# Active Fast Neutron Multiplicity Counting with DT Neutron Generator

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***Abstract*—The active fast neutron multiplicity counting (AFNMC) apparatus was consisted of an array with 36 pieces of liquid scintillator detectors in three rings cylindrical layout, multi-modules 500M14bit digitizers based on PXIe platform, the DT neutron generator, shielding cone and mechanical structure. Its center cavity was 35 cm in radius and 50 cm in height for assaying the standard container of plutonium item. The DT neutron generator was the type of alpha-associated to make the neutron injecting into the assay area being tagged and located on the bottom of detector array. The shielding cone was fixed between the DT generator and the lower ring detector with a hole to let the tagged neutron injecting to the sample assay area. The alpha signal was used as gating signal when doing neutron mutiplicity analysis. The experiments were performed with iron, lead, HEU metal in standard container for technical verification. The SDT values from both conventional and gating FNMC were obtained for comparison. The experimental results indicated this method dramatically reduced the random or non-correlated neutron signal noise and substantially promoted the D and T values sensitivity when the alpha signal gating was enabled.**

***Keywords* —active fast neutron multiplicity counting, AFNMC, alpha-associated DT neutron, generator liquid scintillator, digitizers, HEU, nuclear material assay**

## I. INTRODUCTION

THE challenges has been existed for several decades on the HEU attribute assay in the fields of arms control and nuclear material assay and verification. Some detection options for HEU monitor were reviewed [1] and measurement approach suites for Uranium Mass Attribute System (UMAS) were evaluated [2]. The active neutron multiplicity counting (ANMC), originated from passive neutron multiplicity counting [3] is one of the most important method for U mass assay and accountability.

The ANMC has two branches according to the detected neutron spectrum, one is active thermal neutron multiplicity counting such as AWCC [4], [5], [6] and another is the active fast neutron coincidence [7]and multiplicity counting (AFNMC) [8], [9], [10]. Meanwhile the are mainly three categories of neutron sources used for active interrogation, one is the (alpha, n) neutron source such as Am-Li [11], Am-Be source, the other is the spontaneous self-fission neutron source such as Cf-252, and the last is the DD, DT neutron generator.

NMIS/NWIS was an innovative technology developed by J. T. Mihalczo [12], [13], [14]. in Oak Ridge National Laboratory for nuclear materials/weapon identification and multi-attributes measurements [15]. The interrogation source used were Cf-252 fission timing chamber [12, 14] earlier and upgraded with alpha associated DT generator [16], [17] later. Based on the measured time corelated neutron and gamma signature, the approaches for resolving the U attributes of mass [18], [19], enrichment [20], [21], shape and shielding or cladding material [22] were investigated.

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], And a FNMC apparatus was constructed and verified by experiments of assaying plutonium items [26]. The alpha-associated DT neutron generator was integrated into this FNMC apparatus, making it be suitable for active interrogation (AFNMC). The conventional and alpha gating FNMC method was implemented for technical verification. The constitution of the apparatus, DT neutron generator, the calibration, the experiments and results were introduced in this paper.

## II. AFNMC APPARATUS

The AFNMC apparatus was consisted of an array with 36 pieces of liquid scintillator detectors in three rings cylindrical layout, multi-modules 500M14bit digitizers based on PXIe platform, the DT neutron generator, shielding cone and mechanical structure, HV device, and software for control and data analysis. The generator was the type of alpha-associated to make the neutron injecting into the assay area being tagged and located on the bottom of detector array. The apparatus was assembled in the experimental hall. One PC located in measuring room was connecting the digitizers through Ethernet cable to control the digitizer remotely. The schematic picture was shown in Fig. 1.

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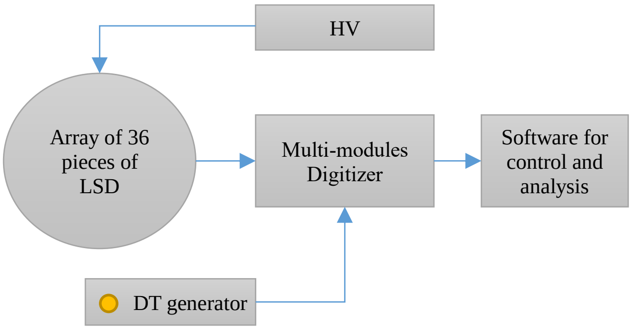



Fig. 1. Schematic of the AFNMC apparatus

## *A. DT Neutron Generator*

The DT neutron generator was self-developed alpha-associated product [27] with compact dimension for portable application. The maximums strength for DT neutron emission was 2E7 $s^{-1}$. The schematic diagram and the photo for this generator were shown in Fig. 2 and Fig. 3.

