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Fast Neutron Multiplicity Counting for High Mass Plutonium Assay

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***Abstract*—The fast neutron multiplicity counting (FNMC) apparatus was consisted of 36 pieces of liquid scintillator detectors in three rings cylindrical layout, multi-modules of 500M14bit digitizers based on PXIe platform, and mechanical structure. Its center cavity was 35 cm in radius and 50 cm in height for assaying the plutonium item in standard container. The digitizers implemented detector's signal acquisition, real-time digital data processing and data throughput. Each detector's light output was calibration with Cs-137 source for nearly equal response. The apparatus detection efficiency for fast neutron calibrated with Cf-252 source was about 3.2%. The fast neutron multiplicity counting analysis was verified with Cf-252 neutron source, then experiments were performed with a serial of different high mass plutonium metals. Two-parameter calibration procedure was used for mass resolving. The mass assay results were consistent with the sample nominal values within maximum bias of 6%. This research achievement demonstrated a promising application for nuclear material assay and verification.**

***Keywords* —fast neutron multiplicity counting, FNMC, liquid scintillator, digitizers, plutonium, nuclear material assay**

I. INTRODUCTION

THE fast neutron multiplicity counting (FNMC) is originated from thermal neutron multiplicity counting[1]. As an innovative technology for nuclear material assay and verification, it does multiplicity analysis by detecting fast neutron directly in tens ns time scale rather than thermal neutron moderated by polyethylene medium in tens μs time scale.

The earliest report about fast coincidence neutron counter using liquid scintillator for plutonium bearing assay was from J. R. Wachter [2]. This prototype counter was setup with four detectors surrounding a 12.7cm-square sample chamber, and analogue electronics for pulse shape discrimination (PSD) and conventional fast timing modules with a resolving time of 30 ns was used for coincidence analysis.

In recently 20's years, the advances of fast ADC and high-speed FPGA technology paved the way for fast pulse digital acquisition and processing [3], later named the Digital Pulse Processing (DPP) technology [4], [5], [6]. The detector signal is processed directly by the fast digitizer in which basic information related to time and amplitude is computed on line by FPGA. This type of digitizers such as CAEN desktop DT5730 or VIM platform V1730 shows superior performance to the conventional analogue electronics [7],[8], and widely used in the research fields of nuclear physics, and nuclear safeguard.

There are different layout for fast multiplicity counting by combination of detector configurations, size and arrangement, introduce by Katherine Frame [9],.L. Nakae[10], D. L. Chichester[11], [12], Enqvist[13], Dolan[14], [15], [16], A. Di Fulvio[17] and Tony H. Shin[18], and Yuezhuang Liu [19], [20]. The experimental samples included plutonium metal plate, oxide plutonium, MOX pellet. The comparison between single-parameter calibration procedure and two-parameter calibration procedure was carried out for plutonium mass resolution [17, 18]. However, the fast neutron cross-talk between adjacent detectors also made significant contribution to the doubles and triples, and results [21], [22] indicated that the mass resolution from three parameter equation was not as good as expected even if the neutron cross-talk correction was considered.

In 2010s, we developed a thermal multiplicity counter (named NPL-NMC) for assaying the high mass plutonium metal items deposited in standard container [23], [24], [25]. By taking the advantages of FNMC for nuclear material assay and verification, a FNMC apparatus was constructed and experiments were carried out to assay these plutonium items. The constitution of the apparatus, the calibration, the experiments and results were introduced in this paper.

II. THE FNMC APPARATUS

The FNMC apparatus was consisted of an array of 36 pieces of liquid scintillator detectors (LSDs) in three rings cylindrical layout, mechanical structure, multi-modules of 500M14bit digitizers based on PXIe platform, HV device, and software for control and data analysis. The apparatus was assembled in the experimental hall. One PC located in measuring room was connecting to the digitizers through Ethernet cable to control the digitizer remotely. The schematic picture is shown in Fig. 1.

