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PRIMA+: A proton Computed Tomography apparatus

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Summary. — The proton Computed Tomography (pCT) is a medical imaging method, based on the use of proton beams with kinetic energy of the order of 250 MeV, aimed to directly measure the stopping power distribution of tissues thus improving the present accuracy of treatment planning in hadron therapy. A pCT system should be capable to measure tissue electron density with an accuracy better than 1% and a spatial resolution better than 1 mm. The blurring effect due to multiple Coulomb scattering can be mitigated by single proton tracking technique. As a first step towards pCT the PRIMA+ Collaboration built a prototype capable to carry out a single radiography and a tomographic image of a rotating object. This apparatus includes a silicon microstrip tracker to identify the proton trajectory and a YAG:Ce calorimeter to measure the particle residual energy.

PACS `87.57.Q` – Computed tomography.
PACS `29.40.Wk` – Solid-state detectors.
PACS `07.20.Fw` – Calorimeters.
PACS `87.53.Bn` – Dosimetry/exposure assessment.

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1. – Introduction

One of the factors that drives the effectiveness of the hadron therapy is the precision by which the dose is delivered to the target volume. The hadron energies should be tuned during the treatment to allow the particle's Bragg peak to completely cover the tumor leaving the nearby healthy tissues as much as possibly unaffected. To achieve this goal the Stopping Power (SP) map for each patient should be measured before the treatment and a detailed irradiation plan based on this information should be defined.

Presently the SP maps are extracted from 3-dimensional images obtained by X-ray Computed Tomography; here the photon attenuation coefficients are translated into SP using conversion tables introducing uncertainties which can be as large as 3 mm [1]. To mitigate this effect the SP map can be directly determined using a proton beam with kinetic energy larger than the one used for treatment. The proton detector system should partially overcome the problems introduced by the intrinsic effect of the Multiple Coulomb Scattering (MCS). Typical targets could be as thick as 20 cm water equivalent: in this case a 200 MeV proton undergoes to a r.m.s. MCS angle of about 40 mrad which corresponds to an r.m.s. of the projected displacement of 3.2 mm [2]. With this numbers a proton projection radiography cannot extract the SP map with a sub-millimeter precision.

A possible solution is to measure the trajectory of each proton both upstream and downstream the target together with the residual proton kinetic energy. With this information the most likely proton path (MLP) could be estimated [3]. The maximum value of the one sigma envelope of a transverse coordinate of the MLP of a 200 MeV kinetic energy proton in 20 cm of water is of the order of 0.5 mm [3]. Assigning the proton energy loss to each MLP and using appropriate algorithms [4] the 3-dimensional SP map can be obtained.

2. – The proton Computed Radiography (pCR) system

The pCR apparatus described in this paper [5] is made by a silicon microstrip tracker followed by a YAG:Ce calorimeter (fig. 1).

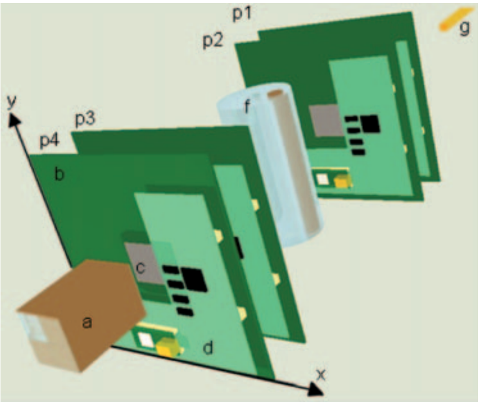

Fig. 1. – Layout of the pCR apparatus: a) calorimeter; b) front-end board; c) microstrip sensor; d) digital board; f) phantom; g) beam pipe; p1-p4) tracker planes.

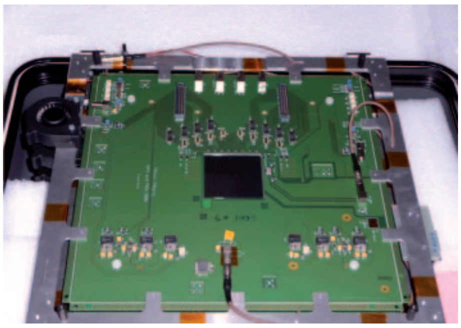

Fig. 2. – A pCR tracker front-end board.

2˙1. *The Tracker system.* – The pCR tracker is made by four planes (fig. 1 (p1-p4)) each one capable to measure the proton trajectory impact point as a 3-dimensional position complemented by information on timing and deposited charge in silicon. A single tracker plane is realized using two identical modules each one carrying a single-sided microstrip sensor at its center. Two modules are coupled back-to-back in order to have the sensors completely overlapping with their strips mutually orthogonal. The module is made by one tracker front-end board (fig. 2) with a tracker digital board (fig. 1 (d)) plugged on it.

The single-sided silicon microstrip sensors are of p-on-n type with a substrate $\langle 100\rangle$ orientation, a thickness of $200 \pm 15\,\mu$m, a strip pitch of $200\,\mu$m and a total depletion voltage equal or less than 75 V. The total number of strips per sensor is 256 in an active area of $51 \times 50.66\,\text{mm}^2$. The fraction of disconnected strips is 3.4×10^{-3}.

