An integrated mobile system for port security

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***Abstract*–An integrated mobile system for port security is presented. The system is designed to perform active investigations, by using the tagged neutron inspection technique, of suspect dangerous materials as well as passive measurements of neutrons and gamma rays to search and identify radioactive and special nuclear materials.**

I. Introduction

In most harbors worldwide inspection systems dedicated to the security of passengers and freight are based on fixed x-ray portals, radiation portal monitors and handheld radiometers. The SLIMPORT project [1], financed by the Italian Ministry for the Economic Development (MISE), is dedicated to the development of an integrated package of tools forming a complete security system to monitor transport of persons and merchandise in harbors.

In this framework we are developing a mobile inspection station (called SMANDRA, the Italian acronym stands for Sistema Mobile per Analisi Non Distruttive e RAdiometriche). The system is conceived as an instrument to perform non-destructive analysis, usable in conjunction with present monitoring devices such as radiation portal monitors, x-ray scanners and others. The aim of the system is to search and identify sources of ionizing radiation or identify dangerous and/or illegal materials inside volumes tagged as “suspect” by conventional surveys as X-ray scans. The system is made of two pieces having a volume less than 0.1 m^3 as follows :

a- A passive unit including two gamma-ray detectors (5”x5” NaI(Tl) and 2”x2” LaBr(Ce)) and two neutron counters (5”x2” liquid scintillator and 3He proportional counter for fast/slow neutrons). The unit will host batteries, power supplies, front-end electronics and CPU.

b- An active unit including a portable sealed neutron generator based on the Tagged Neutron Inspection System (TNIS) technique.

The first unit can be used in standalone mode as a high efficiency spectroscopic radiometer for the detection of ionizing radiation such as gamma-rays, fast and thermal neutrons to search and identify radioactive material as well as Special Nuclear Material (SNM). It can be used as well as detector package connected to the second unit for active interrogation of voxels inside a load by tagged neutron inelastic scattering imaging. SMANDRA will be a mobile system transported by a non-specialized light vehicle, easily operated by non-specialized personnel.

The second unit will host in the present prototype a EADS-SODERN sealed neutron generator with the associated particle detector. For practical applications the yield of the neutron generator will be fixed to 10^7 neutron/s for limiting the radiation hazard and the licensing problems.

The SMANDRA system is described in this paper. Laboratory results obtained so far are also reported.

II. The SMANDRA system

A view of the passive unit of the SMANDRA system is presented in Fig.1 showing the detectors, the front-end electronics and the shadow-bar needed during active interrogations.

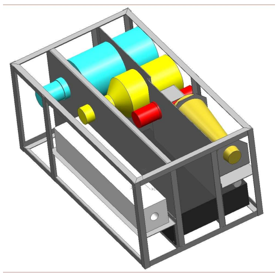

Fig. 1. View of the SMANDRA passive unit, showing the detectors (liquid scintillator light blu; NaI(Tl) yellow; LaBr(Ce) red 3He+poly assembly white), the shadow bar (glod) and the VME mini-crate (black) in the bottom. The shadow bar is made by two sections of iron and lead.

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The dual use of the SMANDRA (active and passive interrogations) sets stringent requirements for the system: a low background, high efficiency detectors for gamma and neutrons, with the need of discriminating the two components of the radiation in the passive mode use and a high count rate capability detectors to be operated in coincidence with the associated particle counter hosted in the neutron generator.

As far as the gamma-ray detection, photon spectroscopy is performed by using both the high resolution LaBr(Ce) detector from Saint-Gobain and the high efficiency NaI(Tl) scintillator from Scionix. The LaBr(Ce) detector offers the ultimate energy resolution for scintillators but it has a limited volume compared with other scintillation materials and suffers from the internal activity [3]. Such fact sets limits in the detection and identification of weak ^{40}K sources [4]. Moreover, the volume limit is particularly important in the active mode when energetic gamma rays up to 6 MeV from inelastic excitation of oxygen and carbon nuclei need to be detected [5]. The NaI(Tl) scintillator was consequently selected to be used as detector for energetic gamma rays in active investigations as well as high efficiency device in the detection and identification of weak gamma sources with a simple decay scheme, when the energy resolution is not extremely important.

