

Fourier Denoising Analysis in B -defined Isochronous Mass Spectrometry

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Date: 2025-11-10T11:34:09+00:00

Abstract

B -defined Isochronous Mass Spectrometry (B -IMS) based on heavy-ion storage rings is a newly developed technique for precision mass measurements of short-lived nuclides. Two time-of-flight detectors are installed in a straight section of the storage ring, measuring the revolution time and the velocity of the stored ions to achieve a high precision of mass measurement. Electromagnetic noises of detection systems are main uncertainty origins of mass values in B -IMS. In the development of B -IMS, a digital Fourier denoising analysis was applied to analyze the timing signals full-waveform sampled by a digital oscilloscope. Several periodic electric components were unexpectedly discovered hidden in the timing signals, and the corresponding frequencies were exactly the aliquots of the oscilloscope sampling rate. Due to this analysis, the systematic deviation existing in the redetermined mass values was removed at 1σ confidence level for nuclei with $Z \geq 15$, and the precision of measured velocities and ion masses was improved by a comparable magnitude, ranging from 7% to 20%. In further research, the amplitudes of these periodic components were related with the voltage sampling range of the oscilloscope and varied periodically in different hours over a day. Due to the widely usage of digital oscilloscopes, this technology would be of interest in the usage with similar electronic equipment.

Full Text

Preamble

Fourier Denoising Analysis in B -defined Isochronous Mass Spectrometry

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B -defined Isochronous Mass Spectrometry (B -IMS) based on heavy-ion storage rings is a newly developed technique for precision mass measurements of short-lived nuclides. Two time-of-flight detectors installed in a straight section of the storage ring measure the revolution time and velocity of stored ions to achieve high-precision mass measurement. Electromagnetic noise in detection systems represents a primary source of uncertainty in B -IMS mass values. In the development of B -IMS, digital Fourier denoising analysis was applied to timing signals that were full-waveform sampled by a digital oscilloscope. Several periodic electric components were unexpectedly discovered hidden within the timing signals, with frequencies that are exact aliquots of the oscilloscope sampling rate. Through this analysis, systematic deviations present in redetermined mass values were removed at the 1 σ confidence level for nuclei with $Z < 15$, while the precision of measured velocities and ion masses improved by a comparable magnitude ranging from 7% to 20%. Further investigation revealed that the amplitudes of these periodic components correlate with the voltage sampling range of the oscilloscope and vary periodically throughout the day. Given the widespread use of digital oscilloscopes, this technique would be of interest for applications involving similar electronic equipment.

Keywords: Denoising Analysis, Oscilloscopes, Ion Velocity and Mass Measurement, B -defined Isochronous Mass Spectrometry

Introduction

B -defined Isochronous Mass Spectrometry (B -IMS) based on heavy-ion storage rings is a powerful tool for precision mass measurement of short-lived nuclides [1–3]. The principle of B -IMS involves simultaneous measurement of velocities [4] and revolution times [5–7] of stored ions using two time-of-flight (TOF) detectors installed in one straight section of the storage ring. This innovative technique achieves high precision and sensitivity in mass measurement.

In conventional Isochronous Mass Spectrometry, the primary uncertainty in mass values originates from the momentum dispersion of stored ions [5–7], although the isochronous mode of storage rings has been applied to mitigate this effect. This problem was significantly alleviated by ion velocity measurement in B -IMS [4]. Consequently, the resolving power and accuracy of mass values become strongly dependent on the precision and accuracy of ion velocities [1, 8, 9].

Noise is ubiquitous in the outcome of any physical experiment, arising from statistical fluctuations and various uncontrollable disturbances affecting the measurement system. In conventional Isochronous Mass Spectrometry, a two-sided moving average method [10] was used to reduce noise [11, 12], primarily moti-

vated by improving detection efficiency of timing signals. However, since momentum dispersion was independent of the electric noise in detection equipment, the influence of electric noise on final results was typically neglected.

In this work, using a typical B-IMS experiment as a benchmark example [13, 14], digital Fourier denoising analysis was applied to timing signals, revealing several unexpected periodic electric components hidden within the signals. A multiple trigonometric fit function was used to describe and remove these periodic components, improving the precision of ion velocities and corresponding ion masses by a comparable magnitude of approximately 7%–20% for ions with proton number $Z \geq 15$. The characteristics of these periodic voltage components are also discussed in this work.

II. The Experiment and the Denoising Analysis

The following discussion is based on experimental data; further details can be found in Ref. [13, 14]. This experiment was performed at the cooler storage ring (CSRe) in Lanzhou and was dedicated to measuring masses of atomic nuclei with isospin $T_Z = -1, -1/2$ in the fp shell. The nuclei of interest were produced via projectile fragmentation of 460 MeV/u $^{78}\text{Kr}^{19+}$ primary beams on a 15 mm ^9Be production target. The CSRe was tuned to isochronous mode with a fixed average magnetic rigidity of $B\rho = 5.528$ Tm, a $B\rho$ acceptance of approximately 0.33%, and a transition point of $\gamma_t = 1.352$ [5–7].

