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MEBT Quadrupole Interference

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Abstract: Beam-based measurements at ISAC's medium energy beam transport section suggest quadrupoles suffer from a reduction in effective length, as a consequence of their close relative proximity.

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DTL Injection Mismatch

A mismatch at DTL injection is known[1] to affect machine tuning, requiring manual de-tuning of the MEBT quadrupoles located between the stripping foil and DTL Tank-1. This procedure is time consuming for the operators and tedious, diminishing the reproducibility and efficiency of machine tuning.

Previous analyses[2] of the section have revealed a four-fold cause for this mismatch:

1. The relatively long (18cm) effective length and low resulting quadrupole current excitations required by the design tune.
2. The lack of inter-dipole quadrupoles[3] causes undesirable transverse-longitudinal (T-L) couplings downstream of the corner.
3. The transverse frame rotation in (x, y) at the foil, between quadrupoles Q5 and Q6 necessitate a precise match, which can be difficult to achieve.
4. Establishment of a time-focus at the foil broadens the energy spread of the beam, which in turn magnifies the importance of T-L couplings.

In this report, a final and consequential optical error is recorded which, together with the above, have compromised the ability to tune the ISAC-I accelerator with precision, instead requiring manual adjustment of the optics.

Simulation Discrepancy

Figure 1 shows the `TRANSOPTR` envelopes obtained from stripping foil to DTL Tank-1, for the on-line tune most frequently obtained by operators when manually tuning MEBT. **This tune shows a diverging beam into ISAC-DTL, significantly differing from the design injection.** It has been observed that the manually defined injection optimization tune frequently presents a similar profile, even though measured DTL transmission frequently exceeds 90%. Figure 2 shows the quadrupoles MEBT:Q8 to Q13 and their respective proximity.

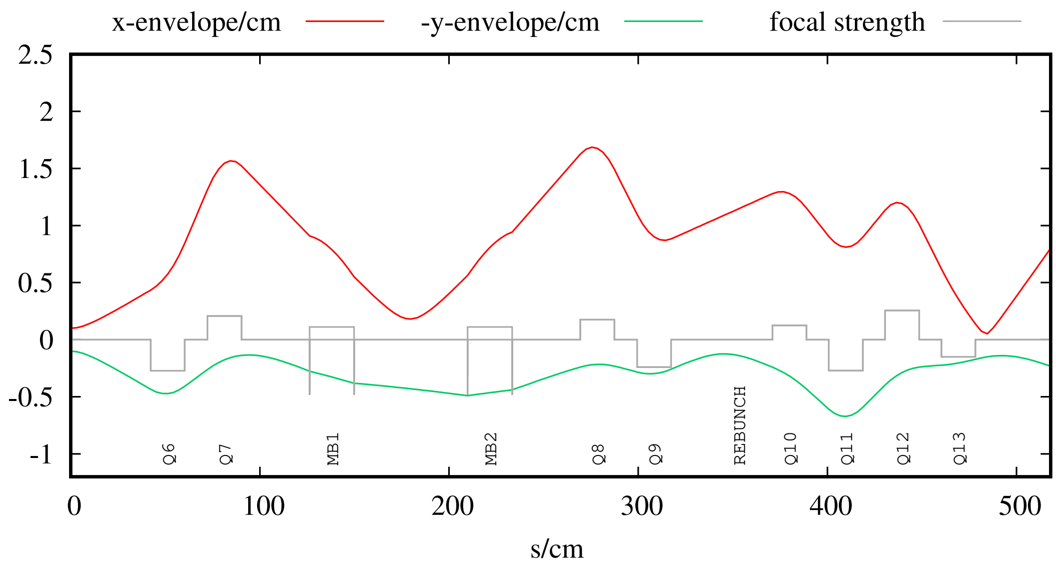

Figure 1: TRANSOPTR simulation of the ISAC-MEBT corner, using dimensions and specifications recorded in[4], using an on-line tune which produces high transmission, manually obtained by operators.

