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SIMULATION AND BEAM EXPERIMENTS OF A MULTI-HARMONICS BUNCHER IN SSC-LINAC*

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Abstract

A compact dual-gap Multi-Harmonics Buncher has been successfully used at the SSC-Linac, a linear accelerator dedicates to beam injection into SSC in HIRFL. SSC-Linac operates at 53.667 MHz, which is forth time of the RF frequency of the SSC. In order to increase the longitudinal capture efficiency, and enhance the current out of SSC, an independent MHB(Multi-Harmonics Buncher) had been installed into the LEBT of SSC-Linac. The fundamental frequency of the MHB is 13.417 MHz. The buncher adopts the mechanical structure of dual-gap and sawtooth waveform is generated by multi-harmonics synthetic technology. Beam performance simulation with MHB have been done with code BEAMPATH. Besides, $^{84}Kr^{14+}$ beam has been bunched successfully using the MHB in our experiments, the maximum bunch efficiency of 86.1% has been measured in experiments.

INTRODUCTION

In 2019, a new linear accelerator named SSC-Linac has been installed as injector of Separate Sector Cyclotron (SSC) in The Heavy Ion Research Facility of Lanzhou (HIRFL). And before that, only a Sector Focusing Cyclotron (SFC) serves as injector in HIRFL, which severely limits the efficient beam time among the whole facility [1].

SSC-Linac mainly consists of the following parts: (a) an normal conducting ECR Ion Source provides heavy ions with 3.728 keV/u; (b) a 4-rod RFQ accelerates the ions to 143 keV/u [2]; (c) several separate IH-DTL [3] accelerate ions up to 1.5 MeV/u. SSC-linac can provide all kinds of heavy ions from carbon to uranium withmass-to-charge ratio between 3-7, and the particles intensity at the entrance of the SSC is greatly improved. The only limitation is that linac operates at rf frequency of 53.667 MHz, while the rf frequency of SSC is set to 13.417 MHz (H=6), so that only 25% ions injected into the SSC can be captured accelerate further.

In order to increase the capture efficiency in SSC, an external MHB has been installed as shown in Fig. 1. Under the action of electric field, coasting beam out of MHB will form a saw-tooth distribution. In this paper, beam bunch efficiency optimization has been done with code BEAMPATH [4]. What's more important, beam experiments with MHB have been done and bunch efficiency has been measured using the BPM downstream of the RFQ.

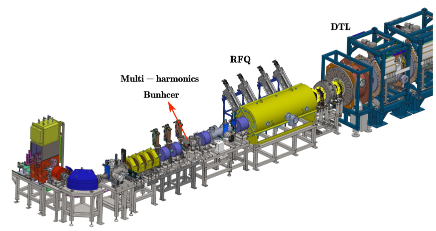

Figure 1: Layout diagram of SSC-Linac, location of the MHB has been marked.

DUAL-GAP TYPE MHB

Assuming for the MHB with fundamental frequency of 13.417 MHz in SSC-Linac with single gap, the leakage field at the both ends of the drift tubes become very large. In stark contrast to the dual-gap design, it has a negligible leakage field, whcih has been adopted by MHB in SSC-Linac. And the required voltage waveform is generated with up to third order harmonics by multi-harmonics synthetic technology. The effective voltage experienced by the particles after passing through the MHB can be expressed as follow

$$V_{total} = \sum_{n=1}^{3} -2V_n \sin\left(\frac{n\theta}{2}\right) \sin\left(2n\pi f t + \varphi_n + \frac{n\theta + \pi}{2}\right). \tag{1}$$

Here θ is 2.44 rad (140°) [5]. Where n, V_n, φ_n, f represents the harmonics numbers of the rf waves, the effective potential seen by the particles, the phase shift of each harmonics wave, the fundamental rf frequency, respectively. So, if we want to get a smooth sawtooth wave, we need set the appropriate parameters of each harmonics as follow [6]

$$V_n = a_n \cdot \frac{V}{-2 \cdot \sin\left(\frac{n\theta}{2}\right)} \quad \varphi_n = -\frac{n\theta + \pi}{2}, \tag{2}$$

where $a_n = \left(-\frac{1}{3}\right)^{n-1}$ represents the coefficients of each harmonics.