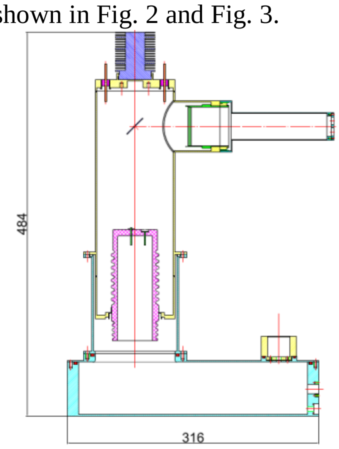



Fig. 2. Schematic diagram of the DT generator

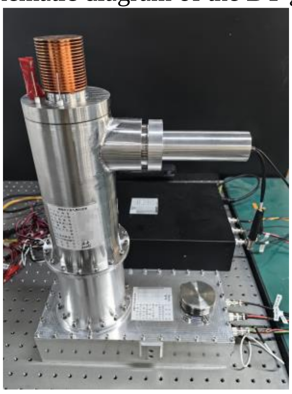


Fig. 3. Photo for the DT generator

DT neutron generator was consisted of two parts: the neutron generator tube, including the alpha-tagging detector, with dimensions 150 mm × 330 mm × 490 mm and weight less than 13 kg; and the power supply and control unit - the black box as shown in Fig. 4. with dimensions 370 mm×250 mm×89 mm and weight less than 2 kg.

The ZnO: Ga scintillator fused on quartz substrate [28] was sealed in the generator tube for alpha particle detection. The effective area was 22 mm in diameter, and the distance to the tritium target was 66 mm. An ET 9125B photomultiplier tube was employed to convert the fluorescence burst to fast electronical pulse with 4ns in rising time and about 100 mV in amplitude, as shown in Fig. 4.

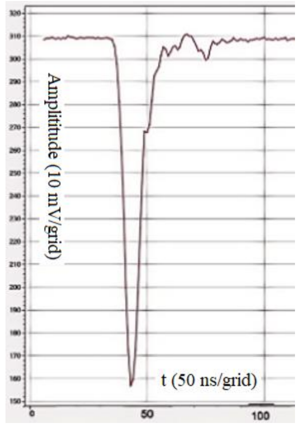



Fig. 4. Waveform of alpha signal

The DT neutron generator was installed on the bottom of detector array with 664 mm in distance from the tritium target to the assay cavity center. The generator was tilted by 5.5 degree to compensate the angle of deflection of tagged neutron.

## *B. Shielding Cone*

A shielding cone made of brass was fixed between the DT generator and the lower ring detectors with a hole to let the tagged neutron injecting to the sample assay area. The shadow from the shielding cone covered all the liquid scintillator detectors to decrease the background counts induced by the untagged neutrons from generator. As shown in Fig. 5, the container (in grey), the shielding cone (in brown) and the generator (in green) were assembled from up to down.

Fig. 5. Diagram for the generator, the shielding cone and the container

## *C. Array of 36 LSDs and Digitizers*

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. 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.

The digitizers were comprised of 5 digitizer modules, one synchronization module, one PXIe imbedded controller and one 9-slot PXIe Chassis. There are 8 channels for each digitizer module, and totally 40 channels by 5 modules. The first 36 channels were used for signal form LSDs and the 37$^{th}$ channel was used for signal from alpha detector. The digitizers implemented detector's signal triggering, acquisition and real-time digital data processing for characteristics.

Please refer to the reference [26] for more details.

