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BEAM PERFORMANCE STUDY OF AN RF STRUCTURE TO ACCELERATE OR BUNCH LOW ENERGY ION BEAMS

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Abstract

The 35.4 MHz split ring Radio Frequency Quadruple (RFQ) of the ISAC-I facility at TRIUMF is designed to accelerate ion beams with a mass-to-charge ration of $1 \leq A/Q \leq 30$ from 2.04 keV/u to 153 keV/u. The RFQ design excludes a bunching section as a special feature. A multi-harmonic 11.8 MHz pre-buncher is used to achieve a time focus at the RFQ entrance. Energy matching into the RFQ requires a boost in energy for higher mass beams ($24 \leq A/Q \leq 30$) due to the limitations with the ion source voltage. A triple gap, 11.8 MHz RF booster has been installed between the pre-buncher and RFQ, to facilitate energy matching. Alternatively, this device can operate as a second pre-buncher to increase RFQ capture and reduce sensitivity to space charge. Various aspects of the RF booster are demonstrated by proof-of-principle measurements.

INTRODUCTION

The Isotope Separator and ACcelerator (ISAC) at TRIUMF produces rare-isotope beams (RIB) for studies in astrophysics, nuclear structure and reactions, electroweak interactions and material science [1].

A variety of radioisotope beams, below the space charge regime, can be generated and accelerated to a high energy area in ISAC-I or to the superconducting linac (SCL) in ISAC-II. In both cases the first accelerator in ISAC-I is a 35.4 MHz split ring, four vane Radio Frequency Quadrupole (RFQ), designed without a gentle buncher or buncher section. The RFQ focusses and accelerates RIB from 2.04 keV/u ($\beta = 0.0021$) to 153 keV/u with a mass-to-charge ratio of $1 \leq A/Q \leq 30$ [2]. The source must extract ions with a bias voltage of up to about ~ 60 kV, depending on A/Q. Current ISAC target modules have issues holding biases beyond $V_s = 48$ kV. Thus for charge to mass ratios of $A/Q \gtrsim 24$ a boost in energy is required for successful RFQ injection.

The pre-bunching of the beam allows the use of an RF device to match the beam energy to the RFQ acceptance. An RF Booster was designed, providing a voltage kick of up to 16 kV to compensate for the target module issues to achieve matching to the RFQ energy acceptance of 2.04 keV/u. The booster has been designed as a three gap RF device, with an aperture large enough to avoid interference with the existing beam envelop. Fig. 1 depicts a schematic of the booster and its position in ISAC-I located between the RFQ and the three harmonic 11.8 MHz pre-buncher. The required booster voltage V_b is determined by the ion's mass-to-charge ratio A/Q and the target module's extraction voltage V_s:

$$V_b = 2.04\,[\mathrm{keV/u}] \cdot \frac{A}{Q} - V_s \quad . \qquad (1)$$

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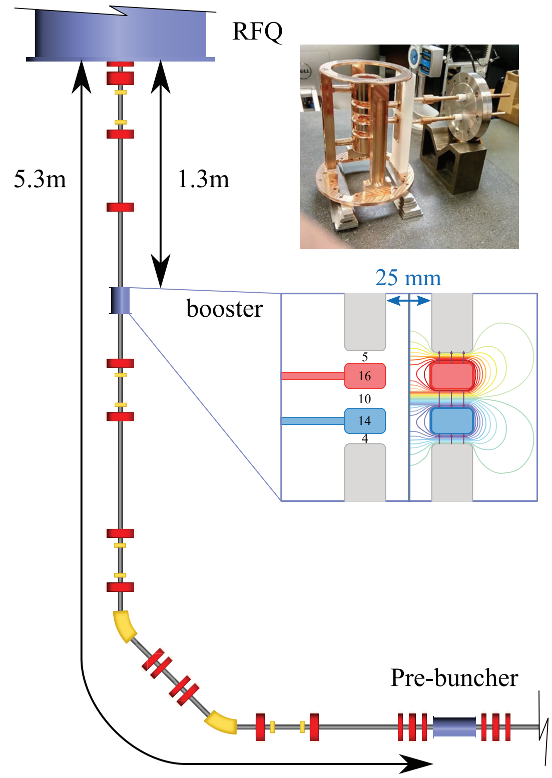

Figure 1: Pre-buncher, booster (inlay photo) and RFQ location at ISAC-I.

