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Longitudinal modulation of electron-cooled $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams at heavy ion storage ring CSRe

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ABSTRACT

The longitudinal dynamics of electron-cooled and radio-frequency (RF)-bunched $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams have been investigated at a heavy-ion experimental cooler storage ring CSRe. An rf-buncher was employed to longitudinally modulate the ion beams. A new resonant Schottky pick-up was applied to monitor the intensities and longitudinal dynamics of stored and electron-cooled ion beams. Using electron-cooling, the separated Schottky noise signals of the $^{12}C^{6+}$ and $^{16}O^{8+}$ ions were clearly observed in the Schottky spectrum. The storage times and the particle numbers of both ion beams were measured by Schottky noise, which demonstrated the ability to perform Schottky mass spectrometry measurements and also the measurement of highly charged ions at the CSRe. In addition, an enhancement of the Schottky noise signals was observed for rf-bunched ion beams, which could be used to diagnose the intensity ion beams at storage rings. Finally, a broadly longitudinal manipulation of the ion beams by scanning the bunching frequency was realized. The investigation of electron–ion recombination experiment at ultra-low collision energies by scanning the bunching frequency of the ion beams at the storage ring CSRe is proposed.

1. Introduction

Heavy ion accelerator facilities combined with cooler storage rings have provided novel opportunities for precision nuclear and atomic physics experiments with highly charged ions and radioactive ions in the last two decades [1,2]. As compared with other apparatus, many unique experiments can be performed with stored and cooled ion beams with very high precision at heavy ion storage rings, such as Schottky mass measurement [3], beta decay measurement [4] and also X-ray precision spectroscopy experiments [5]. In all of such experiments, electron cooling is a powerful method to reduce the momentum spread and shrink the size of the stored highly charged ion beams in storage rings [6]. However, various experiments have to be performed with bunched ion beams which could be produced by using rf-buncher system, such as laser cooling of relativistic ion beams experiments [7,8], precision laser spectroscopy experiments of highly charged ions [9,10], internal target atomic experiments [11,12] and high energy density physics experiments [13–15]. Therefore, the investigations of the beam properties of the electron-cooled and rf-bunched ion beams are required not only from experimental side, but also very important for accelerator studies. The Schottky noise has already been used to diagnose the ion beam properties at most of the heavy ion storage rings. Compared with other diagnostic methods, the Schottky noise diagnostic is an established and non-destructive technique used to monitor properties of the circulating beam, such as beam intensity, revolution frequency, momentum spread, at heavy-ion storage rings [16,17].

Here, we report on an experiment that was conducted to investigate longitudinal dynamics of rf-bunched and electron-cooled $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams at experimental cooler storage ring (CSRe) at the Heavy Ion Research Facility in Lanzhou (HIRFL) [18]. In this experiment, the beam lifetimes and the numbers of $^{12}C^{6+}$ and $^{16}O^{8+}$ ions stored at the CSRe were determined by combining a DC current transformer (DCCT) and a resonant Schottky pick-up [19]. The longitudinal dynamics of electron-cooled and rf-bunched ion beams, including synchrotron motion frequency and the bucket acceptance were investigated by analyzing the recorded Schottky spectra. An enhancement of Schottky noise signals was observed for bunched ion beams. In addition, a broadly

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Table 1
Parameters for longitudinal dynamics measurements at the CSRe.

CSRe parameters	
Circumference	128.80 m
Ion species	$^{12}C^{6+}$ and $^{16}O^{8+}$
Beam energy	120.7 MeV/u
Relativistic β, γ	0.47, 1.13
Revolution frequency	1.083 MHz
Length of e-cooler	3.40 m
Electron current	500 mA
Electron voltage	67.08 kV
Electron beam diameter	50 mm
Transition energy γ_t	2.629
Splitting factor η	0.64
Beam lifetime	~70 s
RF-bunching voltage	30 V
Harmonic number h	50

longitudinal manipulation of the ion beams by scanning the bunching frequency was realized. The application of the rf-buncher to detune the relative collision energy between ions and electrons to conduct the electron–ion recombination experiment at the storage ring CSRe was proposed.

2. Experimental setup

The experiment was carried out on the CSRe [20] at the Institute of Modern Physics (IMP) in Lanzhou, China. The measurement of the longitudinal dynamics of electron-cooled and rf-bunched $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams was performed during a beam time dedicated for a preparation of laser cooling experiments at the CSRe. In the experiment, the $^{12}C^{3+}$ and $^{16}O^{4+}$ ions were produced in an electron cyclotron resonance (ECR) ion source [21]. After accelerated by a Sector Focused Cyclotron (SFC), the ions were injected into the main cooler storage ring (CSRm). After acceleration at the CSRm to an energy of 120.7 MeV/u corresponding to an ion velocity of 47% of the speed of light, the $^{12}C^{3+}$ and $^{16}O^{4+}$ ion beams passed through a stripper carbon foil after a fast extraction from the CSRm thus producing bare $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams. The produced $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams were selected from the second Radioactive Ion Beam Line at Lanzhou (RIBLL2), and then were injected into the CSRe. The schematic view of the experimental setup at the CSRe is shown in Fig. 1.