As far as the neutron detectors, the ^{3}He proportional counter with a polyethylene moderator is a typical choice for such systems operated in passive mode [6]. However, the direct detection of fast neutron both in passive and active mode is an important task that justifies the use of the liquid organic scintillator. In the SMANDRA system, available neutron detectors (an 5” x 2” NE213 detector and an ASPECT SN-01 ^{3}He proportional counter) were employed.

An important distinctive fact of the SMANDRA system is that both type of measurements (passive and active) are managed by a simple CAEN VME electronic front end based on fast digitizers. The front end make use of a prototype battery operated VME mini-crate (4 slots) with a Bridge USB V1718. The mini-crate hosts a HV system (V6533 Programmable HV Power Supply (6 Ch., 4 kV, 3 mA, 9 W) and a V1720 8 Channel 12bit 250 MS/s Digitizer. Inside the V1720, Digital Pulse Processing (DPP) algorithms are implemented by using FPGA, providing on-line for each event the time stamp, the complete integration of the signal, a partial integration of the signal used for Pulse Shape Discrimination (DSP) in the liquid scintillator and the possibility of storing a selected part of the digitized signal. The latter feature is needed in reconstructing off-line coincidences and for the time measurements needed in the active mode.

An intense laboratory work has been completed to characterize the detector performances with the VME front-end comparing with the ones obtained from conventional read-out using NIM electronics, as detailed in the next sections.

III. Gamma Ray Detectors

The NaI(Tl) and LaBr(Ce) detectors have been characterized to verify the energy resolution and the stability as a function of the counting rate. As an example, we report in the following results relative to the LaBr(Ce) detector. Fig. 2 shows the energy resolution measured as a function of the counting rate, as obtained from the on-line analysis performed by DPP up to a rate of 340 kHz. It is important to note that up to this high rate value no dead time of the system was detected when the feature of storing a selected part of the digitized signal is not used. The results obtained with the V1720 card are better than those previously obtained by us with conventional NIM electronics up to 40 kHz and exhibit an ultimate energy resolution (2.9 % @ 661 keV and 2.1 % @ 1330 keV)

This figure is maintained up to a value of 150 kHz. In increasing further the count rate up to 340 kHz the energy resolution is degraded to some extend but is still lower than the value of 3.5% @661 keV guaranteed by Saint-Gobain.

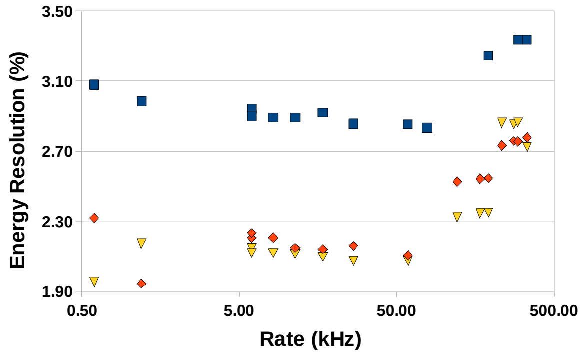

Fig. 2. Energy resolution of the LaBr(Ce) detector measured as a function of the count rate when the V1720 card is used. Bleu squared refers to the 662 keV transition in ^{137}Cs. Yellow triangles and red diamond refer to the 1.17 and 1.33 MeV transitions in ^{60}Co.

However, as evidenced in Fig.3, in increasing the count rate, an impressive positive shift of the peaks (already seen by using the NIM cards) is detected, making the energy calibration strongly rate-dependent. The origin of this effect is currently under investigation.

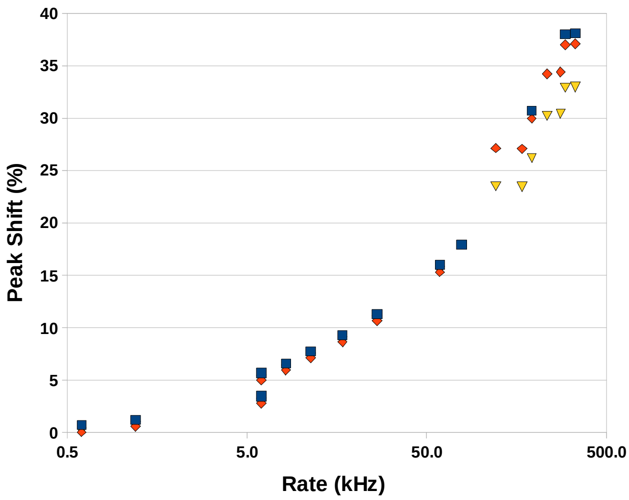

Fig. 3. Peak shift (in %) of the LaBr(Ce) detector measured as a function of the count rate when the V1720 card is used. Bleu squared refers to the 662 keV transition in ^{137}Cs. Yellow triangles and red diamond refer to the 1.17 and 1.33 MeV transitions in ^{60}Co.