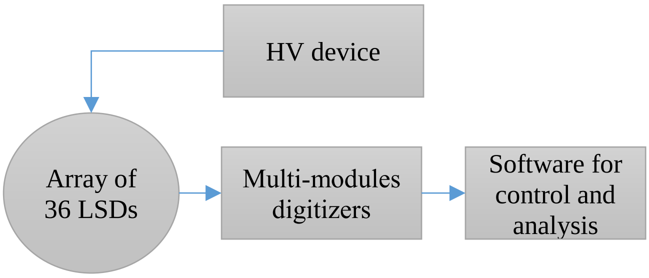


Fig. 1. Schematic diagram of the FNMC apparatus

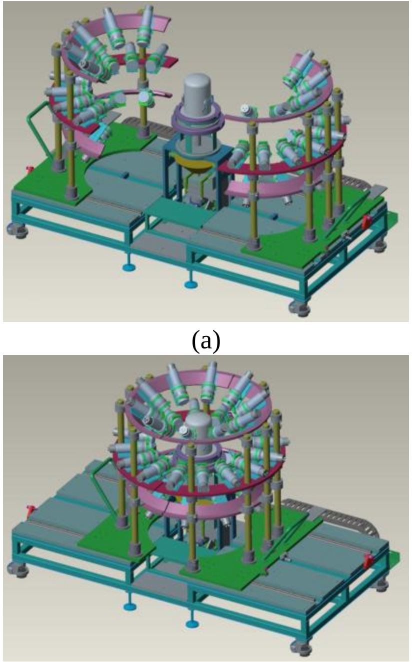
A. *Array of 36 LSDs*

Each liquid detector was made up of a scintillator 3 inches in diameter by 2 inch in depth coupled with a 3 inch in diameter photomultiplier (PMT). A sleeve of 5 mm in thick Pb was used to wrap each detector's main body and the front end for shielding the low energy photos. This made to get a better performance between balancing the neutron gamma PSD discrimination and detection efficiency.

The 36 pieces of liquid scintillator detectors (LSDs) were arranged in three rings cylindrical layout, with 16 prices in center plane and 10 pieced respectively in upper and lower plane. All the detectors in the upper and lower plane were tilted in degree of 38.9 to make the axis line of the detector aiming to the array center. The distance from the chamber center to the detector front end surface is 35 cm.

The chamber cavity of array was 35 cm in radius and 50 cm in height, and suitable for the standard container.

As shown in Fig. 2, the array was installed on the mechanical structure through the aluminum circle belt and poles and divided two halves. Each half can move on the rails to open for sample loading or unloading and close for assaying.



(b)

Fig. 2. Array of 36 LSDs in status of a) open and b) close

B. *Multi-modules Digitizers*

The digitizers were comprised of 5 digitizer modules, one synchronization module, one PXIe imbedded controller and one 9-slot PXIe Chassis, as shown in Fig. 3. Please note there are only 3 digitizer modules for illustrating.

Fig. 3. Multi-modules Digitizers

There are 8 channels for each digitizer module, and totally 40 channels by 5 modules but only 36 channels used. The specifications of the digitizer are 250 M Hz bandwidth, 500M Sample/s and 14-bit ADC resolution. The capability of pulse event rates is more than 50k cps for each channel.

The digitizers implemented detector's signal triggering and acquisition with ADC, and real-time digital data processing with FPGA for characteristics of signal such as triggering time, CFD timing stamp, pulse peak, Qlong and Qshort for PSD discrimination. It is almost the same as CAEN DPP [26], as shown in Fig. 4. The digitizers also manage the data throughput via PXIe bus of backplane with maximum 20 G b/s rate.

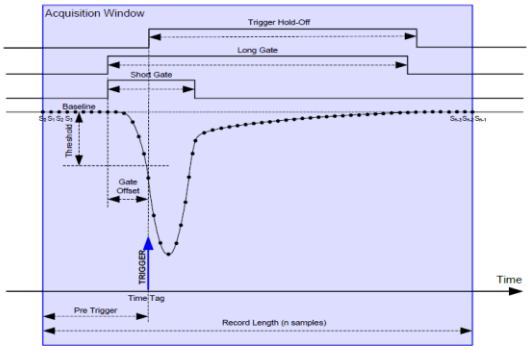


Fig. 4. Diagram summarizing the DPP-PSD parameters

C. *Software for control and processing*

It has three main functions:

1) to control and configure the digitizers for synchronizing, signal acquisition and data processing;
2) to do neutron and gamma discrimination, multiplicity counting analysis and plutonium mass resolving with preset parameters and algorithm;
3) to receive and save the measuring data.

III. CALIBRATIONS

A. *Light output*

The light output of each detector was calibrated with Cs-137 source. The nearly same light output for each detector were made by adjusting the voltage of HV device.

The histogram plots for the energy spectrum of Qlong, pulse peak, PSD scatter in 1-D and 2-D were shown in Fig. 5.

