A Design Study of a High-Count-Rate Energy-Loss Detector

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Abstract

The High Intensity heavy-ion Accelerator Facility (HIAF) under construction is equipped with an advanced radioactive beam line HFRS, which will provide new opportunities for high-energy radioactive nuclear beam physics research in China upon completion. The characteristic of HFRS is its extremely high beam intensity (primary beam intensity of 1 × 10^{11} ppp), which imposes very high counting rate requirements on energy loss detectors used for particle identification. Traditional energy loss detectors generally adopt a signal processing chain consisting of charge-sensitive preamplifier, shaping amplifier, and ADC. This approach suffers from issues such as slow electronic response speed, poor flexibility, and difficulty in handling severe signal pile-up at high counting rates. We propose a new energy loss detector scheme suitable for high counting rates: using a radiation-hard multi-sampling ionization chamber as the energy loss detector, optimizing its structure and readout method to improve detector response speed, employing a fast charge-sensitive preamplifier for initial amplification of the detector signal, followed by direct waveform digitization and subsequent digital algorithm processing. The scheme was validated and tested using both radioactive sources and beam. When tested with a 3-component α source, the acquired waveforms were processed using digital shaping algorithms, achieving an energy resolution (FWHM) of 1.31%. In tests with a 300 MeV/u 56Fe beam provided by RIBLL2, the fast charge-sensitive preamplifier with a time constant $f = 2$ showed no significant pile-up at counting rates approaching 1 MHz.

Full Text

Abstract

The High-Intensity Heavy-Ion Accelerator Facility (HIAF) currently under construction is equipped with an advanced radioactive beam line called HFRS, which will provide new opportunities for high-energy radioactive nuclear beam physics research in China. HFRS is characterized by extremely high beam intensity (primary beam intensity of 1×10^{11} ppp), which imposes very stringent requirements on energy loss detectors used for particle identification. Traditional energy loss detectors typically employ a signal processing chain consisting of a charge-sensitive preamplifier, main amplifier, and ADC. This approach suffers from slow electronic response, poor flexibility, and difficulty in handling severe signal pile-up at high count rates. We propose a new energy loss detector scheme suitable for high count rates: using a radiation-hard multiple sampling ionization chamber as the energy loss detector, optimizing the structure and readout method to improve detector response speed, employing a fast charge-sensitive preamplifier for initial signal amplification, directly acquiring waveforms with a waveform digitizer, and performing subsequent digital algorithm processing. Verification tests were conducted using both radioactive sources and beam. When tested with a three-component α source, digital shaping algorithms applied to the acquired waveforms achieved an energy resolution (FWHM) of 1.31%. In beam tests using 300 MeV/u ^{56}Fe provided by RIBLL2, a fast charge-sensitive preamplifier with time constant τ_f $= 2$ s showed no significant pile-up at count rates approaching 1 MHz.

Keywords: HFRS; ionization chamber; high count rate; fast charge-sensitive preamplifier; waveform sampling; digital shaping algorithm

1. Introduction

Since its inception in the 1980s, radioactive nuclear beam physics has been one of the most dynamic frontier research areas in nuclear science. Major nuclear physics laboratories worldwide have used radioactive beam facilities to achieve significant progress in exploring the limits of nuclear existence, exotic structures of weakly bound nuclei, evolution of shell structure, and studies of exotic nuclear reaction mechanisms, greatly advancing the field of nuclear physics [1-6]. However, as research targets increasingly move away from the β-stability line, the yields of radioactive secondary beams decrease rapidly, and existing facilities gradually fail to meet the demands of nuclear physics research. Consequently, major scientific powers have upgraded or built new large-scale heavy-ion comprehensive research facilities, such as FAIR in Germany [7], SPIRAL2 in France [8], FRIB in the United States [9], and HIAF in China [10]. These facilities share the common feature of having advanced new-generation projectile-fragmentation-type radioactive beam lines with typical beam intensities reaching 10^{11} ppp (particles per period), greatly expanding the scope of nuclear physics research. With these facilities, researchers anticipate discovering more exciting new phenomena and physics.

