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ISAC-HEBT Optics Upgrade

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Abstract: A set of modification to the high energy beamline quadrupole lattice is presented, aiming to improve beam transport downstream of the ISAC-DTL.

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Contents

1 Introduction

This report presents a proposed optics upgrade to the ISAC-I high energy beam transport section, shown in Figure 1 and whose original specification can be found in [1].

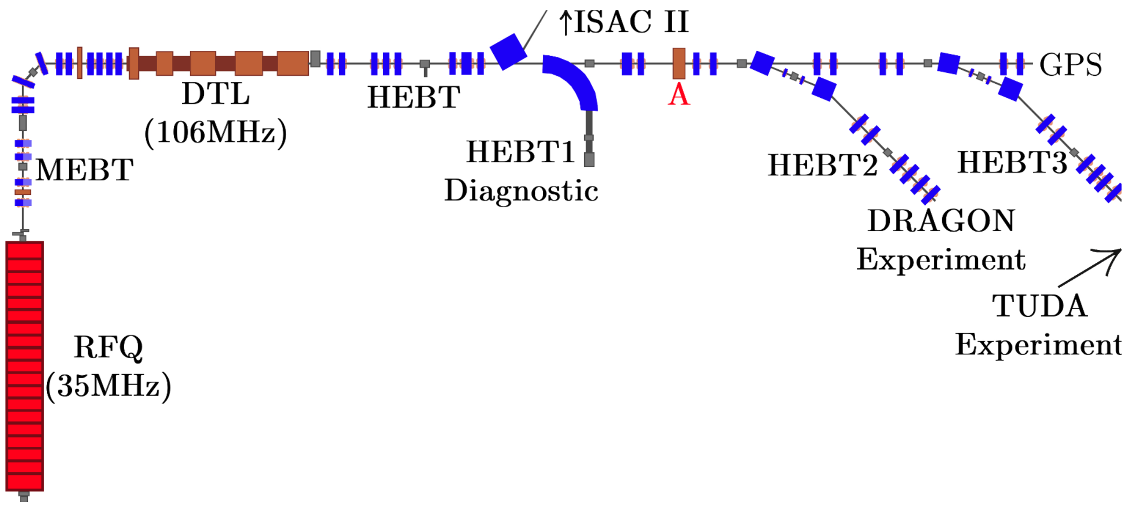

Figure 1: Schematic representation of the ISAC-I accelerator, showing MEBT and HEBT sections.

1.1 Motivation

Though named as a 'high energy' transport section, the DTL's variable output energy capability means experiments frequently request beam E/A values between the RFQ's 0.153 MeV/u to 1.8 MeV/u, the maximum attainable E/A for the DTL, under certain circumstances. Notably, the DRAGON experiment has expressed its interest in beam energies below the RFQ's output, meaning the DTL must be used in a decelerative mode.

This large energy range means the quadrupoles in the section sometimes have to be operated at low gradient. Although mitigation methods exist[2], it remains preferable to operate quadrupoles at the highest possible gradient, to minimize the effects of field uncertainties upon the beam.

Figure 2 shows Monte-Carlo simulations in TRANSOPTR, where the tip-fields have

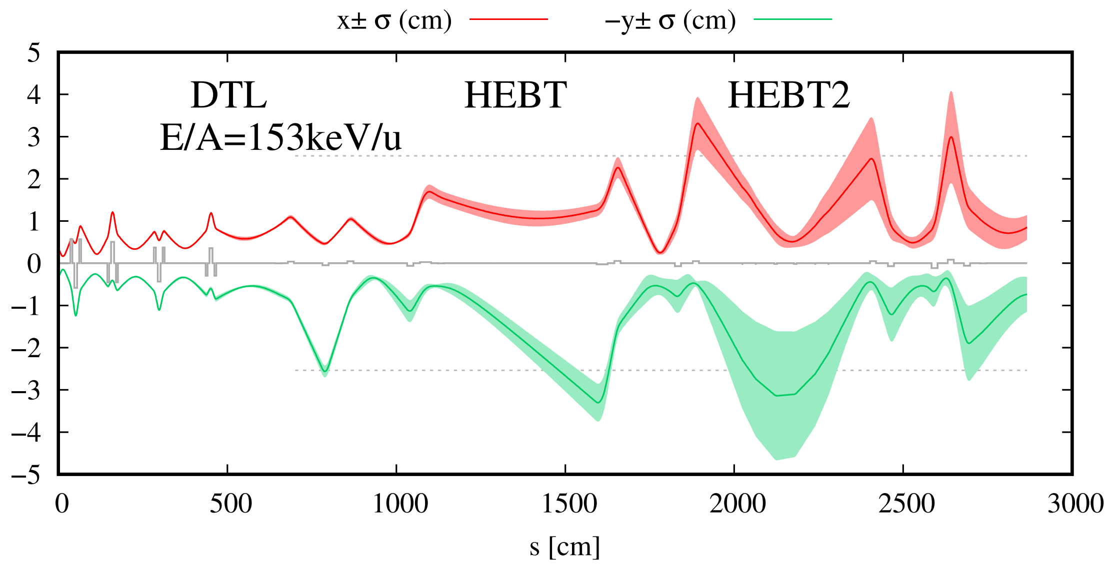

Figure 2: TRANSOPTR Monte-Carlo simulation of $^{22}Ne^{4+}$ tune at E/A=0.153MeV/u from DTL injection to DRAGON gas chamber. 100 iterations are shown, using an up to ±2mT tip-field pseudorandom Gaussian distributed error. Grey dotted lines show approximate vacuum beampipe radius in the section. An A/q=6 beam is shown.

been perturbed by an up to ±5mT Gaussian distributed random error. The mismatches that emerge are expected to cause transmission losses in the 2.54cm (1") aperture radius vacuum beampipe in HEBT, noting that the constriction is ∼1.27cm (0.5") in the HEBT2 bend section.

