DESIGN OF A 10.156 MHz PRE-BUNCHER FOR A HEAVY ION RFQ

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Abstract

LEAF (Low Energy heavy ion Accelerator Facility) is a low-energy high-intensity heavy-ion LINAC complex for multidiscipline research. At present, the beam repetition rate is the same as the LINAC frequency of 81.25 MHz. A lower frequency would be desirable for many types of experiments employing time of flight data acquisitions. A method of increasing the bunch spacing to 98 ns by combining a 10.156 MHz pre-buncher before the RFQ and an RF chopper after the RFQ has been proposed. This paper reports the preliminary design studies of such a low-frequency pre-buncher. According to the simulation result, the bunching efficiency of a 3-harmonic buncher will merely increase by 1% compared to a 2-harmonic buncher. We decide to design a two-harmonic buncher based on the little improvement in bunching efficiency. We optimize the length of electrodes so that the utilization of the parasitic field is maximized. The beam dynamics analysis indicates that the voltage amplitude and the RF power can be lowered by 1.3 times and 2.2 times.

INTRODUCTION

LEAF (Low Energy heavy ion Accelerator Facility) is a low-energy high-intensity heavy-ion LINAC complex that supports multidisciplinary research, such as material irradiation experiments and nuclear astrophysics experiments [1]. As shown in Fig. 1, LEAF is mainly composed of an electron cyclotron resonance ion source (ECRIS), a low energy beam transport (LEBT), a CW 81.25 MHz radio-frequency quadrupole (RFQ), an 81.25 MHz drift tube linac (DTL), a medium energy beam transport (MEBT), and experimental terminals. The facility can provide heavy ion beams covering A/Q (mass to charge) between 2 and 7 with energies adjustable from 0.3 MeV/u to 0.7 MeV/u.

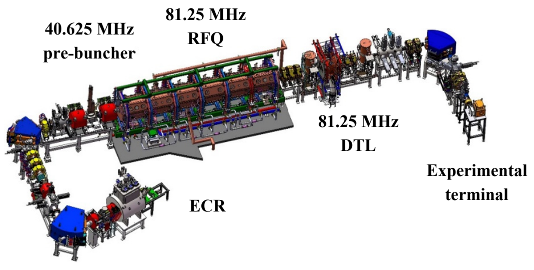

Figure 1: Schematic view of LEAF facility.

The facility was originally designed to operate with a pulse repetition rate of 81.25 MHz at the target. Despite the facility has already been put into operation, a number of nuclear scientists expressed reservations about this rate since the measurement of ^{12}C(α, γ)^{16}O reaction is planned at LEAF. An intense pulsed α beam with greater time separation is required for this experiment to separate the γ-ray events of the ^{12}C(α, γ)^{16}O reaction from the neutron background due to the ^{13}C(α,n)^{16}O reaction [2]. Following the request, a solution conserving as many particles as possible is required, which means simply building a chopper after RFQ to discard 7 out of 8 bunches is excluded. A scheme combining a pre-buncher operating at a fundamental frequency of 10.156 MHz (a factor 8 below the fundamental frequency of the LINAC) and an RF chopper is proposed. Providing an interval of nearly 100 ns between pulses makes it feasible to prevent the time spectra of successive beam pulses from overlapping [2]. The preliminary beam dynamics simulation and optimization of the 10.156 MHz pre-buncher will be discussed in the following sections.

BEAM DYNAMICS SIMULATION OF PRE-BUNCHER

Principles of Multiharmonic Bunching

An idealized voltage formed in a pre-buncher would have a pure sawtooth waveform with a perfectly linear ramp and an instantaneous return to the starting voltage at the start of each period [3]. To produce the desired sawtooth wave voltage, the technique of Fourier synthesis is utilized, which is to combine a series of sinusoidal waves at integer multiples of the fundamental frequency to form a sawtooth wave as a function of time [4]. The sawtooth wave voltage form can be expressed by using the Fourier expansion:

$$V_{(t)} = V_m(\sin \omega t - 0.40 \sin 2\omega t + 0.18 \sin 3\omega t - \cdots + C_n \sin n\omega t) \tag{1}$$

However, in practice combining unlimited harmonics to form a linear sawtooth wave is infeasible considering the cost and complexity of mixing many harmonics. Instead, this waveform is typically approximated with its first 2-4 Fourier components which can be produced via a resonant cavity or resonant circuit. A simulation using limited harmonics and corresponding analytic Fourier coefficients demonstrates that a large percentage of the particles will lose or be captured in the satellite bunches [5]. Consequently, the corresponding coefficients of each harmonic component must be simulated differently from the Fourier coefficients.