Finally, a saturation effect has been also evidenced that reflects in a non linearity of the calibration at high energy. As a summary of the capability (and problems) of the LaBr(Ce) detector, we present in Fig.4 the energy spectrum taken with a cocktail source (^{241}Am,^{137}Cs, ^{22}Na, ^{60}Co, AmBe) at the rate of 340 kHz. The spectrum was re-calibrated with the low energy sources to take into account the rate induced shift. However, the 4.4 MeV transition produced by the AmBe source and the sum peaks of the ^{22}Na and ^{60}Co sources appear at a slightly lower energy than expected because of the saturation.

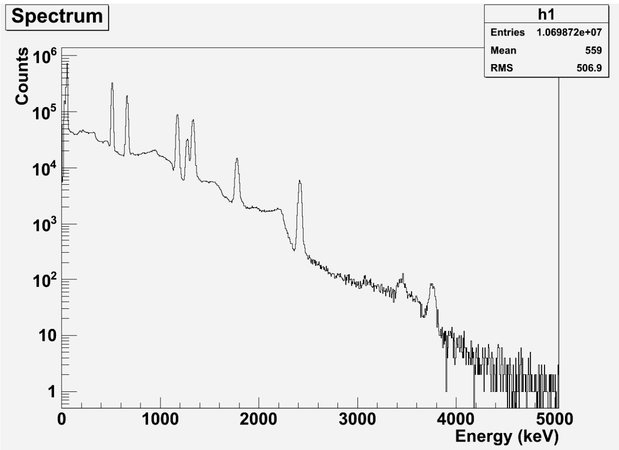

Fig. 4. Gamma ray spectrum taken at 340 kHz by using a cocktail source. For details see the text.

In summary, the LaBr(Ce) detector tested in this work with the V1720 read out shows very good characteristics up to very high rates. Some evidenced rate-dependent effects, as the positive shift and non-linearity at high energy, call for corrections that will be implemented and managed in the SMANDRA information system.

IV. NEUTRON DETECTOR

The neutron-gamma discrimination is also performed on line by the FPGA which provided both the total integration of the liquid scintillator signal (total light) and the integration of the prompt part of the distribution (prompt light). The ratio between the delayed light (obtained by difference between total and prompt ones) and the total light is used to perform on-line the Pulse Shape Discrimination as a function of the total light. Typical plot of a ^{252}Cf source obtained with the 5" x 2" NE213 detector used in SMANDRA is reported in Fig. 5.

Results reported in Fig. 5 demonstrate the capability of the V1720 card of performing on-line PSD. Measurements have been performed up to a rate of 40 kHz, with the neutron sources available in our laboratory. The Figure-of-Merit [7] shown in the upper panel of Fig.5 appears to be not particularly good because of the aging of the detector components. Much better results have been indeed obtained by using a new EJ301 scintillation cell coupled to a new PMT. However the NE213 detector currently included in SMANDRA is sufficient for the tasks of the system.

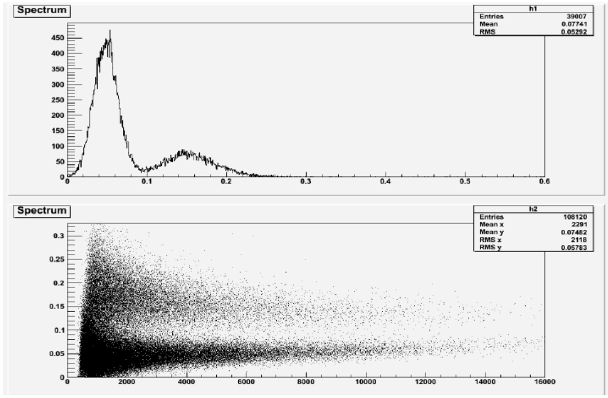

Fig. 5. On-line neutron gamma discrimination obtained with the NE213 liquid scintillator in case of a 252Cf source.