One expects even small errors to the tip-fields to cause envelope size excursions that exceed the aperture radius of the beam pipe in HEBT and HEBT2. This means that transmission losses are expected, particularly at lower energy. This is analogous to findings in the ISAC-MEBT section[3], in which the 18 cm effective length quadrupoles are found to cause an injection mismatch at ISAC-DTL and similar size excursions, particularly in the dispersive (x) plane.

2 Lattice Modifications

This design follows issues on machine development tests for Bayesian Optimization of DTL accelerated beams and satisfies the following criteria:

Constraints

- Requires the least amount of changes to the existing lattice,
- Uses available quadrupoles, identical to those already in use,
- Can be done with a small number of interventions upon the beamline.

Objectives

- Reduce large (x,x') and (y,y') correlations during transport,
- Reduce large size excursions to the beam envelopes, and
- Reduce sensitivity of HEBT/HEBT2 beam envelopes to small field errors.

A summary of the proposed modifications to HEBT are shown in Figure 3.

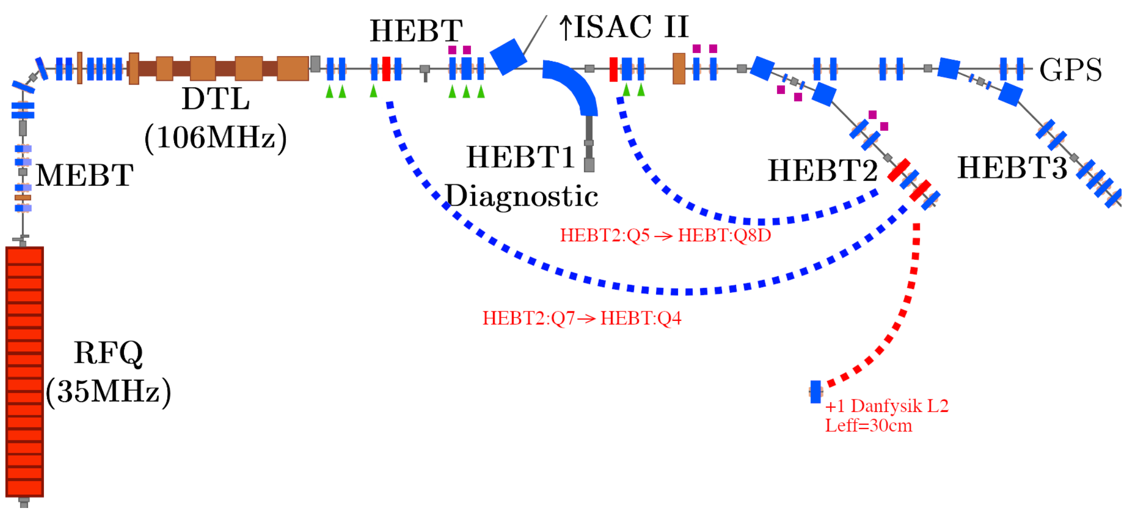

Figure 3: Schematic representation of proposed modification to the HEBT quadrupole lattice, resulting in the new presented design tune. Green arrows indicate polarity reversal, purple boxes indicate polarity switching required.

3 DTL Output Match - HEBT:Q4

Quadrupole HEBT:Q4 has been disabled since September 2012, due to a water leak in its cooling lines. The polarity of Q3 was reversed and Q4 disabled, shown in Figure 4. This results in a large vertical size at Q3, which makes beam susceptible to transmission losses.

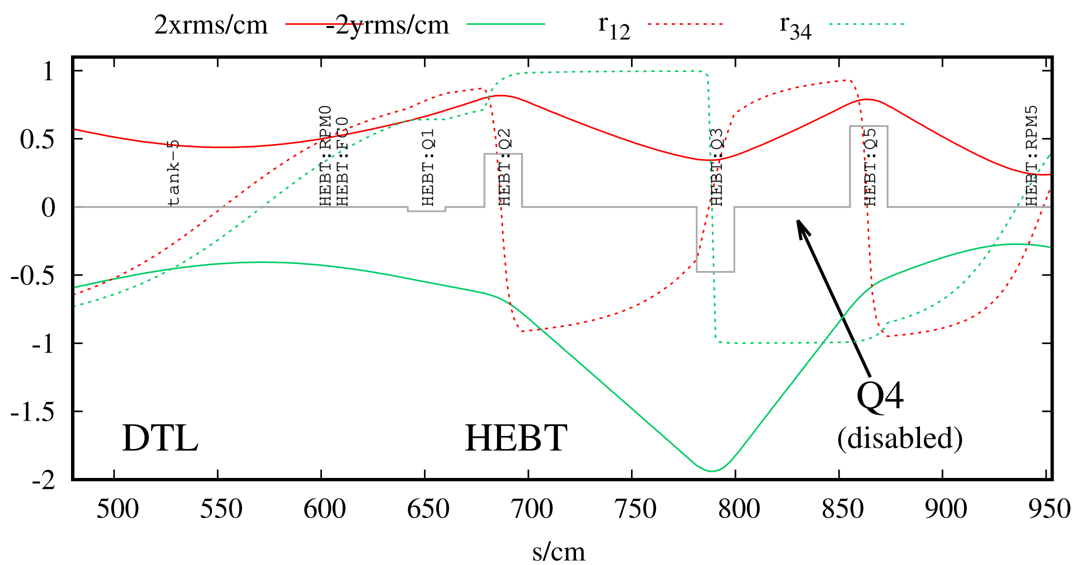

Figure 4: 2rms beam envelopes showing beam through DTL Tank-5, which is matched to the location of HEBT-DB5 using 4 quadrupoles, with disabled Q4. This is the existing configuration as of report writing. Correlation coefficients r_{12} and r_{34} are shown as dotted lines.

