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Detection System of the First Rapidly Relocatable Tagged Neutron Inspection System (RRTNIS), Developed in the Framework of the European H2020 C-BORD Project

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Abstract

The European project entitled "effective Container inspection at BORDer control points" (C-BORD) focuses on the development and *in-situ* tests of a comprehensive cost-effective solution for the generalized Non-Intrusive Inspection (NII) of containers and large-volume freight at the European Union (EU) border. It copes with a large range of targets, including explosives, chemical warfare agents, illicit drugs, tobacco and Special Nuclear Materials. Within the C-BORD project, a new generation of Tagged Neutron Inspection System (TNIS) for cargo containers is foreseen. Unlike its predecessors, this system would be the first Rapidly Relocatable TNIS (RRTNIS). It will be a second-line defense system, to be used on sealed containers in order to detect explosives, illicit drugs and chemical agents in a suspect voxel (elementary volume unit).
We report on the status of the RRTNIS system, in particular the overall design, the characterization of the large-volume NaI(Tl) gamma detectors, the digital analysis of the time measurements and the Data Acquisition System (DAQ).

1. Introduction

In the enforcement of border security of the European Union (EU), the inspection of containerized freight is of crucial importance, as containers could carry dangerous or illicit materials and provide a means for illegal immigration. Since the spectrum of possible combinations of declared goods and illegal substances is so wide, a single technology for Non-Intrusive Inspection

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(NII) is not able to cope with the task. The C-BORD project (effective Container inspection at BORDer control points) was started, in the setting of the European H2020 program, in order to develop a set of modern technologies for the NII of freight cargos. In order to enable the authorities to select in each situation the most effective array of screening technologies, C-BORD proposes its "toolbox", consisting of: Advanced Radiation Management, Next Generation Cargo X-Ray, Tagged Neutron Inspection, Photofission and Evaporation Based Detection. The C-BORD project aims to have at least two independent technologies employed in conjunction, in order to improve inspection results. For this reason, the project is working on realizing an integration of the different techniques in a uniform framework. Live field trials will show proof of the capabilities of the system. Three installations are foreseen: at the seaport of Rotterdam (Netherlands), the seaport of Gdańsk (Poland) and a mobile land-border checkpoint in Hungary.

Here we will present the status of the detection system of the first Rapidly Relocatable Tagged Neutron Inspection System (RRTNIS). The RRTNIS employs a neutron beam to irradiate the cargos. The neutrons react with the materials inside giving off gamma rays, which are then detected by two kinds of detectors. Large (5" $\times$ 5" $\times$ 10") NaI(Tl) detectors are used to detect the gamma rays with the highest energies, and LaBr$_3$(Ce) detector are dedicated to the lower energy gamma-rays. The approach is called Tagged Neutron Inspection Technique (Perret *et al.*, 2006, Pérot *et al.*, 2007). The neutrons are produced in a generator which employs the fusion between tritium and deuterium, producing one neutron ad one alpha particle per interaction. The two particles are collinear and the alphas are used to tag the neutrons and determine their creation timestamps. Alpha particles are detected with a YAP scintillator housed inside the generator. The RRTNIS was designed to be compact and rapidly relocatable.

2. Data Acquisition (DAQ) system

2.1. Electronics

The data acquisition hardware is provided by CAEN s.p.a., one of the partners of the collaboration. It consists of two CAEN 16-channels digitizers that can acquire data with 14-bit resolution at a sampling rate of 500 MS/s and a Digital Constant Fraction Discriminator (DCFD) embedded in the firmware for precise timing measurements, five CAEN 6-Channel 4 kV/3 mA VME HV Power Supply Module, and optical fiber connections using the CAEN CONET2 protocol for fast acquisition. In the digitizer firmware each event is analyzed online with a DCFD. The temporal resolution that is achievable is less than a nanosecond.

2.2. DAQ software architecture

A novel distributed data acquisition system (DiDAQ) was developed for the project. This new DiDAQ is composed of a network of separate processes (Fig. 1), also called servers. Each server manages a single task (*e.g.* data acquisition, data logging…), in order to simplify its development and debugging. Being a distributed architecture, the system is more flexible since any of its servers can stop without compromising the whole network. This feature is especially useful during development, as it is possible to stop, update and restart servers on deployed systems, without stopping the whole infrastructure. Communication is carried out through network sockets, which means that the servers can be hosted in several computers, depending on the needed performances. Every server broadcasts its status and data stream to every one of its clients, and listens for commands received on a dedicated socket. This approach increases the latency of the network (time for a packet to reach the last process), since the different processes are not synchronized and have to wait for the previous processes to publish the data. On the other hand, the throughput is not necessary affected, as the packets could be of significant size. The servers are developed following the state machines paradigm. A global manager collects the status of every server and handles the tasks requested by the user, in order to reduce race conditions. The user interface communicates with the manager as a separate process, in order to be able to have a headless system working on automated activities. The bottlenecks of the DiDAQ are the broadcasts of the data streams, but our tests showed that the performances required by the project were fulfilled.
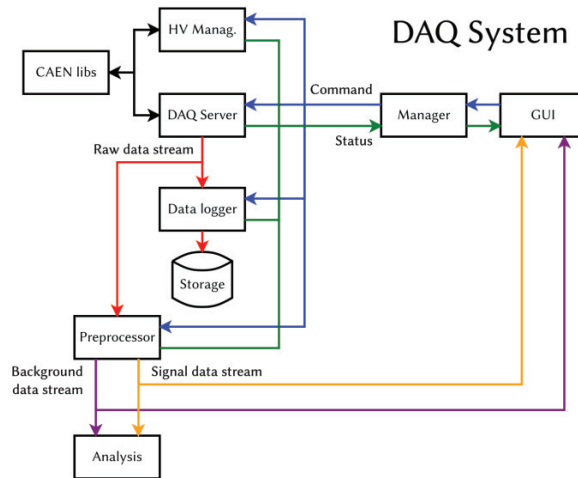
Fig. 1. Data acquisition system architecture.

