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► **To cite this version:**

J. Fey, S. Procz, M.K. Schütz, Vincent Schoepff, Frederick Carrel, et al.. CdTe sensor configurations for robot assisted photon counting gamma camera. *Journal of Instrumentation*, 2021, 16 (07), pp.T07010. 10.1088/1748-0221/16/07/T07010 . cea-03345795

HAL Id: cea-03345795

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Submitted on 21 Sep 2021

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2 CdTe sensor configurations for Robot assisted photon 3 counting gamma camera

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10 Received: date; Accepted: date; Published: date

11
12 **Abstract:** In this work, different Cadmium Telluride (CdTe) sensor configurations are assessed for
13 the usage in a robot assisted portable gamma camera. In the first part, four CdTe sensors, with
14 thickness of 0.45 mm, 1 mm, 2 mm and 3 mm and pixel sizes of 55 μm and 110 μm , are investigated
15 regarding their spectroscopic performance. The photon counting detector Timepix1 is hereby used. The
16 3 mm CdTe sensor shows increase in count rate up to a factor of 1.25 compared to a 2 mm CdTe sensor,
17 1.84 compared to a 1 mm CdTe sensor and up to 2.71 compared to a 0.45 mm CdTe sensor in the case of
18 ¹³⁷Cs. In the second part, the 3 mm CdTe sensor was implemented in a commercially available gamma
19 camera, the iPIX. The system was integrated in the bomb disposal robot and tested in different
20 scenarios. The integrated 3 mm CdTe detector measured 21.5 counts per second emitting from a ⁶⁰Co
21 source with an activity of 2.8 ± 0.07 Gbq in 20-meters distance in an open environment. The acquisition
22 time was 116 seconds. The angular resolution was sufficient for the user to localize the radioactive
23 isotope inside the test structure.

24 **Keywords:** CdTe; Photon counting; Timepix; Gamma camera; Spectroscopy.
25

26 1. Introduction

27 The threat to public safety posed by improvised explosive devices (IEDs) has increased
28 significantly in recent years [1]. In the context of IED, one of the most important aspects, both in terms
29 of real danger and media presence, is the threat of radiological dispersal devices (RDDs). The primary
30 goal of RDDs is neither the damaging of infrastructure nor the injuring of people by the explosive
31 effect, but rather, the contamination of the largest possible area by radioactive substances. The current
32 development state of semiconductor sensors for the detection of both, hard X-ray and gamma-radiation
33 allows to produce highly sensitive, compact gamma cameras. This work addresses the needs of the first
34 responder services to this threat by researching and improving contactless, robot assisted methods for
35 the investigation procedures. The aim is to provide end users with reliable, fast and safe means to
36 investigate IEDs and evaluate the imposed threat.

37 The material as well as the thickness of the sensor are deciding factors of the performance of a
38 gamma camera. High Z semiconductor materials, such as Cadmium Telluride (CdTe), Cadmium Zinc
39 Telluride (CdZnTe) and Thallium bromide (TlBr), offer fast analyzation of the investigated isotope due
40 to their high absorption efficiency. The absorption efficiency can be further improved by increasing the
41 thickness of the semiconductor sensor. However, the effect of charge sharing is increased accordingly
42 [2 - 4]. Charge sharing describes the spreading of information from charge carriers over multiple pixels.
43 The effect is heavily depended on the photon energy of the event and the thickness of the material due
44 to the drift of charge carriers through the sensor layer. The main driving forces are repulsion between
45 charge carriers and diffusion. Thicker sensors archive a higher attenuation efficiency which leads to
46 superior energy resolution to identify the isotope, especially in the high energy region. A smaller pixel

47 size yields a better spatial resolution for localization of the isotope in the region of interest. A crucial
48 aspect in the conception of a Gamma- or Compton camera lies in the dependence of absorption
49 efficiency and the negative effect of the charge sharing on the spatial resolution.
50 In this work, four different ohmic sensor configurations were evaluated for the usage in a gamma
51 camera. The material was supplied by Acrorad (Japan) while the flip-chip bonding was performed by
52 the Freiburg Materials Research Centre (Germany). The 2 mm CdTe sensor was bonded to a Timepix1
53 readout chip with an increased pixel pitch of 110 μm . An increased pixel pitch (pp) counters the charge
54 sharing effect on a hardware level at the detector side. The 0.45 mm, 1 mm and 3 mm CdTe detectors
55 were connected to a Timepix1 readout with 55 μm pp. In this case, the 3 mm CdTe Timepix1 shows the
56 highest effect of charge sharing but also provides the highest attenuation efficiency in photon energies
57 above 100 keV (Fig. 1). Cluster analysis was performed for all detectors since all detector assemblies
58 exhibit charge sharing regardless of configuration.

59 2. Materials and Methods

60 2.1. Cadmium Telluride

61 CdTe is an excellent semiconductor material for hard X-ray and gamma-ray detection. The high
62 atomic number ($Z_{\text{CdTe}} \approx 50$) and density ($\rho = 5.854 \text{ g/cm}^3$ at RT) provide superior attenuation efficiency
63 above 30 keV compared to Si ($Z_{\text{Si}} = 14$) and GaAs ($Z_{\text{GaAs}} \approx 32$) and the wide bandgap energy ($E_{\text{gap}} = 1.44$
64 eV) permits the usage of the detector at room temperature without active cooling. The absorption
65 efficiency can be enhanced furthermore by increasing the thickness of the material [5].

66 CdTe was considered and used as a semiconductor sensor for hybrid photon counting detectors
67 (HPD) of the Medipix chipset family since the beginning of the Medipix collaboration. Previous work
68 investigating the spectroscopic performance of a 1 mm CdTe sensor bump bonded to a Medipix2
69 chipset was presented by Maneuski et al. [6], Ruat and Ponchut [7] and Greiffenberg et al. [8].
70 Measurements regarding the characterization and spectroscopic performance of a Timepix1 chipset in
71 combination with 2 mm CdTe [9, 10] and 3 mm CdTe [5] were shown recently. Cadmium Zinc
72 Telluride (CdZnTe) is another promising semiconductor material in addition to CdTe. Recent work
73 with CdZnTe sensors bump bonded to a Timepix1 chipset [11, 12] and performance investigations [13,
74 14] show encouraging results and are worth investigating in future work.

