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Pixel detectors for imaging with heavy charged particles

Jan Jakubek*, Andrea Cejnarova, Tomas Holy, Stanislav Pospisil, Josef Uher, Zdenek Vykydal

Institute of Experimental and Applied Physics, Czech Technical University in Prague, Horska 3a/22, CZ 12800 Prague 2, Czech Republic

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Abstract

State-of-the-art single quantum counting pixel detectors offer a large potential for different imaging applications. The TimePix pixel device can provide information about position and energy of the detected radiation allowing radiography with charged particles. Heavy charged particles of known initial energy lose their energy partially by going through a specimen material. If the resulting energies of particles passing the specimen are measured, then specimen structure can be revealed. This article shows experimental results of this technique acquired with alpha particles and the TimePix detector. The spatial resolution in detector plane depends on particle energy and can reach submicrometer level. The specimen thickness can be determined with precision up to 320 nm for organic materials if energy loss of individual alpha particle is measured.

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Keywords: Pixel detector; Radiography; Spectroscopy

1. Introduction

When the radiation beam consists of monoenergetic heavy charged particles (protons, alphas, etc.) then their energy decreases by passing through a material as depicted in Fig. 1. Therefore, the structure of the object can be imaged by measurement of the energy loss of individual particles. A suitable position and energy-sensitive detector is required such as TimePix [1].

The hybrid silicon pixel device TimePix [1] was developed at CERN. The device consists of a semiconductor detector chip (300 μm thick silicon) bump-bonded to a readout chip. The detector chip is equipped with a single common backside electrode and a front side matrix of electrodes (256 × 256 square pixels with pitch 55 μm). Each element of the matrix (pixel) is connected to its respective preamplifier, discriminator and digital counter integrated on the readout chip. Each TimePix pixel can work in one of three modes: Medipix mode (counter counts incoming particles), TimePix mode (counter works as a timer and measures time of the particle detection) and time-over threshold (TOT) mode (counter is used as Wilkinson type ADC allowing direct energy measurement in each pixel).

2. Calibration of TimePix device in TOT mode

Each pixel of the TimePix device contains its own analog circuitry. Thus the device contains 65 536 independent channels to be energy calibrated.

2.1. Charge-sharing effect and energy calibration

An ^{241}Am source (750 MBq) emitting gamma rays of 59.5 and 26.3 keV was used for first tests. In all, 2000 frames with exposure time of 50 ms (to assure only a few photons in each frame) were collected with very low threshold settings (~4.5 keV).

A single gamma quantum often creates signal in a cluster of adjacent pixels. The charge created by the particle spreads out during the charge collection process and it can be finally collected by the several adjacent pixels forming the cluster. The charge collected by each pixel in the cluster can be measured with the TimePix device in TOT mode.

*Corresponding author. Tel.: +420 224359181; fax: +420 224359392.
E-mail address: jan.jakubek@utef.cvut.cz (J. Jakubek).

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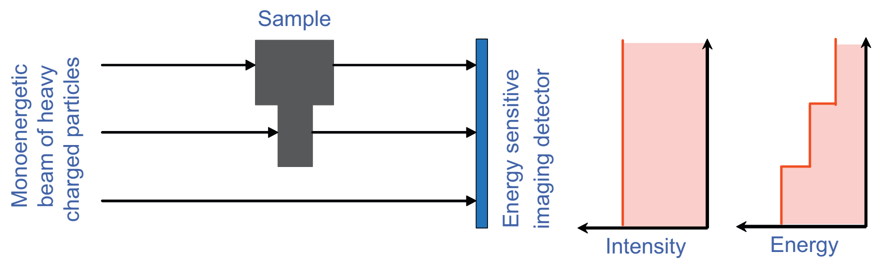

Fig. 1. Principle of radiography based on measurement of energy loss of heavy charged particles penetrating an investigated object.

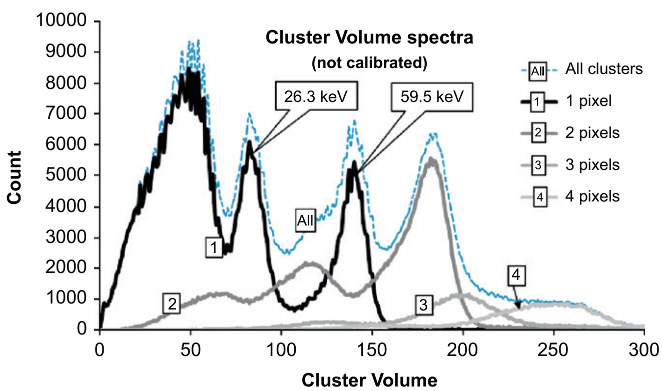

Fig. 2. Cluster-volume spectra of ^{241}Am for different cluster sizes. The broad peak in the low energy region is caused by many overlapping lines of characteristic fluorescent X-rays emitted by the holder made of stainless steel.

