RF-bunching of relativistic $^{12}$C$^{3+}$ ion beam for laser cooling experiment at the CSRe

H B Wang $^{1,2}$, W Q Wen$^1$, X Ma$^1$, Z K Huang$^{1,2}$, D C Zhang$^1$, M Bussmann$^3$, D F A Winters$^1$, Y J Yuan$^1$, X L Zhu$^1$, D M Zhao$^1$, R S Mao$^1$, J Li$^1$, L J Mao$^1$, J C Yang$^1$, H W Zhao$^1$, H S Xu$^1$, G Q Xiao$^1$ and J W Xia$^1$

$^1$Institute of Modern Physics, Chinese Academy of Sciences, 730000 Lanzhou, China
$^2$University of Chinese Academy of Sciences, 100049 Beijing, China
$^3$Helmholtz-Zentrum Dresden-Rossendorf, 01328 Dresden, Germany
$^4$GSI Helmholtzzentrum für Schwerionenforschung GmbH, D-64291 Darmstadt, Germany

E-mail: x.ma@impcas.ac.cn

Abstract. To prepare the upcoming experiment of laser cooling of relativistic $^{12}$C$^{3+}$ ion beams at the experimental cooler storage ring (CSRe), a test experiment was performed with $^{12}$C$^{3+}$ ion beams at an energy of 122 MeV/u on the CSRe, at the Institute of Modern Physics, Lanzhou, China. In this experiment, the main storage ring of CSRm was employed to accumulate and accelerate the ion beam which was injected into the CSRe for the experiments. The number of $^{12}$C$^{3+}$ ions at the CSRe reached $5\times10^8$ for every injection, which satisfied the experimental requirement. To fulfil the laser cooling experiment, the $^{12}$C$^{3+}$ ion beams were bunched by sinusoidal waveforms with fixed and sweeping frequencies, respectively. A resonant Schottky pick-up was employed to record the Schottky spectra of these ion beams. The test experimental results demonstrated that the RF-buncher and diagnostic systems at the CSRe worked well and the CSRe was very stable with $^{12}$C$^{3+}$ ion beams, hereby the CSRe is suitable for laser cooling experiment.

1. Introduction

Realizing a crystalline ion beam is one of the ultimate goals of laser cooling of heavy ion beams at the storage rings. Laser cooling has been considered to be the only one method to realize the crystalline ion beams at the storage ring because of its extremely narrow and strong cooling force [1, 2]. The other motivation for laser cooling at the experimental cooler storage ring (CSRe) at IMP and the ESR at GSI is to extend this technique to the future large accelerator facilities, such as the Facility for Antiprotons and Ion Research (FAIR) at Darmstadt in Germany [3] and the High Intensity heavy ion Accelerator Facility (HIAF) at Lanzhou in China [4]. The precision nuclear and atomic experiments with highly charged ions will greatly benefit from ion beams with ultra-low momentum spread. Therefore powerful cooling techniques are important for future high-quality relativistic heavy ion beams.

Compared to the normal laser cooling experiment at traps [5, 6] and low-energy storage rings [7], laser cooling of relativistic heavy ions can only rely on laser beams counter-propagating with the ion beams and the laser cooling force is predicted to principally increase with the third power of the ion energy due to the fast transition rates in highly charged ions and relativistic Doppler shift [8]. Fortunately, the method by combining only one laser beam and a RF-buncher to cool the ion beams at
storage rings has already been developed by Hangst et al [9], and was applied in many other storage rings such as the TSR [10] and the ESR [11-13] in Germany, and S-LSR [14, 15] in Japan.

To prepare the upcoming experiment of laser cooling of relativistic $^{12}$C$^{3+}$ ion beams at the CSRe, a test experiment of $^{12}$C$^{3+}$ ion beams with the required beam energy for laser cooling experiment was performed. All of the beam diagnostic system and newly installed RF-buncher were employed during the experiment. The experimental results demonstrated that the CSRe is suitable for the laser cooling experiment.

2. Experimental setup
The test experiment was performed with $^{12}$C$^{3+}$ ion beams on the CSRe, at the Institute of Modern Physics, Lanzhou, China. In the experiment $^{12}$C$^{3+}$ ions were produced by an Electron Cyclotron Resonance (ECR) ion source. Then the ions were accelerated by a Sector Focused Cyclotron (SFC), and injected into the main Cooler Storage Ring (CSRm). After accumulation and acceleration in the CSRm, the ion beams were extracted and injected into the CSRe at the energy of 122 MeV/u (the ion velocity of 47% of the speed of light). Since the circumference of the CSRe is 128.8 m, this beam energy leads to the revolution frequency of 1.087 MHz. A schematic view of the experimental setup at the CSRe is shown in figure 1 and the parameter settings of the CSRe for this experiment are listed in Table 1.