V. BUILDING COINCIDENCES

In active interrogation the associated particle detector signal is also processed in the V1720 card. The alpha particles emitted in the ^{3}H(^{2}H,^{4}He)n neutron source reaction are indeed detected in a fast YAP(Ce) scintillation detector embedded inside the neutron generator, coupled to an external HAMAMATSU R1450 PMT. In the laboratory tests performed so far for active interrogations, the associated particle detector cover a fraction of solid angle of about 1 x 10^{-3} so that a rate of 10 kHz is expected in the operation of the neutron generator at a total flux of 10^7 neutron/s. As already mentioned, the limit in the flux is imposed by the allowed neutron dose in the laboratory. In the above condition, the spot of the tagged neutron beam at the object position has been measured to be about 15 cm [FWHM].

In the active mode operations we stored directly all event singles processed by the V1720 card running at a typical total rate of about 50 kHz. Test have been performed with/without writing the interesting part of the digitized signals. Off-line software analyzes the event files reconstructing the coincidence events and the time correlation between detectors. The time resolution depends on the way of handling the data. In the simple analysis using simply the time stamps reflects the intrinsic limit of the V1720 due to the 4 ns width of each digitalization bin. In a more complex analysis using the digitized signals, the time interval from the start time of the digitalization and a given fraction of the front part of the signal is determined for each detector, correcting for the amplitude effect in the extraction of the time. This second type of analysis allows to obtain a time resolution in the correlation between detectors that is better than the intrinsic limit of the V1720 but requires to handle an heavier data stream.

Preliminary results obtained in laboratory tests using gamma-gamma coincidences with a ^{22}Na source and a fast plastic as trigger detectors are as follows, when the lower threshold discrimination is set at about 500 keV:

1) for the LaBr(Ce) scintillator the overall measured time resolution is δt=1.15 ns [FWHM] to be compared with δt=0.90-0.65 ns [FWHM] measured in the same experimental condition but using NIM Constant Fraction Discriminators with different delays;
2) for the NaI(Tl) detector the overall measured time resolution is δt=5.4 ns [FWHM] to be compared with δt=4.2-3.5 ns [FWHM] measured with NIM cards.

The time resolution obtained with the V1720 card by extracting the time coincidence with a simple algorithm correcting only for the signal amplitude seems to be not as good as the one achieved by using NIM CFTD with compensation for amplitude and rise time. We are still working to implement such corrections in our software. However, it has to be noted that the time resolution already obtained with simple algorithms is enough for the present application: a 5 ns time resolution reflects in about 25 cm depth for the inspected voxel by using the 14 MeV tagged neutrons beam.

VI. INFORMATION SYSTEM

The SMANDRA inspection tool is handled by an information system (IS) operated normally under LINUX. The first task of the IS is the slow control of the VME cards by using dedicated CAEN libraries. All parameters are written in a configuration file (CF) that can be edited and charged on the hardware by the button VME RESET in the control interface shown in Fig.6.

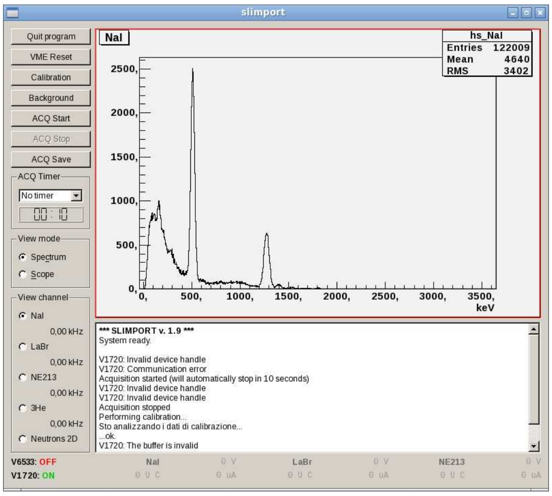

Fig. 6. User interface of the SMANDRA inspection system.

