New Perspectives of X-ray Techniques for Explosive Detection Based on CdTe/CdZnTe Spectrometric Detectors

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Abstract. Conventional explosive detection systems (EDS) based on X-ray technologies are using dual-energy radiography; they provide only a crude material characterization. Recently emerged semiconductors based X-ray detectors offer new capabilities in energy discrimination. This study is aiming at evaluating their interest for EDS. LETI-LDET laboratory has developed several pixellated CdTe/CZT detectors. For X-ray spectral radiography, a detector capable to operate at count rates above 10^7counts/mm^{2}s has been implemented, and associated to a multidimensional spectra analysis. We present the performance get for material identification on experimental data. Two complementary X-ray techniques are used in EDS: diffraction and backscatter techniques. Adapted detector prototypes have been developed. Experimental spectra are presented, and a dedicated processing method introduced for backscatter. For all these techniques, we discuss how CdTe/CdZnTe based spectrometric detectors are well-adapted.

Introduction

After September 11th, 2001, security has become a major issue. Federal law mandates that every checked bag at all commercial airports be screened by explosive detection systems (EDS) or alternative technologies. X-ray based interrogation systems are the most widespread employed. A commonly used technique is conventional radiography exploiting the absorption of transmitted radiation through the examined object. But the performance is low due to the items superimposition that can not be solved by radiographic projection, and to the poor material identification capability. Alternative techniques have been developed, such as dual-energy radiography, backscatter, diffraction, and computed tomography. Dual energy is based on the energetic dependence of material absorption, and consists in splitting the measurement in two energy windows. Tomography provides, through a multi-view acquisition, a reconstructed volume where absorption value has been separated from thickness. Backscatter and diffraction techniques exploit other physical properties of X-ray.
Most radiographic systems take linear projection through the luggage travelling on a conveyor belt in a so-called line scan mode. Detectors used are efficiently collimated linear arrays. For dual-energy capabilities, sandwich detectors have been optimized. They consist of two layers of scintillator-photodiode type, separated by a metal filter. The first (resp. second) layer absorbs the low (resp. high) energy photons. Due to the poor energy separation of this acquisition system, and to a significant noise level resulting from the acquisition speed, the obtained accuracy at best only allows materials to be classified into broad bands such inorganic and organic [1].
The coherent scatter, predominant in the region of about 3-10° forward scatter, leads to the diffraction effect, which is the most material specific of all those associated with X-ray

technique. Examples of this technique for explosives can be found in [2], [3], [4]. Performance is impressive. The detectors used are generally Germanium probes assuring a high spectrometric resolution. But they require cooling process, and their size limits the design of compact multi-pixel systems. Backscatter technique, analysing the radiation scattered in the backward direction, permits the inspection of luggage that can not be imaged by transmission, addressing particular configurations that are not accessible by the other techniques [5]. Depending on collimation, two functionalities are possible: imaging and local investigation. The first one provides only qualitative images. The second one, when using integrating mode detectors, can identify low and high density materials but remains insufficient for explosive discrimination. Compared to radiography, these two last techniques allow a more accurate but necessarily slower identification process, therefore are generally used at a second inspection level. The combination of these complementary X-ray techniques increases the reliability of identification [6], [7].
Recently emerged semiconductor based X-ray imaging detectors offer new capabilities in energy discrimination [8]. They are able to count the photons in several energy channels, thus potentially give access to the energetic dependence of X-ray absorption, which is material specific. Energy sensitive counting mode detectors improve image noise, and allow an accurate material discrimination to be made. LDET laboratory at LETI has been developing several pixellated CdTe/CZT detectors, the corresponding ASICs and associated data processing. This paper is aiming at evaluating their potential gain in performance for the different x-ray techniques in EDS. First we remind explosives characteristics. Then we present spectrometric detectors optimized for radiography purpose, and propose an associated material identification approach. Performance of this system is evaluated on experimental data. Then spectrometric detectors dedicated to low flux rates are introduced. Application to diffraction and backscatter techniques are discussed. In the limited place of this paper, we illustrate the specificity and limits of each technique, referring to the concerned papers for details.