### *D. Software for control and processing*

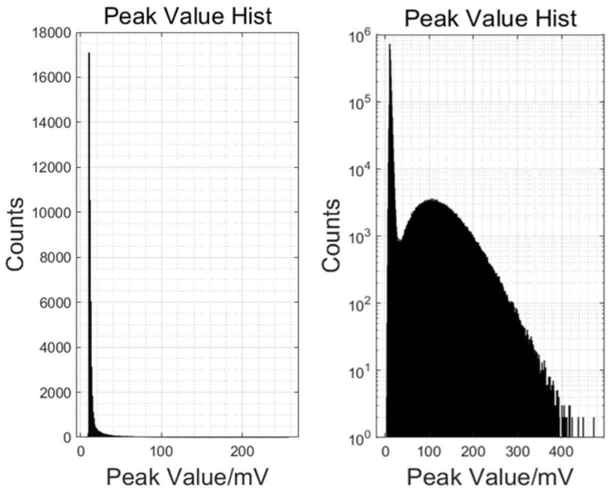
It has four main functions:

1) to control and configure the digitizers for synchronizing, signal acquisition and data processing;
2) to control and configure the DT neutron generator;
3) to do neutron and gamma discrimination and alpha signal discrimination, coincidence measurements, conventional and gating multiplicity counting analysis and uranium mass resolving with preset parameter and algorithm;
4) to receive and save the measuring data.

## III. TEST AND CALIBRATIONS

### *A. Test of the DT Neutron Generator*

The alpha signal was sampled with digitizers and processed for pulse amplitude analysis in preheated without neutron emitting status and in neutron emitting status. As shown in Fig. 6, it indicated that the maximum amplitude of alpha signal was about 100 mV, and the effective signal can be easily discriminated by amplitude with 35 mV thresholds.




(a) (b)

Fig. 6. Amplitude distribution in a) preheated and b) emitting status

The cone area boundary for tagged neutron at the distance of 664 mm was measured with a miniature liquid detector with a diameter of 10mm and a thickness of 10mm. The mini detector was fixed in the center of the assay cavity through an arm attached to a moving slide rail. The rail can move in the horizontal plane precisely along X and Y directions step by step. The gated coincidence measurement was carried out in each step and the coincident counts distribution were obtained. As shown in Fig. 7, the boundary for tagged neutron was 100 mm, which covered the maximums radius for the sample to be assayed.

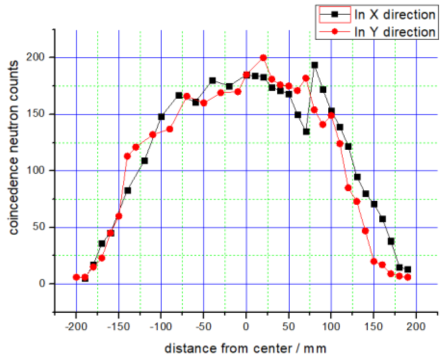



Fig. 7. Tagged neutron distribution along X and Y directions

### *B. Calibration for the Array of LSDs*

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 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 of "slice" of data.

The gated coincidence measurements were carried out for extracting the timing resolution and the time offset for each detector with Cf-252 fission chamber.

The passive multiplicity counting analysis for the Cf-252 source and the background was carried out.

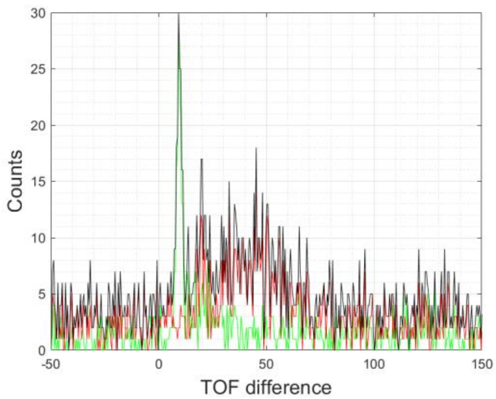
Please refer to the reference [26] for more details.

## IV. EXPERIMENTS AND RESULTS

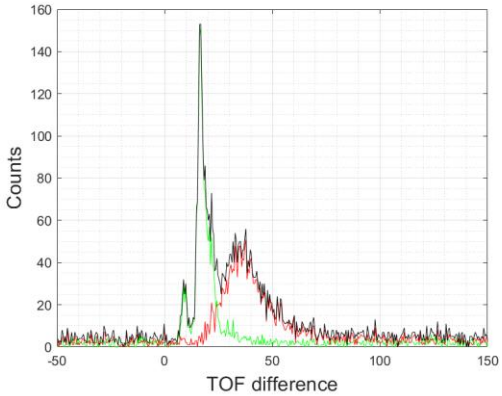
The iron, lead and HEU metal samples respectively deposited in standard container were used for experiments. The background experiments for the empty and the container without sample in the assay cavity were also carried out. The methods for the experiments were TOF spectrum, conventional multiplicity counting and gating multiplicity counting. The measuring time for each experiment was 300s.