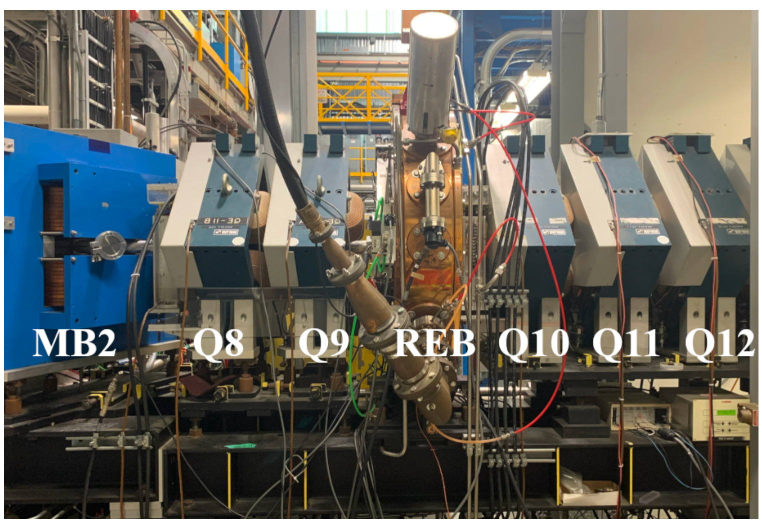

Figure 2: The ISAC-MEBT injection line into DTL, showing magnetic quadrupoles placed against each other, with almost no drift space in-between. Image mirrored horizontally for consistency with Fig. 1.

MEBT Quadrupole B-I Calibration

Magnetic surveys performed on the quadrupoles have been fit to the MEBT *Danfysik L1* type quadrupoles, using a pseudo-Langevin function as done in [5]:

$$B(I) = \frac{a_1}{a_3} \tanh \left[(a_3 I + \frac{1}{3}(a_3 I)^3 + \frac{1}{5}(a_3 I)^5 \right] \quad (1)$$

The fit parameters are listed in Table 1 and plotted with residual error in Figure 3.

Parameter	Value
a_1 [T/A]	(9.23±0.03)×10^{-3}
a_3^{-1} [A]	(86.5±0.5)

Table 1: Pseudo-Langevin B-I calibration for *Danfysik L1* 1987 type quadrupole.

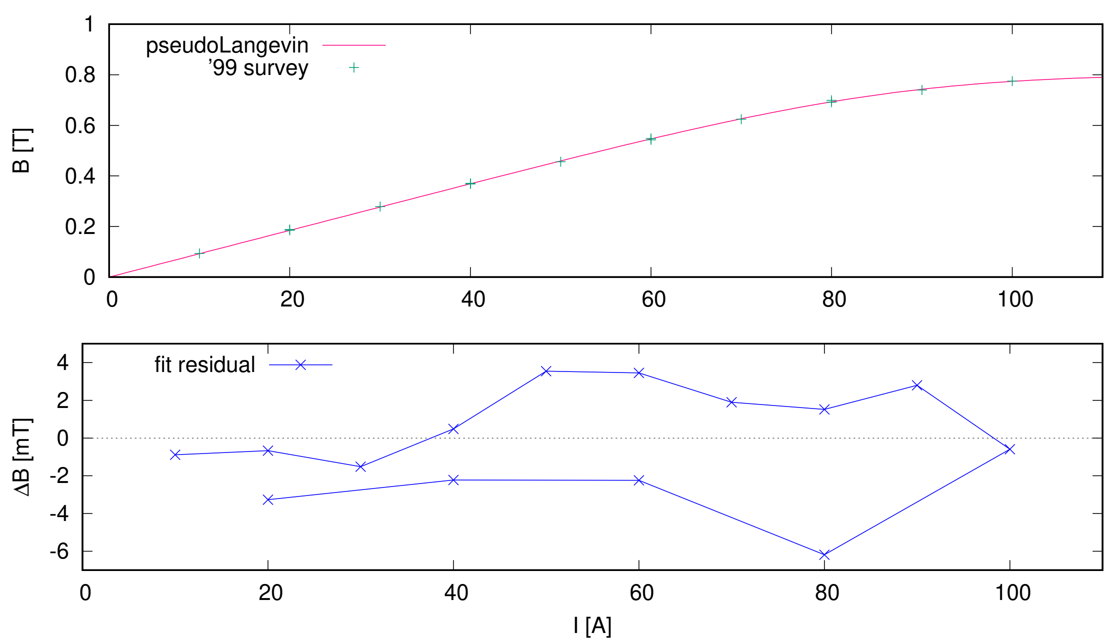

Figure 3: **Top:** Langevin-Like B-I calibration for *Danfysik L1* 1987 type quadrupole, together with **Bottom:** fit residual.

