IL NUOVO CIMENTO **44 C** (2021) 147
DOI 10.1393/ncc/i2021-21147-9

COMMUNICATIONS: SIF Congress 2020

PAPRICA: The PAir PRoduction Imaging ChAmber

G. CALVI(1)(2), I. AVANZOLINI(3)(5), L. BALCONI(2), G. BATTISTONI(1), M. TOPPI(4)(6), M. DE SIMONI(3)(5), Y. DONG(2)(1), A. FANTONI(6), G. FRANCIOSINI(3)(5), M. MARAFINI(7)(5), M. FISCHETTI(4)(5), S. MURARO(1), V. MUCCIFORA(6), V. PATERA(4)(5)(7), F. RONCHETTI(6), A. SARTI(4)(5)(7), A. SCIUBBA(4)(5)(7), G. TRAINI(5)(7), S. M. VALLE(1) and I. MATTEI(1)

(1) *INFN Section of Milan - Milan, Italy*
(2) *Dipartimento di Fisica, Università degli studi di Milano - Milan, Italy*
(3) *Dipartimento di Fisica, Sapienza Università di Roma - Rome, Italy*
(4) *Dipartimento di Scienze di Base e Applicate per l'Ingegneria, Sapienza Università di Roma Rome, Italy*
(5) *INFN Section of Rome - Rome, Italy*
(6) *INFN Laboratori Nazionali di Frascati - Frascati, Italy*
(7) *Museo Storico della Fisica e Centro Studi e Ricerche E. Fermi - Rome, Italy*

received 15 January 2021

Summary. — In the treatment of tumours with charged particle beams, several factors introduce uncertainties in predicting the beam range in the biological tissue. In the treatment planning, safety margins of several millimetres are added to the volume to be treated in order to avoid under-dosage of the tumour. Beam range monitoring techniques have been proposed and studied in order to reduce safety margins and ensure safer treatments. Some of these techniques detect secondary radiation emitted during beam-tissue interaction. The aim of the PAir PRoduction Imaging ChAmber project is to demonstrate the feasibility of a range monitoring technique based on secondary prompt-gamma radiation, detected by means of the pair production mechanism. The project results presented at the SIF Congress 2020 were deepened and updated with new Monte Carlo simulations.

1. – Introduction

Hadrontherapy is an external form of radiotherapy exploiting beams of protons or heavier ions [1]. The typical depth-dose profile of charged particles in tissues is characterized by an increasing dose release ending in a narrow high dose region, called Bragg peak. This feature allows radiotherapists to plan treatments with dose release highly tailored to the target volume. However, several sources of uncertainty in the planning and execution of the therapy can affect the accuracy of the treatment. Consequently, safety margins of several millimetres (up to centimetres) are added to the volume to be treated in order to avoid under-dosage of the tumour [2]. The resulting over-dosage of healthy tissue can have particularly serious side effects in patients with long life expectancy, such as paediatric patients, or in the treatment of tumours close to organs at risk. In order to reduce safety margins, several research groups have proposed and studied devices for measuring the beam range during the treatment [3, 4]. Although some techniques are currently being tested in the treatment room, to date no solution has yet achieved both the 1–2 mm accuracy required by clinics and the reliability for large-scale applications. Some of the proposed range monitoring systems are based on the detection of gamma radiation, emitted by the de-excitation of biological nuclei after the interaction with the beam [5]. The temporal, spatial and energetic spectra of secondary radiation can indeed be correlated with the dose profile.

2. – The PAPRICA device

In 2015, Rohling *et al.* [6] investigated the possibility of using the pair production mechanism in a detector for prompt-gamma imaging and identified some limitations of this technique. Pair production detectors convert the incident photon into a positron-electron pair and track the two particles to compute the photon momentum as

