A Monolithic Array of Silicon Drift Detectors for High-Resolution Gamma-Ray Imaging

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***Abstract*-- In this work, the preliminary results obtained with a high position resolution gamma-ray imaging detector are presented. The detector consists of a single CsI(Tl) scintillator crystal optically coupled to a monolithic array of 19 Silicon Drift Detectors (SDDs), used as photodetectors. In this array, having a total sensitive area of about 1 cm^2, each SDD has a front-end JFET directly integrated on the detector chip, close to the collecting anode. This architecture reduces the electronic noise of each single photodetector to a value small enough to obtain a sub-millimeter position resolution at 122 keV gamma-ray energy. The present detector module represents the development of a previous prototype based on a very limited numbers of SDDs.**

I. Introduction

Several nuclear medicine applications, like breast tumor imaging [1] or radioassisted oncological surgery [2], require the development of small, compact, high-resolution gamma-ray position-sensitive detectors. Actually, in such applications gamma-ray imagers of smaller size and better resolution with respect to the conventional Anger Cameras would present many operative and diagnostic advantages, as recently indicated by the results obtained with detectors based on CsI(Tl) scintillators coupled to Silicon Photodiodes (PDs) arrays instead of conventional photomultiplier tubes [3].

Superior performances in scintillation light detection, with respect to PDs, have been recently obtained by Silicon Drift Detectors (SDDs) [4]. The SDD is in fact characterized by a very low value of output capacitance, typically of the order of 0.1 pF, which is moreover independent from the active area of the device. When compared with a PD of equivalent area and thickness, the SDD then presents a lower value of electronic noise.

In a first prototype of gamma-ray detector for 2-D position measurements, based on a single CsI(Tl) crystal 1.4 mm thick coupled to an array of seven individual SDDs having a sensitive area of 5 mm^2 each, a position resolution of about 0.6 mm FWHM and an energy resolution of about 16% FWHM have been measured at 122 keV by using a ^{57}Co source inside a collimation system having an aperture of 0.3 mm in diameter [5]. Nevertheless, relevant distortions of the images, mostly due to border effects related to the small size of the detector, were observed with this prototype. Moreover, in order to obtain a detection efficiency at 140 keV (^{99m}Tc) compatible with the foreseen medical applications, a thicker CsI(Tl) crystal should be employed. Since the scintillation light collection is strictly related to the detector geometry, this last demand consequently requires an extended photodetector area.

In this work we present a monolithic array of 19 hexagonal SDDs, characterised by a total sensitive area of about 1 cm^2. When coupled to a single CsI(Tl) scintillator crystal having a thickness of 3 mm, this photodetector allows to achieve a sub-millimeter position resolution, with reduced border effects with respect to those showed by the smaller prototype previously developed.

The characterization of the SDD array in terms of noise performances is also presented.

II. Monolithic Array of 19 SDDs with On-Chip JFET

A monolithic array of 19 hexagonal SDDs, arranged in a honeycomb configuration as shown in Fig. 1, has been realized at the Semiconductor Laboratories of the Max Planck Institut (Munich, Germany) [6]. Each SDD has an inner diameter of 2.4 mm and an area of 5 mm^2, leading to an array total area of 95 mm^2. A front-end JFET is directly integrated on each individual SDD chip, thus reducing the stray capacitance of the connection between detector and electronic. Moreover, this architecture minimises the cross-talk and simplifies the readout of the multi-element detector signals [7]. As shown in Fig. 2, the array is mounted within a metallic housing, which also includes a Peltier stage for detector cooling.

An experimental set-up, suitable to carry out measurements on the array stand-alone or in conjunction with

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the scintillator crystal, has been realized. The front-end readout system consists of 19 low-noise voltage preamplifiers mounted close to the SDD module and connected to the integrated JFETs, operated in a source- follower configuration. The electronic noise of each SDD has been evaluated at different peaking times by means of a commercial semi-gaussian shaping amplifier (Tennelec TC244). For gamma-ray measurements, in which all the 19 channels have to be readout simultaneously, a multi-channels electronic system readout previously developed [5] has been employed. This system includes RC-CR^2 shaping amplifiers (6 μs of peaking time), peak stretchers, discriminators, ADC, control logic and a data transmission device to a PC, where a suitable software program performs a real time analysis of each individual gamma-ray event.