There are two straight sections both with a length of 30 m in the CSRe. On one section there are diagnostic systems and the internal gas target and the laser cooling experiment will be performed at this straight section as shown in figure 1. The other section installed electron cooler system. In this experiment, the lifetime of ion beam was measured by a DC current transformer (DCCT). As shown in figure 2, the typical multi-injected beam current of the $^{12}$C$^{3+}$ ion beams is about 300 µA which corresponds to approximately $5.7 \times 10^8$ ions circulating in the ring. The beam lifetime is determined to be less than 5 seconds by an exponential fitting. The too short lifetime is because of the bad vacuum condition at the CSRe (about $2 \times 10^{-10}$ mbar). The resonant Schottky pick-up was used to monitor the revolution frequency and the longitudinal momentum spread of the stored ions. A spectrum analyzer (Tektronix RSA5100A) was used to record the Schottky spectra to get the dynamics and the momentum spread of the beams. Two ultraviolet sensitive photomultiplier tubes (UV PMTs, Eelectron Tube 9403B) and a movable ultraviolet sensitive Channeltron photomultiplier (UV CPM, PHOTONIS CEM4869) were installed to observe the fluorescence produced by the interactions between the ions and the residual gas in the CSRe [16] and the fluorescence from the de-excitation of the projectile ions excited by the laser and the interactions between the ions and the residual gas in the CSRe.

![Figure 1](image_url)  
**Figure 1** Schematic view of the experimental setup at the CSRe, the locations of the resonant Schottky pick-up, RF-buncher, UV PMTs and the UV CPM are shown. The ion beam will be bunched to ten bunches at the CSRe if the RF-buncher operated at the 10th harmonic of the revolution frequency.
Table 1. Parameters of the CSRe in this experiment.

| Parameters          | CSRe          |
|---------------------|---------------|
| Circumference       | 128.80 m      |
| Ion species         | $^{12}$C$^{3+}$ |
| Beam energy         | 122 MeV/u     |
| Relativistic $\beta, \gamma$ | 0.47, 1.13  |
| Revolution freq.    | 1.087 MHz     |
| Transition factor $\gamma_t$ | 2.629   |
| Slip factor $\eta$ | 0.64          |
| Lifetime            | ~ 5 s         |
| Harmonic number $h$ | 10, 20, 35, 50 |
| $\Delta p/p$ inside the bucket | $< 2 \times 10^{-5}$ |

![Figure 2](image_url) The beam current versus storage time measured by the DCCT, and the beam lifetime is 4.45 ± 0.07 s.

In order to produce a counterclockwise force for the laser resonant scattering force during laser cooling experiments, a RF-buncher was installed at the CSRe, for details see Wen et al. [17], we only give a brief introduction here. The sinusoidal waveforms were produced by signal generator (Tektron AFG3235). After amplification, these signals were added on the RF-buncher to modulate longitudinally the ion beam. The frequency of the RF-bunching was set as the harmonic of the revolution frequency $f_{\text{bunch}} = h \times f_{\text{rev}} = h \times v/C$, where $v$ is the velocity of the ion beam, $C$ is the circumference of the storage ring and $f_{\text{rev}}$ is the revolution frequency of $^{12}$C$^{3+}$ ions and the harmonic number $h$ gives the number of ion bunches in the storage ring. In this experiment, the frequency of the RF-buncher was operated from the 10th to 50th harmonic of the revolution frequency and the amplitudes (peak-to-peak value) were set from 100 mV to 500 mV, respectively. Since the beam lifetime (< 5 s) was too short to investigate the longitudinal dynamics systematically, as a result, the beam width and the bunch length were not measured. In order to perform the planned laser cooling experiments at the CSRe, the vacuum has to be improved at least one order of magnitude by baking of the whole storage ring which is under progressing. The relative longitudinal momentum spread of the ions inside the bucket has been determined to be less than $2 \times 10^{-5}$. The synchrotron frequency, which is oscillation frequency of the ions in the bucket, could be extracted from the Schottky spectrum [18].