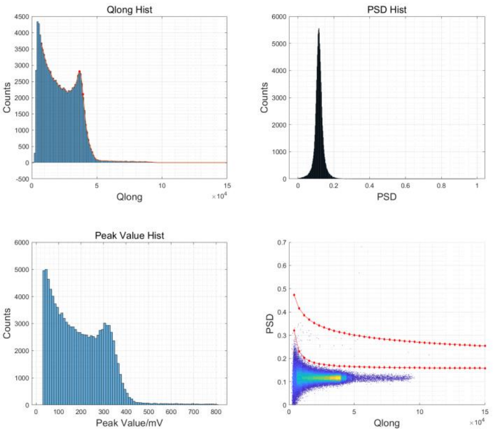


Fig. 5. The plots for Qlong, peak, PSD and 2-D scatter

B. *PSD discrimination and detection efficiency*

The Cf-252 source was used for PSD discrimination parameter calibration for each detector. The measured PSD data was binned by measured light output Qlong. The optimization of the discrimination value was determined and the FOM for the PSD performance was computed for each "slice" of data. An equation for the fit of discrimination point was used:

$$y = a \cdot x^b + c \tag{1}$$

The a, b and c are the coefficients. A line for upper limit neutron discrimination also was determined with (1) in different a, b and c. The typical PSD scatter in 2-D and FoM values for one detector was shown in Fig. 6.

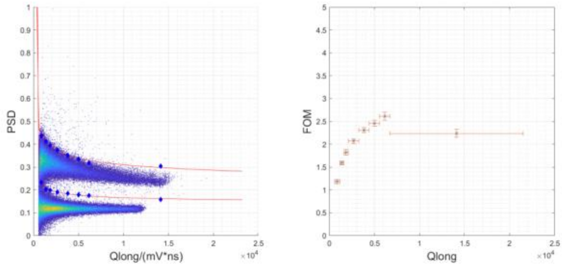


Fig. 6. The plots for PSD 2-D scatter and FoM

The neutron rates for each detector were obtained for three circumstances: in the standard container, naked, and in a 2-inch right cylinder chamber with 3mm in thickness of wall. The rates were shown in Fig. 7. It indicated that neutron rates for the detectors in the lower ring decreased by almost 40 % because the shielding from the bottom case of standard container.

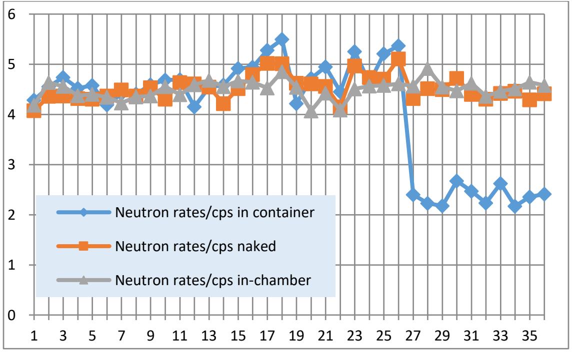


Fig. 7. neutron counting rates

The neutron source is 3mm in diameter by 6mm in height, and the neutron strength was 4.95 E3 s^{-1} at the experimental day. So, the detection efficiency for the FNMC apparatus was 2.95%, 3.29%, and 3.27% respectively. The standard container made the neutron detection efficiency of the apparatus decreased by 10.3%.

C. *Time of flight (ToF)*

The gated coincidence measurements were carried out for extract the timing resolution and the time offset for each detector with Cf-252 fission chamber [27], [28], [29]. It was fixed in the center of apparatus, and the fission timing signal was collected from the chamber and amplified for timing and gating. The typical ToF spectrum from one scintillator detector was shown in Fig. 8. The time offset was determined by tuning the gamma peak to be 1.50 ns. The FWHM of gamma peak was 1.30 ns, extracted by Gaussian fitting.

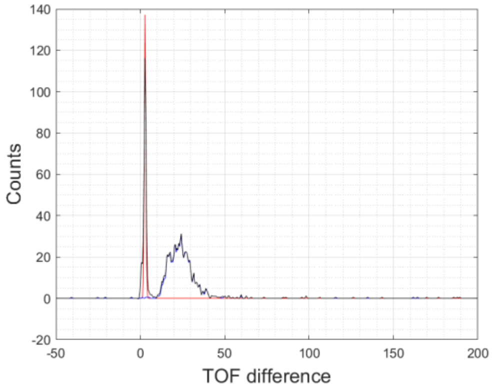


Fig. 8. The ToF spectrum

The average and standard deviation of gamma peak time for all the 36 detectors were 1.52 ns and 0.04 ns respectively. The average and standard deviation of gamma peak FWHM for all the 36 detectors were 1.27 ns and 0.07 ns respectively.

