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A 3-GAP BOOSTER CAVITY TO MATCH ION SOURCE POTENTIAL TO RFQ ACCEPTANCE

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Abstract

The ISAC RFQ can accelerate ions with A/Q ration from 1 to 30 and requires an input energy of 2.04keV/u. The harsh environment of the ISAC on-line ISOL target facility is challenged to meet the energy for the heaviest masses. For these cases we have designed and installed a short three gap device that accelerates the beams produced at source potential to match the required energy for RFQ acceptance. The booster cavity operates at 11.7MHz the RF frequency of the pre-buncher and delivers up to 9.8kV to the beam. The device can also be used as a second buncher to augment the acceptance in the RFQ or to improve the acceptance of higher space charge beams.

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 35.4MHz 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 (β= 0.0021) to 153 keV/u with a mass-to-charge ratio of 1 ≤A/Q≤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 = 52 kV. Thus for charge to mass ratios of A/Q ≥25 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 to10 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 11.8MHz 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:

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

In this paper we present test results of the booster cavity as an energy compensation device and as a supplemental buncher. The relationship between bunch current and space charge is investigated for the bunching case.

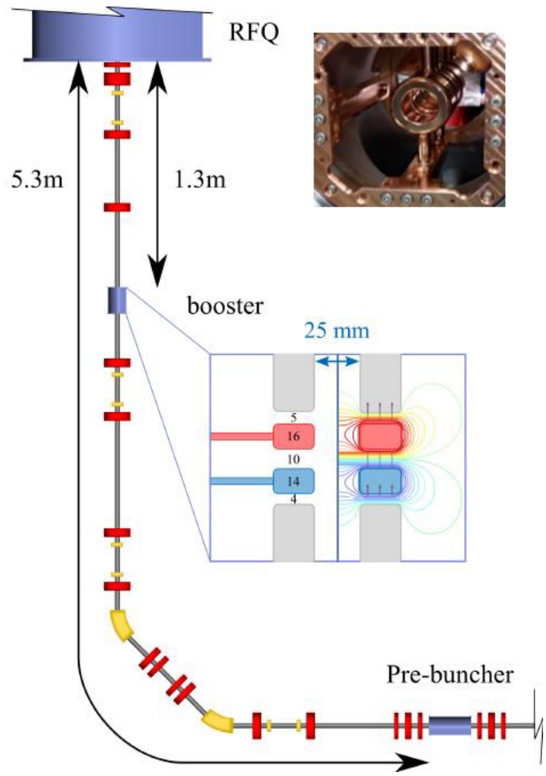

Figure 1: Pre-buncher, booster (inlay photo) and RFQ location at ISAC-I.

BOOSTER DESIGN FEATURES

An efficient design for the booster is a three gap RF device driven by an external lumped circuit. The booster drift tubes operate in a π-mode at 11.8MHz, the pre-buncher's fundamental frequency. An initial variant was described in [3]. The initial device was tested to V_{eff}=7kV and then modified to allow a power increase. The Macor used to support the drift tubes was found to be too lossy and was replaced with a small Teflon brace to support the HV feedlines to the two central drift tubes (Fig. 2).

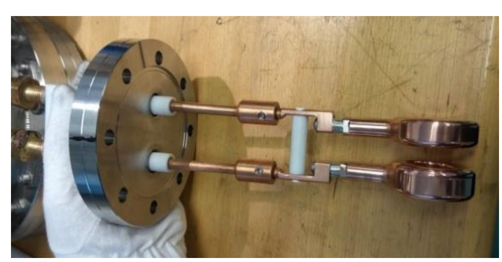

Figure 2: Booster central drift tubes and voltage feed.

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The present design achieves an effective voltage of 9.8 kV, while keeping the peak voltage at the two feed-throughs to reasonable values, ~4.7 kV. A lumped circuit Q of 1500 is attained. The gap spacing is optimized to efficiently accelerate over the velocity range of interest [4].

The booster has to fit within the existing space just up-stream of the final matching optics to the RFQ. The booster electrode aperture is necessarily much larger than the booster gaps, to prevent the limitation of beamline aperture in the existing beamline. This configuration is characterized by significant field penetration inside the drift tubes, as shown in Fig. 1. The drift tube geometry causes an inherent coupling between radial position and longitudinal fields, as depicted in Fig. 3. Thus, off axis particles receive more energy gain than on-axis particles [4], and results in debunching of the beam at the RFQ for typical beam emittances. 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.