The HIAF facility under construction is equipped with a high-energy radioactive beam line called HFRS [11], featuring high incident beam energy (^{238}U^{34+} energy of 800 AMeV) and high intensity (primary beam intensity of 1×10^{11} ppp). HFRS employs the commonly used B -TOF-ΔE method for particle identification in projectile-fragmentation secondary beam facilities. By adjusting the magnetic rigidity B of the beam line, preliminary selection of fragment particles can be performed, and then by measuring the time-of-flight (TOF) and energy loss (ΔE) of particles, different particles can be identified. The key to achieving atomic number Z identification is the energy loss detector. To meet the requirements of various nuclear physics experiments on HFRS, the energy loss detector must be able to operate stably for long periods when the secondary beam intensity exceeds 1 MHz, and achieve good particle identification for particles with $Z \leq 92$. This imposes extremely stringent requirements on both the count rate performance and energy resolution performance of the energy loss detector.

Commonly used energy loss detectors in nuclear physics experiments include semiconductor detectors (mainly silicon detectors), scintillator detectors, and gas ionization chambers. Semiconductor detectors are generally limited in size and cannot be made with large areas. Scintillator detectors have difficulty meeting the energy resolution requirements for particle identification, and both have poor radiation resistance, with performance degrading rapidly under intense radiation [12]. Gas ionization chambers, due to their strong radiation resistance, low cost, and lack of size limitations, are very suitable for applications requiring large detector sensitive areas or high radiation resistance. In particular, the Multiple Sampling Ionization Chamber (MUSIC) can significantly improve the energy resolution of gas ionization chambers through multiple sampling, gradually becoming the best energy loss measurement detector in medium and high-energy particle detection, and has been successfully applied in many laboratories [13-15].

The traditional MUSIC detector typically employs the conventional technical scheme of charge-sensitive preamplifier, main amplifier, and ADC in sequence. However, due to limitations from detector structure, electronics, and data acquisition system dead time, conventional MUSIC cannot operate normally at high count rates and fails to meet HFRS requirements. Therefore, there is an urgent need to develop new MUSIC detection technology that can withstand high count rates.

2. MUSIC Detection Technology and Count Rate

A MUSIC detector typically consists of a cathode, grid, and multiple anodes. The region from cathode to grid is called the drift region, and the region from grid to anode is called the collection region. As shown in [Figure 1: see original paper], when the detector operates, beam particles incident on the detector sensitive volume ionize the working gas to produce electron-ion pairs. Under the electric field, electrons and ions drift toward the anode and cathode respectively, simultaneously inducing current signals on the readout electrodes. However, when beam particles enter at different positions, the drift distance of electrons varies, leading to different durations of induced current signals and making the signal amplitude dependent on the beam incidence position. MUSIC solves this problem by using a grid to isolate the electric field. Only when electrons pass through the grid can signals be induced on the anode. At this point, the fixed grid-anode spacing makes the duration of induced current signals basically consistent, eliminating the correlation between signal amplitude and beam incidence position. Additionally, ions drift toward the cathode and are collected, and they do not pass through the grid. Therefore, the grid also shields the interference of ions on anode signals. This is one reason why MUSIC detectors have good energy resolution. However, due to the shielding effect of the grid, electrons do not produce induced signals on the anode before drifting past the grid. This is dead time caused by the detector structure, generally on the microsecond scale, which is one factor affecting the count rate of MUSIC detectors.

Factors affecting the energy resolution of MUSIC detectors include: statistical fluctuations of ionized electron-ion pairs (intrinsic resolution), electron collection efficiency, detector and electronic noise, and ADC channel resolution. Among these, noise is the most significant factor affecting energy resolution besides statistical fluctuations. Suppressing noise and improving signal-to-noise ratio are necessary approaches to achieving good energy resolution. Generally, low-noise, high-gain charge-sensitive preamplifiers (referred to as preamps) are selected for initial signal amplification. To reduce ballistic deficit and obtain better energy resolution, preamps with longer decay times are typically chosen, resulting in longer falling edges of preamp signals. Then, to further improve signal-to-noise ratio, the preamp signal is usually fed into a main amplifier for filtering, shaping, and amplification, with shaping times of the main amplifier also generally on the microsecond scale. When the count rate increases, signal pile-up phenomena easily occur, affecting the energy resolution of the detector. Therefore, slow electronic response speed is another factor affecting the count rate of MUSIC detectors.