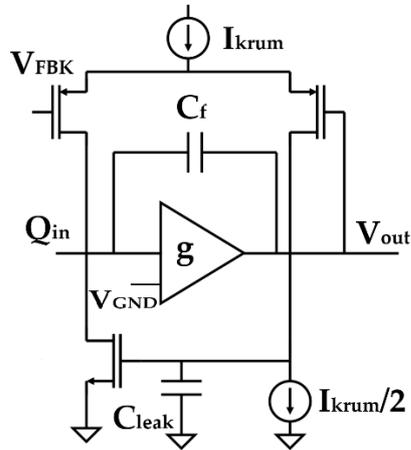
75 2.2. Timepix

76 The Timepix1 is a hybrid pixel detector (HPD) developed by the Medipix2 collaboration CERN
77 [15]. It is fabricated in a CMOS 250 nm process, consists of 256×256 square pixels with a pixel pitch of
78 55 μm , resulting in a sensitive area of 1.98 cm^2 . The detector provides three different counting modes
79 [15]: single photon counting mode (Medipix Mode), Time-Of-Arrival Mode (ToA) and
80 Time-over-Threshold Mode (ToT). For this work, all measurements were carried out using the
81 Time-over-Threshold Mode (ToT).

82 The incoming signal is, individually for each of the 65536 pixels, amplified by a charge sensitive
83 preamplifier and compared to a 4-bit threshold in the discriminator circuit which is connected to a
84 synchronization logic. If the signal exceeds the threshold, a 14-bit counter is incrementing the number
85 of clock units as long as the signal is above the threshold and below 11810 counts in which case the
86 overflow logic stops. The number of incrementing clock pulse is proportional to the input charge and
87 therefore to the photon energy of the event due to a linear discharge of the preamplifier controlled by
88 the IKrum current. This contrasts with single photon counting pixel detectors which discharge using a
89 resistor resulting in exponential decrease of the signal hub [16]. The energy threshold enables
90 compensation of process variations.

91 Different semiconductor sensor materials like Si, CdTe, CdZnTe or GaAs can be connected to the
92 Timepix ASIC and handled by the Krummenacher preamplifier which can process positive and
93 negative charge inputs. The IKrum digital-to-analog-converter (DAC) (Figure 2) and has two
94 functionalities: the compensation of leakage current and the discharge of the preamplifier feedback
95 capacitor, which influences the duration of the return of the peak signal amplitude to the baseline. A

96 higher I_{Krum} current leads to a faster discharge and thus shorter pulses which results in a reduction of
 97 pulse pileup but also to a reduction of signal amplitude, decreasing the energy resolution. The
 98 simulated dependence of the preamplifier output signal and width on the I_{Krum} DAC settings are
 99 shown in [17].
 100



101
 102 **Figure 2.** Schematic of the Krummenacher circuit. The I_{Krum} current controls the leakage current compensation,
 103 in the case of electron collection $I_{Krum}/2$, and the return of the signal to the baseline (adopted from [18, 17]).
 104

105 The Timepix1 and its successor, the Timepix3, were initially aimed for particle detection.
 106 However, in recent years these detectors are used in medical imaging [19], space radiation dosimetry as
 107 well as in commercially available gamma cameras [20] and experimental Compton cameras [9, 21] with
 108 1 mm and 2 mm CdTe sensor configurations.
 109

110 2.3. From GAMPIX prototype to iPIX gamma camera

111 In order to address the need of instrumentation allowing the detection and location of radioactive
 112 materials, CEA List has been developing gamma camera systems for over thirty years [22]. These systems
 113 allow remotely visualizing gamma rays originating from radioactive emitters by superimposing a
 114 gamma image onto a visible image of the scene. Since the late 2000's, CEA List has been working on a
 115 new generation of gamma camera, which resulting prototype is called GAMPIX [23]. This prototype
 116 relayed on the use of a Timepix1 detector equipped with a 1 mm thick CdTe sensor, coupled with a
 117 coded mask ensuring the spatial modulation of incoming gamma flux Figure 3 (a).

118 Coded aperture is a technique of great interest, which allows achieving a good angular resolution
 119 for gamma source reconstruction, while maintaining a high sensitivity of the system. GAMPIX gamma
 120 camera is based on MURA coded masks, consisting in a mathematical arrangement of holes, defining the
 121 rank of the coded mask, into a denal collimator [24]. In the presence of radioactive sources, gamma-ray
 122 will go through holes and be stopped into denal, resulting in the projection of the MURA pattern on the
 123 gamma-sensitive sensor. The high pixelization of Timepix1-based detector allows accurately determining
 124 the location of gamma rays into the semi-conductor sensor, which ensures angular resolution of the
 125 overall imaging system. Indeed, the preferred pixel pitch of 55 μm ensures an achieved precision on
 126 pattern projection estimated around 0.20° , compared to 0.40° for a pixel pitch of 110 μm . This projection
 127 accuracy is a determining factor for the source location reconstruction. Moreover, the symmetry in the
 128 MURA pattern allows, by a 90° rotation of the coded mask, suppressing background noise, without any
 129 additional shielding. This feature, called anti-mask procedure, is of great interest in the case of
 130 measurements in areas subject to high gamma background while preserving lightness of the camera.

131 The GAMPIX prototype was validated in laboratory [25] and deployed in various real environments
 132 in the field of nuclear industry and Homeland Security applications [26]. Performance assessment of the
 133 gamma camera prototype showed that the system was able to perform imaging measurements in a field

134 of view of 50° with an angular resolution ranging from 1.35° to 3.81° depending on the pattern of coded
 135 mask used. As presented in Table 1, the sensitivity of the prototype makes it possible to visualize sources
 136 in less than a minute over the whole range of energies encountered in the field of nuclear industry (i.e.
 137 from ²⁴¹Am at 59.5 keV to ⁶⁰Co at 1.33 MeV) [26].

138 **Table 1.** Sensitivity of GAMPIX gamma camera, according to the rank of the mask (R7 is for rank 7, R13
 139 for rank 13, e2, e4, e8 indicates the corresponding thickness in mm) and to the nature of the radioactive
 140 source. The dose rate was measured in the vicinity of the gamma camera.

