# Detectors for High Resolution Gamma-ray Imaging Based on a Single CsI(Tl) Scintillator Coupled to an Array of Silicon Drift Detectors

C. Fiorini, A. Longoni, F. Perotti, C. Labanti, E. Rossi, P. Lechner, and L. Strüder

***Abstract*-- Silicon Drift Detectors (SDDs) coupled to scintillators have been recently employed successfully in gamma-ray detection. The low value of output capacitance of a SDD allows to reach a lower electronics noise with respect to a conventional silicon photodiode. Detectors based on array of SDDs are of particular interest for gamma-ray imaging. A first prototype conceived for high-resolution imaging is based on a monolithic array of small SDDs (5 mm$^2$ each unit) with on-chip JFET. The first results obtained with a seven-elements array are here reported. For the realization of gamma detectors of larger active areas based on assembled units, SDDs of 30 mm$^2$ of area with external JFET have been produced. We present the experimental results obtained in the characterization of a single CsI(Tl)-SDD unit.**

## I. Introduction

Recent research has shown that gamma detectors based on CsI(Tl) scintillators coupled to Photodiodes (PDs) arrays offers several advantages with respect to the conventional PMT-based detectors. In fact, the availability of arrays of small PDs can allow the improvement of the spatial resolution for γ-ray imaging while the compactness of a scintillator-PDs assembly permits to reduce the size of the detector. Gamma detectors based on arrays of single CsI(Tl)-PD units have been already developed for Nuclear Medicine and for astrophysics experiments [1-3].

Superior performances in scintillation detection with respect to conventional PDs can be obtained by using a Silicon Drift Detector (SDD) [4]. This detector is in fact characterized by a very low value of output capacitance (about 0.1 pF) which is independent from the active area of the device. If compared with a PD of equivalent area and thickness, the SDD then offers a lower value of electronics noise. An energy resolution of 7.49 % and 4.34 % FWHM at 122 keV and 662 keV, respectively, and an energy threshold of 10 keV have been measured at room temperature (20°C) with a single SDD (7 mm$^2$ of active area) coupled to a CsI(Tl) scintillator 5 mm thick [5]. With a first prototype of γ-ray detector for 1-D position measurements, based on a single CsI(Tl) crystal coupled to a linear array of single SDDs (5 mm$^2$ area for each unit), a position resolution better than 0.5 mm FWHM has been achieved [6].

On the basis of the preliminary results achieved with small SDD units, monolithic arrays of SDDs seems to be a promising solution for the realization of small gamma imaging detectors (sensitive area up to few cm$^2$), based on the Anger Camera scheme, with sub-millimeter position resolution. For this purpose, monolithic arrays of small SDDs have been recently realized. Preliminary results with this kind of detector have been obtained with a prototype based on an array of seven hexagonal SDDs of 5 mm$^2$ of active area each, arranged in a honeycomb configuration. Each SDD has a JFET integrated directly on the detector chip. This solution is particularly suitable in the case of monolithic arrays of several units because avoids the mounting and connection of a high number of external front-end transistors. A first evaluation of the imaging capability of this prototype is here presented.

When the active area required for the gamma detector should exceed several cm$^2$, a solution based on monolithic arrays of small units becomes no more practical because of the high number of readout channels. In this case, the performances of gamma detectors based on relatively large SDD units should be evaluated. The contribution to the electronics noise which depends on the SDD capacitance does not change with the active area and the increase of leakage current with the area could be minimized either by an optimization of the fabrication process either by cooling the detector.

In view of the realization of gamma-detectors of larger areas, single SDD units, each one of an active area of 30 mm$^2$ have been realized. In the case of a SDD of large area, where the leakage current is the main factor limiting the performance near room temperature, the use of an external

Manuscript received November 5, 2000. This work was supported in part by Italian ASI and INFN.

C. Fiorini is with Politecnico di Milano, Dipartimento di Ingegneria Nucleare, CESNEF, Via Ponzio 34/3, 20133 Milano, Italy (telephone: +39-02-23996147, e-mail: carlo.fiorini@polimi.it).

A. Longoni is with Politecnico di Milano, Dipartimento di Elettronica e Informazione, Piazza L. da Vinci 32, 20133 Milano, Italy.