In this paper the first test results for the booster cavity operation as an energy compensation device, in addition to use as a supplemental buncher are presented. The relationship between bunch current and space charge is investigated.

BOOSTER PROPERTIES AND LIMITATIONS

An efficient design for the booster is a three gap RF device driven by a external lumped circuit [3]. The design achieves the required effective voltage, 16 kV, while keeping the voltage at the two feedthroughs to reasonable values, ~ 9 kV. The booster operates in a push and pull mode at 11.8 MHz, the pre-buncher's fundamental frequency. Its efficiency is optimized over the velocity range of interest [3].

The booster drift tube geometry causes an inherent coupling between radial position and longitudinal fields, as depicted in Fig. 2. This is due to the fact that the aperture is necessarily much larger than the distance between the booster gaps, to prevent the limitation of beamline aperture. However, this configuration is characterized by significant field penetration inside the drift tubes, as shown in Fig. 1. Thus, off axis particles receive more energy gain than on-

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axis particles [3], that causes debunching of the beam at the RFQ and a reduction in transmission. The radial longitudinal coupling limits RFQ transmission dependent on the relative voltage gain supplied by the RF booster and the transverse size or mis-steering of the beam through the booster.

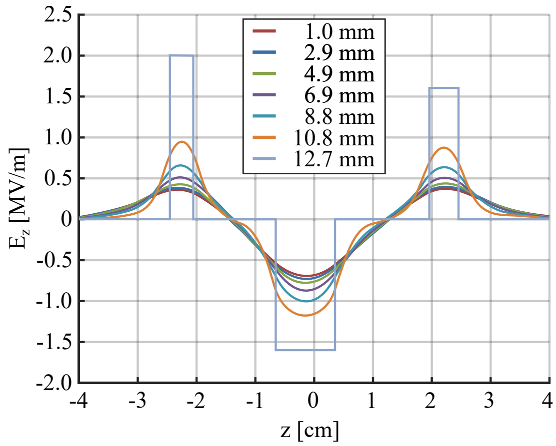

Figure 2: Accelerating field amplitude as a function of radius.

BOOSTER ENERGY KICK

It is found [3] that the expected energy gain through the 3 gap structure is given by:

$$\Delta W(r) = 2.1 \frac{Q}{A} V_0 I_0 (k_s r) \cos\varphi_0 \quad , \qquad (2)$$

where V_0 is the drift tube voltage, $k_s = 2\pi/(\beta_s\lambda) = 141\ \mathrm{m}^{-1}$, and $\beta_s = 0.00175$. A simulation of the expected transmission of the booster cavity is done by integrating a well aligned beam of transverse size $\sigma_t = 3.5$ mm through the booster cavity and comparing the phase spread of the beam at the RFQ against the RFQ acceptance as a function of booster relative voltage (Fig. 3). Beam test results have been done to confirm the actual performance. Fig. 3 displays the effect

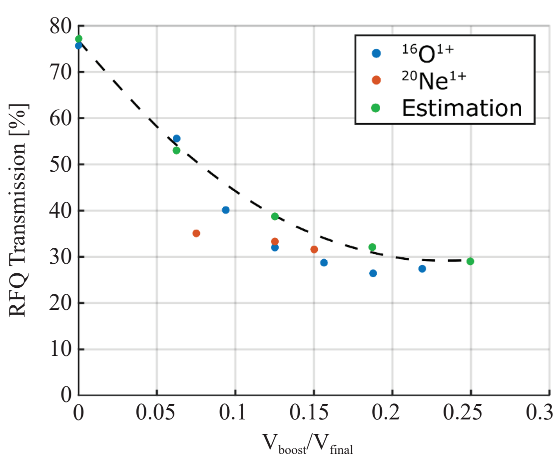

Figure 3: Measured RFQ transmission versus booster voltage, compared against expectation.

