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Physics

Development of Low Energy Range Calorimeter for Proton Tomography

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(Presented by Academy Member Anzor Khelashvili)

A low energy range calorimeter for proton tomography, possible future substitution for X-ray tomography is under development. Furthermore, it can also be used for the precise energy monitoring of the proton beam of the cyclotron. Active elements of the calorimeter are based on thin plastic scintillator tiles. Each element is independently read-out by silicon photomultipliers (SiPM). A dedicated SiPM biasing supply and a preamplifier are developed for signal acquisition. The cosmic ray telescope is used to test the calorimeter elements. Tests have not revealed any issue with the light collection and the amplification of the collected charge, thus leading to a reasonably high value for the particle detection efficiency, as expected. Besides, the amplitudes and the lengths of the obtained signals are sufficient to be digitized with relatively simple apparatus. Development of the Monte Carlo simulation software started. The main goal of the simulation is to qualify the limiting factors of the setup, such as multiple scattering and energy losses of the incident protons before and after passing the body. This will also facilitate the estimation of the range determination uncertainty of the calorimeter. The developed simulation code is able to estimate the range dependence on the proton initial energy, as well as the fluctuations of the energy deposit for protons that are stopped in the calorimeter layer. These results together with the laboratory test data of a single calorimeter element will be presented in this paper. *© 2023 Bull. Georg. Natl. Acad. Sci.*

calorimeter, scintillator, SiPM, proton tomography, hadron therapy

In the second half of the 20th century, the idea about proton tomography method received scientific justification [1], but it was not in great demand in clinics. Now, when proton therapy is becoming an advanced method of treating tumors, there are clinics with proton accelerators in almost every country. Therefore, proton tomography is becoming relevant. Our interest in this topic is due to the construction of a Hadron Therapy Center in Georgia, in Kutaisi (KHC). Two cyclotrons with 230 MeV proton beams (by IBA company, Belgium [2]) will be situated there. Proton tomography uses particles that penetrate the irradiated body, depositing only the part of their energy due to the ionizing losses. By stopping these particles in the calorimeter, the part of the initial energy lost in the body can be estimated. On their way through the tissue, protons experience multiple scattering on dense parts of the body. Coordinate detectors located in front of the calorimeter can provide information on the location of the density thickening.

Proton therapy method can significantly reduce the integral dose received by patients, compared to X-ray method of treatment. When protons are used for scanning, they fully pass through the body, and the minimum energy, loosed for the medium ionization is significantly less compared to that for X-rays. Therefore, the radiation dose received by the body is significantly reduced. The dose reduction factor for proton irradiation of the head of a sick dog was estimated as 50-100 in [3].

This fact becomes an inspiration to create the device that would scan the body with minimal irradiation effects, i.e. low energy proton tomography. Currently, X-rays are used for this purpose, with a high dose of irradiation, which limits their use to control the treatment process. Many institutes have already begun to create Proton Tomography devices and have identified various directions for solving related problem. The main hardware elements of such devices are the calorimeter, measuring the energies of the protons that pass through the body and leave part of the initial energy in dense parts of the body, and coordinate detectors for tracking of the deflected protons in these areas [4-6].

Materials and Methods

Scintillation tiles. The layered hadron calorimeter intended for measuring energies of protons is made of scintillation tiles with individual read out. These tiles were originally manufactured for ATLAS TileCAL (CERN) [7, 8]. The thickness of each of the tiles is 3 mm. Other geometrical dimensions are shown in Fig. 1. Two holes with diameters of 9±0.1 mm are foreseen for calibration of the tiles with a radioactive 137Cs source. The main material used is polystyrene (PSM-115, 0.96-1.05 gr/cm³) with a wave length shifter addition: 1.5% PTP (Para-TerPhenyl, λabs=275 nm, λem=340 nm) and 0.044% POPOP (1,4-bis-(2-(5-phenyloxazolyl))-benzene, λabs=365 nm, λem=420 nm) [8].

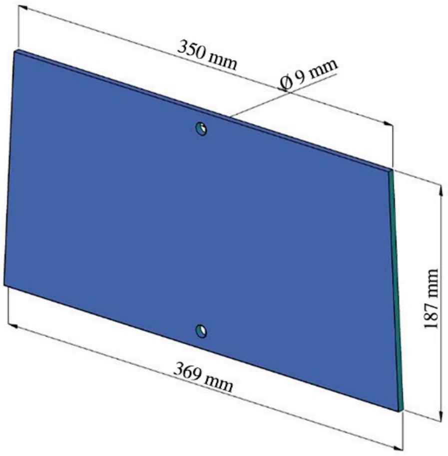

Fig. 1. A scintillator tile.