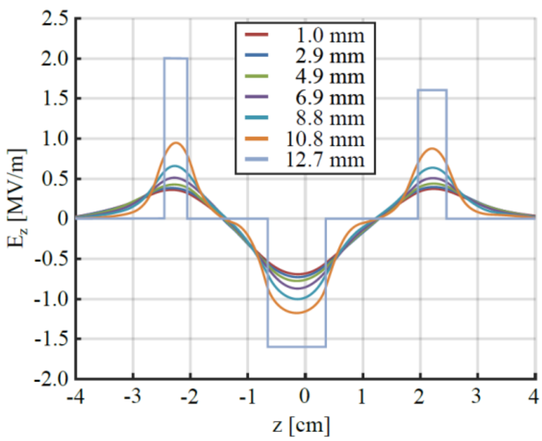

Figure 3: Accelerating field amplitude as a function of beam radius through the booster.

BOOSTER ENERGY KICK

It is found [3] that the expected energy gain through the 3 gap structure is a slowly varying function of the initial velocity and for the A=30 design case is approximately given by:

$$\Delta W(r) \approx 2.1\frac{Q}{A}V_0 I_0\left(k_s r\right)\cos\varphi_0 \qquad (2)$$

where V_0 is the drift tube voltage, $k_s = 2\pi/(\beta_s\lambda)$=141m^{-1} and β_s =0.00175. A simulation of the expected transmission of the booster cavity is done by integrating a well aligned beam of a given beam size 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. Beam test results have been done to confirm the actual performance. Figure 4 displays the effect of the installed RF booster providing energy $^{16}O^{1+}$ with a required terminal voltage of 32.62kV. The booster is powered such that the RFQ injection energy is always optimal as shown in Eq. 1. The reduction in RFQ transmission with increasing relative booster voltage demonstrates the coupling/debunching effects. Beam measurements compare well with simulations shown by the dashed line in Fig. 4 [4] where a beam size of σ=2.5mm is assumed.

BUNCHING MODE

The booster may also be operated at 90 degree phasing, enabling its use as a supplemental bunching device. This mode can be used to augment beam manipulation from the pre-buncher alone to improve the RFQ capture or for stable beam high intensity beam delivery can be used to reduce the impact of longitudinal space charge.

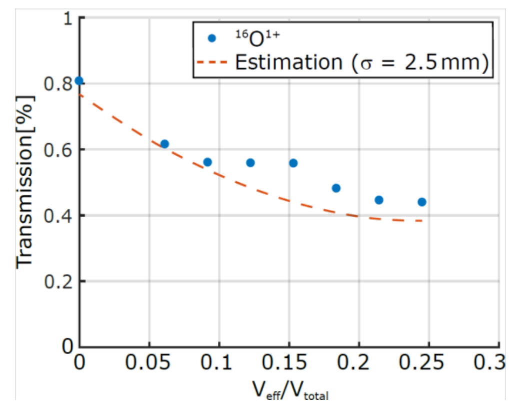

Figure 4: Measured RFQ transmission versus relative booster voltage, compared against simulation for a beam of σ_t = 2.5mm.

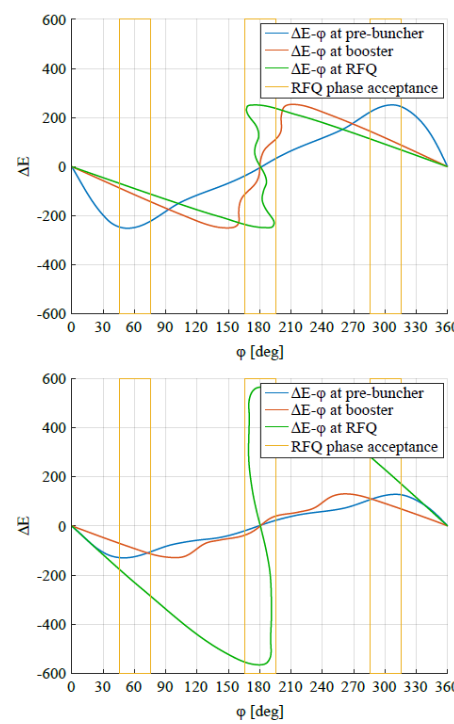

Figure 5: On top is the longitudinal phase space development for the multi-harmonic pre-buncher and at the bottom the longitudinal phase space development for tandem operation (pre-buncher and booster) is depicted for a 16O1+ ion beam at different positions in ISAC-I.