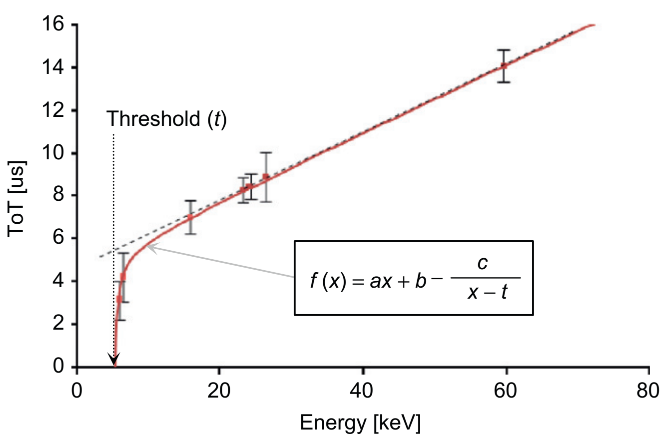

Fig. 3. Time over threshold dependence on particle energy. The dependence is modeled by "surrogate" function f.

The total charge can be revealed by summation of all these fractional charges, i.e. by determination of the cluster volume. The spectrum of ^{241}Am is distorted if the cluster volume is computed directly (without energy calibration). It is demonstrated in Fig. 2 (dashed line).

The clusters can be sorted to categories according to their size (number of pixels). The cluster-volume spectra generated for each category already show both ^{241}Am peaks (see Fig. 2, solid lines).

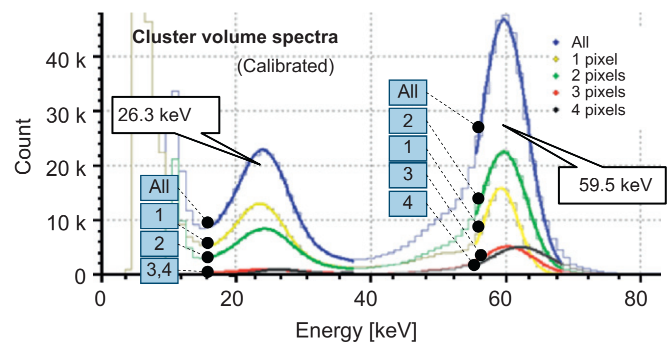

Fig. 4. Cluster-volume (energy) spectra of ^{241}Am measured with calibrated TimePix device in TOT mode. The peak positions are aligned for all cluster sizes now (compare to Fig. 2).

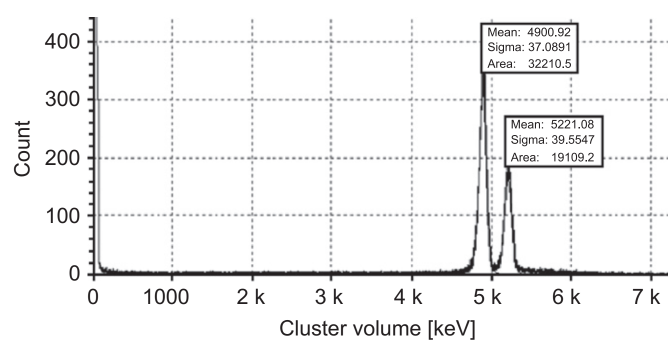

Fig. 5. Cluster-volume (energy) spectrum of combined alpha source (^{241}Am and ^{239}Pu) measured in air. The energy resolution is 37 keV at 5 MeV. The average cluster size was 73 pixels.

2.2. Calibration procedure

We used gamma radiation from different sources[1] for the energy calibration. The cluster-volume spectrum was generated selecting just single-pixel clusters in the measured data for each source. The appropriate peak was identified in the spectrum and fit by Gaussian. The resulting calibration is shown in Fig. 3. The experimental calibration curve can be described by a nonlinear surrogate function f which is shown in the same chart. The function f depends

[1]We used radioactive sources (^{55}Fe: 5.9 keV, ^{241}Am: 59.5 keV) and fluorescent materials emitting characteristic X-rays ($_{26}$Fe: 6.4 keV, $_{29}$Cu: 8.0 keV, $_{40}$Zr: 15.8 keV, $_{42}$Mo: 17.5 keV, $_{48}$Cd: 23.2 keV, $_{49}$In: 24.2 keV). The fluorescence was initiated by a tungsten X-ray tube.

on parameters: a, b, c and t. Values of these parameters are determined by least-squares fit for each pixel.

The per-pixel calibration was tested using the same data set. All frames were per-pixel calibrated to energy. Cluster-volume spectra were thus generated with all peaks well aligned (see Fig. 4).