$$\mathbf{p}_\gamma = \mathbf{p}_{e^+} + \mathbf{p}_{e^-}, \tag{1}$$

where the momentum absorbed by the nucleus involved in pair production is neglected. The study by Rohling *et al.* [6] showed that multiple scattering of the electron-positron pair in the converter medium strongly reduces the resolution of the imaging chamber and introduces a systematic error in the reconstruction of photons emitted far from the detector axis. On the other hand the gamma detection with pair production has several advantages compared to other gamma imaging techniques. A pair production detector mainly exploits the prompt-gamma spectrum components above 4 MeV, *i.e.*, the components with the highest correlation with the position of the Bragg peak, does not require collimators or prompt-gamma time of flight information and can discriminate background events due to the topology of the pair production events. The PAir PRoduction Imaging ChAmber (PAPRICA) project, whose new results are presented in this contribution, deepens the method proposed by Rohling *et al.* [6]. A new chamber and a specific analysis algorithm were developed to achieve the required resolution in range monitoring during a particle treatment. The chamber consists of three detector blocks, as shown in fig. 1(left). The design presents a first layer with a surface area of $5 \times 21\,\mathrm{cm}^2$ and a thickness of 1.5 mm, consisting of approximately 135 lutetium-yttrium oxyorthosilicate (LYSO) fibres, where pair production takes place. Three tracking planes form the second block and measure the direction of the leptons. Each plane consists of ALPIDE (ALice PIxel DEtector) modules [7], MAPS (Monolithic Active Pixel Sensor) detectors segmented into pixels of size $27 \times 29\,\mu\mathrm{m}^2 \times 100\,\mu\mathrm{m}$ silicon thick. The calorimeter is the last chamber block, a 8×32 array of scintillating plastic rods of size $6 \times 6\,\mathrm{mm}^2 \times 5\,\mathrm{cm}$ thick. The calorimeter measures the electron-positron pair energy in order to compute the momentum magnitudes, needed to solve eq. (1). The acquisition trigger is built from the time coincidence between the signal of at least one LYSO fibre of the converter and two scintillating rods of the calorimeter.

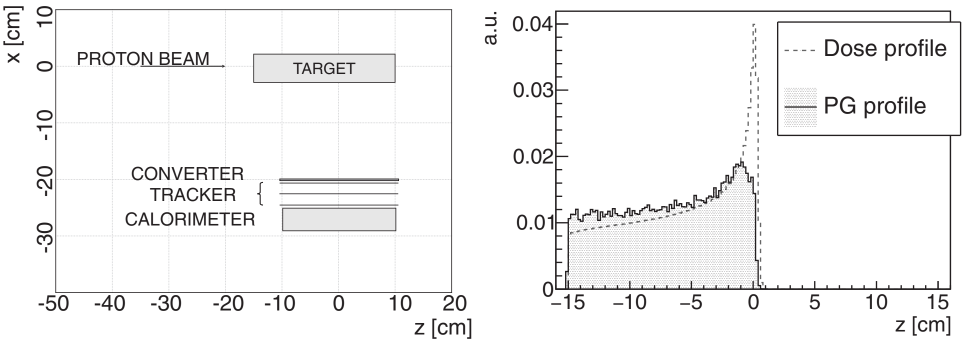

Fig. 1. – Left: visualisation of the simulated FLUKA geometry (x-z plane view). Right: 160 MeV proton beam dose deposition (dashed line) within the PMMA target, superimposed to the spatial emission distribution of the prompt-gammas (PG) along the beam axis (filled area).

3. – Simulation study of the expected performance

A first feasibility study of prompt-gamma imaging with the PAPRICA chamber was carried out by means of a Monte Carlo simulation, developed with the FLUKA code [8]. With a view to a future real treatment study, the chamber performance was evaluated by simulating a 160 MeV proton beam on a $5 \times 5 \times 25\,\text{cm}^3$ polymethil-methacrylate (PMMA) target. The geometry of the simulation is shown in fig. 1(left). The beam, consisting of 10^{11} primaries, is parallel to the z-axis. The chamber is 20 cm far from the beam axis and centred with respect to the expected Bragg peak position ($z = 0.15\,\text{cm}$). In fig. 1(right) the prompt-gamma emission profile along the beam axis is superimposed on the dose profile in the target. The spatial correlation between the position of the Bragg peak and the fall-off of the prompt-gamma profile can be noticed.

A specific algorithm, based on the energy release in the chamber detectors, was developed to recognise pair production events and calculate the momentum of the leptons. The number of detected pairs is 10.5×10^{-8} per proton, with a fraction of background equal to 20% of the selected events. The calculation of the photon momentum via eq. (1) is affected by the neglected nucleus recoil and the lepton deviation from their emission trajectory, due to multiple scattering. This two contributions introduce an angular uncertainty in the reconstruction of the photon direction equal to 5° and 17°, respectively. Once the photon momentum is obtained, the emission point is reconstructed as the point of closest approach of the prompt-gamma direction and the proton beam axis. Figure 2(left) compares the measured emission profile to the actual emission distribution of the detected prompt-gammas. In order to reduce the bias, due to the multiple scattering in the converter layer, an unfolding procedure was applied [9] and the resulting distribution is shown in fig. 2(left). To relate the prompt-gamma profile and the position of the Bragg peak, five simulations of beams of different energies (110, 130, 150, 170, 190 MeV) were carried out. A fit with a Fermi-Dirac function $f_{FD}(z) = p_0(1+\exp((z-p_1)/p_2))^{-1}$ was performed for the fall-off of the unfolded prompt-gamma profiles. The p_1 parameter of the function coincides with the z-coordinate of the distribution fall-off at 50% of its maximum value and was related to the Bragg peak position with a linear calibration, as shown in fig. 2(right). In a real treatment scenario, the accuracy of the chamber in finding the actual emission profile is strongly dependent on the number of photons detected and consequently on the number of primary protons. Identifying as a monitoring volume the distal part of a tumour $1 \times 1 \times 0.2\,\text{cm}^3$, treated with 25 pencil beams of