2.3. Data streams

A dedicated server preprocesses the raw data stream generated by the acquisition server (Fig. 1), and splits it in two separate streams: "background" data, used by the analysis to monitor gain shifts during the acquisition and "signal" data consisting of coincidence data between the alpha detector and the gamma detectors. The raw stream is also saved by a data logger, so that the data can be reused afterwards to simulate the operation of the system. A simulation server can take the place of the DAQ server and can generate a simulated stream using the stored data.

2.4. High count rate tests

Using a set of calibration sources we measured the maximum acquisition rate that the DAQ is capable of supporting. Moving the sources progressively closer to the detectors, we determined that at $2 \cdot 10^5$ 1/s, per NaI(Tl) detector, the system has a dead time of less than 1%. The project specifications state that each NaI(Tl) detector should be able to sustain count rates of at most $2 \cdot 10^5$ 1/s. We therefore concluded that the system is suitable for the task. New tests with higher count rates are scheduled, in order to fully characterize the performances. $LaBr_3(Ce)$ and the YAP detectors were not employed, since they are not yet available.

3. NaI(Tl) Gamma Detectors Tests

In the European H2020 C-BORD project, 20 large NaI(Tl) detectors (5" × 5" × 10") will be part of the RRTNIS. These detectors come from the former EURITRACK project (B. Pérot et al., 2007, C. Carasco et al., 2008). However, before their installation, a comprehensive characterization of this set of detectors was performed. The tests included detailed studies of the energy resolution as a function of energy, the time resolution for different energy thresholds (300 keV and 1000 keV), and the energy resolution as a function of the gamma interaction position. Only the NaI(Tl) detectors were characterized, since the other detectors are still not available.

A set of calibration gamma sources (^{137}Cs, 662 keV, ^{60}Co, 1173 keV & 1332 keV, ^{22}Na, 511 keV & 1275 keV, ^{54}Mn, 835 keV, and ^{88}Y, 898 keV & 1836 keV) and an Am-Be source ($E_\gamma = 4.4$ MeV) were used to perform the measurements. The photomultiplier tube (PMT) anode signals were fed into a VME CAEN digitizer V1730 (500 MS/s, 14 bit). A CAEN HV power supply model V6533 and a CAEN V1718 USB Bridge completed the electronic chain. The analysis of the acquired data was performed using ROOT (Antcheva et al., 2009).

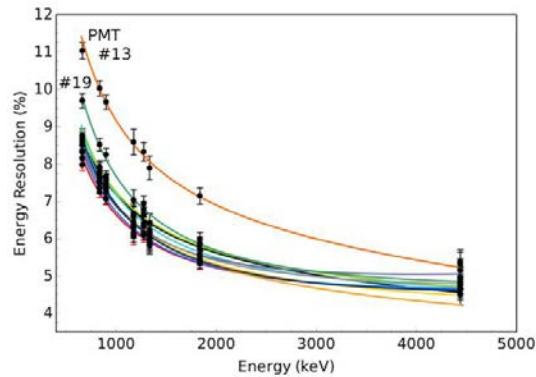*3.1. Energy resolution as a function of energy*

Fig. 2. Energy resolution curves for the set of detectors.

To obtain the energy resolution as a function of the energy itself, one of the sources was placed in front of the widest face (5" × 10") of the detector, approximately at half-height, and its spectrum was measured. The source-detector distance was varied as a function of the intensity of the source, in order to get a suitable count rate for a measurement with enough statistics in a reasonable period of time. The energy resolution curves for the set of detector are shown in **Error! Reference source not found.**. Uncertainties in determining the energy resolution were estimated to be between 2% and 7% of the resolutions themselves, *e.g.* (8 ± 0.4)%. The results were fitted with the equation from Casanovas *et al.* (2012):

$$R(E) = a + \frac{b}{E} + c \cdot E$$

Most of the detectors show similar energy resolution curves. However, detectors 13 and 19 present poor performances. According to the requirements of the project, these have to be replaced with better ones, that are being purchased.

