Charge Sharing between two adjacent strip electrodes in a CdTe detector induced by the same primary photon: Part II.

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1. Aims and summary

This document integrates with the IASF # 435 Internal Report, Part I, describing the experimental set-up and the preliminary results of the measurements performed with an X-Ray detection system based on a 15 strip CdTe detector from Eurorad coupled to a Front-End readout ASIC from eV products. The experimental activity main goal is to extract quantitative evaluations of the charge collected by two adjacent CdTe detector strips induced in the crystal by the same primary photon. The events to be investigated, i.e. charge sharing, mainly refer to the fact that a unique X-Ray event releases in the CdTe detector a charge which is not collected by a single electrode, but rather shared between two adjoining anode strips. Data collected during the tests (the LOG is listed in the Appendix I of the Part I) are processed with dedicated SW tools described in details in the present section of the Report. Processed double charge sharing events data relative to the available CdTe detector configuration will be evaluated and presented according to the inspected features:

- the dependence on the detector bias;
- the dependence on the coincidence time;
- the possibility and the criteria used to filter the true double events discarding the false charge sharing events;
- the behaviour of a 4x4 CZT pixel detector in comparision with the CdTe 15 strip detector;
- the adherence of the experimental results with those provided by the numerical simulation of the strip detector.

The CdTe strip detector has been irradiated with three collimated and uncollimated radioactive sources, ^{109}Cd, ^{241}Am, ^{57}Co and several coincidence times have been set for the acquisition routines.

Appendix I reports with some detail the SW tools used to extract significative charge sharing data from the events collected. In particular, Appendix I also explains the adopted criteria to isolate the desired events from the unwanted ones in order to evaluate with good approximation the double charge sharing interactions.

Applicable Documents:

Authors	Title
E. Caroli et al.	“***Report sull’analisi preliminare dei dati di H/K dell’esperimento CACTμS: andamento di parte dei dati di housekeeping registrati durante il volo transmediterraneo (luglio 2002)***”, RI IASF-Bo, N. 346, 2002
N. Auricchio et al.	“***Descrizione e manuale d’uso dell’elettronica a gamma camera per rivelatori a stato solido segmentati (microstrip pixellati)***”, RI IASF-Bo N. 404, 2004
N. Auricchio et al.	***“Spectroscopic characterization of a Multipixel Detector in an eV Multi Pix 16 Channel ASIC Evaluation System”***, RI IASF-Bo N. 387, 2004
N. Auricchio et al.	*“**eV Multi Pix 16 Channel ASIC Evaluation System**”*, RI IASF-Bo, N. 388, 2004
G. Ventura et al.	***“Charge Sharing between two adjacent strip electrodesin a CdTe detector induced by the same primary photon:Part II.”,*** RI IASF-Bo, N. 435, 2005

2. Analog data processing, experimental set-up and data reliability.

Experimental data reliability has also been investigated by using two separate experimental laboratory set-ups and comparing the results independently collected. As already told in the Part I, most of the experimental data have been collected by using the Takes electronics subsystem (**S1**, Fig. 5, Part I) and the annexed SW; data have also been processed with a set-up built around NIM modules and with a dedicated SW previously used to analyze couples of events in coincidence (**S2**, Fig. 1a, below).

In both the systems, **S1** and **S2**, charge sharing events are selected mainly by using the following criteria:

- the voltage shaped signals from the two adjacent strips are higher than the lower energy thresholds ($V_7 > V_{EMin}$ & $V_8 > V_{EMin}$);
- a unique X-Ray event, whose energy is "a priori" known as emitted by the irradiating radionuclide, releases in the CdTe detector a charge which is shared between two adjoining anode strips; neglecting the trapping phenomena, the off-line analysis of the coded signals from the two strips should give an energy sum equal to the primary photon energy (reconstructed primary photon energy spectrum);
- the signals from the two strips are identified as charge sharing if they overlap within a time of the same order of the majority charge carriers mean live time in the detector crystal, i.e. usually 1-2 μsec for electrons in CdTe. This dictates the use of a 1-2 μsec window coincidence decision logic able to validate the charge sharing events collection and discard other types of interactions.

Both the two processing systems (**S1** and **S2**) used to extract the charge sharing events and to investigate for the data reliability follow the above criteria, even if with different implementations. Some features and differences of the two systems are set in evidence in Table I.

	Takes Electronics (S1)		**NIM modules (S2)**	
SCA or E_{Min}	Internal/Adjustable		NIM, External/Adjustable	
Stretchers	Internal		External/NIM	
Coincidence	Internal		External/NIM	
Coinc. Time	1, 2, 4, 8, 16 μsec		Fixed ≅ 1.5 μsec	
Accepted events	Single & double		Only double	
Ext Gain Adj	Reduction (G<1)		2 Amps, Gain ≅ 3÷4	
Int Gain Adj	50-60		G=1	
Internal Shaping	CR-RC (1a)		None	
ADC	One, 12-Bit Flash (2a)		Two, 12-Bit (1b)	
Coding	Flag bit for single/double events		No flag, only double events	
Acquisition Software	POLCA (3a)		Biparametric (2b)	

(1a) Multiple signal diffentiation, resulting from the combination of the ASIC and the Takes electronics, can produce false interpretations of the amount of charge sharing events due to the presence of overshoots and ringings.

(2a) For double events the A-to-D conversions are performed in succession (stretching actions are sustained till the end of both the conversions).

(3a) Data are organized in files while displayed in a frame, also with an indication of the detected energy, of the count rates, etc. Quasi real time energy spectrum is displayed by selection of a strip.

(1b) Conversions are issued at the same time by the coincidence output (Sample in Fig. 1a).

(2b) Only double events coded data are organized in files. On-line spectrum is displayed for a selectable channel, as well as count rates, etc.