The upstream (TOF1) and downstream (TOF2) time-of-flight detectors were installed approximately 18 m apart in a straight section of CSRe [15]. Each detector consists of a thin carbon foil (ϕ 40 mm, 19 $\mu\text{g}/\text{cm}^2$) and a set of micro-channel plates (MCPs) [16, 17]. When an ion passes through the carbon foil, the foil emits secondary electrons that are guided into the MCPs by perpendicularly oriented electric and magnetic fields in the detector. An electron avalanche forms along the channel length, exits the pore, and is finally collected at the anode [18], producing timing signals as exemplified in Fig. 1 [Figure 1: see original paper]. Fast timing signals from each detector were full-waveform sampled by a digital oscilloscope with a sampling rate of 50 GHz [19]. The measurement duration was set to 400 μs after an injection trigger, corresponding to approximately 600 revolutions of stored ions. At the beginning of this experiment, the oscilloscope's voltage sampling range was set to -250 mV. Later, the sampling range was modified several times between -250 mV and -300 mV before being finally set to -300 mV.

Using a timing signal as an example, Fig. 1 shows the original voltage shape, i.e., the voltage values U as a function of time t , depicted as the gray solid line. The falling and rising edges of this signal correspond to the charging and discharging processes in the MCP anode, respectively. The amplitude U_{min} (the pulse height measured from its maximum value) of each signal follows a Polya-like distribution [20] and is roughly related to the proton number of the ion [17, 21, 22], as discussed in Appendix A.

Fig. 2 [Figure 2: see original paper] shows, for 2874 ions injected within one hour, the original (a) and denoised (b) distributions of fall times corresponding to the two detectors. To investigate hidden problems in the signals, the timing signals were analyzed using a modified digital Fourier transform (DFT):

$$AU(f) = \sqrt{\left[\sum_{j=1}^{n_U} U_j \times \cos(2\pi f \times t_j) \right]^2 + \left[\sum_{j=1}^{n_U} U_j \times \sin(2\pi f \times t_j) \right]^2}$$

where $n_U = 400 \mu\text{s} \cdot 50 \text{ GHz}$ is the total number of voltage data points per injection, f is the frequency, and AU is the amplitude of periodic electric components corresponding to each frequency. Using a randomly selected injection as an example, Fig. 3 [Figure 3: see original paper] shows the $AU(f)$ spectra measured by the two detectors, which are both symmetrical with respect to $f = 25 \text{ GHz}$ (half the sampling rate). Eight predominant peaks appear in the range $0 \leq f \leq 25 \text{ GHz}$, indicating eight periodic electric components hidden in the signals. Notably, the frequencies of these predominant peaks exactly divide this range into equal intervals. Compared with the small revolution frequency of approximately 1.56 MHz for stored ions (calculated using the CSR length of 128.8 m and the Lorentz factor of target ions $\gamma \approx \gamma_t = 1.352$), these predominant peaks are likely caused by the digital oscilloscope itself, especially considering the exact matching relationship between these peak frequencies and the oscilloscope sampling rate.

Fig. 1 shows a timing signal example with an amplitude of approximately -16.88 mV . The original voltage shape (gray solid line) and the denoised voltage shape (red solid line) are both displayed. The amplitude U_{\min} and fall time of this original shape are indicated in the figure. Based on the conventional constant fraction discrimination technique, we developed a new timing method for B-IMS by fitting the falling edge of signals with an exponential-like function. The fall time of each signal is defined as the time for the pulse height to decrease from 10% to 90% of U_{\min} [20]. Fig. 2(a) displays the distribution of fall times for 2874 ions injected within an hour and detected by the two detectors. Two strange zigzag patterns are visible, discovered for the first time in CSR's mass measurement history. Such zigzag patterns typically appear in distributions with small counts of approximately 20 per bin due to mathematical random fluctuations. However, the distribution shown in Fig. 2(a) clearly does not fall into this category and likely originates from signal noise. Since these zigzag patterns were not significant in other experiments, the origin is unlikely to be common problems such as the intrinsic response of the detector or beam oscillation.