Silicon Photomultiplier AFBR-S4N33C013 (3×3 mm^2) produced by Broadcom [9] is used for scintillation light detection from the tiles. The highly transparent protective layer of this SiPM achieves a broad response in the visible light spectrum with the highest sensitivity to the blue and near UV light. According to the manufacturer specifications, the plot of the photo detection efficiency (%) vs absorption spectrum λ(nm) vs over voltage shows the peak efficiency at 420 nm. This agrees well with the emission spectrum of the scintillation tile.

SiPM biasing and readout. An original power supply has been developed to provide a stable bias voltage for SiPMs. It is based on a previously developed modular power supply for the JEDI experiment [10-12]. A single module of the developed power supply is used in the custom-made power supply for this project. It has been sligtly modified, increasing the output voltage range up to 24-34 V. The module is supplied with 37 V, provided by a mains transformer and a simple preregulator with an additional current limiting feature. The output can supply currents up to 100 mA, which is sufficient to power several calorimeter modules simultaneously.

First tests of the selected SiPM in combination with the scintillator tile using cosmic rays revealed the necessity for a descent amplification and shaping of the obtained signals before the analog-to-digital conversion. Unlike traditional PMTs, the SiPMs have considerably higher output capacitance (≈500 pF for the selected model) which introduces additional challenges for the amplifier design. Besides, in order to benefit from their fast responce times, SiPMs require low impedance loading. In principle, a transimpedance amplifier based on a high speed operational amplifier can be a reasonable solution to those requirements. However, numerous developments (including [13]) suggest using transistors in the common-base configuration instead.

The dedicated transistor-based preamplifier has been developed for this project. It consists of three amplification stages of fast bipolar transistors. The first stage uses the common-base configuration and acts as a transimpedance amplifier. The estimated AC input impedance is in the order of few ohms. The third stage uses common-emitter configuration with 50 ohm output impedance and provides the final power gain, which can be varied with the potentiometer. The middle stage – the emitter folower - ensures the impedance matching between input and output stages.

Before assembly, the whole schematics was simulated using NI Multisim software [14] to validate the concept, to identify the weak points and to finetune the values of the passive components. Afterwards, a single channel of the developed preamplifier was constructed with Surface Mount Devices (SMD) components on a compact PCB with the dimentions of 40×15 mm^2. The board also includes an addition RC filter for the SiPM bias voltage. It filters out the high frequency EMI noise arising in the power delivery lines. Besides, the capacitors included in the filter, act as a charge buffer and help to hold the bias voltage during the SiPM breakdown events. Initial tests of the preamplifier board were performed by using an arbitrary signal generator. The gain (not maximum) was estimated to be around 1.25 V/mA. It maintains a good linearity at output signal amplitudes of up to 1 V.

Calorimeter element assemby and tests. As a next step the assembled preamplifier was tested together with a single SiPM attached to the scintillator tile. The SiPM in the SMD package was placed on the tiny PCB to also accommodate the wire connections to the preamplifier. Initially, the SiPM was attached to the corner of the tile, cut at the 45° angle in advance. However, as later tests have revealed, it is beneficial to attach it to the side of the tile to improve the light collection efficiency. The scintillator itself has been wrapped up in a Tyvek 1055B [7] to reflect back the escaping scintillation light. The whole assemly of the single calorimeter module had been tested with cosmics inside a metal box, providing shielding from external light and EMI. The module was placed between the two other scintillators (also with SiPM readout) in a way that the particle passing those two, would also pass the calorimeter module. Outputs of the two trigger scintillators formed a coinsidence signal with a time window of 100 ns. NIM electronics modules were employed for this task. The signals from the calorimeter module were sampled with the help of flash analog-to-digital (FADC) converter board STEMlab 125-14 [15] and acquired for the later analysis by using a custom data acquisition software, which is based on C/C++ and CERN ROOT libraries [16]. The triggering channel of the FADC board was connected to the coinsidence of NIM signal, while the other – to the preamplifier output of the calorimeter module. Therefore, the data were always written regardless of whether the calorimeter module detected particle or not. In such a way the evaluation of the detection efficiency of the tested module became possible.

Results

Measurement. In order to determine the upper limit of the efficiency of the developed calorimeter module, it is essential to distinguish events containing usefull detection signal from the background. This is usually done by building distributions of the collected charge and setting a threshold within the observed gap between signal/background – related parts of the spectrum. However, this became a challenge in the acquired data, since signal and background spectra overlap and there is no such a gap in the distribution. The offset instability arises due to different sources of the noise, such as FADC noise, EMI, SiPM’s dark counts and afterpulses, etc. Although the gain of the preamplifier is rather high, the usefull signals still have small amplitudes since only a single SiPM is used and the scintillator is quite thin (Fig. 2).