Compromised Effective Length Hypothesis

A preliminary hypothesis was made: **Packing magnetic quadrupoles near to each other can reduce their effective lengths.** To test this, TRANSOPTR was used to simulate the Q6 to DTL segment, with a variable introduced to reduce the quadrupole effective lengths. This assumed:

1. Two adjacent quadrupoles will see their effective lengths reduced at the interface, while the fields will remain unaffected on the opposite sides.
2. For quadrupoles with close-by neighbours on both sides, the reduction in effective length will be symmetric about the midpoint.
3. No fringe field simulations were performed for simplicity.

Figure 4 shows the effect of a reduction in quadrupole L_{eff} on the tune from Figure 1. The same setpoints now produce a round converging beam.

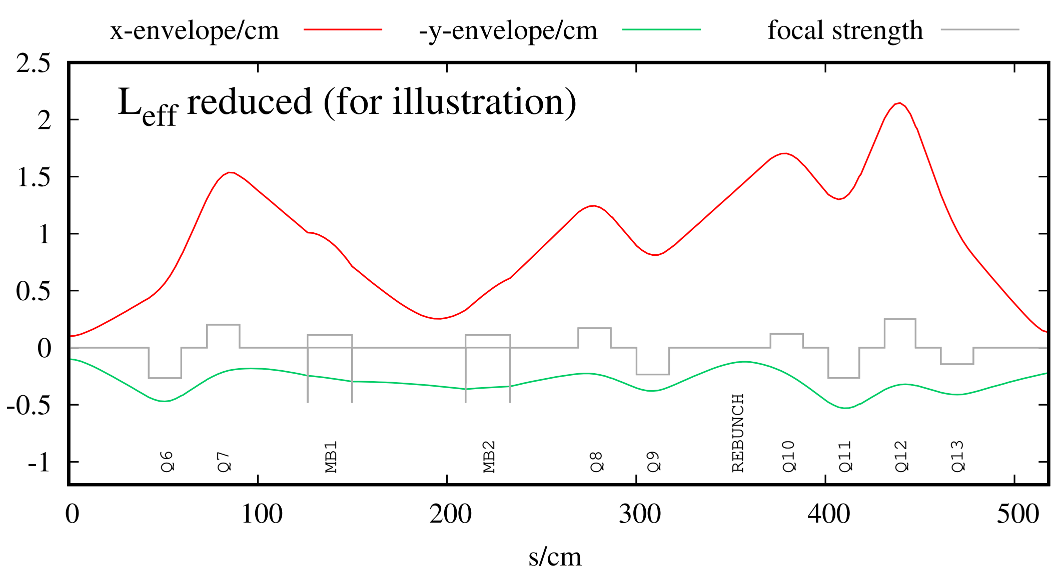

Figure 4: TRANSOPTR simulation of the same tune from Fig. 1, however the effective lengths L_{eff} of adjacent quadrupoles have been reduced by an unspecified ΔL ($2\Delta L$ for quadrupoles Q11 and Q12), for illustration.

In the next section, a beam-based measurement is recorded, having been carried out in MEBT to measure the effective lengths of quadrupoles in that section.

Duelling-Kicks Method

A steerer, quadrupole and profile monitor can be used together to perform a measurement of the effective length of the quadrupole, provided the distances between devices and B-I calibrations are known. The procedure is as follows:

1. Power off any quadrupoles between the steerer, quadrupole of interest and the downstream profile monitor.
2. Use `fancySet`[6] unipolar degaussing alrogithm to set the quadrupole of interest at a given value.
3. Set the steerer to a given negative value, scan the profile monitor.
4. Set the steerer to the same value, but positive, and scan the profile monitor.
5. Check if the centroids from both scans are identical.
6. If not, iterate the quadrupole value with `fancySet` and repeat.

This method allows for the procedural determination of the quadrupole's effective length, by way of determining the requisite strength necessary to counteract the steerer's effect. This was performed using MEBT:XCB9 and MEBT:Q12, using profile monitor DTL:LPM0, a slit scanner and faraday cup, to determine the excitation necessary on Q12 to counter XCB9. Figure 5 shows the data and centroids. From the dataset, it was determined that for a ^{22}Ne^{4+} beam at E/A=0.153 MeV/u, the RFQ's output energy, the requisite current setting for steerer counteraction was 16.9A, producing a tip-field of 0.156 T, using Eq. (1) with parameters from Table 1.