1. Explosive chemical characteristics

The difficulty in explosive detection lies in the fact that the materials contained in a luggage are unknown in number and nature, and they are very chemically close to common materials**.** The effective atomic number (Z_{eff}) of most explosive materials ranges from 7 to 7.7 and their density (ρ) from 1.4 to 1.9. Fig.1-left represents the more common explosive and closed materials in the (ρ, Z_{eff}) space. Depending on the technique and associated method employed, X-ray EDS perform material identification either in this space, or in a space closer to the measurement provided by the detector. In radiography, as detailed afterwards, we get the line-integral of the attenuation coefficient, simply called attenuation. We chose the attenuation given by a dual-counting detector for the representation of Fig.1-right (simulation). Different materials are drawn for increasing thicknesses. From both representations, it appears clearly that explosives are hardly distinguishable from other common materials. In fact the performance is driven by the ratio of material closeness to noise on detector measurement. For instance the ellipse on Fig.1-right results from photonic noise for a typical flux in luggage screening, assuming a perfect detector. It increases for a realistic detector or a lower flux.

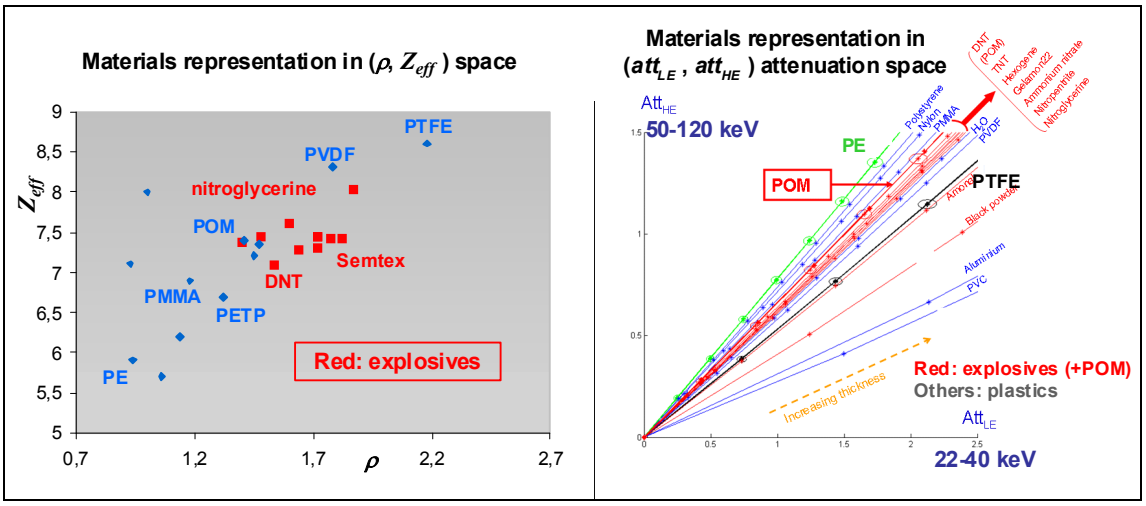

Fig. 1. Representation of explosives and common materials, in (ρ, Z_{eff}) space and in (att_{LE}, att_{HE}) space.

2. Spectrometric detectors for transmission techniques

Detectors made of compound semiconductors such as CdTe and CdZnTe have shown outstanding performance for X and gamma ray spectrometry when operating at room temperature [8]. Thanks to a direct conversion from photon to charges that are collected, and to dedicated electronics, they are able to count the photons in each energy channel. Recently, thanks to the progresses in device technology, energy sensitive CdTe detectors for fast digital X-ray imaging have emerged [9] [10]. These detectors combine a fast read-out electronic circuit providing high count rate capabilities, and a coarse energy resolution obtained with a finite number of counters for each detector pixel. Prototypes have been developed and evaluated [11] [12].

LETI associated to MultiX has developed a novel fast read-out system capable of taking high-resolution spectrometric measurements at high count rates, thus optimized for objects inspected on line scan mode such as luggage in airports. For each pixel, the signal is continuously digitized by a 100 MHz Analog to Digital Converter (ADC), while a FPGA controls acquisition and sets up the energy spectrum on 256 bins. The set of read-out electronic components is coupled to CdTe linear array detectors. This 16 pixels array was purchased from ACRORAD (Japan). Pixel size is 0.8 x 0.8 mm². Detector is 3 mm thick and ensures good stopping power for X-rays of up to 150 keV. Characterization of spectrometric performance in terms of energy resolution and count rate at fluxes up to 2 10^7 photons/mm^{2}s are described in a former paper [13].

