Nuclear Instruments and Methods in Physics Research A 1068 (2024) 169690

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

A novel detector for 4D tracking in particle therapy

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ARTICLE INFO

Keywords:
Particle therapy
Beam monitors
Silicon sensors
Particle counting

ABSTRACT

An innovative beam monitor for particle therapy applications was developed to count protons and carbon ions in clinical beams and was integrated with a Time-to-Digital Converter (TDC) to add the measurement of particles' crossing time. The detector exploits strip-segmented planar silicon sensors with an active thickness of a few tens of μm and the front-end electronics is based on a 24-channel ASIC (named ABACUS) for the discrimination of the particles' signals. The proton counting efficiency shows a dependence on the beam energy because of transversal dimension and pile-up effects, whereas an efficiency between 94 and 98 % with lower energy dependence is found for carbon ions. The time measurements with the TDC allow for the study of the time interval between consecutive particles in one strip, which appears to be compatible with the radio-frequency period of the synchrotron. These results indicate that thin silicon sensors and custom front-end readout with high counting rate capability allow for a full 4D tracking of clinical ion beams, opening the way to future technologies for online monitoring systems.

1. Introduction

Gas-filled ionization chambers (IC) represent the state-of-the-art of beam monitors used in particle therapy to measure the beam position and shape and the particle flux. Even though ICs are widely used in clinics, showing good radiation hardness, the slow charge collection time (∼100 μs) and the low sensitivity (∼1000 particles) prevent ICs from being used for faster irradiation modalities. The medical physics group of the University of Torino and the Nuclear Institute for Nuclear Physics (INFN) is working on the development of new detectors based on silicon sensors for applications in beam monitoring and treatment verification for particle therapy. Thin planar silicon sensors appear to be a promising alternative to ICs, allowing for the direct discrimination of particles, thanks to the short charge collection time (∼1 ns) and to the sensitivity to the single particle [1].

This contribution presents a beam monitor prototype based on strip-segmented silicon sensors developed for direct counting the number of delivered particles and measuring the beam shape at clinical fluence rates (2×10^9 protons/(cm^{2}s) and 5×10^7 carbon ions/(cm^{2}s)). Furthermore, the detector can be connected to a Time-to-Digital-Converter (the CERN PicoTDC [2]) to measure the crossing time of the particles. The beam monitor was characterized with both clinical carbon ion and proton beams at the Centro Nazionale di Adroterapia Oncologica (CNAO) in Pavia, Italy, and the counting efficiency, the beam profiles and the distribution of time interval between consecutive particles are reported.

2. Material and methods

2.1. Silicon sensors

The main challenge at clinical fluence rates is the counting inefficiency due to the overlap of the signals (pile-up) generated by consecutive particles. Therefore, sensors with an active thickness of a

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https://doi.org/10.1016/j.nima.2024.169690
Received 28 June 2024; Received in revised form 22 July 2024; Accepted 1 August 2024
Available online 3 August 2024

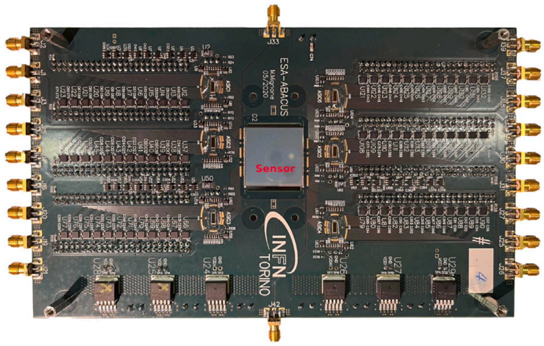

Fig. 1. ESA-ABACUS board.

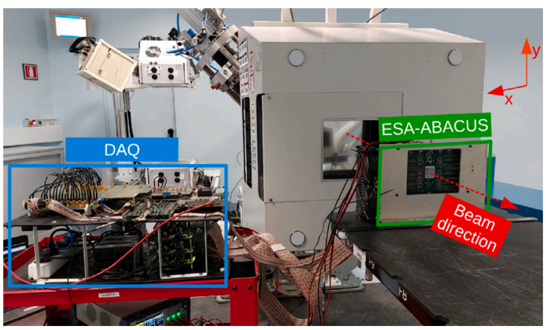

Fig. 2. Experimental setup in a treatment room at CNAO.

few tens of μm were chosen in order to obtain fast signals (duration of about 1–2 ns). Another requirement is the fine segmentation of the sensor to reduce the particle rate per channel, to limit the sensor capacitance and to provide a position resolution. A 60-μm-thick n-on-p diode and a 50-μm-thick Low Gain Avalanche Diode (LGAD) sensor were produced to detect carbon ions and protons respectively, by Fondazione Bruno Kessler (FBK) and INFN. In the LGAD sensor, the gain layer was obtained by implanting boron below the n^{++} electrode with a doping concentration of $\sim 10^{16}$ cm^{-3} and a thickness of ∼1 μm [3,4]. The gain implant is needed to enhance the signal-to-noise ratio for protons, compensating for the much smaller charge in the sensor with respect to carbon ions. Both the sensor areas are segmented in 146 strips with a length of 26214 μm and pitch of 180 μm to achieve a total sensitive area of about 2.6×2.6 cm^2, enough to cover the cross section of a pencil beam (FWHM ∼1 cm at the isocenter). An inter-strip distance of about 80 μm is not covered by the gain implant [4], thus behaving as a dead inter-strip area.