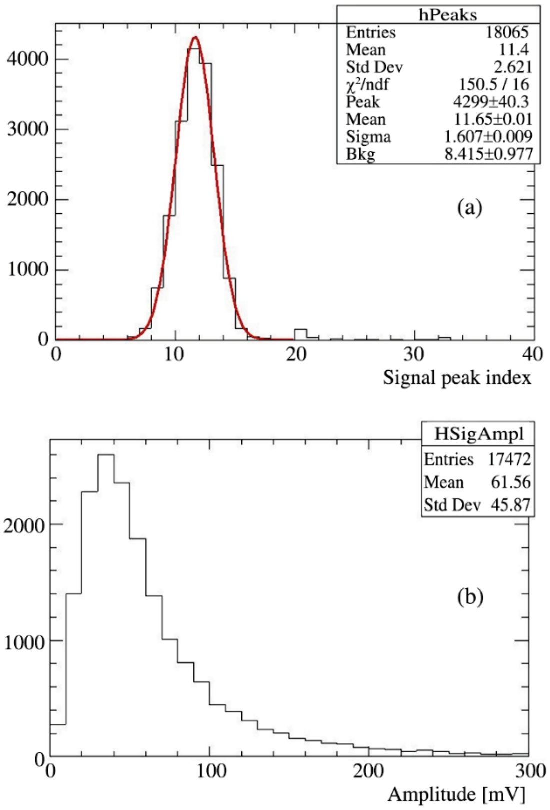

Fig. 2. Distribution of the signal peak positions (a) and the amplitude spectrum of the signals within the fitted Gaussian peak (b).

A novel approach has been employed to successfuly accomplish this task. The signal delays from all of the three detectors are expected to be highly time-constrained. Therefore, the peaks were searched within the calorimeter signal samples and the peak position distribution was built. This produced a Gaussian-like peak on top of some little background. Every event was treated as containing the usefull signal if the peak position fell within the three sigma interval around the mean value of the Gaussian fit. The detection efficiency equal to 0.97 was estimated as the number of events containing usefull signal divided by the number of all events. By adding an additional practical lower threshold of 10 mV on the signal amplitude, this number slightly reduces down to 0.95.

Simulation. We started to develop the simulation software for the layered range calorimeter in order to optimize its performance. Initially, the setup concept was developed in order to estimate the physical performance limits. For the selected setup configuration, it is critical to define $L = f(E)$ dependence of the stopping depth for proton beam energies of up to $E = 230$ MeV (The maximum available energy of the accelerators at Kutaisi Hadron Center). It is also important to select the most suitable degrader material with the right thickness to place in front of the range calorimeter and/or in between the layers.

In order to define the physical limits of the proton tomography resolution, the Monte Carlo simulation has to be performed. The simulation software is being developed in the geant4 [17] framework. The model of the setup consists of the tracking detectors (DC) and the layered range electromagnetic calorimeter. The setup scheme is shown in Fig. 3. The proton beam is directed along the z axis. The tracking detectors are used to reconstruct tracks of individual particles in front and behind the body to scan, or to estimate the spatial resolution. Next to the tracking detectors the range calorimeter is placed. The calorimeter consists of the alternating layers of optically isolated 3 mm-thick scintillators and optional degraders of appropriate thicknesses. The final goal of the simulation is to optimize all important parameters.

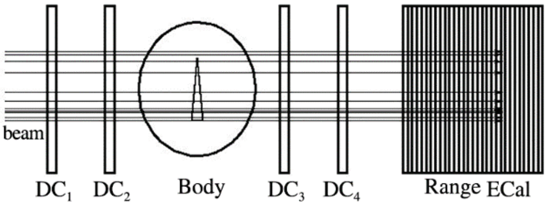

Fig. 3. The setup scheme for the simulation.

For the simulation of physical processes (mainly the multiple scattering and the ionization losses) the low energy physics list (model) of the geant4 framework is used. The setup environment is filled with air. The coordinate (x,y) resolution of the tracking detectors is assumed to be 0.01 mm to estimate the multiple scattering. The distance between the first and the second tracking detectors is equal to 200 mm. The space between the two pairs of the tracking telescopes, where the body is placed, equals to 300 mm. Material of the body is water with modified density.

By simulating the above-described minimal configuration, we have estimated the range dependence on the proton initial energy. The Bragg peak position depth for different energies is shown in Fig. 4a. The curve is known as the Bragg-Koopman dependence. Errors are too small to be visible. We assume that the energy deposit in a layer converted to the emitted light contains only the physical fluctuations. The deposited energy dependence on the particle energy in a layer is shown in Fig. 4b. Actually this is the Bethe-Bloch average deposited energy dependence on the proton energy with physical fluctuations. Additionally, it would be beneficial to experimentally test the calorimeter prototype with β radiation source in order to obtain the fluctuation of the energy deposits at low energies.