Finally, the output signal of the main amplifier is sent to an ADC for amplitude acquisition, which typically requires an external trigger signal for event-by-event data acquisition. The trigger signal can be selected as the time when the beam passes through the MUSIC detector, i.e., the moment of ionization t_0. Depending on the ionization position, the time for electrons to drift past the grid varies. Therefore, there is a time difference Δt between anode signal generation and the t_0 moment, and due to different ionization positions, the Δt value fluctuates on the microsecond scale. Additionally, considering that the peak of the main amplifier signal needs to be within the ADC gate signal, the width of the ADC gate signal should be set to at least several microseconds, as shown in [Figure 2: see original paper]. This is why conventional MUSIC detectors can only achieve count rates of up to a few hundred kHz.

To improve the count rate of MUSIC, international colleagues have made various efforts. Germany’ s GSI replaced the working gas of MUSIC with CF_4, which has faster electron drift speed, to reduce the detector’ s inherent dead time, and by optimizing the shaping times of the charge-sensitive preamplifier and main amplifier, increased the count rate to 200 kHz [16]. Japan’s RIKEN changed the electrodes of MUSIC to conductive thin-film planes and tilted the electrodes at an angle to the beam. Since there is no grid, ionized electrons produce induced signals on the anode from the beginning of drift, thus eliminating the detector’ s inherent dead time. Then, using bipolar shaping main amplifiers to eliminate the influence of ions, the count rate could be increased to 1 MHz [17]. However, this scheme has two drawbacks: first, the detector structure sacrifices energy resolution to improve count rate; second, the subsequent electronic response speed remains slow, making signal pile-up likely. It only uses pile-up rejection to maintain good energy resolution at higher count rates, but in fact, this comes at the cost of reducing the effective count rate. When the count rate is 320 kHz, pile-up events account for 40%, and when the count rate is 1 MHz, pile-up events reach 75% [17]. The pile-up rejection approach largely wastes the beam.

3. High Count Rate Scheme

The main factors affecting the count rate of energy loss detectors can be summarized as: the grid structure of MUSIC leads to slow detector response, the large time constant of the charge preamplifier leads to long signal falling edges and easy pile-up, and the external trigger mode requires setting ADC gate signals several microseconds wide for coincidence acquisition, resulting in large trigger dead time. In response to these issues, we propose a high count rate energy loss detector scheme: (1) optimize the MUSIC detector structure to reduce signal rise time; (2) use a fast charge-sensitive preamplifier to shorten signal falling edge time; (3) abandon the use of main amplifiers and employ self-trigger mode using waveform digitization technology to directly sample the preamplifier output waveform; (4) finally, perform subsequent algorithmic processing.

3.1 Detector Structure Optimization

In terms of detector structure: reducing the collection region spacing can collect electrons faster and reduce the rise time of preamplifier signals. As shown in [Figure 3: see original paper], as the collection region spacing continuously decreases, electrons can be collected faster and the signal rise time shortens. However, reducing the collection region spacing also represents increased difficulty in detector fabrication and degraded shielding effectiveness of the grid on the drift region electric field. Therefore, a balance can be struck between detector fabrication technology and grid electric field shielding by minimizing the collection region spacing of MUSIC as much as possible.

3.2 Fast Charge-Sensitive Preamplifier

The fast charge-sensitive preamplifier used in the high count rate scheme is shown in [Figure 4a: see original paper]. It is a low-noise, high-gain fast charge-sensitive preamplifier developed by the Institute of Modern Physics, Chinese Academy of Sciences specifically for MUSIC detectors. The main advantage is the addition of a JFET (field-effect transistor) at the signal input terminal, which has relatively large input resistance, relatively small input bias current, and low current noise. Additionally, a filter circuit composed of resistors and capacitors was added at the preamplifier power supply, and measures such as large-area copper plating (but not complete plating) on the PCB to provide low-impedance return paths for noise were implemented to obtain a low-noise, high-gain fast charge preamplifier. Its feedback capacitance C_f and discharge resistance R_f product—time constant $\tau f = R${fC}f—is relatively small, making the discharge of the preamplifier feedback capacitance through the resistor faster, thus narrowing the signal falling edge width and reducing the probability of pile-up. As shown in the waveforms of [Figure 4b: see original paper], it is clear that the smaller the time constant τ_f of the preamplifier, the faster the signal falling edge can return to the baseline. The drawback is that it introduces greater ballistic deficit. When the shape of the induced current input to the preamplifier differs, ballistic deficit affects energy resolution. To solve this problem, cathode readout can be added to MUSIC, and ballistic deficit can be corrected using a cathode-anode two-dimensional energy spectrum correlation plot [18].