F. Perotti is with Istituto di Fisica Cosmica 'G. Occhialini', C.N.R., via Bassini 15, 20133 Milano, Italy.

C. Labanti and E. Rossi are with Istituto di Tecnologie e Studio delle Radiazioni Extraterrestri, C.N.R., via Gobetti 101, 40129 Bologna, Italy.

P. Lechner is with KETEK GmbH, Am Isarbach 30, D-85764 Oberschleissheim, Germany.

L. Strüder is with MPI für Extraterrestrische Physik Halbleiterlabor, Otto-Hahn-Ring 6, D-81739 München, Germany.

JFET mounted close to the detector anode has been preferred. In fact, this solution reduces the number of processing steps for the detector production, by avoiding the JFET integration, with the benefit of a lower leakage current. The results of the experimental characterization of a single detector unit are presented in this work.

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

### A. Methods

A first prototype of γ-ray detector for 2-D position measurements has been realized by coupling a single CsI(Tl) scintillator (1.4 mm thick) to an array of seven hexagonal SDDs, arranged in a honeycomb configuration, each one with on-chip JFET. The layout of the array is shown in Fig. 1. Despite the small active area of the array (7×5 $mm^2$), the results achieved with this prototype can be already indicative of the performances achievable with larger detectors based on the same concept. Each SDD unit is characterized by an electronics noise of about 77 and 30 electrons r.m.s., at 20 °C and 0°C respectively, at 6 µs shaping time. The typical quantum efficiency at 565 nm, wavelenght of the emission peak of the CsI(Tl) crystal, is of the order of 70 % (anti-reflecting coatings have not been implemented).

A CsI(Tl) crystal, with a cross-section covering completely the SDD active area, has been coupled to the array by means of a 0.5 µm thick layer of Bicron BC-637 optical coupling. In order to enhance the position resolution capabilities by minimizing light reflections on the crystal surfaces, no reflector was applied to the crystal. This solution, of course, does not optimize the light collection and consequently the energy resolution performances of the detector.

For the determination of the position of interaction, by the centroid method, a multi-channel readout electronics including preamplifier, shaping amplifier, peak detector, ADC and a digital acquisition unit was previously developed [7].

### B. Results

An equivalent gain of 13 $e^-$/keV was measured for the present detector configuration. This parameter has been evaluated first by calibrating the MCA in electrons per channel by irradiating only the SDD with a $^{55}$Fe source and then by irradiating the scintillator-array assembly with a $^{57}$Co source.

The position resolution of the detector has been measured by moving a collimated $^{57}$Co source (collimator diameter of 0.3 mm) over the horizontal axis of the detector in three different points separated by 0.6 mm. The measured position distributions, reported in Fig. 2, show the capability of the detector to distinguish the three source locations. However, the values of source distances in the measured distributions are significantly reduced with respect to reality, mainly due to edge effects related to the limited size of the scintillator and of the SDD array. The measured energy resolution was 13 % FWHM at 122 keV (Fig. 3). All the measurements have been carried out at 0°C.

In Fig. 4a, a test pattern opened on a lead layer (2 mm thick) is shown. A first gamma image of the test drawing has been obtained by irradiating the detector with a $^{57}$Co source through the patterned layer. The result of the measurement is shown in Fig. 4b. Although evident distortions due to border effects of the detector affect the measured image, this first results already shows the detector capability to identify the small details of the drawing. Detector based on SDD arrays of larger size (19 and 61 cells, 1 $cm^2$ and 3 $cm^2$ active area respectively), already in production at MPI, could provide in principle the same imaging capability but with a larger active area.

## III. SDD with External JFET

### A. Methods

Single-unit SDDs of larger areas with respect to the ones previously described have been recently realized at MPI. All these detectors have been produced without integrated JFET. The reduced complexity of the production process, with respect to SDDs with on-chip JFET, has allowed to obtain small values of leakage current. A current of about 200 pA has been measured at room temperature (20°C) for a 30 $mm^2$ detector.

In the following, the experimentation of the 30 $mm^2$ SDD is described. The detector layout is shown in Fig. 5. The detector shape has been chosen to easily realize an array of single units closely assembled.

