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 detection efficiency of stored ions, resulting in poorer mass resolving power for light nuclei with low proton numbers. To overcome this limitation, we developed a dual-microchannel plates (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 electric and magnetic field configurations were also optimized using SIMION-software-based simulations to improve the time resolution. Offline tests with an α-source obtained a total detection efficiency of 94% and a best time resolution of 29.62 $\pm$ 0.80~ps at an electric field $E = 300$ V/mm. These results demonstrate a substantial efficiency gain for light ions and meet the stringent timing performance required for Bρ-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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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 mass precision achieved in IMS experiments strongly depends on the detection efficiency of stored ions, resulting in poorer mass resolving power for light nuclei with low 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 electric and magnetic field configurations were optimized using SIMION-based simulations to improve time resolution. Offline tests with an α-source obtained a total detection efficiency of 94% and a best time resolution of 29.62 $\pm$ 0.80 ps at an electric field 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. The IMS technique was pioneered at the Experimental Storage Ring (ESR) at GSI [**?**], and has since been established at the experimental Cooler Storage Ring (CSRe) at IMP [**?**], as well as at the Rare Radioactive Isotopes

Ring (R3) at RIKEN [**?**]. Much progress has been achieved in IMS experiments for nuclear structure and nuclear astrophysics research.

In an IMS experiment, a cocktail beam comprising highly-charged ions with a broad charge state (Z) distribution, generated via projectile fragmentation or in-flight fission, is 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 [**?**]:

$$\frac{\Delta(m/q)}{m/q} = -\frac{\Delta T}{T} = \frac{1}{\gamma^2}\frac{\Delta v}{v}$$

where γ is the relativistic Lorentz factor of the stored particles and γ_t is the so-called transition energy of the storage ring, a characteristic ion-optical parameter defined by the magnetic lattice configuration. Mass determination is achieved through precision measurement of revolution times using time-of-flight (TOF) detectors [**?**].

Recently, an advanced variant of IMS, called B -defined IMS [**?**, **?**], was developed at CSRe, employing a pair of TOF detectors installed in the straight section of the ring [**?**, **?**]. At the High Intensity Heavy-Ion Accelerator Facility (HIAF) [**?**, **?**], a dedicated spectrometer ring (SRing) [**?**] is currently under construction, where B -defined IMS is also planned for implementation. This configuration enables simultaneous determination of ion velocities [**?**] 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 precision of both revolution time and velocity measurements, directly correlated with the Z-dependent detection efficiency characteristics of the TOF detector. This inherent correlation necessitated rigorous charge-state selection criteria. For example, as demonstrated in the data analysis of an IMS mass measurement for ^{78}Kr fragmentation, all nuclides with $Z < 15$ were systematically excluded to avoid compromised velocity precision caused by low detection efficiency [**?**].

To overcome this limitation and significantly enhance the detection capability of B -defined IMS at SRing, especially for light ions, we designed, simulated, and offline tested a modified TOF detector configuration, inspired by pioneering work from GSI [**?**]. The key innovation of our new detector is its dual-collection design, which simultaneously captures secondary electrons emitted from both the forward and backward sides of the carbon foil. This approach effectively doubles the usable SE yield while providing intrinsic data redundancy. Furthermore, we optimized the electric and magnetic field configurations 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 [**?**]. 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. These SEs are accelerated by an electric field, deflected by a magnetic field onto the MCP, and multiplied in microchannels. Finally, the electron cloud created in the avalanche amplification process is collected by an anode, generating a timing pulse that marks the timestamp of ion penetration through the TOF detector. These timestamps are further analyzed to determine the revolution times and velocities of all stored ions.