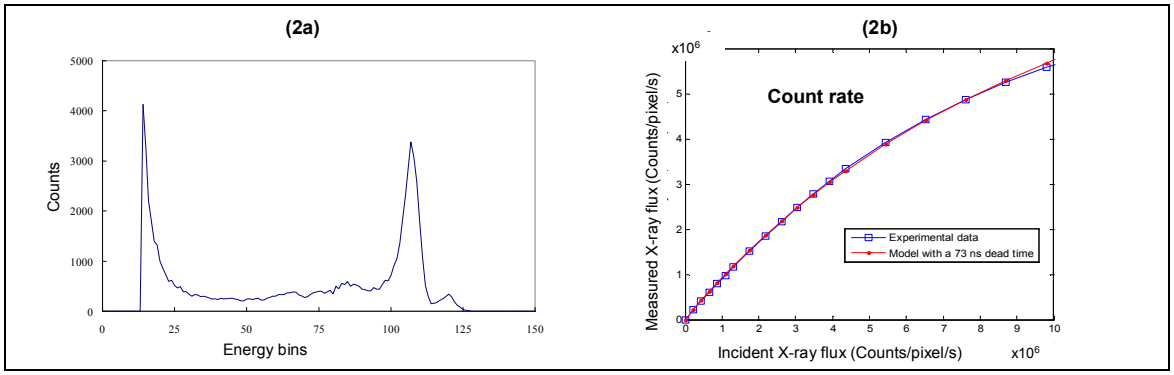

Fig. 2. Performance of a LETI spectroscopic detector.
(2a): Response to an 80 keV X-ray source at high flux. (2b): Count rate performance as a function of flux.

Fig.2a shows the spectrum measured with an 80 keV ESRF X-ray source. Increasing the count rate leads to resolution deterioration and count loss. Up to 2×10^6 photons/pixel/s, we observed that the spectrum does not suffer particularly from pile up phenomena (Fig.2b). A dead time of 73 ns has been calculated by adjusting experimental count rates with a non-paralyzable behaviour model. In a typical configuration for luggage inspection (2×10^6 photons/pixel/s without attenuating object, equivalent to 3.1×10^6 photons/mm^2/s), resolution is 10% at 122 keV.
An accurate model of a semiconductor detector response has been developed. This software permits to predict the detector response depending on its characteristics, and thus to minimize various effects such as charge sharing, pulse pile-up, K-shell escape. It has been linked with a software tool providing realistic radiographic images, allowing the evaluation of detector performance influence in terms of radiograph quality.

3. Spectral radiography and material identification

3.1 Spectral data and identification method

We present here a multi dimensional approach for material identification based on spectral data acquired by any spectroscopic detector. For more details on the method please refer to [14] or [15]. We focus here on the performance obtained with experimental data [16].
A spectroscopic detector is able to provide a number of photons N_i per energy bin, these bins being narrow – about 1.2 keV for our prototype – sufficiently narrow for considering the attenuation function $\mu(E)$ constant inside them. This bin information can be merged into larger channels. For K counters, each of them defining an energy channel $\left[E_{k,\min}, E_{k,\max}\right]$, we get a vector of K measurements:

$$m = \left(m_1, \ldots m_k, \ldots m_K\right) \text{ with } m_k = \sum_{E_{k,\min}}^{E_{k,\max}} N_i$$

Formerly the information is similar to those produced by a multi-counting detector using electronic counters. Numerical merging of spectral data is more complex but offer capabilities such as adaptability or detector correction. The "attenuation measurement", which is precisely the line-integral of the attenuation coefficient, is given by the vector:

$$att = \left(att_1, \ldots att_k, \ldots att_K\right) \quad \text{with} \quad att_k = -\log m_k / m_{k,0}$$

We propose a K-dimensional approach for identification based on *att* vectors. The method is based on an experimental calibration performed on a database, and an identification process using a statistical test. The calibration process consists in placing in the radiographic system a set of various materials and thicknesses, and for each sample, to learn the probability distribution of the attenuation vector *att* using successive measurements at representative noise conditions. This distribution is modelled by a multi-normal law. The thicknesses range should cover the variation range of the examined objects, and be sufficiently fine sampled to allow linear interpolation between two successive thicknesses. Given a current measurement represented by an attenuation vector *att*, the probability density values corresponding to the different calibration samples, including those at interpolated thicknesses, are computed at the point *att*. The values for the different materials are mutually compared, and the highest is selected, giving the more probable material (and incidentally the estimated thickness). Finally, system identification performance is evaluated using a false detection rate (FDR) criterion, estimated on a large set of experiments. For a multi-counting detector, an optimization process is needed to

choose the set of counters (number and bounds of channels) that minimize the FDR. This process is especially important in case of few large counters.