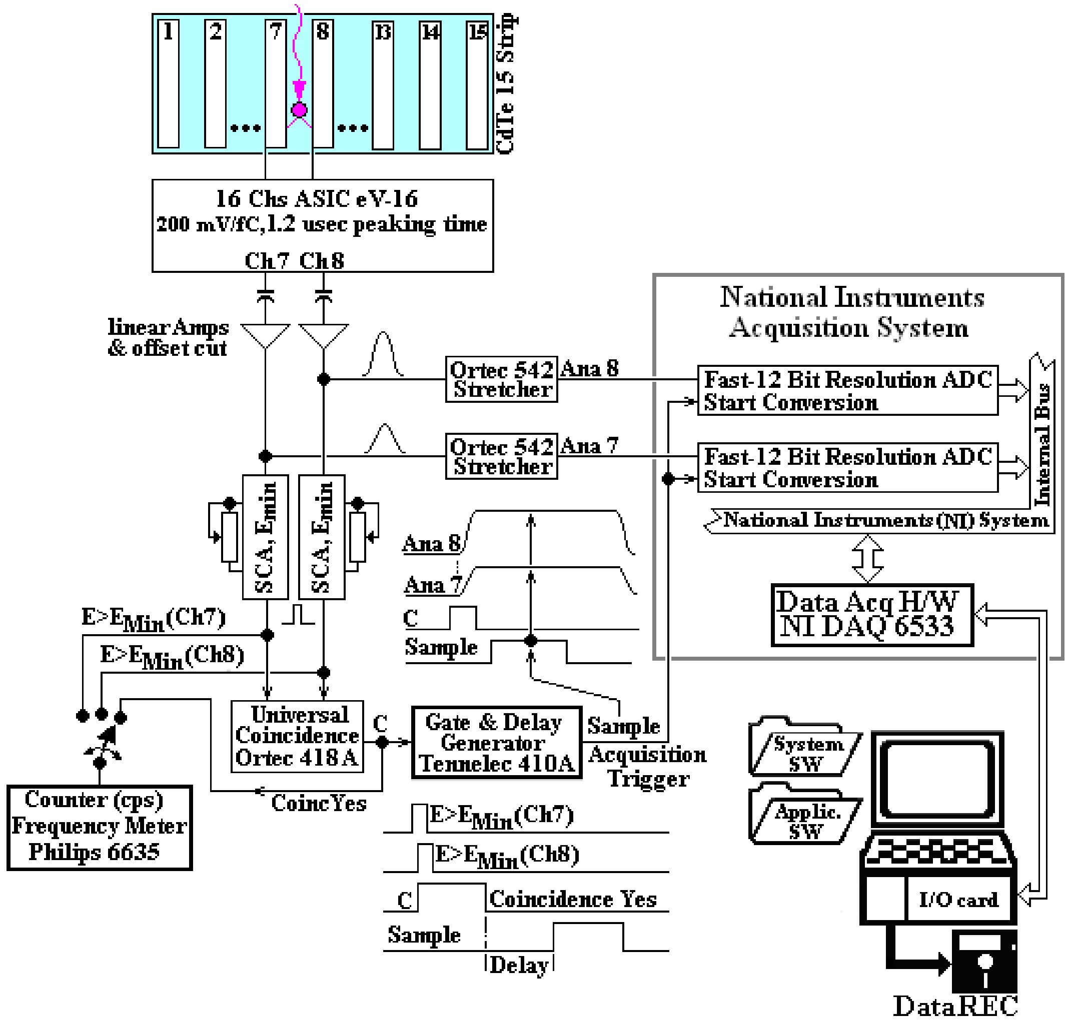


Fig. 1a. Experimental set-up (system **S2**) based on NIM modules and acquisition SW processing couples of coded events in coincidence.

As already told in the foot notes of Table I, probably due to an unoptimized analog coupling of the front-end ASIC and the Takes electronics (**S1**), the data off-line analysis gave an overestimate of the charge sharing events. In particular, the double events maps (Fig. 1b) showed a concentration of data along the $E_X=E_Y$ diagonal which leads to an higher amount of charge sharing events. A straight way to correct for the excess of charge sharing data simply consists in considering the $E_X=E_Y$ data as spurious and, therefore, neglecting them in the double event budget.

A confirmation of the instrumental influence on the charge sharing event amount overestimate also comes out from the numerical simulations, in which no $E_X=E_Y$ data is foreseen at high energies. This required for a totally different and independent experimental verification, able to assure both the correction method and the data reliability. In fact in figure 1c the double events maps acquired with the system S2 are reported: it is evident the absence of the false double events distributed along the diagonal.