Based on the $AU(f)$ spectra shown in Fig. 3, a multiple trigonometric fit function was applied to describe and remove the periodic electric components hidden in the signals:

$$U_{\text{denoised}}(t) = U_{\text{original}}(t) - \sum_{i=1}^8 A_i \times \sin(2\pi f_i \times t + \phi_i)$$

Fig. 1 also shows the denoised voltage shape of the same example signal as a red solid line. Using this denoising analysis, the standard deviation of the baseline in this injection is reduced from approximately 2.2 mV to approximately 1.3 mV. The absolute value of the original amplitude (gray line) is slightly larger than the denoised one (see Appendix A), and the denoising analysis also smoothens the falling edge of the signal. Consequently, Fig. 2(b) shows the denoised distribution of fall times, revealing two Gaussian-like distributions and demonstrating that the problem indicated in Fig. 2(a) has been resolved.

Impact on B-IMS

In this experiment, the details of ion velocity measurement are described in Ref. [4]. The velocity uncertainty for each ion can be estimated during the fitting procedure of ion passage time sequences, i.e., the passage time stamps t as a function of revolution number N . Fig. 4 [Figure 4: see original paper] shows the average relative uncertainties of ion velocities σ_v/v as a function of ion proton number Z . In this analysis, we only use injections with more than 4 ions whose masses are well known in AME2020 [24] (uncertainty $\sigma_{\text{ame}} < 5$ keV), and ion species with counts exceeding 100.

The average relative uncertainties exhibit a decreasing trend from lighter to heavier ions, which can be understood as resulting from higher detection efficiencies and higher signal-to-noise ratios for heavier ions (see Appendix A). The effect of this denoising analysis appears more significant for lighter ions with smaller absolute signal amplitudes.

Given the revolution time T and velocity v , the magnetic rigidity $B\rho$ and orbit length C of stored ions are determined according to:

$$B\rho = \frac{\gamma v}{q/m}, \quad C = Tv, \quad \gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

where the Lorentz factor $\gamma = 1/\sqrt{1 - v^2/c^2}$ with c being the speed of light in vacuum. Nuclei with experimental mass uncertainties < 5 keV in AME2020 [24] and proton numbers $Z \geq 15$ were used as reference ions, accounting for approximately 58% of the total, to construct the $B\rho(C)$ function through a least-squares fit to all experimental $\{B\rho_{\text{exp}}, C_{\text{exp}}\}$ data obtained for each such ion. The m/q value of any ion (i), including unknown-mass nuclei, was then derived directly from this $B\rho(C)$ function, and the error of each m/q value was estimated by analyzing the fit residual of the $B\rho(C)$ function. Further details of this analysis can be found in Ref. [3].

Using reference ion species with counts exceeding 100 and isospin $T_Z = \pm 1/2$ as examples, Fig. 5 [Figure 5: see original paper] shows the mass differences between the new experimental masses M_{exp} and the masses from AME2020 M_{ame} [24] as a function of ion revolution times T .

In Fig. 5(a), an obvious systematic deviation is visible in mass values for ions with isospin $T_Z = 1/2$, which are far from the center of the isochronous mode at $T \approx 638.4$ ns (calculated using the CSRe length of 128.8 m and the Lorentz factor of target ions $\gamma \approx \gamma_t = 1.352$). The experimental masses were used to calculate the normalized chi-square χ_n . The resultant $\chi_n = 3.58 \pm 0.20$ for $T_Z = \pm 1/2$ ions is 17.9 times larger than the expected value of 1, indicating that additional effects should be considered in the data analysis.

By applying the denoising analysis as shown in Fig. 5(b), the resultant $\chi_n = 0.93 \pm 0.20$ and $\chi_n = 1.01 \pm 0.22$ for $T_Z = \pm 1/2$ ions respectively both fall within the expected interval of 1. Based on the comparison of normalized chi-square values, the systematic deviation in mass values is believed to be removed (at least) for nuclei with $Z \geq 15$ in this experiment.

In addition to improving accuracy, the precision of mass values is also enhanced through this denoising analysis. For convenient comparison, Fig. 6 [Figure 6: see original paper] shows the relative magnitude of uncertainty reductions for ion velocities $\Delta\sigma(v) = 1 - \sigma_{\text{den}}(v)/\sigma_{\text{ori}}(v)$ (black open blocks) and ion masses $\Delta\sigma(M) = 1 - \sigma_{\text{den}}(M)/\sigma_{\text{ori}}(M)$ (red circles) as a function of ion proton number Z . Both uncertainty reductions exhibit decreasing trends from lighter to heavier ions of similar magnitude. The mass deviation shown in Fig. 5(a) would affect mass uncertainty estimation [3] and lead to a larger reduction in mass uncertainty than in velocity uncertainty.

It is worth mentioning that the velocity error estimation introduced in Ref. [4] and the m/q error estimation introduced in Ref. [3] are completely independent in this experiment. The decreasing trend of velocity uncertainty values shown in Fig. 4 was not directly considered or used in the mass determination analysis in Ref. [3]. The precision improvements in both velocities and masses closely match in order of magnitude, which appears coincidental. Yet this apparent coincidence strongly suggests an underlying mathematical correlation between these two physical quantities in B-IMS, which was not specifically identified or demonstrated in previous work.

