WG6 IPNDV Experimental Technology Data Sheet

December 4, 2019, Antonin Vacheret, UK; Sakari Ihantola, Finland; Kari Peräjärvi, Finland; Anders Axelsson, Sweden

Name of Experimental Campaign:
Belgium exercise to investigate performance of measurement methods

Technology Name: Direction-sensitive Neutron Detector

Physical Principle/Methodology of Technology:
The detector is composed of 64 scintillator cubes (4 x 4 x 4). Characteristic dimension of the plastic scintillator cube is 5 cm. Each scintillator cube is covered from three sides with LiF:ZnS(Ag) phosphor screens. The cubes are oriented in such a way that the screens form four horizontal and vertical layers inside the detector.

Neutron detection is based on the detection of n+Li-6 -> He-4+t reactions. These reactions produce characteristic signals with long decay times that can be used to separate the neutron capture events from the faster-decaying signals produced by gamma rays and muons. In the IPNDV experiments, the trigger of the data acquisition was based on two parameters: the signal amplitude and the time the signal amplitude remained above a given threshold. With proper trigger settings the background of gamma rays and the muons could be efficiently rejected without much loss of neutron capture signals. Figure 1 presents the detector.

Figure 1. nFacet 3D detector. Weight: 16 kg. Size: 25 x 25 x 27 cm³

What Does the Method Determine/Measure (e.g., presence of nuclear material, isotopics, mass):
The basic data collected are the number of neutron captures detected by different detector cubes/voxels in different measurement configurations. In addition to the total number of neutrons, analysis of the spatial distributions of neutrons captured allows conclusions concerning the directions from which the neutrons are arriving as well as their kinetic energies. For example, thermal neutrons are preferentially captured by the detector voxels near the surface of the detector compared to fast neutrons. Figure 2 presents a typical voxel hit map. The more neutrons are detected, the warmer is the voxel color.

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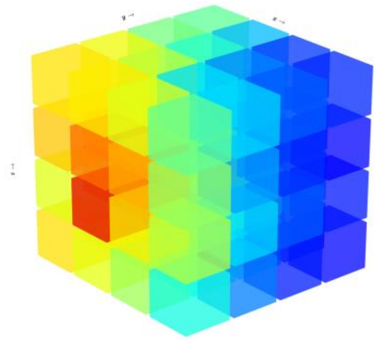

Figure 2. Typical voxel hit map

What Is the Applicability to IPNDV:

Possible areas of applicability to disarmament verification may include:

- Monitoring storage of neutron-emitting objects (nuclear weapons, warheads, or special nuclear material components): Register changes in spatial distribution, spectral properties, or intensity of neutron sources.
- Monitoring processes involving neutron-emitting object: tracking the movement (or successive positions) of a neutron source.
- The large number of separately recording cubes/voxels may allow the creation of a complex and specific but non-revealing "fingerprint" of any neutron-emitting system, that would be difficult to reproduce using another arrangement of neutron source(s)—a suitable arms control "template."
- Absence measurements; direction sensitivity may facilitate the resolution of false alarms or inconsistencies.

Type of Data Collected by the Technology:

- Count rate of neutrons (and gamma rays) in each of detector cubes/voxels.
- For neutrons, the registered rate is the rate of thermal-neutron absorption reactions. Proton recoil reactions during neutron thermalization are currently not registered.
- Count rate distribution between cubes yields information on direction of source(s) and some information on neutron energy distribution (higher energy will give relatively higher count rates in inner cubes).
- All data are collected in time-stamped list-mode, allowing post-processing possibly with more elaborate analysis approaches or for different purposes than applied online.
- Some data were collected with event trigger conditions that may allow the identification and study of the cosmic muon background at the location, and at least quantitative study of the gamma flux present during the collection of these data.

