New calorimetry based on silicon pixel detectors

A. Rakhmatullina, V. Zherebchevsky, N. Maltsev, D. Nesterov, D. Pichugina, N. Prokofiev
Saint Petersburg State University, Russia

LXX International conference "NUCLEUS – 2020. Nuclear physics and elementary particle physics. Nuclear physics technologies“, October 11 – 17, 2020, Online.

Digital Calorimetry

Nowadays calorimetry plays a key role both in experimental studies in high-energy physics and in applied research. Digital calorimeters can be used in nuclear medicine [1] for precise measurements of the beam energy. Also these calorimeters can be used in various experiments in nuclear physics. For charge particles energy identification with high energy resolution the new methods of digital calorimetry can be applied [2].

Digital calorimeters consist of several segmented layers and register the total number of beam particles passing through the detector volume while analogue calorimeters detect the total deposited energy in a given volume. Digital calorimeters have a high granularity compared to other types of calorimeters, therefore the electromagnetic showers (caused by different particles) can be registered with high accuracy. In this work, the new type of compact digital electromagnetic calorimeter based on silicon pixel sensors for the electron beam energy (low-energy electrons from linear accelerator: LINAC-200 at JINR) identification

The present work goals:

1. A digital calorimeter consisting of four layers of silicon pixel detectors and led absorbers was proposed for high-efficient identification of electron beam energy.
2. The absorbers parameters were calculated based on the geometric characteristics of the existing experimental setup. The method of the energy identification by using this digital calorimeter (associated with a change in the intensity of the registered particles on each detecting layer) has been developed (Calculations and Simulations).
3. For developed digital calorimeter the GEANT4 Monte Carlo simulations were done for different energies and absorbers thicknesses in order to find the best geometrical parameters of absorbers (Simulation).

Experimental Setup

The experimental setup consists of four monolithic active silicon pixel detectors (in telescope configuration) 15 mm * 30 mm, 50 µm thick, mounted on supporting structures together with their DAQ boards. The distances between the detectors are variable. The entrance and exit windows of the setup is made of aluminum foil 30 µm thick.

This experimental setup has been successfully tested on cosmic rays and at linear electron accelerator (LINAC-200) for the charge particles track identifications. To create the digital calorimeter the lead absorbers were added between modules with the pixels detectors.