of the installed RF booster providing energy to two separate ion species. The booster was operated such that RFQ injection energy was always optimal as shown in Eq. 1. Decreasing RFQ transmission with increasing relative booster voltage demonstrates the aforementioned debunching effects. Beam measurements compare well with estimated behaviour shown by the dashed line in Fig. 3 [3].

BUNCHING MODE

The booster may also be operated at 90 degree phasing, enabling its use as a supplemental bunching device. This is important to augment the RFQ capture from the pre-bucher alone. In addition, for cases where high intensity stable beams are to be accelerated it can be used to minimize the effects of space charge on the longitudinal time focus at the RFQ, which represent the dominant space charge limitation for the linac.

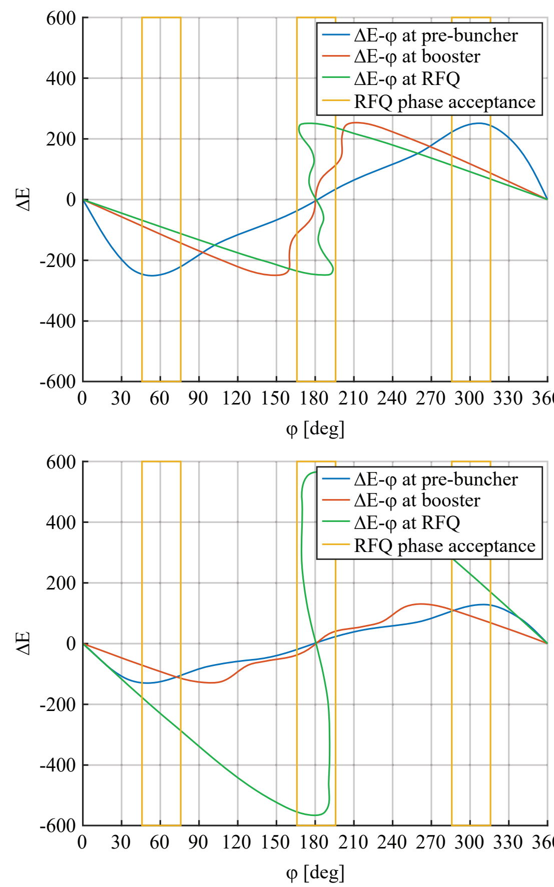

Figure 4: On top is the longitudinal phase space development for the multi-harmonic pre-buncher and at the bottom the longitudinal phase space development for tandem operation (pre-buncher and booster) is depicted for a $^{16}O^{1+}$ ion beam at different positions in ISAC-I.

Fig. 4 (top) shows the effects of bunching the beam with the multi-harmonic pre-buncher only, highlighting the evolution of the time focus from pre-buncher to RFQ entrance. The booster can be used to provide further bunching (with increased energy spread), as evidenced at the bottom of Fig. 4. This extra bunching is particularly useful for lighter beams,

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where solo pre-buncher operation typically has a lower capture efficiency in the RFQ thought to be due to insufficient stability of low voltage optics or pre-buncher RF systems.

SPACE CHARGE

Typically the ISAC linear accelerators boost the energy of low intensity RIB beams but there are cases where high intensity stable beams are required. Space charge effects at high bunch current tend to debunch the beam at the RFQ entrance, reducing the RFQ transmission. A simulation of the space charge effect is illustrated in Fig. 5 [4]. Given the booster's position 1.3 m upstream of the RFQ, it can be operated in tandem with the pre-buncher as a double bunching system to counteract space charge effects, thereby increasing the amount of beam within the RFQ acceptance.