IV. Feature of the Periodic Electric Components

To understand the origin of periodic electric components hidden in the timing signals, the amplitude AU and phase ϕ values from the Fourier transform shown in Fig. 3 were also examined. Due to the special relationship between the oscilloscope sampling rate f_0 and the frequency of each peak f , the phases satisfy $\phi = \phi_0 + 2a\pi$ where a is an integer and ϕ_0 is the initial phase in the region symmetrical about 0 to π . Using the Fourier peaks with frequency 12.5

GHz as an example, Fig. 7 [Figure 7: see original paper] shows the amplitudes AU (a) and initial phases ϕ_0 (b) as a function of time during this experiment.

At the beginning of this experiment, the oscilloscope's voltage sampling range was set to approximately -250 mV. Near the 4th, 6th, and 8th days, the voltage sampling range was modified three times between approximately -250 mV and approximately -300 mV. The amplitude AU values shown in Fig. 7 exhibit sudden changes at the corresponding times, while ϕ_0 appears independent of this modification. Within periods corresponding to the same voltage sampling range, AU and ϕ_0 appear to vary periodically throughout the day synchronously. Two effects may cause this variation in AU and ϕ_0 : one is the large temperature variation in Lanzhou during winter, and another is the periodic variation of the city power supply voltage in Lanzhou.

In addition to the example experiment with a ^{78}Kr primary beam [13, 14] discussed above, the denoising analysis was also applied to B-IMS experiments with primary beams of ^{58}Ni [2, 3] and ^{36}Ar [25, 26]. Using the Fourier peaks with frequency 12.5 GHz in TOF2 as an example, Fig. 8 [Figure 8: see original paper] shows the AU values as a function of the oscilloscope's voltage sampling range. Four sets with different voltage sampling ranges were specifically performed in the ^{36}Ar experiment [25, 26]. This oscillation exhibits a non-negligible influence, with its amplitude demonstrating a universal positive correlation with the oscilloscope's voltage sampling range. Due to the widespread use of digital oscilloscopes, this effect should be considered in data analysis when using similar electronic equipment.

V. Conclusion

In this work, digital Fourier denoising analysis was applied to timing signals that were full-waveform sampled by a digital oscilloscope. Several periodic electric components were discovered hidden in the original voltage shapes of signals, with frequencies that are exact aliquots of the oscilloscope sampling rate. Based on this analysis, systematic deviations in mass values were removed at the 1 confidence level for nuclei with $Z \geq 15$, and the precision of ion velocities and masses was coincidentally improved by a comparable magnitude of approximately 7%–20%. From the dramatic consistency in the order-of-magnitude improvements for both mass and velocity precision, we firmly believe that advancement of next-generation mass spectrometry based on storage rings must steadfastly concentrate on the fundamental physical challenge: how to further improve the precision and accuracy of velocity measurements.

From the discussion of the amplitude and phase of these periodic electric components, we can conclude with near certainty that the issue originates from the oscilloscope itself. Given our limited expertise in oscilloscope operational principles, we regret our inability to provide specific diagnostics regarding the root cause or hardware-level improvement recommendations. Through this work, we aim to alert peers using similar electronic components that these periodic elec-

tric components warrant particular attention, especially in physics experiments with inherently low signal-to-noise ratios, where they may introduce significant interference.

Appendix A: The Amplitude Distribution of Signals

This appendix provides details about the amplitude distribution of signals. This information is not central to the main work, but its absence may hinder readers' understanding.

Using the original voltage shapes of signals in TOF2, Fig. 9(a) [Figure 9: see original paper] shows the amplitude distribution of signals produced by 100 ions of $^{47}\text{Cr}^{24+}$ and $^{21}\text{Na}^{11+}$, respectively. Each distribution follows a Polya-like form due to the statistical nature of the secondary emission process in electron-multiplier systems [20]. The difference between these distributions mainly arises from variations in interactions between ions and the carbon foil. Generally, ions with larger proton numbers experience greater energy loss when passing through the carbon foil [27], causing the foil to emit more secondary electrons. Consequently, detection efficiency and average amplitude are both related to ion proton number, relationships that have been used in ion identification [17, 21, 22].

For the same signals in TOF2 shown in Fig. 2, Fig. 9(b) [Figure 9: see original paper] displays the amplitude distribution using both original (blue solid line) and denoised (red dotted line) voltage shapes. The counts corresponding to signals with amplitude > -20 mV are significantly improved. Based on our previous research on detector performance [16, 17], this phenomenon precisely demonstrates that denoising analysis leads to more accurate signal amplitude extraction.

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