From previous analyses[4, 3], transverse correlation coefficients whose absolute value reach near unity are indicative of highly eccentric phase space distributions, which in turn imply sensitivity to small field errors in the quadrupoles. This is particularly true for the vertical dimension in the optics without Q4.

Finding-1: It is proposed to replace the defective Danfysik L1 type quadrupole with another functional unit. Additionally, to preserve transverse alternating gradients, polarities for HEBT:Q1, Q2 and Q3 must be reversed.

Figure 5 shows the re-commissioned HEBT:Q4 together with reversed polarities for Q1 to Q3. Comparing to Figure 4, one appreciates both the reduction in transverse

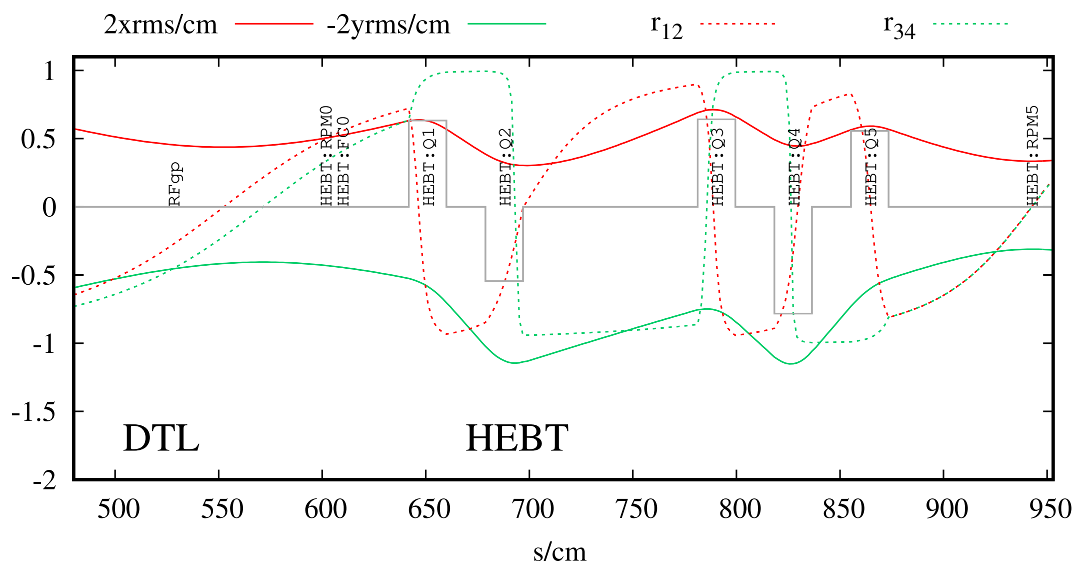

Figure 5: 2rms beam envelopes shown with a re-activated HEBT:Q4, which needs to be swapped due to a water leak issue. The new lattice reduces size excursions, particularly in the vertical dimension. Correlation coefficients r_{12} and r_{34} are shown as dotted lines.

envelope size excursions. Additionally, the correlation coefficients r_{12} and r_{34} are kept from reaching near ± 1 in the new design. Reversal of polarities for Q1 to Q3 makes this particularly true for the x (dispersive) plane.

4 Zero Degree Transport - HEBT:Q8D

Next, the drift from HEBT:Q8, prior to both DSB:MB0 and HEBT1:MB0, up to HEBT:Q9 is addressed. From Figure 2, this covers the region from s= 1000 to $\sim$1700 cm, which features the largest vertical excursion in 2rms beamsize up to that point, excluding downstream optics.

The transport optics are improved by reversing the polarities for HEBT:Q6, Q7, Q8, Q9 and Q10, while also adding an 18 cm effective length quadrupole upstream of HEBT:Q9, dubbed HEBT:Q8D, creating the triplet Q8D-Q9-Q10. This allows for the creation of a waist in transport. Envelopes from this new arrangement, including a re-activated Q4, flipped polarities for Q1, Q2 and Q3, are shown in Figure 6.

