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Time-Spread Manipulation Using Longitudinal RFQ Mismatch

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Abstract: In this note, I report a new operational configuration for TRIUMF's RFQ-DTL postaccelerator, in which the MEBT bunch rotator rf cavity is left unused both with and without charge stripping in the medium energy section. For the former case, manipulation of the synchrotron oscillation in the RFQ enables time-spread minimization in the MEBT section.

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1 Overview

Accelerated beams from ISAC's rf quadrupole linac (RFQ) transit the medium energy beam transport (MEBT) section, which includes a 90° dual dipole chromatic bend[1, 2] section and two rf cavities[3], prior to injection in the separated function drift tube linac (Fig. 1).

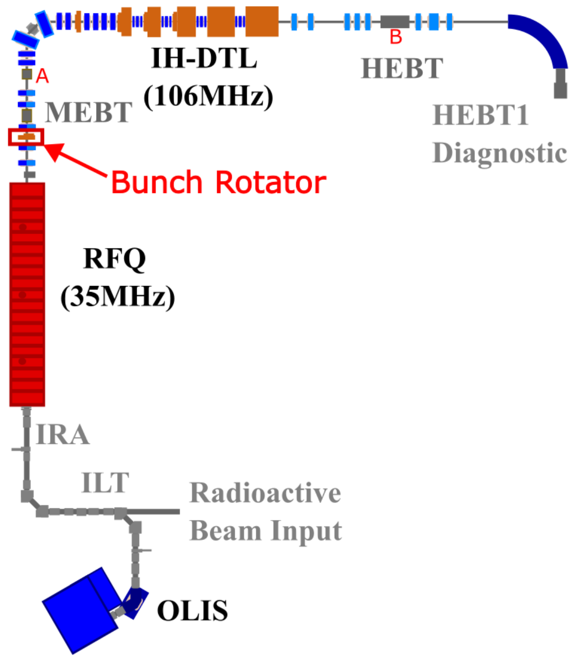

Figure 1: The linac at ISAC-I with labeled sections. 35 MHz bunch rotator cavity location outlined.

To date, the bunch rotator rf cavity, a triple-gap split ring bunching cavity[3] which was developed at INR-RAS[4], of similar design to the DTL bunchers, has been used to perform a time-focus at the stripping foil in MEBT (Fig. 1, A).

In this report, I record that this cavity can be left unpowered for two important cases: unstripped and stripped beams in MEBT.

2 Recalling the MEBT Tune

The MEBT tune has been exposed and discussed in past reports, most notably [1, 2], including a sensitivity analysis of the optics. A longitudinal overfocus issue is also diagnosed in [5] for low A/q beams, broadening the energy spread into the MEBT corner. For convenience, the MEBT design tune is shown in Fig. 2. Two rf cavities are used:

1. The 35 MHz bunch rotator cavity time-focuses beam at the MEBT foil,
2. The 106 MHz rebuncher time-focuses into DTL Tank-1 for further acceleration.