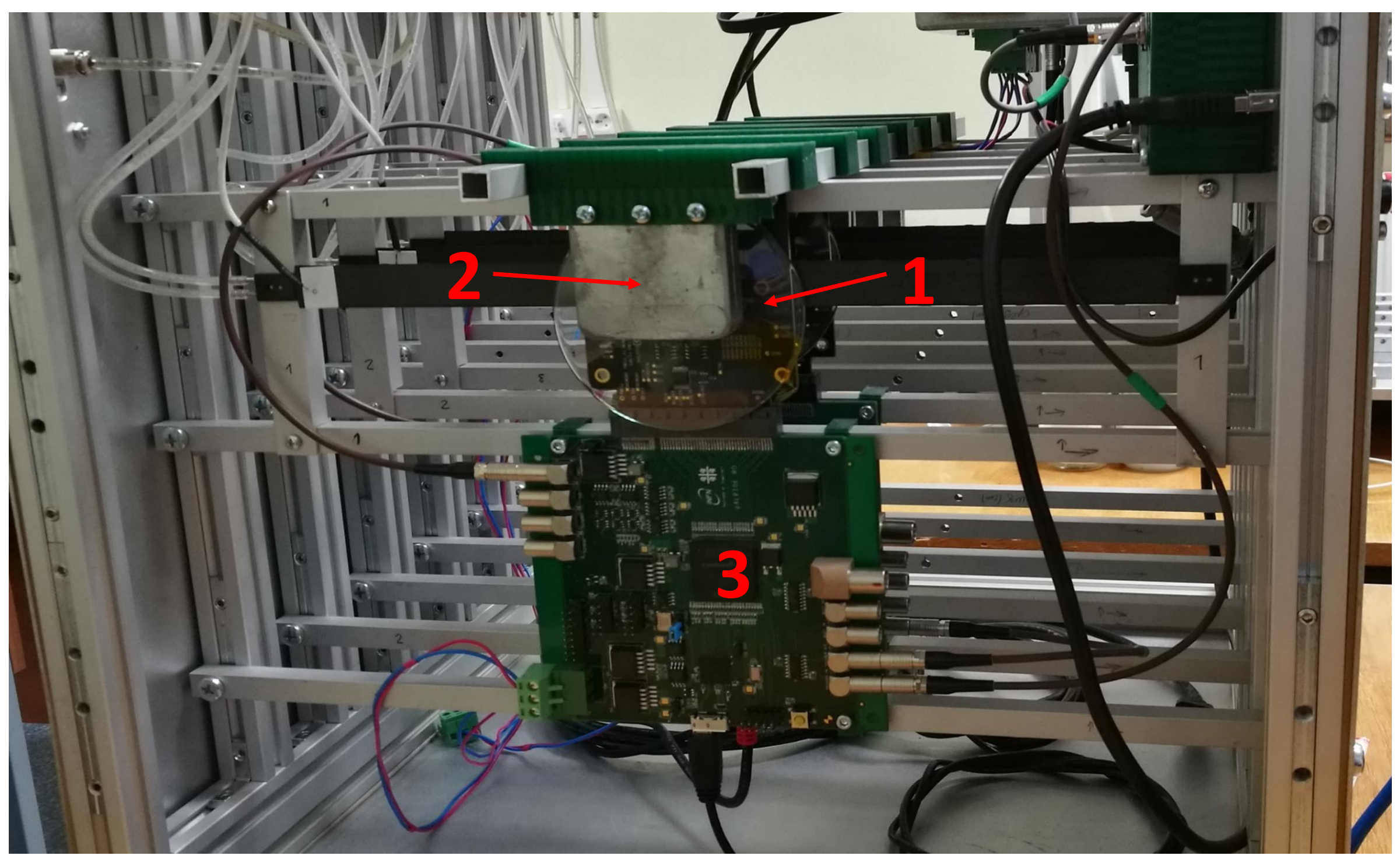

Fig. 1 The Experimental setup based on 4 monolithic active pixel sensors (1) with lead absorbers (2) and DAQ boards (3).

Calculations

Modern sampling calorimeters consist of segmented layers of the absorbers and a detecting modules. The most important characteristic of the absorber is the Molière radius R_M. A cylinder with a Molière radius R_M contains 90% of the particles formed in the electromagnetic shower. The task of sampling calorimeter is to register as many particles of this shower as possible. In digital calorimeters with pixel detectors, two options are realized:

1. The absorbers with a minimum Molière radius R_M such as tungsten (R_M= 0.899 cm) could be used.
2. The several pixel detectors could be implemented in one sensitive layer .

Both of these options increase the cost of such calorimeter. To create a cheaper calorimeter, one can use the fact that the longitudinal dimensions of an electromagnetic shower caused by particles are energy dependent, so an absorber can be made of lead (Pb) with a Molière radius R_M of 1.6 cm. Table 1 shows the calculations of the length L(95%) of a lead cylinder that will contain 95% of the electromagnetic shower caused by electrons of different energies E (from 50 to 250 MeV):

$$L(95\%) = X_0(ln\left(\frac{E\cdot(Z+1.24)}{610\ MeV}\right) + 0.08\cdot Z + 8.6)$$

E (MeV)	L(95%) (cm)
10	8,67356
50	9,57485
100	9,96301
200	10,3512
250	10,4761

Table 1. The calculations of the length **L(95%)** of a Pb cylinder that will contain 95% of the electromagnetic shower produced by electrons of different energies **E**

In this case, it is possible to create a more simplified, cheaper and compact calorimeter that can measure the energy of a monoenergetic electron beam by registering the change in the particle intensity on each detection layer.