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Constraints (e.g., time to install the equipment, measurement times including distance from object, dose rate required, required Cd shielding to limit the count rate):

- Time to install: "Plug and play"—some simple functionality checks.
- Background measurement is needed; time similar to or longer than source measurement.
- The current implementation of this technology primarily envisages low-radiation intensity applications such as border control. Problems would be encountered with neutron rates exceeding several kHz. For this reason, considering the maximum measurement distances available in the current experiment, the more intense neutron emitters (assemblies with large amounts of reactor-grade Pu) were not measured. There is no inherent problem with using this technology in a really high radiation environment, but considerable re-design would be needed relative to the current prototype. In other words, the specific implementation would need to be tailored to a specific application.

Physical Description/Diagram/Photos of the Experimental Setup/Layout:
The measurements were carried out with the nFacet detector located 95 cm (standard) or 190 cm (for high-intensity measurements) from the measured objects (fuel assemblies).

The sketch below (Figure 3) is not drawn to scale but contains the most important distances and dimensions. Note the nearby graphite pile containing a strong neutron source (shielded by graphite and cadmium).

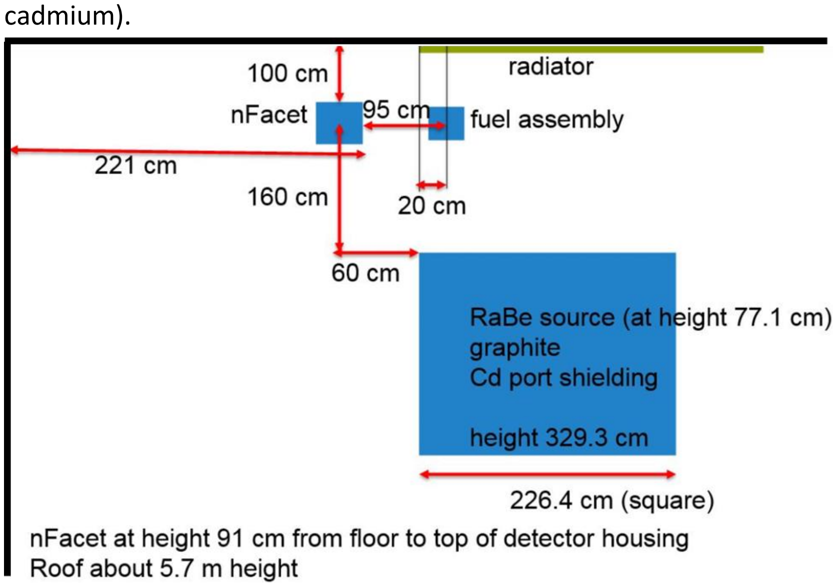

Figure 3. Schematic drawing of the measurement room

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The center of the fuel assemblies was approximately 37 cm from the floor, so the detector was not centered on the measured assembly in the vertical dimension. Also note the fact (see next section) that one of the assemblies was a “composite” with different MOX compositions axially.

In order to check the accuracy of the directional analysis, the detector was rotated by 90 degrees after about half the total measurement time in each configuration. One measurement was also performed with the detector rotated by 180 degrees. By combining the list-mode data from these different orientations, this will allow the study of the influence of multiple sources on the results.

There was a significant “laboratory neutron background” in the measurement area. This necessitated the collection of background data at the various measurement positions.

Specific Objects Measured (which of the experimental objects were measured; if not described elsewhere, describe experimental objects here):
Stainless-steel enclosed hexagonal 19-pin bundles of MOX fuel with the following content were measured at a distance of 95 cm (center of fuel assembly to face of detector enclosure) unless otherwise noted:

- 3.5wt% Pu with 88wt% (160 g) ^{239}Pu (average quantities, see below);
- 5.1wt% Pu with 79wt% (180 g) ^{239}Pu (measured at 190 cm when un-shielded).

Both assemblies had an active (MOX-filled) length of 50 cm.

The first assembly consisted of MOX with 96wt% ^{239}Pu in the central section of 20 cm, and the end sections of 15 cm each consisted of MOX with 79wt% ^{239}Pu. The figures above for this assembly are linear averages formed from the properties of both types of MOX.

The expected neutron emission rates for the two bundles are:

- 37000 n/s Pu for the “mixed” assembly with an average of 88wt% ^{239}Pu;
- 93000 n/s for the assembly with 79wt% ^{239}Pu.