Radionuclide	Dose rate ($\mu\text{Sv}\cdot\text{h}^{-1}$)	R13 – e2	R7 – e4	R7 – e8
²⁴¹ Am	0.25	3 s	1 s	1 s
¹³⁷ Cs	2.50	300 s	60 s	20 s
⁶⁰ Co	3.84	Not detected	400 s	60 s

141 From 2010, CEA List started the industrial transfer of GAMPIX prototype toward CANBERRA, now
 142 MIRION Technologies. The resulting commercial system, called iPIX and pictured on Figure 3 (b), is
 143 based on the same technology as GAMPIX [27]. This commercial version was completely redesigned for
 144 compactness (L × l × P = 9 cm × 9 cm × 18.85 cm) and shielding was optimized for improving system
 145 weight (2.5 kg). The anti-mask procedure was automated, and the connection simplified using
 146 Power-over-Ethernet method for simultaneous communication and power supply purpose.
 147
 148
 149



(a)



(b)

150 **Figure 3.** (a) Picture of GAMPIX second-generation gamma camera developed by CEA List; (b) Picture of iPIX
 151 gamma camera, industrialized version of GAMPIX and commercialized by MIRION Technologies.
 152
 153
 154
 155
 156

157 3. Results

158 A sufficient bias was applied to all investigated detector assemblies during the presented
 159 measurements to ensure full charge collection efficiency. This was verified by measuring the count rate
 160 of the detector versus increasing sensor bias voltage under identical X-ray tube settings. The maximum
 161 charge collection efficiency is achieved when the count rate reaches saturation. The leakage current was
 162 measured before the experiments with no radiation present (Table 2). The high leakage current of the
 163 0.45 mm CdTe is due to the effect of the processing of the thin material. A new dicing process was
 164 implemented which permits significant cleaner edges of the bonded sensor. The improved
 165 performance of this process can be seen in the low leakage currents of the 1 mm and 3 mm thick
 166 detector assemblies. In the case of the 2 mm sensor, the observed increase in leakage current is due to

167 an earlier bonding date of the detector assembly. There is no surface preservation on the as-diced chip
168 edge. Over time, degradation effects occur which lead to greater surface leakage currents.

169 **Table 2.** Detector settings and configurations used for the measurements of 3.1 and 3.2.

Sensor thickness	Bias (V)	Leakage current (μA)	Pixel pitch (μm)
3 mm CdTe	-1200	2.5 ± 0.2	55
2 mm CdTe	-600	8 ± 1.2	110
1 mm CdTe	-450	2.1 ± 0.2	55
0.45 mm CdTe	-230	43 ± 4	55

170
171 The DAC for leakage current compensation (IKrum) and the clock frequency were set to the same
172 value for all assemblies to ensure comparable results regarding the spectroscopic performance (Table
173 2). All measurements were taken with a clock frequency of 9.6 MHz and IKrum 5 which corresponds to
174 an IKrum current of roughly ~ 7.5 nA [15]. At IKrum 5, the mean pulse duration of a 100 keV photon is
175 ~ 6 μs [18]. All detectors passed stability measurements with radiation present and continues operation
176 in the range from 12 to 24 hours with the configurations shown in Table 2.

177 Even while performing cluster analysis, the charge sharing effect has a strong influence on the
178 energy resolution of the sensor. This is caused by the limited rise time of the preamplifier in the pixel
179 cell and the higher number of pixels marking the edge of the cluster, which have deposited energy of
180 the event, but the threshold was not exceed. This, so called dead energy, has a greater impact on the
181 energy resolution with increasing cluster size of the event since more surrounding pixels exhibit the
182 dead energy effect.
183

184 3.1. Spectroscopic Performance

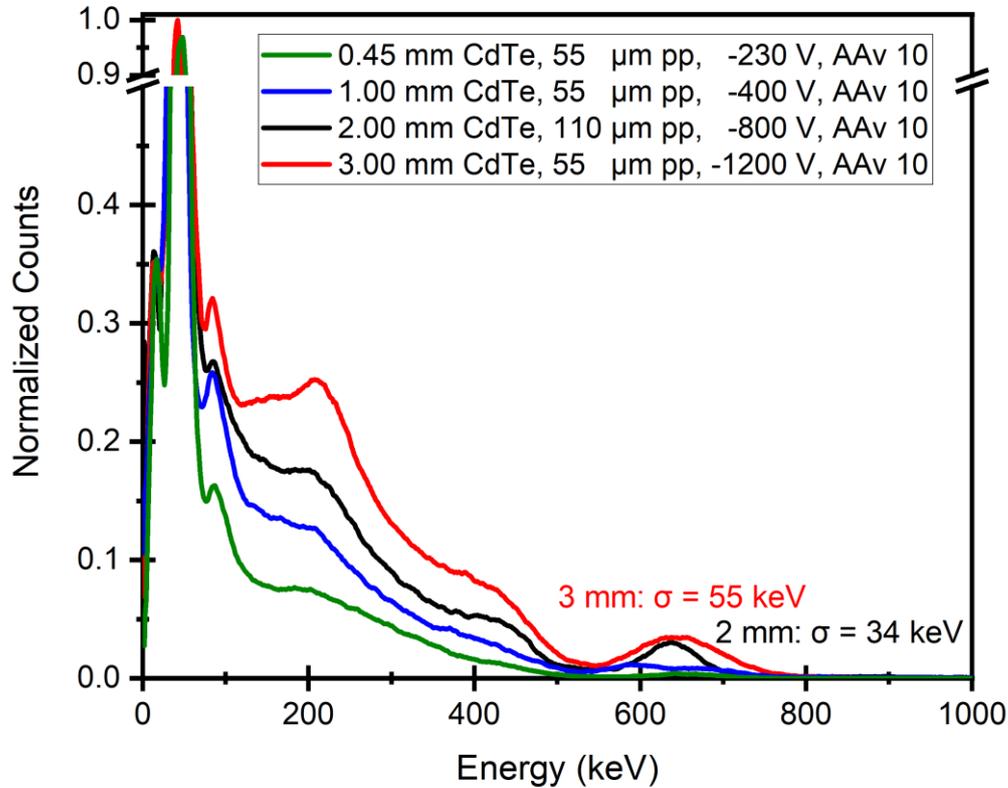
185 The common radioactive sources $^{137}\text{Cesium}$ (^{137}Cs), $^{152}\text{Europium}$ (^{152}Eu) and $^{60}\text{Cobalt}$ (^{60}Co) are
186 investigated by the different detector assemblies in a laboratory environment. All detectors were
187 calibrated by the noise edge method [28] in Pixelman 2.2.3 [29]. The acquisition time was determined
188 for each setup individually to minimize event pile up. Since the thickest sensor exhibits the highest
189 attenuation efficiency, a time was chosen with, on average, 5 events per frame for the 3 mm CdTe
190 detector. All measurements were performed in a fixed timeframe of 1000 s and a fixed distance from
191 source to detector of 60 mm. Cluster analysis was performed for each measurement which identifies
192 counting pixels exhibiting charge sharing as well as separated fluorescence photons and contributes
193 them to their original event. Gaussian fitting is used for the primary gamma ray line of each spectrum
194 and the sigma (σ) is calculated with $\sigma = w/2$. Fig. 4, Fig. 5 and Fig. 6 show the measured spectra for
195 ^{137}Cs , ^{152}Eu and ^{60}Co . The raw spectra were normed in ToT-value on the x-axis a distinguished feature in
196 the spectrum were adjusted to the correlated energy because the TOT values differ per detector. The
197 spectra are superimposed on each other to visualize the difference in performance. All spectra were
198 smoothed by moving average of 10 and the count rate was normalized.