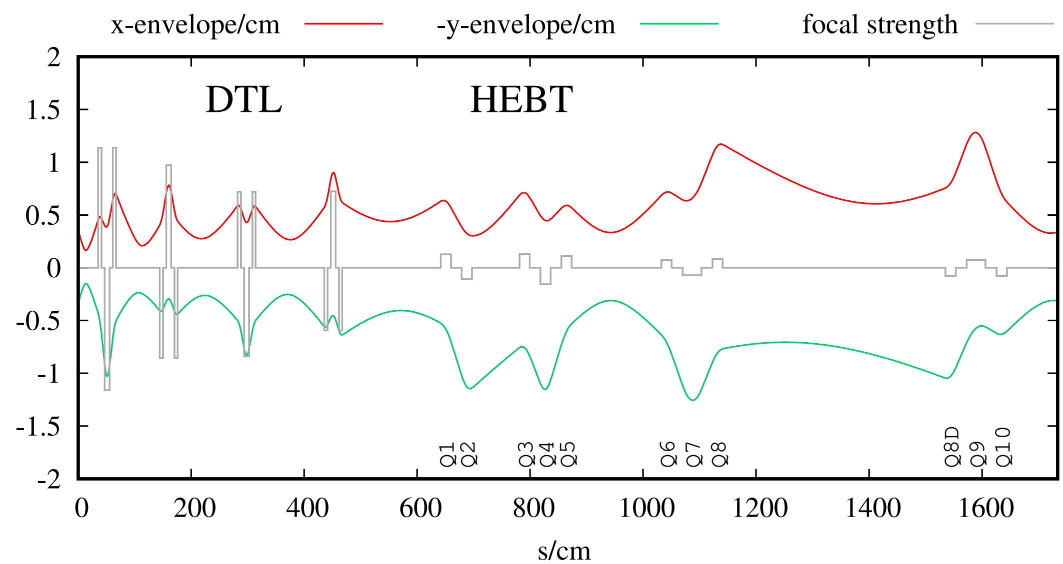

Figure 6: 2rms beam envelopes from DTL injection up to location of the HEBT bunchers, where a round waist is required, with new proposed lattice configuration. Quadrupole Q8D has been added, completing a triplet with Q9 and Q10.

Finding-2: It is proposed to add a quadrupole (HEBT:Q8D) upstream of the existing Q9, to create a triplet. Polarities for HEBT:Q6, Q7, Q8, Q9 and Q10 are reversed with respect to the original configuration.

4.1 Elimination of Prague Magnet Shortcut

Addition of the quadrupole Q8D would require support infrastructure where there is presently a gap below the beamline which allows for personnel and equipment to cross from one side to the other. In preliminary discussions with beamlines group, Q8D would likely require a new support table which would occupy most of this gap.

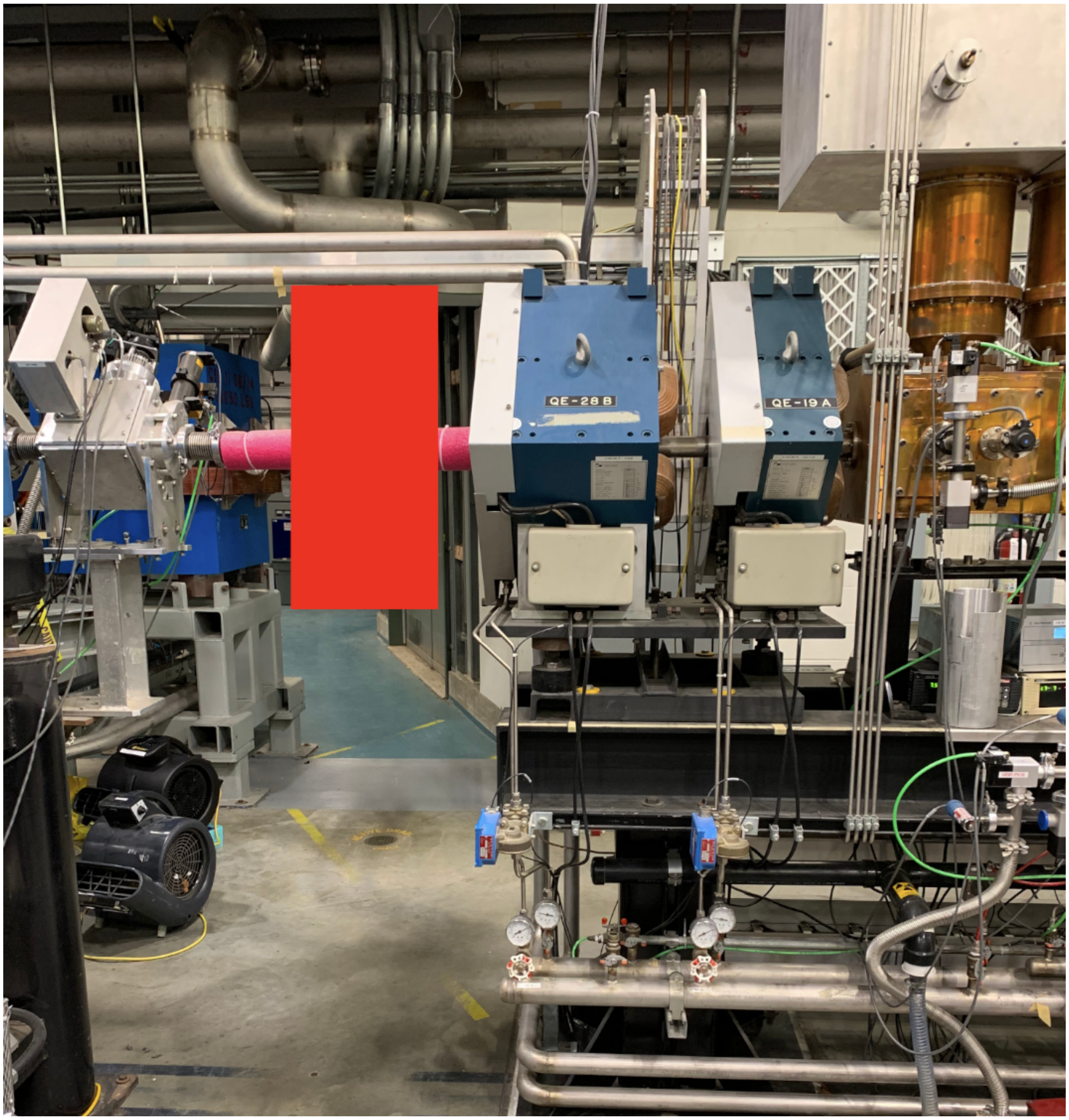

Figure 7: A new Q8D L1 type quadrupole (red box) would require support infrastructure which would fill the existing gap below the beamline.