III. Noise Performances

The characterization of the SDD array, in terms of energy resolution and electronic noise of each individual unit, has been carried out by irradiating the array itself with a ^{55}Fe source and using a working temperature of 0°C. Although these performances are expected to improve by means of further cooling of the array, the working temperature of 0°C, easily reached by Peltier cooling device, has been preferred in the perspective of development of gamma cameras for medical applications (e.g. hand-held gamma probes for radioguided surgery).

As an example, the ^{55}Fe energy spectrum measured at 2 μs of peaking time in one element of the array, is shown in Fig. 3. The energy resolution is 165 eV FWHM at 5.89 keV, corresponding to an electronic noise of 13.5 electrons rms. The electronic noise of the same array element measured at different peaking time values is shown in Fig. 4. From this figure we can argue that, despite the reduction of the parallel noise contribution due to the moderate device cooling, in the range of peaking time values (5-10 μs) useful to detect the CsI(Tl) signal (main fall time of about 1 μs) without a relevant ballistic deficit, the ENC is significantly higher than the minimum obtainable value. In order to exploit the noise performances offered by the SDD at the optimum peaking time of about 2 μs, in principle scintillation crystals having shorter decay times (e.g. LSO, 40 ns) should be preferred. However, these crystals present a scintillation efficiency smaller than that offered by CsI(Tl) and, therefore, the optimum choice of the scintillator with respect to the overall performances in gamma-ray detection should be matter of a dedicated study.

The ^{55}Fe individual energy spectra, measured with the 19 SDD units at 2 μs of peaking time, are shown in Fig. 5. All units achieved a rather good energy resolution, with the exception of unit #8 which is characterized by much worse performances, probably due to a damage of the device during the bonding phase. This unit has been therefore excluded in the subsequent measurements. As shown in Fig. 6, the electronic noise of the other 18 SDDs spans from 13.5 up to 18.0 e- rms and the average value is of the order of 15.9 e- rms.

As mentioned in Section I, for gamma-ray measurements a custom 19-channels readout electronic has been employed, which includes RC-CR^2 shaping amplifiers having 6 μs of peaking time. The electronic noise of the 18 *good* SDD units, as measured with this electronic, is shown in Fig. 7. It spans from 21.2 up to 34.2 e- rms and the average value is of the order of 26.1 e- rms.

IV. The CsI(Tl)-SDD Detector

A CsI(Tl) crystal, completely covering the active area of the SDD array, has been coupled to this device by means of a layer of Bicron BC-637 optical interface 0.5 mm thick and a thin layer of optical grease. A sketch of the mounting/coupling scheme is shown in Fig.8, while a picture of the detector assembly is shown in Fig.9. The crystal thickness was 3 mm, leading to a detection efficiency of about 80% at 122 keV. All crystal surfaces have been polished; in order to enhance the light collection on the SDD array, a Millipore paper reflector was applied on the top of the crystal. A system gain of 15.4 e-/keV has been measured in this condition. All measurements here reported have been carried out with the CsI(Tl)-SDD detector cooled to 0°C.

For an assigned calibration source position, the interaction point (X_{ph},Y_{ph}) of any gamma-ray photon inside the scintillator was assumed to be represented by the weighted mean (centroid) between the geometric position of the centre of each individual SDD and the corresponding amplitude of the signal detected by the same photodetector. The gamma-ray photon energy E_{ph} was instead assumed to correspond at the simple sum of all signal amplitudes. In particular, X_{ph}, Y_{ph} and E_{ph} are given by the following expressions:

$$X_{ph} = \frac{\sum_j \left(\sum_i X_{ij} * E_{ij} \right)}{\sum_j \left(\sum_i E_{ij} \right)}$$

$$Y_{ph} = \frac{\sum_j \left(Y_j * \sum_i E_{ij} \right)}{\sum_j \left(\sum_i E_{ij} \right)}$$

$$E_{ph} = \sum_j \left(\sum_i E_{ij} \right)$$

where X_{ij} represents the X coordinate of the centre of the $SDD_{i\text{-th}}$ element pertaining to the array row having an Y coordinate Y_j. The quantity E_{ij} denotes the amplitude signal measured in an individual SDD array element, above a threshold E_{thr} that was set at a value corresponding to about 75 e^-. This value represents about 4% of the mean electrical charge collected by the whole array when the energy of incident gamma-rays is 122 keV. Consequently, the minimum detectable signal in each individual photodetector was forced to be 2.8 times larger than the average electronic noise of the array.

