DESIGN STUDY FOR 10 MHz BEAM FREQUENCY OF POST-ACCELERATED RIBs AT HIE-ISOLDE*

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Abstract

An increased bunch spacing of approximately 100 ns is requested by several research groups targeting experimental physics at HIE-ISOLDE. A design study testing the feasibility of retrofitting the existing 101.28 MHz REX (Radioactive ion beam EXperiment) RFQ [1] with a sub-harmonic external pre-buncher at the ISOLDE radioactive nuclear beam facility has been carried out as a means of decreasing the beam frequency by a factor of 10. The proposed scheme for the 10 MHz bunch repetition frequency is presented and its performance assessed with beam dynamics simulations. The opportunity to reduce the longitudinal emittance formed in the RFQ is discussed along with the options for chopping the satellite bunches populated in the bunching process.

INTRODUCTION

The HIE-ISOLDE project represents a major upgrade of the ISOLDE nuclear facility with a mandate to significantly improve the quality and increase the intensity and energy of radioactive ion beams (RIBs) produced at CERN [2, 3, 4]. The project is focused on an upgrade of the existing REX linear accelerator [5] with a new superconducting linac delivering post-accelerated beams at energies over 10 MeV/u, for mass-to-charge ratios up to $A/q = 4.5$. The post-accelerated RIBs at ISOLDE have characteristically low intensities, making transmission and purity very important design considerations. During the second stage of the HIE-ISOLDE upgrade it is planned to install a multi-harmonic buncher (MHB) initiating the formation of the longitudinal emittance outside of the RFQ at a sub-harmonic frequency 10 times lower than its 101.28 MHz resonant frequency. In order to ensure a clean gap between the 10.128 MHz bunches, specified by the experimental users as $< 10^{-2}$ of the total intensity, the MEBT between the RFQ and IH-DTL will be modified to include a chopper structure capable of removing the 101.28 MHz satellite bunches from the bunch train. The extended 98.7 ns bunch spacing will permit time-of-flight particle identification and background suppression techniques to be used by the experiments, and the MHB-RFQ system could increase the A/q-resolution of the facility. A concept of the proposed changes to the existing REX lattice is shown schematically in Figure 1.

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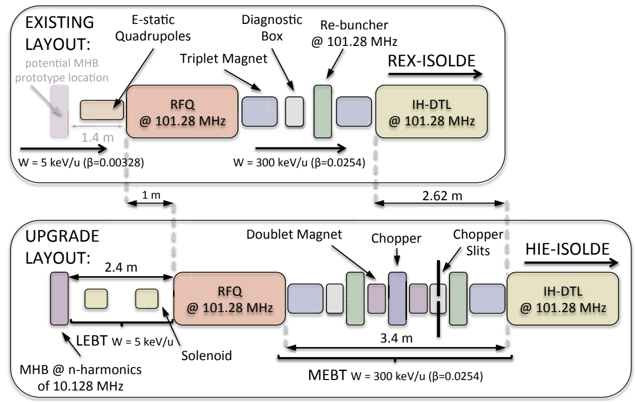

Figure 1: Schematic of the existing (top) and upgrade layout (bottom) with 10 MHz bunching system.

BEAM DYNAMICS STUDIES

A beam dynamics study was carried out to assess the feasibility of externally bunching into the REX RFQ, see [6] for more details. A `PARMTEQ` [7] model was used to characterise the acceptance of the RFQ and to systematically study the transmission and emittance growth through the RFQ as a function of various design parameters.

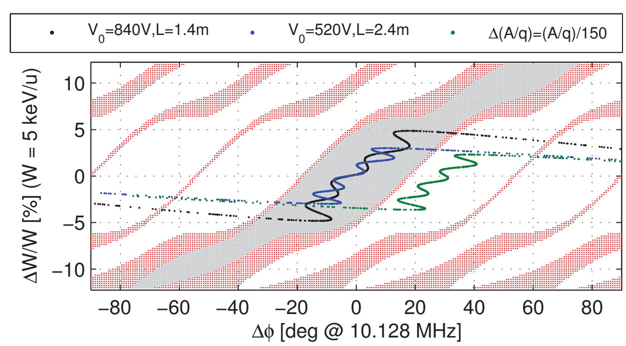

Figure 2: Longitudinal acceptance of REX RFQ.