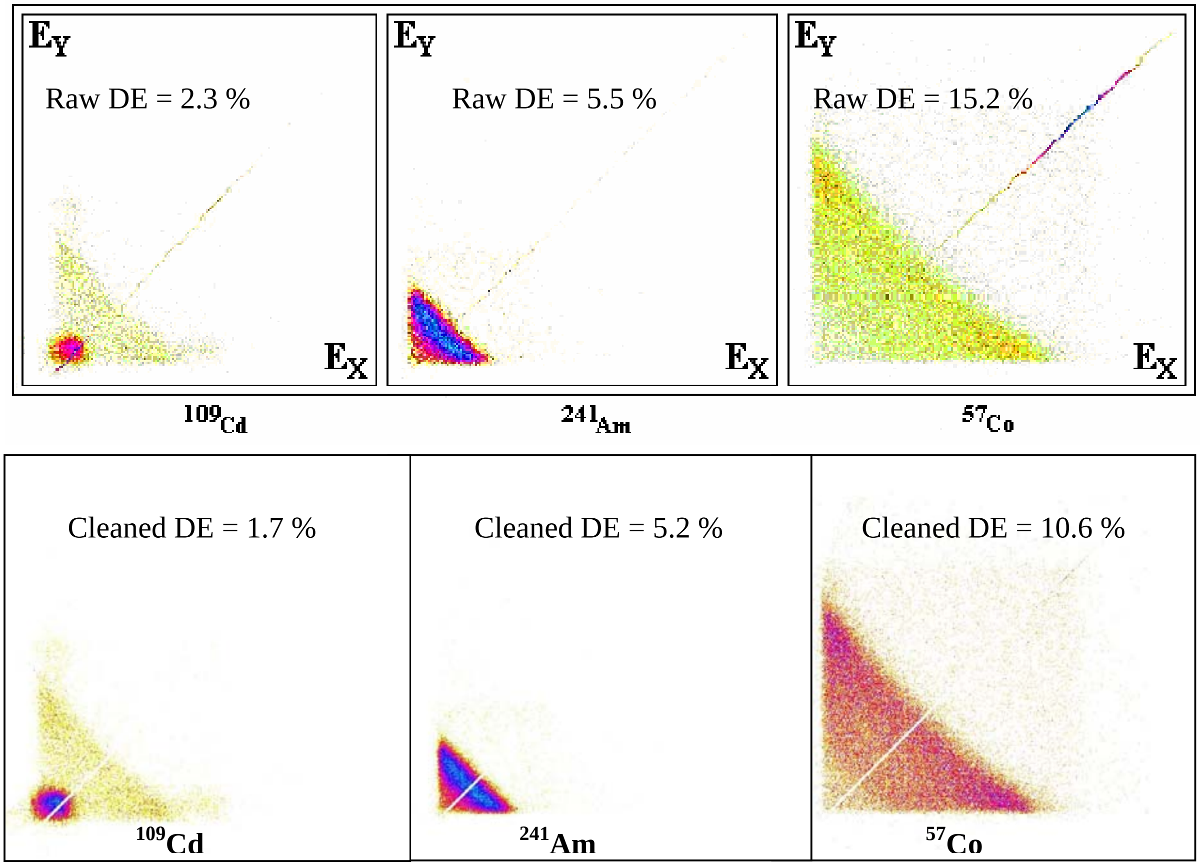


Fig. 1b. E_X-E_Y double events maps extracted without any correction from raw data accumulated with three different X-Ray sources (above). Double "false" events are distributed along the line E_Y=E_X, while charge sharing double events are grouped at lower energies (diffuse and rarefied points). Coincidence time is 1 µsec. Corrected double events maps (below).

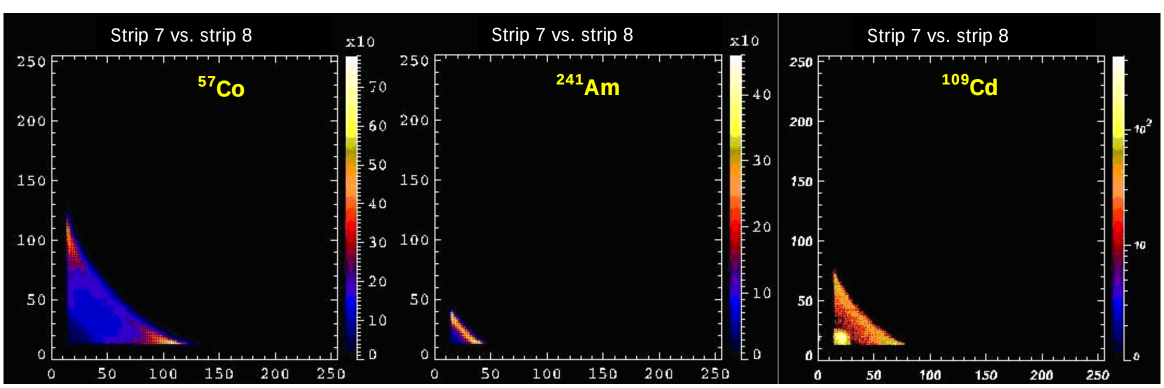


Fig. 1c. Double events maps acquired with the system S2 (Fig. 1a) irradiating the microstrip detector with three different radioactive sources. The coincidence time is ~1.5 µsec.

With the system **S2** (Fig. 1a) data from the SCA's (Single Channel Analyzers, used as E_{Min} thresholds) and the coincidence output, set for the acceptance of two coincident events within 1-2 μsec, were successively accumulated in a Counter/Frequency-Meter. The results of simple computations on mean data were compared with the homogeneous (coincidence time 1-2 μsec) corrected data extracted with the **S1** system.

The count rate ($\mathbf{N_{7ToT}}$ & $\mathbf{N_{8ToT}}$) from the SCA's includes any event overcoming the threshold E_{Min}, i.e. single ($\mathbf{N_{S7}}$ & $\mathbf{N_{S8}}$) and double or coincident events ($\mathbf{N_D}$):

$$\mathbf{N_{7ToT} = N_{S7} + N_D}$$

$$\mathbf{N_{8ToT} = N_{S8} + N_D}$$

$$\mathbf{N_{ToT} = N_{7ToT} + N_{8ToT} + 2\,N_D}$$

$\mathbf{N_{7ToT}}$ and $\mathbf{N_{8ToT}}$ were measured as well as $\mathbf{N_D}$; evaluated mean values of $\mathbf{\langle N_D \rangle / \langle N_{ToT} \rangle}$ were then compared with the corrected double events extracted with the system **S1**.

The results relative to 60 keV X-Rays ^{241}Am and 122 keV X-Ray ^{57}Co are summarized and compared in Table II. Since the system **S2** collects data with a fixed coincidence time (≅ 1.5 μsec), only the data with the same coincidence time were considered for the system **S1** as reasonably comparable.

Table II

	System S1		System S2	
	ψ=[N_D]$_{Corrected}$/N_{TOT}	$\Delta\psi/\psi$	ψ=[N_D]$_{Measured}$/N_{TOT}	$\Delta\psi/\psi$
X-Ray Source	Corrected charge sharing events (%)	Estimated error (%)	Measured charge sharing events (%)	Estimated error (%)
^{241}Am	5.2	0.3	5.99	1.07(*)
^{57}Co	10.6	0.3	10.6	0.7(*)

(*) Limited statistics.

As explained in Table I, the system **S1** allows collection of data with different coincidence times (1, 2, 4, 8, 16 μsec) while system **S2** has a fixed coincidence time window (≈ 1 μsec). It has already been shown that data collected with **S2**'s coincidence time of about 1 μsec fit with those collected with **S1** after a simple correction procedure. The same stands for coincidence times of 2 μsec; this is supposed to be due to a bad coupling (probably multiple differentiations between the front end ASIC and the system **S1** causes overshoots and ringings on analog signal paths) the overestimate of double event amount disappears at coincidence times higher than 2 μsec (Table III).

Table III

Coincidence time (μsec)	Raw charge sharing events (%)	Corrected charge sharing events (%)
1	15.05	10.90
2	15.17	10.95
4	11.11	10.95
8	11.20	11.04
16	11.09	10.93

^{57}Co 122 keV emission line.

The effect, shown in Fig. 2 on double raw charge sharing events, is more marked at high X-Ray energies, e.g. at 122 keV ^{57}Co emission line. Furthermore, since both the numerical simulation does not anticipate any similar feature and data collected with **S2** confirms the effect is due to an improper instrumental behaviour at coincidence times lower than 4 μsec, it is justified the possibility to correct for the overestimate of charge sharing events.