For the connection between SDD and front-end electronics, the detector anode has been bonded to the gate of a Digifet from Gresham (UK), glued on the same ceramic of the detector chip. The Digifet is a n-channel JFET characterized by a nominal gate capacitance of 0.9 pF and a measured transconductance of 4.4 mS. On the Digifet chip, also a feedback capacitor of 0.15 pF was integrated. The following part of a charge preamplifier, suitable designed with the Digifet as input transistor and with the on-chip feedback capacitor, has been mounted very close to the ceramic holder.

In order to characterize a single unit SDD-scintillator, the SDD has been coupled to a CsI(Tl) scintillator 10 mm thick. The crystal has a cross-section of the same shape of the SDD layout shown in Fig. 5, just slightly smaller (about 0.2 mm on each side) in order to allow the bonding connections of the SDD at the extremity of its active area. The scintillator was wrapped with white Millipore filter paper and coupled to the SDD by means of a layer of Bicron BC-637 optical coupling.

### B. Results

The SDD was first test with direct X-ray irradiation of $^{55}$Fe and $^{241}$Am radioactive sources. In Fig. 6, the spectrum of the $^{241}$Am source measured at room temperature with a semigaussian shaping time of 0.5 µm is shown. The measured energy resolution at 6 keV was 550 eV and 600 eV at 0.5 µs and 6 µs shaping time, respectively. Further studies on the same detector, not here reported, have shown that the resolution was limited mainly by partial collection of the charge at the SDD anode. This limitations are strictly connected to a low drifting field inside the detector due to a low value of depletion voltage (= the voltage required to fully deplete the detector wafer) which was only 30V. This value in the present detector corresponds approximately to a wafer resistivity of about 6 kΩcm, much higher than foreseen. This problem will be overcome in further productions where SDD with higher depletion voltage, leading to a higher drifting field, will be realized.

In Fig. 7 the spectrum of a $^{137}$Cs source measured at room temperature (20°C) and with 6 μs shaping time is shown. The resolution at the 662 keV peak is 5.2 % FWHM. An energy threshold around 30 keV can be set by the identification of the Ba-X line. In Fig. 8 the spectrum of a $^{152m}$Eu source measured at 0°C and 12 μs shaping time is shown. The resolution at the 122 keV peak is of 8.4 % FWHM (10.9 % FWHM was measured at 20°C). Finally, in Fig. 9 the spectrum of a $^{241}$Am source measured at 0°C and 12 μs shaping time is reported. The energy resolution at the 59.5 keV peak is of 11.9 % FWHM and the energy threshold at this temperature is around 10 keV.

With the present detector was also possible to show experimentally the capability of this configuration to operate in an extended energy range, as recently proposed [8]. The two $^{241}$Am spectra shown in the same pulse height distribution reported in Fig. 10 has been measured by placing the source on the opposite side of the SDD with respect to the side where the scintillator was optically coupled. The two spectra are due respectively to direct detection by the SDD and to indirect detection by means of the scintillator. From the spectra, a system gain of 35 e-/keV was also evaluated.

This measurement shows how the SDD-scintillator detector could operate in principle in a wide energy range, from few keV (direct detection) to hundreds keV or even few MeV (indirect detection by means of a scintillator). This feature could be of interest in astrophysics applications, where often two sets of different kind of detectors are required to cover the keV-MeV energy range, and in X-ray and γ-ray dosimetry. The discrimination between “direct” spectrum and “indirect” spectrum could be carried out for instance by implementing a pulse-shape-discrimination. In fact, while the preamplifier pulse (Fig. 11a) corresponding to a direct SDD detection is characterized by a fast rise-time, the pulse corresponding to a SDD-CsI(Tl) detection (Fig. 11b) is characterized by a slow rise-time, limited by the scintillator decay time and by the SDD drift time (this last contribution being negligible in the direct detection).

## IV. Conclusions

In this work we have presented the recent results obtained in the development of SDDs to be used with scintillators for high-resolution gamma-ray imaging. First, a small imaging detector based on a monolithic arrays of seven SDD with on-chip JFET coupled to a single CsI(Tl) scintillator has show a capability of discriminating position of interactions separated by 0.6 mm, as well as imaging capability. The achieved energy resolution is 16 % FWHM at 122 keV. Detector of the same kind but with larger active are now under development. These detectors, which are identical for topology, are expected to show similar performances.