In this work, the main characteristics of a digital calorimeter based on four pixel detectors with layers of lead absorbers with different thicknesses were simulated.

Simulation of the Calorimeter Setup

The simulation of a digital calorimeter in GEANT4 was based on a real experimental setup and contained the following elements (see Figure 2):

1. Lead collimator 15 cm thick, inner hole diameter 4 mm
2. Entrance window (30 µm thick aluminum foil)
3. Four silicon monolithic active pixel detectors 15 mm * 30 mm
4. Lead absorbers of different thicknesses (the thickness of the absorbers changed during the simulation, see below)

Due to geometry of the experimental setup, the distance between the detectors and the lead absorbers was set 15 mm after each detector and 10 mm after each lead absorber.

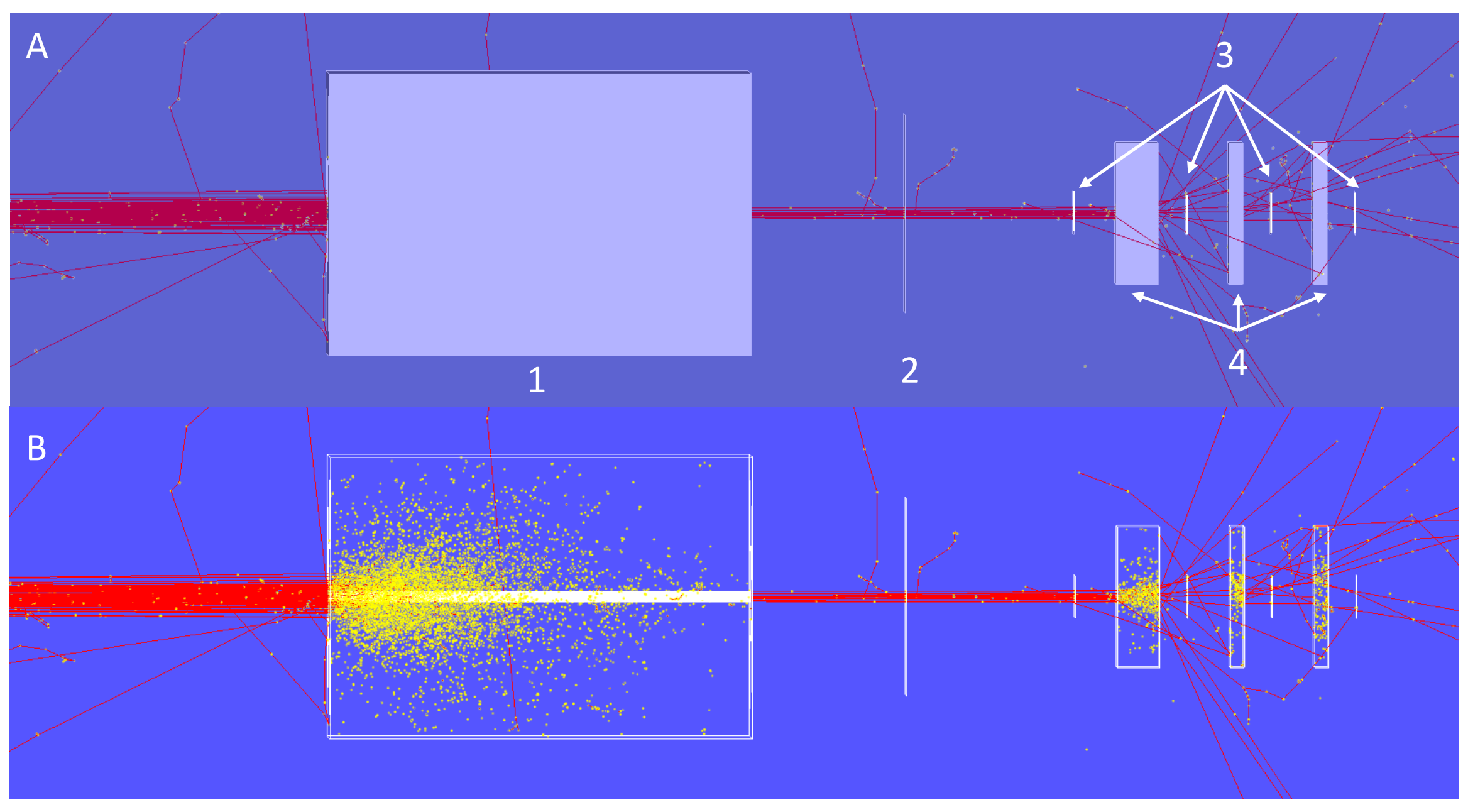

Fig.2 GEANT4 simulation experimental setup. A – the general scheme of the experimental setup, B – the same, with transparent volumes. Red lines are the electron tracks, yellow dots indicate the interaction points. The photon tracks were removed from the picture.