The prebuncher used in SSC-Linac mainly consists of two gaps. The physical view is shown in Fig. 2. The cavity longitudinal inner wall spacing is 49.2 mm in total, which is a very compact structure for beam bunching. The electric field can be formed in two gaps as shown in Fig. 2.

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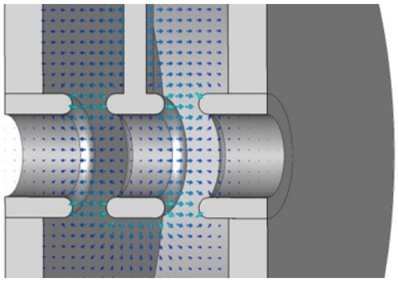

Figure 2: Schematic diagram of the three-dimensional structure of the MHB, together with the field distribution simulated by CST [7].

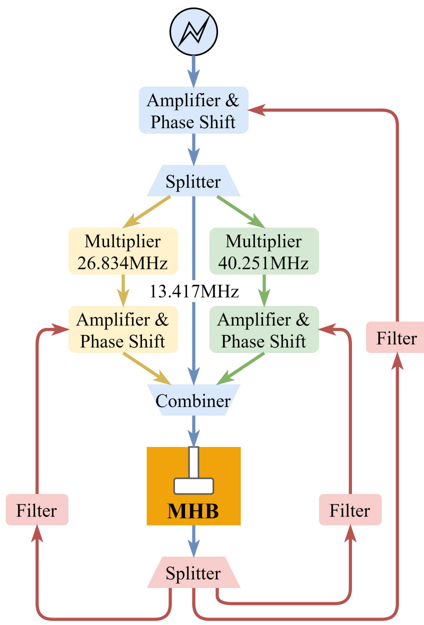

Figure 3: Flow diagram of the multi-harmonics buncher control system.

Figure 3 shows the control system of MHB. In detail, the fundamental wave of MHB is 13.417MHz divided into three groups and two of them are converted into second and third harmonics respectively by multipliers. Then these three signals are synthesized into one wave by means of an combiner. The synthesized RF signal is then amplified by a broadband amplifier. After that, wave are output to the central tube through an impedance converter.

SIMULATION OF THE MULTI-HARMONICS BUNCHER

Beam performance has been simulated with code BEAMPATH, Before simulation, the source program upgrade for adding the function of setting the phase of each harmonic independently has been done.In Fig. 4, it shows all the components involved in our simulations, in addition to MHB, there are RFQ and two solenoids. $^{84}Kr^{14+}$ ion was used in simulations.

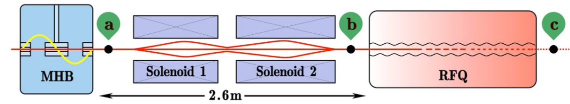

Figure 4: The main components included in the simulation.

Firstly, acceptance of RFQ aer as shown in Fig. 5, among them, marked with red will be captured by SSC eventually. The mission of the MHB is to bunch more particles into the red acceptance.

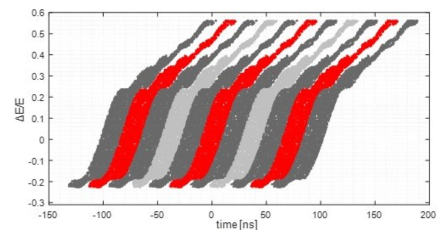

Figure 5: The longitudinal acceptance of RFQ.

After adding fundamental wave of MHB, distribution turn to be sin wave out of MHB, particles with different energy will concentrated to one acceptance. So Instead of the uniform distribution, there is a periodic distribution of three bunches with less particles called satellite bunch and one bunch with more particles called main bunch, so bunch efficiency is defined as the ratio of the particles number in the main bunch to the total particles number in these four bunches as shown in Fig. 6. And maximum efficiency with only fundamental wave is 70.2%. Bunch efficiency reaches a peak of 86.2% when first, second and third harmonic operate at the same time. Another point to note is that compared to the previous two-harmonic bunching, the increase in bunch efficiency under three harmonics is not very significant, only a 3.6% increase, indicating that MHB with three harmonics is the most cost-effective.

BEAM EXPERIMENTS WITH MHB IN SSC-LINAC

The MHB was installed online in 2019, and Fig. 7 is what it looks like in real. Both ends are connected to the vacuum piping through bellows, as for the bunch efficiency measurement, we use the button-type BPM which is 15.3 cm downstream of RFQ in SSC-Linac.