The first results on the characterization of single SDD of larger area and with external JFET have also shown satisfactory performances. An energy resolution of 8.4 % FWHM at 122 keV and a threshold of 10 keV have been measured at 0°C. Detectors of this kind will be assembled in arrays in order to cover a more extended active area, as required by several applications in Astrophysics and Nuclear Medicine. SDD of 1cm$^2$ have been also produced and they will be tested in the short future.

## V. Acknowledgment

The authors would like to thank A. Delzanno for the help during the measurements.

## VI. References

[1] G.J. Gruber, et al., "A discrete scintillation camera module using silicon photodiode readout of CsI(Tl) crystals for breast cancer imaging", *IEEE Trans. Nucl. Science*, Vol. 45, n. 3, pp. 1063-1068, 1998.

[2] B.E. Patt, et al., "High resolution CsI(Tl)/Si-PIN detector development for breast imaging", *IEEE Trans. Nucl. Science*, Vol. 45, n. 4, pp. 2126-2131, August 1998.

[3] E. Labanti, et al., "PICsIT: the high-energy detection plane of the IBIS instrument on-board INTEGRAL", *Proc. SPIE*, Vol. 2806, p.269, 1996.

[4] E. Gatti, and P. Rehak, "Semiconductor drift chamber - An application of a novel charge transport scheme", *Nucl. Instr. and Meth.*, A 225, 608, 1984.

[5] C. Fiorini, A. Longoni, F. Perotti, C. Labanti, P. Lechner and L. Strüder, "Gamma Ray Spectroscopy with CsI(Tl) Scintillator coupled to Silicon Drift Chamber", *IEEE Trans. Nucl. Science*, Vol. 44, n. 6, pp. 2553-2560, 1997.

[6] C. Fiorini, F. Perotti, C. Labanti, A. Longoni, E. Rossi, "Position and Energy Resolution of a new Gamma-ray Detector based on a single CsI(Tl) Scintillator coupled to a Silicon Drift Chamber Array", *IEEE Trans. on Nucl. Sci.*, Vol. 46, n. 4, 858-864, 1999.

[7] C. Fiorini, A. Longoni, F. Perotti, C. Labanti, E. Rossi, P.Lechner and L.Strüder, “First Prototype of a Gamma-Camera Based on a Single CsI(Tl) Scintillator Coupled to a Silicon Drift Detector Array”, *IEEE Trans. on Nucl. Sci*, Vol. 47, n. 6, pp. 1928-1932, December 2000.

[8] C. Labanti, et al., “Silicon drift chamber with extended energy range”, *Proc. SPIE*, Vol. 4140, pp.324-332, 2000.

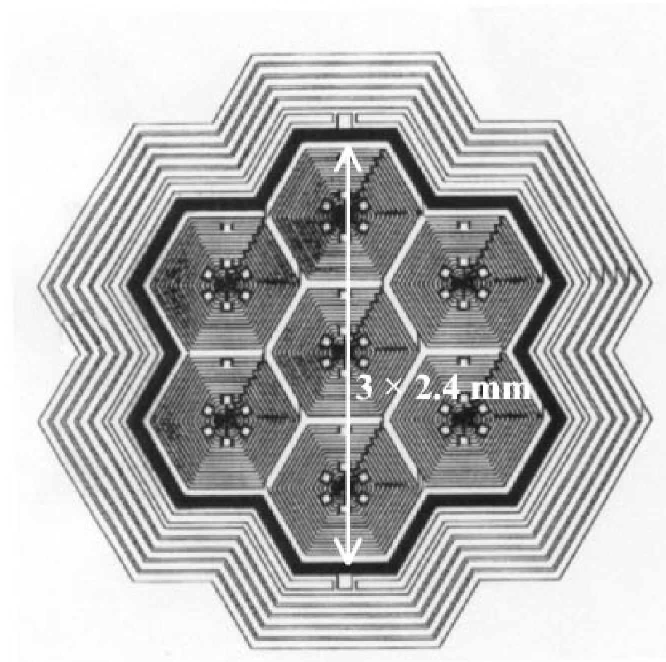



Fig. 1. Layout of the monolithic array of seven-SDDs. The detector side where the drift rings and the front-end JFET are integrated is shown in the figure. The scintillator is coupled to the opposite side of the detector.