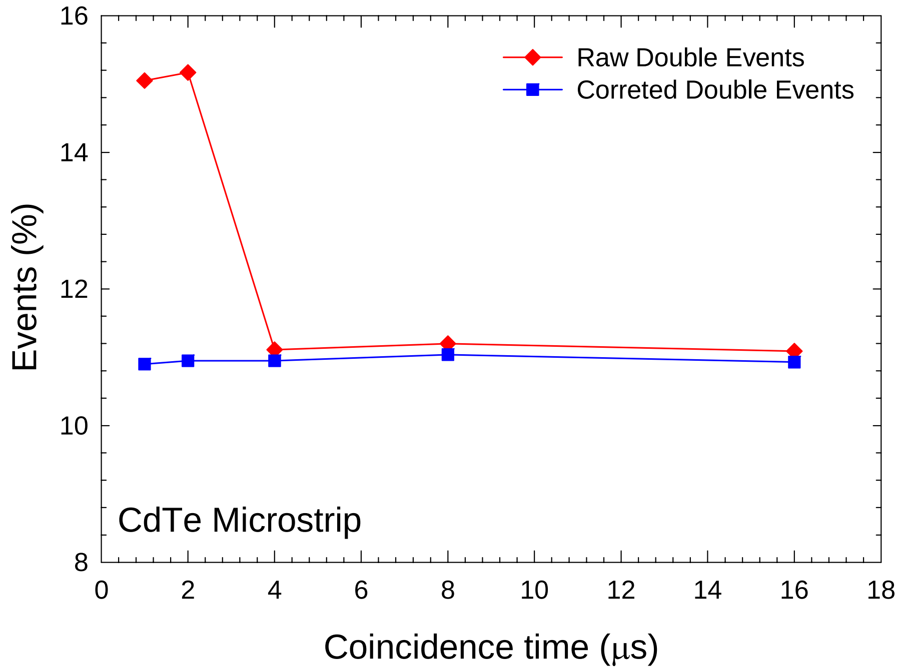


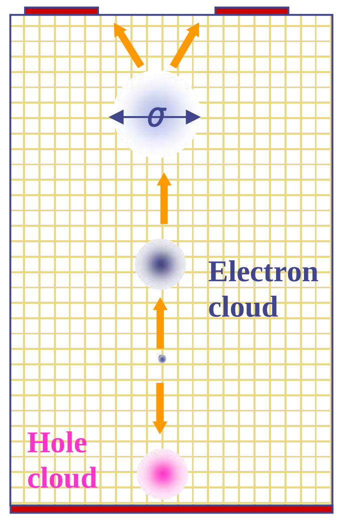
Fig. 2. Behaviour of the charge sharing event amount as a function of the coincidence time. Both raw and corrected data are shown. The percentages are evaluated by simply dividing the detected double events (raw or corrected, respectively) by the total counts overheading the E_{Min} threshold and accepted by the coincidence circuitry.

As expected and also anticipated by the numerical simulations, the charge sharing events for data collected with the system **S1** are independent from the coincidence time after the correction procedure and are equal to the charge sharing events collected with the system **S2**. Furthermore, since charge sharing events should occur in times of the same order of the majority charge carriers mean live time in the detector crystal, i.e. usually 1-2 μsec for electrons in CdTe, unless otherwise specified, from here on only coincidence time of 1 and 2 μsec will be considered: data collected with **S1** require an off-line correction while data provided by **S2** should not.

3. Simulation of the charge induced on two adjacent strip electrodes.

Starting from a transport model including trapping and diffusion, we have developed a numerical simulator of the charge transient signals and of the nuclear spectra by which the charge due to double events is properly summed. The simulator has been applied to the CdTe strip detector with the aim to study and optimize the detector response.
The general features of the simulation tool are:

- 2D finite difference method;
- Ramo's theorem in 2D;
- carrier trapping ⇨ the charge induction ends when the carrier is trapped before reaching the collecting electrode;
- carrier diffusion (see figure on the right) ⇨ a Gaussian spatial distribution of the carrier clouds spreads out following $\sigma = 4\,(Dt)^{1/2}$, where D = diffusion coefficient. The charge sharing between strips occurs as a consequence of diffusion;
- MC for photoelectric generation (including Fano and noise).



The specific features of the simulation tool are:

- the temporal sequence of induced charge events is considered;
- if, on one strip, a signal Q1 appears (see fig. 3), then a coincidence window tc is opened and other eventual signals Q2 (above the threshold) will be summed.

In this way, the charge shared among two strips due to the same photon (true doubles) is summed QT=Q1+Q2 and no charge is lost in the reconstructed spectra. However, if in the same temporal window, there is a contribution from another photon, the charge reconstruction fails (false doubles).

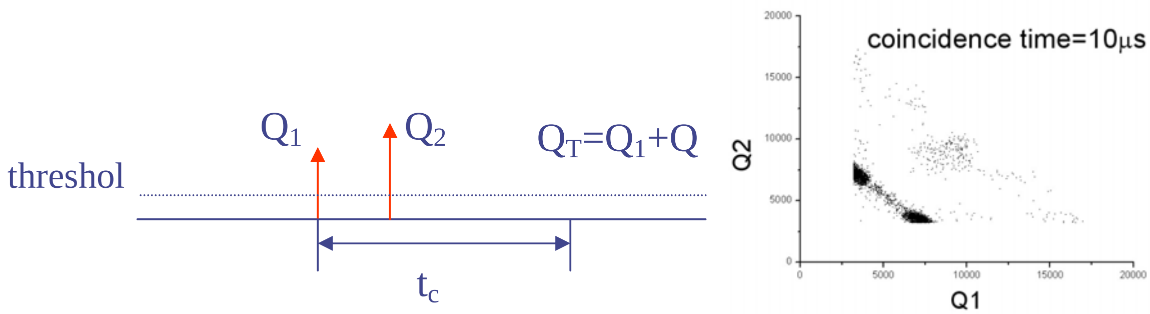


Fig. 3. Scheme of the reconstruction approach of the doubles events by summing the charge induced on two strips (left). Example of a Q2 vs Q1 map of the double events collected with ^{241}Am at t_c = 10 μs (right).