Simulation for Calorimeter at Different Energies of the Electrons

The low-energy electrons have strong scattering in air before calorimeter entrance window. In Figure 3 one can see that the cross section of a 50 MeV electron beam is much larger than the size of the detectors. Therefore, it was decided to use a 15 cm long lead collimator with an inner hole diameter of 4 mm (as shown in Figure 2).

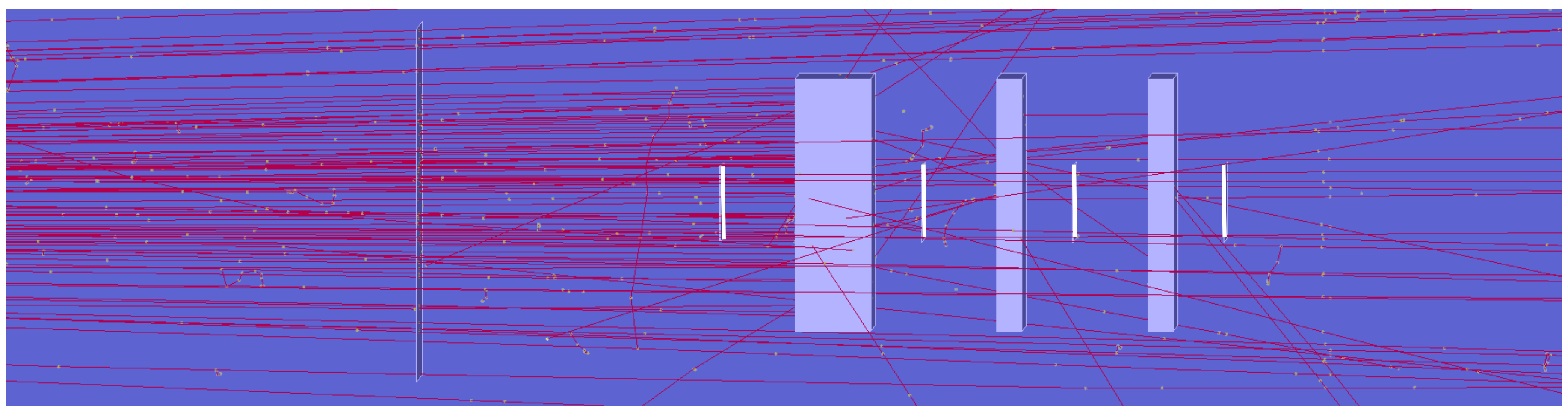

Fig.3 GEANT4 simulation of electron beam with 50 MeV energy. Red lines are electron tracks, the lines from photon tracks were removed.

In Table 2 the simulations of electron beam (at different energies) intensity (on Pixel Detectors) after lead collimator are shown. The number of electrons on each detector was calculated as a function of the beam energy.

For the first detector, the number of electrons that did not lose their energy when passing through the collimator, or with insignificant energy losses (no more than 5 MeV) - column “**N (E0 - 5 Mev)”**, as well as the total number of electrons that reached the first detector (column “**N total”**). The thicknesses of all lead absorbers were set 2 cm.