2.2. Readout electronics and DAQ system

A front-end board, named ESA-ABACUS (Fig. 1), was developed for the readout of the silicon strips by means of six 24-channel ASICs (named ABACUS), designed at the INFN of Torino [5]. Each channel features a Charge Sensitive Amplifier (CSA) characterized by a wide input dynamic range (4–150 fC), followed by a leading-edge discriminator. A common threshold voltage for all channels of each chip is provided by an on-board Digital to Analog Converter (DAC) and can be fine-tuned channel by channel through an internal DAC to compensate for the non-uniformity in the channel pedestals (DC offset value at the output of the CSA). The dead time of the ABACUS channel was shown to be between 5 and 10 ns [5], corresponding to a full counting efficiency of 100% up to an input frequency of 100 MHz or larger, depending on the input charge. When the particles' signals are discriminated, the generated digital pulses are propagated out-of-chip to be counted by three Kintex7 FPGA boards (KC705 evaluation board), sampling the ABACUS outputs at 1 GHz and implementing a counter for each channel to store the number of crossing particles. The same FPGA boards are used to program the thresholds and a LabVIEW program was developed to read the values of the counters every 100 ms, to select thresholds and to store data for the off-line analysis. Alternatively, the digital pulses can be acquired by the CERN PicoTDC [2] after a proper translation of the digital signals, to measure the time of arrival of the particles. The CERN picoTDC features 64 channels with 3-ps bin size and a dynamic range of 205 μs. It can operate in streaming mode, acquiring all the input events, or in trigger mode, in which only events occurring in a specific time window are stored. In trigger mode, a window with programmable width is open back in time depending on the set latency whenever a trigger signal arrives. It must be noted that only 12 channels of the ESA-ABACUS can be connected to the picoTDC in the current configuration of the setup. The DAQ of the PicoTDC is based on a Virtex7 FPGA board with a dedicated firmware developed at CERN.

2.3. Measurements at CNAO

Two ESA-ABACUS boards were characterized with carbon ion and proton clinical beams respectively at CNAO (Pavia). The ESA-ABACUS was placed at the isocenter with the strips parallel to the couch plane and perpendicular to the beam direction (Fig. 2). Both the sensors were depleted with a negative bias voltage of 200 V. The internal DACs were set to the optimal values measured with characterization tests in the laboratory to compensate for the channel pedestal non-uniformity. The optimal thresholds to discriminate the particles' signals from the noise were selected by performing threshold scans while irradiating the sensor as described in [6].

In order to assess the counting efficiency of the detector, several runs were performed with different clinical energies in the available range (60–230 MeV protons and 115–400 MeV/u carbon ions) and three nominal beam intensities available at CNAO (20, 50, 100%) expressed as a percentage of the clinical fluence rate. For each run, the dose delivery system was configured to deliver 20 identical beam deliveries (spills) with the same energy and intensity. The number of particles per spill was set to 2×10^7 for carbon ions and 2×10^9 for protons. The counting efficiency was computed as the total number of particles detected in by the ESA-ABACUS (PPS) divided by the number of particles estimated from the charge collected by the CNAO ICs.

The performances of the beam monitor integrated with the CERN PicoTDC were only studied with carbon ions of different energies and intensities, connecting eight ESA-ABACUS channels to the TDC. The acquisitions were performed in trigger mode, setting a 10-μs-wide window and sending an external trigger signal at a frequency of 50 kHz using an external pulse generator.

3. Results

3.1. Counting of particles

Fig. 3 reports as an example the number of carbon ions counted as a function of the time in one strip during a run with an energy of 115.23 MeV/u. The beam delivery structure characterized by spill and inter-spill times is well observable and the total number of particles detected per spill in such a strip is also shown. By combining the particles per spill of all the channels, the beam projection on the axis perpendicular to the strips can be obtained. Figs. 4 and 5 each present three beam projections corresponding to three energies for carbon ions and protons respectively. As expected, the larger is the energy and the narrower is the beam, characterized by a FWHM ranging between ∼0.6 and ∼1.0 cm for carbon ions and ∼0.7 and ∼2.4 cm for protons. Fig. 6 displays the counting efficiency of the ESA-ABACUS for carbon ions as a function of the energy for three beam intensities. The narrowing of the beam with the increase of the energy results in a better efficiency