5 Reversible HEBT2 Bend Section and DRAGON Triplet

The design investigation reported herein found that allowing for the collective reversal of polarities for HEBT:Q11, Q12, HEBT2:Q1, Q3 and Q4 allows for optimized transport at lower beam energies, for example around 153keV/u. However, the short quadrupoles HEBT2:Q1 (tied-in with HEBT2:Q2) have an approximate peak gradient limit of 3 T/m[1], meaning the envelopes shown in Figure 8 are only feasible for up to roughly 254keV/u.

Beyond this E/A, the short quadrupoles in the HEBT2 bend are insufficiently powerful to create a symmetry point about the mid-corner point. The waist downstream of HEBT2:Q4, at the location of HEBT2:RPM4, degrades, as shown in Figure 9. Thus, when this condition is encountered, the polarity for HEBT:Q11 to HEBT2:Q4 should be flipped using polarity switches, restoring the original configuration.

Finding-3: Quadrupoles HEBT:Q11, Q12 and HEBT2:Q1 to Q4 should feature polarity switching, enabling optimized transport for lower energy beams to DRAGON.

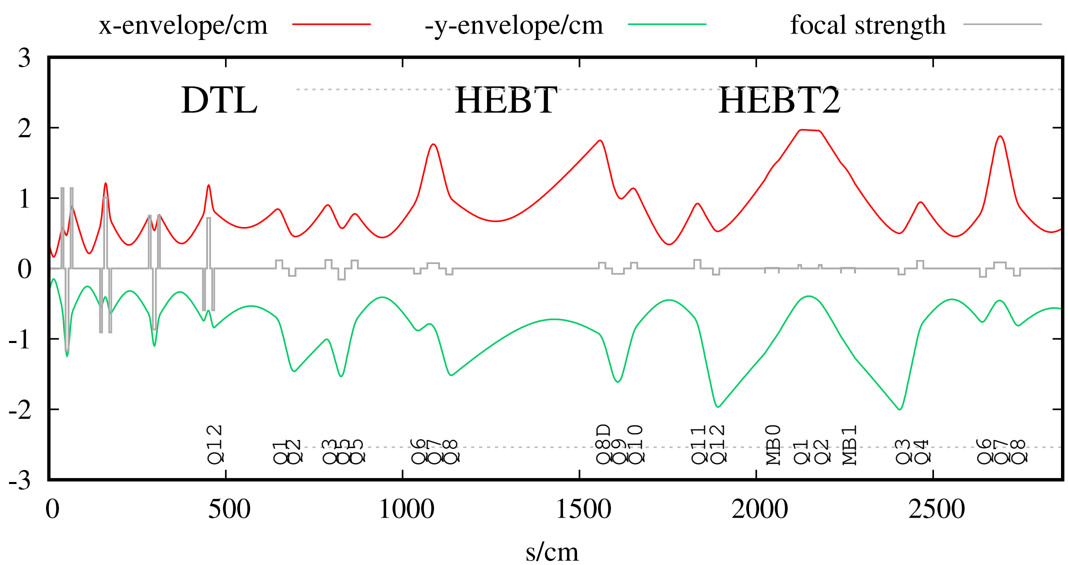

Figure 8: Modified HEBT section lattice including reversed polarity for HEBT2 bend (low-energy mode).

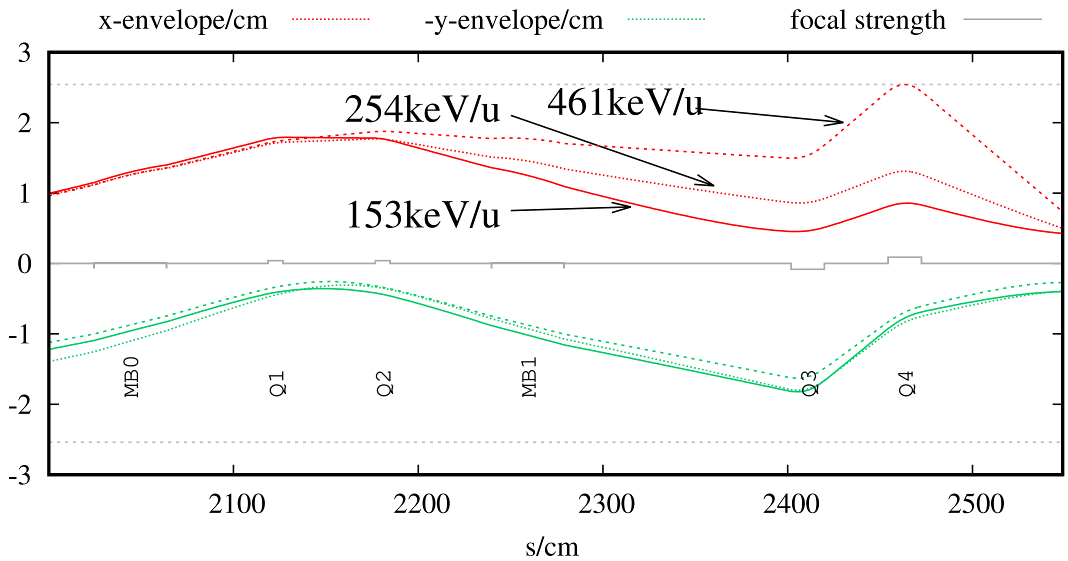

Figure 9: Demonstration of the limitations from HEBT2:Q1 and Q2, which prevent dispersive plane (x) focusing for tunes beyond Buncher-1 E/A (254keV/u).