The longitudinal acceptance on the beam axis of the RFQ is shown over half a 10.128 MHz period in Figure 2; five 101.28 MHz buckets are clearly identifiable with the target bucket shaded and centred. The red points in phase-space lie outside of the acceptance and are not captured by the rf system. The energy acceptance of the RFQ is large (±5%), which has recently been verified experimentally [8]. Superimposed are simulated beams matched using an MHB mixing the first four harmonics of 10.128 MHz in different scenarios: located at $L = 1.4$ and 2.4 m up-

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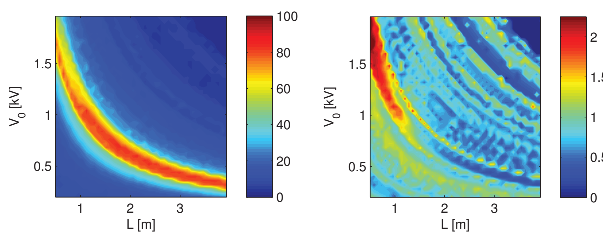
stream of the RFQ, with effective voltages[1] $V_0 = 840$ and 520 V, respectively. The intersection of the beam tails with the acceptance of the other buckets illustrates how the satellite bunches are populated. In the latter scenario, the A/q-resolution is demonstrated as $\frac{\Delta(A/q)}{A/q} \sim \frac{1}{150}$; this beam contaminant would be accelerated by the RFQ in the adjacent satellite bunch and removed by the chopper.

A survey of the transmission and longitudinal emittance at exit from the RFQ is plotted in Figure 3 as a function of the distance L between the MHB and RFQ and the effective bunching voltage V_0. In this systematic study, the MHB was represented as a thin lens and no emittance growth was assumed either in the MHB or the Low Energy Beam Transfer line (LEBT) before the RFQ. As L is increased, V_0 is decreased in inverse proportion such that the focal point is kept constant at some ~ 30 cm inside the RFQ, where the adiabatic bunching section of the RFQ electrodes is located.



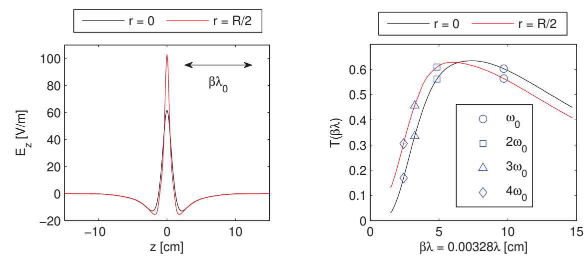
(a) Transmission after RFQ [%]. (b) Longitudinal emittance: ratio with dc injection, $\epsilon_{\mathrm{MHB}}^{\mathrm{rms}}/\epsilon_{\mathrm{dc}}^{\mathrm{rms}}$.

Figure 3: Survey of L and V_0 for a four-harmonic MHB.

The study concluded that an MHB mixing at least three frequency components could achieve transmissions of over 80% with reasonable effective voltages of $V_{\mathrm{eff}} \lesssim 1$ kV and minimal degradation of the emittance for $L > 1.4$ m, see Figure 3(b). The beam energy spread from the ion source was simulated as $\pm 0.1\%$. The longitudinal emittance is reduced in certain cases because the beam is bunched tighter inside the RFQ acceptance.

RFQ Pre-buncher (MHB) Design

A single-gap, grid-less MHB, similar to those employed at ATLAS, ANL [9] and ISAC, TRIUMF [10], was studied to avoid the transmission losses ($\sim 20\%$) associated with gridded bunchers that are unacceptable for the acceleration of rare RIBs. The buncher consists of two drift-tubes driven in 'push-pull' mode, i.e. $-V/2$ and $+V/2$, housed inside a grounded vacuum chamber, see e.g. [9]. The bunching field leaks to ground over a distance $\sim \beta\lambda_0 = 97$ mm outside of the drift-tubes, as shown in Figure 4(a). The aperture ($2R = 20$ mm) was specified as small as possible, keeping the beam envelope well within half the aperture, and the gap size made accordingly small to boost the transit-time efficiency of the higher harmonics; the ratio of the aperture to gap size ($2R/g = 4$) was limited by the strong radial dependence of the transit-time factor, which acts to increase the width of the time-focus created by the MHB. The geometry of the drift-tubes was optimised over four harmonic components to minimise the power dissipated, $P \propto \frac{1}{\tau_0}\int_{-\tau_0/2}^{+\tau_0/2} V^2(\tau)\,\mathrm{d}\tau$, where $V > V_{\mathrm{eff}}$ because of transit-time effects. The transit-time factor for the optimised structure is shown in Figure 4(b) along with the off-axis result, at $r = R/2$. The transit-time effects increase the total power required by a factor of ~ 3.



