PERFORMANCE OF A RESONANT SCHOTTKY PICK-UP IN THE COMMISSIONING OF RARE-RI RING

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Abstract

Rare-RI Ring was constructed at RIKEN RIBF for precise isochronous mass spectrometry of unstable nuclei. In June 2015, we performed the first commissioning of the ring using ^{78}Kr beam with the energy of 168 MeV/nucleon. We successfully carried out the individual injection which is one of the characteristics of the ring, and also we succeeded in the storage of ^{78}Kr ions for a few seconds.

We evaluated the performance of the resonant Schottky pick-up which was installed in the Rare-RI Ring. The purpose of the resonant Schottky pick-up is a monitor for tuning of the isochronous field in the ring. The resonant Schottky pick-up detected single ^{78}Kr ions, where the frequency resolution was $1.29{\times}10^{-6}$ (FWHM). The resolution is in the same order of the required isochronicity. The sensitivity and resolution of the resonant Schottky pick-up are sufficient for the tuning of isochronous optics.

INTRODUCTION

Determining masses of extremely neutron-rich nuclei is important for study of nuclear structure and nucleosynthesis. Such unstable nuclei which locate far from β-stability line are short lived and rare, so here we call such nuclei rare RIs. In order to measure masses of rare RIs precisely, Rare-RI Ring was constructed at RIBF [1, 2]. Because rare RIs are randomly produced by nuclear reactions with intense primary beam from the cyclotron complex, only one rare RI is injected into the ring by using the individual injection with the fast kicker system.

We employ the isochronous mass spectrometry method. For high precision of the masses ($\Delta m/m \sim 10^{-6}$), we require to tune the isochronous field in the order of 10^{-6}. As a monitor for the tuning, we adopt a resonant Schottky pick-up. The resonant Schottky pick-up was designed by the systematic 3D electromagnetic simulations with Micro Wave Studio [3], and was tested offline before installation in the ring [4]. From Schottky spectra, we obtain the revolution frequency information of circulating ions. The momentum change of a stored ion causes the frequency change in the Schottky spectrum, so the isochronicity indicates no change in frequency, despite momentum change of the stored ion. The resonant Schottky pick-up is required to have high sensitivity such that it can detect a single ion with sufficient resolution. In the present study, we evaluated the performance of the resonant Schottky pick-up in the commissioning.

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RESONANT SCHOTTKY PICK-UP

The resonant Schottky pick-up consists of a pillbox-type resonant cavity and ceramic gap. The resonant cavity is made of aluminum with outer diameter, length, and inner diameter of 750, 200, and 320 mm, respectively. Figure 1 is the photographs of the resonant Schottky pick-up. When the beam pass through the resonant Schottky pick-up, an electromagnetic field is induced in the cavity. The change of magnetic flux in the induced electromagnetic field is detected by a pick-up loop. The coupling factor of the pick-up loop was optimized to be one. By adjusting the position of two tuners, the resonance frequency is changed in the range of 173 ± 1.5 MHz.

We performed an offline test of the resonant Schottky pick-up with a network analyzer. We determined the shunt impedance R_{sh} with the bead method. As the result, we acquired basic quantities of the resonant cavity: the resonance frequency f_{res} = 171.43 MHz, R_{sh} = 161 $k\Omega$ and unloaded quality factor Q_0 = 1880.

ONLINE RESULT AT COMMISSIONING

The first commissioning of Rare-RI Ring using ^{78}Kr beam with the energy of 168 MeV/nucleon was carried out

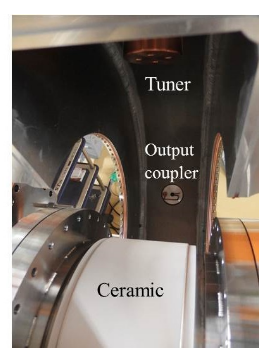

Figure 1: (Left): The resonant Schottky pick-up divided in half. The Schottky pick-up has a pillbox-type resonant cavity. (Right): Inside of the resonant cavity. In the upper part, a tuner for fine tuning the resonance frequency is shown. In the lower part, a pick-up loop for detecting the induced magnetic flux is shown.