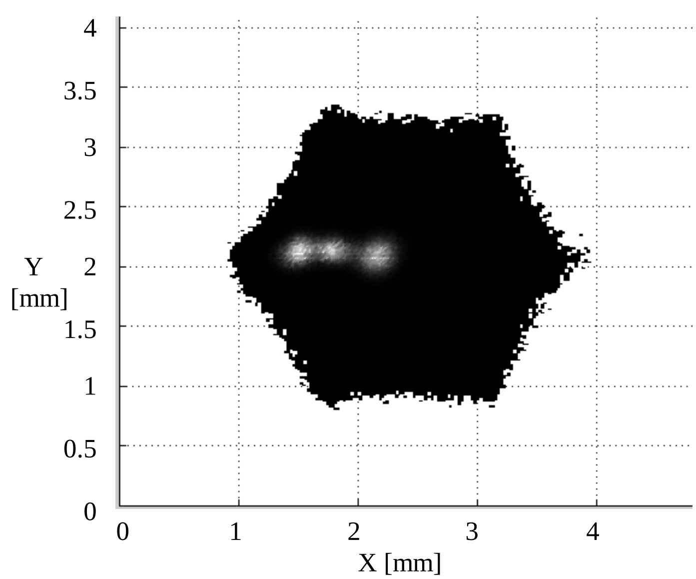



Fig. 2. Measured position distribution corresponding to three different interaction points separed by 0.6 mm.

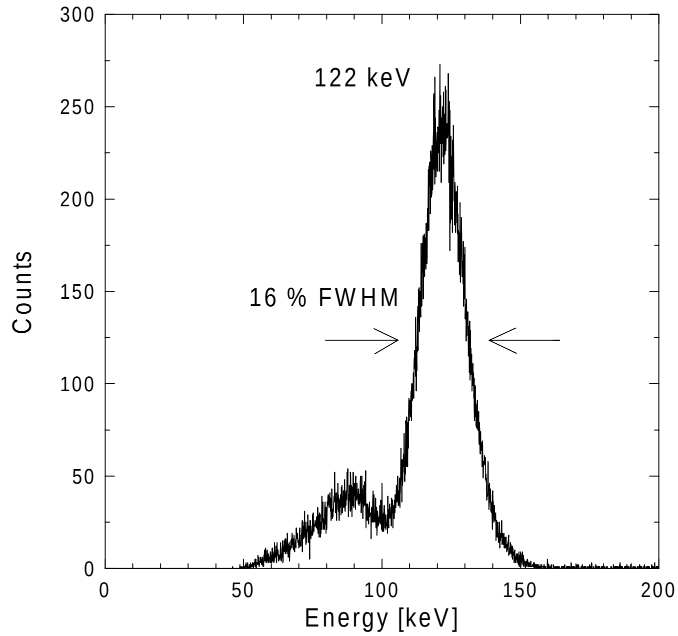
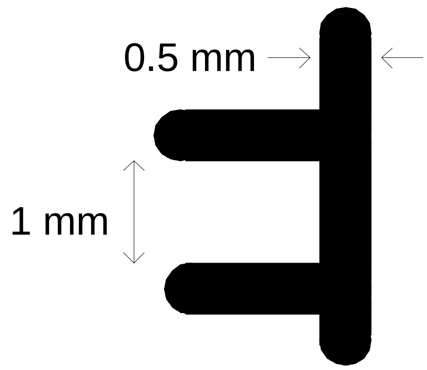
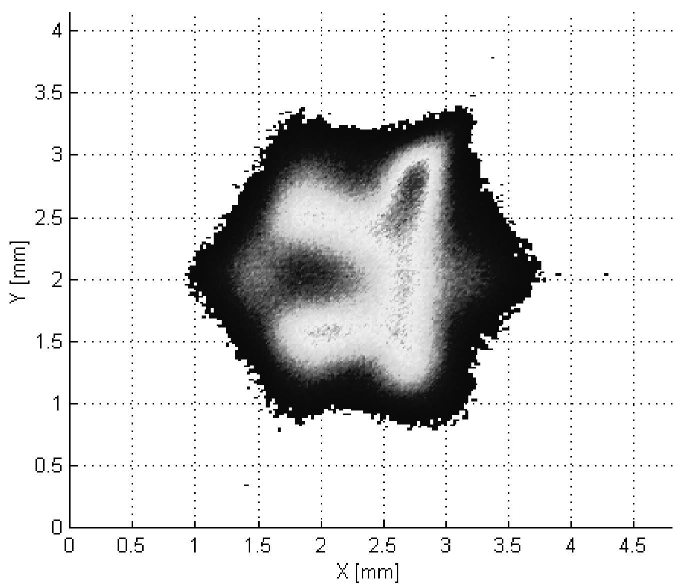



Fig. 3: Energy spectrum measured with the SDD array coupled to the single CsI(Tl) scintillator at 0°C.




