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SAWTOOTH WAVE BUNCHER UPGRADE FOR SFC CYCLOTRON *

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Abstract

To increase extracted beam intensity, the SFC cyclotron requires that the sawtooth wave buncher on its injection line provide the effective voltage up to 2.5kV and cover a wide frequency range of six times. We develope a multi-harmonic synthesis method by combining a broadband amplifier and impedance transformer, which provide a high-voltage single-gap buncher at limited space and cost. With this method, the maximum voltage of the new buncher exceeds 2.5kV and the beam intensity increases by a factor of 6.7.

INTRODUCTION

The Heavy Ion Research Facility in Lanzhou (HIRFL) is the largest heavy ion accelerator complex in China, which consists of two electron cyclotron resonant (ECR) ion sources, sector focused cyclotron (SFC), separated sector cyclotron (SSC), cooling storage ring ring (CSR), radioactive beam line and experimental terminal [1]. The injector SFC cyclotron is a 1.7 meters sector-focused cyclotron with the K value of 69. It is equipped with two exteranl ECR ion sources named LECR3 and SECRAL-II respectively [2]. The layout of SFC injection system is shown in Fig. 1. A linear buncher B02 was installed in the vertical beam line section underneath the cyclotron center area, about 2.3 meters upstream the inflector. As the only buncher used in the

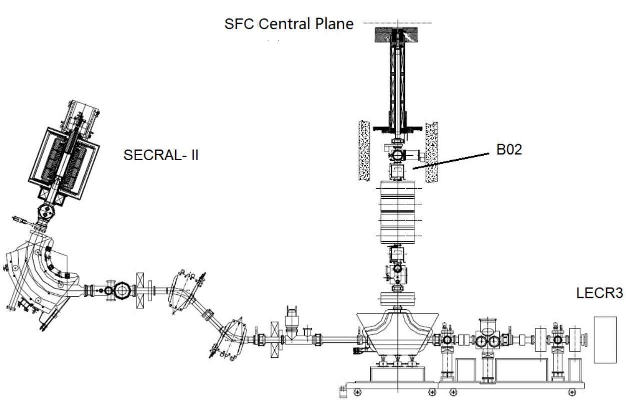

Figure 1: Layout of SFC axial injection system.

axial injection system, the B02 in principle improves the injection efficiency of the SFC and increases the extracted beam intensity compared with the case without it. However, from the operation in the past few years, there are still 3 aspects need to be improved: (1) intense beams with high and intermediate charge states from ECR ion sources requires high bunching voltage to compensate space charge effect; (2) there is no half-frequency mode which can increase longitudinal matching efficiency between SFC and SSC in cascade with SSC [3]; (3) equipment faults of B02 due to aging components have reduced the beam supply time of SFC [4].

PHYSICAL REQUIREMENTS

In this chapter theoretical description of axial velocity modulation of continuous DC ion beam is given as well as the special physical requirements. The overall specification of buncer is shown in Table 1.

SFC is a multi-particle and variable energy accelerator, and the design specifications of the buncher should adapt to its transformation range. The voltage amplitude of the buncher can be expressed as [5]

$$V_b = (\beta\lambda/L)(\eta)V_{inj} , \tag{1}$$

where L is the bunching distance, η is the effective duty cycle, and V_{inj} is the injection voltage. In our case the maximum ECR extraction voltage is 25 kV. The distance from the buncher to the inflector is 2.3 meters and $\beta\lambda$ is 16 mm when operating in the first harmonic mode with the maximum frequency of 16 MHz. These parameters give us an estimation of 1200 V for the saw-tooth voltage.

Due to mismatching of the SFC's extraction radius (R=0.75 meters) with the SSC's injection radius (R=1.0 meters), when SFC works at the mode h=1 and SSC at h=2, the longitudinal match efficiency between the two cyclotrons is only 50% in theory [3]. To regain the lost beam, a additional half-frequency bunching mode is required. In this mode, the buncher operates at half-frequency of SFC RF frequency with the double bunching voltage squeezing the original two packets into the one that can be accepted by the RF of SSC. Therefore, the buncher working frequency range is changed from 5.5-16.0 MHz to 2.75-8.0 MHz with the Maximum bunching voltage increasing from 1.27 kV to 2.54 kV.