These neutron emission rates include both spontaneous fission neutrons and neutrons from (α,n) reactions.

Both assembles were measured:

- Un-shielded (measurement at 190 cm for unshielded assembly with 79 wt% ^{239}Pu);
- With CH2 (5 cm) + Pb (1 cm) shielding;
- With Cd (2 mm) shielding;

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Process Required to Analyze the Data (include any software used):
Some basic results are presented on-line (including intuitive graphics) during the measurement; more elaborate analysis is possible immediately following measurement using existing tools (Python scripts) to post-process the collected list-mode data.

Final analysis (e.g., quantitatively taking into account the measured background) at present requires more "manual" post-processing (i.e., scripting, programming).

Preliminary Results (qualitative, not quantitative; e.g., did the method perform as expected, if not how was it different):
Different measurement configurations together with the total neutron count rates are listed in Table 1. Note that the counting rate achievable in the current system, primarily developed for low-rate measurements (see above) is limited by the data acquisition system. Therefore, event trigger conditions applied were set to significantly limit the counting rate, which also results in very efficient rejection of non-neutron events. The same trigger conditions were used in all measurements listed in Table 1.

Table 1. Performed measurements and associated neutron count rates. Measurements highlighted with the green color are discussed more in this chapter.

Run type	Distance [m]	Rotation [°]	Height [m]	Neutron rate [Hz]
Background	0.95	0	0.91	**51**
Background	0.95	0	0.91	**52**
Background	0.95	90	0.91	**52**
Background	0.95	180	0.91	**55**
Background	1.9	0	0.91	-
Background	1.9	90	0.91	**51**
Bare Pin				
79%	1.9	0	0.91	**117**
79%	1.9	0	0.91	**109**
79%	1.9	90	0.91	**109**
79%	1.9	90	0.91	**112**
88%	0.95	0	0.91	**104**
88%	0.95	90	0.91	**102**

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Pin + Cd				
79%	0.95	0	0.91	**164**
79%	0.95	90	0.91	**164**
88%	0.95	0	0.91	**106**
88%	0.95	90	0.91	**101**
Pin + CH2 + Pb				
79%	0.95	0	0.91	**152**
79%	0.95	180	0.91	**134**
88%	0.95	0	0.91	**93**
88%	0.95	90	0.91	**89**

In the following, the X/Y/Z neutron depth distributions in the detector are illustrated using three examples: 79% Pin + Cd, detector at 0 and 90 degree and 79% Pin + CH2 + Pb, detector at 0 degree. Analysis at the single voxel level is still in progress. Figure 4 presents the X/Y/Z distributions of Zinc Sulfide/Li-6 layers inside the detector.

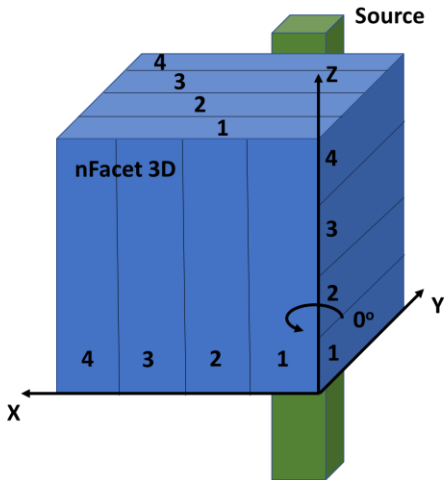

Figure 4. Schematic drawing of the detector. This is the so-called 0 degree measurement orientation.

During the measurements the detector was always rotated counterclockwise. Figures 5, 6, and 8 present the X/Y/Z neutron distributions in three different measurement configurations mentioned earlier and highlighted with green in Table 1. Note that in a single measurement the total number of neutron counts in every projection (X/Y/Z) is the same. Figures 5 and 6 are related to measurements with the 79% fuel assembly.