(a) $E_z(z), V = 1$ V. (b) $T(\beta\lambda)$ on and off-axis.

Figure 4: Transit-time factors $T(\beta\lambda)$ of optimised MHB.

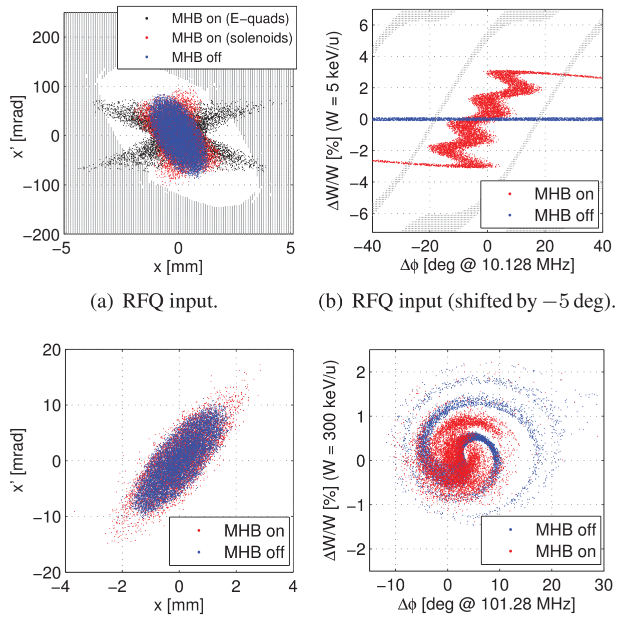
LEBT Beam Dynamics

The 3D field map of the MHB, simulated using CST EM Studio®, was integrated into the TRACK [11] particle tracking code to evaluate the higher-order effects that were neglected in the study reported in [6]. These effects include the transit-time and phase dependence of the MHB's respective longitudinal and radial field components, chromatic aberrations and non-isochronous effects in the LEBT, i.e. path-length differences for off-axis particles. Even in the absence of grids, the rf defocussing in the MHB is small ($\frac{\Delta r'}{r} = R_{21} \sim 0.2\,\mathrm{m}^{-1}$) and the beam envelope is only slightly perturbed; the rms transverse emittance growth induced by the MHB is negligible at $\sim 1\%$. The LEBT must be adjusted to accommodate the MHB because the existing lattice, composed of electrostatic quadrupoles, does not tolerate the energy spread of $\pm 3\%$ that will be introduced; the chromatic aberrations were simulated and compared with the RFQ acceptance in Figure 5(a) (see 'E-quads') for a normalised, total design emittance of 0.3 mm mrad (4D-waterbag). The chromatic effects are largely mitigated with the use of solenoids between the MHB and RFQ, which is also shown in Figure 5(a) (see 'solenoids'). In addition, non-isochronous effects increase the bunch length at injection to the RFQ, see Figure 5(b) and compare with the ideal case in Figure 2. The phase-lagging at the focal point can be mitigated by shifting the bunch position ~ -50 deg (at 101.28 MHz) inside the RFQ acceptance. Geometric aberrations are still to be included in the LEBT and further design work is ongoing to reduce the emittance growth.

Once the CNC files used to machine the RFQ electrode modulations were acquired in late 2012, a 3D electrostatic field map in the vicinity of the RFQ electrodes was computed and included in the TRACK code to successfully

[1] V_0 is the effective amplitude of the fundamental harmonic frequency, including transit time factor; the amplitudes of the other harmonics are scaled accordingly to give a least-squares fit to a linear 'saw-tooth' energy modulation within a phase range of $\pm 150°$ at $\frac{\omega_0}{2\pi} = 10.128$ MHz: $V_{\mathrm{eff}} = V_0\,(\sin\omega_0 t - 0.43\sin 2\omega_0 t + 0.21\sin 3\omega_0 t - 0.10\sin 4\omega_0 t)$.

benchmark the PARMTEQ beam dynamics model used previously.