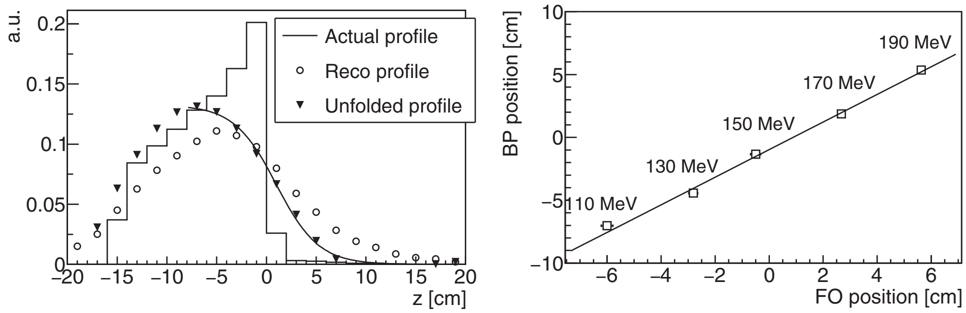

Fig. 2. – Left: normalized profiles of prompt-gamma emission obtained from 160 MeV protons impinging on a PMMA target. The actual production distribution (solid line), the reconstructed profile (circles) and the unfolded profile (triangles) are compared. Right: linear calibration of the Bragg peak (BP) position as a function of the 50% fall-off (FO) coordinate of the unfolded prompt-gamma profile.

160 MeV, each with 10^8 protons, the number of primaries is 2×10^9. The corresponding number of counts in the measured prompt-gamma profile is equal to 200. This value can be increased by a factor of 10 assuming a larger detector consisting of 10 PAPRICA units is built. To assess the resolution of the PAPRICA chamber in range monitoring, twenty prompt-gamma profile of 2000 counts, obtained from a simulation of 160 MeV proton beam, were analysed using the unfolding procedure and the Fermi-Dirac fit. Twenty Bragg peak positions were computed from the 50% fall-off coordinate by means of the calibration in fig. 2(right). The resolution of the PAPRICA chamber was finally evaluated as the root mean square (RMS) of the deviations from the true Bragg peak coordinate, resulting in (3.9 ± 0.6) mm.

4. – Conclusion

The PAPRICA project studies the feasibility of a range monitoring technique in proton therapy, based on the detection of secondary prompt-gamma radiation exploiting the pair production mechanism. The performance of the chamber was studied by means of Monte Carlo simulations, involving proton beams of different energies incident on a PMMA target. The accuracy achieved in the measurement of the 160 MeV Bragg peak position is approximately 4 mm. Although the resolution of the chamber is lower with respect to the one required by the clinics, the result is promising and will be verified in the simulation of a real treatment where the in-homogeneity of the target introduces new interesting challenges.

REFERENCES

[1] Durante M. *et al.*, *Nat. Rev. Clin. Oncol.*, **14** (2017) 483.
[2] Paganetti H., *Phys. Med. Biol.*, **57** (2012) R99.
[3] Dauvergne D. *et al.*, *NIRS-ETOILE Joint Symposium on Carbon Ion Therapy* (2009) `http://hal.in2p3.fr/in2p3-00363382`.
[4] Parodi K. and Assmann W., *Mod. Phys. Lett. A*, **30** (2015) 1540025.
[5] Krimmer J. *et al.*, *Nucl. Instrum. Methods Phys. Res. A*, **878** (2018) 58.
[6] Rohling H. *et al.*, *IEEE Trans. Nucl. Sci.*, **62** (2015) 2023.
[7] Aglieri Rinella G, *Nucl. Instrum. Methods Phys. Res. A*, **845** (2017) 583.
[8] Ferrari A. *et al.*, CERN-2005-010, SLAC-R-773, INFN-TC-05-11 (2005).
[9] Schmitt S., *J. Instrum.*, **7** (2012) T10003.