The VME cards status and the values for the HV channels with the measured board temperatures are reported on the bottom of the interface. Automated operations are also performed both for the energy calibration of the gamma ray detectors (CALIBRATE) and the determination of the ambient background for all detectors (BACKGROUND). The BACKGROUND button define the acquisition of the corresponding energy spectrum for each SMANDRA detector as well as the automated estimate of the threshold values for the definition of an alarm for gamma rays and neutrons corresponding to a given probability of detection (normally PD=90%) at a selected confidence level (normally set at the value CL=95%). Both parameters can be changed by the operator in the CF. The acquisition of the selected part of the digitalized signal (SCOPES) is also activated for each detector in the CF. After selecting a give measurement time, the acquisition can be started (ACQ start). The graphic interface presents a selection of the digitalized signal (SCOPES) or the energy spectra (SPECTRA) for a given SMANDRA detector.
A 2-dimensional plot is also available on-line to verify the neutron-gamma discrimination in the NE213 liquid scintillator.

During the acquisition, the system controls that the number of the acquired gamma rays and neutrons is not exceeding the threshold defined during the background measurements printing a written alarm to the operator that alert for the presence of gamma rays and/or neutrons exceeding the ambient background.

After the end of a given measurement (in automatic time selected mode or pushing the ACQ stop button), the data can be saved on disk for further analysis.

The described IS can be defined as an "expert user interface". A more simple user interface is in progress with a completely automated analysis system.

VII. DETECTION AND IDENTIFICATION OF RADIACTIVE SOURCES

Laboratory tests have been completed to verify the possibility of detecting the presence of a radioactive material (gamma ray or neutron sources) and identifying the type of source. As a guidance, the IEC 62327 'standard for hand-held instruments for the Detection and Identification of Radionuclides [8] has been considered. A 3 s time has been selected to verify that the presence of alarms in the NaI(Tl) for the gamma rays whereas 10 s cycle is used for neutrons.

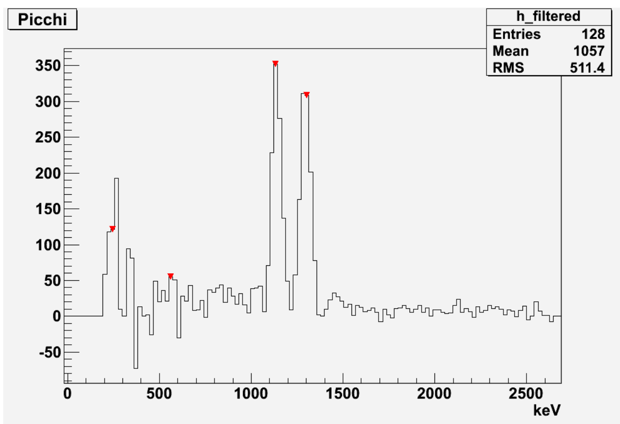

Fig. 7. Example of identification of a 400 kBq ^{60}Co source placed at 270 cm from SMANDRA in 1 minute measurement. For details see the text.

In case of the gamma ray, SMANDRA detects a 0.4 MBq 60Co at 270 cm from the front face of the detector (with an equivalent dose of 20 nSv/h) and 0.4 MBq ^{241}Am at 80 cm from the front face of the detector (with an equivalent dose of 2.5 nSv/h) with a PD=90% at CF=95%. This result has to be compared with the IEC62372 requirement of detection for a source that produce 500 nSv/h at the front face of the detector.

After the alarm, the identification of the gamma source requires 1 minute measurement. The acquired gamma ray spectrum is processed by the SMANDRA software that subtracts the continuous part of the distribution evidencing only the peaks that are automatically fitted with Gaussian function. This analysis produces the report with the data relative to the peak structures that are used to identify the source. As an example, we report in Fig.7 the processed 1 minute spectrum for a ^{60}Co source placed at 270 cm from SMANDRA, evidencing clearly the 1.17 and 1.33 MeV peaks.

In case of neutrons, SMANDRA, after a proper energy windowing, detects in 10 s a ^{252}Cf source placed at 140 cm from the detector surface with PD>90% at CF=95%, demonstrating a sensitivity about 60 times larger more than required by the IEC62372.

IX. DETECTION AND IDENTIFICATION OF SPECIAL NUCLEAR MATERIAL

A campaign dedicated to the detection of Special Nuclear Material (SNM) has been completed at the PERLA laboratory of the Joint Research Center of the European Commission in Ispra. Several Pu and U samples having different enrichment and weight have been studied with SMANDRA. We report here only few examples of the measurements.

