The PAPRICA (PAir PRoduction Imaging ChAmber) project

A. Fantoni, V. Muccifora, F. Ronchetti,
M. Toppi (Resp. Ass.)
A. Orlandi (Tecn.), L. Passamonti (Tecn.), D. Pierluigi (Tecn.), A. Russo (Tecn.)

1 Introduction and PAPRICA motivation

Particle therapy (PT) is a well-established technique for cancer treatment in which the dose deposition inside the patient body is made by heavy charged particles (protons or heavier ions) instead of the photons or electrons used in the conventional radiotherapy. The energy release mechanism of charged particles, driven by the interactions with the nuclei electrons, results in the well-known Bragg Peak distribution. This feature has suggested the use of light nuclei ($Z \leq 8$) use as "precision projectiles" to treat deep radioresistant tumors close to organs at risk. Ideally, the beam range inside a patient should be equal to the value prescribed by the Treatment Planning System (TPS), but indeed there are several range uncertainties during the actual irradiation due to patient positioning, patient's anatomical changes, beam delivery and dose calculation. To this aim, a tool for an online beam range monitoring, during the PT treatment, is essential to improve the treatment quality assurance and the therapy efficacy. To address the fundamental issue of range monitoring in PT, several in-vivo techniques have been proposed. All existing methods are based on the detection of the neutral (photons and neutrons) or charged secondary radiations exiting the patient's body, produced in the nuclear interactions of charged particle beams with the tissue nuclei, that are correlated to the BP position. The main objective of the PAPRICA (PAir PRoduction Imaging ChAmber) project is to demonstrate the feasibility of an online beam range monitoring in PT treatment by means of the detection and backtracking of the emitted prompt-gammas (PG) in the interaction of the beam with the patient, exploiting the Pair Production (PP) mechanism. PAPRICA targets mainly PG with energies larger than 4 MeV and will profit from a properly designed detector to maximise the PP detection efficiency. The PAPRICA design oversees three detector blocks, as shown in Figure 2. A converter layer, made of a high Z material to maximise the PP cross section ($\sigma_{PP} \propto Z^2$), is used as a target for the photon conversion. A tracking system consisting in a set of three tracking stations based on silicon pixel detectors provides the e^+e^- direction to reconstruct the interaction vertex. The needs in terms of momentum resolution and minimization of the multiple scattering and of the energy loss suffered by the leptons inside the tracker itself has suggested the use of monolithic active pixel sensors (MAPS) for the three tracker stations. Finally a matrix of pixelated plastic scintillator acts as a calorimeter, measuring the pair kinetic energy left.

2 The tracker system of PAPRICA at LNF

The tracking stations of the PAPRICA chamber are based on the ALPIDE (ALice PIxel DEtector) [1] sensor, developed for the Outer Barrel of the new Inner Tracking System (ITS) of the ALICE detector, built in view of the LHC Run 3 [2, 3]. Tests of ALPIDE telescopes, performed within the ALICE collaboration using minimum ionization particles, have shown a tracking efficiency

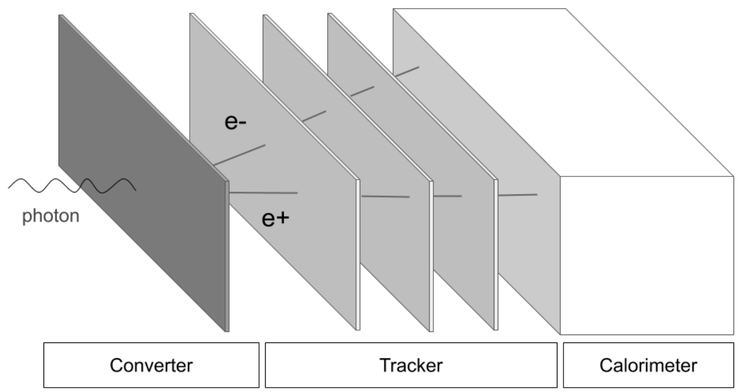

Figure 1: Sketch of the PAPRICA design: the converter, the tracker and the calorimeter blocks are shown.

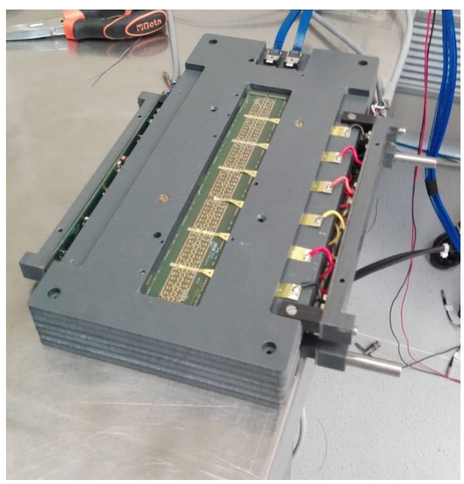

Figure 2: The PAPRICA tracker.