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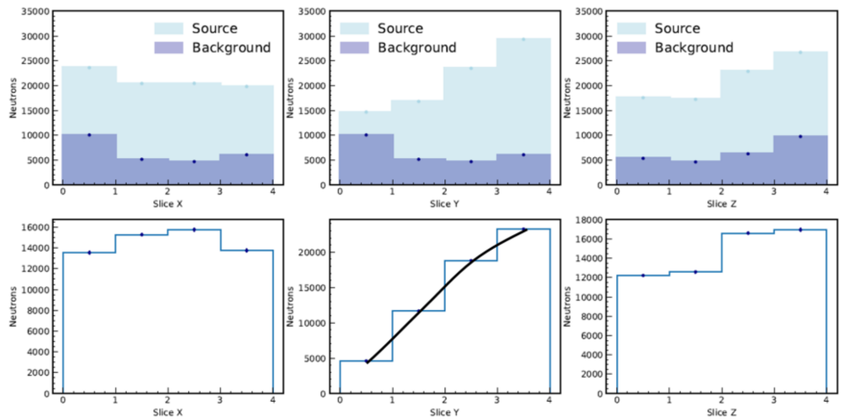

Figure 5. 79% Pin + Cd, 0 degree. Lower row presents the background subtracted neutron distributions.

As shown in Figure 5, scattering from the environment plays a role in the background neutron distributions. Figure 5, background subtracted Z-distribution shows that more neutrons are detected on the top layers. This effect is not yet understood; possible explanations may include back-scattering from somewhere in the environment, and details in the source-detector geometry. Notice that the fast neutrons have better chances to penetrate deeper inside the detector.

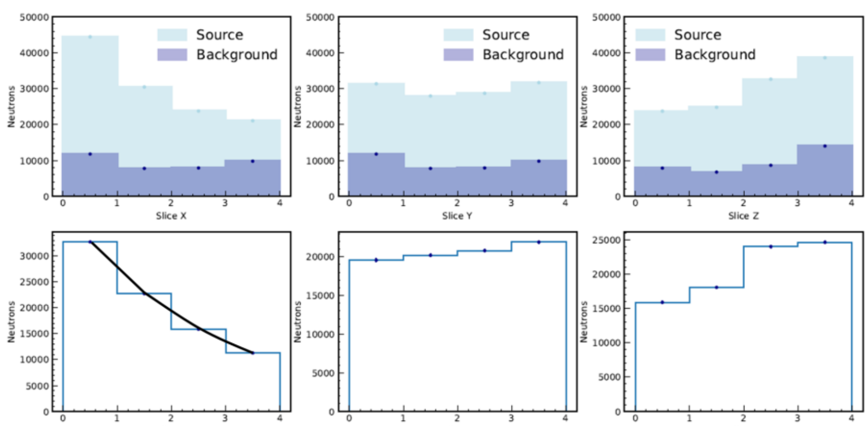

Figure 6. 79% Pin + Cd, 90 degree (counterclockwise rotation)

In order to easily demonstrate detector's directional sensitivity/source localization capability, the X and Y background subtracted neutron distributions of 79% Pin + Cd at 0 degree (data from Figure 5) and 90 degree (data from Figure 6) are presented in Figure 7.

