DESIGN AND TEST OF THE TRIPLE-HARMONIC BUNCHER FOR THE NSCL REACCELERATOR*

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Abstract

A unique triple-harmonic buncher operating at the fundamental frequency of 80.5 MHz upstream the Radio Frequency Quadrupole (RFQ) linac has been designed, manufactured and tested at the National Superconducting Cyclotron Laboratory (NSCL) to meet the requirement of a small output longitudinal beam emittance from the reaccelerator. The buncher consists of two coaxial resonators with a single gridded gap. One cavity provides both the fundamental and the third harmonic simultaneously with λ/4 and 3λ/4 modes respectively, while the other provides the second harmonic in λ/4 mode. This buncher combines the advantages of using high quality factor resonator and only a pair of grids. Details on design considerations, electromagnetic simulations, and primary test results are presented.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University is developing a facility named ReA3 to demonstrate the technical feasibility and performance characteristics for stopping and reaccelerating rare-isotope beams, as an important step towards a next-generation rare-isotope facility in the United States [1]. Beams of rare isotopes will be produced and separated in-flight at the NSCL Coupled Cyclotron Facility and subsequently stopped by a novel gas stopper, breeded by a state-of-the-art electron beam ion trap based charge-breeder, and reaccelerated by a modern linear accelerator. The linac consists of a low energy beam transport line, a cw radio-frequency quadrupole, a quarter wave resonator based superconducting linac, and a high energy beam transport line [2]. ReA3 will delivery various exotic beams with charge-to-mass ratios (Q/A) of 0.2 – 0.4 and variable energies of about 0.3 to 3 MeV/u.

Nuclear experimental programs require a beam on target with an energy spread of ~1 keV/u and a bunch length of ~1 ns simultaneously. Therefore, a longitudinal beam emittance of less than 0.3 π·ns·keV/u from ReA3 is demanded. Since the intensities of the rare-isotope beams will be low, the scheme of using an external multi-harmonic buncher upstream of the RFQ has been adopted to produce a small longitudinal emittance beam from RFQ with high bunching efficiency [3-6]. A unique triple harmonic buncher using two high quality factor resonators with one pair of grids has been designed, fabricated and tested at NSCL for this application.

DESIGN CONSIDERATIONS

The buncher is designed to operate with three harmonics, a fundamental frequency of 80.5 MHz and two additional harmonics of 161 and 241.5 MHz, respectively. The fundamental frequency, same as that of the downstream RFQ and superconducting cavities, is mainly determined by the small longitudinal beam emittance requirement. Since beams from the charge breeder will have a larger intrinsic energy spread (e.g. ΔE ~ ±25eV/u for Q/A = 0.25), the beam micro-bunch frequency should not be lower than ~80 MHz, otherwise the longitudinal emittance of the bunched beam will be too large to achieve the required time and energy resolution on target. Considering the higher bunching efficiency and lower output longitudinal emittance needed, a total of three harmonics are chosen for the operation of the buncher [6]. A high quality factor resonator was proposed, which needs a lower power amplifier to drive it. This buncher consists of two coaxial cavities, as shown in Fig. 1. One cavity provides both the fundamental and the third harmonics. The other cavity provides the second harmonic with a λ/4 mode. The dual frequency cavity will operate simultaneously at the λ/4 and 3λ/4 modes, as was done at PIAVE in Legnaro [5]. The buncher bunches beams with a nominal relativistic velocity β = 0.00507 (beam energy of 12keV/u), so the βλ is small especially for harmonics. For example, βλ = 9.4 mm for second harmonic. On the other hand, the beam diameter is about 30mm at the buncher position in order to match it into RFQ. Therefore gridded electrode tubes are necessary to achieve uniform field distributions and thus satisfactory transit time factors. We proposed to design the buncher in such a way that all three harmonics are applied in one single gridded gap. This configuration with only one pair of grids minimizes the beam losses on grids and makes the buncher longitudinally more compact as well.

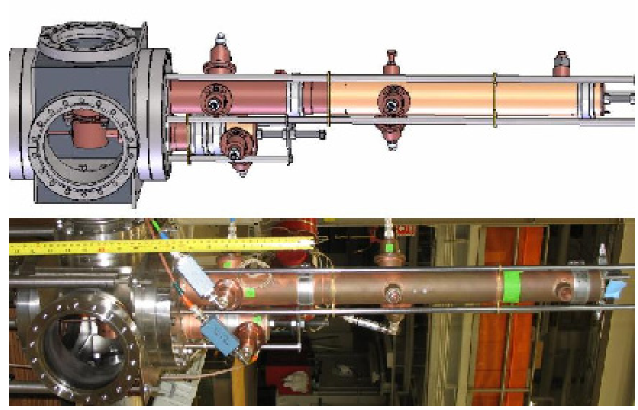

Figure 1: Triple harmonic buncher with two coaxial resonators and a single gridded gap: design drawing (top), photograph (bottom).