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Beam Dynamic Simulation with Acceleration Gap Electric Field

The beam dynamics simulation of the LEAF front-end beamline calculated with ideal and realistic 3D fields has been completed using the TRACK code [6], separately. In the illustration given in Fig. 2, a continuous beam from an ECR ions source will be applied a longitudinal kick (see Fig. 3) in the pre-buncher upstream of the radio frequency quadrupole linac. This pre-buncher is placed 1.1 m from the radio frequency quadrupole. Two solenoids are placed upstream of the buncher and RFQ, respectively, providing transverse focusing to match the RFQ transverse acceptance. The initial beam parameters and beamline information are given in Table 1.

Figure 2: Layout of the LEAF front-end beamline.

Table 1: The Beam Parameters Before the Pre-buncher

Parameters	**Before pre-buncher**
Ions species	U(A/Q=7)
Beam current	100 euA
Kinetic energy	14 keV/u
Input energy spread	0.05%
Distance to RFQ	1.1 m
$\boldsymbol{\varepsilon}_{(x,y)}$ (cm*mrad)	0.042
$\boldsymbol{\alpha}_{(x,y)}$	1.0
$\boldsymbol{\beta}_{(x,y)}$ (cm/rad)	50

This simulation is first carried out with only the accelerating gap electric field as shown in Fig. 4. The buncher was first simulated with the fundamental frequency, the higher harmonics 20.3125 MHz and 30.478 MHz were then added in proper amplitude and phase to make an effort for high bunching efficiency. Figure 5 illustrates the modulated particle distributions in the case of three harmonic number combinations (1^{st}, 1^{st}+2^{nd}, 1^{st}+2^{nd}+3^{rd}) at the entrance of RFQ. The white region corresponds to the longitudinal phase space acceptance in RFQ, while the red region stands for the modulated beam. The accelerating voltage of each harmonic and the corresponding bunching efficiency are listed in Table 2. The bunching efficiency refers to the number of particles entering the RFQ acceptance compared to the total number of particles in one RF period of buncher.

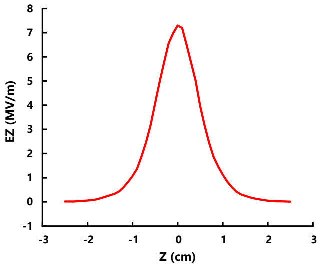

Figure 3: The longitudinal electric field distribution along the beam axis in the gap at radial position r = 0 mm.

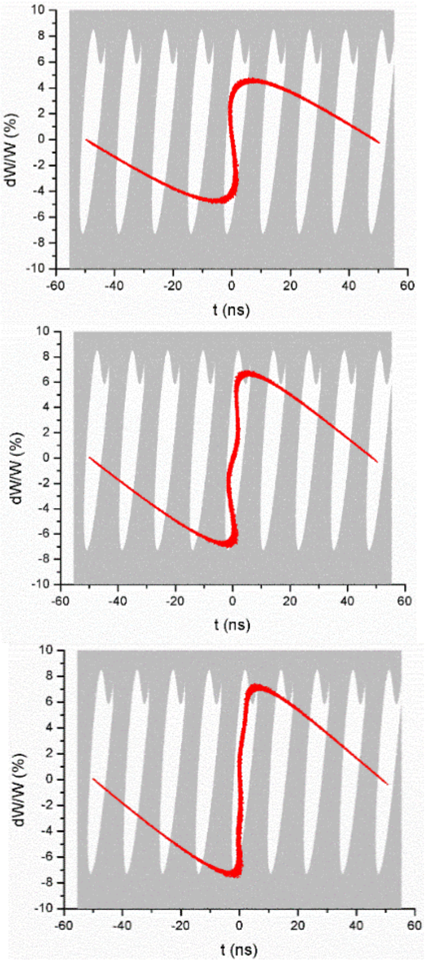

Figure 4: Modulated beam particle distributions vs. RFQ longitudinal acceptance.

Table 2: The accelerating voltage and bunching efficiency with different harmonics calculated for the U(A/Q=7) ion beam

Harmonic	**Voltage (kV)**	**Efficiency (%)**
1-harmonic	5.15	69.8
2-harmonics	8.04	75.8
3-harmonics	8.49	76.9

Table 2 shows that the combination of the first and second harmonic results in improved bunching, with 75.8% of particles modulated into the main bunch acceptance. However, due to the low-frequency regime and RFQ energy spread acceptance, the bunching efficiency combined with the first three harmonics increases by only 1% compared to the efficiency achieved by the 2-harmonic buncher. The TRACK calculations indicate that the pre-buncher must provide a voltage of U=8 kV. The dissipation power (P) scales as P~V^2, so thermal issues become significant for a multi-kV lumped-circuit MHB [7]. Thus, a two-harmonics coaxial resonator-based buncher has been designed.