Gamma rays spectra from standard 6 g Pu samples with enrichment in ^{239}Pu in the range 61-95% have been studied. In this case the superior energy resolution of the LaBr(Ce) scintillator is needed to disentangle the complex spectra [9]. Typical results for a 61% enrichment source are presented in Fig.8 where the upper panel reports the raw (uncalibrated) spectrum for a 5 minute acquisition when the dose released in front of SMANDRA is about 500 nSv/h after a 6 mm Fe absorber. At high energy is present the structure due to the internal activation of the LaBr(Ce) scintillator (1440-1470 keV [3]). The analysis software produces automatically the calibrated spectrum in the middle panel, where only the peak structures survives. The final step is the subtraction of the ambient background, that produces the spectrum in the lower panel. Few gamma ray transitions are visible in this spectrum: the lines at 373, 414 and 451 keV from the ^{239}Pu and those at 208, 662 and 772 keV from the ^{241}Am. Such transitions are also evidenced in the spectra measured with Pu sample with different enrichment but with ratios that are a function of the isotopic composition of the sample. Gamma ray signatures have been also studied in larger samples up to about 170 g. At the same time, SMANDRA is also collecting the neutron signal from the samples. Typical results are reported in Fig.9 in term of counts per unit mass of the sample in the 3He-poly assembly versus the ^{239}Pu enrichment of the sample. In this plot the small 6 g samples are indicated as CBNM whereas ENEA01 indicates the largest one. Results from a calculated neutron emission for the CBNM samples are also reported.

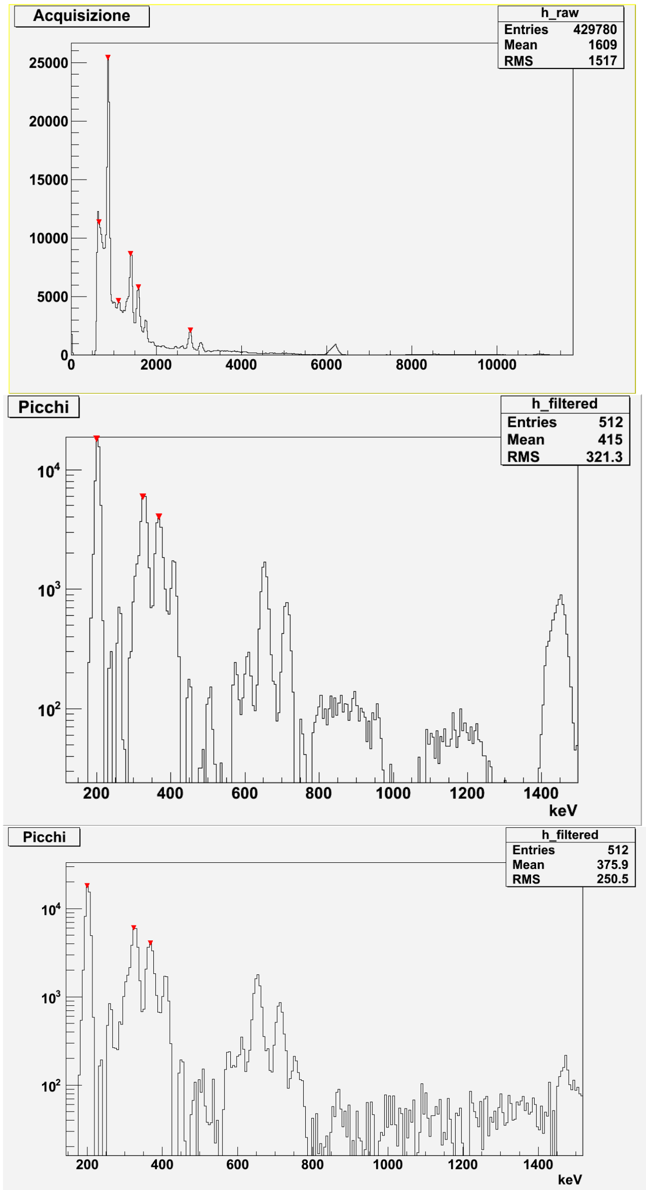

Fig.8 Gamma ray spectrum of a 61% enriched 6 g Pu sample at different stages of the data processing. For details see the text.

