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Model Coupled DTL Drifting Tune On-Line

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Abstract: A model computed drifting DTL tune is established on-line, using the TRANSOPTR model of the accelerator. This is achieved by manually detuning the MEBT section optics to correct DTL Tank-1 injection. Using this technique, a machine tune at $E/A = 0.151$ MeV/u was established during a development shift on 2022-05-12 with a recorded average transimssion of 97.7% and beam size agreement at profile monitor HEBT:RPM5.

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1 Introduction

Ongoing beam dynamics investigations at ISAC-I aim to make use of the newly built TRANSOPTR model of the ISAC linac's[1, 2] medium[3] and high[4] energy sections to control the optics in software. Following three years of development, this report documents the successful strategy to establish a model computed tune through the unpowered ISAC drift tube linac (DTL). This was first achieved during an exploratory tuning session in May 2022. Experimental tuning software was tested on-line, computing the machine optics in real time and allowing the operator to load these values to the apparatus.

The significance of these reported developments is further underlined by the persistent difficulties with establishing precise model tunes in the ISAC-DTL[5], necessitating manual tuning of its optics by operators for beam delivery. There has been an implicit belief at TRIUMF over the years that the DTL quadrupoles did not behave as expected, though this was only evidenced by the aforementioned tuning demands of the section; beam transmission would still be in the high 80's and mid 90's after operator intervention, suggesting any such hypothetical error was not major. Repeated discussions with operators also placed suspicion upon the DTL quadrupole steerers, which have remained turned off and disused over the years as a result.

Using the envelope model of the machine and sequential optimization [6] to compute a tune from first-principles, meaning without resorting to previously saved values for the optics, in real-time, and demonstrating high transmission and beam profile agreement downstream, thus demonstrates that the DTL's components are free of flaws in operation. Moreover, the main discovery reported herein is the root cause of these perennial tuning issues: The ISAC MEBT section. Ongoing analysis of the section's optics has revealed error modes, arising from the design tune's sensitivity to small quadrupole field errors, a topic which is first presented and discussed.

2 A Look at ISAC-MEBT

The MEBT corner is described in [7] as being singly achromatic, introducing couplings between transverse and longitudinal phase spaces. Since the bend in MEBT is along x, the couplings are between canonical pairs (x,x') and (z,z'). Once this is initiated in a beam, the focal lengths of quadrupoles will become smeared out over a range $f \pm \Delta f$. Over a sufficient distance, the transverse-longitudinal correlations in the $\boldsymbol{\sigma}$-matrix can cause the emergence of a beam halo, with particles falling outside of the tune assumption but remaining sufficiently proximal to the reference particle allowing transport.

Once particles 'fall out' of the tune-assumed beam distribution, they cannot be recovered and will likely lead to transmission loss, especially when the beam must pass through narrow apertures. This condition cannot be 'tuned out' downstream. The emergence of such a halo out of the MEBT corner is shown in Fig. 1, with low intensity tails around both (x, y) distributions. All locations at ISAC-I and ISAC-II will continue to see such chromatic effects, which may ultimately limit transmission to experimental stations.

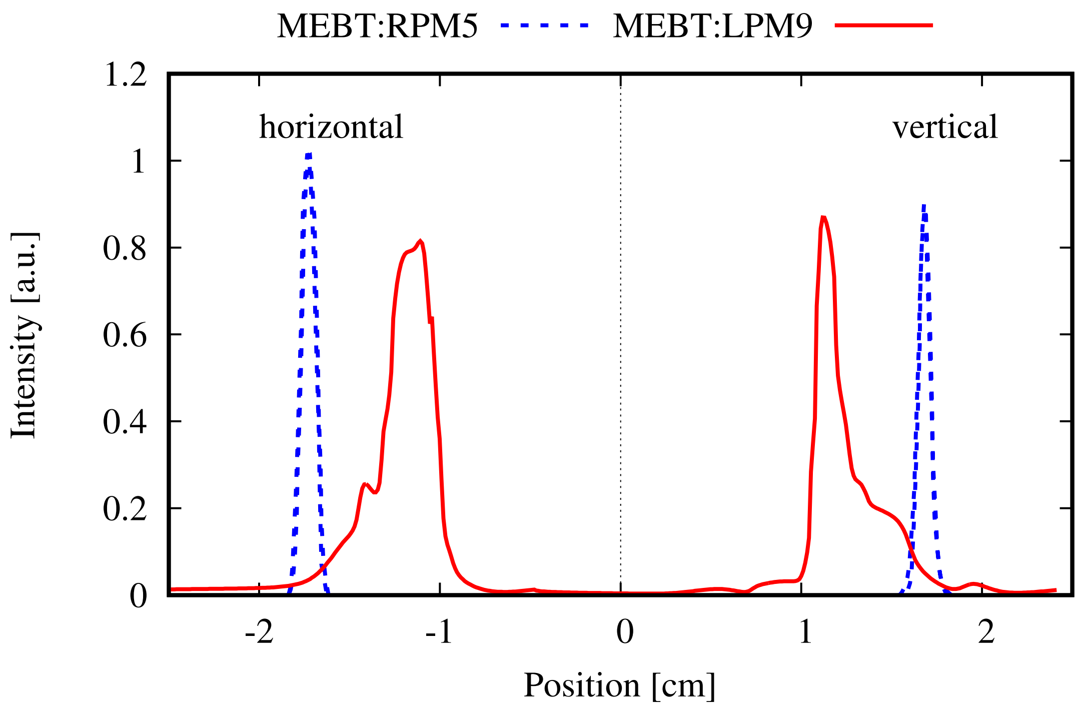

Figure 1: Overlay of representative beam profiles for MEBT:RPM5 and MEBT:LPM9, showing the emergence of low intensity tails in the distribution after MEBT corner transit.

