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Time-of-flight radio-frequency mass separator for continuous low-energy ion beams

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Abstract

A novel concept for a time-of-flight radio-frequency mass separator for low-energy beams is investigated. The concept is based on two sets of deflectors with sinusoidally-varying applied voltage and at least one Einzel lens. Results of analytical calculation and numerical simulation are presented and compared. Potential advantages of such a scheme include a resolving power similar to that of simple electromagnetic separators while at lower costs, as well as the possibility to incorporate the scheme relatively easily into existing electrostatic beam transport systems.

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1. Introduction

The separation of ions with different charge-to-mass ratios q/m is important in physics, chemistry, and many other areas of research and application. Various mass separation techniques exist and the choice of which technique to employ depends on the beam properties of the ions to be separated and the desired resolving power. Classical electromagnetic separators make use of the difference in the rigidity of ions in magnetic fields and are, for example, used for the separation of isotopes [1]. Linear radio-frequency (RF) quadrupole mass filters [2] or similar ion trap devices make use of mass-dependent motional instabilities to separate ions. They are widely applied in analytical chemistry or in the form of residual gas analyzers. High resolution mass separation can be performed in Penning traps by making use of the difference in the ions' cyclotron frequencies; resolving powers sufficient to separate isobars [3] or even nuclear isomers [4] are achieved. High resolution mass separation of continuous beams is also obtained in Smith-type RF mass spectrometers [5,6]. Ions injected into the system perform two cyclotron orbits in a magnetic field. Passing twice through an RF acceleration cavity they are only transmitted if the change in beam energy is compensated in the second turn. In the case of pulsed ion beams with constant energy the time of flight of ions can be utilized to achieve mass separation. Such a separation is, for example, utilized in RF separators for high-energy (> 50 MeV/nucleon) rare isotope beams [7,8]. These devices make use of a beam's time structure that has been imprinted by the acceleration process and the time-of-flight difference after a drift length where the ions pass through a high-voltage radiofrequency beam deflector.

In this paper we evaluate and discuss a concept to mass-separate continuous low-energy ion beams of energies in the range of a few keV to tens of keVs using a combined RF and time-of-flight technique. This scheme shares similarities with the RF separator for high-energy beams and the RF Smith spectrometer mentioned above. The simplicity of the technique and the possibility of implantation in existing electrostatic ion beam transport systems make this technique interesting.

2. TOF-RF mass separation

The concept of time-of-flight radio-frequency (TOF-RF) mass separation is illustrated in Fig. 1. Stated in the order in

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which an ion would encounter them, the system consists of a beam deflector, an Einzel lens, another beam deflector, and a mass-selecting aperture. It should be noted that the sequence of such ion optical elements is typical for a section of an electrostatic beam transport system for ion beams with energies below a few tens of keV. Each set of the deflectors shown consists of two orthogonal pairs of deflection plates, one for deflection in the x-direction and one for the y-direction with respect to the coordinate system used in the figure. To the two x-deflection plates of both the entrance and exit deflectors, RF voltages $u_x(t) = u_0 \sin(\omega t)$ and $-u_x(t)$ are applied. Similarly, to the y-deflector plates of both deflectors, RF voltages $u_y(t) = u_0 \sin(\omega t + \pi/2)$ and $-u_y(t)$ are applied, phase shifted by 90° with respect to those applied to the x-deflector plates. The Einzel lens in the center between both deflectors focuses a beam leaving the first deflector onto the entrance of the second deflector, i.e. the ion trajectories make the same angle with respect to the z-axis as they did upon leaving the first deflector. The aperture, a circular hole centered on the z-axis, stops ions that are further away from the beam axis than the inner radius of the aperture.