Finally, the L1 type quadrupole HEBT2:Q5 is removed, instead creating a triplet with Q6,Q7 and Q8. Quadrupole Q7 is swapped for a Danfysik L2 type quadrupoles, with effective length 33cm, which allows for a low-divergence round (x,y) match at the DRAGON gas chamber, regardless of the HEBT2 bend quadrupole polarities.

Finding-4: A matching triplet before the DRAGON experiment will improve the ability to produce a round waist at the DRAGON gas chamber, requiring removal of HEBT2:Q5 and replacement of HEBT2:Q7 with a 33cm effective length L1 type Danfysik quadrupole.

6 Sensitivity Analysis

The modified lattice is subjected to Monte-Carlo TRANSOPTR simulations in which each magnetic quadrupole's tip field is perturbed by adding a uniformly distributed pseudorandom number in the range ±2mT to each quadrupole, at each iteration. Note that each quadrupole possesses a unique random perturbation. The mean and variance of the resulting (x, y) envelopes are then computed from the dataset.

This is first carried out at 153keV/u, corresponding to RFQ accelerated beam without any RF cavities in the DTL. The beam's longitudinal divergence has been minimized at the start - this is akin to establishing an energy focus with either of bunch rotator or rebuncher cavities in MEBT. First, Figure 10 shows an A/q=6 beam at 153keV/u. To the right hand side of the figure, Bovet's mismatch parameter is shown:

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

Recalling that $\mathcal{D}$=1 corresponds to perfect overlap for two phase space ellipses, at the ±2mT field uncertainty level, the existing HEBT-DRAGON optics is expected to depart from a match. Note that presented computations for $\mathcal{D}$ assume perfect transmission.

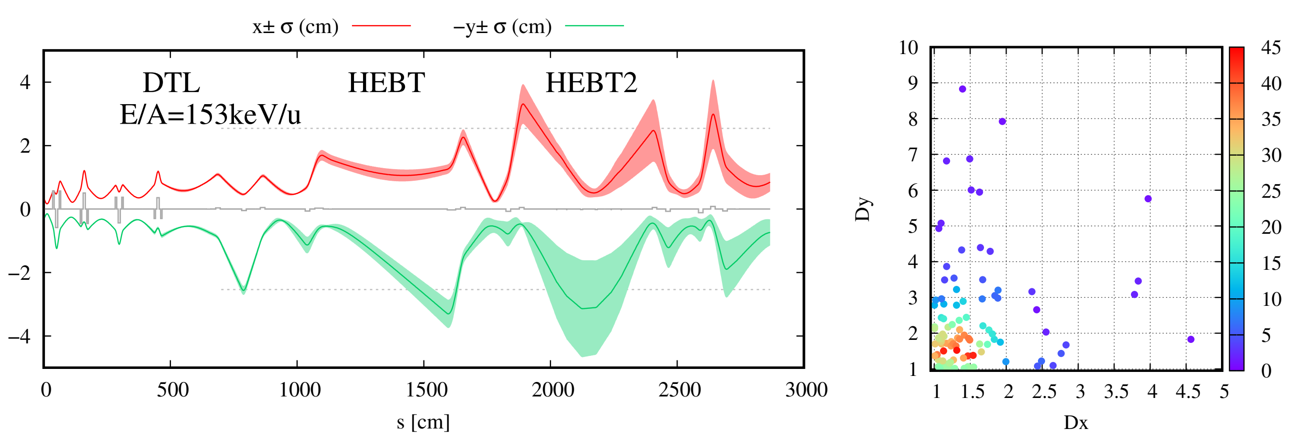

Figure 10: TRANSOPTR Monte-Carlo simulations from DTL to DRAGON showing effect of a uniformly distributed ±2mT independent pseudorandom error applied to each quadrupole tip field. The envelopes' mean and variance are shown on the left, while the mismatch parameters at DRAGON are shown on the right.

Clustered around $(\mathcal{D}_x, \mathcal{D}_y) \approx$ (1.25,1.5) is a large spread of expected values for $(\mathcal{D}_x, \mathcal{D}_y)$. One does not expect a match to the DRAGON gas target, instead requiring corrective tuning of the quadrupoles in HEBT2. Excursions in y are prominent at HEBT:Q3 (s ~750cm), HEBT:Q9 (s ~1600cm), the HEBT2 bend (s ~2000-2300cm) and HEBT2:Q7 (s ~2700cm). In the dispersive plane, envelope excursions occur at HEBT:Q10 (s ~1700cm), HEBT:Q12 (s ~1800cm), HEBT2:Q3 (s ~2400cm) and HEBT2:Q6 (s ~2700cm). There are 8 loci where 153keV/u envelopes are expected to rival the aperture. Suppression below 238keV/u is achieved by flipping the polarity of the HEBT2 bend, shown in Figure 11. Beyond Tank-1 energy, regular polarity is suitable, shown in Figure 12.