The absence of achromatic lenses traces its origin to a re-design of the charge selection corner, reported in 1997. A change was made to the RF frequency of the downstream MEBT rebuncher RF cavity, from 23 to 35 MHz due to RF engineering considerations. For this reason it is reported that the achromatic lenses were removed [8]. This was done to shorten the length of the charge selection section, minimizing longitudinal bunch growth due to an excessive drift between the bunch rotator and rebuncher. The newer, reduced rebuncher RF wavelength imposed stricter constraints on the longitudinal acceptance ($\beta\lambda$) of the cavity. Though the final design mitigates Δt growth due to excessive drift, it produces a chromatic beam everywhere downstream of MB1.

2.1 MEBT Corner Design Tune

The MEBT design tune is shown in Fig.2, starting from a round waist at the chopper slit, where the (x, y) reference frame rotates by 45°. The doublet (Q6,Q7), mirrored with (Q8,Q9), produces a focus-to-focus through the corner in the dispersive plane, while relying upon the dipole edge effects for vertical focusing. While this accomplishes a round waist at the midpoint of the rebuncher, it also introduces chromatic couplings, shown in Fig. 2 as the dotted purple line, representing transfer matrix element $\mathcal{M}_{16}$, the (x, Pz) coupling. The injected DTL beam is therefore expected to deviate

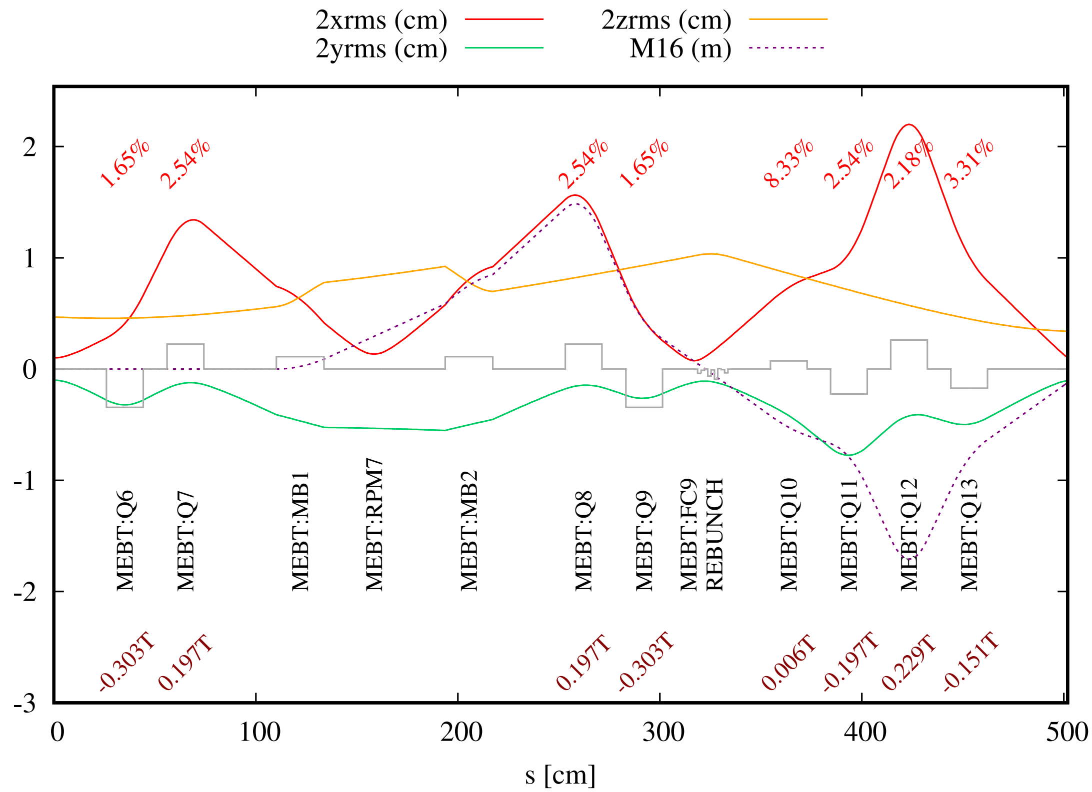

Figure 2: The design tune of the ISAC-MEBT corner, showing 2 rms (x, y, z) envelopes at A/q = 6. Additionally, the transfer matrix element $\mathcal{M}_{16}$, involved in the (x, Pz) coupling, is shown in purple. The A/q = 6 quadrupole tip fields are shown for each quadrupole at the bottom of the figure, in green. The percent error of a hypothetical 5 mT field error is shown for each quad at the top, in red.

from its design assumption of an uncoupled input $\boldsymbol{\sigma}$-matrix[9, 10, 11]. The introduced couplings to the $\boldsymbol{\sigma}$-matrix, shown in Fig. 3. This condition is inherent to the design of the MEBT optics and cannot be tuned out, only minimized.