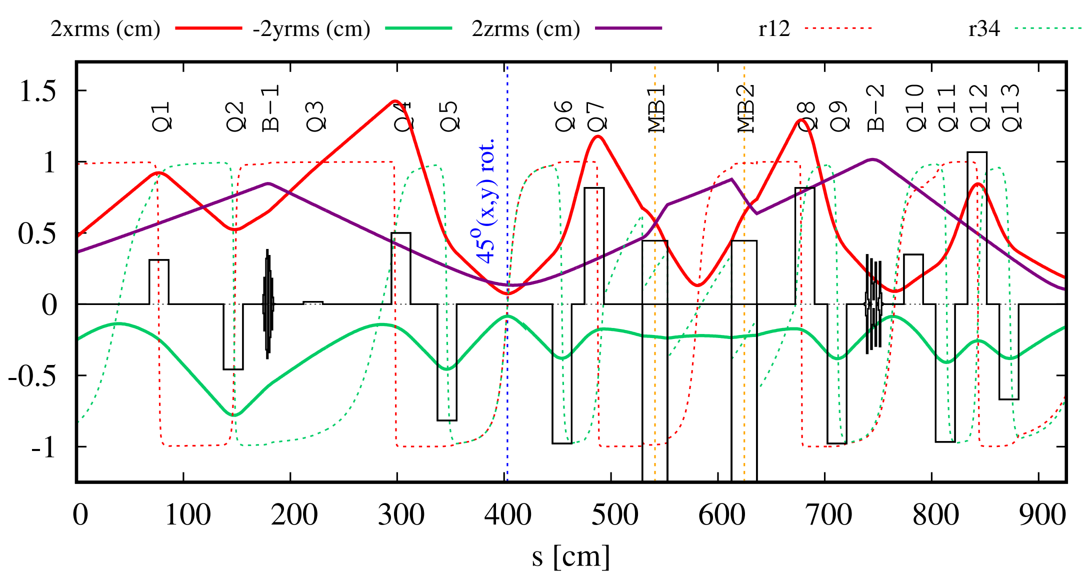

Figure 2: Design MEBT section tune, as presented in [1]. `Trace-3D` simulations are also shown in [3].

Operation of the bunch rotator increases the procedural burden upon the operators: The rf cavity must be adequately phased with the correct amplitude, so as to avoid changing the beam energy in MEBT.

Additionally, there are two quadrupole tunes that have been used by the MEBT section designers: Rotator off and rotator on[6]. As the MEBT tune does not produce a transverse waist at the cavity, it is also liable to induce transverse-longitudinal couplings in the beam, much like the RF booster cavity[7]. Together with documented diurnal-like temperature-transmission correlations[8], there is a strong motivation to identify modes of operation using less of the rf cavities concurrently.

2.1 Looking Back at the Time-Focus Effect

The original `Trace-3D` MEBT simulation is shown in Fig. 3; the simulation starts at RFQ exit and terminates at the stripping foil. **Observe: Should the rotator be unpowered, the size of the z-envelope at the foil would exceed the vertical axis on the plot!**

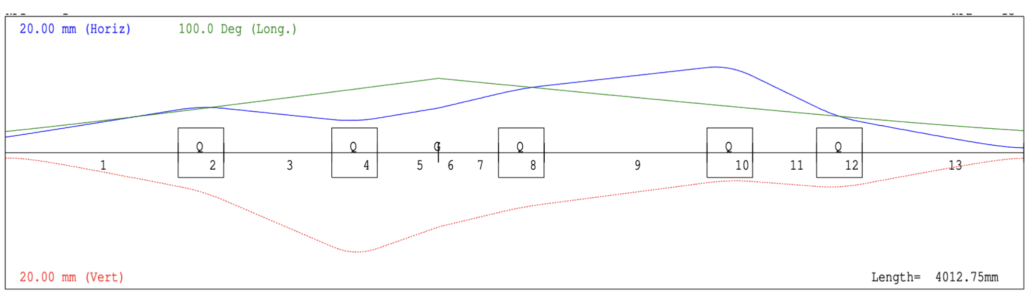

Figure 3: Original `Trace-3D` simulation of RFQ accelerating beam in the MEBT section, showing horizontal (blue), vertical (red, negative) and longitudinal (green) envelopes. In this image, the rotator cavity is used to time-focus at the foil. The rotator is located at the inflection in the z-envelope.

Thus, one would expect an order of magnitude reduction in the beam's time-spread at the foil, when comparing bunch rotator on and off tunes. This is also evident when scrutinizing Fig. 2.

2.2 Effect of the Bunch Rotator

Analysis of previous instances of time-focusing with the bunch rotator by operations suggest the rf cavity causes roughly a factor of two reduction in the time-spread of the beam at the stripping foil[9], consistently, over the last decade. For reference, an example operationally measured time-spread is shown in Fig. 4.