(a) RFQ input. (b) RFQ input (shifted by -5 deg).

(c) RFQ output. (d) RFQ output.

Figure 5: Phase space comparisons with MHB on ($V_0 = 520$ V and $L = 2.4$ m) and MHB off (dc injection).

With the MHB situated 2.4 m upstream of the RFQ, see Figure 1, the main source of rms transverse emittance growth occurs due to chromatic effects in the LEBT at the level of $\Delta\epsilon_{\mathrm{t}}^{\mathrm{n,rms}} \approx 25\%$. However, the rms longitudinal emittance output by the RFQ is reduced by $\Delta\epsilon_{\mathrm{l}}^{\mathrm{n,rms}} \approx -30\%$. The beam phase space at output from the RFQ is shown in Figures 5(c) and 5(d), and the results are collected in Table 1. The bunch train intensity distribution out of the RFQ includes 82% of beam in the main bunch with $\sim$ 14% distributed over the nine other satellite bunches; the remaining fraction is either lost in the RFQ or is transmitted but not accelerated.

MEBT Design

The studies to date have focused on chopping the satellite bunches in the Medium Energy Beam Transfer line (MEBT), after the RFQ, at a location where the bunch structure is well formed but the beam energy is still relatively low.[2] A schematic layout of the MEBT is shown in Figure 1 and the first-order optics of a chopper line design is shown in Figure 6, using the TRACE 3-D code [7]. The space constraints in the experimental hall allow the total length of the system to be increased by up to 2.62 m. A satisfactory solution is found by extending the MEBT to a total of 3.4 m; the RFQ can then be moved downstream by 1 m. The MEBT is designed to reuse existing REX components that will be recovered as the linac is upgraded. A second rebuncher will be needed to keep the bunch length short through the chopper. A 4 mrad kick, equivalent to a deflection of 33 kV cm, is sufficient to remove the satellite bunches, where the emittance is defined conservatively as equal to the normalised RFQ acceptance of 0.66 mm mrad. The most challenging aspect of the chopper design is the short bunch spacing ($\beta\lambda = 75$ mm) between the main bunch and its nearest satellite, combined with the large 30 mm aperture. A resonant two-frequency chopping system, similar to that reported in [10], which combines two sinusoidal voltages to biased chopper plates at 10.128 and 20.256 MHz is being considered, as is a travelling wave chopper. The technical choice will be based on the predicted emittance growth in studies that are still to be completed.

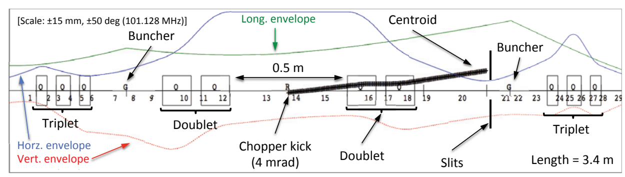


Figure 6: MEBT optics design, $\epsilon_t^{\mathrm{n}} = 0.66$ mm mrad.

Table 1: Nominal Performance of 10 MHz Bunching System at Output of the RFQ ($W = 0.3$ MeV/u, $\beta = 0.0254$)

MHB	T [%]	$\epsilon_{t,x,y}^{\mathrm{n,rms}}$ [mm mrad]	$\epsilon_{l}^{\mathrm{n,rms}}$ [ns keV/u]
On	82	0.060, 0.063	0.16
Off	94	0.051, 0.051	0.24

CONCLUSION

Post-accelerated RIBs with a 10 MHz bunch frequency can be realised at HIE-ISOLDE with good transmission ($\sim$ 80%) and beam quality ($\Delta\epsilon_{\mathrm{t}}^{\mathrm{n,rms}} \approx +25\%$ and $\Delta\epsilon_{\mathrm{l}}^{\mathrm{n,rms}} \approx -30\%$) by retrofitting the REX RFQ with an MHB.

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[2] In principle, chopping could also take place before the RFQ. This approach was discounted because of the need to 'grid' the chopper plates and the concomitant loss of transmission, see e.g. [12]; the aperture is far larger than the permitted longitudinal extent of the chopper fields, which must be $\ll \beta\lambda_0 = 97$ mm.

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