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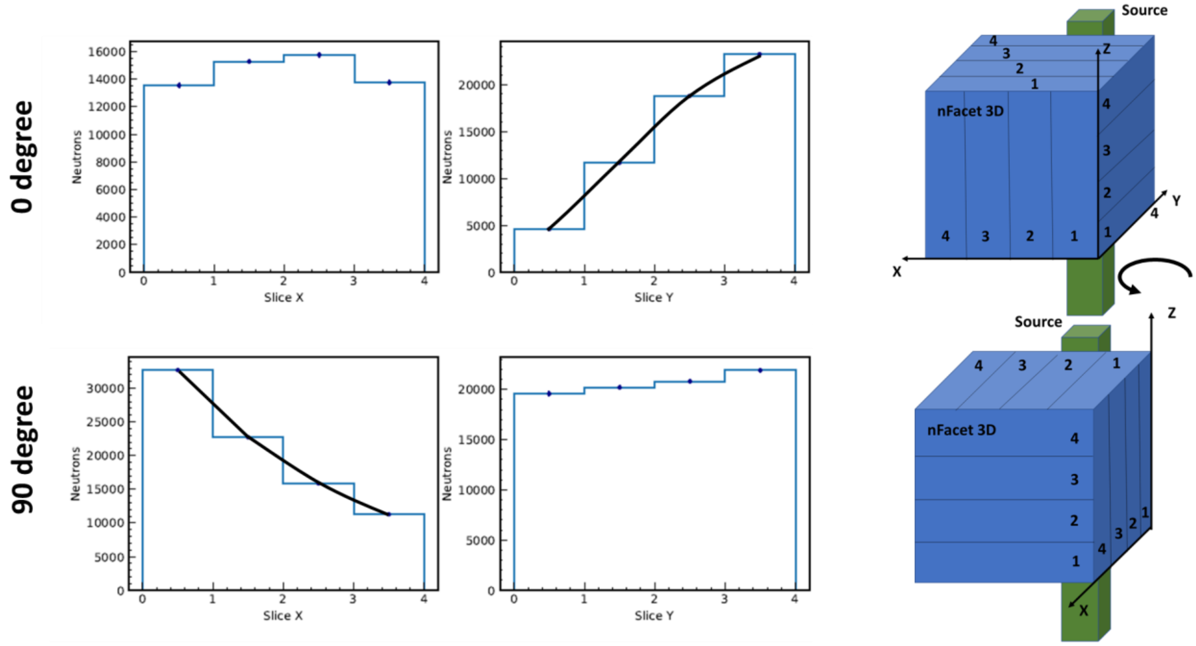

Figure 7. Background subtracted 79% Pin + Cd, 0 and 90 degree

The data in Figure 7 are self-explanatory. Figure 8 is related to measurements with the 79% pin plus the CH2 and the Pb shield.