100 000 electrons in the beam					
Energy of the electron beam E0	Detector 1		Detector 2	Detector 3	Detector 4
	N (E0-5Mev)	N total			
200 MeV	**15225 (15%)**	18081	10814	2260	413
150 MeV	**8908 (8,9%)**	10299	4066	870	136
100 MeV	**3626 (3,6 %)**	4171	788	184	17
50 Mev	**755 (0,7 %)**	809	47	12	0

Table 2. The number of electrons on each detector with using the lead collimator

When the electron beam passes through the lead, a large amount of photons is produced. It is shown in the Figure 4.

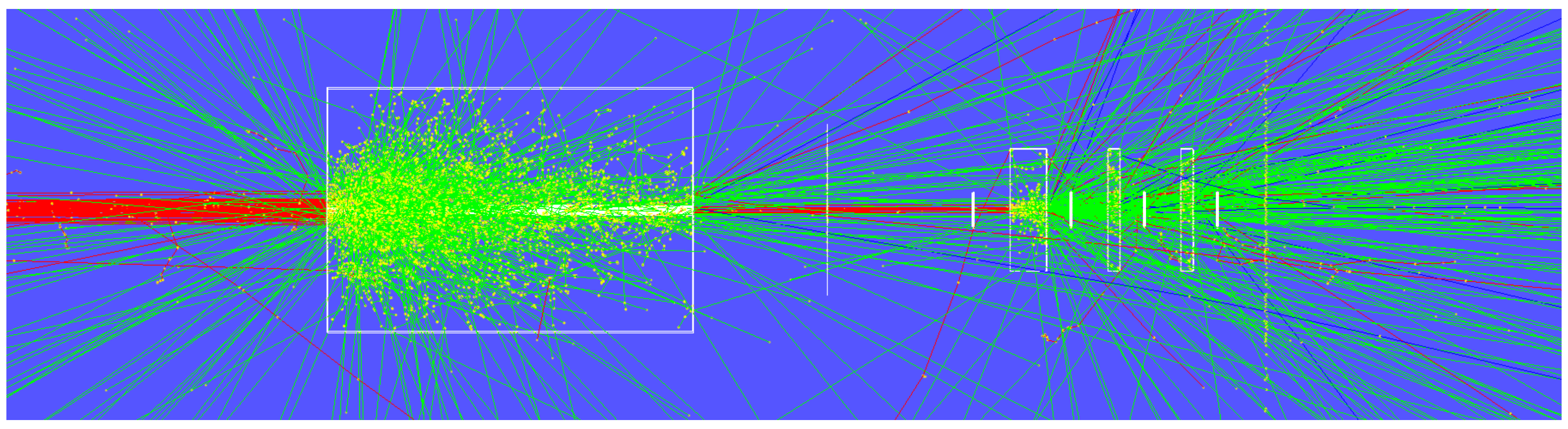

Fig.4 GEANT4 simulation of electron beam with 150 MeV energy. Red lines are electrons, green lines are photons.

The detector can register photons with energies no more 10 keV. The number of such photons (10 keV or less) for each detector depending on the beam energy is shown in the Table 3 below.

Photons with energy 10 keV or less (100 000 electrons in the beam)				
Electron beam energy	Detector 1	Detector 2	Detector 3	Detector 4
200 MeV	10	2	1	1
150 MeV	12	2	1	0
100 MeV	6	1	0	0
50 Mev	2	0	0	0

Table 3. The number of photons registered by each detector

The number of detected photons is small compare to the number of electrons (see Table 2 and Table 3), therefore, in further calculations, only electrons are taken into account.

Calorimeter Simulation with Different Thicknesses of Absorbers

The energy of a monoenergetic electron beam is determined by measuring intensity of the particles, registered by each detector. After the first detector, the beam particles enter the absorber and produce an electromagnetic shower. In an experiment, the beam energy can be determined using the simulation results by counting the number of particles registered at the second, third, and fourth detectors and comparing their values (see Figure 7). Thus, for a digital calorimeter of this type, it is necessary to correctly select the thickness of the lead absorbers in order to determine the energy in the selected range (the range of 50 – 200 MeV was chosen).