(a)




(b)

Fig. 4. (a) Pattern opened on a lead collimator. (b) Measured position distribution of the gamma-ray interactions produced by the $^{57}Co$ source through the collimator.

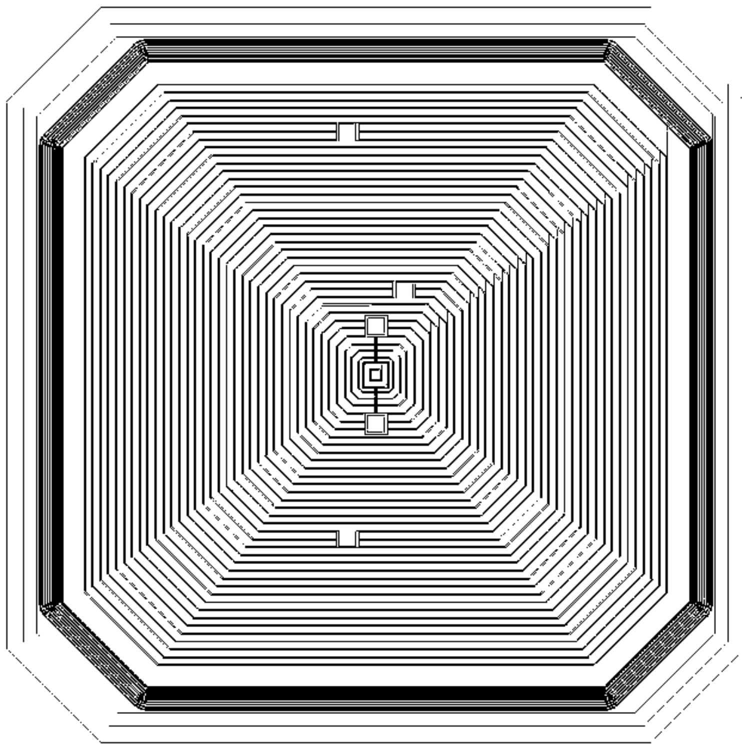


Fig. 5. Layout of the 30 mm$^2$ SDD with external JFET.

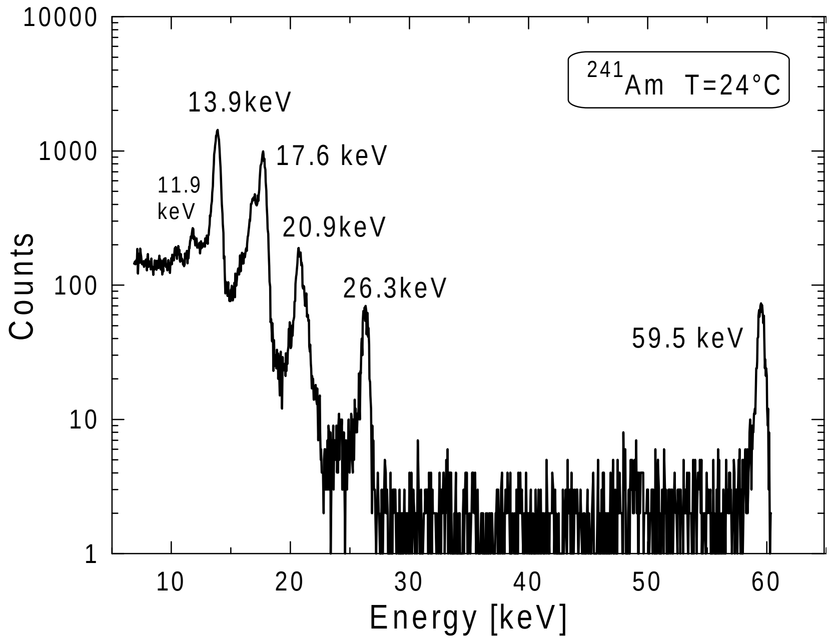



Fig. 6. Spectrum of the $^{241}$Am source measured at room temperature (24°C) with the SDD at 0.5 μs shaping time.