3.2 Experimental Results

In terms of Z_{eff} (fig.1), explosives as well as common materials, are surrounded by PE (Polyethylene) and PTFE (Polytetrafluoroethylene). POM (Polyoxymethylene) cannot be distinguished from explosives, making it an appropriate candidate for an explosive simulator. In this study our database is composed of PE, POM and PTFE. Acquisitions are performed with the detector prototype presented in §2, and the following X-ray generator parameters: 120 kV, 0.9 mA and 2 mm Al filtration, acquisition time 50 ms. For comparison purpose a sandwich detector has been used. It is composed of two layers (0.5mm thick Gd2O2S layer, and 3.0mm thick CsI) separated by a 0.12 mm silver filter.

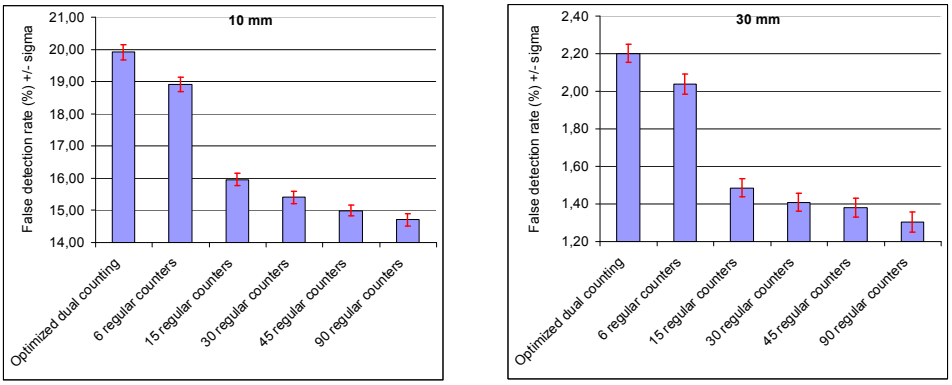

Fig. 3. Performance (False detection rate) for the identification of 10 mm (left) and 30 mm (right) of POM.

Different energy counters configurations were compared by adjusting the number K of counters and the corresponding thresholds. The tested configurations are K = 2, 6, 15, 30, 45 and 90 in the 22 - 130 keV energy range. For dual counting (K = 2), the configuration was optimized. For K > 2, counters have a regular energy width and cover the whole energy range. The results, expressed in terms of false detection rate, are presented in Fig.3 for 10 mm and 30 mm objects. They show a continuous performance increase with the number of counters. FDR is divided by roughly 1.5 (resp.2) when comparing two optimized counters to 90 regular counters for the 10mm (resp.30 mm) object. In similar experimental conditions, the spectrometric detector (90 counters) was compared to the sandwich detector while keeping the same photon statistics per pixel. The FDR decreases by a factor 3 (from a FDR= 41% to 14%) for a 10 mm object using a spectrometric approach, compared to the sandwich detector. It decreases by 15 (from a FDR= 20% to 1.3%) for a 30 mm object.

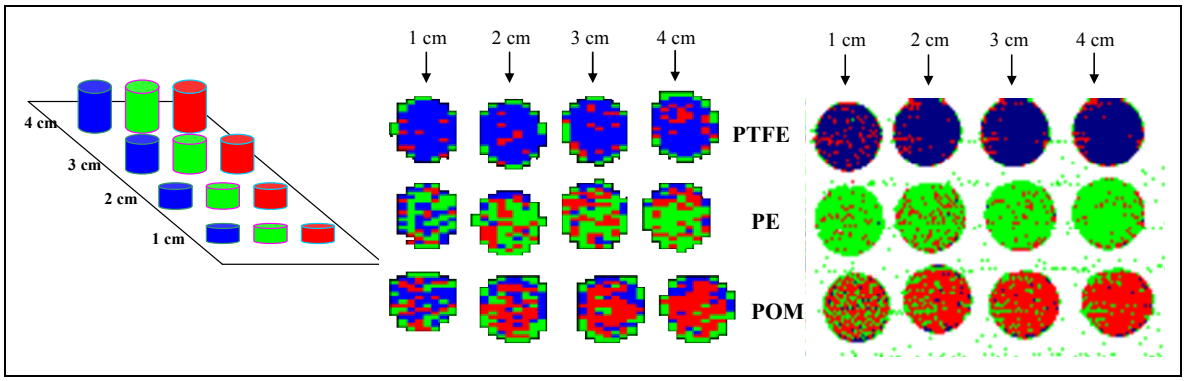

Fig.4. Colour imaging by identification process, using a sandwich detector and a spectroscopic one.

