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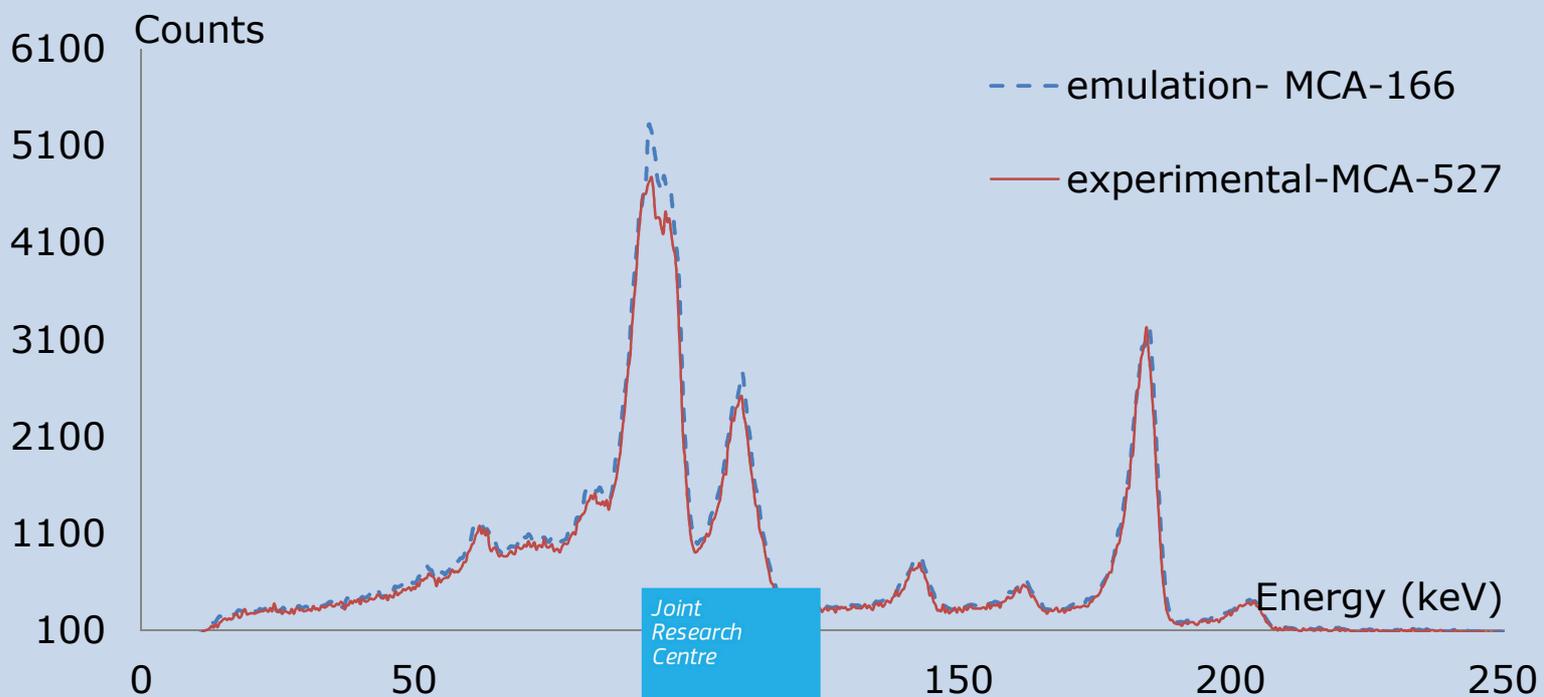
# Gamma spectrometry emulator at AS3ML: First comparison between measured and emulated spectra

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## **Abstract**

The present technical note is related to the development of a gamma emulator under development in the AS3ML laboratory. The object of the present technical note is to evaluate the performances of this gamma emulator by comparing experimental spectra and emulated spectra.

## 1. Introduction

The present technical note is related to the development of a gamma emulator under development in the AS3ML laboratory. The object of the present technical note is to evaluate the performances of this gamma emulator.

In this framework, a library of gamma spectra, was created and experimental spectra of  $^{137}\text{Cs}$ , Uranium oxide or alloy and Plutonium oxide were collected with high, medium and low resolution detectors, respectively Ge and  $\text{LaBr}_3$ , NaI and CZT detectors.

This technical note summarizes the first comparison test between measured/original and emulated/emulated spectra.

## 2. Gamma spectrum simulator/emulator

### 2.1 Introduction

The new electronic Multi-Channel Spectrum Generator for gamma spectrometry is based on a CPU board. The software to control the instrument is "Open" in order to implement in an independent way the acquisition of count rates and Spectrums. The functional principle is depicted in figures 1a and 1b.

The present MCSG is both a simulator<sup>(1)</sup> and an emulator<sup>(2)</sup>:

A Wi-Fi emitter, placed in a "dummy source" container sends a signal with an ID to a receiver, placed on the CPU board, within the detector capsule.

This receiver measures the signal strength and based on the ID, the FPGA simulates (after transposition and randomization) the Poisson pulse distribution and time distribution of the source. The resulting generated digital pulse feed the emulation system (DAC) which produces the electrical pulse as would do the original detector. The electric signal is then send to the amplifier of the MCA.

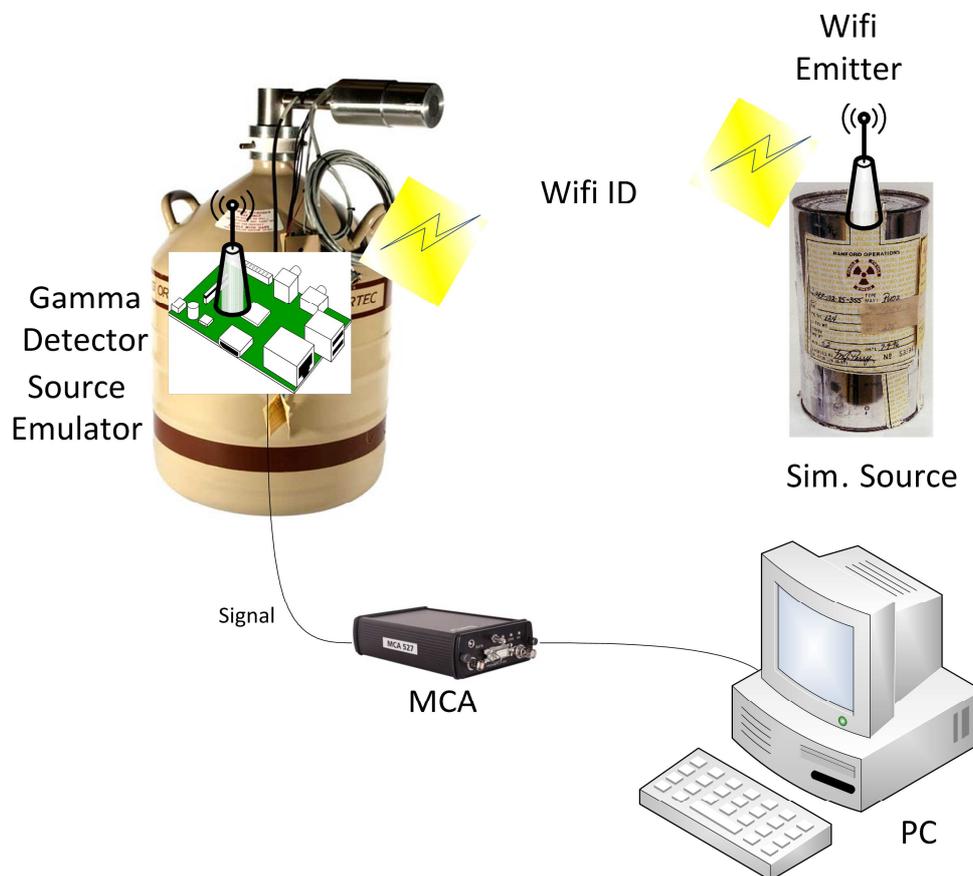


Fig.1a: Functional principle of the Multi-Channel Acquisition Chain

- (1) A Simulator is an environment which, by the means of a software replicate the general behavior of a system starting from a conceptual model
- (2) A Emulator replicates the behavior of a piece of hardware ( for instance a gamma detector) with another piece of hardware