Beam Dynamic Simulation with Accelerating Gap and Leakage Electric Fields

An RF model was built in CST Microwave Studio (CST MWS) [8]. The electric field patterns in the vacuum chamber for the 1st harmonic (10.156 MHz) and the 2nd harmonic (20.3125 MHz) are provided below (see Fig. 6). The practical field along the chamber axis is not symmetric and there is leakage field outside the electrodes, which will influence the effective energy gain.

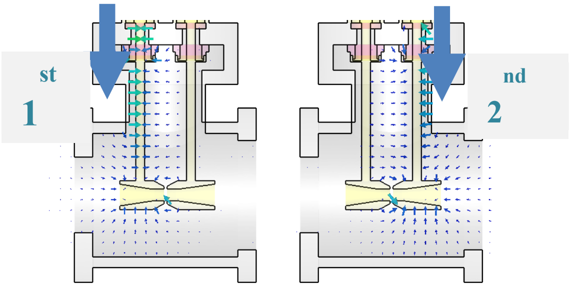

Figure 5. The electric field pattern in the chamber from an axial cut plane along the buncher.

The effect of the leakage field of each harmonic should be estimated by evaluating the corresponding transit time factor (TTF). The transit-time factor is the ratio of the energy gained in the time-varying RF field to that in a DC field [9]. The factor for each harmonic wave can be estimated by the following approximation:

$$T_i = \frac{\int_{-\frac{L}{2}}^{\frac{L}{2}} \mathrm{E_i}(0,z)\cos\frac{2\pi z}{\beta\lambda_i}dz}{\int_{-\frac{L}{2}}^{\frac{L}{2}} \mathrm{E_i}(0,\ z)dz} \qquad (2)$$

Where T_i is the transit-time factor for the ith harmonic wave, λ_i denotes the wavelength for the ith harmonic wave. $\mathrm{E_i}(0,z)$ presents the longitudinal electric field along the beam axis at radial position $r = 0$. L is denoted by the axial distance which contains the electric field. β refers to a nominal relativistic velocity (0.0054826 with the beam energy of 14 keV/u). The impact of the leakage electric fields cannot be disregarded, due to the high TTFs for the low frequencies, 0.64 for the 1st harmonic and 0.34 for the 2nd harmonic. Nonetheless, optimizing the electrode length can potentially harness the positive influence of the leakage field. Simulations were implemented with various electrode lengths under the same beam condition. The corresponding coefficients of the two harmonic components are adjusted to produce the highest bunching efficiency. When the length of electrodes aside from the parasitic field of 1st harmonics is set to 61 mm to make sure that particles pass through a length of $\beta\lambda_1/2$ prior to entering the gap, it can allow us to decrease the RF voltage amplitude of the first harmonic in 1.4 times to 3.7 kV and power of the first harmonic in 3 times to 220 W. But during the optimization of the electrode aside from the parasitic field of 2nd harmonic, it was found out the length of $\beta\lambda_2/2$ (25 mm) is too short, whereas the length of $3\beta\lambda_2/2$ (107 mm) is too long, given the available installation space. To achieve the optimal balance and fulfil the highest bunching efficiency, the length of the electrode is set to $\beta\lambda_2$ (66 mm), at the cost of the higher power requirement of the 2nd harmonic. The comparison of simulation results under different conditions is listed in Table 3 and demonstrates that the optimized parasitic field can effectively decrease required voltage and power.

Table 3: The Comparison of Simulation Results Under Different Conditions.

Parameters	**Without parasitic field**	**With parasitic field**	
Elec1/mm	-	$61(\beta\lambda_1/2)$	
Vf1/kV	6.41	3.7	
Pf1/W	660	220	
Elec2/mm	-	$107(3\beta\lambda_2/2)$	$66(\beta\lambda_2)$
Vf2/kV	1.63	1.3	2.5
Pf2/W	42	26	103

CONCLUSION

A new buncher operating at the 8th subharmonic of the RFQ frequency, 10.156 MHz is equipped upstream of the heavy ions RFQ to increase the bunch spacing to 100 ns at the detectors. The beam dynamics simulation shows that the bunching efficiency of the new buncher with the first two harmonics can reach 75.8%. We have successfully decreased the voltage amplitude by 1.3 times and the power by 2.2 times by optimizing the electrode length featuring a π-mode.

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