RF DESIGN AND COMMISSIONING OF A NOVEL MULTI-HARMONIC BUNCHER FOR THE TRIUMF 500 MeV CYCLOTRON

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Abstract

The horizontal injection section of the TRIUMF 500 MeV cyclotron has been replaced after 50 years of operation and the historic buncher configuration which consists of two separated double-gap bunchers for the 1st and 2nd harmonics of the cyclotron RF frequency of 23.06 MHz were successfully replaced with a multi-harmonic buncher operating on three harmonics. The novel multi-harmonic buncher structure has two electrodes and three gaps: one electrode driven with 1st and 3rd harmonics and the second electrode – with the 2nd harmonic. It is a combination of two double-gap structures having one common gap inside the cavity. The device is now installed and operational. The RF design, fabrication and commissioning results are presented and discussed in the article.

INTRODUCTION

The new horizontal injection section design for the TRIUMF 520 MeV cyclotron necessitated the development of a three-harmonic buncher. A new concept of the three-harmonic buncher was developed and studied with respect to beam dynamics [1]. Finally, the new three-harmonic buncher has been installed and successfully commissioned [2].

NOVEL THREE-HARMONIC BUNCHER

Concept

Originally, we considered for the design a well-known multi-harmonic single gap buncher with two drift tubes driven with coaxial RF resonators [3]. However, to suppress the effect of parasitic tails outside the drift tubes, a one-gap structure required more longitudinal space than was available in the new injection section design. On the other hand, a one-gap structure also required relatively high RF voltage due to its low TTF (transit time factor). Another approach is to employ two double-gap structures, as was implemented for the PIAVE project at LNL INFN [4]. This is very efficient due to the high TTF but is not compact enough longitudinally.

To reduce the longitudinal footprint, we decided to use a combination of two double-gap structures sharing one common gap, as shown in Fig. 1. There are two drift tubes and three gaps. The first drift tube has a gap-to-gap distance of βλ/2 for the 1st harmonic and 3βλ/2 for the 3rd harmonic. It must be driven with a 2nd-harmonic resonator, which can be represented as a QWR (quarter-wave resonator) for the 1st harmonic and 3QWR/2 for 3rd harmonic. The second drift tube has a gap-to-gap distance of βλ/2 for the 2nd harmonic and is driven with a QWR for the 2nd harmonic.

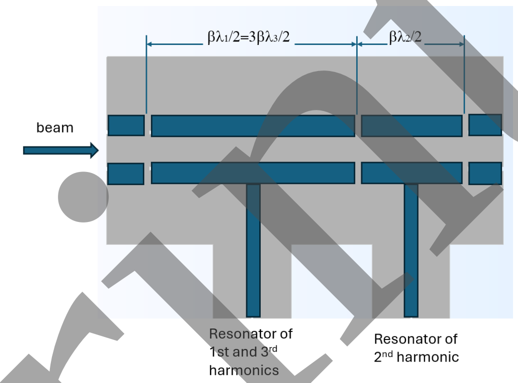

Figure 1: Novel multi-harmonic buncher RF structure concept.

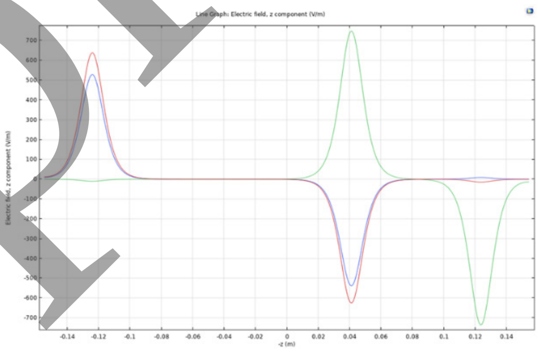

Figure 2: Distribution of longitudinal component of electric field along the structure for three harmonics (1st – red, 2nd – green, 3rd – blue).

Figure 2 shows the distribution of the longitudinal component of the electric field along the structure for three harmonics (1st – red, 2nd – green, 3rd – blue). This distribution shows the relative values from COMSOL RF module [5] solutions (computed independently for each harmonic) for the RF structure, and is used for beam dynamics simulations [1] to determine the required RF amplitudes to be applied to the drift tubes; TTF and R_{sh}/Q_o presented on Table 1. The buncher structure has quite high TTF (efficiency) and moderate required RF amplitudes Vo.

RF Design

The buncher RF structure consists of a chamber with drift tubes separated with RF feedthroughs and outside resonators with couplers, pickups, and tuning elements (Fig. 3). Initially, we considered spiral (coil) resonators but opted for coaxial lines (3-1/8”) due to the complexity of the

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coil design for the 1st and 3rd harmonics. We employ two bent, shorted-end coaxial line resonators connected to the beam line. The complete design and COMSOL RF model of the buncher are shown in Fig. 4 and Fig. 5. Resonator frequency tuning is implemented with moveable shorting plungers. The two-harmonic resonator, beyond the plunger, is equipped with a piston positioned at the minimum of the electric field for the 3rd harmonic; moving the piston inward decreases the 1st harmonic frequency and increases the 3rd harmonic frequency (Fig. 6). The piston position maintains a frequency ratio of 3 between the 3rd and 1st harmonic frequencies over a practical tuning range. The piston was set once and has not required adjustment during the extended operating period. RF coupling to the resonators is provided by inductive loops. To mitigate unwanted crosstalk between the 1st and 2nd harmonic, Coupler 1 for the 1st harmonic is installed in a position of minimum magnetic field where it has minimum coupling for the 3rd harmonic. Coupler 3 for the 3rd harmonic is installed in a location of maximum magnetic field for the 3rd harmonic. There is some coupling for the 1st harmonic and we mitigate that with a 10 dB attenuator installed on the 3rd harmonic amplifier output. This mitigation doesn't cost much for RF power because the 3rd harmonic requires less than 1 W. The 2nd harmonic resonator is equipped with an inductive Coupler 2 installed close to the shorting tuning plunger. The LLRF system for the three-harmonic buncher was designed at TRIUMF [6]. For RF feedback, simple capacitive pickups are installed on the resonators, and their signals are filtered within the LLRF system.

