Design and offline test of dual-MCP time-of-flight detector with forward-backward secondary electron collection for isochronous mass spectrometry at HIAF-SRing

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Abstract

Isochronous mass spectrometry (IMS) conducted with a heavy-ion storage ring has been proven to be a powerful tool for precision mass measurements of short-lived nuclei in the past decades. However, the achieved mass precision in the IMS experiments strongly depends on the efficiency of the detector. This leads to a poorer mass resolving power for light nuclei with smaller proton numbers. To overcome this limitation, we developed a dual-microchannel plate (MCP) time-of-flight (TOF) detector capable of collecting secondary electrons (SEs) emitted in both forward and backward directions when ions pass through a thin carbon foil. Meanwhile, the time resolution was improved by increasing the electric field strength E, in which the homogeneity was also optimized through varying the potential of equalizing ring. From offline tests with an α-source, a total detection efficiency of 94% and a best time resolution of 29.62 ± 0.80 ps at E = 300 V/mm were achieved. These results show a substantial efficiency gain for light ions and meet the stringent timing performance required for B -defined IMS at HIAF-SRing.

Full Text

Design and Offline Test of a Dual-MCP Time-of-Flight Detector with Forward-Backward Secondary Electron Collection for Isochronous Mass Spectrometry at HIAF-SRing

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Abstract: Isochronous mass spectrometry (IMS) conducted with a heavy-ion storage ring has proven to be a powerful tool for precision mass measurements of short-lived nuclei over the past decades. However, the achieved mass precision in IMS experiments strongly depends on detector efficiency, which leads to poorer mass resolving power for light nuclei with smaller proton numbers. To overcome this limitation, we developed a dual-microchannel plate (MCP) time-of-flight (TOF) detector capable of collecting secondary electrons (SEs) emitted in both forward and backward directions when ions pass through a thin carbon foil. The time resolution was improved by increasing the electric field strength E, whose homogeneity was also optimized by varying the potential of an equalizing ring. Offline tests with an α-source achieved a total detection efficiency of 94% and a best time resolution of 29.62 $\pm$ 0.80 ps at E = 300 V/mm. These results demonstrate a substantial efficiency gain for light ions and meet the stringent timing performance required for B -defined IMS at HIAF-SRing.

Keywords: time-of-flight detectors, isochronous mass spectrometry, storage ring

Introduction

Nuclear masses play an essential role in our understanding of nuclear structure and the origin of chemical elements in the universe. Over the past decades, IMS has proven to be a powerful tool for precision mass measurements of short-lived nuclei. Pioneered at the Experimental Storage Ring (ESR) at GSI [1], the

IMS technique has since been established at the experimental Cooler Storage Ring (CSRe) at IMP [2–9] and at the Rare Radioactive Isotopes Ring (R3) at RIKEN [10–12], yielding significant progress in nuclear structure and nuclear astrophysics research.

In an IMS experiment, a cocktail beam comprising highly-charged ions with a wide charge state (Z) distribution is generated via projectile fragmentation and/or in-flight fission and injected into the storage ring. For ions stored in the ring, the revolution times (T) exhibit a first-order dependence on the mass-to-charge ratio (m/q) and velocity (v), expressed as [13–16]:

Δ(m/q) where γ is the relativistic Lorentz factor of the stored particles and γt is the so-called transition energy of the storage ring, a characteristic ion-optical parameter defined by the magnetic lattice configuration. The mass value is determined by measuring revolution times using micro-channel plate (MCP) based time-of-flight (TOF) detectors [17–20]. For such detectors, an offline characterization using an alpha source yielded a time resolution of 180 ps (FWHM) and a detection efficiency of 54% at E = 130 V/mm [17].

Recently, an advanced variant of IMS called B -defined IMS [21, 22] was developed at CSRe, employing a pair of TOF detectors installed in the straight section of the storage ring [23, 24]. At the High Intensity Heavy-Ion Accelerator Facility (HIAF) [25, 26], a spectrometer ring (SRing) [27] is currently under construction, where B -defined IMS is also planned for implementation. Employing two TOF detectors enables simultaneous determination of ion velocities [28] and revolution times, with the supplementary velocity determination significantly enhancing the mass accuracy and resolving power of IMS. Crucially, experimental data revealed a pronounced Z dependence in the accuracy and precision of both revolution time and velocity measurements, directly correlated with the Z-dependent detection efficiency characteristics of the TOF detector. In previous IMS experiments, detector efficiency increased with atomic number Z and saturated around Z 30 when about 33 ions were simultaneously stored in the ring, reaching approximately 56% saturation efficiency for this case [17].