The section's optics are defined by quadrupole lenses of 182 mm [12] effective length, with aperture radius 2.6 cm. After the stripping foil, this produces tunes which feature relatively low quadrupole tip-fields (Fig. 2, bottom). The quadrupole tip-field errors are shown at the top of the same figure, as percentages. To understand the significance of those numbers, it is instructive to consider the transformation of an elliptical phase space distribution.

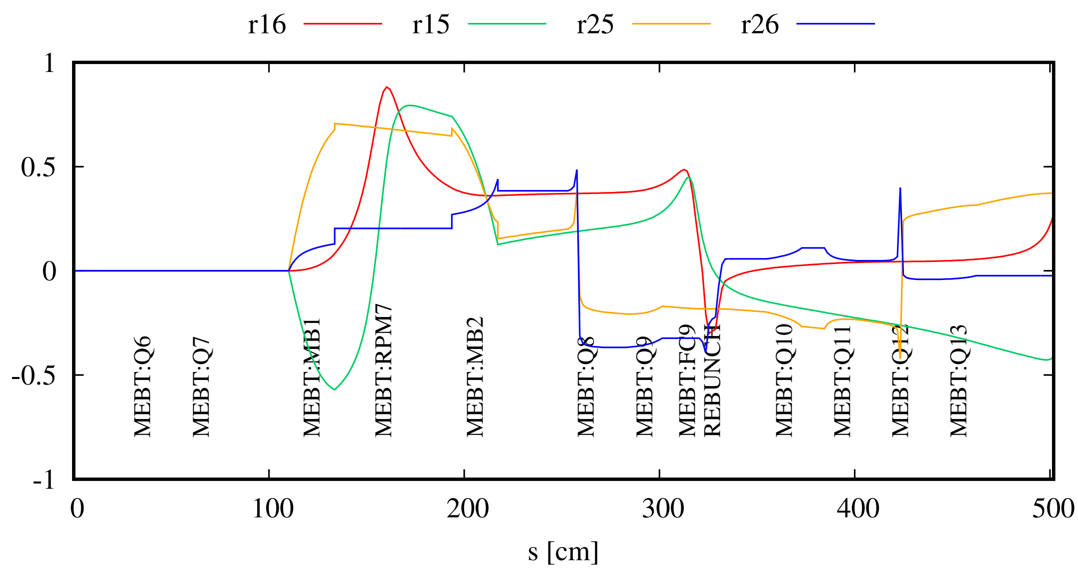

Figure 3: Beam-matrix computed correlation coefficients between coordinate pairs (x, Px) and (z, Pz), numbered as (1,2) and (5,6), respectively. The dipole MB1 initiates these correlations, which persist downstream.

2.2 Tune Eccentricity

Suppose two separate tunes call for the transformation of a distribution through a quadrupole. The first tune transforms **P1** into **P1'** and the other **P2** in to **P2'**, shown in Figure 4. Both distributions have the same area (emittance) and produce the same 2 rms size in x, though their momenta are different. The distribution bounded by **P1'** (Fig. 4, dotted red) has a higher correlation coefficient r_{12} when compared to **P2'** (same figure, dotted blue).

Since the transformation through the quadrupole depends on the phase space coordinates themselves, a larger extent produces a larger mismatch, appreciable in the figure as the lesser overlap of the more eccentric distribution when compared to the tune assumption. In other words, tunes which call for the transformation of skinny, highly elliptical distributions are more susceptible to the accumulation of transformation errors, leaving a considerable fraction of the distribution outside the tune assumption. This can be quantified by using Bovet's mismatch parameter:

$$\mathcal{D} = \frac{1}{2}(\beta_2\gamma_1 + \gamma_2\beta_1 - 2\alpha_1\alpha_2), \tag{1}$$

together with the common overlap equation for two ellipses;

$$\frac{S_C}{S} = \frac{4}{\pi}\sqrt{\arctan(\mathcal{D} - \sqrt{\mathcal{D}^2 - 1})}. \quad (2)$$

By computing S_C between the tune assumption (Fig. 4, dotted ellipses) and the actual transformation (same figure, solid ellipses), we obtain a quantification of the mismatch resulting from the quadrupole field error, shown in Figure 5. The smaller the eccentricity of the distribution, the lesser overall mismatch results from any given field error. A symptom of tunes with such highly correlated ellipses is the presence of absolute values r_{12} near unity, which will result in quadrupole transformations sensitive to field errors. The MEBT corner tune further possesses such high transverse beam matrix correlations, shown in Figure 6.