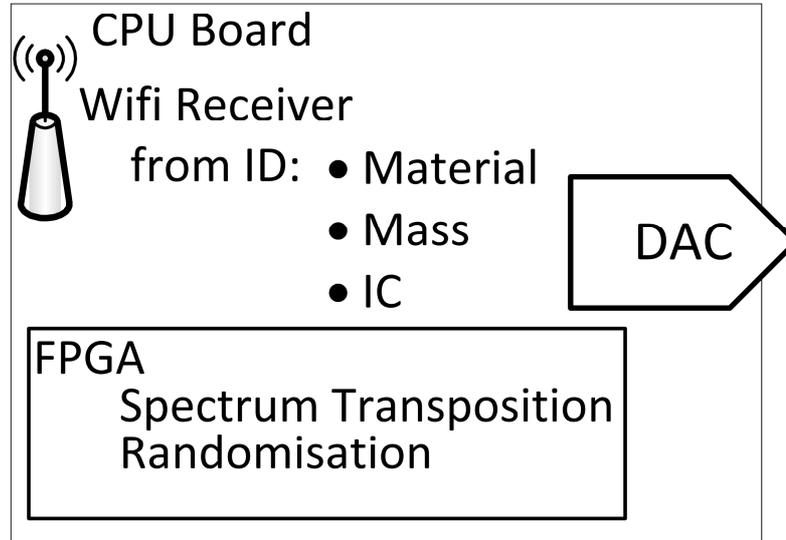
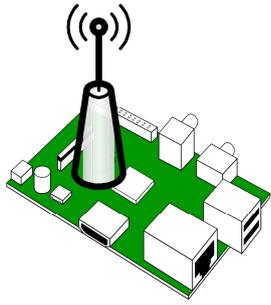


Fig.1b: Gamma detector/source emulator

## 2.2 Multi-Channel Spectrum Generator Description

The new MCSG prototype for gamma spectrometry will have high sampling generating rates (if possible 200K) and an digital to analogue converter (DAC) for 4K Channels.(if possible future version with 8 or 16K)

The system is composed of a FPGA with his VHDL code for the control of the acquisition.

One example of codes to generate the signal was provided in order to test properly the instrument (e.g. generate an output from a spectrum file type IAEA .SPE)

The system may be programmed via a USB port and can transmit the data via Ethernet.

The use of "Power over Ethernet" (PoE) is an advantage as on plant only one cable is needed for data transmission and power.

Random number generator

For the spectral deconvolution a random number generator based on a uniform distribution is used. The seed of the generator is initialized through a spots access and consequent reading of a value produced by one of the ADC present on the microcontroller board. The acquired value, reasonably white noise generated by electronics, is converted and used as seed.

### **2.2.1. Real time deconvolution with PIC32 micro**

There are two possible approaches to make real time deconvolution with PIC32 micro.

#### **2.2.1.1. Uniform sampling**

The gamma spectrum is normalized and, through a running sum, the cumulative and interpolated is calculated in a vector with a sufficiently high number of elements.

Ideally, the vector should have a size at least two orders of magnitude higher than the resolution of the spectrum to be modeled.

In practice the size is determined by the fast access memory available on the micro. In our case the memory size is 512 KBytes.

At each iteration, we perform a Monte Carlo sampling with a random number between 1 and the number of elements in the array.

The values of high occurrence are more present inside the vector table.

The probability to extract one of them is proportional to the occurrence of the distribution.

On 1-2k Channel spectrums, the approach is advantageous on the computational point of view. The micro employs less than 2microSec to determine the energy value to be converted.

The total time for the generation of a virtual photon including the DA conversion is approximately of 3.5 microseconds. Under these conditions the system INPG should be able to generate up to 300k values / Sec.

With spectra with a higher resolution (4k Channel), the onboard RAM of the micro is at the limit of the capacity to ensure a good statistic of generation of the pulse train.

In these conditions it would be preferable to consider a different approach to deconvolution.

#### **2.2.1.2. Dichotomous binary search**

Starting from the cumulative of the spectrum to be modeled, it performs a binary search algorithm that identifies the index of a determined value of the distribution.

The Binary search never uses more than  $\log_2 N$  (log base 2 of N rounded up) comparisons for search hits or search misses.

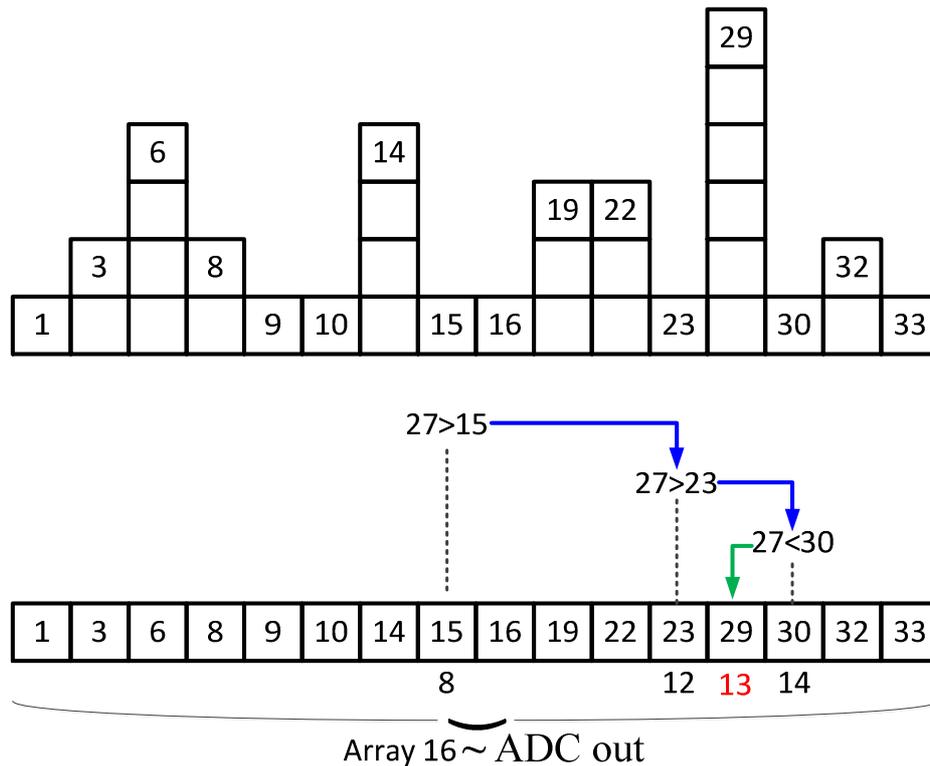


Fig.2: Dichotomous binary search

In the figure above our array size is 16, the random value that we received is 27, using the dichotomous binary search we start at the middle of the Array (array(8)) and found the value 15, 27 is higher so again we divide the remaining part of the array by 2 ( $8/2=4$ ) and go to the array position (12), the value is still lower than 27,

So once again we divide the remaining part of the array by 2 ( $4/2=2$ ) and go to the array position (14), here we found the value 30 which is higher so if have to go back by a value that is calculated by dividing the remaining part of the array by 1 ( $2/2=1$ ) and go to the array position (13), this will be the value to be generated by the ADC.