During the experiment at the CSRe, an electron cooler EC-300 [22] was continuously employed to cool the $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams to reduce the momentum spread and shrink the size of the stored beams. A rf-buncher was employed to longitudinally modulate and manipulate the ion beams, and the detailed description of the rf-buncher can be found in reference [23]. A DC current transformer (DCCT) was used to measure the ion beam current. A resonant Schottky pick-up [16,19] was employed to investigate the longitudinal beam dynamics of $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams. The Schottky pick-up detects the induced resonant signals of ions circulating in the storage ring, and the signals are recorded by a spectrum analyzer of Tektronix RSA 5106A [24]. By Fast Fourier Transformer (FFT), the frequency domain of the Schottky spectra can be obtained. It should be noted, that the resonant Schottky pick-up installed at the CSRe has one ion sensitivity potential as already demonstrated for beta decay measurement at the heavy ion storage ring ESR at GSI [25]. The main experimental parameter settings are listed in Table 1. The circumference of the CSRe is 128.8 m leading to a revolution frequency of 1.083 MHz for ion beams at an energy of ~120 MeV/u. The electron cooler was operated with an electron current of 500 mA and a high voltage of 67 kV during the experiment. In order to longitudinally modulate the ion beams, a sinusoidal rf voltage of 30 V was applied on the rf-buncher at the 50th harmonic of the revolution frequency to capture and bunch the ion beams under electron cooling.

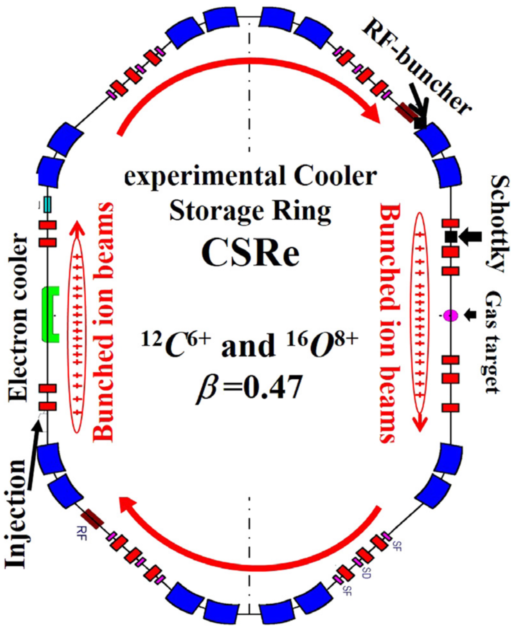

Fig. 1. Schematic view of the CSRe and the experimental setup for longitudinal dynamics measurements of $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams. The locations of the Schottky resonator, the rf-buncher, and the electron cooler are indicated.

3. Longitudinal dynamics of electron-cooled and rf-bunched ion beams

3.1. Measurement of the lifetimes and the intensities of $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams

In the experiment, since the $^{12}C^{6+}$ and $^{16}O^{8+}$ ions have very small difference of mass-to-charge ratio (~3.18×10^{-4}) [26], they cannot be separated by the analyzing magnets before injected into the heavy ion storage ring CSRe. Therefore, both of them were injected and circulating in the CSRe. Since the electron-cooling was applied for all the storage time, these two ions can be separated in the momentum phase space, and as can be found in Fig. 2 of the Schottky spectrum of electron-cooled beams. From the beginning to 150 s, the coasting $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams were circulating in the CSRe. It can be found that the $^{12}C^{6+}$ ion beams were modulated when the rf-buncher system was operated at the harmonic number of revolution frequency of $^{12}C^{6+}$ ions with a sinusoidal-waveform voltage, while the $^{16}O^{8+}$ ion beam was still coasting ion beam.

In storage rings, the difference of the revolution frequencies between the $^{12}C^{6+}$ and $^{16}O^{8+}$ ion beams can be written as [27]:

$$\frac{\delta f}{f_{rev}} = -\frac{1}{\gamma_t^2}\times\frac{\delta(m/q)}{m/q} + \left(1-\frac{\gamma^2}{\gamma_t^2}\right)\times\frac{\delta v}{v} \tag{1}$$

where f_{rev} is the revolution frequency, m is the ion mass, q is the charge of the ion, γ is the relativistic Lorentz factor, γ_t is the transition energy of the accelerator, and $\delta v/v$ is the relative velocity difference. By employing the electron cooling, the velocities distribution of the stored ion beams will be dramatically reduced, and the velocity difference of the $^{12}C^{6+}$ and $^{16}O^{8+}$ ions can be neglected, therefore for the electron cooled beams Eq. (1) can be written as:

$$\frac{\delta f}{f_{rev}} \approx -\frac{1}{\gamma_t^2}\times\frac{\delta(m/q)}{m/q} \tag{2}$$

By taking the charges and masses of $^{12}C^{6+}$ and $^{16}O^{8+}$ ions into account, the calculated difference of the relative frequency between these ions is $\delta f/f = 4.6\times10^{-5}$ corresponding to momentum difference of $\delta p/p = 7.0\times10^{-5}$ by using the equation $\delta p/p = 1/\eta\cdot\delta f/f$, which agrees with