The total yield n_{se} of SE emission is proportional to the stopping power dE/dx for an individual charged particle [**?**]:

$$n_{se} = \Lambda \cdot \frac{dE}{dx}$$

where Λ is a constant of proportionality. Critically, both signal amplitude and detection efficiency for a given ion are positively correlated with n_{se}, establishing n_{se} 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 the forward SEs, as illustrated in the inset of Fig. 1(a). This established setup results in severely constrained detection efficiency, particularly for light ions where measurements yield merely ~15% efficiency for C, N, and O ions at about 400 MeV/u [**?**]. Such limitations critically impede precision velocity determinations required by the recently developed B -defined IMS, which demands both higher efficiency and improved time resolution for accurate mass measurements of short-lived nuclei.

To overcome these limitations, 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. This improvement is particularly important for light ions with low atomic number (Z), where higher detection efficiency is critical. Furthermore, the magnitudes of both the electric and magnetic fields are maximized to improve time resolution.

As illustrated in Fig. 1, the detected ions, electric and magnetic fields are oriented perpendicular to each other. The electrode plates create a uniform electric field, which are assigned different potentials according to the distance between neighboring electrodes. The required 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 determined by the field strengths, 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, the SEs should be guided isochronously from the foil to the MCP surface with a constant transport time (t) [**?**].

However, the energy spectra of SEs manifest a velocity spread with a most probable initial value of $v(0) \approx 1$ mm/ns [**?**] upon emission from the foil. This leads to a fluctuation in transport time, which can be approximately estimated as being proportional to the initial velocity spread and inversely related to the electric field strength. Hence, the time resolution decreases with ascending E. Consequently, much higher voltages must be applied to the electrodes to form 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 the transport time of SEs from the foil to the MCP surface, depending on their emission positions. Consequently, in addition to the intrinsic velocity spread of SEs, their spatial distribution contributes substantially to the overall time fluctuation.

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

To visualize the resulting motion characteristics of electrons under the actual field distribution, we present in Fig. 2 the simulated trajectories of SEs, where red and blue lines represent the paths of forward- and backward-emitted SEs, respectively. It can be clearly seen that the simulated equipotential lines of the electric field distributions further indicate that the field inhomogeneity exhibits a clear position dependence, particularly pronounced around the aperture region of the electrode plate.

We implemented an equalizing ring to mitigate the field inhomogeneity caused by the aperture and thereby improve time resolution, following our previous work [**?**, **?**]. The potential of the equalizing ring was optimized using SIMION simulations. We conducted comparative simulations for electric field $E = 180$ V/mm, the strongest field ever achieved in our detectors used in IMS experiments [**?**, **?**]. As shown in Fig. 3, the results demonstrate that applying an optimized potential of 6600 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.

III. Offline Test

Having established the working principle and structural design of the dual-MCP TOF detector, it is essential to experimentally validate its performance prior to its application in 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 benchmark 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 were implanted in the downstream detector used for coincidence. For time resolution measurements, an additional MCP detector served as the coincidence detector. SEs emitted from both sides of the foil were guided isochronously by crossed electric and magnetic fields to the active surfaces of their respective MCP detectors. Accordingly, timing performance was quantitatively assessed by measuring the fluctuation of the time difference between coincidence signals. The waveforms of all signals generated by 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 housed in a vacuum chamber, in which a pressure of 5×10^{-8} mbar could be achieved after baking at 150°C for 24 hours. An external dipole magnet surrounded the chamber and produced the required static magnetic field.

Representative 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 one, due to variations in multiplication gain among individual MCP detectors caused by manufacturing differences.

The intrinsic time resolution of the TOF detector is characterized by the standard deviation σ of $\Delta T_1 = T_F - T_B$. As the transport times from forward and backward MCPs are two independent events, it is reasonable to assume that $\sigma^2 = \sigma_F^2 + \sigma_B^2$, where σ_F and σ_B denote the corresponding standard deviations for a single detector branch (forward or backward). This gives $\sigma_F = \sigma_B = \sigma/\sqrt{2}$. The obtained time-of-flight spectrum of ΔT_1 is shown in Fig. 6 at $E = 180$ V/mm. The time resolution σ is obtained by fitting the histogram with a Gaussian function.