3.3 Waveform Digitization

In recent years, with the rapid development of high-speed sampling ADC and FPGA technology, waveform digitization technology has been increasingly widely applied in nuclear physics experiments [19]. Signal waveforms carry the most original and detailed information from the detector, and by analyzing waveforms, various desired information can be extracted.

The high count rate scheme uses waveform digitization technology to directly sample the preamplifier output waveform, abandoning the use of main amplifiers. Its advantages include: digitized signals are no longer disturbed by noise in subsequent circuits; waveform digitization technology supports self-triggered waveform acquisition, which can eliminate the dead time caused by ADC gate width shown in [Figure 2: see original paper]; after acquiring waveform information, even if pile-up occurs, algorithms can be developed using waveform information for pile-up correction. This correction can be performed event-by-event without requiring pile-up rejection, greatly improving beam utilization efficiency.

3.4 Digital Shaping Algorithm

Data after waveform digitization can be processed using digital shaping algorithms. Digital shaping algorithms have the advantages of being unaffected by analog circuit noise, enabling filters that are difficult to implement with analog components, and having easily adjustable parameters. Examples include the triangular shaping algorithm with good count rate performance, the trapezoidal shaping algorithm that can compensate for ballistic deficit [20], and the HYPER algorithm for processing pile-up signals [21]. Various algorithms have their characteristics and applicability. Below we introduce the more general main amplifier circuit CRpz-RC digital algorithm.

3.4.1 CRpz-RC Circuit Digitization As shown in [Figure 5: see original paper], the output voltage V_{PZ} of the pole-zero cancellation circuit can be regarded as the voltage division of V_{CSA} on resistor R_1, with a division ratio of Z_C//R_{PZ}/(Z_C//R_{PZ} + R_1), where Z_C = 1/(SC_1) is the S-domain model of the capacitor, and the symbol "//" represents parallel connection. This voltage division ratio is the transfer function H(S) of the pole-zero cancellation circuit. Letting τ_1 = R_{PZ} · C_1 and τ_2 = (R_{PZ}//R_1) · C_1, after rearrangement we have:

$$H(S) = \frac{S + \frac{1}{\tau_1}}{S + \frac{1}{\tau_2}}$$

The preamplifier output signal' s falling edge is described by a negative exponential function, which in the S-domain can be expressed as: V_{CSA}(S) = Q_{max}/(S + 1/τ*f). From the voltage division relationship, the pole-zero cancellation output V*{PZ}(S) satisfies:

$$V_{PZ}(S) = \frac{\tau_2(\tau_f - \tau_1)}{\tau_1(\tau_f - \tau_2)} \cdot \frac{Q_{\max}}{S + \frac{1}{\tau_1}} + \frac{\tau_f(\tau_2 - \tau_1)}{\tau_1(\tau_f - \tau_2)} \cdot \frac{Q_{\max}}{S + \frac{1}{\tau_f}}$$

When R_{PZ} → +∞, it becomes a CR differential circuit, and V_{PZ}(t) becomes:

$$V_{PZ}(t) = \frac{\tau_f - \tau_2}{\tau_f - \tau_2} Q_{\max} e^{-t/\tau_f}$$

When τ_1 = τ*f, pole-zero cancellation occurs, and V*{PZ}(t) becomes:

$$V_{PZ}(t) = \frac{\tau_2}{\tau_1} Q_{\max} e^{-t/\tau_1}$$

According to Kirchhoff' s Current Law (KCL, charge conservation), the output voltage V_{PZ} of the pole-zero cancellation circuit satisfies:

$$\frac{V_{CSA} - V_{PZ}}{R_{PZ}} + C_1 \cdot \frac{d(V_{CSA} - V_{PZ})}{dt} = \frac{V_{PZ}}{R_1}$$

After sampling with sampling interval dt = Δt, the input V_{CSA} = x[n] and output V_{PZ} = y[n] become discrete sequences. Substituting into the above equation and rearranging yields the recurrence relation [22]:

$$y[n] = \frac{(1+k_1+k_2)\cdot x[n] - (1+2k_1+k_2)\cdot x[n-1] + k_1\cdot x[n-2] + (1+k_1)\cdot y[n-1] - k_1\cdot y[n-2]}{1+k_1}$$

where: k_1 = Δt/(R_{PZ} • C_1), k_2 = Δt/(R_1 • C_1); by adjusting k_1 to make τ_1 = τ_f, pole-zero cancellation is achieved, and by adjusting k_2, differentiation is achieved.