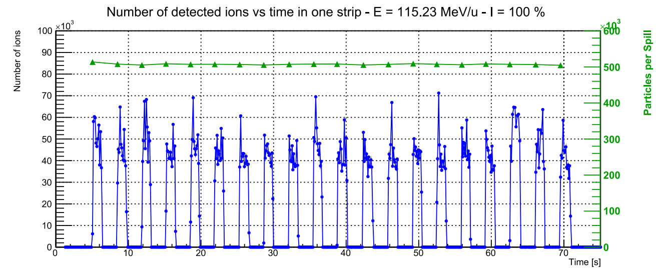

Fig. 3. Number of carbon ions (blue circles) and total number of carbon ions per spill (green triangles) detected in one strip as a function of the time.

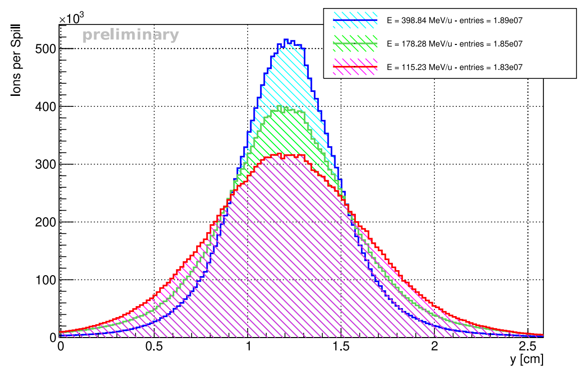

Fig. 4. Projections on the axis perpendicular to the strips of one spill for three carbon ion energies: 115 (red), 178 (green), 399 (blue) MeV/u.

at higher energies, because less particles are lost in the spot tails not contained in the sensor. Additionally, the decrease of the efficiency with larger beam intensity indicates the increasing effect of the pile-up, leading to a variation of the efficiency of 1% or less.

Concerning the counting of protons, it must be recalled that the geometric efficiency of the LGAD sensor is approximately 56% because of the inter-strip dead region. However, a much lower efficiency (Fig. 7) was found for protons with a dependence on the energy. Considering for example the dataset corresponding to beam intensity 20%, the initial increase of the efficiency up to ∼42% may be justified by the shrinking of the beam width leading to larger beam containment. Then, the main contribution to the decrease down to ∼20% is the reduction of the signal-to-noise ratio with the increase of the energy. Because of the larger fluence rate used with protons, the pile-up affects the efficiency more significantly in comparison to carbon ions. This can be noticed considering that the efficiency variation between intensities 20 and 100% at fixed energy ranges between ∼10% (226 MeV) and ∼20% (62 MeV).

3.2. Time of arrival of carbon ions

Fig. 8 shows the distribution of the time interval between consecutive particles in a strip acquired using a 10-μs-wide window at the maximum energy (398.84 MeV/u) and intensity. Because of the bunch structure of the beam, the distribution is characterized by different peaks separated by a precise time interval (∼363 ns at 398.84 MeV/u) compatible with the radio-frequency period of the accelerator. Fig. 9 reports the radio-frequency period measured for different carbon ion energies and intensities compared with the expected values computed from the circumference of the synchrotron and the particles' energy. The measured period is independent of the intensity and results compatible with the expected values for all energies at a significance level of 5% ($Z_{Gauss} \sim 0.3$).

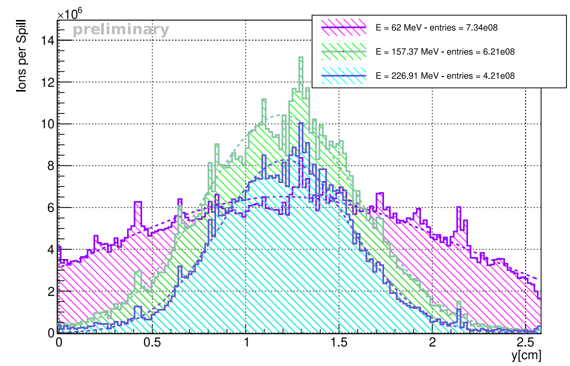

Fig. 5. Projection on the axis perpendicular to the strips of one spill for three proton energies: 62 (red), 157 (green), 227 (blue) MeV.

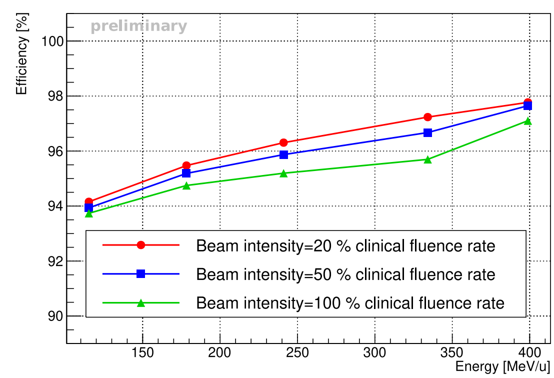

Fig. 6. Counting efficiency of carbon ions as a function of the energy for three beam intensities expressed as percentage of the clinical fluence rate.