In B -IMS, velocity information is used to calculate the magnetic rigidity B and orbital length C, establishing a universal calibration curve for deducing masses of nuclides of interest. Low detection efficiency for low-Z ions results in inaccurate B values, thus affecting the B -C relation used to calculate masses of high-Z nuclides. This inherent correlation necessitates rigorous charge-state selection criteria. For example, as demonstrated in data analysis from a B -defined IMS mass measurement of 78Kr fragmentation, all nuclides with Z < 15—where detection efficiencies were lower than 30%—were completely excluded to avoid compromised velocity precision [6].

To overcome this limitation and significantly enhance detection capability for B -defined IMS at SRing, especially for light ions, we designed, simulated, and conducted offline tests with an α source on a modified TOF detector inspired by pioneering work at GSI [29]. The key innovation of our new detector is its dual-

collection design, which simultaneously captures secondary electrons emitted from both forward and backward sides of the carbon foil. This approach effectively doubles the usable SE yield while providing intrinsic data redundancy. Furthermore, we enhanced the electric and magnetic field strengths to improve time resolution. This paper presents the design principles, SIMION-based simulations for field optimization, and comprehensive offline test results utilizing an α-particle source, demonstrating substantial improvement in both detection efficiency and timing performance.

II. Principle and Structure

The TOF detector employed for isochronous mass measurements is a foil-MCP timing detector [19]. It consists of a 19 µg/cm^2 carbon foil and a Chevron-shaped MCP. When ions penetrate the carbon foil, SEs are emitted from the outermost layer of the foil material due to surface effects. Although SEs are generated by ionization, only those from surface atoms (typically a few nm) can overcome the surface barrier and escape from the material, meaning the properties of emitted SEs are independent of foil thickness and other conditions [30, 31]. These SEs are accelerated by an electric field and deflected by a magnetic field onto the MCP surface. The MCP consists of about 10^6–10^8 parallel channels with 5-µm diameter, with each individual channel providing a gain of 10^4–10^7 as an electron multiplier. Incident electrons are multiplied through avalanche amplification by striking the channel walls.

Finally, the electron cloud created in the microchannels is collected by an anode, generating a timing pulse that marks the timestamp of ion penetration through the TOF detector. The revolution times and velocities of all stored ions are determined by analyzing these timing signals.

The total yield nse of SE emission is proportional to the stopping power dE/dx for an individual charged particle [?]: nse = Λ ·where Λ is a constant of proportionality. Critically, both signal amplitude and detection efficiency for a given ion are positively correlated with nse, establishing nse as the key determinant of measurement sensitivity.

It is worth noting that SEs can be emitted from both sides of the foil. However, the previous TOF detector employed at CSRe only collected forward SEs, as illustrated in the inset of Fig. 1(a). This established setup results in severely constrained detection efficiency, particularly for light ions, yielding merely 15% efficiency for C, N, and O ions at about 400 MeV/u [17]. Such low efficiency critically impedes precision velocity determinations required by recently-developed B -defined IMS.

Therefore, we implemented an upgraded dual-collection design (Fig. 1(a)) that simultaneously captures forward and backward SEs. This approach enables dual timestamp measurements for each ion traversal using symmetrically positioned MCP detectors, effectively doubling the usable SE yield and providing intrinsic redundancy. Such improvement is particularly important for light ions with low

atomic number (Z), where higher detection efficiency is critical. Furthermore, strengths of both the electric and magnetic fields were maximized to improve time resolution.

As illustrated in Fig. 1, the electric and magnetic fields are perpendicular to each other along the SE trajectories. The electrode plates create a uniform electric field, with different potentials assigned based on gap distances between neighboring electrodes. The magnetic field is provided by an external dipole magnet.

Regarding SE trajectory, it depends on the strengths of the electric and magnetic fields. The length (L) and height (H) of the trajectory, labeled in Fig. 1(b), are given by:

eB^2 , eB^2 , H = where E is the electric field strength, B is the magnetic field strength, m is the electron mass, and e is the elementary charge. In principle, SEs should be guided isochronously from foil to MCP surface with a constant transport time (t), given by [30]:

However, the energy spectra of SEs manifest a velocity spread with a most probable initial value of (0) 1 mm/ns [32] when emitted from the foil. This leads to transport time fluctuations that can be approximately estimated as:

e · E · (0), where Δt represents the time fluctuation or transport time spread.

Thus, time resolution decreases with ascending E from Eq. 5. Consequently, much higher voltages must be applied to the electrodes to create a stronger electric field.

The aperture in the electrode plate, necessary for ion passage, introduces significant inhomogeneity in the electric field. This non-uniformity causes variations in SE transport time from foil to MCP surface depending on emission position. Consequently, in addition to the intrinsic velocity spread of SEs, their spatial distribution contributes substantially to overall time fluctuation.