Similarly, according to KCL, establishing the differential equation for the RC low-pass filter circuit yields the input-output recurrence relation [23]:

$$y[n] = (1-k_3)\cdot x[n] + k_3\cdot y[n-1], \quad n \geq 1$$

$$y[n] = x[n] = 0, \quad n \leq 0$$

where x[n] and y[n] are the input and output sequences of the RC circuit respectively, and k_3 = R_2 • C_2/(R_2 • C_2 + Δt). Adjusting k_3 selects the filter shaping parameters.

The preamplifier signal can implement the CRpz-RC algorithm through iterative processing using equations (8) and (9).

4. Verification Tests

The scheme was tested using the Multiple Sampling Ionization Chamber (MUSIC) on the Lanzhou Radioactive Ion Beam Line (RIBLL2) [15]. The MUSIC on RIBLL2 uses mylar films as entrance and exit windows. The drift region height between cathode and grid is 90 mm. To shorten the signal rise time, the collection region height between grid and anode was optimized to 4 mm, with grid wire radius of 0.1 mm and wire spacing of 2 mm. The sensitive area is 380 mm long, divided into 8 equally spaced anodes, each 45 mm, equivalent to 8 small ionization chambers in series. In medium and high-energy radioactive beam experiments, the anode-segmented MUSIC can be considered to have essentially the same energy loss rate between each anode through multiple small-distance sampling, meaning each anode signal is independently sampled. The uncertainty of single sampling can then be reduced through multiple sampling to improve energy resolution [24]. If the energy resolution of a single measurement is σ_0 and the number of samplings is N, the final energy resolution is $\sigma = \sigma_0/\sqrt{N}$. In practice, anodes can be paralleled in pairs into 4 channels as needed to increase signal amplitude.

The specific connection test diagram is shown in [Figure 6: see original paper]. The MUSIC readout anodes are connected to the fast charge preamplifier (PreAmp) for initial signal amplification, and then the waveform signals are sent to a waveform digitizer for sampling. To match interfaces, the charge preamplifier output PCIe interface is converted to LEMO output via an adapter board.

4.1 Energy Resolution Test

The MUSIC was tested using a three-component α source (^{239}Pu at 5.16 MeV, ^{241}Am at 5.48 MeV, and ^{244}Cm at 5.80 MeV). The α source was attached to a collimator on the cathode and emitted toward the first anode sampling unit after collimation. The working gas was P10 (90% Ar + 10% CH_4) in flow mode, operating MUSIC at atmospheric pressure. Anode and cathode signals were extracted through the fast charge preamplifier. The cathode was biased at -2940 V, grid at -166 V, and anodes were grounded.

A Tektronix MSO 5204B oscilloscope was used for waveform sampling, which offers the advantages of high sampling rate and adjustable dynamic range. The fast charge preamplifier signal was connected to the oscilloscope for data acquisition. The acquired waveforms were processed using the CR-RC^4 shaping algorithm simulated from the main amplifier circuit: the average of the first 1000 data points of the preamplifier signal was taken as the baseline, and the entire waveform data was subtracted by the baseline to return the baseline to zero channel. Parameters k_1, k_2, and k_3 were adjusted to make the shaping parameters of CRpz and RC^4 consistent, achieving good filtering effects. As shown in [Figure 5: see original paper], from left to right are the original preamplifier signal, CRpz differential high-pass filtered and pole-zero cancelled signal, and RC^4 integrated low-pass filtered and shaped signal. After shaping, the peak of the signal was selected for spectrum filling. The anode energy spectrum result is shown in [Figure 7a: see original paper], and the two-dimensional correlated energy spectrum of anode and cathode is shown in [Figure 7b: see original paper].

After using the CRpz-RC^4 digital shaping algorithm, the energy resolution for the α source ^{241}Am is 1.31% (FWHM) for the anode, meaning the energy resolution of a single anode unit can reach 1.31% (FWHM). Under ideal conditions, according to $\sigma = \sigma_0/\sqrt{N}$, the best energy resolution achievable by an MUSIC composed of 8 small-unit ionization chambers in series can reach about 0.5%, meeting the needs of most nuclear physics experiments.