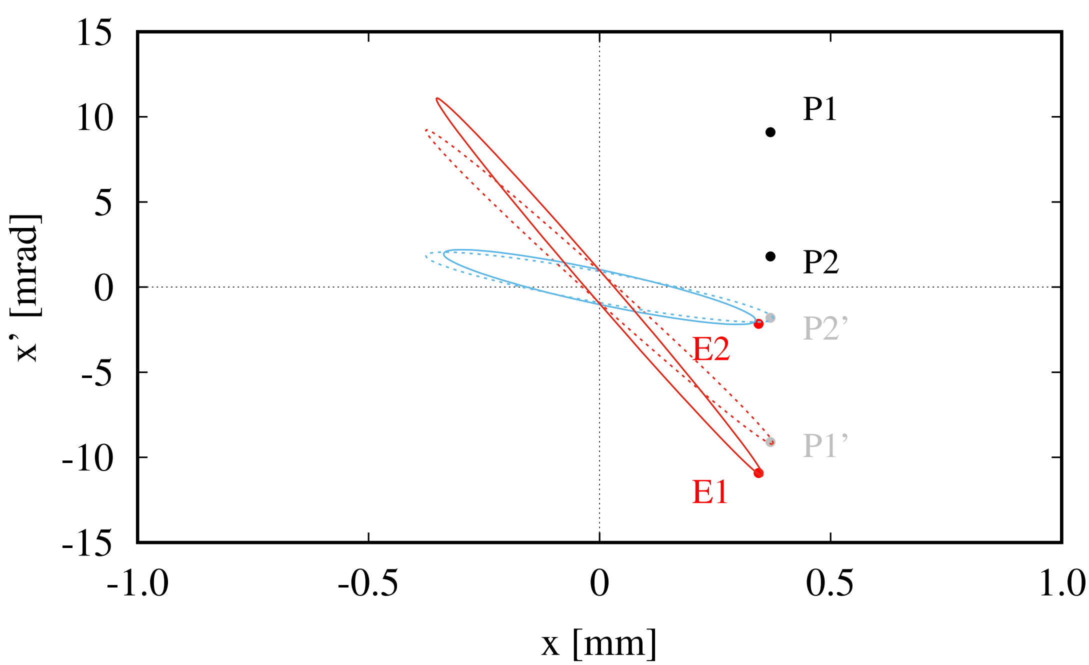

Figure 4: The points **P1** and **P2**, representing the original maximum extent of an initial beam distribution have been transformed by a quadrupole with a field error. The tune assumption is that (**P1**,**P2**) are transformed to (**P1'**,**P2'**), but in reality they have been transformed into (**E1**,**E2**).

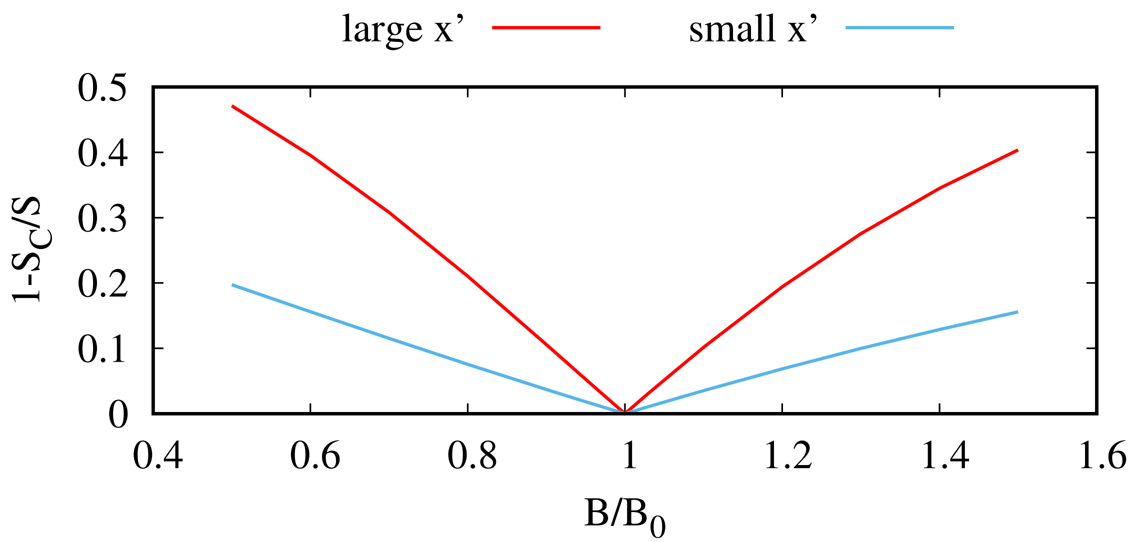

Figure 5: Transverse mismatch defined as 1-S_C/S, the ratio of area overlap between actual and expected ($B = B_0$) ellipses after transformation through a quadrupole with a field error. The x-axis shows the quadrupole field normalized to the tune expectation, while the y-axis values are that of Eq. (2).

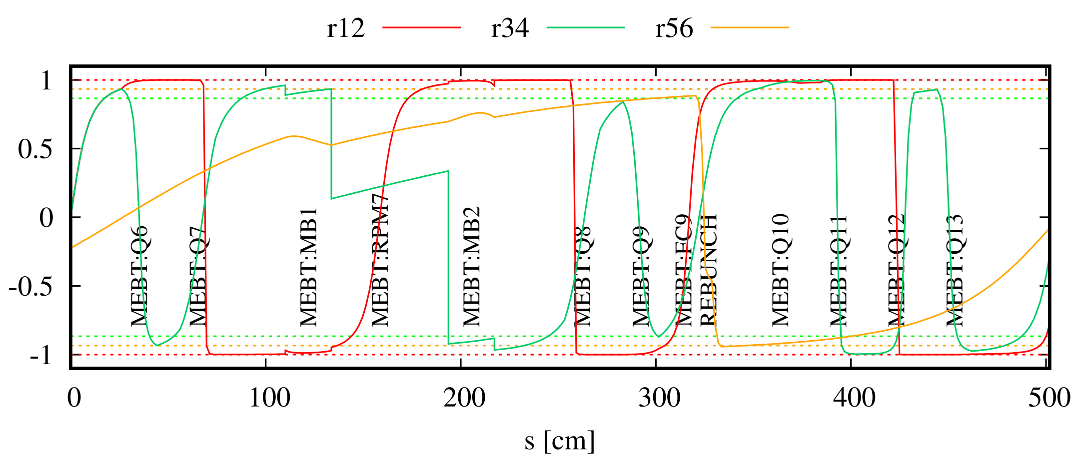

Figure 6: Beam matrix correlation coefficients between canonical coordinates in TRANSOPTR, showing strong transverse correlations r_{12}, r_{34} and r_{56}. An A/q = 30/5 beam has been used at E/A = 0.153 MeV/u.