199 The relative absorption efficiency of all sensors was evaluated in comparison to the 3 mm CdTe
200 sensor which exhibits the greatest attenuation efficiency. Previous work investigated the relative
201 absorption efficiency of 1 mm and 0.45 mm CdTe sensors [5]. The data was corrected for the different
202 number of inactive pixels per sensor caused by crystal inhomogeneities and degenerating effects like
203 corner peel. The measurement error was calculated by Gaussian error propagation law.
204

205 3.1.1. Cesium-137

206 ^{137}Cs is an isotope used in the medical environment for radiation therapy. Therefore, in the context
207 of the evaluation of the performance of a gamma camera. The acquisition time was set to 10 ms for all

208 detectors. The lab source has an activity of 3.58 ± 0.09 MBq at the time of the experiment. Figure 4
 209 presents the measured spectra of ^{137}Cs with the different detector assemblies.



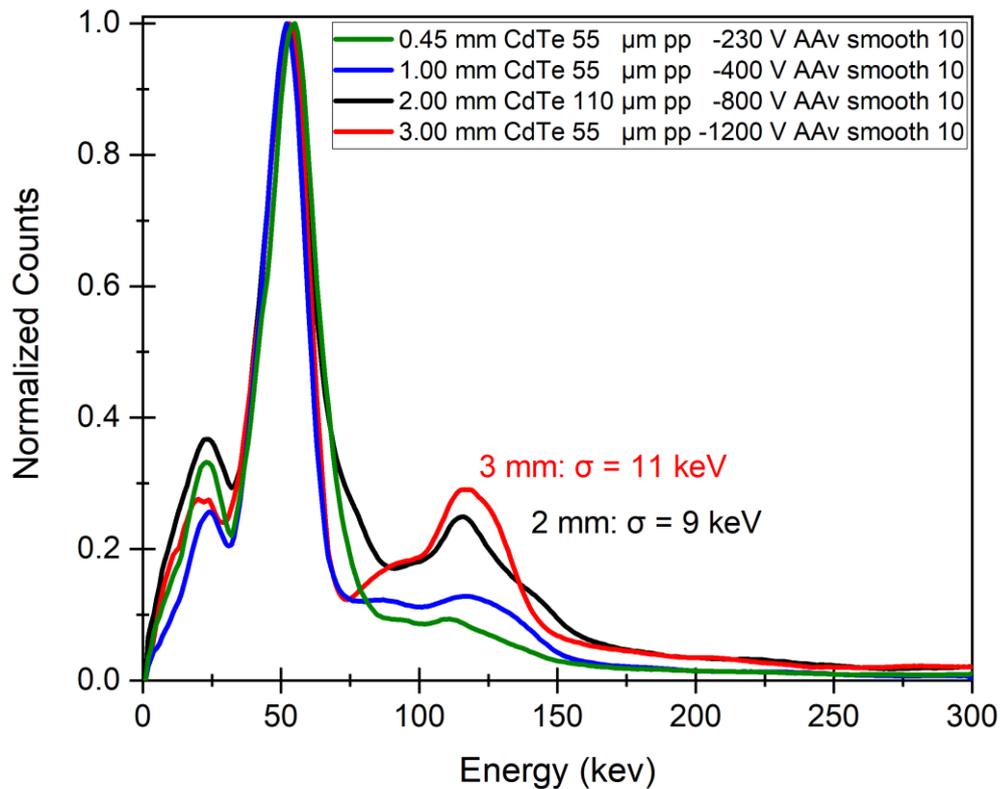
210
 211 **Figure 4.** Spectra of ^{137}Cs investigated by four different detector configurations in this work. The sigma of the
 212 gamma ray line at 667 keV is shown.
 213

214 The characteristic gamma ray line of ^{137}Cs at 667 keV can be identified with all investigated
 215 detector configurations with a significant correlation in amount of counts and attenuation efficiency of
 216 the different sensors. A sigma of 55 keV is achieved for the gamma ray line in the case of the 3 mm
 217 CdTe sensor which exhibits the strongest charge sharing of all configurations caused by the thickness
 218 of the sensor layer and the 55 μm pixel pitch. In direct comparison, the 2 mm CdTe sensor shows, with
 219 greater 110 μm pixel pitch, a decreased sigma of 34 keV resulting in a more defined peak of the gamma
 220 ray line. The 0.45 mm CdTe sensor exhibits a comparable sigma to the 2 mm CdTe configuration. This
 221 is achieved by the significant thinner sensor material which results in less charge sharing and a
 222 comparable energy resolution even with a 55 μm pixel pitch. Besides the Ba L X-ray line of the source at
 223 32 keV another peak is visible in all four spectra at 75 keV. This peak corresponds to the Pb k-edge
 224 energy ($K_{\alpha 1}$ 75 keV) and is originating from the Pb enforced shielding in the measurement
 225 environment.

226 A relative absorption efficiency of (0.370 ± 0.003) for 0.45 mm CdTe, (0.544 ± 0.002) for 1 mm CdTe
 227 and (0.801 ± 0.002) for 2 mm CdTe in comparison to the 3 mm CdTe was measured.

228 3.1.2. Europium-152

229 ^{152}Eu is a gamma and beta emitter used in hard-gamma brachytherapy. At the time of the
 230 measurement, the lab source had an activity of 0.28 ± 0.01 MBq. The set acquisition time for all sensors
 231 was 32 ms, which was chosen to minimize event pile up. Figure 5 shows the ^{152}Eu spectra measured
 232 by the four investigating detector configurations.