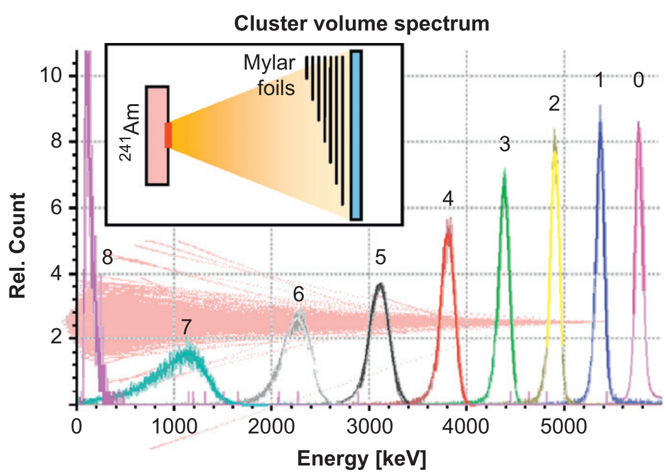

Fig. 6. Energy spectrum of alpha particles from ^{241}Am passing through a sample composed of 8 overlapping mylar foils (inset).

2.3. Energy calibration with heavy charged particles

The total amount of energy deposited by heavy charged particles is much higher than energies of photons used for the TimePix calibration. Since the surrogate function f is linear in the high-energy region, we used its extrapolation. According to our test (see Fig. 5) this gives satisfactory results.

3. Determination of spatial resolution

Usage of the TimePix device for radiography with heavy charged particles was tested using ^{241}Am source of 5.5 MeV alpha particles penetrating through a sample consisting of eight overlapping mylar foils (thick 4 μm each) defining nine areas of the detector surface covered by different foil thickness. Spectra measured in these areas are shown in Fig. 6.

The acquired calibration of energy to thickness is shown in Fig. 7. It is possible to measure the equivalent thickness

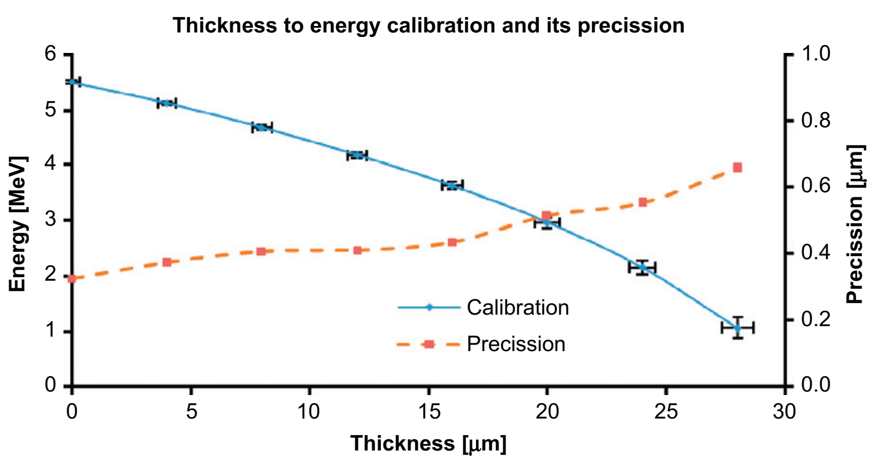

Fig. 7. The solid curve (left vertical axis) shows dependence of measured particle energy on the foil thickness. The dashed curve (right vertical axis) shows precision of thickness determination.

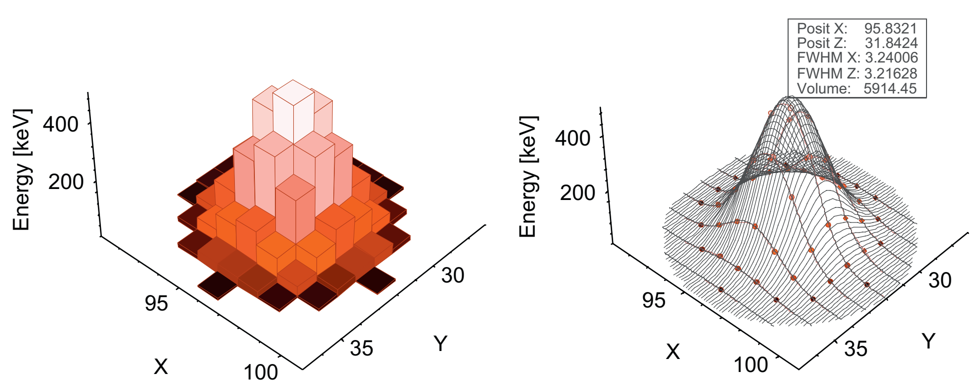

Fig. 8. Cluster of pixels (left) caused by a single 5.5 MeV alpha particle. The detector was operated in TOT mode. The response of each pixel was translated to energy (see Fig. 3). The cluster is perfectly gaussian shaped (right).