Meanwhile, the timing performance can also be estimated from the time difference between the forward or backward MCP and the coincidence MCP. The details of the α source, which contains 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 depending on the α energy. Hence, with a two-component α source, this results in two peaks in the time spectrum

for $\Delta T_2 = T_{Coin} - T_F$, as seen in Fig. 7. The sigma is deduced to be 51.5 ps, where a double Gaussian function with common standard deviation is employed for the fit. It is found that the σ of $\Delta T_2 = T_{Coin} - T_F$ is larger than that of $\Delta T_1 = T_F - T_B$ at the same electric field strength ($E = 180$ V/mm). This is due to the dispersion of the flight paths of α particles from the carbon foil to the coincidence MCP detector. This dispersion in α particle trajectories brings a time fluctuation, which is estimated to be about 30 ps and results in a larger σ in Fig. 7.

Figure 8 presents the time resolution results obtained from offline tests, where the detector' s timing performance was measured at different equalizing ring voltages for each configured electric field strength E. As can be seen, the best time resolution can be achieved at a proper equalizing ring voltage for each E. In general, the best time resolution of 29.62 ± 0.80 ps was achieved when the highest electric field $E = 300$ V/mm was applied. The results clearly demonstrate that optimal time resolution can be achieved by adjusting the equalizing ring potential at each E value, confirming the effectiveness of this optimization approach.

As shown in Fig. 9, systematic improvements in the best achievable time resolution were observed with increasing electric field strength. The time resolution of the TOF detector was enhanced by a factor of ~1.5 when increasing the electric field strength from 180 V/mm to 300 V/mm, which required applying a maximum voltage of 13 kV to the equalizing ring. These performance improvements necessitate corresponding engineering enhancements, including high-specification HV cables and feedthroughs to prevent sparking, along with precision manufacturing of electrodes to maintain field integrity under high-voltage operation.

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

For detection efficiency testing, a square silicon detector (15 mm × 15 mm) was aligned as a coincidence detector with 100% detection efficiency for α particles, as shown in Fig. 4. All obtained events were triggered by coincidence signals from the silicon detector. Thus, the detection efficiency of the TOF detector was determined as the count ratio between the MCP and silicon detectors. Usually, the energy of SEs should be large enough to cause multiplication in the pores of the MCP. As the electric field strength increases, it accelerates the SEs to higher impact energy, resulting in better efficiency until a plateau is reached [**?**]. In Fig. 10, the detection efficiency at different E is displayed. Our results show

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, owing to the maximum 60% open area ratio of the MCP, which defines its effective sensitive area. Consequently, if Λ electrons are emitted from the foil, the probability of detecting at least one electron is [**?**]:

$$\eta = 1 - e^{-\Lambda \cdot \varepsilon}$$

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

Finally, detection efficiency is measured to be 76% and 73% from the forward and backward MCP detectors, respectively. According to Eq. 7, the average number of forward- and backward-emitted electrons can be calculated to be 2.40 and 2.16 in this case, which are consistent with previous studies of SEs ejected by ions from foils [**?**].

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

$$\eta_{Total} = 1 - (1 - \eta_F)(1 - \eta_B)$$

where η_{Total} is the detection efficiency of the integrated detector, and η_F and η_B are those of the forward and backward MCPs, respectively. The total efficiency of the integrated detector is calculated to be 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 a remarkable 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 the electric field strength from 180 V/mm to 300 V/mm through optimization of the uniform electric field using equalizing rings with a maximum voltage of 13 kV.

The excellent agreement between offline test results and simulations validates our ion-optics model and provides a reliable foundation for future developments. While these performance gains require corresponding engineering advancements, including high-specification high-voltage instruments and precision manufacturing to ensure operational stability, they represent a significant step forward in detector technology for experiments with radioactive ion beams.

This development successfully addresses previous limitations in detection efficiency and time resolution. The enhanced detection capability particularly benefits mass measurements for light ions, while the improved time resolution ensures more accurate velocity determinations for stored ions. These combined advancements directly contribute to reducing uncertainties in determinations of revolution time and velocity, which are 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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