### *A. ToF from Alpha Signal*

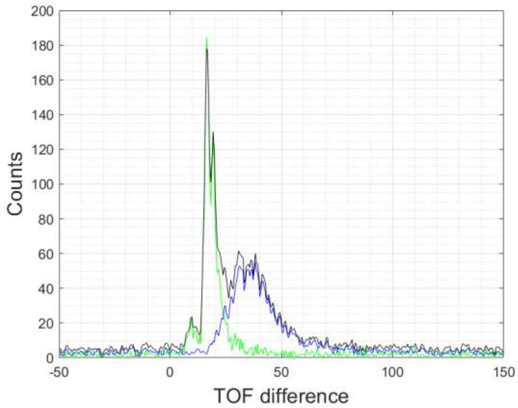
The TOF spectrum from one detector in the center ring were shown in Fig. 8. In the figures, the line in green refers to the gamma signal, the red or blue line refers to the neutron signal, and the black line refers to all the signal.



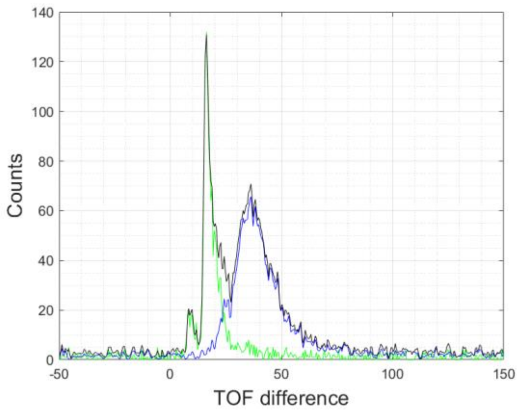

a) empty



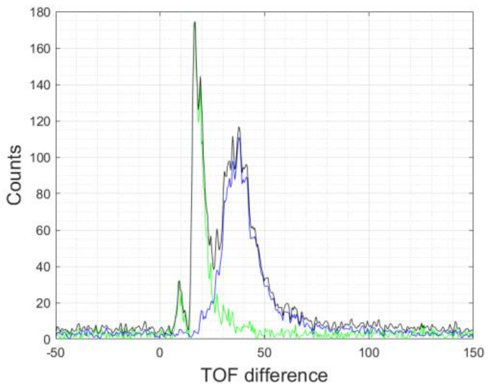

b) container without sample




c) container with Fe




d) container with Pb




e) container with HEU

Fig. 8. Assaying results and biases.

There were three peaks (two gamma peaks and one neutron peak). The first peak was from inelastic gammas in generator and almost stable. The second peak was from inelastic gammas in the reaction of tagged DT neutron with the container and the sample. The third peak was from the scattered neutron in both inelastic and elastic reaction of tagged DT neutron with the container and the sample, and the fission neutrons if the sample was fissile nuclear material. There was a little increment in neutron counts for Pb sample compared Fe because the scatter cross section for Pb larger than Fe. There was a significant increment in neutron counts for HEU sample because the introduced fission contribution.

## *B. AFNMC Experiments*

The gate window for multiplicity analysis was from 20 ns to 120 ns. The measured SDT (Single, double and triple) from conventional multiplicity counting method were shown in Table I. Because the yields of the generator were unstable in about several percent fluctuation, all the results were normalized to 35k cps based on the measured effective alpha count rates when doing active interrogation.