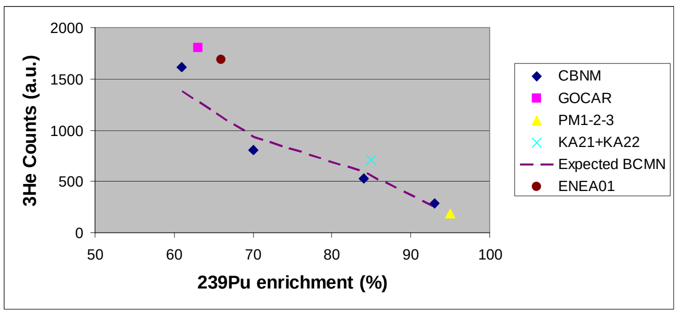

Fig.9 Neutron signature per unit mass of Pu samples in the 3He-poly assembly as a function of the enrichment in ^{239}Pu.

X. ACTIVE INTERROGATIONS

The complete SMANDRA system including the passive detector unit as well as the box containing the neutron generator is shown in Fig. 10. The EADS SODERN TPA17 neutron generator has been employed in the laboratory tests with a neutron flux limit of 10^7 neutron/s. The associated alpha particles are detected with the YAP(Ce) scintillator embedded in the neutron generator with an external HAMAMATSU R1450 PMT.

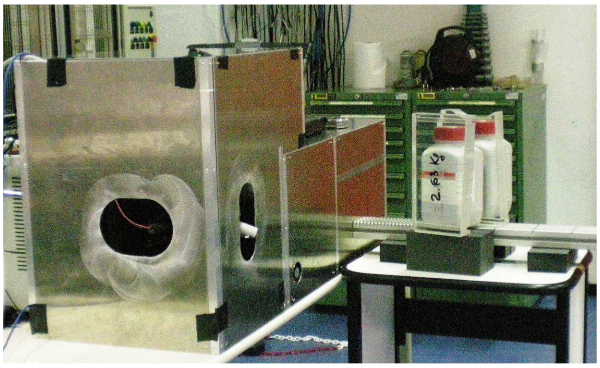

Fig.10 Active interrogation tests with SMANDRA.

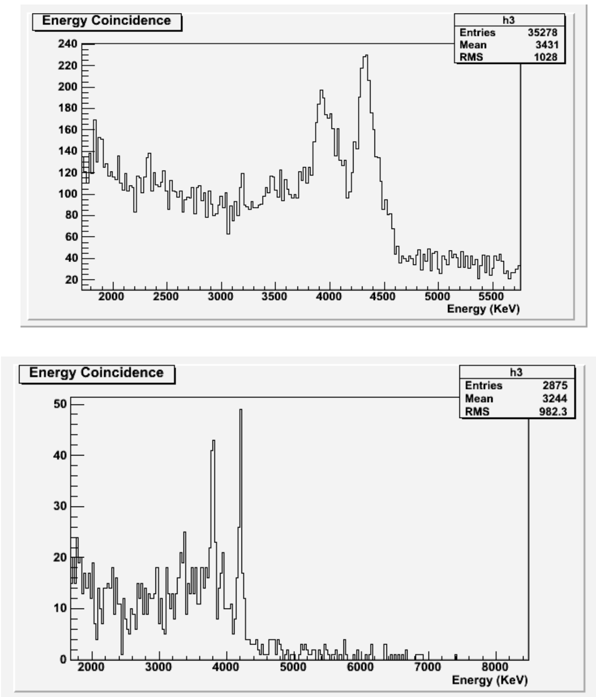

Fig.11 Gamma ray spectra measured from a 3 kg sample of graphite powder bombarded with neutrons.

The sample was positioned at about 30 cm from the front face of the detector unit. In such position the tagged neutron beam have a diameter of about 15 cm. Several chemicals and Uranium samples have been bombarded. Typical measuring times for chemical samples are about 15 minutes. As an example, we report in Fig.11 the gamma ray spectra measured in coincidence with the associated particles of a 3 kg sample of graphite powder. The 4.4 MeV gamma rays from the carbon nuclei are easily detected both in the NaI(Tl) and LaBr(Ce) detectors. The analysis of the gamma and neutron spectra measured in active interrogations is in progress.

XI. SUMMARY AND CONCLUSIONS

The mobile SMANDRA inspection system has been tested in laboratory conditions for the two distinctive tasks: as a high sensitivity passive spectroscopic system and as a complete inspection system using tagged neutrons.

Results obtained are now under analysis to obtain a complete mapping of the system performance in view of the final field testing planned for the next fall.

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