Table 1: Design Parameters of Buncher

Parameter	Value
Input Frequency	5.5~16.0MHz
Input Level	7dBm
Work Frequency	5.5MHz~16.0MHz
Work Frequency∗	2.75MHz~8.0MHz
Voltage	≤1.27kV
Voltage∗	≤2.54kV
Amplitude Stability	≤1%
Phase Stability	≤1°

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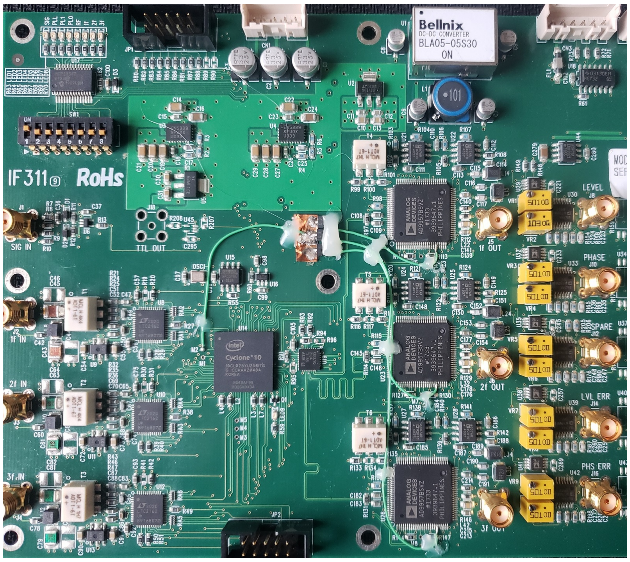

Figure 2: Sawtooth wave synthesis.

RF DESIGN OF THE NEW BUNCHER

Based on different specifications of operating frequency and bunching voltage, the sawtooth buncher is realized with different methods at different facilities. These include: (1) resonator-based multi-harmonics buncher developed at ATLAS or FRIB [6]; (2) high voltage direct forming method used at HIRFL or SPIRAL [3, 7]; (3) double drift system proposed by Goldstein and Laisne [8]; (4) low-level multi-harmonic synthesis and wide frequency band amplifier used in RIKEN.

Considering the limiation in space, the broad frequency band and high bunching voltage, and the maintainance, the present system is designed to be modular, which includes a sawtooth wave generator, wide-band amplifier and power supply, electrode, and impedance transformer.

Sawtooth Wave Generator

The sawtooth wave generator is designed to generate low-level sawtooth waves by combining fundamental wave, 2nd harmonic, and 3rd harmonic. The voltage signal composed of three harmonics is given by

$$V(t) = V_0[sin(\omega t) - 1/3sin(2\omega t) + 1/9sin(3\omega t)], \quad (2)$$

where V_0 is the fundamental wave voltage, $V(t)$ is the total voltage, and ω is the frequency of fundamental wave. As described in Fig. 2, the fundamental wave is generated by Quadrature Digital Up Converters (QDUC) chip, Analog Devices AD9957, which functions as a universal IQ modulator and agile upconverter. The AD9957 integrates a high-speed, direct digital synthesizer (DDS), a high performance, high speed 14 bit digital to analog converter (DAC), clock multiplier circuitry, and digital filters onto a single chip. In order to optimize the waveform generation both the amplitude and phase of the fundamental wave are precisely regulated with a feedback loop. RF pick-up signals from the electrode are filtered by the corresponding bandpass filter and conditioned, then sampled by 16-bit ADC. Digital signal processing of the sampled RF signals is implemented in FPGA. IQ demodulator, cordic, and PID controller module were implemented with Verilog code. The 2nd and 3rd harmonics are generated and regulated in the same way.

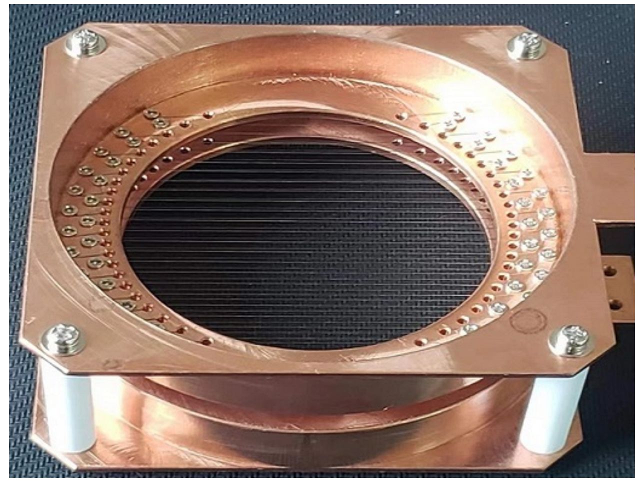

Figure 3: Electrode.