3.1 Coincidence time effect

The effect of the coincidence time has been studied. The used threshold is 3200 e^-, the bias voltage applied on the detector is -100 V, illuminating the microstrip detector with ^{241}Am and ^{57}Co. The coincidence time ranges from 1 to 10 μs. As confirmed experimentally, the double events are not affected by coincidence time (see figure 4). The false and multiple events (n>2) increase with the coincidence time.

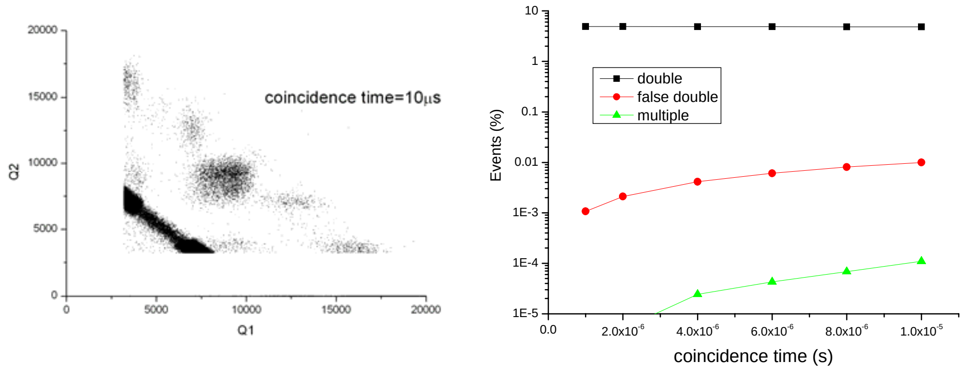


Fig. 4a. Q2 vs Q1 map of the double events collected with ^{241}Am at t_c = 10 μs (left). Percentage of true doubles events (black line), false double events (red line) and multiple events (green line) as a function of the coincidence time (right).

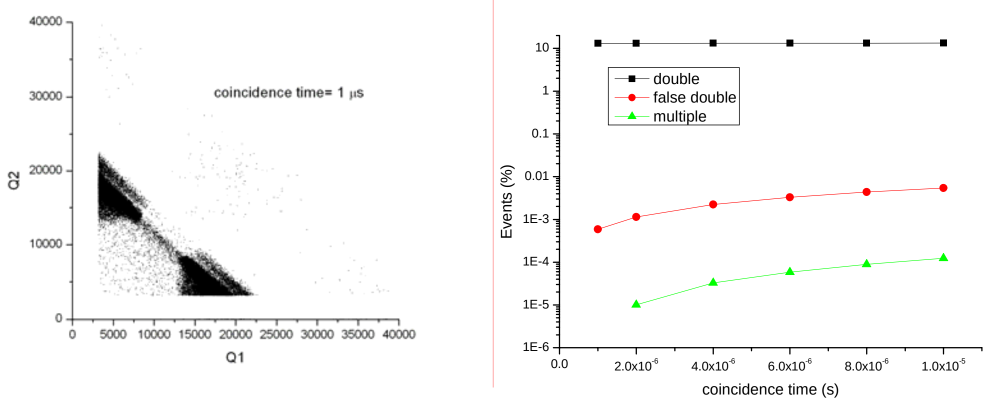


Fig. 4b. Q2 vs Q1 map of the double events collected with ^{57}Co at t_c = 1 μs (left). Percentage of true doubles events (black line), false double events (red line) and multiple events (green line) as a function of the coincidence time (right).

At 60 keV ~ 5% of events and at 122 keV ~13 % of events are shared (11% experimentally).

4. The dependence on the detector bias.

As explained in detail in the Part I, the monocathode of the CdTe detector is biased at a negative high voltage while the anode strips are DC coupled to the inputs of an ASIC eV-16. Being the guard ring held at 0 V bias, the signals from strip # 7 and # 8 are extracted and analogically processed. Data have been collected at three bias voltages, –75V, –100V, –125V (Table IV). The adjacent strips # 7 and # 8 have been chosen as most qualified for the sharing charge condivision tests since they are placed in the central part of the CdTe detector and should then be less sensible to possible effects due to the electrical field non uniformities near the external sides of the detector body. Fig. 5 shows the charge sharing events Vs X-ray energy for three bias voltages.

Table IV. Experimental results as a function of the applied voltage.

	Bias Voltage		
	– 75 V	– 100 V	– 125 V
Source	Charge sharing events (%)	Charge sharing events (%)	Charge sharing events (%)
^{109}Cd	1.67±0.67	1.74±0.44	1.64±0.65
^{241}Am	5.42±1.05	5.23±0.29	4.92±1.03
^{57}Co	11.23±0.50	10.61±0.29	9.84±0.53

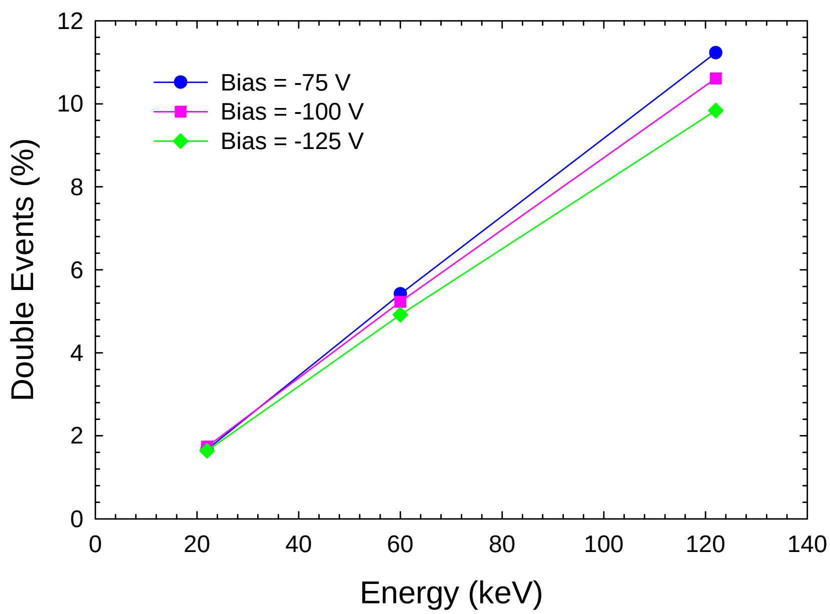


Fig. 5. Double events as a function of the energy at different bias voltage values.