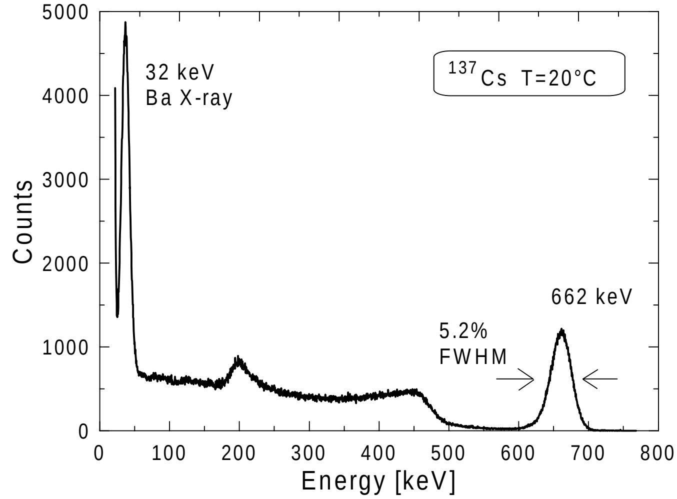



Fig. 7. Spectrum of the $^{137}$Cs source measured at room temperature with the CsI(Tl)-SDD detector.

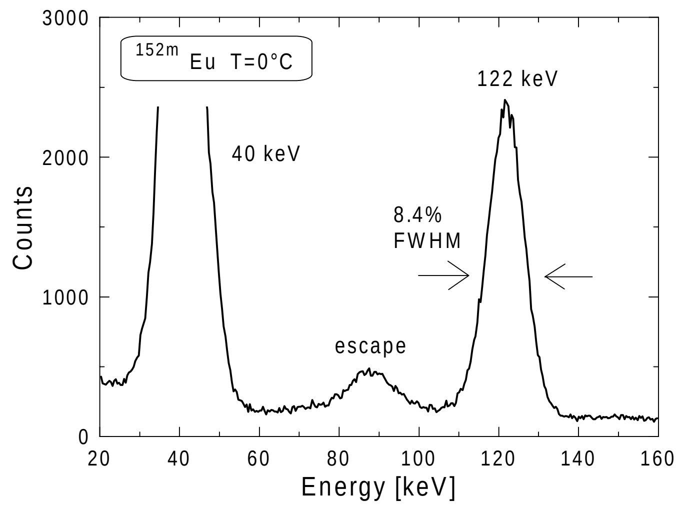



Fig. 8. Spectrum of the $^{135m}$Eu source measured at 0°C.

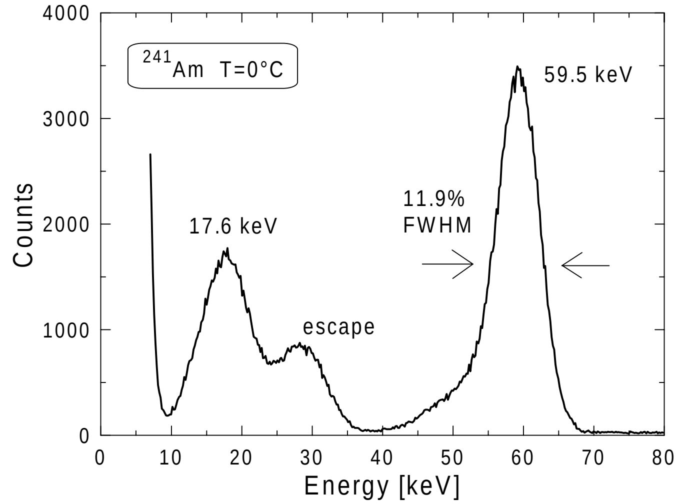



Fig. 9: Spectrum of the $^{241}$Am source measured at 0°C.