3.2. Time resolution

To obtain the time resolution of all the detectors, coincidence measurements were performed between a fast plastic scintillator (EJ-228, cylindrical 2" × 2") and each one of the NaI(Tl) detectors using the two 511 keV gamma rays from a [22]Na source. Fig. 3 shows a scatter plot of the FWHM time resolution (threshold: 300 keV) plotted vs. the energy resolution at 662 keV for the 20 detectors. From Fig. 3 we observe that detectors 4, 6 and 14 show time resolutions greater than 3.5 ns, which is the limit of our requirements. Therefore, those detectors need to be replaced as well.
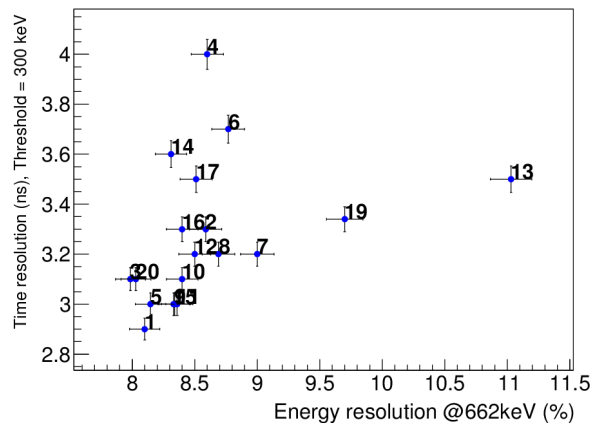

Fig. 3. Scatter plot of the time resolution as a function of the energy resolution for all C-BORD NaI(Tl) detectors.

3.3. Energy resolution as a function of the gamma interaction position

To study the energy resolution as a function of the gamma interaction position, we employed a tungsten collimator and lead bricks as partial shielding of the crystal. The gamma rays were thus allowed to enter a small portion of the crystal volume. The mono-energetic ^{54}Mn source (E_γ = 835 keV) was used to perform the measurements. We studied the response of the detector in four configurations: a "far" configuration, in which the gamma beam entered the crystal at a point located at 3 cm from the low end of the detector (far from the PMT); a "central" configuration, in which the gamma flux hit the center of the crystal; a "near" configuration, in which the point of interest was located at 3 cm from the top end of the crystal (near the PMT); and a non-collimated configuration (without any collimator or shields). The non-collimated configuration was meant to compare the collimated results to the normal working conditions.

We also performed Monte Carlo simulations (using GEANT4) of the collimated configurations. The simulation showed that, with these experimental set-ups, more than 99 % of the events recorded in the spectrum belong to full-energy interactions of gamma photons that are absorbed into a 3 cm thick layer around the central region allowed by the collimators. Therefore, we can be sure that most of the scintillation photons are being created close to the zone where the gamma photons enter the crystal. The simulation was used only to determine the interaction area and not the scintillation processes, nor the light propagation in the crystal.
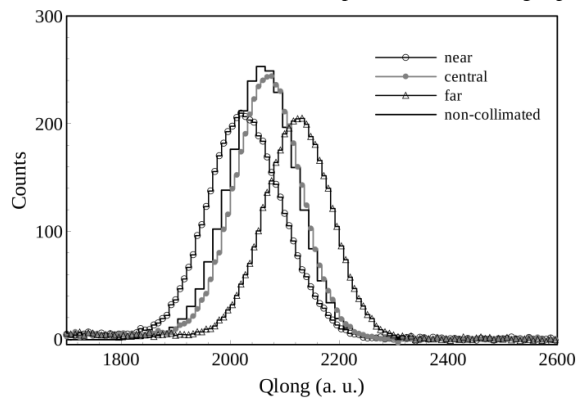

Fig. 4. ^{54}Mn spectra acquired in the studied detectors configurations (see text for details).

In Fig. 4, typical real spectra are shown for each of the detector configurations mentioned. The most interesting result is related to the centroid of the full-energy peak. For each collimated configuration, the centroids show a different position, with results comparable for all detectors. For the "far" position the centroids have their greatest values, followed by the "central" and "near" positions respectively (as shown in Fig. 4). For the non-collimated configuration, the full-energy peak centroid almost matches the centroid of the "central" configuration. The deviations of the centroids for the "near" and "far" configurations are around ±2%, with respect to the non-collimated position. However, the dominating condition is the "central" configuration, due the higher solid angle coverage. Moreover, the average resolution of the non-collimated configuration roughly corresponds to the "central" configuration. The centroid shifts are still under investigation.

4. Conclusions

We presented here the status of the NaI(Tl) detectors and DAQ of the first Rapidly Relocatable Tagged Neutron Inspection System (RRTNIS) of the H2020 European C-BORD project, emphasizing the work performed prior to the integration of the first prototype. A new Distributed Data Acquisition System (DiDAQ) was developed for the project. This DiDAQ follows the approach of distributing the tasks on different processes, communicating through network sockets. The performance tests of the DiDAQ, showed that it is able to cope with the requirements of the project. A set of 20 large (5" × 5" × 10") NaI(Tl) detectors was characterized, in order to determine which ones have performances within the project specifications. The characterization analyzed both the energy resolutions, as a function of gamma energy and interaction location in the crystal, and the time resolution. In this campaign of measurements, we determined which detectors have to be replaced, because they are not within the project requirements.

Acknowledgements

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