3. Longitudinal RF-bunching of relativistic $^{12}$C$^{3+}$ ion beam

3.1. RF-bunching by fixed frequency sinusoidal-waveforms
To test the RF-buncher system, the injected ion beams were bunched by radio-frequency sinusoidal waveforms at various harmonic numbers and bunching voltages. The Schottky spectra of RF-bunched $^{12}\text{C}^{3+}$ at 35th harmonic number with an amplitude of 300 mV and 50th harmonic with an amplitude of 500 mV are shown in figure 3. The horizontal axis and the vertical axis are frequency and time, respectively. In figure 3 (a) and (b), there are many peaks in the Schottky spectra, and the distance between every adjacent peaks are the synchronous oscillation frequency $\omega_s$ of the ions inside the bucket, which can be written as [19]:

$$\omega_s = \frac{\omega_{rev}}{\beta} \sqrt{\frac{qehnU_b}{2\pi mc^2}}$$

where $\omega_{rev}$ is the revolution frequency of the ion beams, $\beta$ the relativistic factor, $q$ the charge state of the ions, $h$ the harmonic number, $\eta$ the momentum slip factor, $\gamma$ the relativistic Lorentz factor, $c$ the velocity of the light, and $U_b$ the effective bunching voltage which can be written as

$$U_b = 2U_0 \sin \frac{\pi hL}{C}$$

where $U_0$ is the voltage added on the RF-buncher, $L$ the length of the parallel plate of the RF-buncher, and $C$ the circumference of the CSRe.

By using equation (1), the effective bunching voltages can be calculated from the extracted synchrotron frequency of the Schottky spectra. The effective RF-bunching voltage in the figure 3 (a) and (b) are about 38 V and 145 V, respectively. These bunching voltages are enough to produce the counteract-force for the laser cooling experiments.

![Figure 3](image)

**Figure 3** Schottky spectra for RF-bunched $^{12}\text{C}^{3+}$ ion beams bunched by sinusoidal waveforms. For figure (a) the harmonic number is 35th and the voltage is 300 mV while for figure (b) the harmonic number is 50th and the voltage is 500 mV.

3.2. *Longitudinal momentum spread of $^{12}\text{C}^{3+}$ ion beam inside of the bucket*

Since laser cooling is only working at the longitudinal direction of the ion beams, the longitudinal momentum spread of the ion beams is the most important index during the laser cooling experiment. The Schottky spectrum shown in figure 4 is the projection of the slice-1 in figure 3 (b), the horizontal axis is frequency and the vertical axis is the Schottky noise power intensity. The longitudinal momentum spread can be obtained by the frequency distribution of the ion beam by the equation

$$\frac{\Delta p}{p} = \frac{1}{\eta} \frac{\Delta f}{f}$$

(3)
where $\Delta f/f$ can be derived from the measured Schottky spectrum, and $\eta$ is the momentum slip factor of the accelerator, $\eta = 1/\gamma^2 - 1/\gamma_r^2$, where $\gamma$ is the relativity Lorentz factor and $\gamma_r$ is transition energy of the accelerator. The Gaussian fitting result of the Schottky spectrum is show in figure 4 with a red line, from which we can deduce that the relative momentum spread is about $1.25 \times 10^{-5}$. But one should note, the relative momentum spread is the result of the bucket acceptance, not resulted from electron-cooling.

![Figure 4](image.png)

**Figure 4** Schottky spectrum of the projection of slice-1 in figure 3 (b), the momentum spread is about $1.25 \times 10^{-5}$ obtained from Gaussian fitting (a red line) which indicates the acceptance of the bucket.

3.3. RF-bunching of $^{12}\text{C}^{3+}$ ion beams by sweeping frequency sinusoidal-waveforms

The observed Schottky spectrum by sweeping the frequency of the RF-buncher is shown in figure 5, the RF-buncher was operated at the 35th harmonic number and the voltage of 500 mV. The sweeping speed was 5 Hz per second. From figure 5, it can be seen that the ions were bunched and scanned by the RF-buncher. The ion beams will be cooled when a resonant laser beam is applied with this RF-bunched and swept ion beams during the next laser cooling experiment.

![Figure 5](image.png)

**Figure 5** Schottky spectrum for RF-bunched $^{12}\text{C}^{3+}$ ions bunched by a sinusoidal waveform of sweeping frequency at the speed of 5 Hz/s at the harmonic number of 35th and the voltage of 500 mV.