To estimate this effect quantitatively, we employed SIMION software to precisely calculate electric field distribution and simulate electron transport dynamics from carbon foil to MCP surface in detail. Our simulations modeled the initial kinetic energy of SEs using a Maxwellian distribution peaking at 2.1 eV [32], with uniform isotropic emission angle and position covering the entire sensitive area of the foil [33].

To visualize the resulting motion characteristics under actual field distribution, Fig. 2 presents simulated SE trajectories, where red and blue lines represent forward- and backward-emitted SEs, respectively. The simulated equipotential lines of the electric field distributions further indicate that field inhomogeneity exhibits clear position dependence, particularly pronounced around the aperture region of the electrode plate.

We utilized an equalizing ring to mitigate field inhomogeneity caused by the aperture and thereby improve time resolution, following our previous work [17,

19]. The equalizing ring potential was optimized through SIMION simulations. A minimum in time resolution was obtained at an optimal equalizing ring potential by observing their correlation at fixed E strength in simulation. The optimal potential for actual operation was then determined through close inspection of this correlation in offline tests. Consequently, the optimal result from offline tests is adopted for application rather than that from simulation. We conducted comparative simulations at E = 180 V/mm, the strongest field ever reached in our detectors used in IMS experiments [17, 19]. As shown in Fig. 3, applying an optimized potential of 6000 V to the equalizing ring produces significantly improved field homogeneity compared to the regular potential configuration of 3425 V, particularly in the critical region around the aperture. The influence of this potential on time resolution is demonstrated in the next section (refer to Fig. 8 in Sec. III).

III. Offline Test

Having established the working principle and structural design of the dual-MCP TOF detector, experimental validation of its performance is essential prior to online IMS experiments. While simulations provide valuable insights into secondary-electron transport and expected timing characteristics, real-world effects such as field inhomogeneity, assembly tolerances, and electronic response can significantly influence detector behavior. To address these factors, offline measurements with an α-particle source were conducted to test the time resolution and detection efficiency of the prototype. The experimental setup and results are presented below.

The offline test setup is schematically illustrated in Fig. 4. A dual-component α-particle source composed of ^{241}Am and ^{244}Cm was placed upstream of the carbon foil so that emitted α particles passed through the foil and implanted into a coincidence detector downstream. For time resolution measurements, an additional MCP detector served as the coincidence detector. SEs emitted from both sides of the foil are guided isochronously by perpendicular electric and magnetic fields to the active surfaces of their respective MCP detectors. Timing performance was characterized by measuring fluctuations in time differences between coincidence signals. Waveforms from all detectors were recorded by a digital oscilloscope (LeCroy 604Zi, 10 GS/s sampling rate and 400 MHz bandwidth) for further analysis. The entire setup was installed in a vacuum chamber achieving 5$×10^{-8}$ mbar pressure after baking at 150 °C for 24 hours. An external dipole magnet surrounded the chamber.

Typical output signals from the offline time resolution measurements are shown in Fig. 5. The amplitude of the backward signal is noticeably smaller than that of the forward signal due to variations in multiplication gain among individual MCP detectors.

The intrinsic time resolution of the TOF detector is characterized by the standard deviation σ of ΔT_1 = T_F - T_B. Since transport times from forward

and backward MCPs are independent events, it is reasonable to assume that $\sigma^2 = \sigma\_F^2 + \sigma\_B^2$, giving $\sigma\_F = \sigma\_B = \sigma/\sqrt{2}$, where σ_F and σ_B denote the standard deviations for single detector branches (forward or backward). The obtained time-of-flight spectrum of ΔT_1 at E = 180 V/mm is shown in Fig. 6. The time resolution σ is obtained by fitting the histogram with a Gaussian function.

As another assessment method, timing performance can also be estimated from time differences between the forward or backward MCP and the coincidence MCP. Details of the α source, containing two radioactive nuclides ^{241}Am and ^{244}Cm, are listed in Table 1, particularly the energies of emitted α particles. The time of flight from foil to coincidence MCP varies with α energy, resulting in two peaks in the time spectrum for ΔT_2 = T_{Coin} - T_F when using a two-component α source, as seen in Fig. 7. The sigma is deduced to be 49.8 ps, where a double Gaussian function with common standard deviation fits the spectrum. The σ of ΔT_2 = T_{Coin} - T_F is larger than that of ΔT_1 = T_F - T_B at the same electric field strength (E = 180 V/mm). This is due to dispersion in the flight paths of α particles from carbon foil to coincidence MCP, which introduces additional time fluctuation estimated to be about 30 ps and results in a larger σ in Fig. 7.