In order to illustrate the gain in performance, we tested the identification process on an object composed of the 3 database materials, with thicknesses from 3 to 8 mm (Fig.4). Every pixel is coloured accordingly to the estimated material, using the following colour code: blue for PTFE, green for PE and red for POM. The enhanced identification capability of the spectrometric detector compared to the sandwich detector can be deduced visually by the reduction of colour mixing for each insert.
Future works for that technique concern objects superimposition and tomography.

4. Diffraction technique

The diffraction effect is due to coherent scatter, predominant in small angle forward scatter (<10°). The acquisition geometry is presented in Fig.5a (angle not at scale). It has been shown that the measured spectra represent accurate signatures of the analysed materials [2] [3] [4]. A high energetic resolution of the detector is required for identification, due to the number of material specific peaks (Fig.5b). Germanium detectors are commonly used. They present a high resolution, but at the price of complex cooling system. At LETI, we tested semi-conductor detectors in diffraction configuration. The prototype probe MINIGAMI is optimized for low flux, and assures an energy resolution of 1.7 % at 122 keV, and detection efficiency of 80-85 % at 122 keV. An example of obtained spectrum is shown on Fig.5b, compared with Germanium. Preliminary studies demonstrate that this resolution is acceptable for identification. CZT detectors are working at room temperature. Moreover, the compactness of CZT detectors permits to develop multi-pixel detectors, linear or array, and thus to envisage new geometries or faster acquisitions thanks to parallelization.

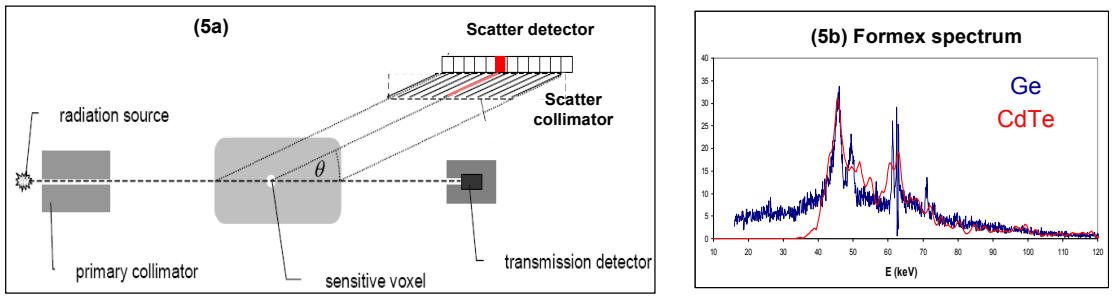

Fig. 5. (5a) Scheme of a diffraction system. (5b) Spectra comparison between Germanium and CdTe detector.

5. Back-scatter technique

X-ray backscatter technique is an alternative for configurations where conventional radiography is not convenient. It occurs for too attenuating objects, or sided-only access objects, typically objects placed close to a wall such as abandoned luggage. In fact two different techniques are based on Compton backscatter principle: imaging and local investigation. Imaging systems can be used to screen the content of a luggage. They use wide-angle beam sources and integration detectors so that they provide only qualitative images of the first depths on the part. Backscatter images can help the user to visualize the shape of some suspicious objects but do not allow material identification. The second technique consists, thanks to a high collimation on both irradiation and detection paths, in analysing a small volume, which can be scanned inside the part. When an integrating detector is used, discrimination between low and high density materials is possible but not between explosives and close materials. Such backscatter systems have been developed for medical [5] [17], non destructive testing [5][18] and security applications [19].