The front-end ASIC for the microstrip read-out, designed in AMS $0.35\,\mu$m CMOS technology, consists of 32-channels, each equipped with a charge-sensitive amplifier, a shaper and a comparator that produces a digital output by comparison with an external threshold. For testing and calibration the ASIC can be pulsed to inject a known charge, via a bank of 0.5 pF capacitors, into the preamplifiers.

The silicon microstrip sensor and its read-out ASICs are glued and micro-bondend onto the front-end board. The microstrip sensor is glued onto a square aperture located at the center of the board. The precision of the gluing operation is not very important: the absolute spatial alignment of the eight sensors of the tracker is done using tracks when no phantom is present between the tracker planes. The front-end board hosts the DACs used to set the threshold voltage for each ASICs.

The 256 digital signal lines are connected to the tracker digital board plugged on the front-end board. The digital board mounts a Xilinx Spartan FPGA which samples in parallel the signal lines to find active strips. The FPGA operates in pre-trigger mode continuously sampling at 50 MHz the strip signals but acquiring data only in a time window of about $5.1\,\mu$s around the trigger ($4\,\mu$s before and $1.1\,\mu$s after). For each active strip its number, the signal start time with respect to the trigger and its duration, are formatted together event building ancillary information. Data is then moved to a RAM memory (4×16 Mbit chips, able to store up to 5×10^5 events). The board hosts an ethernet module used for data and command communication.

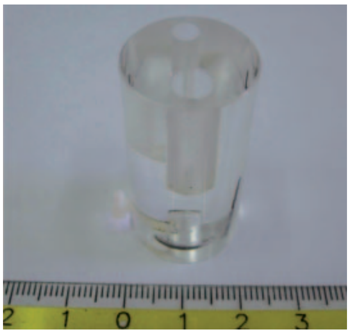

Fig. 3. – The tomography phantom: 20 mm external diameter with 4 mm and 6 mm diameter holes.

3. – Calorimeter system

The pCR calorimeter is made by four YAG:Ce (Yttrium Aluminum Garnet activated by Cerium) scintillating crystals assembled in an optically decoupled 2×2 matrix. Each crystal has a $3 \times 3\,\mathrm{cm}^2$ cross-section and a depth of 10 cm to stop up to 230 MeV kinetic energy protons.

The calorimeter measures the residual proton energy and generates the trigger signal. To use the calorimeter close to the stray magnetic field always present near a beam line the selected crystal should have a light emission wavelength fitting the sensitivity spectrum of silicon photodiodes. Furthermore the light emission decay constant should be fast enough to be used in a high particle flux environment. The YAG:Ce crystals match these requirements having an emission ligth peak at 550 nm and a light decay constant of 70 ns with an integrated light output relative to NaI of 40% (35000 photons/MeV) almost insensitive to operating temperature. The material is not hygroscopic and has a density of $4.56\,\mathrm{gcm}^{-3}$. Each crystal is glued to a Hamamatsu S3204 photodiode. The read-out electronics consists of a charge-sensitive amplifier and a $1\,\mu$s peak time shaper. The analog signals are sampled by an acquisition board hosting 14 bit 10 MHz Flash-ADCs. The analog signals are also sent to comparators whose logical *or* output is used for triggering. The eigth least significal bits of the trigger counter are used to produce a Global Event Number tag to synchronize tracker and calorimeter data.

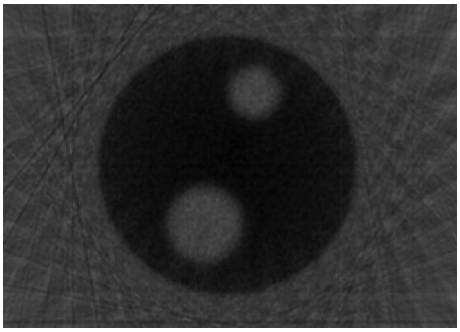

Fig. 4. – FBP reconstructed image.

4. – pCT images

The pCR system has been tested at INFN-LNS in Catania using 60 MeV protons. In particular a cylindrical phantom made of PMMA (fig. 3) has been mounted between plane 2 and 3 of the tracker and data have been taken rotating the object at 36 different angles in steps of 10 degrees. On average about 2×10^6 events per angle have been collected. The Filterd back-Projection (FBP) algorithm implemented in [6] has been used to reconstruct the tomographic image of the phantom. The effect of the MCS on the proton trajectories has been reduced selecting protons which do not deviate more than ±4 mrad from the nominal beam direction. Figure 4 shows a picture of the FBP reconstructed image.

5. – Conclusions

A system for pCR has been developed and tested as a first step towards a proton tomography equipment to be used in pre-clinical studies. The apparatus is made by a silicon tracker followed by a YAG:Ce calorimeter and collect data in single proton mode. The system has been tested using a 60 MeV proton beam at the Catana line of INFN-LNS. Collected data have been used to reconstruct radiographies and tomographic images to extensively test the device.

The PRIMA+ collaboration is presently working on the development of a similar pCT equipment with an enlarged field of view ($5 \times 20\,\mathrm{cm}^2$); this system will reconstruct tomographies of objects with dimensions close to the ones of clinical interest.

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