Figure 4: Transmission line transformer.

Electrode and Impedance Matching Unit

Figure 3 shows a improved grid with parallel wires made of 0.1 mm wire spaced 3 mm apart. The grid is aligned with a similar grid 6 mm away. Compared with the existing B02 grid, the improved grid increases the transmissivity by 10%.

The impedance transformer is used to match the capacitive load of the electrode with the 50 Ω output impedance of the power amplifier. Considering the frequency range of 2.75-48 MHz, a 1:9 transmission line transformer is used to convert 50 Ω to 450 Ω load (Fig. 4). As a result, the required maximum output power is reduced to one-ninth and the 2500 W broadband RF amplifier meets the requirements.

RF Broadband Amplifier

The broadband RF amplifier amplifies the sawtooth wave that combines the fundamental wave, 2nd harmonic, and

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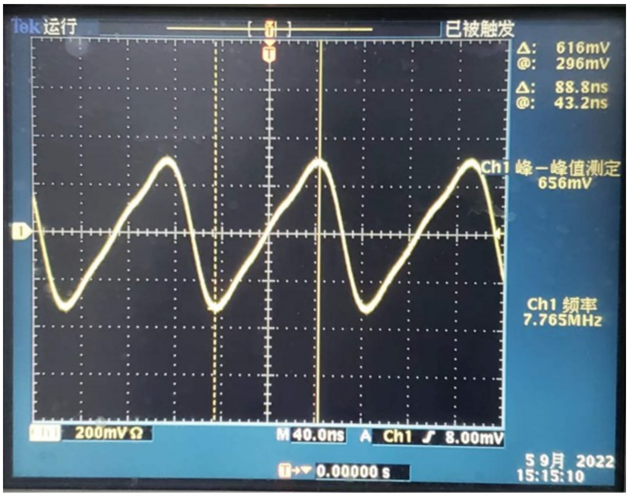

Figure 5: Sawtooth wave pickup

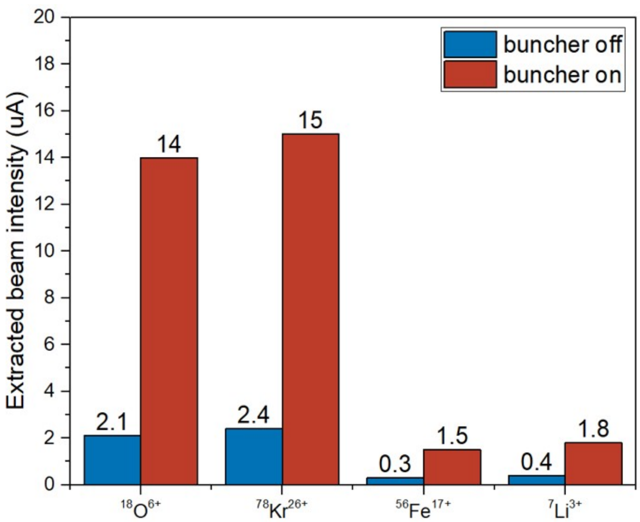

Figure 6: Beam test results

3rd harmonic. It consists of one power supply unit and two amplification units. The maximum input is 4dBm, the output power is 2500W for the fundamental wave, 250W for the 2nd harmonic and 25W for the 3rd harmonic, and -20dB for the harmonic suppression.

PERFORMANCE AND BEAM TEST

The new buncher has been installed online since September 2022. Several beam experiments have been carried out. The system has turned out to be reliable in operation and very useful in increasing the intensity level of the beam. In Fig.6 we have collected preliminary results for some heavy ion beams. As seen the gains in the beam intensity ranges from 4.5 up to 6.7. Next step, the detailed beam tests will be carried out, especially the half frequency mode which designed to improve SSC beam intensity.

CONCLUSION

A compact high voltage and broadband sawtooth wave buncher has been developed for the SFC cyclotron. The buncher is capable of being operated at full-frequency mode and half-frequency mode with the frequency ranging from 2.75 MHz to 8.0 MHz and 5.5 MHz to 16.0 MHz, and providing the effective voltage up to 1.27 kV and 2.54 kV respectively. Laboratory and online beam tests show that a 4.5 to 6.7 times gain in the beam intensity can be achieved with this method. The online test also verify the reliability and stability of the newly-designed system.

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