During drift, the infinitesimal transfer matrix is only nonzero for elements $\mathbf{F}_{12}, \mathbf{F}_{34}$ and $\mathbf{F}_{56}$. Skinny ellipses arise from long inter-quadrupole drifts, which horizontally shear the phase space distribution, shown in Fig. 7. This makes the tune more sensitive to small field errors, for example from hysteresis. To understand what effects this can have on the beam envelope, the tune from Fig. 2 was used in TRANSOPTR to perform a Monte-Carlo simulation, by repeatedly computing the envelope through MEBT while applying a random error on each quadrupole tip-field. Two prominent error modes are seen to emerge.

Observe the variation in 2 rms horizontal size at DTL injection (Fig. 8, top, s = 500 cm), which can exceed the 1.4 cm drift tube aperture diameter for Tank-1 [1]. The variability in the resulting x-envelopes predicts horizontal 2 rms broadening of up to a factor of two. The result at the bottom of the figure illustrates another possibility: while the 2 rms sizes remain better bounded, an anomalous phase advance emerges after the dipoles, which acts to change beam from horizontally converging to diverging out of the MEBT section. Injected DTL beam significantly deviates from the design assumption [10] in size and couplings. Since the transverse DTL tune assumes fully decoupled beams other than for (x, Px), (y, Py) and (z, Pz), this compromises the ability to use computed DTL quadrupole gradients on-line as they will produce low transmission.

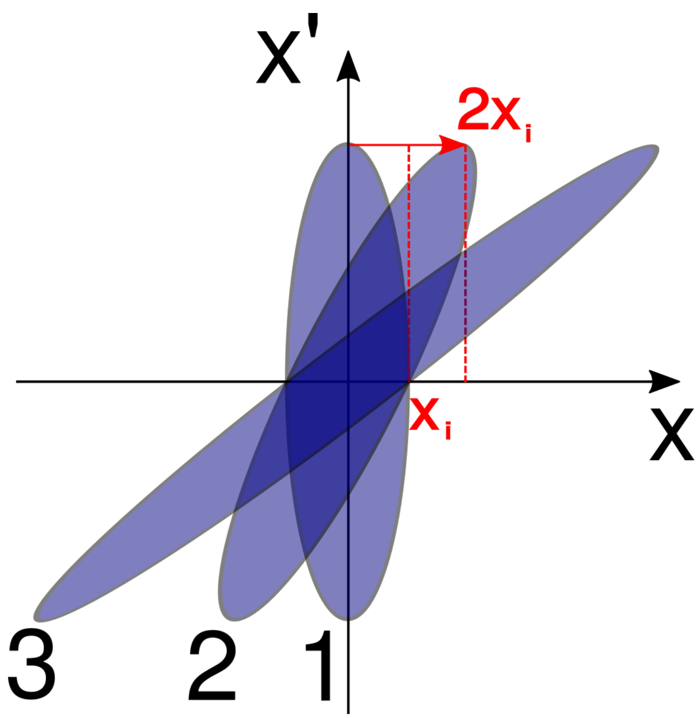

Figure 7: A hypothetical phase space ellipse (**1**) initially with α=0 and a half-width x_i, drifts a distance d causing it to double in size (**2**). A particle initially at the peak of the ellipse (0,$\sqrt{\gamma_x \epsilon_x}$), will travel a transverse distance 2x_i as the beam doubles in size. If the drift distance is larger, more shearing will result, broadening the extent of the distribution in phase space (**3**).