D. *Test of multiplicity*

The multiplicity counting analysis for the Cf-252 fission chamber and the background were carried out, and the measured SDT (Singles， Doubles and Triples) were shown in Table I.

TABLE I
Measured SDT for Cf-252 and background

	Measuring time/s	S/cps	D/cps	T/cps
Cf-252	300	2888 ±3.1	108.7 ±0.7	2.38 ±0.14
Cf-252	1000	2881 ±1.7	107.3 ±0.4	2.42 ±0.08
background	600	39.7±0.3	0.135±0.015	0

IV. EXPERIMENTS AND RESULTS

There were seven plutonium items used for FNMC assay. Each item was deposited in a standard container. The sketch diagram for the container was shown in Fig. 9.

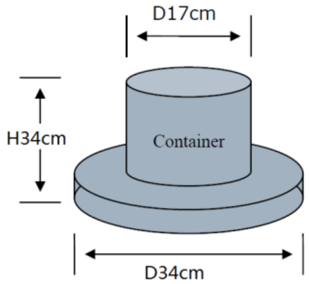


Fig. 9. Sketch diagram for the container

Each container was loaded by turn on the support base in the FNMC apparatus cavity, and the measuring time was 300s. The measured SDT were shown in Table II.

TABLE II
Measured SDT for plutonium items

	S/CPS	D/cps	T/cps
1	385.5 ±1.1	9.38 ±0.19	0.257 ±0.049
2	416.6 ±1.2	10.07 ±0.20	0.277 ±0.046
3	898.0 ±1.7	42.35 ±0.45	2.827±0.192
4	830.7 ±1.7	20.68 ±0.28	0.498 ±0.067
5	968.2 ±1.8	24.31±0.31	0.690 ±0.077
6	2500.5 ±2.9	123.31 ±0.76	7.783 ±0.311
7	5086.5 ±4.1	553.18 ± 2.06	95.76 ±1.80

As the values of T for some items were less than 1 cps and the statistical uncertainty of counting were large rather than accepted, the two-parameter calibration procedure using S and D values was implemented for mass resolution. The equation was listed as following:

$$\frac{D}{m_{eff}} = A + B \cdot \left(\frac{D}{S}\right) + C \cdot \left(\frac{D}{S}\right)^2, \tag{2}$$

D refers to Doubles, in unit of cps, *S* refers to the Singles, in unit of cps, m_{eff} refers to the effective mass in items, in unit g, A, B and C refer to the coefficient from calibration, which were 0.082 ±0.022, 16.024 ±0.892 and 234.274 ±6.963 respectively.

The results of m_{eff} from assay were determined with (2), as shown in Fig. 10. The relative biases for these items were less than 6%.

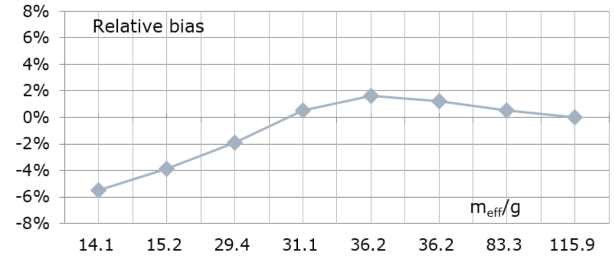


Fig. 10. Assaying results and biases.

V. CONCLUSIONS

The fast neutron multiplicity counting (FNMC) apparatus was constructed, calibrated and applied for assaying the high mass Pu items. The apparatus was consisted of an array of 36 pieces of liquid scintillator detectors in three rings cylindrical layout, multi-module of 500M14bit digitizers based on PXIe platform, and mechanical structure, and software for control and data analysis. The two-parameter calibration procedure using S and D values was implemented for mass resolution. The mass assay results were consistent with the sample nominal values within maximum bias of 6%.

This research achievements demonstrated a promising application for assaying high mass Pu items in the fields of nuclear material assay and verification. Further work will be taking such as the two parameter and three parameter equations for mass resolving, neutron cross-talk correction, multiplication correction and spectra analysis for oxidization in the future.

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