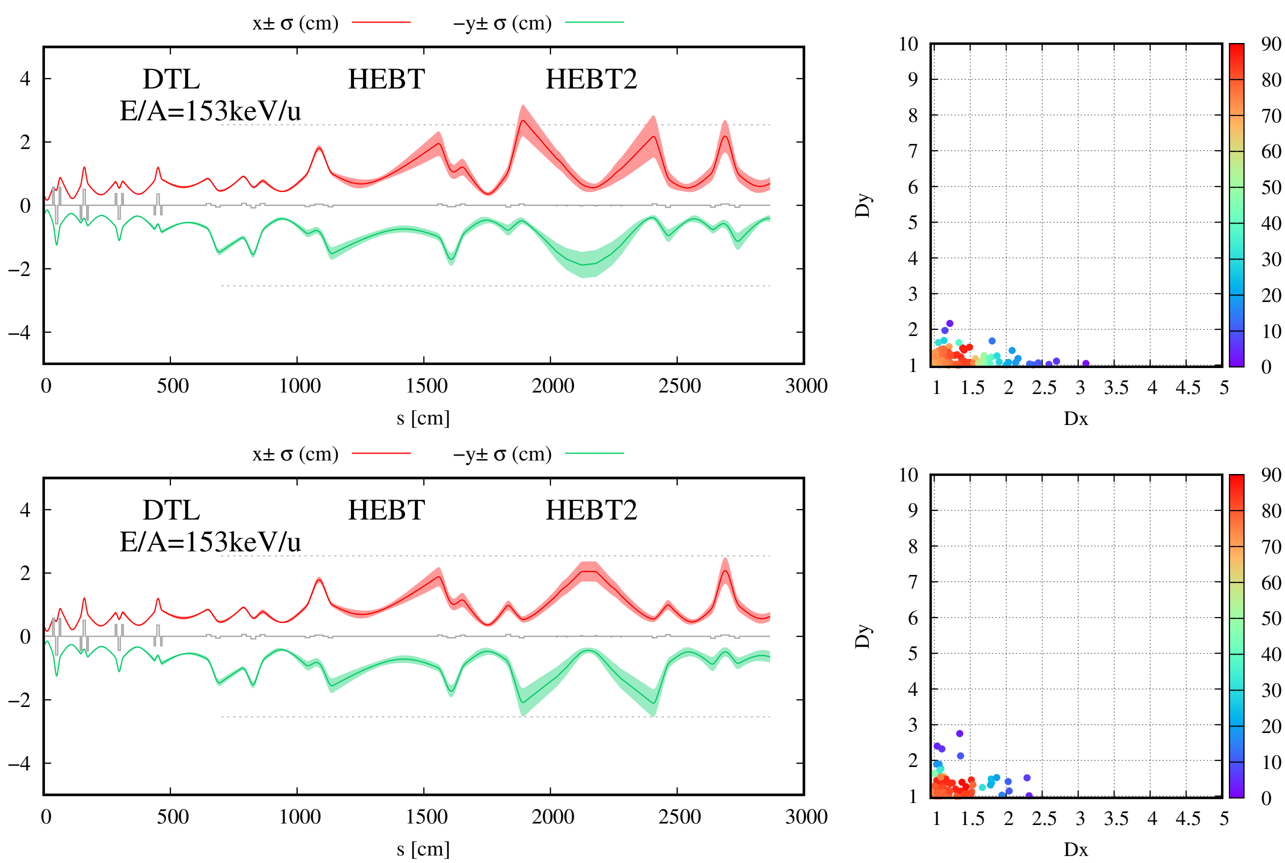

Figure 11: TRANSOPTR Monte-Carlo simulations from DTL to DRAGON showing **Top:** the new lattice with original polarity in the HEBT2 bend and **Bottom:** new lattice with reversed HEBT2 bend polarity (low-energy mode). In both cases, the effect of a uniformly distributed $\pm$2mT independent pseudorandom error applied to each quadrupole tip field. The envelopes' mean and variance are shown on the left, while the mismatch parameters at DRAGON are shown on the right.