The first tests of this method were simulated with all lead absorbers of 3 cm thick, after which it became clear that with such a thickness of the absorbers, too few particles in this energy range reach the last detector (Figure 5), and that the thickness of the absorbers must be reduced as the electromagnetic shower spreads in order to better register the longitudinal characteristic of the shower.

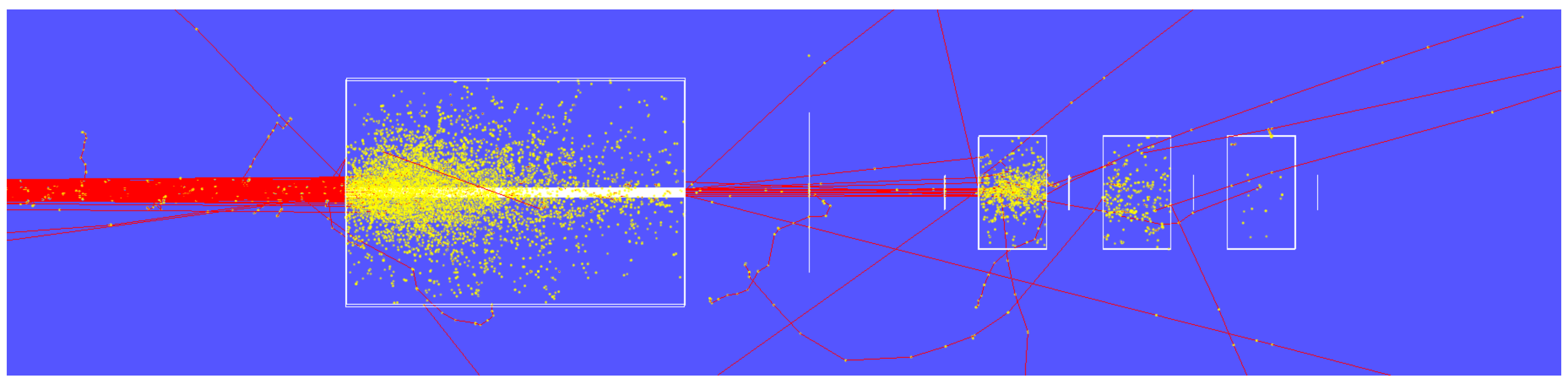

Fig.5 GEANT4 simulation of electron beam with 200 MeV energy. Red lines are electrons, green lines of photons are deleted (see Table 3), the lead absorbers are 3 cm thick.

Then calorimeters based on pixel detectors with the following thicknesses of lead absorbers were simulated:

A. The first absorber is 4 cm, the second is 2 cm, the third is 0.5 cm
B. The first absorber is 3 cm, the second is 2 cm, the third is 0.5 cm
C. The first absorber is 2 cm, the second is 2 cm, the third is 0.5 cm
D. The first absorber is 2 cm, the second is 0.5 cm, the third is 0.5 cm

For variants A-D, graphs of the dependence of the intensity on the electron beam energy were plotted (Figure 6, the intensity of the electron beam was normalized to the number of electrons arriving at the first detector).