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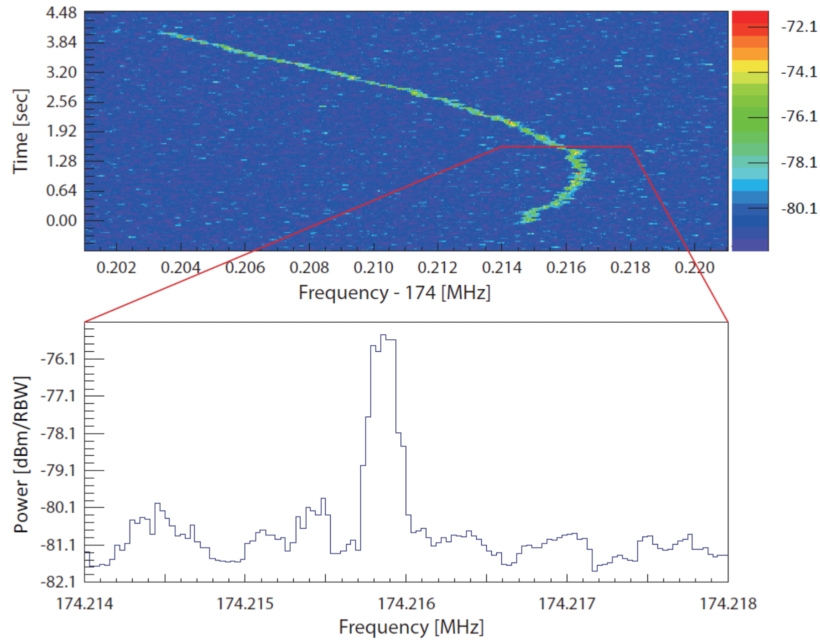

Figure 2: The upper part is a spectrogram of a single ^{78}Kr ion. The ^{78}Kr ion was stored for 4 s. The lower part is a zoomed FFT spectrum in a frame of 32 ms. The output signal power is $P = -65.8$ dBm which is obtained by integrating the peak after subtracting the thermal noise. The frequency width is 224 Hz in FWHM.

in June 2015. We succeeded in injecting ^{78}Kr ions into the ring, by using the individual injection method with the fast-response kicker system. At first, the storage of ^{78}Kr ions was confirmed by a thin TOF detector installed in the ring [5]. The periodic pulses from the TOF detector were observed for approximately 25 μs, which corresponded to 60 turns in the ring. From this measurement, the revolution time of ^{78}Kr ions was obtained, and then resonance frequency was adjusted to be approximately 174.2 MHz, by moving the tuner position, where the 66th harmonics was taken. The first order correction of isochronicity was applied by adjusting the trim coils installed in the dipole magnets. After a storage of 700 μs, typical measurement time of mass spectrometry, the ^{78}Kr ions were successfully extracted by the same kicker magnet [6, 7].

Then, the operation mode of the ring was switched to the storage mode for the performance evaluation of the resonant Schottky pick-up. In the storage mode, the ^{78}Kr ions were stored for approximately 5 s. We successfully observed the signals of single ^{78}Kr ions in the Schottky spectrum, as shown in Fig. 2. The upper part of Fig. 2 is a spectrogram of ^{78}Kr. In this plot, the horizontal and vertical axis are the resonance frequency and time after injection, respectively. The lower part of Fig. 2 is a zoomed FFT spectrum in a frame of 32 ms. The vertical axis represents the induced power in dBm/Resolution Band Width (RBW). The frequency width was 224 Hz in FWHM, so here the frequency resolution was 1.29×10^{-6}. The measured signal power was $P = -65.8$ dBm, where P was obtained by integrating the peak in the Schottky spectrum after subtracting thermal noise background. For comparison, we calculated the expected signal power P_{cal}. P_{cal} was calculated using the following equation which represents the signal power of single ion with charge q [8, 9],