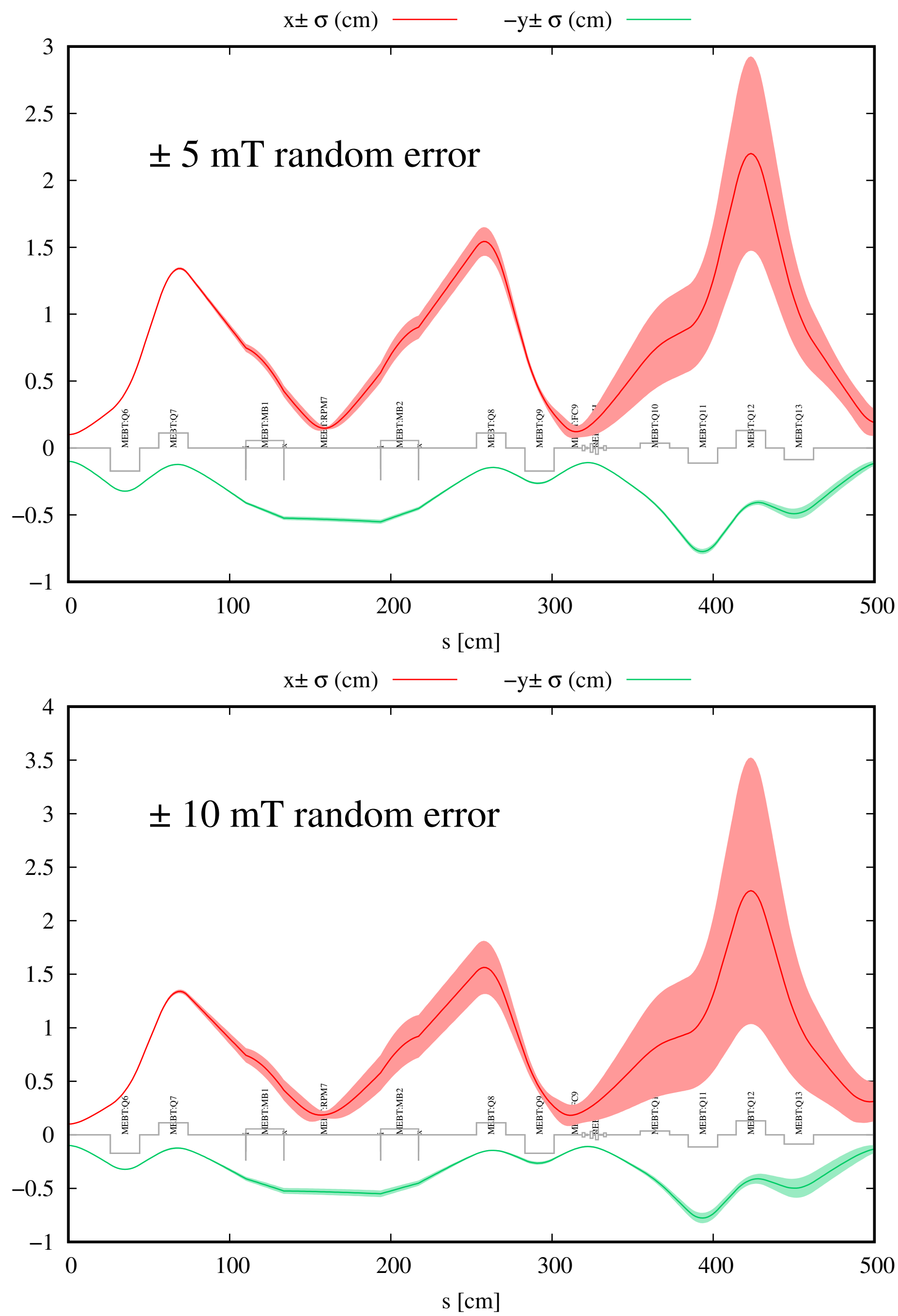

Figure 8: Two separate 100 TRANSOPTR runs of the ISAC-MEBT section using an A/q = 30/5 beam at E/A = 0.153 MeV/u. A ± 5 mT (**top**) and 10 mT (**bottom**) random Gaussian error has been applied to each quadrupole tip-field in the section at each iteration, representing possible cases of unknown quadrupole field errors, for example due to hysteresis.

3 TRANSOPTR Computed ISAC-DTL Drifting Beam Tune

The envelope model of the DTL was used to compute a drifting beam tune through the linac, for a ^{4}He^{+} beam at a $E/A = 0.151$ MeV/u, measured online. The starting beam distribution used by TRANSOPTR is shown in Figure 9 with values listed in Table 3. The starting transverse distribution is based on model investigation initial conditions used in [1, 2]

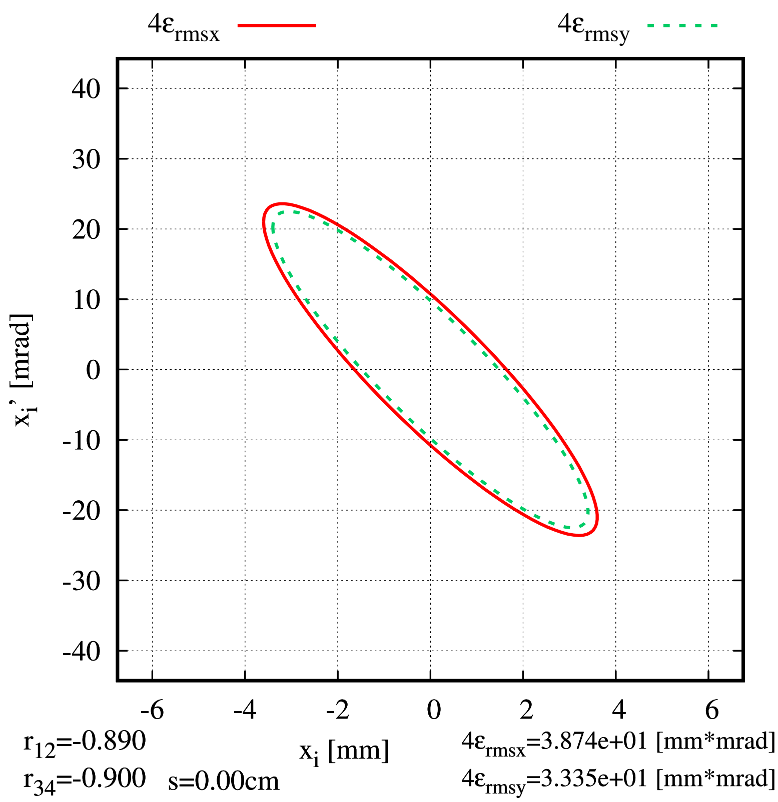

Figure 9: 4rms containment ellipses for transverse dimensions at DTL Tank-1 injection.