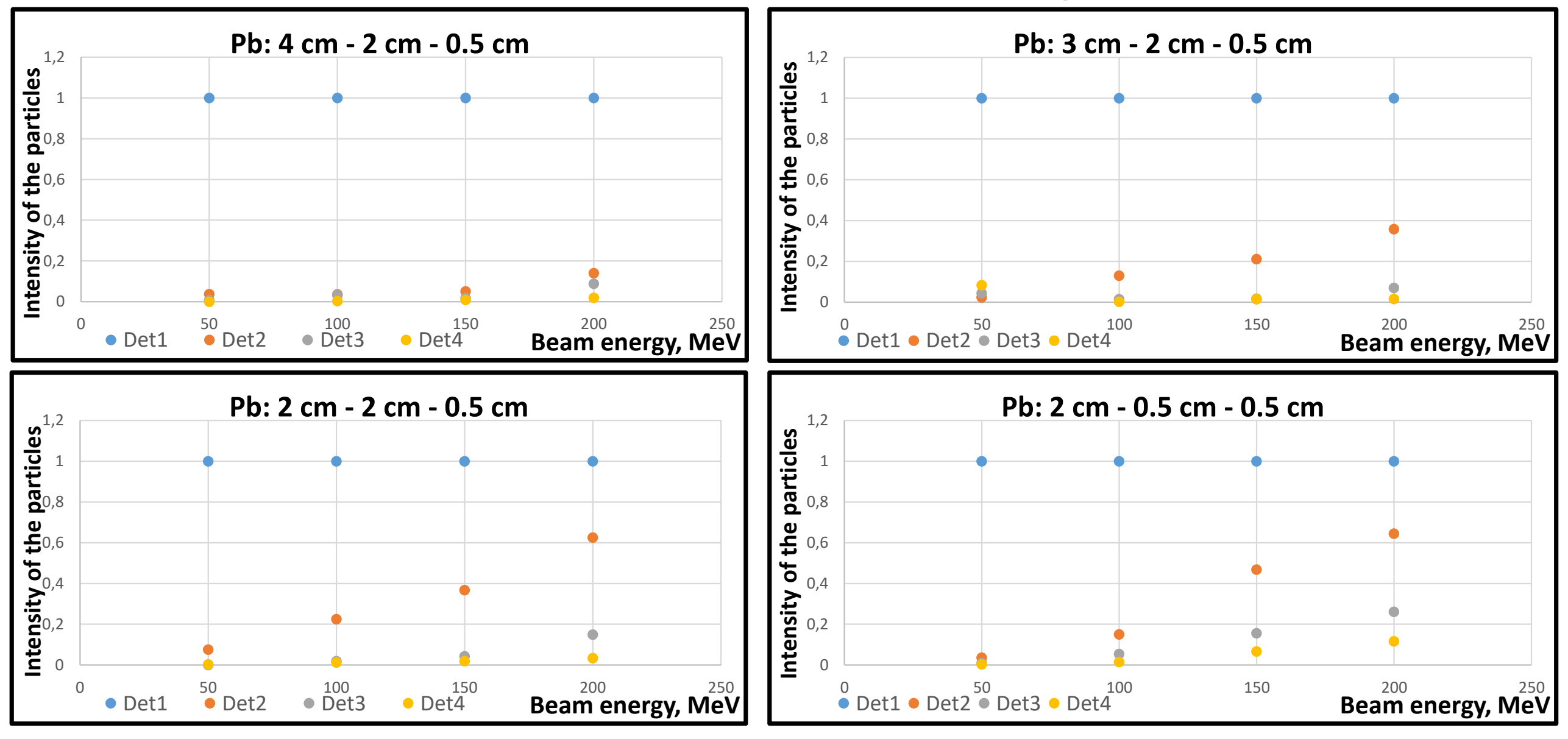

Fig.6 Graphs of the dependence of the intensity of registered particles of each detector on the energy of electron beam with different thicknesses of lead absorbers.

After simulating options A-D and following analysis, it was decided to simulate another option, with absorbers thicknesses 1.5 cm, 0.5 cm and 0.5 cm (Figure 7). This choice of absorber thicknesses turned out to be the most convenient for determining the energies in the selected range of beam energies (50 - 200 MeV).

The lead absorbers of these thicknesses have already been prepared. The full experimental setup in a calorimeter mode will be tested at the LINAC-200. The results of measuring the energy of the electron beam by the calorimeter will be verified by measuring the energy of the beam from its deflection in a magnetic field.