Figure 6 shows the distribution and centroids, starting at XCB9, shown in red/blue for positive/negative deflection while Figure 7 shows only the centroids and the determined crossover point. It is found that an interface effective length reduction of $\triangle L$=-1.0 cm/interface is necessary to explain the on-line data. A measurement error analysis follows in the next section.

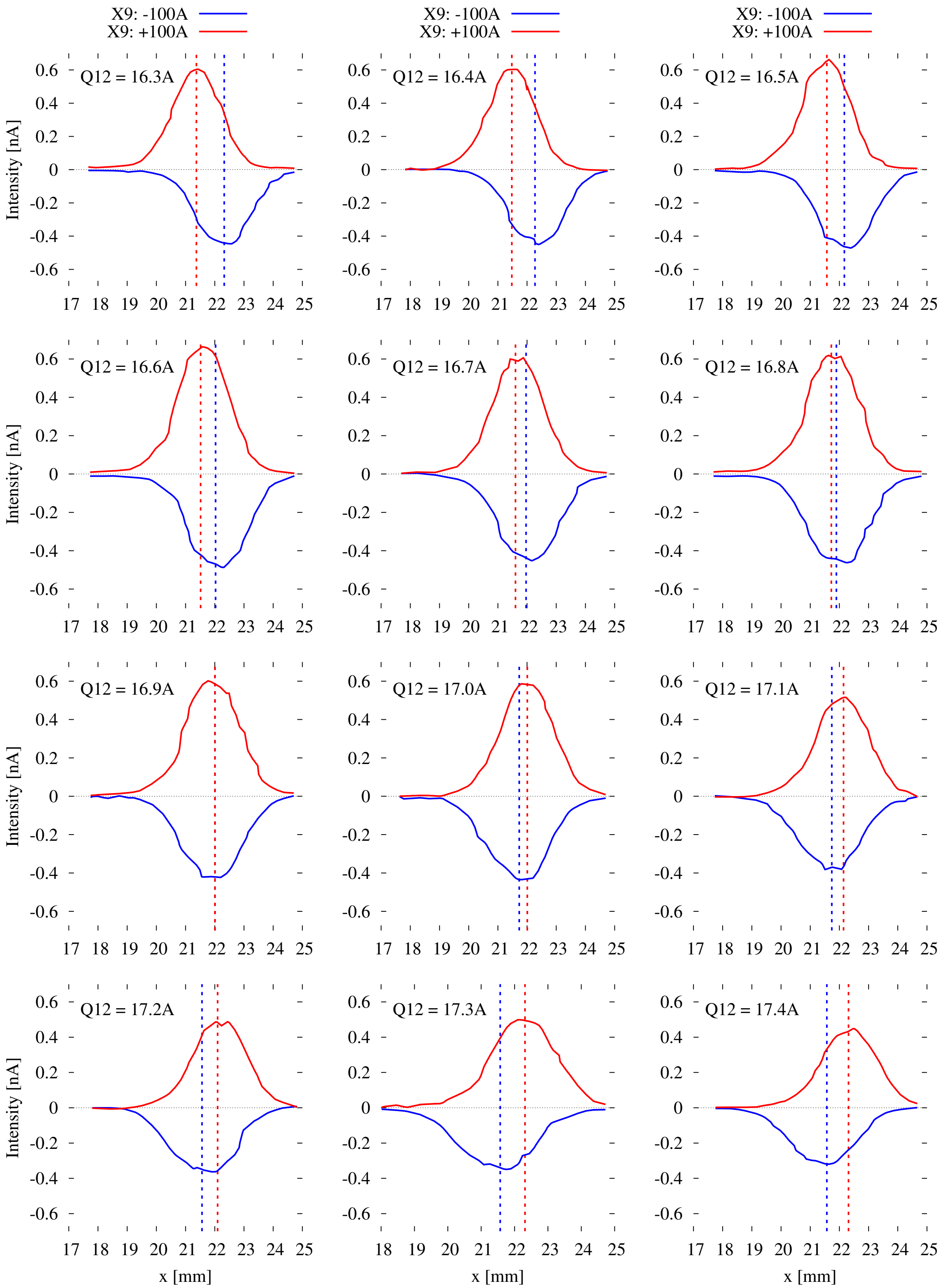

Figure 5: Linear position monitor comparison of DTL:LPM0 readings, with MEBT:Q10, Q11 and Q13 unpowered and Q12 at various current excitations. In all cases, the steerer XCB9 was run at -100A and +100A and the traces compared. Profiles at XCB9 = -100A are vertically inverted for clarity.