$$P_{cal} = \frac{1}{8}(qef)^2 R_{load}, \tag{1}$$

where e is an elementary charge, f is a revolution frequency, and R_{load} is calculated from the equation; $R_{load} = R_{sh}/Q_0 \times Q_{load}$. For ^{78}Kr beam with the energy of 168 MeV/nucleon, P_{cal} = -145.1 dBm. Actually, the pick-up signals were amplified by two low-noise amplifiers with the gain of 81 dB, and were sent to the counting room by a 30 m cable. Take into account the gains of the amplifiers and transmission losses of -2 dB, the expected signal power is obtained to be P_{cal} = -66.1 dBm. The observed Schottky signal power P is in good agreement with the expected P_{cal}.

If the isochronous field is perfectly fulfilled, the frequency peak observed in the spectrogram of Fig. 2 should not change even though the momentum of the stored ion changes. This means that observed curve in Fig. 2 should be a straight line. However we found a frequency shift which is considered to be caused by the momentum change due to the interactions with residual gas in the ring. The vacuum was still in the order of 10^{-5} Pa without the baking procedure.

Figure 3 shows the revolution time of ^{78}Kr ions as a function of momentum, where the revolution time was measured by the plastic scintillation counters placed at the entrance and exit of the ring, and the momentum was obtained from the position of ^{78}Kr ion at the dispersive focal plane in the injection beam line. The data was well reproduced by the fitted curve of the 2nd order polynomial, as shown by

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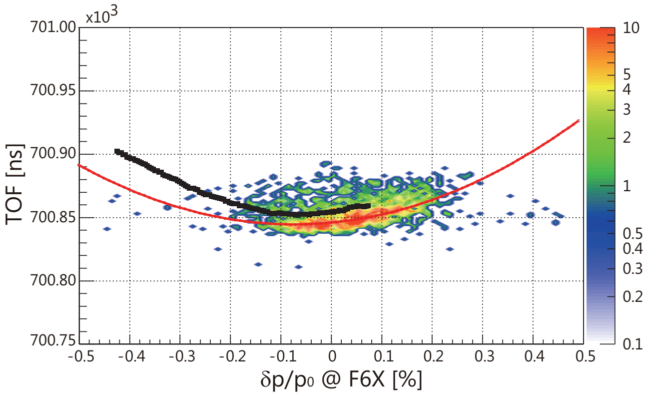

Figure 3: Revolution time as a function of the momentum of ^{78}Kr ions. Red curve is a fitted curve of the 2nd order polynomial. Black curve was obtained from the Schottky data after the conversion of the resonance frequency into the revolution time and the time after injection into the momentum based on the energy loss calculations in residual gas in the ring.

red curve. This indicates that the first order correction of isochronicity was properly applied. The black curve represents the converted data from the resonant Schottky pick-up as shown in Fig. 2. The revolution time was calculated from the resonance frequency taking into account the harmonics number. The momentum was calculated from the time after injection, by assuming that the ^{78}Kr ion loses kinetic energy in residual gas in the ring. The black curve is consistent with the red one. The injected ^{78}Kr ion with nearly central momentum moved along this curve. Thus, behavior of ^{78}Kr ion in the ring is suggested so that the ion lost kinetic energy gradually during storage of 4 s due to the energy loss process in residual gas.

CONCLUSION AND PROSPECT

First commissioning of the Rare-RI Ring using ^{78}Kr beam was performed successfully in June 2015. We confirmed injection into the ring and storage of single ^{78}Kr ions for a few seconds. The resonant Schottky pick-up detected single ^{78}Kr successfully. Based on the Schottky spectrum, the observed signal power is almost same as the expected signal power. The frequency resolution of $\sim 1.29 \times 10^{-6}$ was calculated from the width of the Schottky spectrum. The performance of the resonant Schottky-pick up is sufficient in terms of sensitivity and resolution. In addition, we will be able to evaluate the long term stability of the Rare-RI Ring operation based on the results of analysis which is in progress.

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