By increasing the bias voltage the double events are diminished because the interstrip gap decreases, as seen in the simulation study.

4.1 Bias voltage effect

The effect of the applied voltage has been simulated. The used threshold is 3200 e^-, the coincidence time is 1 μs and the bias voltage applied on the detector is -75, -100, -125 V. The microstrip detector is illuminated with ^{241}Am and ^{57}Co. A stronger dependence is observed in simulated results, compared with the experimental results (see table V).
The X-Y distribution and the Q2 vs Q1 maps of the double events as a function of the applied voltage are reported in fig. 6 and 7.
By increasing the bias voltage the double events are decreased, as confirmed experimentally.

Table V. Simulated results at different applied voltages.

	Simulated Double Events (%)		
Source	-75 V	-100 V	-125 V
^{241}Am	6.35	4.91	3.73
^{57}Co	15.92	13.14	11.19

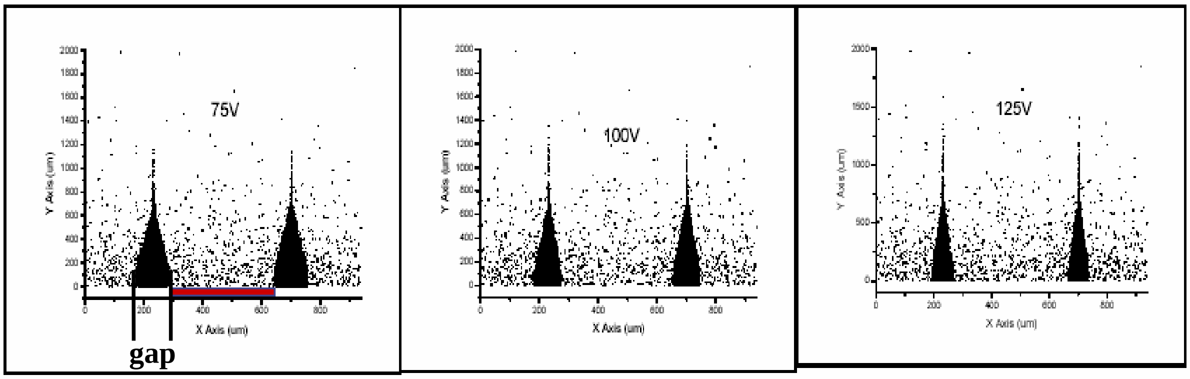


Fig 6. X-Y distribution of the double events as a function of the applied voltage. By increasing the bias voltage the interstrip region decreases. The red bar represents the strip size.

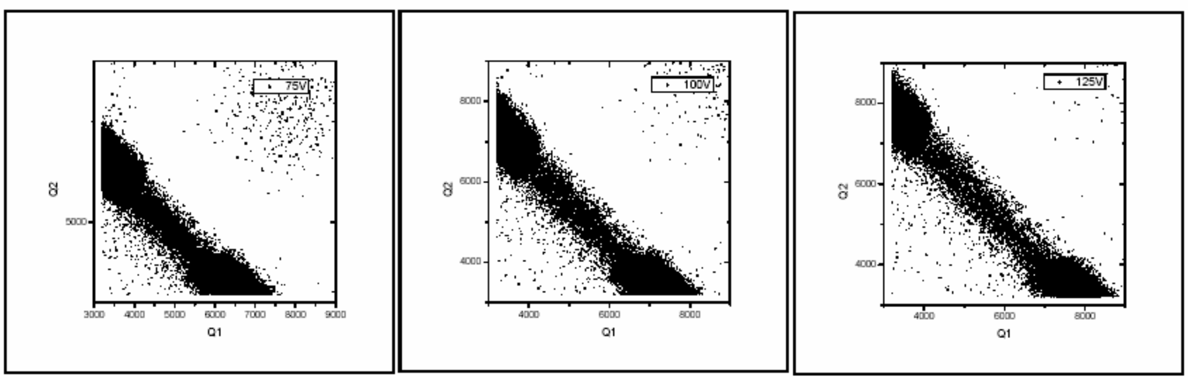


Fig 7. Q2 vs Q1 maps of the double events as a function of the applied voltage. By increasing the bias voltage the collected charge (Q2 and Q1) enhances.

5. The behaviour of a pixellated CZT detector.

Charge sharing events have been also evaluated by direct data accumulation from a 4x4 pixel CZT detector manufactured by eV products (2 x 2 mm pixel size, 0.2 mm gap, 5 mm thick, HV= –550 V, readout electronics ASIC eV-16 with 200 mV/fC and 1.2 μsec peaking time). As anticipated in Part I, two sets of data have been collected with uncollimated ^{57}Co source to investigate on the charge sharing contribution, the first from the adjacent pixels # 5 and # 6, the second from the pixels # 5 and the pixel # 10 bordering at a corner (see Fig. 8).

Table VI: summary of the results for the data collected from the couples Pix5&6, Pix5&10 when irradiated by a 2 mm diameter collimated ^{57}Co and 900 s accumulation time.

Pixel pair	**Coinc. time (μs)**	Charge sharing events (%)	Estimated error
Pix5&6	1	4.05	0.03
Pix5&6	2	4.01	0.03
Pix5&6	4	4.03	0.03
Pix5&6	8	4.04	0.03
Pix5&10	1	0.45	0.01
Pix5&10	2	0.50	0.01
Pix5&10	4	0.49	0.01
Pix5&10	8	0.48	0.01

In order to get a realistic evaluation of the double charge sharing events, the correction mechanism simply consist in eliminating the events with $E_X=E_Y$ and considering just the events with energies outside the diagonal straight line. An effect of the effectiviness of the correction can be mainly seen with the ^{57}Co source, since the primary photons are almost monoenergetic and characterized by an energy of 122 keV which, being far from the low energy regions, simplifies the distinction between false and true double events. The correction or cleaning procedure applied to the double events ^{57}Co spectrum shown in **Fig. 8** makes disappear the 244 keV energy peak due to double false charge sharing events.
Some comments may help to better understand the figures:

- the spectra labelled as “X spectrum” and “Y spectrum” are the spectra constructed by considering the raw data collected by the pixel # 5 and # 6 (10), respectively;
- the spectra “X double events” and “Y double events” are the energy spectra extracted respectively from the data of pixel # 5 and # 6 (10), considering only the events induced in the detector by the same primary photon and shared by two pixels;
- the “double events spectrum CL” is the energy spectrum derived from the individual “X” and “Y” double events spectra and obtained by summing the energy contribution of two pixels, after discharging the double false events. This energy spectrum permits to directly verify the fact that the primary photon energy is shared between two adjacent pixels and to discard undesired events (i.e. double primary photons).

