Prototype development of a multi-radio-frequency quadrupole (MRFQ) mass filter

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The multi-radio-frequency quadrupole (MRFQ) mass filter selectively separates ions of a specific mass by utilizing betatron resonance in ion motion within a radio-frequency quadrupole (RFQ). In the MRFQ mass filter, a skew component is deliberately introduced into the quadrupole electric field to induce betatron resonance. By applying multiple RF voltages at different frequencies and adjusting the amplitude of both RF and DC voltages, betatron resonance can be controlled, allowing the selective removal of undesired ions such as isobars through resonance while isolating the target ions. Numerical calculations have demonstrated that this approach achieves significantly higher mass resolution than that obtained using conventional quadrupole mass spectrometers.[1] In this report, we present the development of a prototype MRFQ mass filter for experimental validation.

Figure 1 presents a schematic cross-section of the MRFQ mass filter. The quadrupole electrodes are arranged horizontally and vertically, whereas the skew electrodes are positioned at a 45° orientation. The opposing electrodes are designed to maintain an equipotential condition. The quadrupole electrodes generate a quadrupole electric field by applying DC-offset AC voltages of opposite polarity in the horizontal and vertical directions.

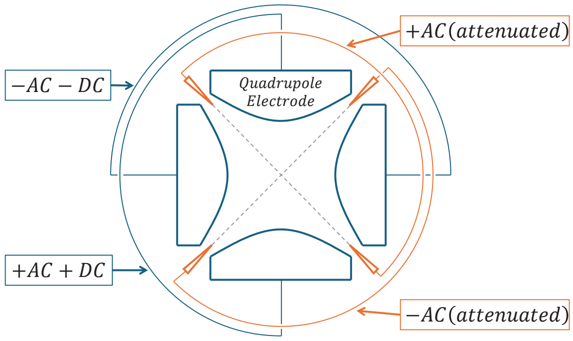

Fig. 1. Conceptual cross-sectional diagram of the MRFQ mass filter, showing the quadrupole electrodes (blue) and skew electrodes (orange).

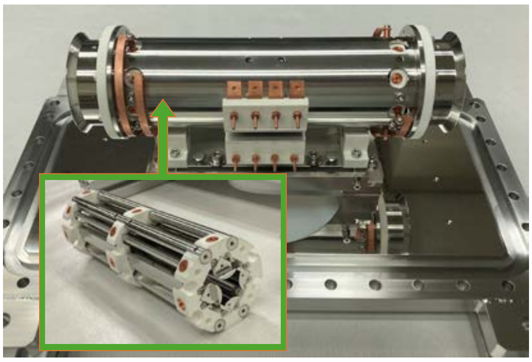

Fig. 2. Main body of the MRFQ mass filter (bottom left) and external view of the MRFQ (top center).

The presence of higher-order modes in this electric field degrades the sharpness of betatron resonance, thereby reducing mass resolution. To suppress these higher-order modes and achieve a more uniform quadrupole field, the cross-section of the quadrupole electrodes was precisely machined into a hyperbolic shape. Additionally, the electrodes were mounted onto precisely fabricated ceramic holders to minimize misalignment, further enhancing field purity.

In a pure quadrupole field, the potential along the 45° direction is equal to the ground potential. Based on this principle, the skew electrodes were designed to be thin, flat plates installed at a 45° orientation. When an attenuated AC voltage is applied to these skew electrodes, an additional quadrupole field component, referred to as the skew component, is introduced.

This field component, when combined with the quadrupole field generated by the primary quadrupole electrodes, does not alter the DC component of the quadrupole field but induces a slight rotation of the AC component relative to the DC component. This selective rotation of the AC component results in the excitation of betatron resonance. To ensure the accuracy of the generated electric field, the skew electrodes were also mounted onto ceramic holders with high precision, similarly to the quadrupole electrodes.

Figure 2 shows a photograph of the main body and an external view of the MRFQ mass filter. The main body consists of four quadrupole electrodes and four skew electrodes, which are mounted onto ceramic holders. This assembly is inserted into a SUS tube, with input and output electrodes attached at both ends. The input and output electrodes generate a potential along the beam axis, controlling the injection and ejection of ions.

In this study, we fabricated a prototype MRFQ mass filter as an experimental demonstration of a novel mass separation technique based on betatron resonance. Future work will involve experimental measurements of the mass resolution using actual ions with this prototype.

Reference

1) M. Wakasugi *et al.*, in this report.

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