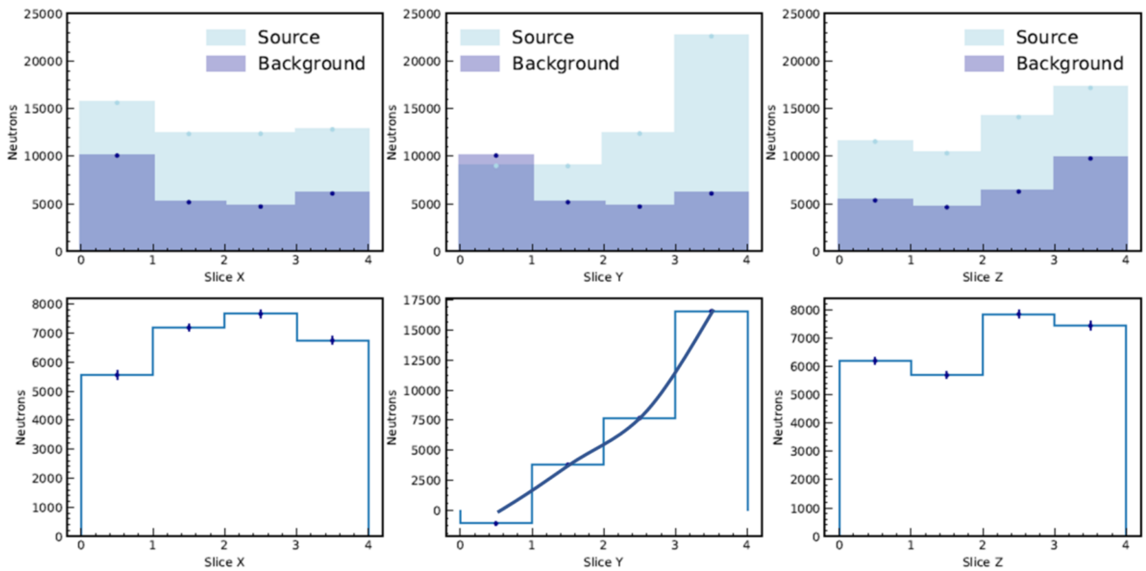

Figure 8. 79% Pin + CH2 + Pb, 0 degree

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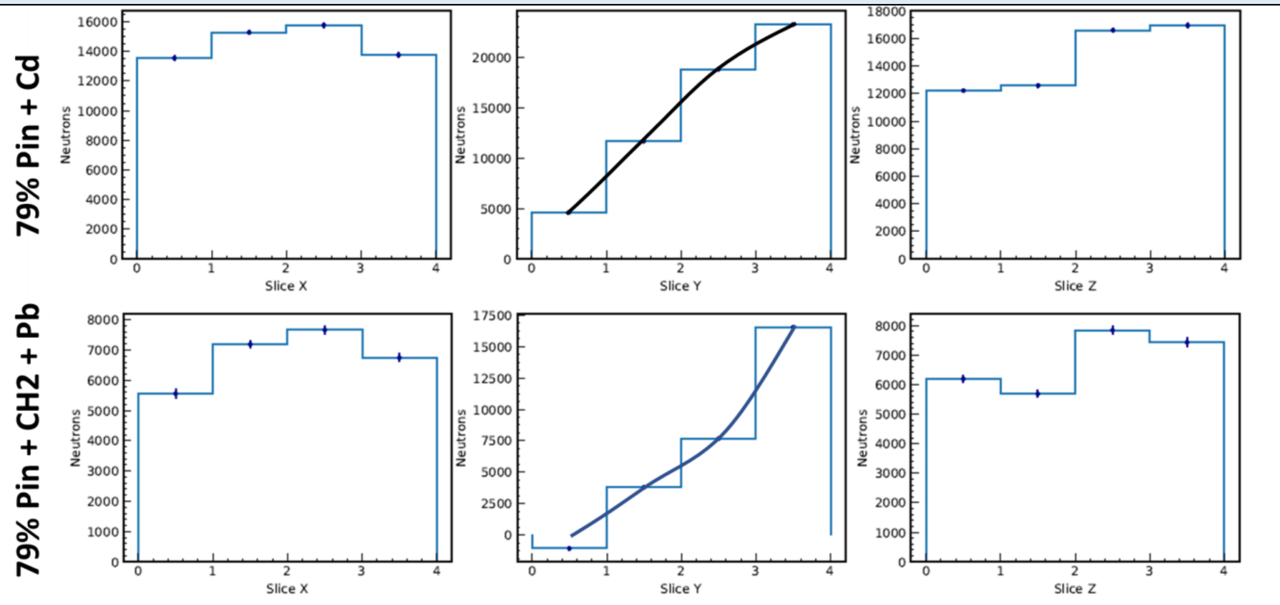

Figure 9. Background subtracted 79% Pin + Cd, 0 degree and 79% Pin + CH2 + Pb, 0 degree X/Y/Z distributions

Figure 9 allows an easy comparison of neutron distributions related to Cd and CH2+Pb shields. Based on Y-distributions it is obvious that the CH2+Pb configuration produces a softer neutron spectrum than Cd. The Y-distribution with the CH2 + Pb shield also suggests that the detector has a very good detection efficiency for thermal neutrons. In this configuration neutrons are not able to pass the detector.

In conclusion, nFacet 3D is a functioning new prototype neutron detector. In addition to neutron counting, it provides directional and energy information that is often very useful. The detector can be used in a mode with very low sensitivity to gamma rays and muons. The technology is also scalable and can be optimized for the application at hand. Notice that so far, we have not analyzed the data at the single-voxel level.

Final Results (if available; if not, estimate of when final results will be available):
The main target in the final analysis is to extend the analysis to single-voxel level. Obtained results will also be compared to simulated fluxes and energy spectra provided by other groups.

Conclusions from the scenarios where multiple sources are in the room can be drawn by combining background subtracted data collected in different detector orientations.

Lesson Learned (e.g., what went well, what went wrong or not as expected, do the results confirm what we said in the technology tables?):

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If the measurements have to be made in the presence of an elevated laboratory background, the role of background measurements is very important. Background needs to be measured in the same location and detector orientation as the source measurements. Signal to background is an important parameter.