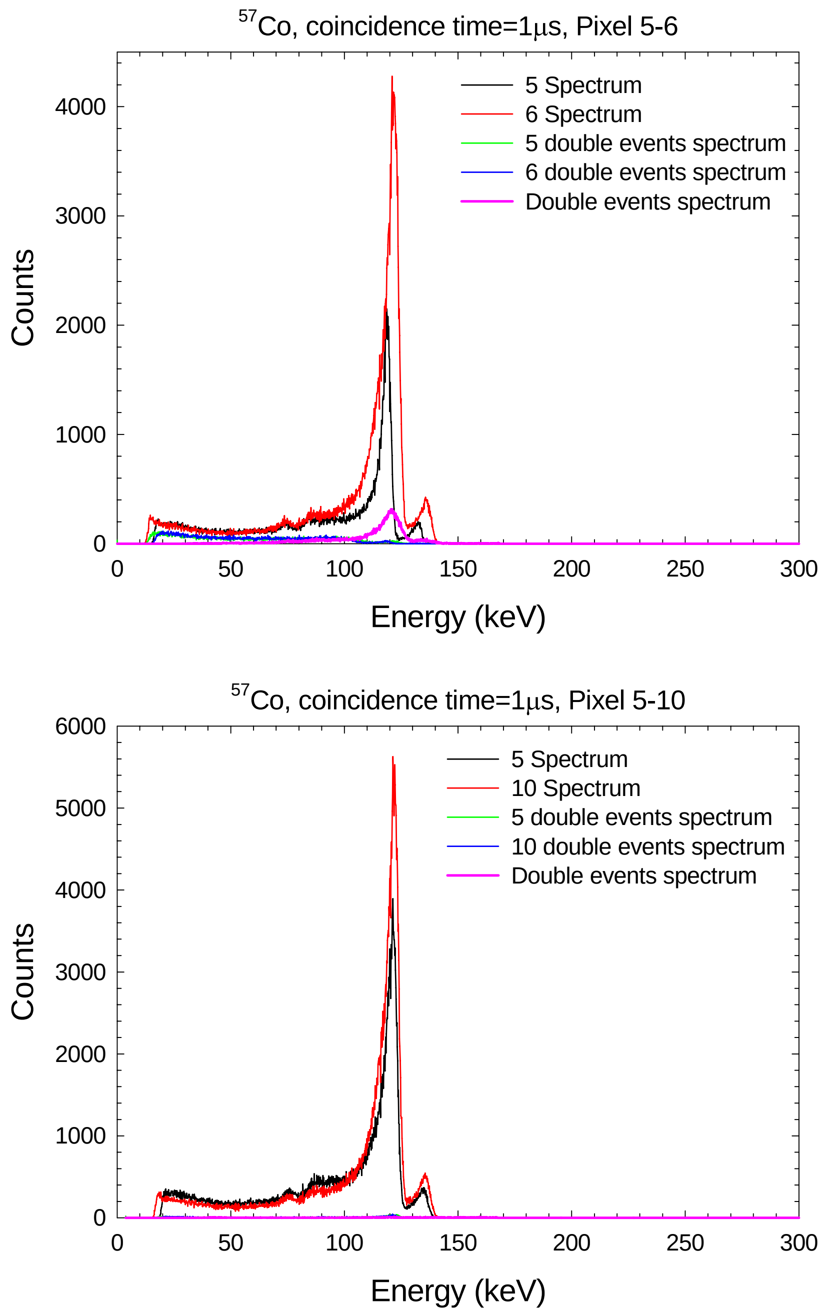


Fig. 8. Corrected energy spectra obtained irradiating the multipixel CZT detector with a ^{57}Co source: the energy peak at 244 keV, due to false double events, is disappeared as consequence of correcting.

Some interesting features can be extracted from a direct comparison of this spectrum with that of **Fig. 14, PartI** relative to the stripped CdTe. First of all, as expected, the energy resolution of the CZT pixel detector is remarkably better than that of the CdTe stripped detector (individual energy spectra of the pixels # 5 an # 10); in fact, the secondary 136 keV ^{57}Co line is well resolved as well as the low energy noise contribution is limited to less than 10% with respect to the 122 keV peak counts, while for the stripped CdTe detector the low energy noise contribution is approximately 60% of the counts at the 122 keV peak.

The comparison between the double events measured before correcting and corrected double events irradiating the detectors with a ^{57}Co source is shown in figure 9:

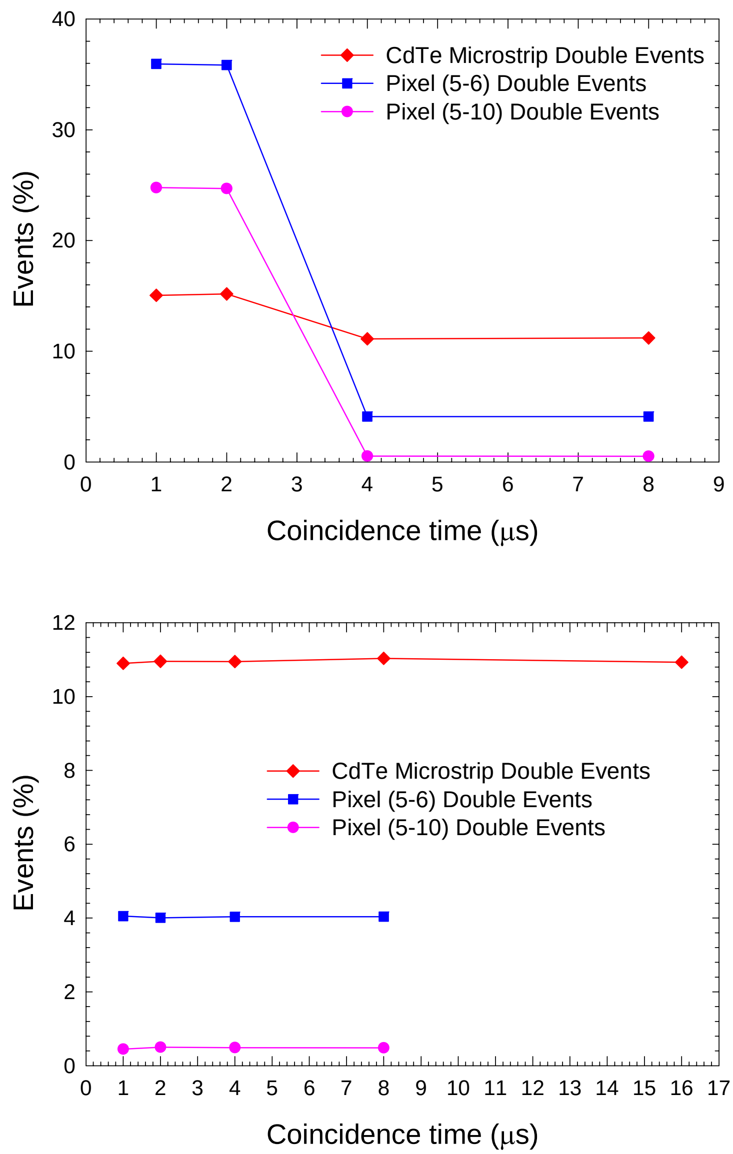


Fig. 9 Double events as a function of the coincidence time before correcting (above) and after correcting (bottom).

It is worth noticing that the coincidence time do not influence on charge sharing events, as mentioned above (Section 2).

6. Data off-line analysis and results.

The off-line analysis, based on a SW written in IDL (Interactive Data Language) environment, performs the following tasks:

- data file retrieval and first approximation data analysis, i.e. evaluation and separation of the double events from the total;
- statistical evaluations, i.e. total count accumulated by each strip, single and double events count rates, percentages of the double events, etc;
- energy spectra for any strip of all events accumulated;
- energy spectra for any strip of the charge condivision events;
- histograms of the charge condivision events;
- maps of the charge condivision events, i.e. assumed as **x** a strip and **y** the other, the energy E_y is represented as a function of the energy E_x. The inspection of a map has the ability to distinguish between charge condivision events (caused by a unique primary photon) and double coincident events due to the excitations of the two strips due to two separate photons (false events for the purposes of the experiment): in fact, in the map representation the charge condivision events share part of the primary photon energy and then are almost uniformly distributed in the E_x-E_y low energy region, while the “double-false” events are distributed, mainly for the ^{57}Co source (photon energy of 122 keV), in the high energies regions being concentrated around the diagonal E_x=E_y.

7. Conclusions.

The objectives of the experiment consist in considering the charge detected by the two adjacent strips in the CdTe bulk by a single primary photon, i.e. double event charge signals collected by two independent detector strips within the coincidence window. To measure this effect the region between the strips (intermediate gap) shall be irradiated by a radioactive source. Due to the dimension of the gap, a high precision motion control with a strongly collimated X-Ray spot (ideally, it should be required a point-like X-Ray spot irradiating the detector gap) is needed to be sure to expose the desired region.

However, since the available radioactive source activities are not too high and the collimator dimensions set a limit to reasonable accumulation times combined with the fact that it is almost impracticable to excite a detector region strictly limited to the inter-strip gap, problems can arise to collect reliable data statistically significant. In the laboratory set-up the finite dimension of the spot has geometrical dimensions higher than the intergap distance, implying that double charge condivision events are mixed with other double-type events. In other words, the combination of the too large physical dimensions of the irradiated detector areas and the limited Gamma-Ray source activities have the consequence that signals in coincidence within the window set for the measurements are not all due to charge condivision events, but can be originated by different interaction mechanisms.

In particular, data enabled as valid by the coincidence circuit, not always satisfies the main charge sharing criteria, in the sense that they can be considered by the acquisition system as acceptable, but are false from the point of view the charge condivision: e.g. two different primary photons contemporary impinging on the two adjacent strips inside the coincidence window time are considered as double event by the HW coincidence circuit but they are not charge condivision events. In conclusion, the main drawback is represented by the fact that the coincidence HW circuit does not permit to directly distinguish between charge condivision events, induced by a single primary photon, and double events, produced by two coincident primary photons or other double events. Off-line analysis on collected data can permit to partly isolate the charge-shared data from undesired coincident ones: unwanted data are rejected by SW off-line action guided by the physical considerations just described above. Since the probability of false events increases with the coincidence time, to increase the percentage of true charge condivision events is preferable to use coincidence times as lowest as possible, i.e. of the order of the signal peaking time. Furthermore, in order to avoid that primary photons, originated by multiple energy emission sources, could make more difficult to extract the charge sharing events, most measurements have been performed with semi-open sources (mainly ^{57}Co with a cylinder collimator of 1.5 mm diameter) since a unique energy (122 keV) is delivered to the detector.

Raw collected data are retrieved and first selected depending on their molteplicity by analizing the coded field which specifies if the event is single or double. The resulting double event data are then filtered to eliminate the "false" charge sharing ones by the following two actions:

- events whose energy is higher than the dynamic range of the Analog-to-Digital Converter (ADC) are discarded as saturating and do not contribute to the budget;
- double events whose energy sum $E=E_X+E_Y$ give an energy contribution equal to the double of the peak emission of the radioactive source are eliminated. This corresponds to eliminate events which distribute in a map representation along the line $E_X=E_Y$.

The filter action provides the user with a new file of "cleaned" double event data in which only true charge sharing events should be included. This file is the input for further analysis, i.e. statistics, single strip spectra, combined strip spectra, map representation, etc.

Finally we can conclude that:

1. the coincidence time do not influence the percentage of double events;
2. for a 2.0 mm pitch CZT detector **4.1%** of events are shared at 122 keV
3. for a 0.5 mm pitch CdTe detector **11%** of events are shared at 122 keV and **5.2%** of events are shared at 60 keV
4. By increasing the bias voltage the double events are decreased, as seen in the simulation study.
5. Since the experimental results agree with the MC results, the simulation tool can be used to optimize the detectors geometry (i.e. the pitch and width of strips or pixels) in segmented systems for different applications: e.g. medical applications and space instrumentations.