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ELECTROMAGNETIC SIMULATIONS

Although the required bunching voltage is not high (<1kV) and the design of λ/4 resonators is conventional, cross-talk between the two cavities due to the coupling through the gridded gap must be evaluated. MAFIA code was used to simulate the resonators and determine the electromagnetic properties of the triple harmonic buncher.

A schematic layout of the buncher is shown in Fig. 2. Both of the resonators have a shorter length than those in ideal λ/4 cases to achieve the desired resonant frequencies. The lengths of the dual and single frequency cavities were reduced about 20% and 40% respectively. These reductions are mainly due to the capacitive load from the gridded gap, the dielectric vacuum isolators and the tube supports. As a result, a strong coupling was observed between the two resonators, which not only decreased the effective voltage across the gap but also made the tunings much difficult especially for the third harmonic.

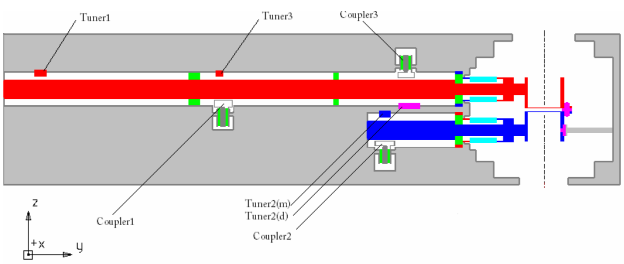

Figure 2: Layout of the triple harmonic buncher.

One of the solutions currently adopted in the design is to add an rf filter on the electrode that connects to the second harmonic cavity. This filter is only for the third harmonic (very small impedance for third harmonic and very large for others). MAFIA simulation showed the effective voltage across the gap for the third harmonic increased significantly with the filter. The calculated quality factors are 2020, 3170, 4140 for 80.5, 161, 241.5 MHz, respectively. Simulation also found the 50mm diameter of the tube is large enough not necessary to use conic electrodes to deal with the fringing fields.

An adjustable magnetic power coupler is used for each harmonic to provide critical coupling. Each harmonic also has an adjustable pickup and the pickups are carefully positioned to reduce the interference between different modes of oscillations, as shown in Fig. 2.

MECHANICAL DESIGN

Standard size copper tubes were chosen for both the inner and outer conductor of the resonators. One side of the outer conductors is directly welded on the vacuum chamber while the inner conductor welded on the chamber through a ceramic. The inner and outer conductors are welded each other on the other side. Two Teflon washes were installed between the inner and outer conductors to improve the stiffness for the dual frequency resonator. Both resonators are placed in air without water-cooling. A pair of copper tubes with grids on one end is used as the electrodes. Each 50mm diameter electrode is directly connected to the inner conductors of the two coaxial resonators and housed in a 20cm cubic stainless steel vacuum chamber.

The buncher grid has a 50mm diameter, made by ThinMetalParts (Colorado Spring, CO). Both the thickness and width of the copper grid is 0.005” with square meshes spaced 1mm apart, as shown in Fig. 3. The grids are clamped 4mm apart and self aligned on pins in the copper electrodes so that the grids on each grid are also aligned to minimize the interception of beam.

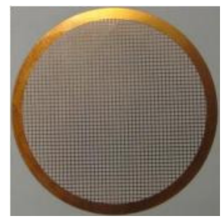

Figure 3: The 0.005” thickness and 50 mm diameter copper grid. Square mesh with grid width of 0.005” spaced 1mm apart.

A 4 mm diameter cylindrical copper rod that connects the bottom of the housing chamber and the electrode of the second harmonic cavity is used as a filter for third harmonic. The rod is electrically isolated to the electrode by a dielectric spacer. This filter can also be used to tune both the third and second resonant frequencies by changing of the thickness of the dielectric spacer.

There is a movable finger sleeve connecting inner and outer conductors for the dual frequency cavity for coarse frequency tuning. The fine frequency tuners for the fundamental and second harmonics are placed close to their maximum magnetic fields, while that for the third harmonic near its maximum electric field. Cylindrical coppers with diameters of 12, 10, and 6 mm are used for the fundamental, second and third harmonic, respectively, which provides about total 100kHz tuning range.

EXPERIMENTAL TESTS

After assembly, this buncher was measured with low rf and then beam tested on the electron cyclotron resonance ion source (ECRIS) test stand at the NSCL. Fig. 3 is a photo of the test stand beam line showing various beam diagnostic tools and instruments. Two solenoids upstream the buncher provide transverse focusing. A fast Faraday cup (FFC) approximately 75cm downstream the buncher is used to measure the longitudinal beam temporal profile after the buncher. The FFC is a 50 Ohm coaxial cone with a grounded copper grid in front of the collector similar to that in Legnaro [5]. This output of the FFC is sent into an oscilloscope .