3.4. Observation of $^{12}\text{C}^{3+}$ and $^{16}\text{O}^{4+}$ by Schottky noise signals

The ions of $^{12}\text{C}^{3+}$ and $^{16}\text{O}^{4+}$ have almost the same charge-mass ratio, therefore, it is not possible to separate them from the ion source and at the CSRm. However, since these two ion species still have a very small difference of charge-mass ratio, the two ion beams could be separated after electron cooling and be observed on the Schottky spectrum. This observation has already been confirmed at the experimental storage ring ESR at GSI. The frequency distribution of the ion beams at the storage ring can be written as [20, 21]:

$$...$$
\[
\frac{\Delta f}{f} = -\frac{1}{\gamma_i^2} \times \frac{\Delta (m/q)}{m/q} + \left(1 - \frac{\gamma^2}{\gamma_i^2}\right) \times \frac{\Delta v}{v} \tag{4}
\]

Where \(f\) is the evolution frequency, \(m\) is the mass, \(q\) is the amount of charge, \(\gamma\) is the relativistic Lorentz factor, \(\gamma_i\) is the transition energy of the accelerator, and \(\Delta v/v\) is the velocity spread. By employing the electron cooling, \(\Delta v/v\) can be considered to be negligible small (zero), and therefore equation (4) becomes

\[
\frac{\Delta f}{f} = -\frac{1}{\gamma_i^2} \times \frac{\Delta (m/q)}{m/q} \tag{5}
\]

By careful calculation, the relative frequency difference between the \(^{12}\text{C}^{3+}\) and \(^{16}\text{O}^{4+}\) is \(4.6 \times 10^{-5}\). Since the Schottky pick-up was operated at 243 MHz, the 224th harmonic of the revolution of the ion beam, the \(\Delta f\) of \(^{12}\text{C}^{3+}\) and \(^{16}\text{O}^{4+}\) should be about 11.2 kHz, which can be easily observed in the Schottky spectrum. As mentioned before, after improving the vacuum of the CSRe, the ratio and lifetimes of these two ion species can be measured directly by the Schottky spectrum. In addition, the sympathetic cooling of \(^{16}\text{O}^{4+}\) by laser cooled \(^{12}\text{C}^{3+}\) is under consideration. The simulation work has already been started and the detailed discussion of this subject will be given elsewhere.

4. Conclusion

A test experiment of \(^{12}\text{C}^{3+}\) ion beams was performed at the CSRe to prepare the upcoming laser cooling of relativistic Li-like carbon ion beams. All of the experimental setup and parameters which will be used for the next experiment were tested during this beam time. The test experiment showed that the resonant Schottky pick-up system and the RF-buncher worked well for \(^{12}\text{C}^{3+}\) ion beams at an energy of 122 MeV/u by electron cooling at the CSRe and the CSRe is very stable for every injection beam lifetime. The problem of vacuum of the CSRe will be solved during summer maintenance time, before the next beam time.

In the forthcoming laser cooling experiment, an ultraviolet sensitive CPM system which has been installed inside of the vacuum will be used to observe fluorescence signals, and a cw laser system [22] and a pulsed laser system [23] will be transported from TU Darmstadt and HZDR to IMP, respectively. The relativistic lithium-like \(^{12}\text{C}^{3+}\) ion beams will be cooled by combining a scanning cw laser beam and a RF-buncher after the pre-electron-cooling. This is a very promising way to enlarge the momentum acceptance of the laser force by scanning the bunching frequency or the laser wavelength. Both methods will be used to investigate the dynamics of the ultra-cold ion beams and strong-coupling effects at the CSRe. In addition, we will have a possibility for the first time to realize laser cooling experiment by combining a pulsed laser system and a cw laser system. This would be greatly helpful to study laser cooling and make this promising technique ready for routine application before future storage rings become operation, e.g. FAIR in Darmstadt, Germany and HIAF in Lanzhou, China. The precision laser spectroscopy experiments of Li-like and Na-like highly charged ions will also be implemented in future storage ring facilities [24].

Acknowledgments
The experiment was performed within the Laser Cooling Working Group. This work was supported by National Natural Science Foundation of China through grant no. 11221064 and GJHZ1305.

References
[1] Habs D, and Grimm R 1995 Annu. Rev. Nucl. Part. S. 45 391-428.
[2] Schramm U, and Habs D 2004 Prog. Part. Nucl. Phys. 35 583-677.
[3] Henning W F 2004 Nucl. Instrum. Meth. B 214 211–215
[4] Yang J C, Xia J W, Xiao G Q, Xu H S, Zhao H W, Zhou X H, Ma X W, He Y, Ma L Z, Gao D Q, Meng J, Xu Z, Mao R S, Zhang W, Wang Y Y, Sun L T, Yuan Y J, Yuan P, Zhan W L, Shi J,
Chai W P, Yin D Y, Li P, Li J, Mao L J, Zhang J Q, and Sheng L N 2013 *Nucl. Instrum. Meth. B* **317** 263-265.

[5] Birkl G, Kassner S, and Walther H 1992 *Nature* **357** 310-313.