Figure 8 presents time resolution results from offline tests, where timing performance was measured while varying equalizing ring voltages at each electric field strength E. As shown, optimal time resolution was achieved at a suitable equalizing ring voltage. In general, the best time resolution of 29.62 $\pm$ 0.80 ps was obtained with the highest electric field E = 300 V/mm. These results demonstrate that better time resolution can be achieved at higher E with optimized equalizing ring potential, confirming the effectiveness of this optimization approach.

Better time resolution was observed with increasing electric field strength, as shown in Fig. 9. The time resolution improved by a factor of 1.5 when increasing E from 180 V/mm to 300 V/mm, where a maximum voltage of 13 kV was applied to the equalizing ring. These performance improvements necessitated corresponding engineering enhancements, including high-specification HV cables and feedthroughs capable of withstanding high voltage, along with precision manufacturing of electrodes to avoid sparking. During offline tests, the detector operated stably for more than 24 hours under each electric field strength from 180 V/mm to 300 V/mm without any observed discharge or sparking.

For comparison, simulation results of time resolution are also presented. Figure 9 compares optimal time resolution from offline measurements with simulation results at different electric field strengths. Both datasets exhibit similar improving trends with increasing E, although simulated values are underestimated due to exclusion of realistic factors such as electronic timing jitter and transit time spread in the MCP. These results confirm the anticipated improvement in time resolution with increasing E, consistent with design principles established in Section II.

For detection efficiency testing, a square silicon-based detector (15 mm$×$15 mm) with 100% detection efficiency for α particles was aligned as the coincidence detector, as shown in Fig. 4. All coincidence events were triggered by signals from the silicon detector, allowing determination of TOF detector efficiency from the count ratio between MCP and silicon detectors.

Typically, SE energy must be sufficient to cause multiplication in MCP pores. As electric field strength increases, SEs are accelerated to higher impact energy, resulting in better efficiency until a plateau is reached [17]. Figure 10 shows detection efficiency at different E values, demonstrating constant efficiency above E = 180 V/mm up to 300 V/mm.

The MCP detector does not always generate a signal when SEs impinge on its surface due to its maximum 60% open area ratio, which defines its effective sensitive area. Consequently, if Λ electrons are emitted from the foil, the probability of detecting at least one electron is [34]:

$$= 1 - e^{\wedge}(-\Lambda \cdot),$$

where is detection efficiency, Λ is the average number of emitted electrons, and is the probability of detecting one electron (equal to the open area ratio, 60%).

Finally, detection efficiency was measured to be 76% and 73% for forward and backward MCP detectors, respectively. Since energy deposited at the foil entrance surface is slightly lower than at the exit surface, SE yield in the backward direction is less than forward yield, resulting in lower detection efficiency (refer to Eq. 2 and 7). The average numbers of forward- and backward-emitted electrons are calculated to be 2.40 and 2.16, respectively, consistent with previous studies of SE ejection by ions from foils [35].

The total efficiency of the dual-MCP TOF detector is calculated as:

$$\_\{\text{Total}\} = 1 - (1 - \_\text{F})(1 - \_\text{B}),$$

where $\_\{\text{Total}\}$ is the total detection efficiency of the integrated detector, and $\_\text{F}$ and $\_\text{B}$ are those of forward and backward MCPs. Thus, the total efficiency is 94% for α particles with kinetic energy of approximately 5 MeV.

IV. Summary

A dual-MCP time-of-flight detector has been developed and tested to enable precision mass measurements of short-lived nuclei at HIAF-SRing. This upgraded detector design utilizes simultaneous collection of secondary electrons from both sides of a carbon foil, thereby significantly enhancing detection efficiency. Through comprehensive offline tests, the detector achieved an excellent total efficiency of 94% for α particles with kinetic energy of approximately 5 MeV and demonstrated a 1.5-fold improvement in time resolution by increasing electric field strength from 180 V/mm to 300 V/mm, with optimized uniform electric field using equalizing rings at a maximum voltage of 13 kV.

Agreement between offline tests and simulations validates our ion-optics model and provides a reliable foundation for future developments. These gains represent a significant step forward in detector technology for radioactive ion beam experiments with storage rings. This advancement, however, requires corresponding engineering improvements, such as high-specification high-voltage instruments and precision manufacturing to ensure operational stability.

This development successfully addresses previous limitations in detection efficiency. The enhanced detection efficiency, together with improved time resolution at higher electric field, particularly benefits mass measurements for light ions and ensures more accurate velocity determinations for stored ions. These combined advancements directly contribute to reducing uncertainties in revolution time and velocity determinations—critical parameters for B -defined isochronous mass spectrometry. Consequently, the new detector system enables substantial improvement in mass resolving power for B -defined IMS, opening new possibilities for nuclear mass measurements of short-lived isotopes in future experiments at HIAF-SRing.

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