An oscillator (Frequency Synthesizer PTS 500, Programmed Test Source Inc.) generates an 80.5MHz signal. This frequency is doubled and tripled by the Triple Harmonic Module developed at NSCL. Each frequency signal is then send into a separate amplifier (PTEK 100W 10-100MHz, Worldwide 20W, Model Kaw 1040 MI, 1-512MHz) through an individual RF Voltage Regulator (developed at NSCL for cyclotron rf control). There is a phase shift between the voltage regulator and amplifier for both second and third harmonics. Each amplifier is connected its coupler on the buncher through a directional coupler. Signals from the pickups are then send back to the voltage regulators. RG142 double shield cables are used for all the connections.

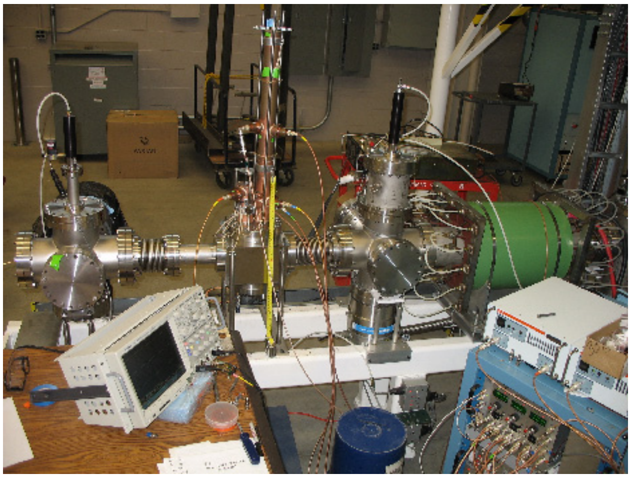

Figure 4: Experimental setup for the beam test of the triple harmonic buncher.

A low intensity single-charge state helium beam was produced with 20kV ECRIS extraction voltage. This 5keV/u beam was tuned to pass through the buncher grids and collected by the FFC. For the initial beam tests, only fundamental frequency was applied. The buncher voltage was scanned in a wide range so we observed the bunching and over-bunching processes on the oscilloscope. However, the direct signal obtained from the oscilloscope, as shown in Fig. 5, indicated that the temporal durations were much longer than anticipated. We believe that the time resolution of our FFC may be not as high as we expected. Therefore, a Matlab based code was written to quantify various impacts. This code includes the simulation of the beam bunching process with different input conditions, variable time response of the FFC. We first conducted beam simulations to obtain the longitudinal temporal profiles with different buncher voltages and different initial beam energy spreads. Then we introduced a time response constant (τ) for the FFC and recalculate the simulated temporal distributions based on the time constant τ and tried to fit the traces recorded from the scope. As an example, Fig. 5 shows the temporal distributions at the entrance of buncher vs. at the FFC in the left, and simulated temporal distributions and the real trace recoded from oscilloscope. From the data analyses, we determined the time response constant τ=1.6ns that is close to our estimation, and the initial beam energy spread ΔE=11.5eV/u that also agrees with other measured from ECRIS. We are going to test the buncher with all three harmonics in the next step.

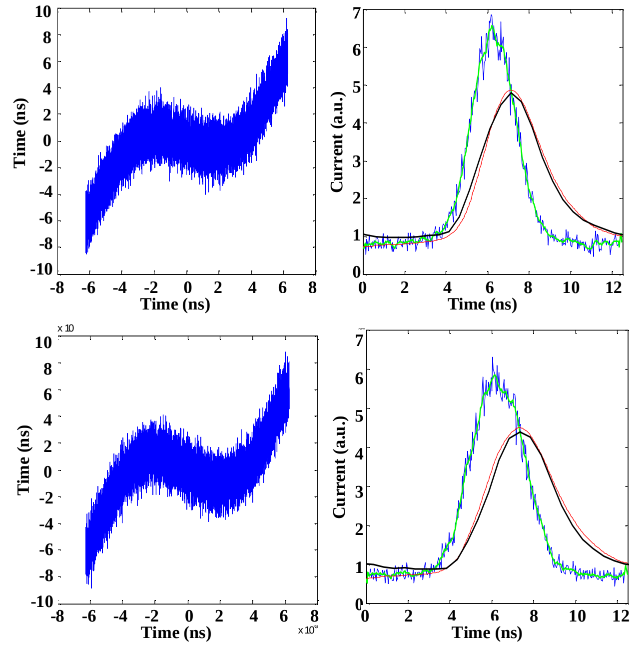

Figure 5: Temporal distributions at the entrance of buncher vs. at the FFC (left), projected temporal profiles (right): raw data (blue), smoothed data (green), trace from scope (black), fitted distribution (red), with initial beam energy spread ΔE=11.5eV/u and FFC time response constant τ=1.6ns. Buncher voltage Vb=174V (tops) and Vb=205V (bottoms).

SUMMARY

The unique triple harmonic buncher consisting of two coaxial resonators with a single gridded gap for ReA3 was designed, fabricated and tested at NSCL. The results of the primary tests confirmed our design goals. Further experiment measurements on the test stand together with beam simulations are planed to develop the procedures on how to tune and operate the triple-harmonic buncher optimally. This buncher will be installed in the ReA3 and started commissioning in Spring 2009.

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