This tune was loaded on-line and beam was then sent from MEBT:FC9, the first Faraday cup after the MEBT corner, to HEBT:FC5, located in diagnostic box-5, which includes an RPM for profile readings. Initially, maximum transmissions of roughly 80% were obtained, through a combination of (x,y) steering in the MEBT section, whose optics had been set to a TRANSOPTR computed tune for ^{4}He^{2+}, shown in Appendix A, which was scaled for $A/q = 4$. Informed with the understanding of tune eccentricity in MEBT from Section 2, the medium energy optics from Q6 to Q13 were manually detuned, with MEBT:Q10 turned off, allowing for use of Q10 to 13 as a triplet, though with equal length lenses. By detuning the MEBT quadrupoles, while keeping the ISAC-DTL and HEBT quadrupoles set to the TRANSOPTR computation, a time-averaged DTL drifting tune transmission of 97.7% was recorded, including good beamsize agreement at HEBT:RPM5, shown in Figure 10.

Quadrupole	Type	Current [A]	Aperture Radius [cm]	L_{eff} [cm]
DTL:Q1	DTL-Short	66.87	1.1988	5.8000
DTL:Q2	DTL-Long	63.2	1.1988	8.7000
DTL:Q3	DTL-Short	64.05	1.1988	5.8000
DTL:Q4	DTL-Short	44.31	1.1988	5.8000
DTL:Q5	DTL-Long	53.78	1.1988	8.7000
DTL:Q6	DTL-Short	55.29	1.1988	5.8000
DTL:Q7	DTL-Short	35.99	1.1988	5.8000
DTL:Q8	DTL-Long	46.76	1.1988	8.7000
DTL:Q9	DTL-Short	46.67	1.1988	5.8000
DTL:Q10	DTL-Short	30.27	1.1988	5.8000
DTL:Q11	DTL-Long	41.61	1.1988	8.7000
DTL:Q12	DTL-Short	40.66	1.1988	5.8000
HEBT:Q1	L1-1987	0.000	2.6000	18.2000
HEBT:Q2	L1-1987	5.019	2.6000	18.2000
HEBT:Q3	L1-1987	5.844	2.6000	18.2000
HEBT:Q5	L1-1987	7.688	2.6000	18.2000
HEBT:Q6	L1-1987	6.19	2.6000	18.2000
HEBT:Q7	L2-1987	5.73	2.6000	33.1500
HEBT:Q8	L1-1987	4.48	2.6000	18.2000

Table 1: Optimized drifting tune with starting parameters from Table 2 for $^{4}He^{+}$.

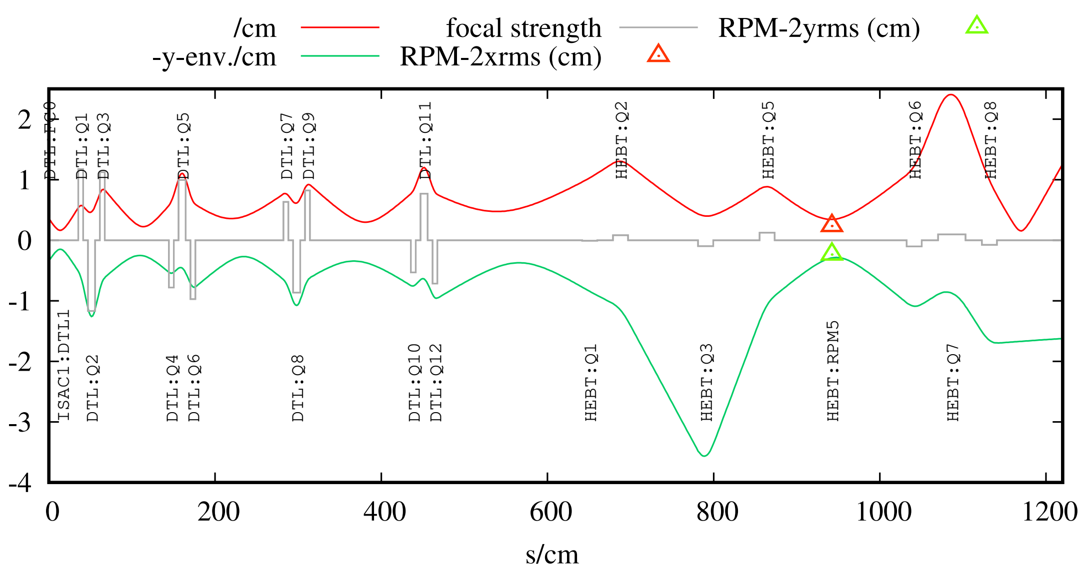

Figure 10: On-line TRANSOPTR computed ISAC-DTL tune at drift, for $E/A = 0.151$ MeV/u, as measured at the HEBT1 station. Beam size readings at HEBT:RPM5 were performed.

Finding 1: Manual detuning of the MEBT section allows for the use of TRANSOPTR computed ISAC-DTL and HEBT triplet quadrupole tunes, with high transmission.