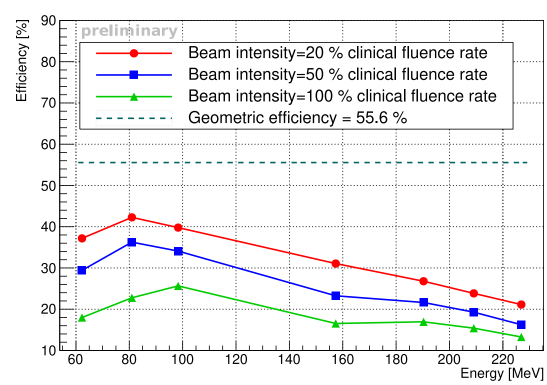

Fig. 7. Counting efficiency of protons as a function of the energy for three beam intensities expressed as percentage of the clinical fluence rate.

4. Discussion

The number of particles estimated from the CNAO ICs was chosen as a reference to evaluate the counting efficiency of the detector. It must be underlined that such a reference is affected by systematic uncertainties. The conversion from the charge collected by ICs to the corresponding number of particles has never been verified directly, but it has been derived through the dose measured in reference conditions and Monte Carlo simulations to determine the number of particles needed to achieve the same dose [7]. Possible systematic uncertainties in the simulation may come from the error on the mean energy loss, the lateral distribution of the beam and number of particles lost in interactions with air not properly simulated. Such uncertainties have not been taken into account yet in the reported results. The only considered

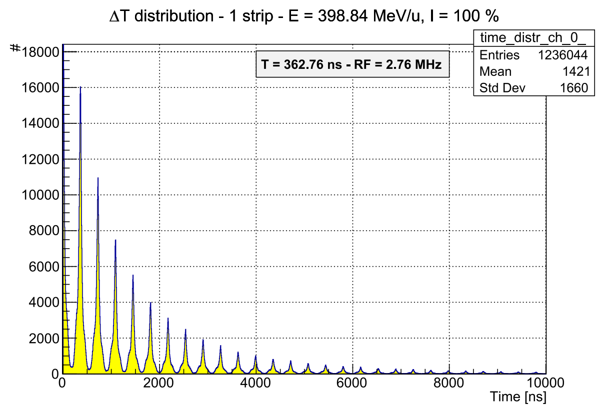

Fig. 8. Distribution of the time interval between consecutive carbon ions in one strip for energy 398.84 MeV/u.

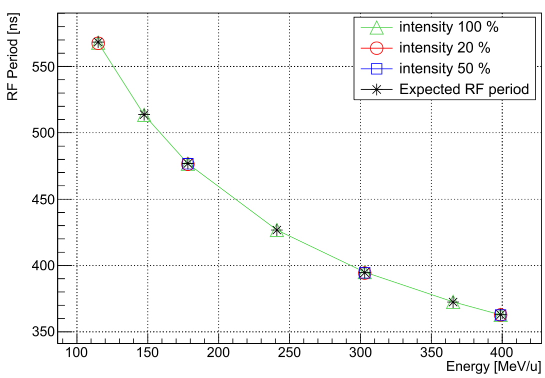

Fig. 9. Radio-frequency period vs energy with carbon ions intensities 100, 50 and 20% (green triangles, blue squares and red circles respectively) compared with expected values (black stars).

uncertainty is the Poissonian error on the number of counted particles, which is also propagated on computation of the efficiency (error bars are not visible because of the size of the markers).

The main contributions to the inefficiency found for counting protons are the low signal-to-noise ratio of the LGAD sensor and the non-complete compensation of the channel by channel pedestal non-uniformity, which results in unexpected peaks and valleys in the proton beam projections. The measurements with carbon ions are much less affected thanks to the larger signal-to-noise ratio.

5. Conclusion

The reported results prove the feasibility of developing a detector based on thin silicon sensors for the full 4D tracking at high rates of therapeutic beams. A counting efficiency between 94 and 98% was found for carbon ions, whereas more investigations are needed to better optimize the LGAD sensor for the detection of protons. Further studies are ongoing to mitigate the observed pile-up effect and to understand possible systematic uncertainties. A new production of ABACUS chip with a larger threshold fine-tuning range will be used to compensate for the pedestal non-uniformity. Furthermore, activities are ongoing for integrating the presented beam monitor with other detectors for measuring the range of clinical carbon ions in a target by means of the prompt gamma timing technique [8].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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