4.2 Count Rate Test

To verify the performance of the overall scheme at high count rates and compare differences in time constants, MUSIC was tested using a 300 MeV/u ^{56}Fe beam provided by RIBLL2. The detector operating conditions were identical to the radioactive source test. The anodes were grounded and signals were extracted. To increase signal amplitude and improve signal-to-noise ratio, the 8 anode units were paralleled in pairs into 4 channels, with each channel having a beam deposition energy of 26.3 MeV. Signals from the 4 channels were amplified by the preamplifier and sent to the DT5740 waveform digitizer for waveform acquisition.

As shown in [Figure 8: see original paper], from top to bottom are the preamplifier output waveforms with time constants of 100 s, 20 s, and 2 s. It can be seen that channels with smaller time constants are less prone to signal pile-up. The fast charge preamplifier channel with τ_f = 2 s showed no obvious pile-up and stable baseline even at count rates approaching 1 MHz. In contrast, the 100 s and 20 s channels experienced severe pile-up and quickly exceeded the ADC range. The test results demonstrate that the count rate capability of the τ_f = 2 s channel has been significantly improved.

4.3 Discussion of Test Results

Achieving both high energy resolution and high count rate is difficult. To meet the requirements of the HFRS facility, after extensive attempts, we propose a high count rate energy loss detector scheme suitable for the HFRS beam line. The detector and fast charge preamplifier used in the scheme were introduced, and overall verification tests with radioactive sources and beam were conducted. The test results show that while maintaining energy resolution, the count rate capability has been significantly improved. In beam tests, the fast charge preamplifier showed no obvious pile-up at count rates approaching 1 MHz. After waveform sampling and processing with the MSO 5204B oscilloscope, the energy resolution (FWHM) of a single anode unit can reach 1.31%, meeting the needs of most nuclear physics experiments. Therefore, the high count rate energy loss detector scheme is feasible. The next step will be to develop a triggerless DAQ system to cooperate with self-triggered waveform sampling and achieve data synchronization and alignment between different detector systems.

From the radioactive source and beam test results, the scheme using fast charge preamplifier plus waveform sampling is feasible, achieving good results in both energy resolution and count rate. When using the fast charge preamplifier, its tolerable count rate is significantly better than conventional preamplifiers, and there is no obvious difference in energy resolution compared to conventional schemes. In fact, selecting a charge preamplifier with a large time constant in experiments is to reduce preamplifier capacitor discharge, ensure charge collection, and reduce ballistic deficit. Using a fast charge preamplifier would cause ballistic deficit and degrade energy resolution. However, for the multiple sampling ionization chamber MUSIC, as shown in [Figure 1: see original paper], due to the added grid shielding, only ionized electrons that pass through the grid produce induced current on the anode. The grid-to-anode spacing is small and fixed, making the induced current duration from the beam very short and consistent, with uniform induced current shape. When using a fast charge preamplifier, capacitor discharge is relatively small, discharge time is the same, and the total discharge proportion is the same (proportion: e^(-t_w/τ_f), where t_w is the induced current duration). At this point, the pulse amplitude decreases linearly. Moreover, when the input induced current shape differs, ballistic deficit can be corrected through the anode-cathode correlation energy spectrum plot. Therefore, the fast charge preamplifier is feasible in the MUSIC experimental environment, significantly improving count rate without affecting energy resolution. Additionally, when the fast charge preamplifier is combined with waveform sampling and digital algorithms, it greatly reduces the complexity of the detection system.

References

[1] URREGO-BLANCO J P, BINGHAM C R, BRANDT B V D, et al. Nuclear Instruments Methods in Physics Research, 2007, 261(1-2): 1112. DOI: 10.1016/j.nimb.2007.04.257.

[2] SORLIN O, PORQUET M G. Progress in Particle Nuclear Physics, 2008, 61(2). DOI: 10.1016/j.ppnp.2008.05.001.

[3] BAUMANN T, SPYROU A, THOENNESSEN M. Reports on Progress in Physics, 2012, 75(3): 036301. DOI: 10.1088/0034-4885/75/3/036301.

