fassò, A. Ferrari, P.G. Ortega, A. Mairani, P.R. Sala, G. Smirnov, V. Vlachoudis, The FLUKA Code: Developments and Challenges for High Energy and Medical Applications, Nuclear Data Sheets vol. 120, 2014, pp. 211-214

[4] Radu A. Vasilache, Maria – Ana Popovici, Mihai Straticiuc, Mihai Radu, Andreea Groza, The Development of Novel Array Detector for Overcoming the Dosimetry Challenges of Measuring in Very Short Pulsed Charged Particle Beams - The ELIDOSE Project, Radiation Protection Dosimetry, Vol. 183 (1-2), 2019, pp. 285–289

[5] V. Vlachoudis, FLAIR: A Powerful But User Friendly Graphical Interface For FLUKA, Proc. Int. Conf. on Mathematics, Computational Methods & Reactor Physics (M&C 2009), Saratoga Springs, New York, 2009

Acknowledgments

This work has been supported by the national project PNCDI III 5/5.1/20 ELI/2016 (“ELIFLUKA”)