A gamma-ray event inside the scintillator was processed only when a signal larger than E_{thr} was detected in at least 5 photodetectors. The processed events were then binned and accumulated in a matrix having dimensions of 256x256. The bin size was about 32 μm along the *X* axis and about 38 μm along the *Y* axis respectively.

The position resolution of the detector has been evaluated by moving a collimated ^{57}Co source (collimator hole diameter of 0.3 mm) over nine different points separated by 1 mm in both *X* and *Y* directions. The 2D results of this scan are shown in Fig. 10, in which the irradiation points can be clearly distinguished. In Fig. 11, a section of the position distribution, measured along the *X* axis, of two contiguous irradiation points is reported. According to the gaussian fit of the measured distributions, a position resolution of 0.65 mm FWHM, which includes the contribution of the collimator hole size, has been estimated. The energy resolution measured in the same conditions was about 17.4 % FWHM at 122 keV. This value was obtained by a Gaussian fit of the energy spectrum shown in Fig. 12, disregarding the broadening introduced by the contribution of the source line at 136 keV.

The present results are quite similar to those previously obtained with a smaller prototype [5], position resolution of 0.6 mm and energy resolution of 16 % FWHM. The present performances have been however achieved with a detector having a larger FOV and a higher detection efficiency.

We point out that the sub-millimeter position resolution here presented has been achieved by using a photodetector array having a pixel size of 2.4mm. This result represents a relevant advantage, in terms of simplicity and performances, with respect to ‘discrete’ Gamma Cameras, based on scintillator + photodetector arrays, which have an intrinsic resolution pixel size limited. However, the energy resolution is not as good as the one achieved by using arrays of single CsI(Tl)-PD (see for instance ref. [3]), because in our case the photon energy is determined by summing the signal of all pixels (therefore summing also all the noises) while by using a single CsI(Tl)-PD pixel, only the noise of a single PD contributes to the energy resolution.

In Fig. 13, a small opening drilled in a lead layer (2 mm thick) is shown. A gamma-ray image of the patterned layer has been obtained by irradiating the detector with a ^{57}Co source through the layer itself. As shown in this figure, obtained from the raw data without any further processing, the present detector is able to image the pattern in all its details without relevant distortions. This conclusion held for all images recorded in the central portion of the array, where border effects are still not too noticeable.

V. CONCLUSIONS

In this work we have presented the results obtained in the development of a monolithic array of 19 SDDs with on-chip JFETs to be used in gamma-ray imaging with scintillators. The SDD array has been characterized at 0°C by a direct X-ray irradiation. An average electronic noise value of 15.9 e- and 26.1 e- has been measured with a peaking time of 2 μs and 6 μs, respectively. When coupled to a single CsI(Tl) scintillator 3 mm thick, a position resolution of 0.65 mm FWHM and an energy resolution of 17.4 % FWHM at 122 keV have been measured.

Based on this architecture, larger FOV detectors for medical diagnostic systems as well as for small animal imaging systems are currently under study.

VI. REFERENCES

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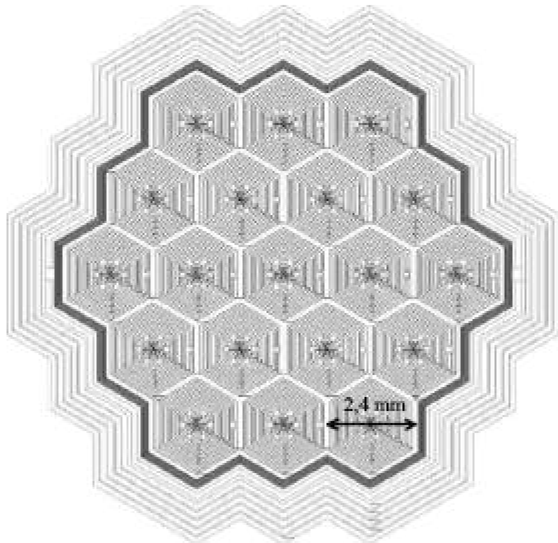

Fig. 1. Layout of the monolithic array of 19-SDDs. The detector side where the drift rings and the front-end JFET are integrated is shown. The scintillator is coupled to the opposite side of the detector.