We will first consider what happens using just the x-deflectors, which means no RF voltage will be applied to the y-deflectors. Ions of differing mass streaming continuously into the system with the same energy will have different velocities. Because of the electric field generated by the sinusoidally-varying voltage u_x discussed previously, these ions will be accelerated at the first deflector according to their mass and when they arrive. The ions then drift with constant but mass dependent velocity until they reach the Einzel lens, whereupon they are focused into the second deflector. In the second deflector, the ions will again be accelerated. If the time an ion takes to go from the start of the first deflector to the start of the second deflector is an integer multiple of the period of the sinusoidal voltage, then the second deflector will accelerate the ions the same as previously, thus reversing any trajectory changes made by the first deflector. This time of flight is mass dependent, so only ions with a certain charge to mass ratio will satisfy this condition. For ions with the wrong q/m ratio the trajectory changes will not be entirely reversed and the beam deflection may even be exaggerated. The ions will continue their path until they reach the aperture position. Those with the correct q/m ratio will pass the aperture because their direction is parallel and they are close to the z-axis of the system. Ions with the wrong q/m ratio will behave differently. At the position of the aperture their beam will sweep up and down along a line $y = 0$ in the xy plane, according to their mass and when they entered the system. Since they sweep over the aperture a fraction of the wrong ions will still be transmitted, which is not desirable.

In order to avoid the transmission of these wrong ions the y-deflectors are employed by applying an RF voltage u_y as discussed above. With u_x and u_y being out of phase by ninety degrees, the ions will form circular orbits at the aperture according to their mass. The time at which the ions enter the system becomes inconsequential, or in other words, ions of a particular mass will always be seen at a certain distance from the z-axis at the aperture. It is in this way that the system works with continuous ion beams, and furthermore, the time-of-flight of an ion and the RF-voltage applied to the deflectors primarily determines the separation.

3. Analytical description

In the following analytical description of the TOF-RF concept simplifying assumptions are made. First, the electric field generated by each pair of deflector plates is considered uniform inside the deflectors and non-existent outside of them. Second, the Einzel lens is approximated by a thin lens centered between the two deflectors. Third, we assume no energy spread. Finally, we assume a beam with no emittance. It is clear that the real system will show deviations from this simplified scheme. The effects have been analyzed via computer simulations and the results are discussed in Section 4. The coordinate system used for the analytical description is the same as the coordinate system shown in Fig. 1. For simplification we will first consider one pair of deflectors per deflector assembly. The results are trivially generalized later.

Fig. 2 shows many of the variables used in the analytical description. As shown in the diagram, arbitrary ions with mass m and charge q come in to the system with kinetic energy K in the $+z$-direction. Both deflectors have length l and plate separation h. The drift region between the first and second deflectors has length s, and the drift region between the second deflector and the aperture has length d. The angle that an ion trajectory makes with the z-axis upon exiting the first deflector is denoted by α_1, and likewise the angle upon leaving the second deflector is denoted by α_2. By an appropriate choice of ω, the angular frequency of the sinusoidal voltage, we admit ions of mass $m = M$ and energy K to pass through the aperture. Of the variables that are not pictured, V is the amplitude and n is the har-

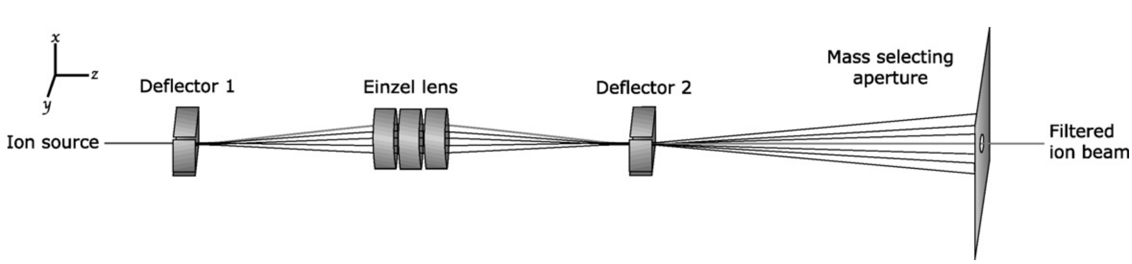

Fig. 1. Schematic for a time-of-flight radio-frequency (TOF-RF) mass separator for continuous low-energy ion beams. This schematic shows a system with the minimum number of necessary components.