In our specific case the number of comparisons is equal to the resolution of the digital-analog converter (DAC) then  $N = 12$  for each iteration / emulated photon.

The FOR loop executed at each iteration will keep the micro busy for about 5 microsecond. Summing the 1.5 microsecond necessary for the conversion, the total generation time of a photon and 'approximately 6.5 microseconds.

Under those conditions the system INPG is able to generate up to 150 k values / Sec.

The PIC32MZ version of microcontroller is equipped with a math coprocessor that greatly reduces the calculation time needed to determine the value of energy to be passed to the converter. The extraction time is in fact lower than the microsecond. Summing the 1.5 microsecond necessary for the conversion, the total generation time of a photon is approximately equal to 2.5 microseconds. Under these conditions the system MMSG is able to generate up to 400k values / sec.

The DAC has a output rise time/fall time of 30nsec.

### 2.2.2. Test with the reference spectrum

To test the quality ' of the impulses produced by the MCSG system we used a typical spectrum of a plutonium sample ( Fig. 3).

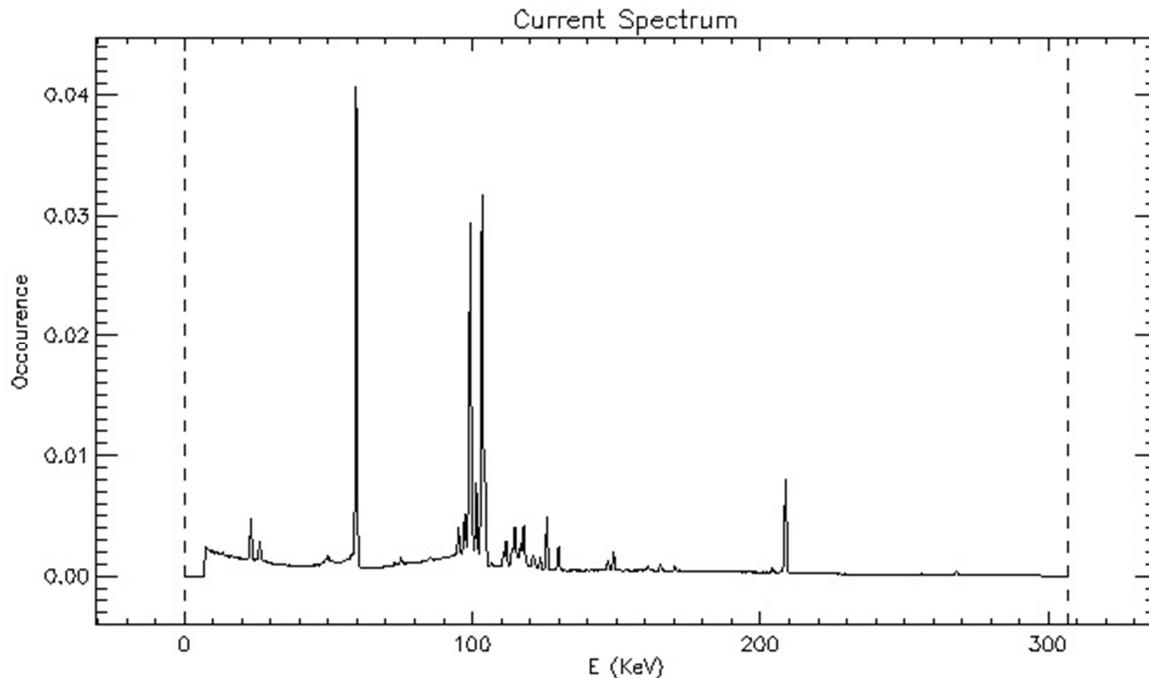


Fig.3: Plutonium test spectrum

The source spectrum is in .spe format and can be manipulated by the application iNPG\_Tool developed ad hoc to transfer the data to the pulse generator or later called pulsator (MCSG).

Once we feed the pulsator, it will generate a virtual range train with frequency determined by the activity of the source described in the .spe file. In this case 8000 pulses / sec.

When connecting to the output of the pulsator to the input of a multichannel analyzer it is possible to reconstruct the spectral shape generated and compare it with the reference spectrum.

## 3. Experimental

Measurements were performed in PERLA laboratory with the following detectors:

- a germanium planar detector ORTEC P3, type GLP-16XXX/10-S shielded against external background radiation. The detector has an active surface of 200 mm<sup>2</sup> and a resolution of 562 eV at 122 keV ( 1μsec and 50 Kcps).
- a LaBr<sub>3</sub> detector, 1.5 inch\*1.5 inch brought to market under the trade name BrillanCe-380, shielded against external radiation, and with a resolution of 3% at 662 keV
- a NaI detector 3 inch\*3/4 inch, with a resolution of 7% at 662 keV
- a 500 mm<sup>3</sup> CZT microspek detector, with a resolution of 2.5% at 662 keV at room temperature,

Collection time 230 nsec for NaI and 10 nsec for Ge.

The LaBr<sub>3</sub> is not used in safeguards application. However, due to its medium energy resolution, which is in-between that of the germanium detector and NaI scintillator, it was used for the present test.

The NaI detector is also commonly used for Safeguards application for attribute test and 235 U determination.

The detector signal was processed with the MCA-166 S/N 150 for all detectors, except the LaBr<sub>3</sub> and the spectra were digitalised into 1024 or 4096 channels and with a variable amplifier gain.

For all detectors, the amplifier gain was adjusted in a way that at least 5 channels were considered for the calculation of the full width at half maximum.

The sources measured are listed in table1.

Detector	Measured source
Ge	<sup>137</sup> Cs and PuO <sub>2</sub> ( CBNM Pu61)
LaBr <sub>3</sub>	U <sub>3</sub> O <sub>8</sub> (CBNM U446)
NaI	<sup>137</sup> Cs and U alloy( MTR plate)
CZT	U <sub>3</sub> O <sub>8</sub> (CBNM U446)

Table 1: Source used versus detector type

The dead time was kept low for all measurements to avoid pile-up effects.

## 4. Comparison between experimental and emulation

### 4.1 Germanium detector

Due to its very good energy resolution, the germanium detector is commonly used in safeguards applications for determining the plutonium or uranium isotopic composition.