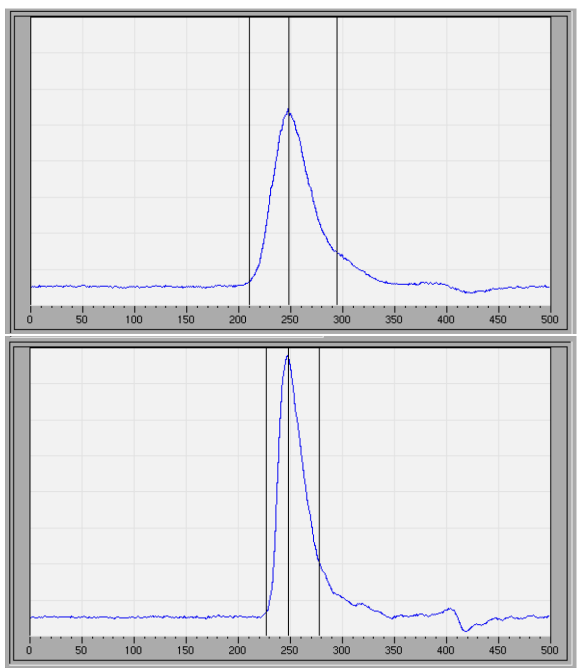

Figure 4: Typical operational measurement of time-spread at the MEBT stripping foil using a time-resolved Faraday cup. **Top:** time-spread with bunch rotator off, with a measured full-time spread of 3.4 ns. **Bottom:** time-spread with rotator on, full-time spread is 2.0 ns, a 1.7 factor reduction.

The procedure followed by operators in Fig. 4 calls for minimization of the time-spread of the beam by way of adjusting the bunch rotator's amplitude[6]. Thus, the rough factor of two reductions represent what is typically operationally achieved.

Finding: The measured effect upon beam of the bunch rotator cavity appears to be less significant than suggested by design assumptions.

Inference: This means the longitudinal bunch appears to possess a lesser divergence than assumed in design simulations.

Supposition: It may thus be possible to mainuplate the synchrotron (longitudinal) oscillation in the RFQ to reduce the time-spread at the foil, obviating bunch rotator use.

3 Synchrotron Oscillation in the RFQ

A comparison between PARMTEQ-M and TRANSOPTR simulations of the ISAC-RFQ is published in [10], showing the envelope code's agreement with ray-tracing simulations, in the first order dominated regime. These simulations show the nature of the synchrotron oscillation through the RFQ linac, in which the bunch completes 8 cycloidal-like size variations during accelerator transit.

A new operational technique is to purposely manipulate the synchrotron oscillation in the RFQ, by way of slightly increasing the voltage to roughly 102% of the nominal value as obtained by the RFQ cutoff test[2], while adjusting the prebuncher all-frequencies by a few degrees. The comparison between nominal and manipulated tune cases is shown in Fig. 5.

From the nominal (dotted lines) tune, the RFQ amplitude has been increased by $\sim$1.7% and the injection phasing by 2°, altering the nature of the synchrotron oscillation, and producing a reduction noted Δz at the end of the simulation, coinciding with the MEBT stripping foil. This effect should rival the documented effects of the bunch rotator cavity shown in the previous section.