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Standard Bunching

Fig. 5 (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 in the bottom of Fig. 5. This extra bunching is particularly useful for lighter beams, 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 the pre-buncher RF systems.

Bunching in Space Charge Regime

Typically the ISAC linear accelerators boost the energy of low intensity RIB beams but there are cases where high intensity stable beams are required. Longitudinal space charge at high current tends to debunch the beam at the RFQ entrance, reducing the RFQ transmission. A simulation of the space charge effect is illustrated in Fig. 6 [5]. Given the booster's position 1.3m 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.

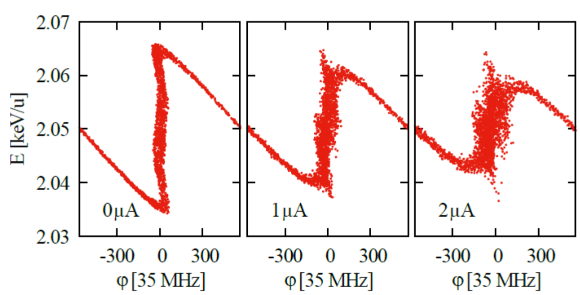

Figure 6: PARMELA simulated particle distribution including space charge effects for three different bunch charges and an A/Q = 30 for 2000 particles. [5]

Beam test results were performed with a 20Ne1+ beam and are presented in Fig. 7. A combination of different collimators and attenuators near the source were used to adjust different beam intensities from 0 to 13μA. RFQ capture data was taken for different combinations of bunching with the prebuncher and the booster. The source energy was constant for all measurements. A transmission of 25% is expected in the RFQ during acceleration of an unbunched beam, as presented in Fig. 7, in blue.

Establishing a time focus, either with the pre-buncher, booster or both, causes an increase in RFQ transmission, as expected. For example, at low intensity, up to 80% transmission is observed for pre-buncher alone (yellow line) and 85% for the tandem of prebuncher and booster (purple line). As the beam current increases space charge reduces the RFQ transmission for the prebunched beam eventually to a transmission equivalent to the unbunched case. Solo booster bunching operation is represented by the red line in Fig. 7. An RFQ transmission of 60% was achieved with the booster in single mode operation, in line with expectations. The sensitivity to space charge is significantly reduced since the debunching distance is considerably shorter than when using the pre-buncher. An increase in the space charge on-set by a factor of ~10 is demonstrated. Tandem operation with the pre-buncher is depicted as the purple line in Fig. 7. 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 non-space-charge regimes.

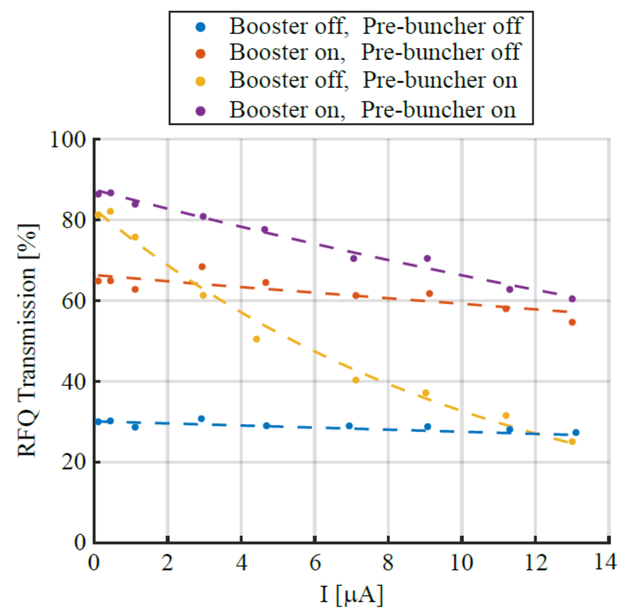

Figure 7: Booster operating as a buncher in different modes, as single or tandem with the pre-buncher, for 20Ne1+.

CONCLUSION

A three gap rf device of very low beta has been designed, built and tested to supply up to 10kV to match an ion beam to the velocity acceptance of the ISAC RFQ. Two operation modes have been demonstrated with beam measurements. In acceleration mode, the booster has been used to augment the source potential by up to 25% 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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