The planar Ge structure is required for analysis with MGA ( plutonium) or MGAU ( uranium) to present the best achievable resolution without which the analysis cannot be done.

#### 4.1.1 <sup>137</sup> Cs source

Fig.4 and fig.5 show the <sup>137</sup>Cs experimental spectrum and several emulated spectra prepared for different pole zero adjustments from 50 to 750keV and from 640 keV to 670 keV respectively. All emulated spectra were normalized to the 662keV line of the experimental spectrum.

It can be observed that for the emulated spectra:

a strong low energy tailing deforms the full-energy peak at 662 keV,

there is no improvement of the simulation when changing the pole-zero,

the ratio Compton/peak height is much higher than for the experimental spectrum.

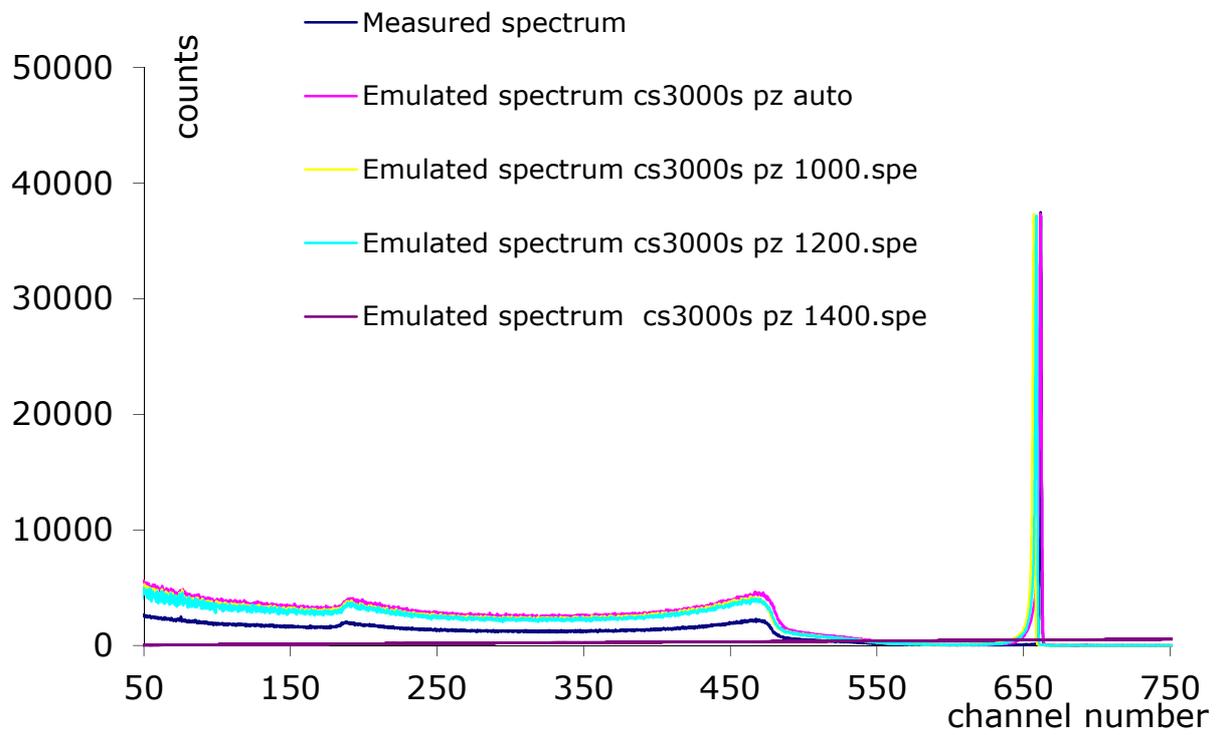


Fig. 4:  $^{137}\text{Cs}$  source measured with the planar germanium detector for different values of the pole zero and between 50 and 750 keV

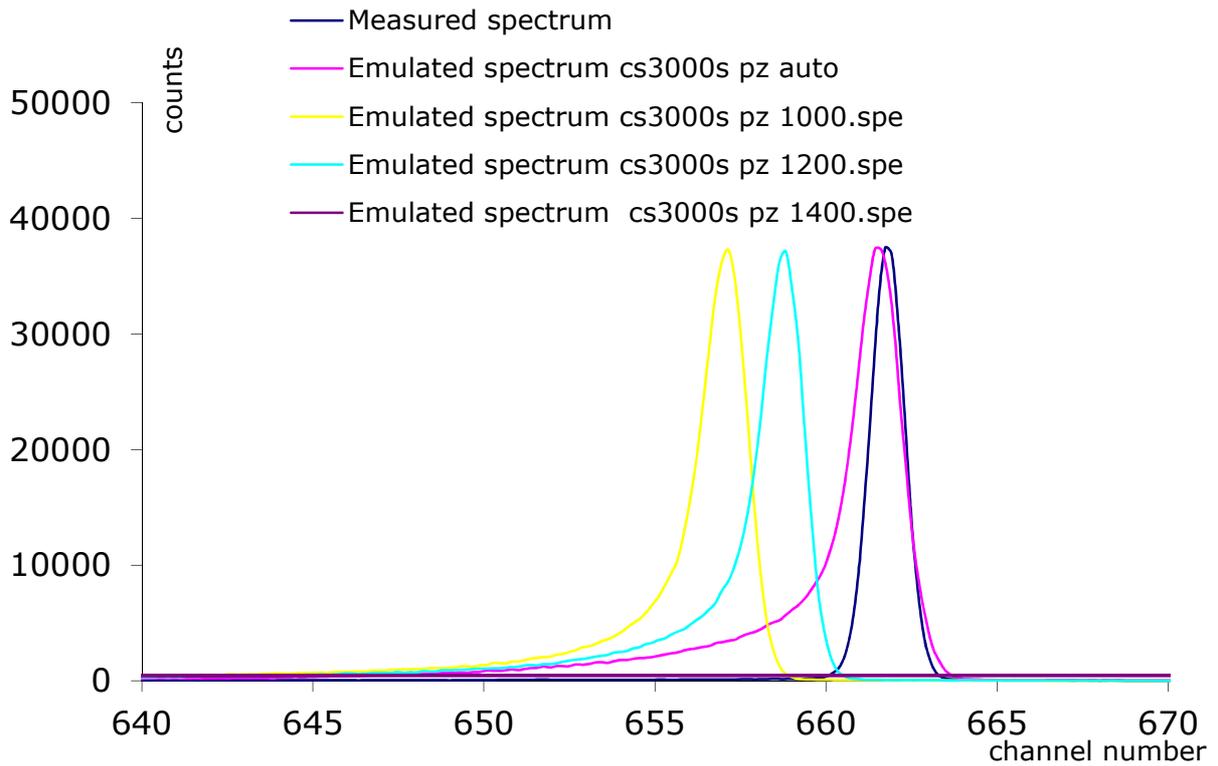


Fig.5:  $^{137}\text{Cs}$  source measured with the planar germanium detector for different values of the pole zero and between 640 and 670 keV

Table. 2 gives the full width at half maximum (FWHM) and the full width at a ten of the maximum (FWTM) for the experimental and emulated spectra.