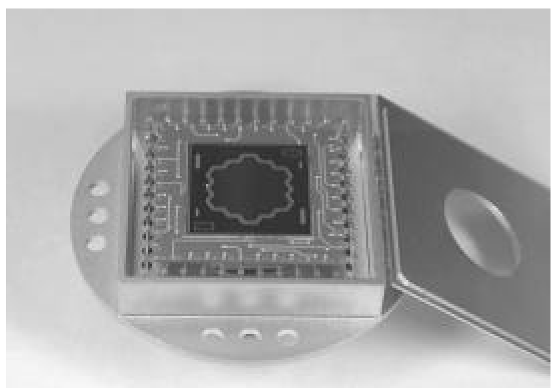

Fig. 2. The detection module based on the 19-SDD array.

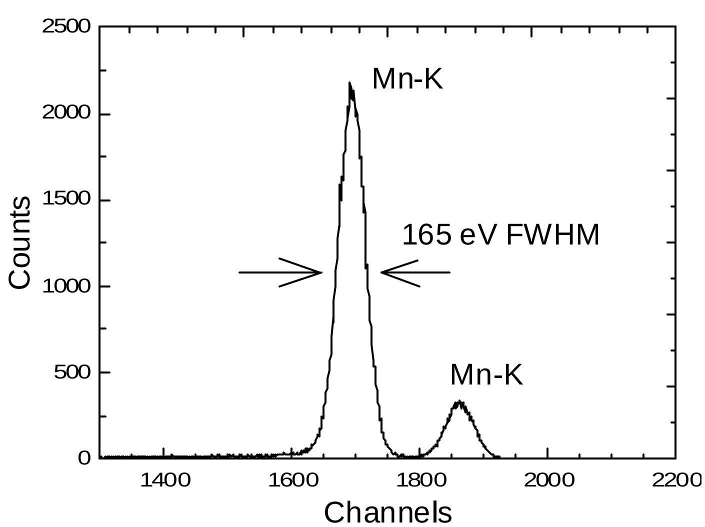

Fig. 3. Spectrum of the ^{55}Fe source measured at 0°C with one unit of the 19-SDD detector, with a peaking time of 2 μs (TC244 shaping amplifier).

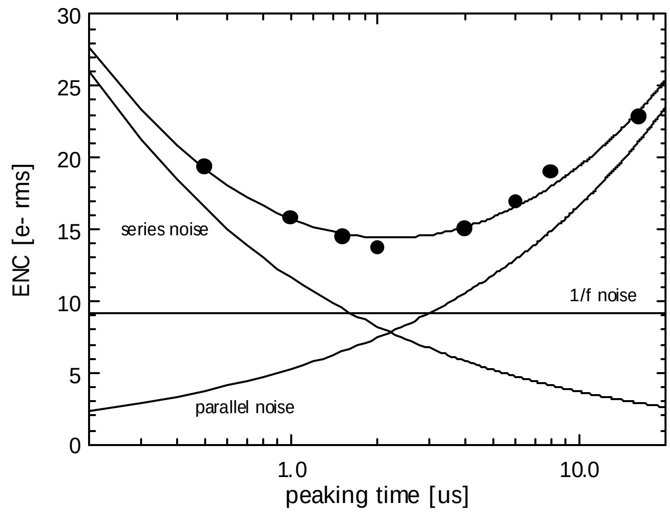

Fig. 4. Electronic noise versus peaking time (TC244 shaping amplifier).

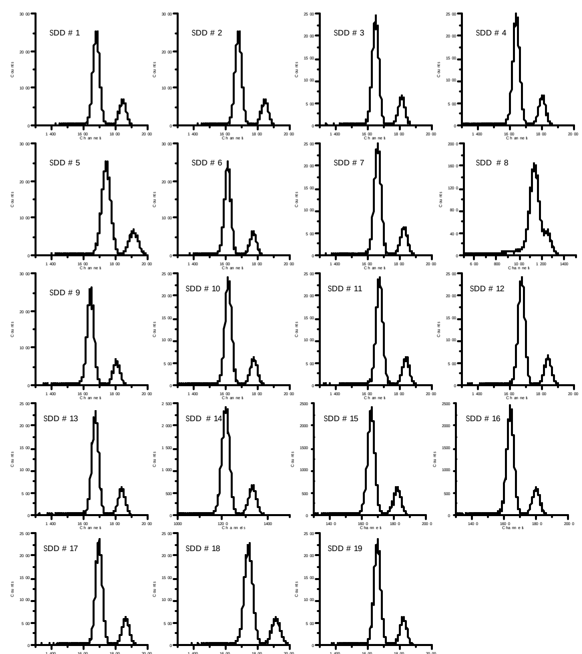

Fig. 5. ^{55}Fe spectra recorded with all 19 units of the array at 2 μs of peaking time.