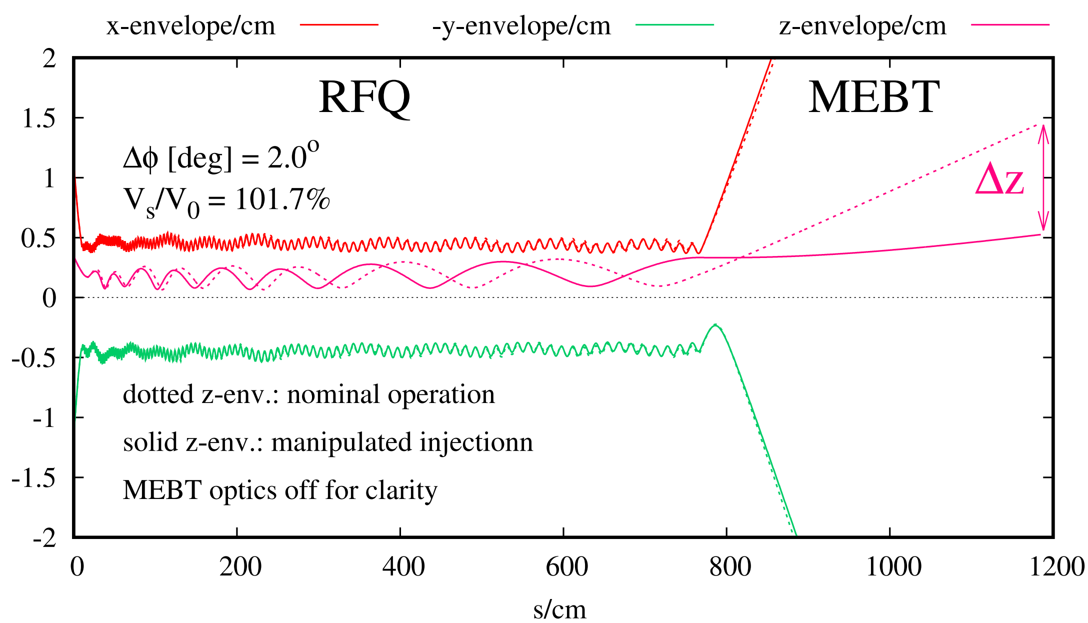

Figure 5: Comparison of nominal and manipulated RFQ tunes. A reduction Δz is achieved at the stripping foil, where the simulation terminates. The MEBT quadrupoles are left off for clarity. Observe the nearly identical transverse envelopes, in either case.

4 On Line Verification

During June 2024, a ^{7}Li^{+} beam from the OLIS surface source was used during machine development at ISAC to verify this new operational mode. A MEBT foil was inserted and the tune downstream adjusted to select ^{7}Li^{2+}. Instead of using the rotator, which was left unpowered, the amplitude was increased and prebuncher all-frequencies phase adjusted while looking at both MEBT:FC7 and MEBT:FC9, in addition to the profile monitor MEBT:RPM7, all downstream of the MEBT stripping foil.

Operations measured the transmission which is documented in [11], with transmission summary shown in Fig. 6. Beam was accelerated to full operational E/A in this tune, meaning MEBT Rebuncher and all DTL cavities are operating. Importantly, this demonstrates that omission of the bunch rotator cavity together with this synchrotron technique does not comporomise capture efficienty and transmission through DTL.

Cup Transmissions	
IOS:FC6 to ILT:FC49	88.7%
ILT:FC49 to MEBT:FC5	71.9%
MEBT:FC5 to MEBT:FC9	84.5%
MEBT:FC9 to HEBT:FC5	91.7%
HEBT:FC5 to SCB1:FC0	92.9%

Figure 6: RIB Operations measured transmissions along the RFQ-DTL and up to SEBT, using the novel operational mode detailed herein. ^{7}Li^{2+} is accelerated to 1.53 MeV/u in this tune.

5 Summary

This new operational mode was made possible by using beam based modelling investigations to infer a possible tuning strategy, which was then verified on-line by operations. Instructions communicated to accelerator operators enabled establishment of a high transmission RFQ-MEBT-DTL tune, without using the bunch rotator cavity.

The significance of this is twofold:

1. This mode of operation simplifies the tuning procedure for operators,
2. This is inherently a more reliable mode of operation, as there is one less rf cavity that can become unstable or trip off.

Together with the demonstration of operation of unstripped beam without using the rotator[12] in which similar transmissions are achieved, machine development investigations backed with TRANSOPTR modelling have shown a new operational mode for the ISAC linac, in which the bunch rotator cavity remains unpowered.

6 Acknowledgements

Thanks to RIB operators for on-line tuning, which both helped verify the experimental possibility elaborated herein, while also helping to craft initial tuning procedures for this novel operational method.

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