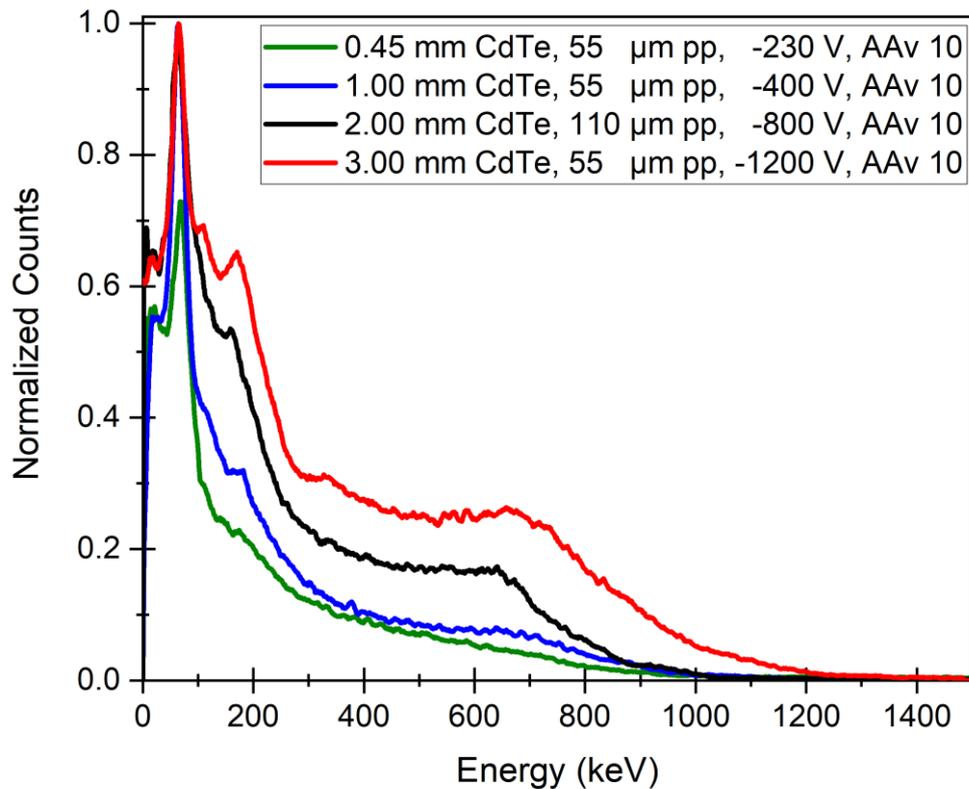
233
 234 **Figure 5.** Spectra of ^{152}Eu investigated by four different detector configurations in this work. The sigma of the
 235 gamma ray line at 122 keV is shown.
 236

237 The ^{152}Eu isotope exhibits a characteristic gamma ray line at 122 keV which is resolved with a
 238 sigma of 11 keV in the case of the 3 mm CdTe sensor configuration with 55 μm pixel pitch. As with the
 239 characteristic ^{137}Cs gamma ray line, the 2 mm CdTe sensor with 110 μm pixel pitch shows an improved
 240 sigma of 9 keV. The 1 mm and 0.45 mm sensors show a significantly less distinguishable peak at 122
 241 keV caused by a reduced attenuation efficiency at the corresponding energy.

242 For ^{152}Eu , the difference in absorption efficiency between the investigated sensors is less evident
 243 than for ^{137}Cs and ^{60}Co . This is due to the Sm L-lines at 40 keV (Sm $K_{\alpha 1}$) and 39 keV (Sm $K_{\alpha 2}$), originating
 244 from the ^{152}Eu decay chain, which have an absorption efficiency above 99% for all investigated sensors.
 245 In addition, the emitted beta particles of ^{152}Eu are absorbed in the first few μm of the sensor layer
 246 regardless of the thickness. However, multiple gamma ray lines at energies >200 keV contribute to the
 247 observed ratio in relative absorption efficiency compared to the 3 mm sensor of (0.637 ± 0.003) for 0.45
 248 mm CdTe, (0.777 ± 0.003) for 1 mm CdTe and (0.944 ± 0.003) for 2 mm CdTe.
 249

250 3.1.3. Cobalt-60

251 ^{60}Co is used in medical radiotherapy as a radiation source and therefore common in most hospitals
 252 and a potential isotope in an IED. In this investigation, it is used to evaluate the spectroscopic
 253 performance of the detectors for high energy photons since ^{60}Co exhibits two characteristic gamma ray
 254 lines at 1173 keV and 1333 keV. At the time of the experiment, the used lab source had an activity of
 255 6.55 ± 0.16 Mbq. The acquisition time was set to 5 ms. Figure 6 presents the measured spectra of ^{60}Co
 256 investigated by the different detector assemblies in this work.



257
258 **Figure 6.** Spectra of ^{60}Co investigated by four different detector configurations in this work.
259

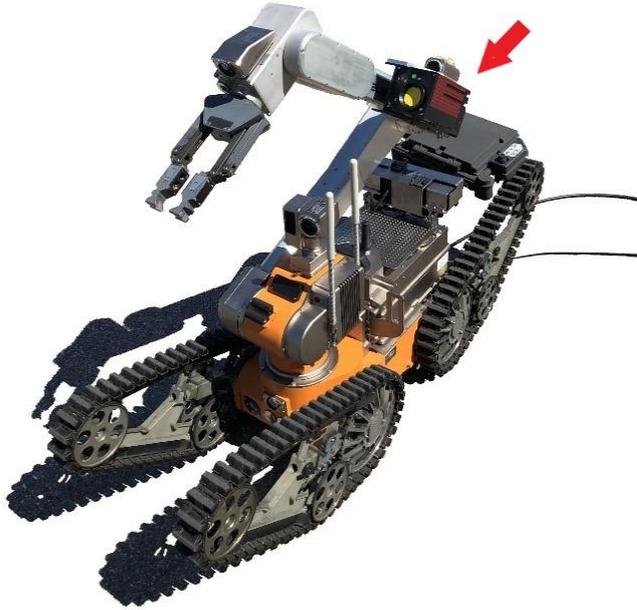
260 No photo peak of the gamma ray lines at 1173 keV and 1333 keV can be distinguished regardless
261 of detector configuration. This is due to the presence of undetected escape photons originating from the
262 predominant Compton scattering, the limited energy resolution of the Timepix1 detector and the low
263 attenuation efficiency of $\sim 8.8\%$ in the case of the 3 mm CdTe sensor. An even thicker sensor would be
264 desirable for ^{60}Co . A significant reduction in overall count rate can be overserved for the 1 mm and 0.45
265 mm sensors. As with the ^{137}Cs spectrum, the Pb ($K_{\alpha 1}$ 75 keV) is visible.

266 A significant reduction in overall count rate can be overserved for the 1 mm and 0.45 mm sensors
267 with a relative absorption efficiency of with (0.238 ± 0.002) for 0.45 mm CdTe and (0.396 ± 0.004) for 1
268 mm CdTe compared to the 3 mm CdTe. The 2 mm CdTe sensor exhibits the same effect as the thinner
269 sensors but to a lesser degree with a relative absorption efficiency compared to the 3 mm sensor of
270 (0.641 ± 0.005) .