There is an increase of at least 30% of the FWHM when the spectrum is emulated. The low energy tailing peak is made visible with the increasing of the ratio FWTM/FWHM ranging from 0.35 for the experimental spectrum to a minimum of 0.53 for the emulated spectra.

Spectrum	origin	FWHM		FWTHM keV	Peak pos.	DT (%)	CR (cps)	Gain	FWHM/FWHM exp.	FWHM/FWTHM
		ch	keV							
p3cs710.spe	experimental	6,27	<b>1,192</b>	<b>2,194</b>	3480,4	6,1	6107	5*1.5	1,00	<b>0,35</b>
cs3000s pz auto.spe	emulated	9,19	1,712	5,563	3551,2	5,7	5531	5*1.1	<b>1,44</b>	0,61
cs3000s pz 1000.spe	emulated	8,74	1,639	4,624	3527,2	8,3	5532	5*1.1	1,38	0,53
cs3000s pz 1200.spe	emulated	8,26	1,545	4,684	3536,4	5,8	5529	5*1.1	1,30	0,57
cs3000s pz 1400.spe	emulated	8,76	1,636	5,073	3544,1	5,7	5530	5*1.1	1,37	0,58

Table 2: Values of the FWHM and FWTHM at 662 keV

### 4.1.2 PuO<sub>2</sub> sample

Fig.6 shows the Pu CBNM standard experimental spectrum and several emulated spectra prepared for different pole zero adjustments from 55 to 300 keV and after normalization of all emulated spectra to the 208keV line of the experimental spectrum.

It can be observed that for the emulated spectra:

- a strong low energy tailing deforms the full-energy peaks and this effect is clearly visible for typical isolated lines at 59.54 keV and 208 keV,

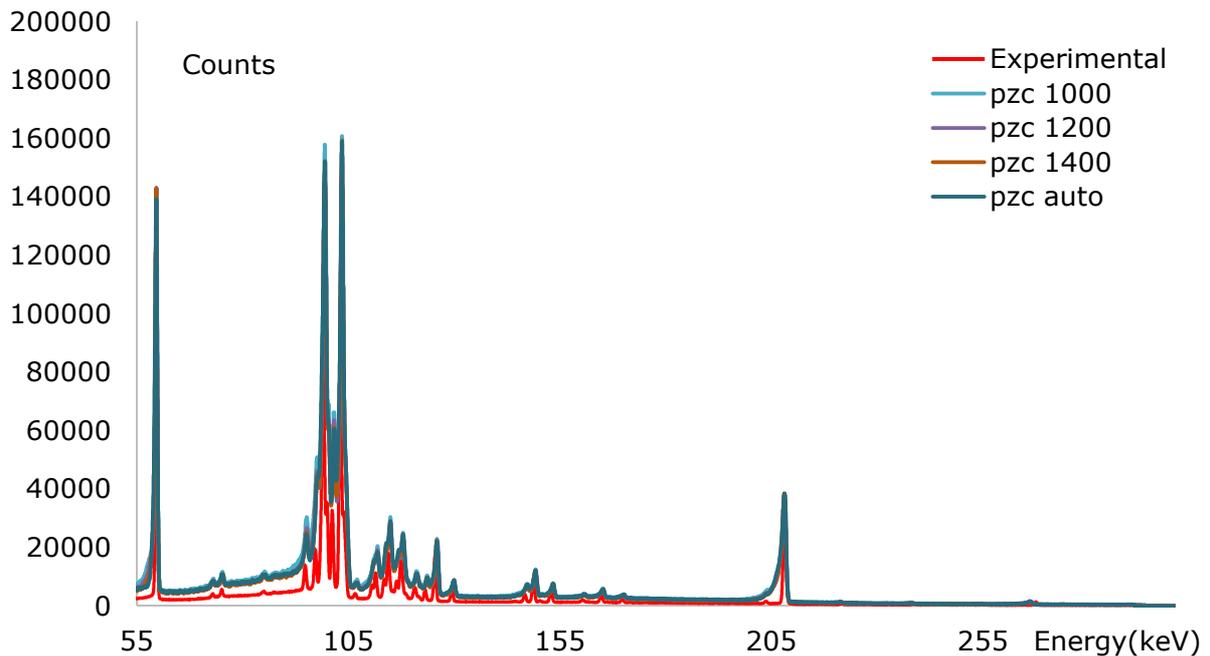


Fig.6: Measurement of the Pu CBNM sample with the germanium planar detector, from 55 keV to 300 keV

Fig.7a and fig.7b present the same series of experimental and emulated spectra for the 59.54 keV and 208 keV peaks.

Apart of the fact that the different values of the pole zero adjustment cannot lead to an improvement of the line shape, we can see that the low energy tailing is much more pronounced at 208 keV compared to the line at 59.54 keV.

Table 3 shows that there is an increase of:

- the resolution of 10% and 56% minimum at 59.54 keV and 208 keV respectively when the spectra are emulated,
- the ratio FWTM/FWHM ( from 1.89 to a minimum of 2.36 at 59.54 keV and from 1.84 to a minimum of 2.90 at 208 keV), depending on the pole zero adjustment of the emulated spectra.