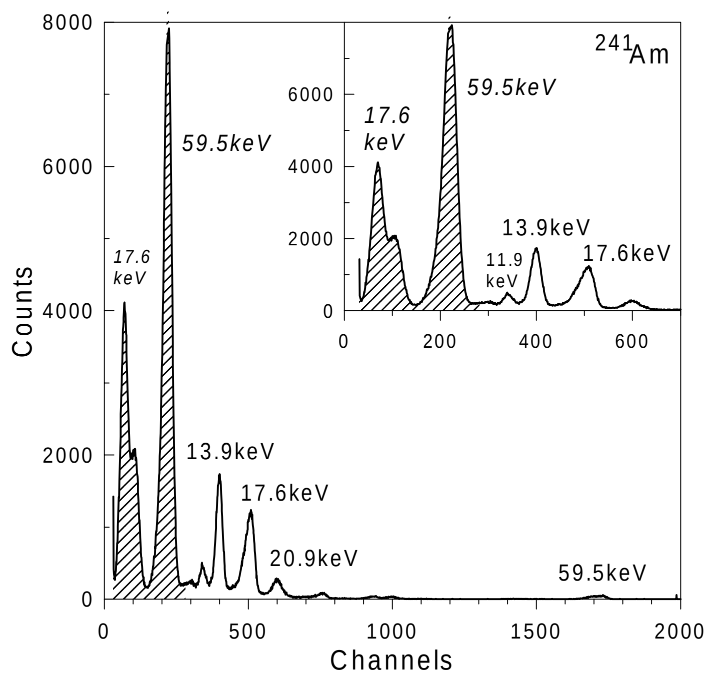
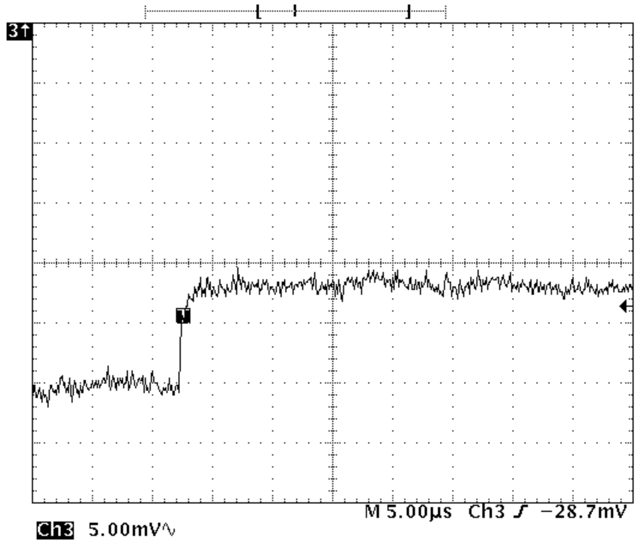
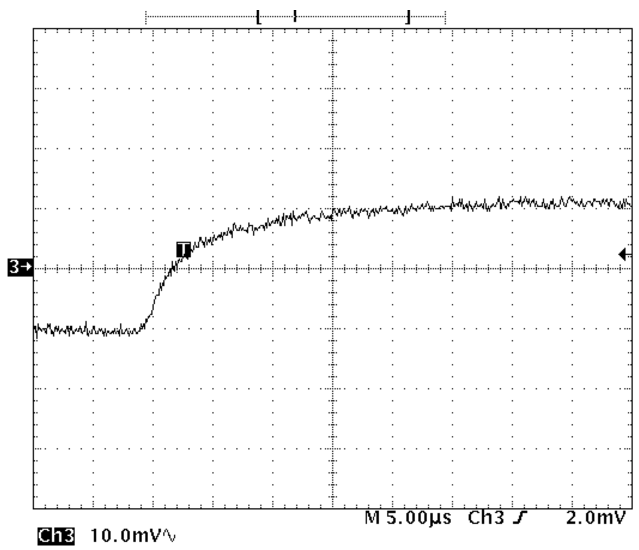



Fig. 10. Spectra of the $^{241}$Am source measured at 0°C respectively by means of direct detection with the SDD and by means of detection with the scintillator-SDD system (patterned region of the pulse height distribution).




(a)




(b)

Fig. 11. Examples of two pulses at output of the preamplifier in correspondence of (a) an event detected directly by the SDD, (b) an event detected by the scintillator. The different rise times in the two cases are clearly visible.