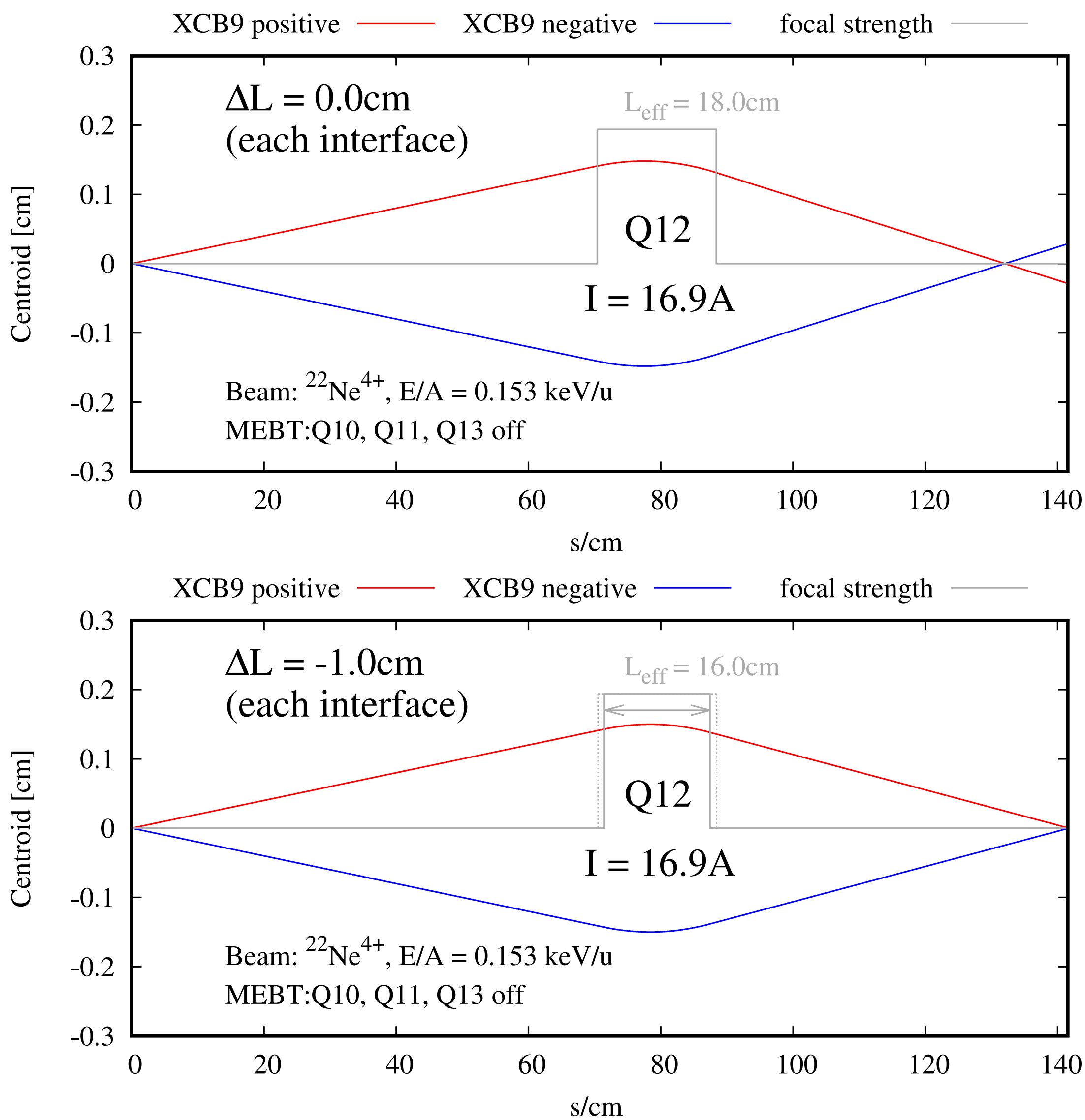

Figure 6: `TRANSOPTR` computed centroids for a ± 2 mrad deflection from MEBT:XCB9, transiting through **Top:** the design 18 cm effective length for Q12 and **Bottom:** a shortened Q12 which returns the beam to the centerpoint at profile monitor DTL:LPM0. A reduced L_{eff} is necessary to reproduce the on-line data.