Our laboratory has developed a new X-ray backscattering technique based on the scanning in depth of the inspected part with a highly collimated spectrometric probe (Fig.6a). Spectral measurements are acquired with an energy-resolved CdTe single pixel detector at different depths perpendicularly to the surface of the examined part. The estimation of density ρ and effective atomic number Z_{eff} is performed by an original process using a model constructed from calibration measurements on reference materials, and including a correction of multiple scatter. The acquisition system and identification process are detailed in [20]. In case of non-planar objects, the knowledge of the surface shape is needed. It may be used of prior information coming from either visual recognition for visible object, or from previously backscatter images in case of an object hidden in a luggage.
A first experimental prototype has been designed for portable configurations and tested. An industrial X-ray tube with a tungsten target is used in the same conditions as a portable X-ray industrial tube, i.e. with a 120 kV voltage, and with an X-ray flux limited by the tube current (1mA) and the maximum acquisition time (20 min). We chose a scattering angle of 120°, cylindrical collimators with a full aperture of 2.4° and distances $d_{source\text{-}vol}$ and $d_{vol\text{-}detecteur}$ of 23cm. This defines a scan volume of about 0.7cm^3. The probe consists in a 5mm thick CdTe pixel detector providing good resolution detected spectra (resolution 3 keV at 122 keV), highly collimated. Different materials have been tested (Fig.6b). For each material, 20 measurements have been performed. Despite the very low detected flux, the results are promising with a good discrimination of common materials. Density and Z_{eff} values estimated by our method are close to the theoretical ones. Notice the discrimination of pure water from hydrogen peroxide (H_20_2) at 30%, which is a very interesting result for liquid explosive detection. Experiments on real explosives are planned. Future developments will focus on the use of multi-pixels spectrometric detectors in order to improve and significantly speed up the identification.

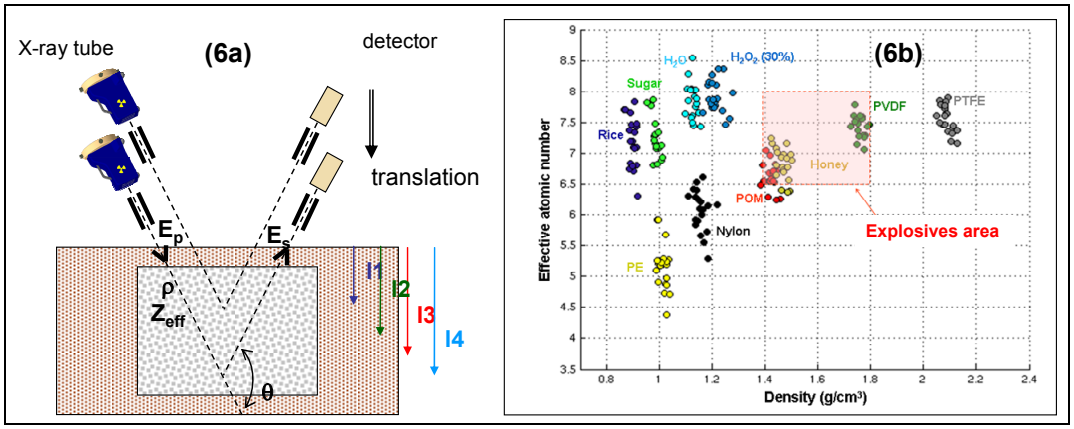

Fig. 6. (6a): Scheme of the experimental prototype of the portable scanning backscatter system. (6b): Results of characterization of some inert materials.

Conclusion

X-ray based systems are the most widespread employed in EDS. Conventional radiography provide information on the shape but not the nature of the luggage content. When using dual-energy technique based on two-layers detectors, the obtained accuracy at best only allows materials to be classified into broad bands such inorganic and organic. Spectrometric semiconductor detectors provide multi energy information which enables, thanks to a dedicated processing method, an accurate material discrimination. Diffraction (small angle scattering) is a complementary X-ray technique in EDS, allowing the characterization of the molecular structure of the observed materials. CdTe/CdZnTe detectors provide spectral information with a resolution sufficient for that technique, while being easier to use than Germanium detectors, which require cooling systems.

Backscatter technique is an alternative technique for specific configurations. Using spectrometric detectors, a precise local characterization can be reached. For all these techniques, CdTe/CdZnTe based spectrometric detectors are well-adapted. Moreover, the possibility to design them in linear or matrix geometry is particularly important for EDS, because it enables to accelerate acquisition thanks to parallelization and to develop portable probes or imaging systems. These conclusions can interestingly be extended to other domains, particularly detection of nuclear material, waste inspection, composite NDT.

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