TABLE I
Measured SDT with conventional multiplicity analysis

| | S/CPS | D/cps | T/cps |
|---|---|---|---|
| empty | 1.415E4 | 108.6 | 0.506 |
| container | 1.575E4 | 120.9 | 0.708 |
| Fe | 1.490E4 | 114.9 | 0.608 |
| Pb | 1.612E4 | 133.0 | 0.722 |
| HEU | 1.630E4 | 206.8 | 9.523 |

The measured SDT (Single, double and triple) from gating active multiplicity counting method were shown in Table II. The S values

TABLE II
Measured SDT with gating active multiplicity analysis

| | S/CPS | D/cps | T/cps |
|---|---|---|---|
| empty | 109.9 | 0.70 | 0 |
| container | 307.9 | 2.19 | 0.010 |
| Fe | 331.4 | 2.36 | 0.017 |
| Pb | 413.6 | 3.53 | 0.019 |
| HEU | 696.1 | 39.44 | 3.841 |

From Table I and Table II, it indicated that the S rates were suppressed by about 25 ~50 times. The ratio of D/S and T/S for HEU sample were increased by about 4.5 times and 9.5 times respectively. In other words, the alpha gating FNMC method made the random or non-correlated neutron signal noise from the generator source totally cleared, and substantially promoted the D and T values sensitivity for the HEU mass attributes.

# V. CONCLUSIONS

The active fast neutron multiplicity counting (AFNMC) apparatus was constructed. It consisted of an array with 36 pieces of liquid scintillator detectors, multi-modules 500M14bit digitizers, the DT neutron generator, shielding cone and mechanical structure. The DT neutron generator was the type of alpha-associated and the alpha signal was used as gating signal when doing AFNMC assay.

The experiments were performed with iron, lead, HEU metal in standard container for technical verification of this method.

The SDT values from both conventional and gating AFNMC were obtained for comparison. The experimental results indicated this method dramatically reduced the random or non-correlated neutron signal noise and substantially promoted the D and T values sensitivity when the alpha signal gating was enabled.

This research demonstrated a promising application for HEU mass attributes assaying in the fields of nuclear material assay and verification. Further work will be taking on such as the algorithm for HEU mass resolution, cross-talk correction, multiplication correction in the future.