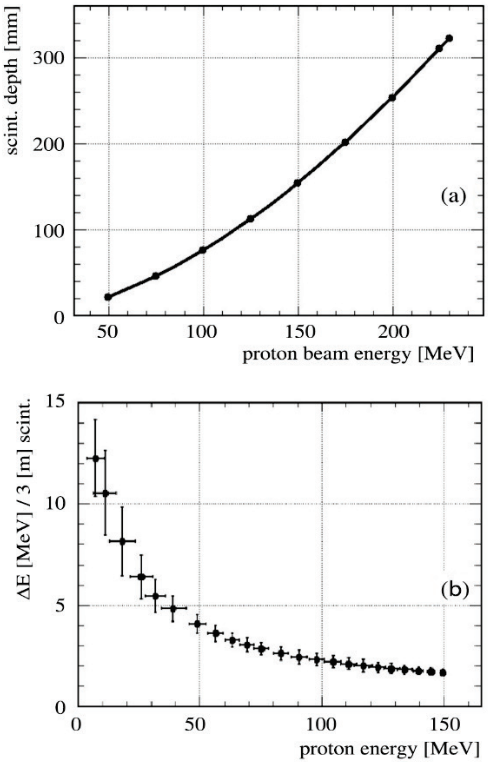

Fig. 4. The Bragg-Koopman dependence (a) and the proton energy deposition in a single layer at different energies (b).

Conclusion

The initiated development of a low energy range calorimeter has been described in this work. The laboratory tests of the first prototype of a single calorimeter element, as well as the Monte Carlo simulation of the setup show very promising results, endorsing the authors for full-scale calorimeter development and its successful implementation for proton tomography.

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ფიზიკა

დაბალენერგეტიკული ზონური კალორიმეტრის შექმნა პროტონული ტომოგრაფიისთვის

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ნაშრომის მიზანია დაბალენერგეტიკული ზონური ადრონული კალორიმეტრის შექმნა პროტონული ტომოგრაფიისთვის, რომელსაც პოტენციურად შეუძლია ჩაანაცვლოს რენტგენული ტომოგრაფია. კალორიმეტრი გამოიყენება აგრეთვე ციკლოტრონის პროტონული ნაკადის ენერგიების ზუსტი მონიტორინგისთვის. აქტიური ელემენტებია თხელი სცინტილატორული ფილები. თითოეული ელემენტიდან სიგნალი რეგისტრირდება სილიკონური ფოტოგამამრავლებლით (SiPM). SiPM-ის სიგნალის გაზომვისა და დროითი პარამეტრის განსაზღვრისთვის შექმნილია ორიგინალური კვების წყარო და წინასწარი გამაძლიერებელი. კალორიმეტრის ელემენტების შესამოწმებლად გამოყენებული იქნა კოსმოსური სხივები, რომლებიც რეგისტრირდებოდა სცინტილატორული ტელესკოპით. ტესტებმა არ გამოავლინა რაიმე პრობლემა სინათლის შეკრებასა და გენერირებული მუხტის გაძლიერებასთან დაკავშირებით, რის შედეგადაც მიღწეულ იქნა ნაწილაკების დეტექტირების მაღალი ეფექტურობა. ამასთან, მიღებული სიგნალების ამპლიტუდები და ხანგრძლივობა საშუალებას იძლევა სიგნალების გაციფრულება მოხდეს შედარებით მარტივი აპარატურის გამოყენებით. დაწყებულია მონტე კარლოს მეთოდით კალორიმეტრის სიმულაციის პროგრამული უზრუნველყოფის შექმნა. სიმულაცია მიზნად ისახავს ტომოგრაფის მუშაობის შემზღუდველი ფაქტორების შეფასებას და კალორიმეტრის ძირითადი პარამეტრების ოპტიმიზაციას. სიმულაციის ძირითადი ამოცანებია სკანირების დროს პროტონების მრავალჯერადი გაბნევისა და ენერგიის დანაკარგების საშუალო მნიშვნელობების დადგენა გამოსაკვლევ სხეულში გასვლამდე და მის შემდეგ, კალორიმეტრში ცდომილებების ინტერვალების შეფასება. სიმულაციური კოდის გამოყენებით დადგენილია ტომოგრაფის მუშაობის შემზღუდველი ფიზიკური პროცესები. კერძოდ, პროტონების მრავალჯერადი გაბნევა და ენერგეტიკული დანაკარგები. შეფასებულია ფლუქტუაციების დამოკიდებულება პროტონის საწყის ენერგიაზე. კალორიმეტრში გაჩერებული პროტონებისთვის ასევე შეფასებულია შრეში გამოყოფილი ენერგიის ფლუქტუაციები.

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