Observation-1: Use of the documented 18 cm effective lengths for the corner and injection line consistently produces low transmission DTL tunes. Manual de-tuning of Q6 to Q13 is consistently required to maximize DTL transmission, when DTL and HEBT are tuned using MCAT[7].

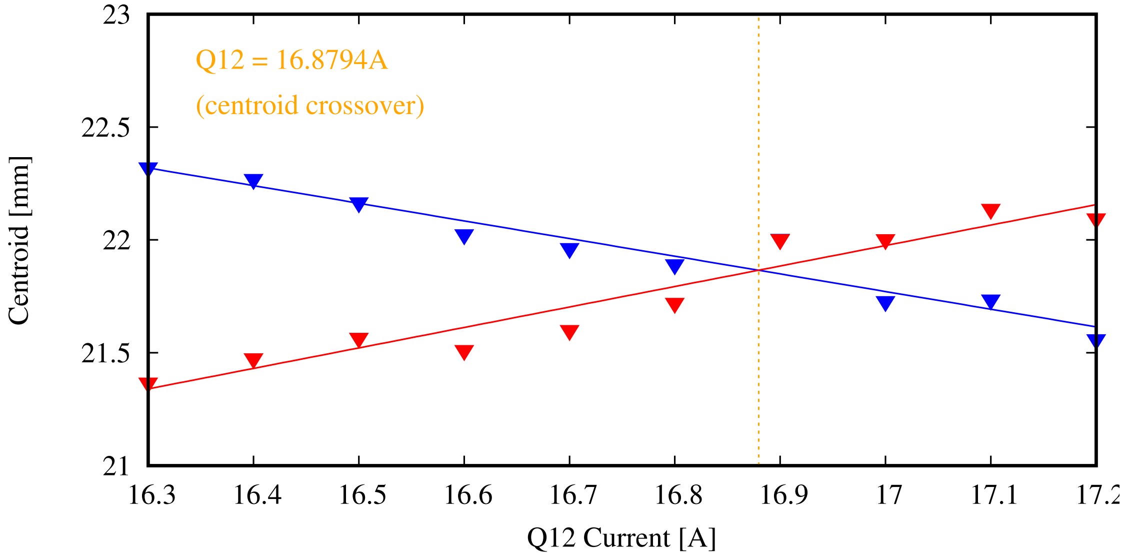

Figure 7: Computed beam centroids with fit linear functions by linear regression.

Error Estimation

In [8], remanent pole-tip fields for *Danfysik 1987 L1* type quadrupoles are estimated at 7.7 mT, used here to simulate nonzero gradients in MEBT:Q10, Q11 and Q13 while unpowered. An estimation of the error on the change in computed effective length can be made. The maximum centroid error is obtained by assuming Q10, 11 and 13 possess a negative remanent field. Figure 8 shows this would imply an effective length reduction of ΔL=-0.60 cm/interface. Taking this into account with the simulation from Fig. 6 (bottom), a final error arising from quadrupole magnetization is found, listed in Table 2 and corresponds to the operational MEBT tune shown in Figure 4. Finally, analysis of the beam energy error found that a 2% E/A change in MEBT caused negligible centroid displacement at LPM0.

Quadrupoles	L_{eff} [cm]	L-error [cm]	Interfaces
Q6,Q7,Q8,Q9,Q10,Q13	17.2 $\pm$ 0.2	-0.8	single neighbour
Q11,Q12	16.4 $\pm$ 0.4	-1.6	two neighbours

Table 2: Implied effective lengths from MEBT corner to DTL injection based on quoted remanent errors from [8]. L-error is the error with respect to the 18 cm effective length assumption.