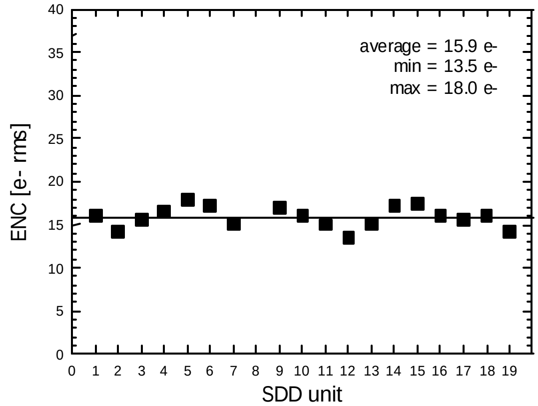

Fig. 6. Electronic noise of the SDD units of the array measured at 2 µs of peaking time.

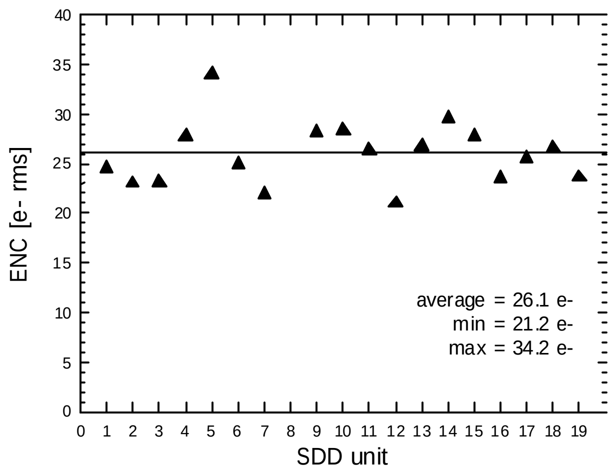

Fig. 7. Electronic noise of the SDD units of the array measured with the 19-channels electronic, at 6µs of peaking time.

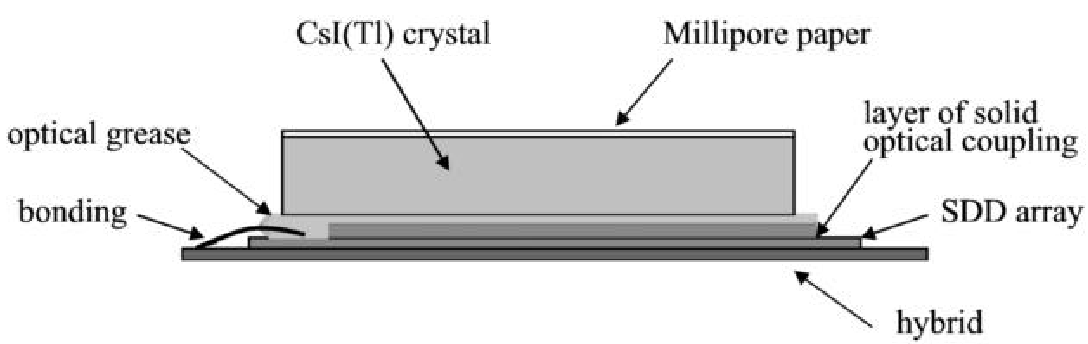

Fig. 8. Schematic drawing of the coupling between the CsI(Tl) scintillator and SDD array.