Beam BPM signal of 50 µs will be collected after each adjustment of MHB parameters, for example as shown in Fig. 8, there is a subfigure magnified to see the micro bunch. During the 50 µs, there are about 670 main bunch signals and 2000 satellite bunch signals, which means we will get 670 sets of bunch efficiency data and calculate the average.

Main facilities involved in the experiments are ECR ion source, MHB, RFQ, and BPM, normal ECR ion source provides 120 µA ion beam. The voltage and phase of each harmonic can be adjusted separately and monitored in real time through the remote-control interface. Besides, beam

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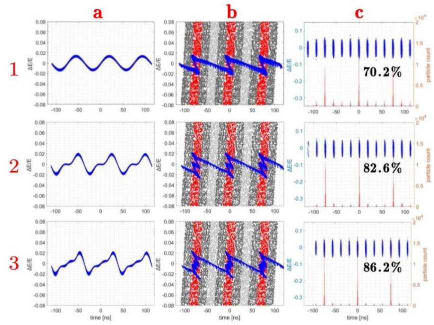

Figure 6: Particle distribution at different place under different setting. Each row represents a situation of **(1)** first harmonic operates, **(2)** first and second harmonic operate, **(3)** first, second and third harmonic operate. Each column of pictures represents the particle distribution at a specific location which is **(a)** at the exit of multi-harmonic buncher, **(b)** at the entrance of RFQ, **(c)** at the exit of RFQ, respectively.

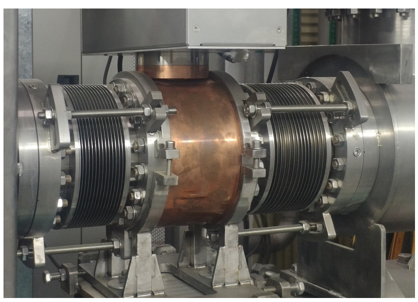

Figure 7: MHB has been installed on beamline.

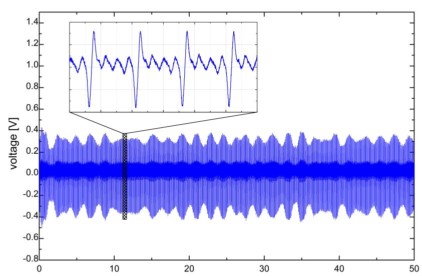

Figure 8: Signal obtained from BPM with 50 μs, and it's clearly that main bunch has a larger voltage compared with the satellite bunch.

transmission was optimized by adjusting the solenoids and the correctors. Beam current measured by the ACCT on the MEBT is about 100 μA during our experiments. BPM signal under three condition is plot in Fig. 9, and it's obviously that the voltage of main bunch increase as the harmonics adding. Finally, according to the experiments, the highest bunch efficiency is 86.1%.

SUMMARY

Beam dynamics simulations using BEAMPATH with the MHB predicated that the maximum bunch efficiency would be 86.2%. This results guide the optimization strategy of

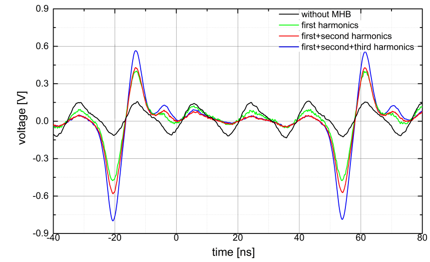

Figure 9: BPM signal under fifferent setting of MHB.

Table 1: Summary of Bunch Efficiency in Simulations and Experiments

Situation	Bunch.Eff	
	Experiments	Simulation
1st	69.8%	70.8%
1st+2nd	82.1%	83.3%
1st+2nd+3rd	86.1%	87.8%

the bunch efficiency in the real operation. The MHB with fundamental frequency 13.417 MHz has been installed on the beamline, and the beam commissioning was carried out successfully. In the beam experiments, effect of each harmonic on the bunch efficiency was measured carefully, results showed that its maximum bunch efficiency was 86.1% which was in good agreement with the simulation results. Due to the bunch efficiency optimization of MHB together with outstanding performance of SSC-Linac, the extracted beam current of SSC has been increased one order magnitude higher than before.

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