273 3.3. Implementation and field testing

274 After investigating the spectroscopic performance in chapter 3.1 and 3.2, a field test campaign was
275 initiated to evaluate the influence of a thicker sensor on the localization capabilities of the gamma
276 camera. The 3 mm CdTe sensor has the highest attenuation efficiency of the investigated sensors and
277 the 55 μm pixel pitch permits the necessary spatial and angular resolution for the localization of the
278 threat. Therefore, a 3 mm CdTe Timepix1 detector assembly with 55 μm pixel pitch was implemented
279 in the iPIX gamma camera. Figure 7 shows the camera mounted on the robot Telemaxx manufactured
280 and provided by Telerob GmbH (Germany). A specific mounting solution of the gamma camera was
281 provided by ZIPPERMAST GmbH (Germany) which mounts the iPIX on the robotic arm. Following

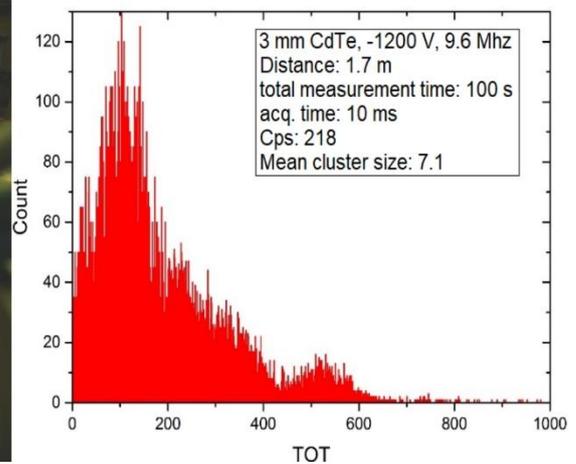
282 this approach, it was possible to remain the manipulation capabilities of the robot on investigating
283 objects while having a 360° radius for the FOV of the gamma camera.
284



285 **Figure 7.** Telexx by Telerob with the iPIX mounted on the arm. The mounting method does not negatively
286 influence the manipulation ability of the robot while permitting at the same time a 360° radius for the position of
287 the gamma camera.
288
289

290 3.3.1. NBC testing side

291 During the project, it was possible to carry out a field test of the modified iPIX at the NBC testing
292 side of the Austrian army at the DABSCH Kaserne (Austria). A room was prepared for investigation
293 with a simili, containing a radioactive source, placed inside. The complete system could be tested
294 under realistic conditions outside the lab environment [30]. Figure 8 (a) shows the superimposed image
295 of the gamma camera with localized radiation source in a suitcase. ^{137}Cs is the investigated isotope with
296 an activity of 36 ± 0.9 Gbq. The distance from source to detector was 1.7 meters with 218 recorded
297 counts per second (Cps). Figure 8 (b) presents the spectrum which was simultaneously recorded in 100
298 seconds.



299
300

(a)

(b)

301 **Figure 8.** (a) Investigation of a prepared smili at the NBC testing side. A ^{137}Cs source with an activity of 36 ± 0.9
 302 Gbq is placed inside and localized by the 3 mm CdTe sensor with 218 Cps. (b) The spectrum which was recorded at
 303 the same position in 100s. The mask R7 – e4 (Table 1) was used for the measurement.

304 In comparison to the normalized ^{137}Cs spectrum measured in the lab, shown in Figure 4, the raw
 305 ToT-values are presented on the x-axis in Figure 8 (b). A total measurement time of 100s was chosen
 306 since it represents a realistic time frame to investigate a suspicious object in case of an emergency
 307 situation regarding the potential isotope present. The overall spectrum is noisier which is a result of the
 308 lower event count. However, the gamma ray line at 662 keV can be distinguished.

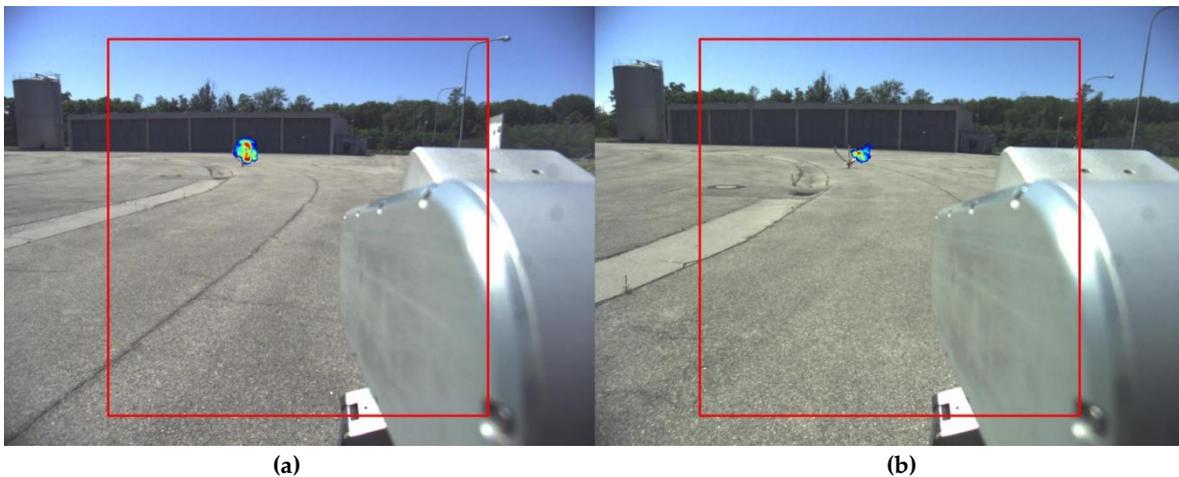
309 3.1.2. Nuclear Powerplant test facility

310 A second field test was performed with the iPIX configuration described in section 3.3 at a nuclear
 311 power plant test site. A ^{60}Co source was placed inside a test structure which is 150 cm wide and 100 cm
 312 in height. Three tubes are in equal distance and the isotope is placed randomly in one arm. The source
 313 has an activity of 2.8 ± 0.07 Gbq which corresponds to a dose rate of ~ 1 mSv/h in 1 m distance. Table 3
 314 shows the results of the measurements. Figure 9 presents the distance 25 meters (a) and 20 meters (b).
 315 Figure 10 shows the distance 15 meters (a) and 12 meters (b) respectively. The attenuation efficiency of
 316 the 3 mm CdTe sensor in the energy region of ^{60}Co enables a timely localization of the test object with a
 317 maximum of 200 s in the case of 25 meters distance. It was possible to visually localize the isotope in the
 318 right arm of the structure at 20 meters.
 319

320 **Table 3.** Distance measurement at the nuclear power plant test facility. The isotope ^{60}Co with an activity
 321 of 2.8 ± 0.07 Gbq is investigated. The visible localization is the ability of the user to identify the
 322 radioactive source placed inside the right arm of the test structure on the superimposed image of the
 323 iPIX.