[6] Schätz T, Schramm U, and Habs D 2001 *Nature* **412** 717-720.

[7] Schröder S, Klein R, Boos N, Gerhard M, Grieser R, Huber G, Karafilidis A, Krieg M, Schmidt N, Kühl T, Neumann R, Balakin V, Grieser M, Habs D, Jaeschke E, Krämer D, Kristensen M, Music M, Petrich W, Schwalm D, Sigray P, Steck M, Wanner B, and Wolf A 1990 *Phys. Rev. Lett.* **64** 2901-2904.

[8] Schramm U, Bussmann M, and Habs D 2004 *Nucl. Instrum. Meth. A* **532** 348-356.

[9] Hangst J S, Nielsen J S, Poulsen O, Shi P, and Schiffer J P 1995 *Phys. Rev. Lett.* **74** 4432-4435.

[10] Eisenbarth U, Mudrich M, Eike B, Grieser M, Grimm R, Luger V, Schätz T, Schramm U, Schwalm D, and Weidemüller M 2000 *Hyperfine Interact.* **127** 223-235.

[11] Schramm U, Bussmann M, Habs D, Kuhl T, Beller P, Franzke B, Nolden F, Steck M, Saathoff G, Reinhardt S, and Karpuk S 2006 *AIP Conference Proceedings* **821** 501-509.

[12] Bussmann M, Habs D, Schramm U, Beckert K, Beller P, Franzke B, Kozuharov C, Kühl T, Nörtershäuser W, Nolden F, Steck M, Karpuk S, Geppert C, Novotny C, Saathoff G, and Reinhardt S 2007 *Proceedings of the Workshop on Beam Cooling and Related Topics, COOL 07* **1** 226-229.

[13] Bussmann M, Schramm U, Habs D, Steck M, Kühl T, Beckert K, Beller P, Franzke B, Nörtershäuser W, Geppert C, Novotny C, Kluge J, Nolden F, Stöhlker T, Kozuharov C, Reinhardt S, Saathoff G, and Karpuk S 2007 *J. Phys.: Conf. Ser.* **88** 012043.

[14] Tanabe M, Ishikawa T, Nakao M, Souda H, Ikegami M, Shirai T, Tongu H, and Noda A 2008 *Appl. Phys. Express* **1** 028001.

[15] Nakao M, Hiromasa T, Souda H, Tanabe M, Ishikawa T, Tongu H, Noda A, Jimbo K, Shirai T, Grieser M, Okamoto H, and Smirnov A V 2012 *Phys. Rev. ST Accel. Beams* **15** 110102.

[16] Wen W Q, Lochmann M, Ma X, Bussmann M, Winters D F A, Nörtershäuser W, Botermann B, Geppert C, Frömmgen N, Hammen M, Hannen V, Jöhren R, Kühl T, Litvinov Y A, Sánchez R, Stöhlker T, Vollbrecht J, Weinheimer C, Dimopoulou C, Nolden F, and Steck M 2013 *Nucl. Instrum. Meth. A* **711** 90-95.

[17] Wen W Q, Ma X, Bussmann M, Yuan Y J, Zhang D C, Winters D F A, Zhu X L, Li J, Liu H P, Zhao D M, Wang Z S, Mao R S, Zhao T C, Wu J X, Ma X M, Yan T L, Li G H, Yang X D, Liu Y, Yang J C, Xia J W, and Xu H S 2014 *Nucl. Instrum. Meth. A* **736** 75-80.

[18] Wen W Q, Ma X W, Zhang D C, Zhu X L, Meng L J, Jie L, Liu H P, Zhao D M, Wang Z S, Mao R S, Zhao T C, Wu J X, Ma X M, Yan T L, Li G H, Yang X D, Liu Y, Yang J C, Yuan Y J, Xia J W, Xu H S, Xiao G Q, and Zhao H W 2013 *Chinese Phys. C* **37** 107005.

[19] Boussard D 1986 *CERN* **86-11** 749-782.

[20] Bosch F, Litvinov Y A, and Stöhlker T 2013 *Prog. Part. Nucl. Phys.* **73** 84-140.

[21] Litvinov Y A, and Bosch F 2011 *Rep. Prog. Phys.* **74** 016301.

[22] Beck T, Rein B, and Walther T 2013 *CLEO: 2013, Optical Society of America, San Jose, California* JTh2A 66.

[23] Siebold M, Hein J, Wandt C, Klingebiel S, Krausz F and Karsch S 2008 *Opt. Express* **16** 3674-3679.

[24] Backe H 2007 *Hyperfine Interact.* **171** 93-107.