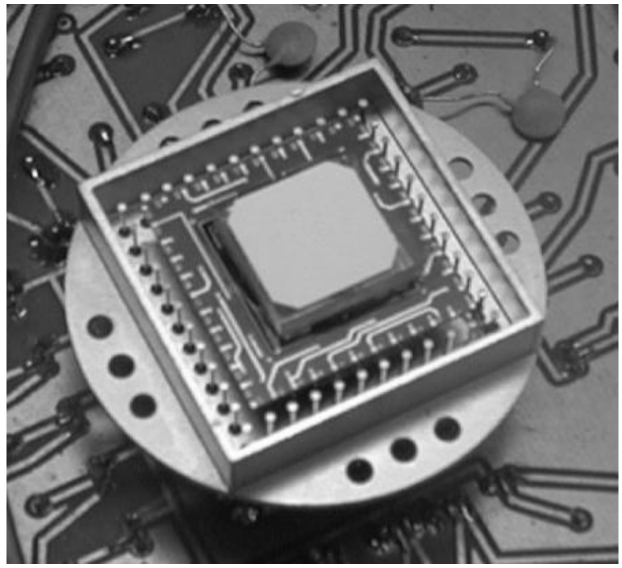

Fig. 9. Picture showing the scintillator/SDD array assembly

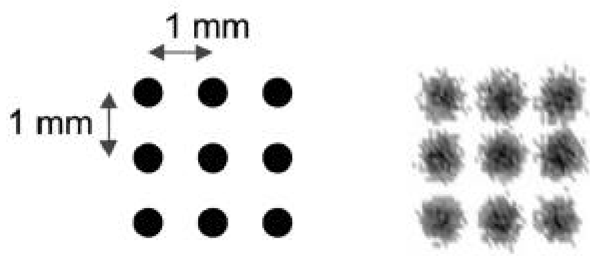

Fig. 10. Image (right) obtained by scanning the gamma-ray detector, over a grid of points separated by 1 mm in each direction (left), by means of a collimated ^{57}Co source (diameter of the collimation system aperture = 0.3 mm).

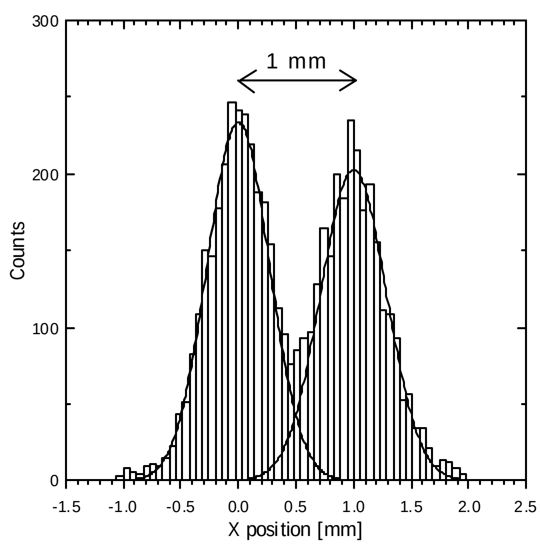

Fig. 11. Position distribution, along the *X* axis of the gamma-ray detector, of two irradiation points separated by 1 mm. The estimated position resolution is 0.65 mm FWHM. A MCA resolution of 32μm/channel has been used in the measurement.

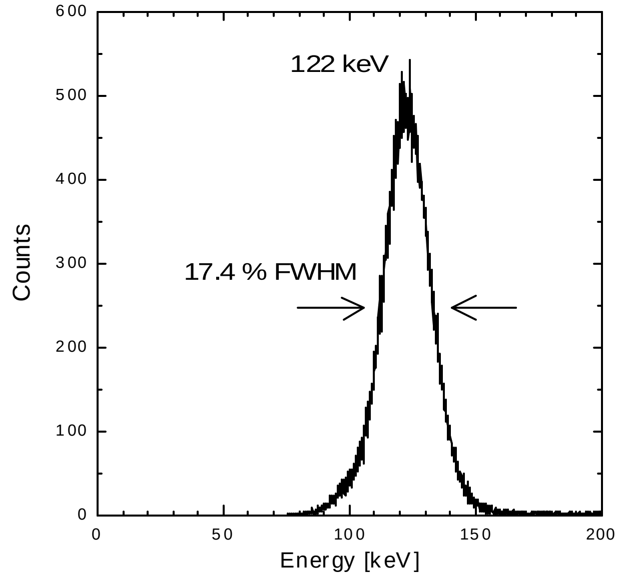

Fig. 12. Energy spectrum of the ^{57}Co source measured with the CsI(Tl)-SDD detector.

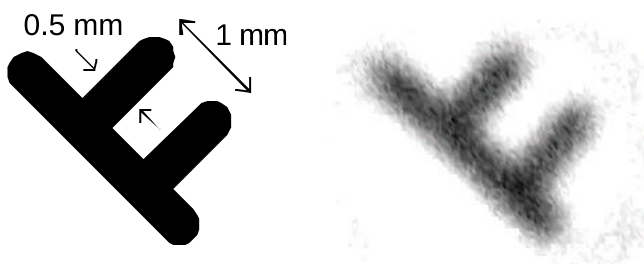

Fig. 13. Image of a small opening drilled in a lead layer, irradiated by a ^{57}Co source.