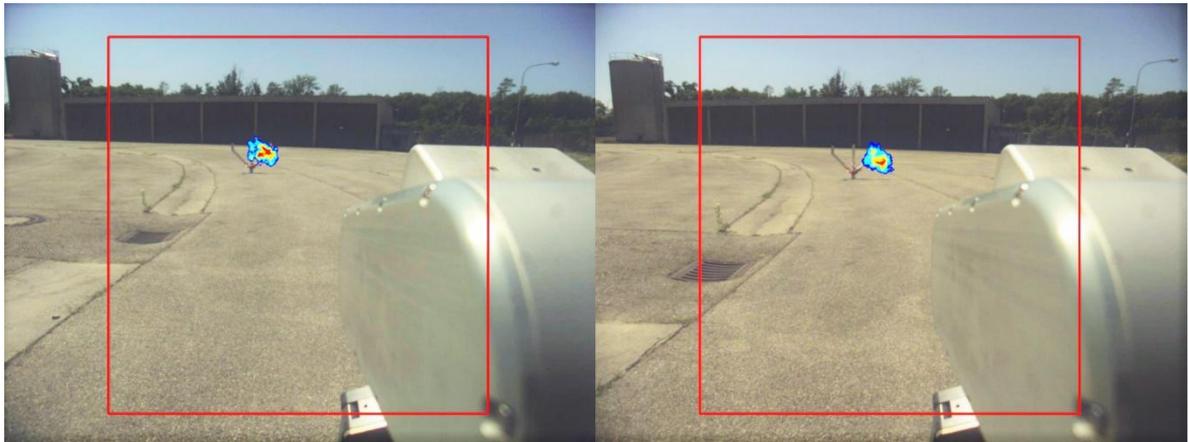
Distance (m)	Cps	Acquisition time (s)	Visible localization
25	13.2	200	No
20	21.5	116	Yes
15	37.1	91	Yes
12	43.8	72	Yes

324
 325



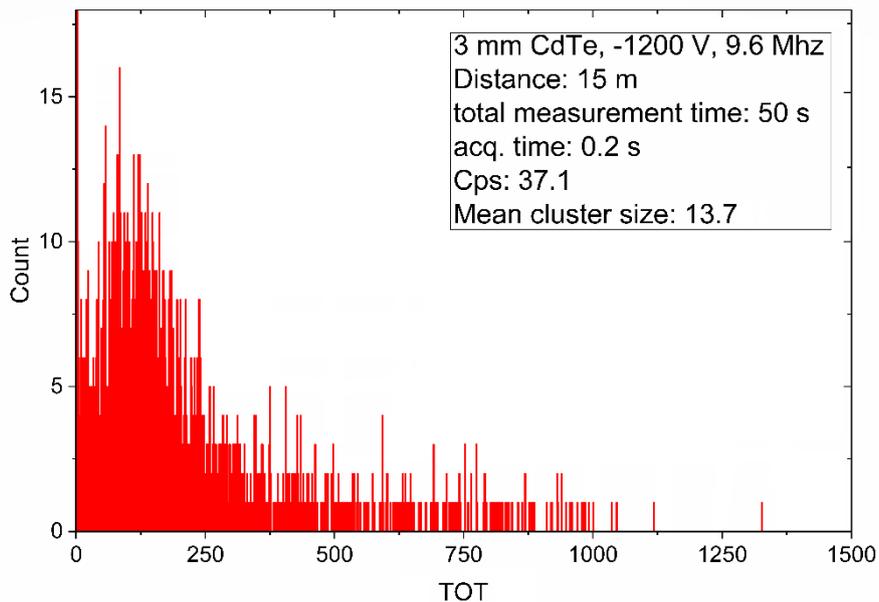
326 **Figure 9.** A ^{60}Co source with an activity of 2.8 ± 0.07 GBq (dose rate of ~ 1 mSv/h in 1 m distance) is placed in a
 327 structure which is 100 cm in height and 150 cm wide with three tubes in equal distance from each other. In (a), the
 328 distance between source and gamma camera is 25 meters. The sensor registered 13.2 Cps and the superimposed
 329 image was taken with an acquisition time of 200 s. It is not possible to identify the tube with the source. In (b), the
 330
 331

332 distance between source and camera was reduced to 20 meters resulting in 21.5 Cps. It is possible to identify the
333 right tube as the source of radiation with 116 s acquisition time.
334



335
336 (a) (b)
337 **Figure 10.** The distance of detector and source is reduced to 15 meters in (a) and 12 meters in (b). In both cases, it
338 can be determined visually that the source is placed in the right arm of the structure. For the 15 meters distance,
339 37.1 cps with an acquisition time of 91 s were evaluated. The right image with 12 meters distance yield 43.8 cps
340 with an acquisition time of 72 s.
341

342 A spectrum was recorded at 15 meters distance between the ^{60}Co source and detector shown in
343 Figure 11. The total measurement time was 50 s due to on-site time restrictions. The spectrum is noisier
344 than the spectrum in the lab environment. This is expected due to the distance of 15 meters to the
345 source resulting in a low count rate. The information would not be feasible to identify the investigated
346 isotope, however, the presence of high energy photons can be determined since the cluster analysis
347 detects and sufficiently excludes alphas and muons from the evaluation [5].
348



349
350 **Figure 11.** ^{60}Co spectrum recorded during the measurement series at the nuclear power plant test facility. The
351 distance between source and detector is 15 meters with a total measurement time of 50 s. The mask R7 – e4 (Table
352 1) was used for the measurement.
353

354 A test parkour was prepared inside the power plant which is designed to evaluate the
355 maneuverability and manipulation capabilities of the robot as well as localization of hidden radioactive
356 sources. Video 1 shows a short clip of the iPIX mounted on the Telemaxx at the parkour during
357 ENRICH 2019 (Austria).

358
359 Supplementary Material Video

360 **Video 1.** This video shows the Telemaxx bomb disposal robot with the iPIX mounted on the side arm
361 during ENRICH 2019 (Austria). The iPIX used the 3 mm CdTe detector configuration. The parkour is
362 designed to test the maneuverability and manipulation possibilities of the robot. In addition,
363 radioactive sources must be localized.

364 3.4. Comparison to related work in the field

365 The presented approach uses the small pixel pitch of the Timepix ASIC and cluster analysis to
366 guarantee a high angular resolution of the gamma camera by means of the MURA coded aperture as
367 well as to provide spectroscopic information. A comparable gamma camera design approach is the
368 Caliste-HD [31], which uses a CdTe hybrid detector with a 16 x 16 pixel matrix with 580 μm pixel pitch
369 and MURA coded mask for the localization capabilities. The pixel size used in Caliste-HD is much
370 higher than in the iPIX to reduce charge sharing effects without performing a cluster analysis. The
371 relation of sensor thickness to pixel pitch enables the evaluation of single pixel events only for
372 spectroscopic investigation. This results in a superior energy resolution. The gamma ray line of ^{152}Eu at
373 121 keV is resolved with a sigma of 0.9 keV in comparisons to the sigma of 11 keV of the 3 mm CdTe
374 Timepix used in this work. However, as both coded-aperture imaging systems use a MURA mask, the
375 highly pixelated Timepix has an angular resolution ranging from 1.3° to 3.8°, depending on the isotope,
376 while the Caliste-HD system is reporting an angular resolution of only 7° in the case of ^{152}Eu [31].