[4] CASTEN R, SHERRILL B. Progress in Particle and Nuclear Physics, 2000, 45: S171. DOI: 10.1016/S0146-6410(00)00108-3.

[5] TANIHATA I, SAVAJOLS H, KANUNGO R. Progress in Particle and Nuclear Physics, 2013, 68: 215. DOI: 10.1016/j.ppnp.2012.07.001.

[6] YE YanLin, YANG XiaoFei, LIU Yang, HAN JiaXing. SCIENTIA SINICA Physica, 2020, 50(11) (in Chinese) DOI: 10.1360/SSPMA- (叶沿林、杨晓菲、刘洋、韩家兴. 中国科学：物理学、力学、天文学, 2020, 50(11): 10.)

[7] SPILLER P, FRANCHETTI G. Nuclear Inst Methods in Physics Research A, 2006, 561(2): 305. DOI: 10.1016/j.nima.2006.01.043.

[8] GALES S. Progress in Particle Nuclear Physics, 2006, 59(1): 22. DOI: 10.1016/j.ppnp.2006.12.021.

[9] THOENNESSEN M. Nuclear Physics, 2010, 834(1-4): 688c. DOI: 10.1016/j.nuclphysa.2010.01.125.

[10] YANG J C, XIA J W, XIAO G Q, et al. Nuclear Instruments and Methods in Physics Research Section B Beam Interactions with Materials and Atoms, 2013, 317: 263. DOI: 10.1016/j.nimb.2013.08.046.

[11] Nucl Instr and Meth B, 2020, 469: 1. DOI: 10.1016/j.nimb.2020.02.026.

[12] KRANER H W. Nuclear Instruments Methods in Physics Research, 1984, 225(3): 615. DOI: 10.1016/0167-5087(84)90114-5.

[13] CHRISTIE W B, ROMERO J L, BRADY F P, et al. Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers

Detectors and Associated Equipment, 1987, 255(3): 466. DOI: 10.1016/0168-9002(87)91213-7.

[14] BAUER G, BIESER F, BRADY F P, et al. Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment, 1997, 386(2-3): 249. DOI: 10.1016/S0168-9002(96)00883-2.

[15] ZHANG X H, TANG S W, MA P, et al. Nuclear Instruments Methods in Physics Research, 2015, 795(sep.21): 389. DOI: 10.1016/j.nima.2015.20004000600080001000012000014000.

[16] STOLZ A, FAESTERMANN T, KOERNER H J, et al. GSI Report, 1998, 33.

[17] KIMURA K, IZUMIKAWA T, KOYAMA R, et al. Nuclear Inst Methods in Physics Research A, 2005, 538(1-3): 608. DOI: 10.1016/j.nima.2004.08.100.

[18] LIU J, JIANG H, CUI Z, et al. Nucl Instr and Meth A, 2021, 1014: 165751. DOI: 10.1016/j.nima.2021.165751.

[19] ZHANG Honghui, YANG Haibo, LI Liangrong, et al. Nuclear Physics Review, 2023, 40(86-91) (in Chinese) DOI: 10.11804/NuclPhysRev.4 (张洪辉, 杨海波, 李良荣, 等. 原子核物理评论, 2023, 40(86-91).)

[20] VALENTIN, T., JORDANOV. Nucl Instr and Meth A, 2003, 505(1-2): 347. DOI: 10.1016/S0168-9002(03)01094-5.

[21] LIU J, LI H, WANG Y, et al. Real time digital implementation of the high-yield-pileup-event-recover (hyper) method[C/OL]//IEEE Nuclear Science Symposium Conference Record. 2008. DOI: 10.1109/NSSMIC.2007.4437051.

[22] JIAN-BIN Z, XU H, REN-BO W, et al. 核技术: 英文版, 2014(1): 5. DOI: 10.13538/j.1001-8042/nst.25.010403.

[23] ZHANG H Q, LI Z D, TANG B, et al. 核技术: 英文版, 2019, 30(7): 5. DOI: 10.1007/s41365-019-0638-7.

[24] TANG Shuwen, DUANG Limin, SUN Zhiyu, et al. Nuclear Physics Review, 2012, 29(1) (in Chinese) DOI: 10.11804/NuclPhysRev.29.01 (唐述文, 段利敏, 孙志宇, 等. 原子核物理评论, 2012, 29(1): 5.)

Note: Figure translations are in progress. See original paper for figures.