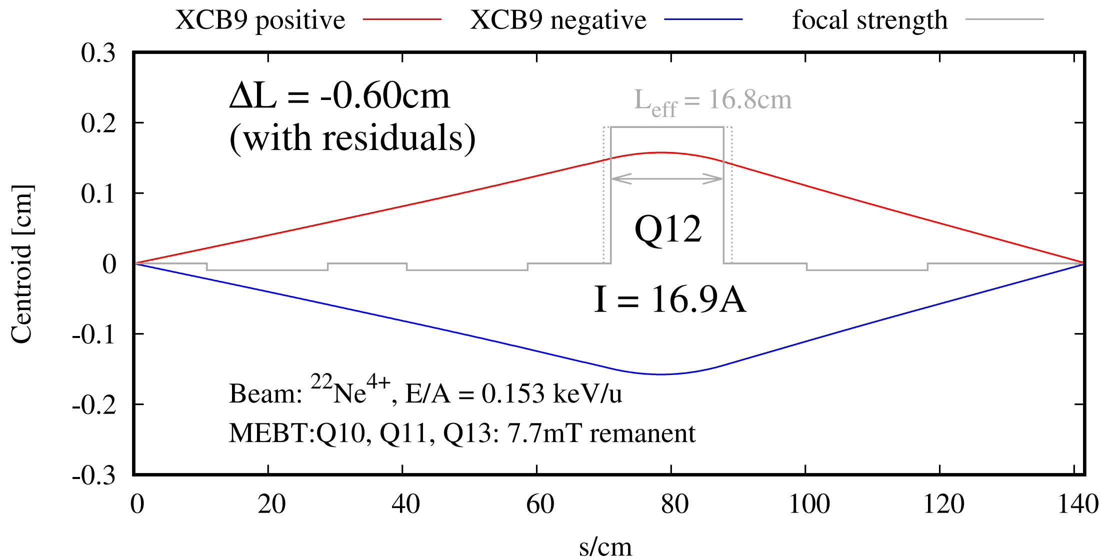

Figure 8: TRANSOPTR computed centroids for a ±2 mrad deflection from MEBT:XCB9, transiting through Q12. Residual magnetization errors on the unpowered quadrupoles have been used to find the change in ΔL at the interface.

Finding-1: Beam-based measurements suggest quadrupole effective lengths in the MEBT corner and DTL injection line of (17.2±0.2) cm for Q6 to 13, with Q11 and Q12 possessing a (16.4±0.4) cm effective length.

Finding-2: The derived -0.8 cm/interface reduction in quadrupole effective length means the optical and physical device centerpoints no longer coincide along the optical path s.

Recommendation-1: Quadrupole lenses of similar make to those in MEBT should be placed on a test bench, replicating the optics, or magnetic simulations should be carried out: two close-adjacent quadrupoles, and four close-adjacent ones. Magnetic measurements can then be made to refine the understanding of their fields.

Device	original s [cm]	corrected s [cm]	L_{eff} [cm]	Interface(s)
MEBT:Q6	51.25	50.86	17.2	Q7
MEBT:Q7	81.27	81.67	17.2	Q6
MEBT:Q8	278.39	277.99	17.2	Q9
MEBT:Q9	308.39	308.80	17.2	Q8
MEBT:Q10	379.97	379.57	17.2	Q11
MEBT:Q11	409.74	409.74	16.4	Q10,Q12
MEBT:Q12	439.51	439.51	16.4	Q11,Q13
MEBT:Q13	469.27	469.68	17.2	Q12

Table 3: Corrected optics model for the MEBT corner and DTL injection line, assuming the derived -0.8 cm/interface reduction in quadrupole effective length. In both cases, the coordinate s is measured from the location of profile monitor MEBT:RPM5.

Conclusion

This report has shown beam based data suggesting the MEBT corner and DTL injection line quadrupoles possess a reduced effective length, due to their close mutual proximity. Tune computations using 18 cm effective length likely do not accurately represent the envelopes through the corner and into DTL.

The assumption made in this report is that effective length shortening happens on the interface side for two close-adjacent quadrupoles. The reduction is symmetric about the midpoint for lenses with neighbours on both sides. **For single-neighbour quadrupoles, an implication is that the optical centerpoint may no longer coincide with the physical centerpoint of the magnets.** Considering remanent magnetization errors for the unpowered quadrupoles, the found -0.8 cm/interface reduction in L_{eff} results in the optics as listed in Table 3.

Although these measurements strongly imply a shortening of the quadrupole effective lengths, they make no statement on the nature of the fringe fields. Per Recommendation-1, measurements or simulations of *Danfysik-L1* quadrupoles arranged as in MEBT would provide more insight into the nature of the fields.

Acknowledgements

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