Table 1: Buncher Operational RF Parameters

fo MHz	TTF	R_{sh}/Q_o Ohm	Q_o	P_o W	V_o V
23.06	0.982	78.25	1206	25.14	2178
46.12	0.933	88.29	1306	1.79	642
69.18	0.863	39.33	1365	0.65	265

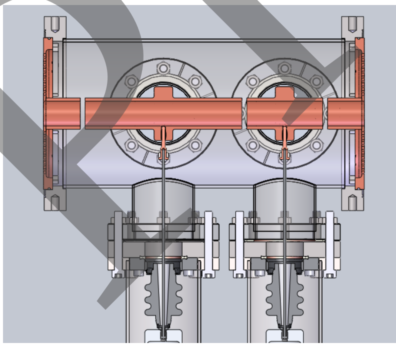

Figure 3: Design of the structure: drift tubes in vacuum chamber separated with RF feedthroughs from resonators outside of vacuum.

RF Feedthroughs

The EFT2013093 Kurt Lesker RF feedthrough was selected and tested prior to installation at 2.5 kV and 71 MHz CW using a dedicated RF HV test jig. During the test we observed stable feedthrough impedance matching behaviour with no heating.

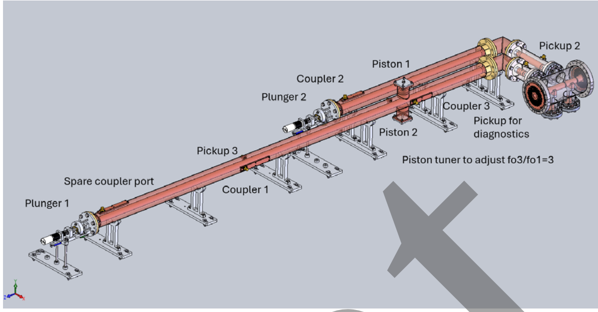

Figure 4: Complete design.

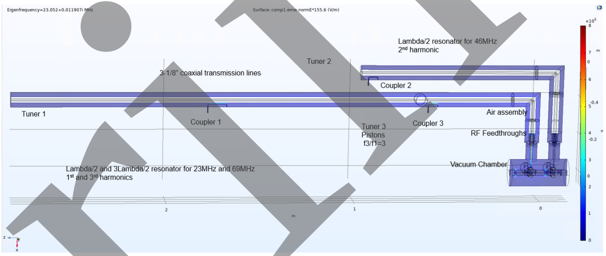

Figure 5: COMSOL RF model of the buncher.

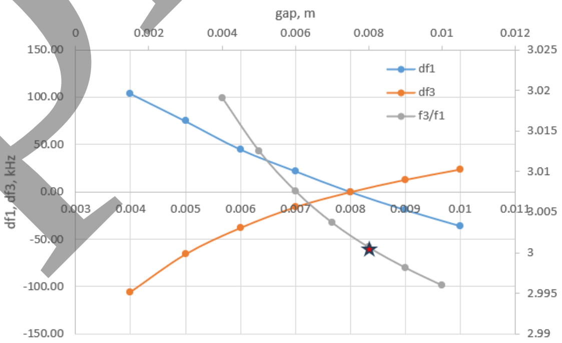

Figure 6: RF tuning of two-harmonic resonator with piston in location of minimum of electric field for 3rd harmonic; moving the piston inward decreases the 1st harmonic frequency and increases the 3rd harmonic frequency.

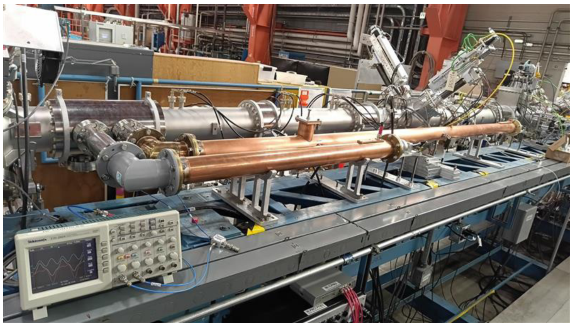

Figure 7: Buncher installed to the TRIUMF cyclotron new injection line.

COMMISSIONING

The buncher was fabricated at TRIUMF, assembled to the injection line (Fig. 7) and tuned for frequency and impedance matching at low signal levels. The quality factors Q_o for each harmonic were measured and are presented in Table 1.

After beam tuning, the required RF power for each harmonic was measured and is presented in Table 1. The RF amplitudes V_o for each harmonic have been calculated from the measured RF power, quality factors Q_o and calculated R_{sh}/Q_o (COMSOL) and presented in Table 1. The voltage V_o for 1st harmonic agrees quite well with beam profile measurement results. The difference is within 10%.

The buncher RF frequencies and matching were tuned once and operated reliably in 2025-2026.

CONCLUSION

The novel three-harmonic buncher has been proposed, designed, fabricated, and commissioned in the new injection line of the TRIUMF 520 MeV Cyclotron. The buncher has been operating reliably since May 2025.

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