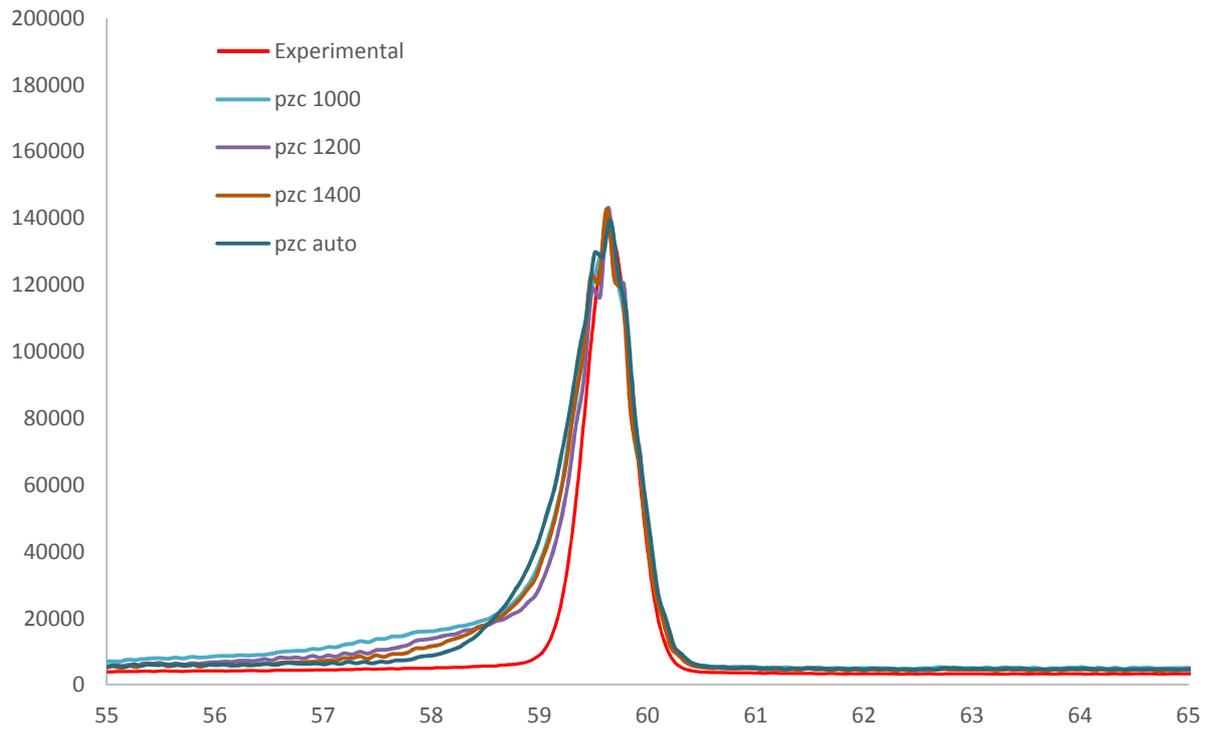


Fig.7a: 59.54 keV line after normalization of the peak height

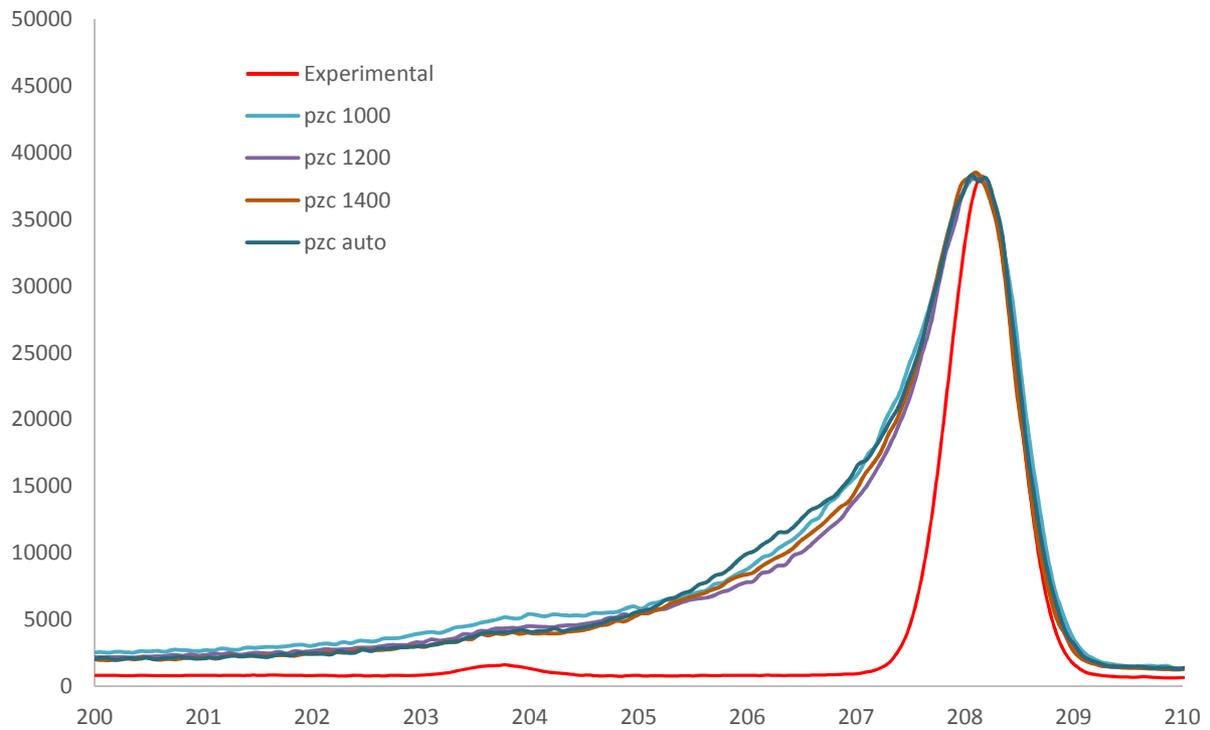


Fig.7b: 208 keV line after normalization of the peak height

Spectrum name	origin	DT (%)	CR (cps)	Gain	Energy=59,54 keV				Energy=208 keV			
					FWHM keV	FWTM keV	FWHM/FWHM exp.	FWTM/FWHM	FWHM keV	FWTM keV	FWHM/FWHM exp.	FWTM/FWHM
p3cbnm611.spe	experimental	11	10950	20*0.98	0,52	0,99	1,00	1,89	0,73	1,34	1,00	1,84
pu3000s pz auto.spe	emulated	9	8821	5*1.1	0,68	1,62	1,31	2,36	1,22	3,88	1,68	2,90
pu3000s pz 1000.spe	emulated	11	8823	5*1.1	0,62	1,70	1,18	2,74	1,29	4,05	1,77	3,03
pu3000s pz 1200.spe	emulated	9	8821	5*1.1	0,57	1,55	1,09	2,72	1,13	3,75	1,55	2,81
pu3000s pz 1400.spe	emulated	9	8815	5*1.1	0,59	1,58	1,14	2,66	1,13	3,81	1,56	2,85

Table 3: Values of the FWHM and FWTM for the Pu CBNM standard

## 4.2 LaBr<sub>3</sub> detector

A uranium CBNM standard was measured with a 1.5\*1.5 inch LaBr<sub>3</sub> and Fig.8 shows the experimental and two emulated spectra prepared with different amplifier gain adjustment. One can identify the typical lines of <sup>235</sup>U ( 143, 163, 185 202, 205 keV). There is a good agreement between experimental data and emulated data.

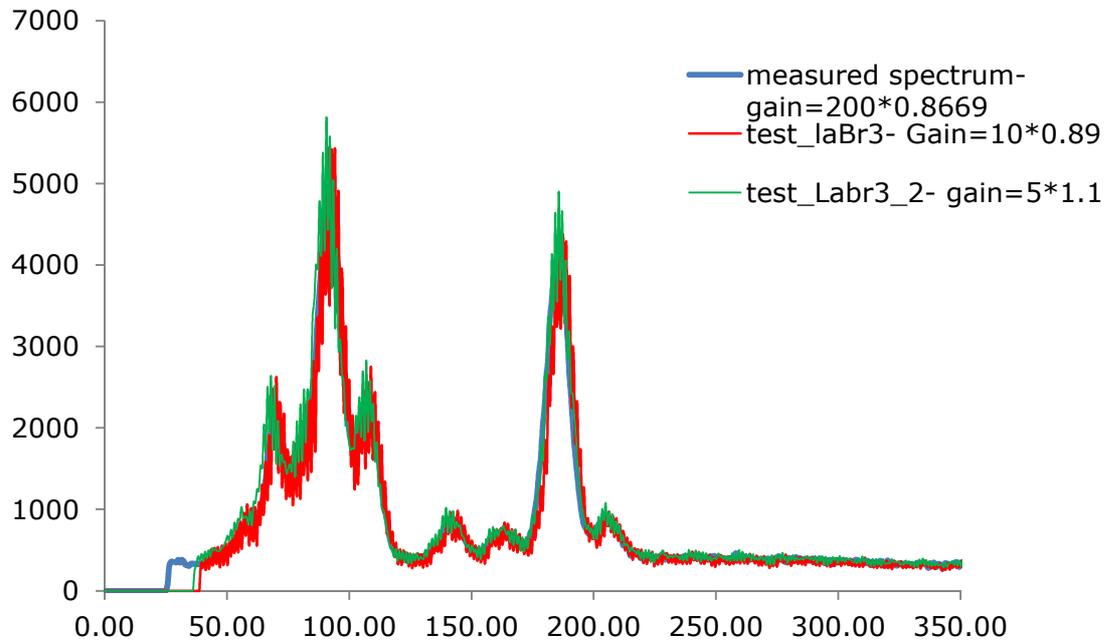


Fig.8: Measurement of the CBNM446 Uranium sample with a 1.5\*1.5 LaBr<sub>3</sub> detector

## 4.3 NaI detector

A Cs137 source and a highly enriched Uranium MTR plate were measured with a 3 inch\*3/4 inch NaI detector and fig.9a and 9b show the experimental and emulated spectra for the <sup>137</sup>Cs and U plate respectively. In both cases, the emulated spectrum fits very well to the experimental data.