$> 99\%$ and a fake hits rate $< 10^{-6}$/pixel/event, exceeding the PAPRICA required performances in terms of achievable spatial resolution ($\simeq 5\mu$m) [1]. The ALPIDE chip is a 15 mm $\times$ 30 mm MAPS, implemented in a 180 nm CMOS imaging sensor process. Each layer of the PAPRICA tracker is based on a OB-HIC (Hybrid Integrated Circuit) of the Outer Barrel (OB) of the ALICE ITS [4]. The OB-HIC consists of an assembly of two rows of 7 ALPIDE chips, for a total of 14 ALPIDEs with overall surface $\simeq 21 \times 3$ cm^2, soldered and glued on an FPC (Flexible Printed Circuit). The FPC provides the connection for the powering, the bias voltage of the sensors and the lines for signal propagation.
The LNF group is the responsible for the developing and building of the PAPRICA tracker. At the end of the 2020 the tracker has been fully assembled. During 2021 simple tests that check the operation of the three layers after the assembly have been performed successfully. The develop-

ment of the necessary software and firmware to make the tracker work and acquire data with an external trigger has been performed during 2021. Still an effort is necessary to develop the readout software to be finally interfaced with calorimeter for DAQ, in particular the busy signal from the tracker in order to have the two detectors syncronyzed during the data acquisition. A cosmic ray test to acquire some tracks has been set-up. The cosmic-ray tracks will be reconstructed with a tracking algorithm developed for PAPRICA as described in [6]. During the 2021 the tracker has been moved in the Department of Scienze di Base ed Applicate per l'Ingegneria of Sapienza University of Rome in order to assemble the final PAPRICA detector with an absorber plane and the calorimeter. The final PAPRICA detector will be tested in 2022 in two planned data taking:

1. Test at ENEA with γ of 4.4 MeV from Am-Be source in order to study the PAPRICA performances in measuring γs in the energy range of interest
2. Test at CNAO with p beams to measure the spatial resolution on backtracking and so the PAPRICA range monitoring capabilities

3 MC study of PAPRICA performances

Two papers describing the PAPRICA obtainable performances have been published during 2021 [6, 7]. A FLUKA Monte Carlo simulation of a prompt photon source impinging on the PAPRICA detector has been performed in order to optimise its geometry, with a focus on each PAPRICA subdetector: the converter, the tracker, the calorimeter. The following conclusions were reached in the framework of this work:

1. The intrinsic limit on the prompt photon reconstruction considering the low prompt gamma energy range (1-10 MeV) is the recoil of the nuclei participating in the e^+e^- pair production, giving a degradation on the angular resolution of $\sim 3°$.
2. Due to the low pair production cross section at the prompt gamma energies, a high atomic number material for the converter has been chosen: the thickness of the converter assures to have a sufficient e^+e^- pair statistics to reconstruct the impinging photon direction. On the other hand the converter thickness contributes to the angular resolution degradation due to the multiple scattering suffered by the leptons pair while exiting the converter surface. The optimised PAPRICA converter thickness is a trade-off between the resolution on the single reconstructed prompt photon and the produced statistics.

Finally the expected PAPRICA performances in retrieving the Bragg peak position for an absolute verification of the proton beam range have been computed in a more realistic case scenario, with $\sim 3 \times 10^9$ 160 MeV protons impinging on a PMMA target and considering a 1 sr PAPRICA detector to increase the collectable prompt gamma statistics. A resolution on the retrieved Bragg peak of ~ 1 cm has been obtained, demonstrating that the PAPRICA detector, with larger solid angle, would not be able to perform an absolute range verification with the clinically required resolution of ~ 2 mm on the computed beam range. Nevertheless, there is room for optimisation of the proposed pair production imaging technique and further investigations to perform a 3D imaging and to improve the PAPRICA resolution on the imaged photons are foreseen and will be subject of future studies.

4 Publications

1. M. Toppi et al., Front. Phys. 9:568139. doi: 10.3389/fphy.2021.568139, DOI: 10.3389/fphy.2021.568139
2. G. Calvi et al., IL NUOVO CIMENTO 44 C (2021) 147, DOI:10.1393/ncc/i2021-21147-9

References

1. G. Aglieri Rinella, Nucl. Instrum. Methods. Phys. Res. A 845 (2017)
2. ALICE Collaboration, Upgrade of the ALICE Experiment: Letter of Intent, J. Phys. G 41 (2014) 087001.
3. ALICE Collaboration, ALICE collaboration technical design report for the upgrade of the ALICE inner tracking system, J. Phys. G 41 (8) (2014) 087002.
4. A. Di Mauro, Nuclear Inst. and Methods in Physics Research, A 936 (2019)
5. G. De Robertis *et al.*, A MOdular System for Acquisition, Interface and Control (MOSAIC) of detectors and their related electronics for high energy physics experiment, EPJ Web of Conferences 174, 07002 (2018), MPGD 2015
6. M. Toppi et al., Front. Phys. 9:568139. doi: 10.3389/fphy.2021.568139, DOI: 10.3389/fphy.2021.568139.
7. G. Calvi et al., IL NUOVO CIMENTO 44 C (2021) 147, DOI:10.1393/ncc/i2021-21147-9.