## References

[1] Daren Norman, Seth McConchie, Mark E. Abhold, Martin Morgan-Reading, Highly Enriched Uranium (HEU) Detection Options, Los Alamos Nat. Lab., Los Alamos, NM, USA, Tech. Rep. LA-UR-14-21979, 2014.
[2] J. Knowles, E. Brubaker, S. McConchie, M. Williamson, Uranium Mass Attribute System (UMAS) Study: Evaluation of Options Against the Arms Control Evaluation Criteria, Pantex Plant and Y-12 National Security Complex, USA, Tech. Rep. Y/PM-20-005, 2020, DOI:10.2172/1608124.
[3] D. G. Langner, J. E. Stewart, M. M. Pickrell, M. S. Krick, N. Ensslin, and W. C. Harker, “Application guide to neutron multiplicity counting,” Los Alamos Nat. Lab., Los Alamos, NM, USA, Tech. Rep. LA-13422-M, 1998, doi: 10.2172/1679.
[4] Menlove H O, “Description and operation manual for the active well coincidence counter”, Los Alamos Nat. Lab., Los Alamos, NM, USA, Tech. Rep. LA-7823-M, 1979.
[5] Elhakim, El Gammalw. I. Zidane. "A proposed semi-empirical method for 235U mass calibration of the active-well neutron coincidence counter." Nuclear Instruments and Methods in Physics Research A, 565 (2006) 731–741.
[6] Ferrari, Francesca , and P. Peerani. "Performance of an active well coincidence counter for HEU samples." Radiation Measurements, 45.9(2010): 1034-1043.
[7] W.H. Geist, L.A. Carrillo, N. Ensslin, K. Ianakiev, D.R. Mayo, M.C. Miller , “Evaluation of a fast neutron coincidence counter for the measurements of uranium samples”, Nuclear Instruments and Methods in Physics Research A, 470 (2001): 590–599.
[8] Hao Zhou, Hongtao Lin, Guorong Liu, et al. “A neutron multiplicity analysis method for uranium samples with liquid scintillators”, Nuclear Nuclear Instruments and Methods in Physics Research A, 797(2015): 70–76
[9] J.L. Dolan, M.J.Marcath, M.Flaska, et al. "Active-interrogation measurements of fast neutrons from induced fission in low-enriched uranium." Nuclear Instruments & Methods in Physics Research A, 738.feb.(2014): 99-105.
[10] Di, Fulvio A. , et al. "Fast-neutron multiplicity counter for active measurements of uranium oxide certified material." Nuclear Instruments and Methods in Physics Research A, 907(2018): 248-257.
[11] Goddard, B. , et al. "Evaluation of Am-Li Neutron Spectra Data for Active Well Type Neutron Multiplicity Measurements of Uranium." Nuclear Instruments & Methods in Physics Research A, 830(2016): 256-264.
[12] Mihalczo J, Pare V, Valentine T, “Nuclear weapons identification system”, IEEE Nuclear Science Symposium & Medical Imaging Conference (1996), 1: 44-45, DOI: 10.1109/nssmic.1996.590888
[13] Mattingly, J. K. , et al. "Physical and mathematical description of Nuclear Weapons Identification System (NWIS) signatures." Oak Ridge Y-12 Plant, Oak Ridge, Tennessee, Tech. Rep. Y/LB-15946-R1, 1997.
[14] Mihalczo J , Mullens J A , Mattingly J ,et al. "Physical description of nuclear materials identification system (NMIS) signatures." Nuclear Instruments & Methods in Physics Research A, 450(2000): 531-555.
[15] Mihalczo J T , Mattingly J K , Neal J S ,et al. "NMIS plus gamma spectroscopy for attributes of HEU, PU and HE detection." Nuclear Inst & Methods in Physics Research B, 213.Jan(2004):378-384.
[16] Hausladen P A , Bingham P R , Neal J S ,et al. "Portable fast-neutron radiography with the nuclear materials identification system for fissile material transfers." Nuclear Instruments & Methods in Physics Research B, 261.1-2(2007):387-390.
[17] Hausladen, P. A. , J. S. Neal , and J. T. Mihalczo . "An alpha particle detector for a portable neutron generator for the Nuclear Materials Identification System (NMIS)." Nuclear Inst. and Methods in Physics Research B, 241.1-4(2005): 835-838.
[18] Canion, Bonnie , S. Mcconchie , and S. Landsberger . "Point Kinetics Framework for Characterizing Prompt Neutron and Photon Signatures From Tagged Neutron Interrogation." IEEE Transactions on Nuclear Science, 64.7(2017): 1761-1768.
[19] Tweardy, Matthew C. , S. Mcconchie , and J. P. Hayward . "A Point Kinetics Model for Estimating Neutron Multiplication of Bare Uranium Metal in Tagged Neutron Measurements." IEEE Transactions on Nuclear Science, PP.7(2017):1-1.
[20] Mattingly J , Valentine T , Mihalczo J ,et al. "ENRICHMENT AND URANIUM MASS FROM NMIS FOR HEU METAL." (2000).
[21] Crye, Jason Michael, "ENRICHMENT DETERMINATION OF URANIUM METAL IN SHIELDED CONFIGURATIONS WITHOUT CALIBRATION STANDARDS. " PhD diss., University of Tennessee, 2013.
[22] T. A. Wellington, B. A. Palles, J. A. Mullens, et al. "Recent Fast Neutron Imaging Measurements with the Fieldable Nuclear Materials Identification System." Physics Procedia, 66(2015): 432-438.
[23] Ligao CHEN, Xiaobo LIU, Jian GONG, et al. Neutron multiplicity counter design and calibration[J]. Journal of Tsinghua University (Science and Technology), 2014, 54(2): 159-163
[24] Li-Gao, Chen , et al. "Variance analysis for passive neutron multiplicity counting." Nuclear Science and Techniques, 26.2(2015):54-58.
[25] Xiaobo Liu, Ligao Chen . "A two-parameter iterative approach of multiplication correction for assaying plutonium metal parts with neutron multiplicity counting." Nuclear Instruments and Methods in Physics Research A, 1016(2021):165779
[26] Xiaobo Liu, Jiansheng Li, Yu Jin, “FAST NEUTRON MULTIPLICITY COUNTING FOR HIGH MASS PLUTONIUM ASSAY”, The 9th International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications, ANIMMA, Valencia, France, 2025.
[27] Jian Tang, Pu Zheng, Meng Liu, *et al.*, Zhang. The design and sealed operation of a portable alpha-tagging neutron generator[J]. Journal of Instrumentation, 2025, 20(07): 18.
[28] J.-X. Chen et al., “Development of the ZnO:Ga nanorod arrays as an alpha particle scintillation screen for the associated particle neutron generator”, Appl. Phys. Lett. 120 (2022), 193502.