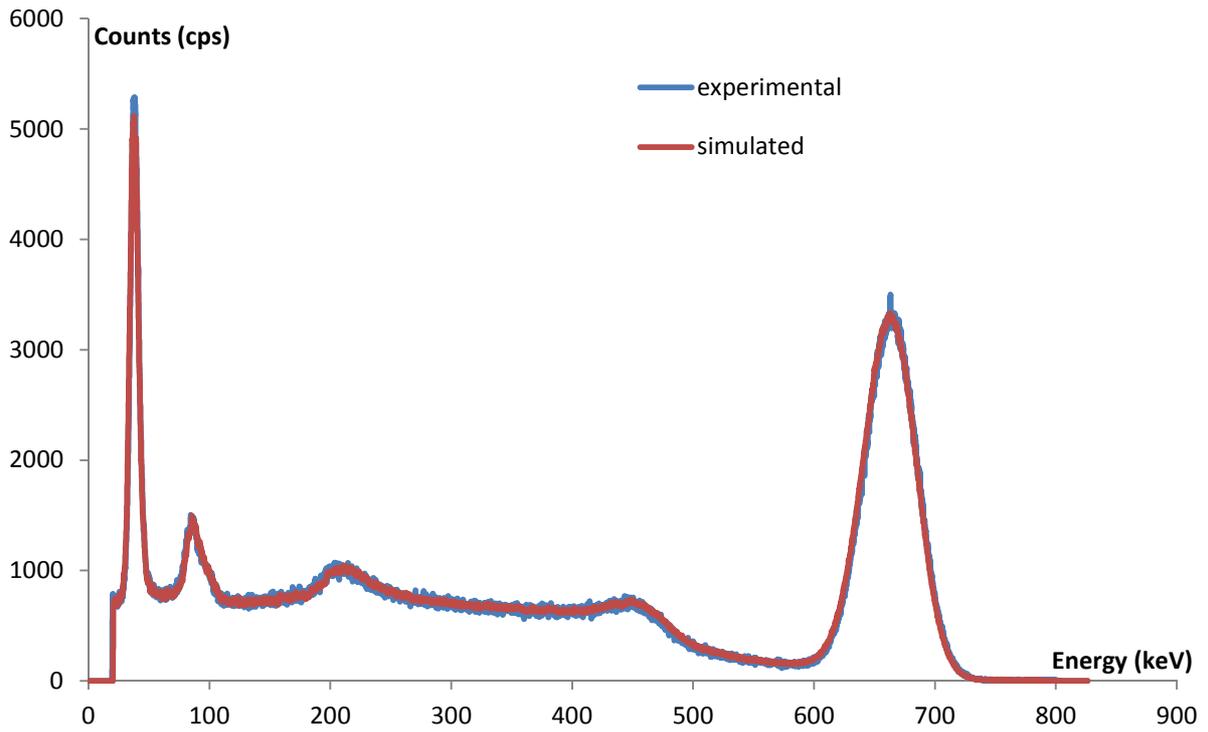


Fig.9a: Measurement of the <sup>137</sup>Cs source with a 3 inch\*3/4 inch NaI detector

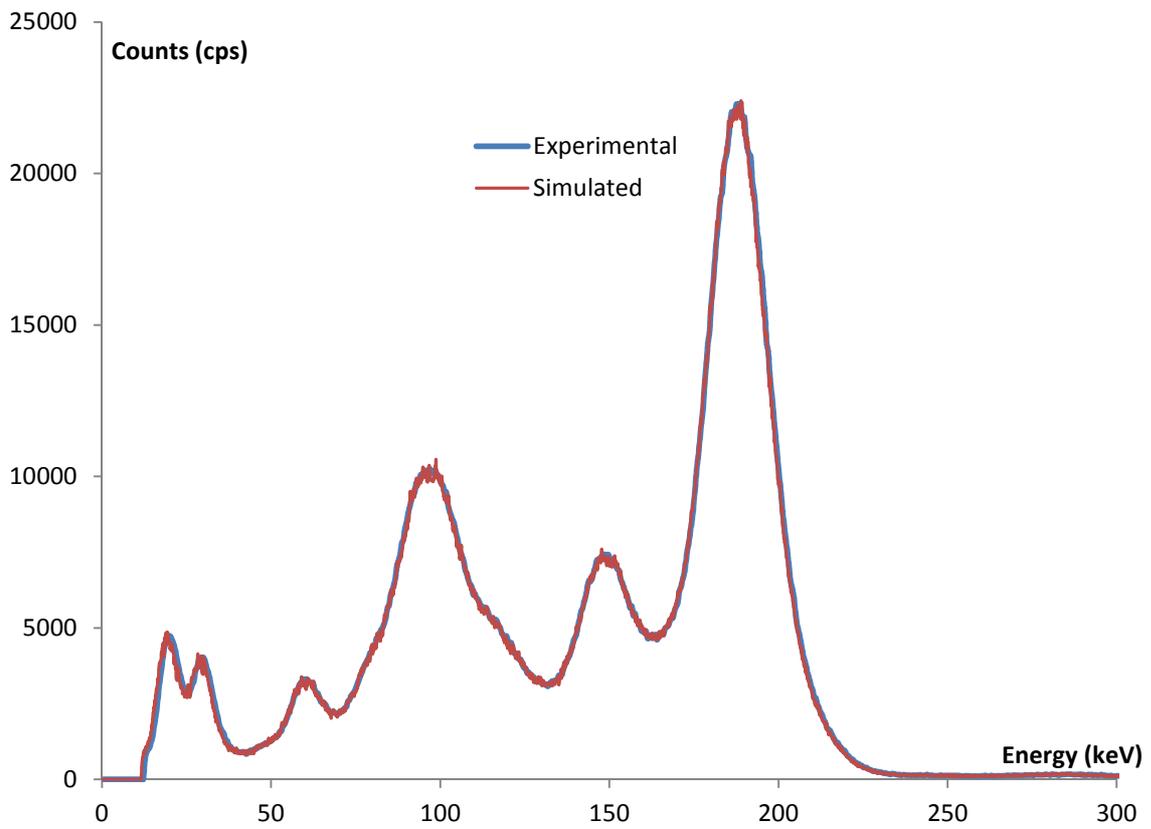


Fig.9b: Measurement of an highly enriched uranium plate with a 3 inch\*3/4 inch NaI detector

#### 4.4 CZT detector

Fig. 10a and fig. 10b show the emulated spectrum of a CBNM446 ( $U_3O_8$  with an  $^{235}U$  enr.=4.43 wt%) and the corresponding experimental spectrum on different energy ranges. The energy resolution at 185.7 keV is slightly higher for the emulated spectrum (4.988 keV) compared to the experimental spectrum (4.817 keV). This is due to the different ways to process the pulse in either the MCA-166 and MCA-527 [2]. However, the agreement between experimental and emulated is still very good.