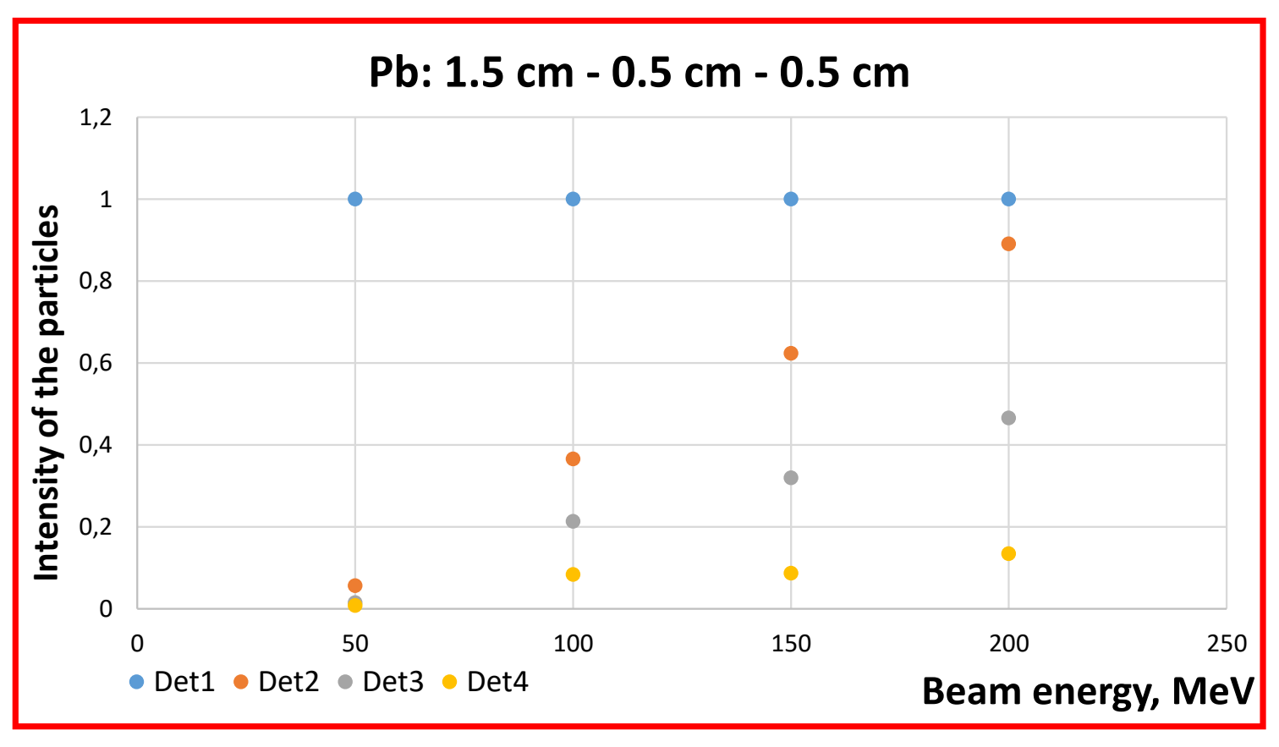

Fig.7 Graph of the dependence of the intensity of registered particles of each detector on the energy of electron beam.

Conclusions

In present work the concept of a digital calorimeter based on four monolithic active pixel detectors was proposed for measuring the energy of a monoenergetic electron beam in the energy range 50 - 200 MeV. Based on calculations of the electromagnetic shower parameters as well as on the GEANT4 simulations, the calorimeter lead absorbers with different thicknesses (1.5 cm, 0.5 cm, 0.5 cm along the propagation direction of the electromagnetic shower) were chosen. Next, this digital calorimeter will be tested on an electron beam. During the experiment at the linear electron accelerator, the calorimeter characteristics will be compared with the simulations.

Literature

[1] M. Varga-Kofarago, “Proton CT -- a novel diagnostic tool in cancer therapy”, arXiv:1903.08087, 2019
[2] A.P. de Haas, G. Nooren, T. Peitzmann et al., “The FoCal prototype - an extremely fine-grainedelectromagnetic calorimeter using CMOS pixel sensors” JINST13 P01014, 2018

The reported study was supported by RFBR, research project No. 18-02-40075.