Finding 2: The DTL quadrupole polarities used in report [1] are reversed from the on-line installation. On-line polarities for DTL triplet-1 can be found in [13]

4 Conclusion

This report presents a milestone in model coupled tuning for the ISAC-DTL: The establishment of a model computed drifting tune through the linac structure, which will serve as a baseline for machine optics recomputations with accelerated beam. Ongoing investigative work into the ISAC linac optics has provided insight into expected tune sensitivities in the MEBT section, causing a mismatch at DTL Tank-1 injection. This has been the cause of ISAC-DTL tuning difficulties over the years, due to the relatively tight aperture constrictions in the linac (drift tube apertures are down to 1.0 cm). In particular, model computed tunes loaded in the quadrupole triplets will produce below optimum transmission due to the injection mismatch condition.

Procedurally, operations considers the MEBT section optics as ”untunable”[14], except for Q2 and Q3. Only steering is performed in MEBT, and current tuning procedures specify which devices can be detuned and by how much. The same procedures call for the manual ajdustment of the DTL quadrupoles, in order to achieve maximum attainable transmission. The findings in this work suggest that this is the wrong approach: Past investigations into the DTL quadrupoles found no abnormalities in the devices. On the other hand, analysis of the MEBT design tune, together with the low operating setpoints produced by its quadrupoles, results in a section design tune which is expected to deviate from simulations. An important advantage of the approach presented herein is that the MEBT section only needs to be detuned manually once, as its energy is constant. On the other hand, considerable operator time is devoted to tuning the DTL quadrupoles as the machine energy is progressively increased.

The demonstration that manual detuning of the MEBT optics including and beyond the corner allows for the establishment of a very high transmission tune calls for deeper investigations into the medium energy section optics. Better understanding how to remediate these issues and control the beam with greater precision should allow for the eventual implementation of strict use of model-computed values, and the expectation that they produce optimum DTL injection. Until that time, this report concludes with the suggestion that operations reviews its tuning procedures for the section. Regarding the implementation of model coupled accelerator tuning techniques at ISAC-I, the presented findings should allow for the start of accelerated beam tests using model computed tunes.

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Appendix

A ^{4}He^{2+} Drifting DTL to HEBT Tunes - New Calibrations

Parameter	Value
x_i	0.10 cm
x'_i	0.01 rad
r_{12}	0.00
E_i/A	0.150 MeV/u
m_0	3725.98 MeV/c^2
q	2

Table 2: Initial beam parameters used for `TRANSOPTR` tune computations in this work. Starting parameters for dimensions (x, y) are identical.

Quadrupole	Type	Current [A]	Aperture Radius [cm]	L_{eff} [cm]
MEBT:Q6	L1-1987	7.718	2.6000	18.0000
MEBT:Q7	L1-1987	6.108	2.6000	18.0000
MEBT:Q8	L1-1987	6.398	2.6000	18.0000
MEBT:Q9	L1-1987	8.552	2.6000	18.0000
MEBT:Q10	L1-1987	4.394	2.6000	18.0000
MEBT:Q11	L1-1987	7.979	2.6000	18.0000
MEBT:Q12	L1-1987	7.889	2.6000	18.0000
MEBT:Q13	L1-1987	4.108	2.6000	18.0000
DTL:Q1	DTL-Short	34.41	1.1988	5.8000
DTL:Q2	DTL-Long	31.21	1.1988	8.7000
DTL:Q3	DTL-Short	33.62	1.1988	5.8000
DTL:Q4	DTL-Short	20.67	1.1988	5.8000
DTL:Q5	DTL-Long	24.44	1.1988	8.7000
DTL:Q6	DTL-Short	23.28	1.1988	5.8000
DTL:Q7	DTL-Short	17.02	1.1988	5.8000
DTL:Q8	DTL-Long	23.26	1.1988	8.7000
DTL:Q9	DTL-Short	23.8	1.1988	5.8000
DTL:Q10	DTL-Short	14.5	1.1988	5.8000
DTL:Q11	DTL-Long	20.8	1.1988	8.7000
DTL:Q12	DTL-Short	20.76	1.1988	5.8000
HEBT:Q1	L1-1987	0.000	2.6000	18.2000
HEBT:Q2	L1-1987	2.264	2.6000	18.2000
HEBT:Q3	L1-1987	2.639	2.6000	18.2000
HEBT:Q5	L1-1987	3.179	2.6000	18.2000
		Prague Magnet		
HEBT:Q6	L1-1987	5.664	2.6000	18.2000
HEBT:Q7	L2-1987	3.235	2.6000	33.1500
HEBT:Q8	L1-1987	4.454	2.6000	18.2000
		HEBT-GPS		
HEBT:Q6	L1-1987	2.816	2.6000	18.2000
HEBT:Q7	L2-1987	1.341	2.6000	33.1500
HEBT:Q8	L1-1987	0.000	2.6000	18.2000
HEBT:Q9	L2-1987	1.141	2.6000	33.1500
HEBT:Q10	L1-1987	3.745	2.6000	18.2000
HEBT:Q11	L1-1987	4.636	2.6000	18.2000
HEBT:Q12	L1-1987	2.65	2.6000	18.2000
HEBT:Q13	L1-1987	2.651	2.6000	18.2000
HEBT:Q14	L1-1987	4.645	2.6000	18.2000
HEBT:Q15	L1-1987	3.738	2.6000	18.2000
HEBT:Q16	L1-1987	2.722	2.6000	18.2000
HEBT:Q17	L1-1987	2.135	2.6000	18.2000
HEBT:Q18	L1-1987	3.121	2.6000	18.2000

Table 3: Optimized drifting tune with starting parameters from Table 2 for $^4He^{2+}$.