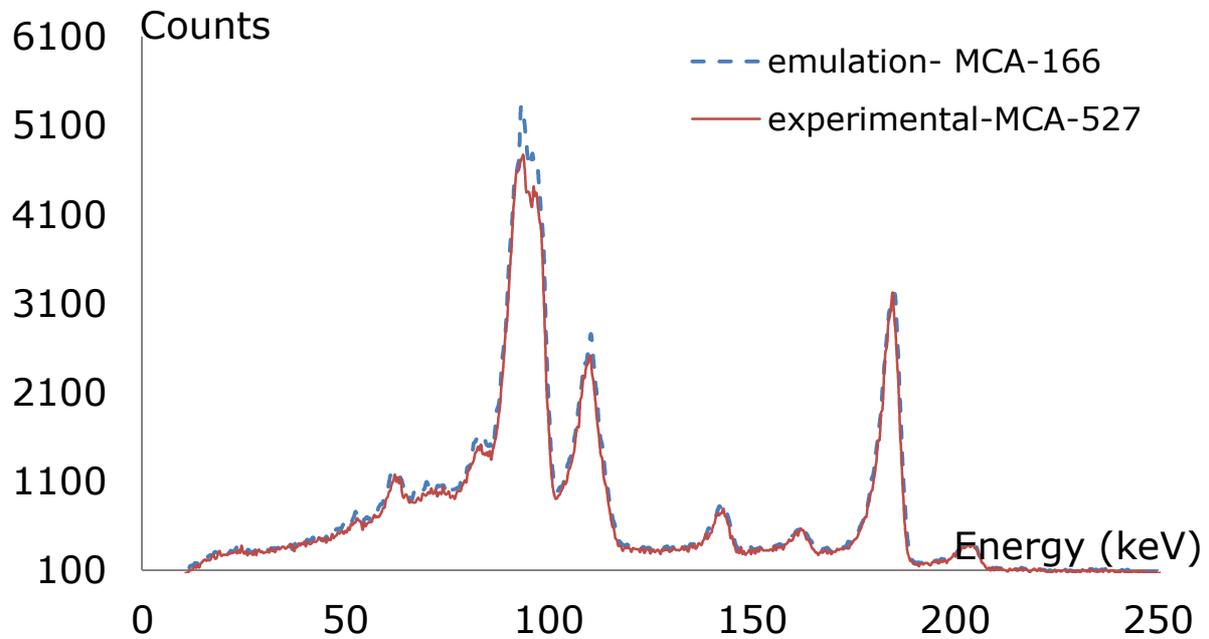


Fig.10a: Measurement of an uranium CBNM sample with a 500 mm<sup>3</sup> microSPEC CZT detector

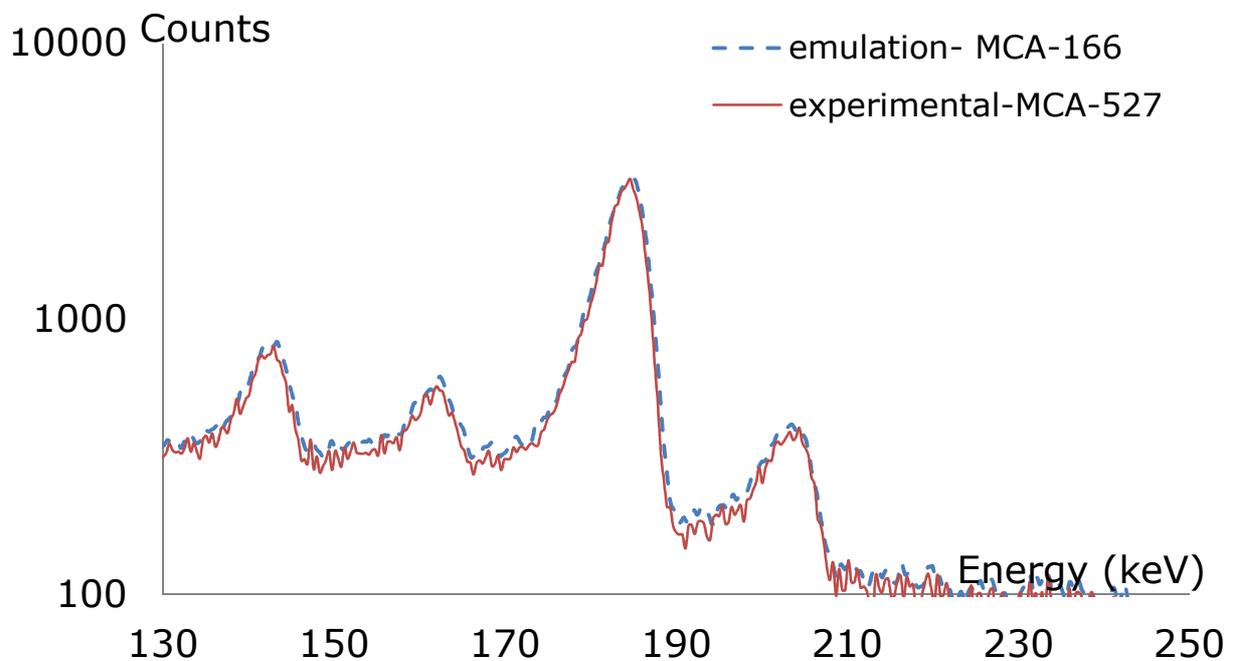


Fig.10b: Measurement of an uranium CBNM sample with a 500 mm<sup>3</sup> microSPEC CZT detector, between 130 keV and 250 keV

## 5. Conclusion

The results of this first test shows that, the quality of the spectra varies a lot from one detector type to the other: the simulation were good concerning the  $\text{LaBr}_3$  detector, but much less good concerning the germanium detector where the peak shape is strongly deformed by low-energy tailing and the increase of the energy resolution.

Modification of the MCSG is required in a view to achieve a good spectrum quality for high resolution detectors. The implementation of a faster DAC will be the next development phase of the MCSG.

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## List of abbreviations and definitions

MCSG: Multi-Channel Spectrum Generator

INPG: Intelligent Nuclear pulse Generator

DAC: Digital to Analog Converter

FPGA: field-programmable gate array

VHDL: Verilog Hardware description language

PoE : Power over Ethernet

MCA : Multi Channel Analyser

FWTM: Full width at Tenth of Maximum

FWHM : Full width at Half Maximum

MGA: Multi group analysis for Plutonium

MGAU: Multi group analysis for Uranium

CBNM: Central Bureau for Nuclear Measurement

MTR: Material Testing Reactor

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