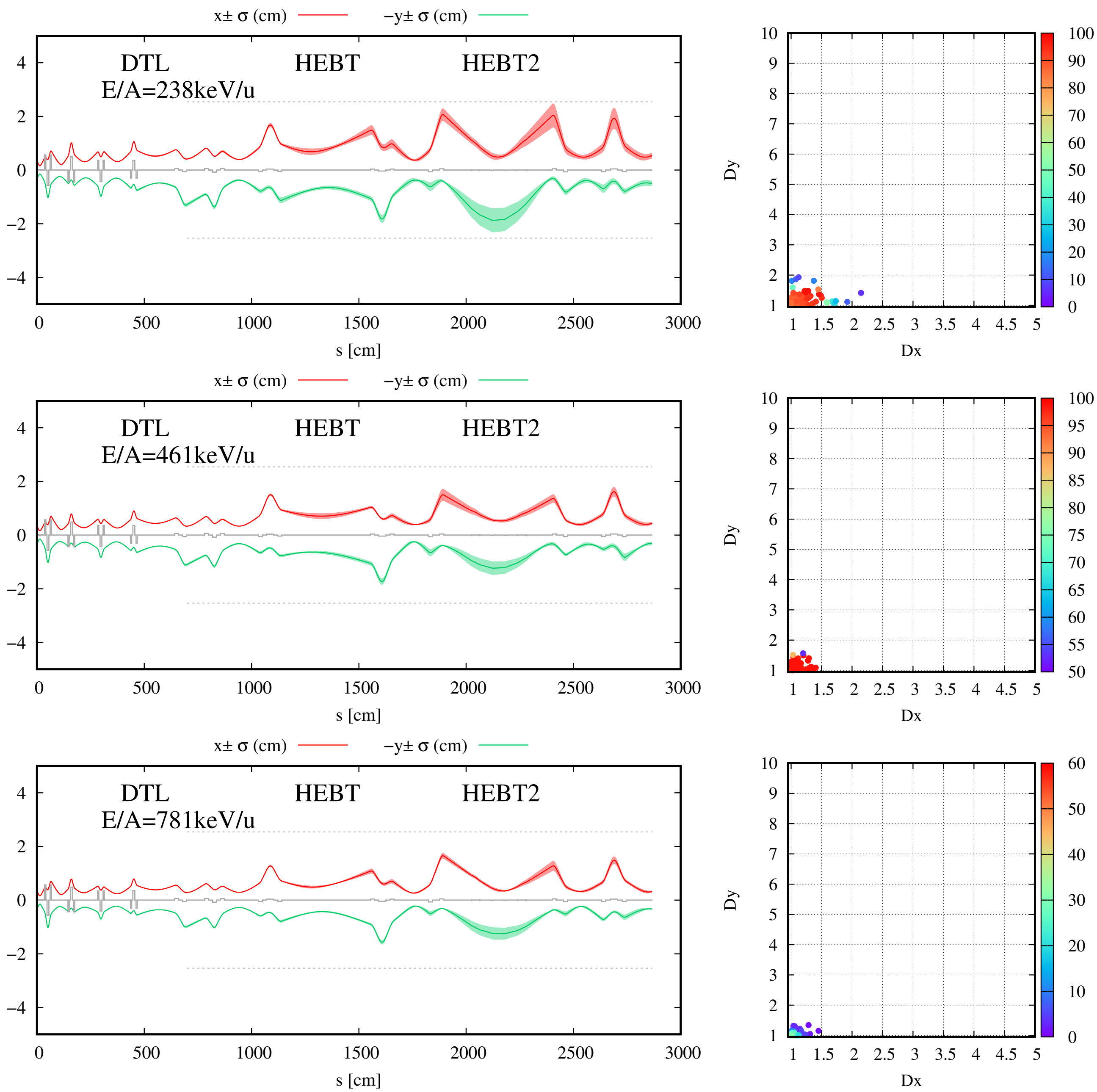

Figure 12: TRANSOPTR Monte-Carlo simulations from DTL to DRAGON showing **Top:** the new lattice with original polarity in the HEBT2 bend and **Bottom:** new lattice with reversed HEBT2 bend polarity (low-energy mode). In both cases, the effect of a uniformly distributed ±2mT independent pseudorandom error applied to each quadrupole tip field. The envelopes' mean and variance are shown on the left, while the mismatch parameters at DRAGON are shown on the right.

7 Layout

Layouts are listed below, referenced to existing quadrupole centrepoint locations[5] for clarity. Polarities are shown in each table, with the following convention: *Negative polarity means beam converges in the x-plane.*

DTL Exit Match

Centrepoint positions referenced to HEBT:Q1				
Element Name	Element Type	Position s [mm]	Eff. Length l [mm]	x-polarity
HEBT:Q1	danfysik L1	0.0	180.0	-
HEBT:Q2	danfysik L1	37.0	180.0	+
HEBT:Q3	danfysik L1	139.5	180.0	-
HEBT:Q4	danfysik L1	176.5	180.0	+
HEBT:Q5	danfysik L1	213.5	180.0	-

Table 1: Centrepoint positions for DTL exit match quadrupoles at the start of HEBT. Quadrupole polarities are given in terms of horizontal (x) plane effect, where negative means converging.

HEBT Dual-Triplet Transport				
Centrepoint positions referenced to HEBT:Q6				
Element Name	Element Type	Position s [mm]	Eff. Length l [mm]	x-polarity
HEBT:Q6†	danfysik L1	0.0	182.0	+
HEBT:Q7†	danfysik L2	45.3	331.5	-
HEBT:Q8	danfysik L1	90.5	182.0	+
HEBT:Q8D	danfysik L1	522.5	182.0	-
HEBT:Q9	danfysik L2	567.7	331.5	+
HEBT:Q10	danfysik L1	613.0	182.0	-

Table 2: Centrepoint positions for HEBT dual triplet transport segment. Quadrupole polarities are given in terms of horizontal (x) plane effect, where negative means converging. Quadrupoles requiring polarity switching are marked with a † symbol.

HEBT2 Bend Section				
Centrepoint positions referenced to HEBT:Q11				
Element Name	Element Type	Position s [mm]	Eff. Length l [mm]	x-polarity
HEBT:Q11†	danfysik L1	0.0	182.0	+
HEBT:Q12†	danfysik L1	53.0	182.0	-
HEBT2:Q1†	danfysik L1	289.4	80.0	+
HEBT2:Q2†	stinson[6]	347.4	80.0	+
HEBT2:Q3†	stinson	577.5	182.0	-
HEBT2:Q4†	danfysik L1	630.0	182.0	+

Table 3: Centrepoint positions for HEBT2 bend section the start of HEBT2. Quadrupole polarities are given in terms of horizontal (x) plane effect, where negative means converging. Quadrupoles requiring polarity switching are marked with a † symbol.

HEBT2 Matching Triplet				
Centrepoint positions referenced to HEBT2:Q4				
Element Name	Element Type	Position s [mm]	Eff. Length l [mm]	x-polarity
HEBT2:Q4†	`danfysik L1`	0.0	182.0	+
remove HEBT2:Q5				
HEBT2:Q6	`danfysik L1`	177.5	182.0	+
HEBT2:Q7	`danfysik L2`	225.5	331.5	-
HEBT2:Q8	`danfysik L1`	273.5	182.0	+

Table 4: Centrepoint positions for HEBT2 bend section the start of HEBT2. Quadrupole polarities are given in terms of horizontal (x) plane effect, where negative means converging. Quadrupoles requiring polarity switching are marked with a † symbol.

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