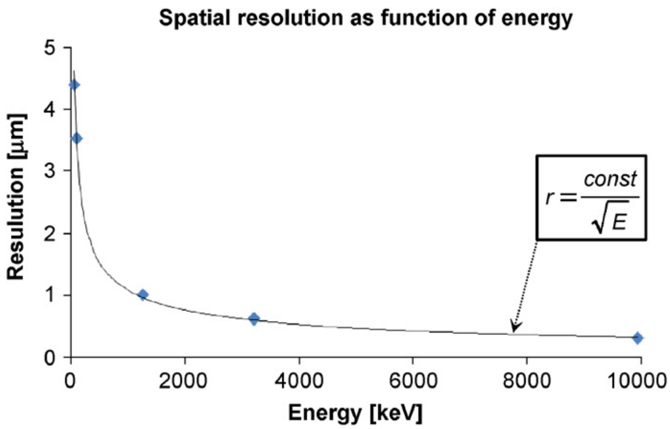

Fig. 9. Measured spatial resolution reached by Gaussian fit as dependending on the energy of the laser pulse. The dependence is modeled by a simple empiric function shown in the inset (*const* = 35).

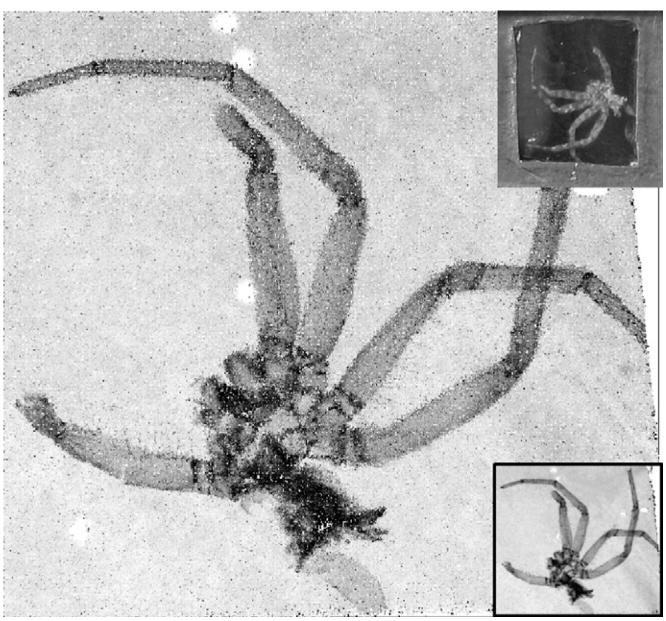

Fig. 10. Spider slough (see photo in upper inset) radiograph obtained by measurement of energy losses of 5.5 MeV alpha particles. The image looks dotted because only 720,000 alpha particles were used for 1 megapixel image (i.e. les then one particle per pixel). The small bottom inset shows original 65 kilopixel image (12 particles per pixel).

of thin organic samples with a resolution of 300–600 nm (for single alpha particle) with the calibrated device. The precision can be remarkably further improved by averaging if higher number of particles is used (the precision reaches 50 nm with 50 particles).

3.1. Cluster shape and subpixel spatial resolution

If the sensor bias voltage is low, then the charge collection process is slow and diffusion dominates the process causing the charge spread. The cluster shape then nicely fits to a 2D Gaussian (see Fig. 8).

3.2. Subpixel resolution tests with laser shots

The subpixel resolution achieved by Gaussian fit of each individual cluster was tested using a focused red laser shot (shorter than 1 ns) with adjustable intensity. The ionization caused by such a shot in silicon is similar to that caused by an alpha particle.

An area of 1×2 pixels was scanned by the laser with a step of 1.25 μm in both directions. Only a single shot was generated in each step. The difference between the known laser position and the position determined by the fit was evaluated. The procedure was repeated for different laser intensities to simulate different particle energies. Since the cluster size depends on the particle energy, the resulting precision depends on the energy as well (see Fig. 9).

4. Radiography with heavy charged particles

A radiographic measurement was performed with a ^{241}Am source of 5.5 MeV alpha particles in vacuum. The specimen was placed directly onto the detector surface and fixed by a mylar foil. The investigated specimen was a spider slough. About 60,000 frames were collected in 16 h. All frames were per-pixel calibrated; the clusters were localized and fitted. The resulting energy image is shown in Fig. 10. The low number of particles allowed just low "subpixelization"; thus, the resolution was enhanced "only" to 1 megapixel.

5. Conclusions

The silicon pixel device TimePix is well suited for radiography using measurement of heavy charged particle energy loss. This technique offers a very high spatial resolution of about 300 nm.

Acknowledgments

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