377 Scintillator based gamma cameras show a 6.0° angular resolution at 356 keV with a $\text{LaCl}_3(\text{Ce})$
378 scintillator consisting of 22 x 22 voxels using URA coded aperture [32] and 5.6° angular resolution with
379 a CsI (Na) detector module consisting of 20 x 20 voxels using a MURA coded aperture [34].

380 The CsI (Na) compact hybrid gamma camera was used to investigate the position of UO_2 pellets with
381 4.1 % enriched ^{235}U and an activity of 1.14 μCi [34]. The results were used to predict the minimum
382 required detection time and count rate for monitoring different amounts of UO_2 pellets at 10-meters
383 distance between source and detector. A localization time of 199.4 s and a count rate of 30.9 cps was
384 found feasible to use the CsI (Na) compact hybrid gamma camera in the proposed scenario. In this
385 work, it was possible to localize a ^{60}Co source in 20-meters distance in 116 s with a significant lower
386 count rate per second of 21.5 Cps. The estimated required time of localization in a time crucial situation
387 agrees with the localization times stated in this work.

388 A single layer Compton camera is another camera concept which uses Compton scattering for isotope
389 localization by reconstructing the scattering angle [35]. The advantage to renounce the coded-aperture
390 system enables the construction of smaller and lighter camera systems. However, since the
391 localization principle relies on Compton scattering, the detection efficiency of the camera is declining
392 with decreasing energy of the investigated isotope. Furthermore, the distance between source and
393 camera has to be known for position identification.

394 Recently, a hybrid Compton camera was proposed, combining a classical Compton camera and a pinhole
395 camera in a single detector system. This hybrid camera achieves a sigma of 3.5 keV at the gamma ray
396 line of ^{137}Cs at 662 keV, in comparison to sigma 55 keV of the 3 mm CdTe Timepix, and an angular
397 resolution of 10° [36].

398 . Discussion and Conclusions

399 Four different CdTe sensor configurations were bonded on Timepix1 readout ASIC to evaluate the
400 spectroscopic performance for the integration in a gamma camera used on a robotic platform for
401 counter measurements for radioactive threats.

402 Energy resolution is systematically better with greater pixel size and thinner sensors due to less
403 charge sharing present. The 2 mm CdTe 110 μm pp detector exhibits a sigma 34 keV for the ^{137}Cs
404 gamma ray line at 662 keV compared to sigma 55 keV for the 3 mm CdTe 55 μm pp detector. A
405 negative influencing factor on the energy resolution is the deposition of not registered energy around a
406 cluster due to the threshold of the individual pixel cell. This effect increases with overall cluster size
407 due to a greater number of surrounding pixels. However, the attenuation efficiency of a sensor is an
408 important aspect for a gamma camera since it allows efficient charge collection for a fast localization of
409 the radioactive source especially for high energy gamma rays which pose an extensive threat to public
410 safety. For the common isotope ^{137}Cs , the 3 mm CdTe sensor shows increase in count rate up to a factor
411 of 1.25 compared to a 2 mm CdTe sensor, 1.84 compared to a 1 mm CdTe sensor and up to 2.71
412 compared to a 0.45 mm CdTe sensor (Fig. 4, ^{137}Cs).

413 In a scenario in which the possible source of radiation is unknown to the user, the extension of the
414 field of view (FOV) of the camera by means of the possible distance between source and detector
415 enables the first assessment of the situation in a timely matter. This depends on the attenuation
416 efficiency and angular resolution of the detector. The integrated 3 mm CdTe detector measured 21.5
417 counts per second emitting from a ^{60}Co source with an activity of 2.8 ± 0.07 Gbq in 20-meters distance in
418 an open environment. The acquisition time with visual identification by the user was 116 seconds.

419 The relative absorption efficiency measured in section 3.2 allows the calculation of the estimate
420 acquisition time of a 1 mm CdTe sensor in the same scenario. In 20-meters distance from the source, the
421 1 mm CdTe sensor would have a predicted 8.5 cps resulting in 293 s acquisition time. For the intended
422 use of the gamma camera to assisted in situations where the public safety is concerned, the time
423 difference in localization of the source is significant for immediate decisions on appropriate
424 countermeasures. The angular resolution was sufficient for the user to localize the radioactive isotope
425 inside the test structure without knowing the placement for this measurement. At a 25-meters distance
426 between detector and source, it was not possible for the user to distinguish the placement of the source
427 inside the test structure.

428 A teleoperated robot platform with manipulation capabilities in combination with a gamma
429 camera can assist police, fire workers and personal from nuclear powerplants in hazard and security
430 operations. It poses the prospect to position the user and personal in a safe distance from a radioactive
431 threat while, at the same time, remain the possibilities of interaction with the investigated object.
432 Furthermore, in the frequent case of non-attacks, in which suspicious objects turn out to be harmless,
433 the 3 mm CdTe sensor improves investigation speed significantly compared to the 1 mm CdTe sensor.
434 For future work, it is worth investigating even thicker CdTe sensors in combination with highly
435 pixelated ASICs such as the Timepix1 as well as other high Z sensor materials such as CdZnTe and TiBr
436 which have similar or superior attenuation efficiency as CdTe while are available in greater sensor
437 thickness.

438

439 **Author Contributions:** Conceptualization, J.F. and S.P.; methodology, J.F. and S.P.; software, J.F. and S.P.;
440 validation, M.K.S., J.S.U. and J.F.; formal analysis, J.F.; investigation, J.F. and M.K.S.; resources, M.F., F.C., A.F. and
441 V.S.; data curation, , M.K.S., J.S.U. and J.F.; writing—original draft preparation, J.F., S.P. and V.S.; writing—review
442 and editing, J.F.; visualization, J.F.; supervision, S.P. and M.F.; project administration, S.P. and M.F.; funding
443 acquisition, M.F.. All authors have read and agreed to the published version of the manuscript.

444 **Funding:** This research was funded by the German Federal Ministry of Education and Research (BMBF), grant
445 number 13N14328.

446 **Acknowledgments:** The authors would like to express their thanks to all collaborations partners of project
447 “DURCHBLICK” (BMBF, grant no. 13N14328) in particular Andreas Ciossek of Telerob GmbH (Germany) for
448 providing the robot and Frank Woodcock of ZIPPERMAST GmbH (Germany) for manufacturing the mounting
449 solution of the iPIX. We would like to thank the Fraunhofer FKIE (Germany), the Bundesheer (Austria) and the
450 organizers of the ENRICH for the opportunity of on-site testing of the system.

451 **Conflicts of Interest:** The authors declare no conflict of interest.

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