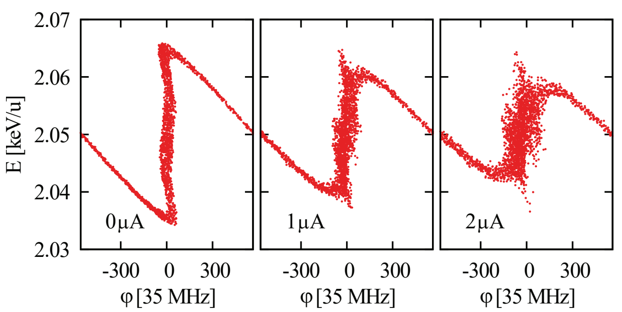

Figure 5: PARMELA simulated particle distribution including space charge effects for three different bunch charges and an A/Q = 30 for 2000 particles. [5]

The RFQ transmission is measured with four possible pre-buncher and booster combinations, involving each device either being on or off. A combination of different collimator and attenuators at the source are used to adjust different beam intensities. The source energy was constant for all measurements. A transmission of 25 % is expected in the RFQ during acceleration while both, pre-buncher and booster are turned off, as presented in Fig. 6, in blue.

Establishing a time focus, either with the pre-buncher, booster or both, causes an increase in RFQ transmission, as expected. For example, up to 80 % transmission are observed for $^{20}Ne^{1+}$, depicted as yellow line in Fig. 6. Note that space charge reduces the RFQ transmission for the pre-bunched beam eventually to a transmission equivalent to the unbunched case.

Solo booster buncher operation is represented by the red line in Fig. 6. Initial simulations suggest that more than 55 % of the beam will be transmitted through the RFQ [3]. An RFQ transmission of 60 % was achieved with the booster in single mode operation, slightly exceeding expectations. The sensitivity to space charge is significantly reduced with an increase in the space charge on-set by a factor of ∼ 10. Tandem operation with the pre-buncher is depicted as the purple line in Fig. 6. It gives higher low current values that reduce to booster only values at high space charge. The pre-buncher's sawtooth RF is better suited to produce a time focus, compared to the booster's purely sinusoidal RF for

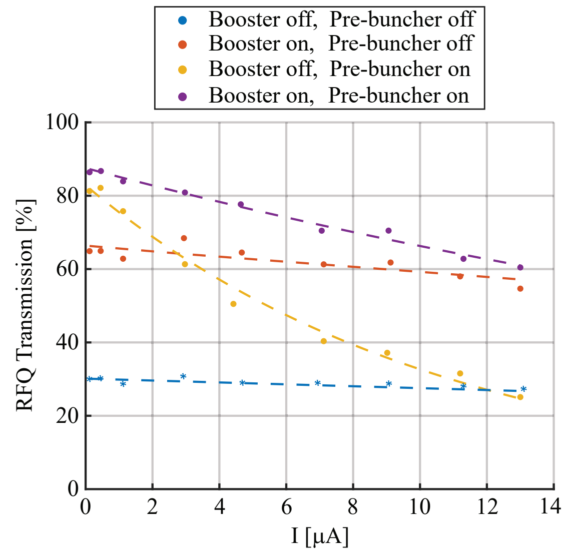

Figure 6: Booster operating as a buncher in different modes, as single or tandem with the pre-buncher, for $^{20}Ne^{1+}$.

non-space-charge regimes. The booster's close proximity to the RFQ allows for an effective countering of space-charge effects since there is insufficient time for bunch decoherence in the investigated current regimes.

CONCLUSION

Two operation modes have been demonstrated with beam measurements. In acceleration mode, the booster has been used to augment the source potential by more than 20 % for reasonable RFQ transmission. Higher relative voltages are less efficient due to strong radial longitudinal coupling. When operated as a buncher, the booster can be used in tandem with the pre-buncher (or solo) to improve the RFQ transmission and provides a ∼10-fold increase of the onset of space charge effects, by mitigating those effects on the time focus at the RFQ entrance.

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