TRIUMF Beam Physics Note
TRI-BN-16-03
August 22, 2016

Optics to EMMA

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Abstract: The new section connecting SEBT3:MB4 to EMMA target is under construction. The optics are described, and current settings and tolerances given.

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1 Introduction

The experimental hall layout evolved over time (see [6, 1, 2]). See Figure 1 for the layout of EMMA. Locations of the quadrupole centres are a close match to the TIGRESS (SEBT3A) beamline. We will not investigate variations in layout in this note. The purpose of this note is (1) to derive quadrupole characteristics, which determines which quad types of the available ones to be used. These may differ from that specified in the figure. (2) To calculate tunes, and (3) to find tune sensitivities, which have implications on the quadrupole control and power supplies. Quadrupole specifications here supersede those specified in Stinson's note of 2006[7].

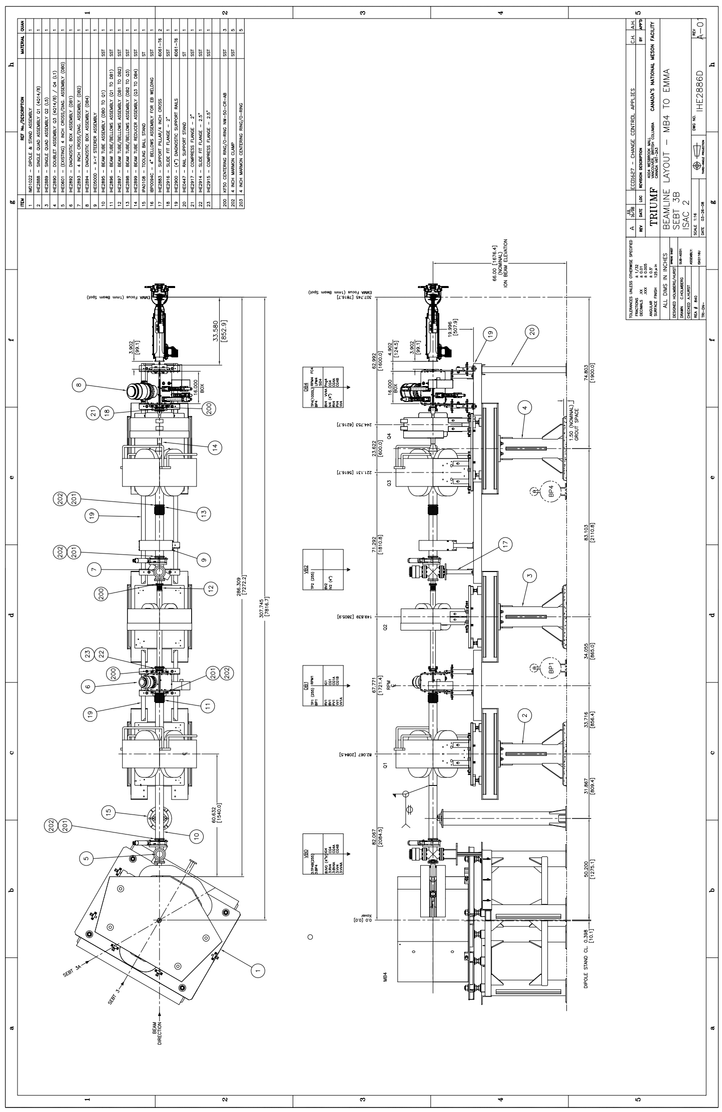

Figure 1: Layout as drawn before quadrupoles types were changed to those specified in this note. The quad centers reamin as on this drawing.

2 Quad Types

2.1 SEBT3B Quads

The maximum assumed beam rigidity is $B\rho = 2.5$ Tesla-metres. It is based upon operational experience with the existing superconducting linac[5].

Table 1: Maximum size and field requirements of the SEBT3B quads arising from the optics, along with recommended types and maximum (rounded up) currents required for those choices.

Quad	$\int B' ds$/Tesla	Beamsize/cm	Recommended	Max. Current/A
SEBT3B:Q1	4.50	5.7	L5	120
SEBT3B:Q2	3.79	5.1	L1	30
SEBT3B:Q3	3.89	9.6	4Q14/8	300
SEBT3B:Q4	3.72	5.1	L1	65

2.2 SEBT3,3A Quads

In the preceeding, the maximum assumed beam rigidity is $B\rho = 2.5$ Tesla-metres. It is based upon operational experience with the existing superconducting linac[5]. This is less than the 3 T-m upon which the existing SEBT beamlines were based, and allows some economizing. For this reason, I also considered replacing the existing quadrupoles with smaller ones, if desired. These possibilities are shown in Table 2.

Table 2: Maximum size and field requirements of the SEBT3B quads arising from the optics, along with recommended types and maximum (rounded up) currents required for those choices.

Quad	Existing type	$\int B' ds$/Tesla	Beamsize/cm	Recommended Type
SEBT:Q21	L2	3.44	3.6	L2
SEBT:Q22	L5	3.63	5.7	L5
SEBT3:Q1,4	L6	4.04	4.8	L1
SEBT3:Q2,3	L2	2.36	3.9	L8
SEBT3A:Q1	4Q14/8	3.11	5.4	L5 or L1
SEBT3A:Q2	L5	3.75	4.2	L8
SEBT3A:Q3	4Q14/8	5.50	6.0	L6
SEBT3A:Q4	L8	4.41	3.3	L8

3 Tunes

From the ISAC2 superconducting linac to the EMMA target, the existing SEBT3 line consists of two 30° dipoles with a symmetric 4 quadrupole arrangement between them. These must be tuned achromatic: as the dipoles are the same sign, this requires that dispersion derivative be zero at the symmetry point. (By contrast, the TIGRESS line SEBT3A has the dipoles at opposite signs, so the

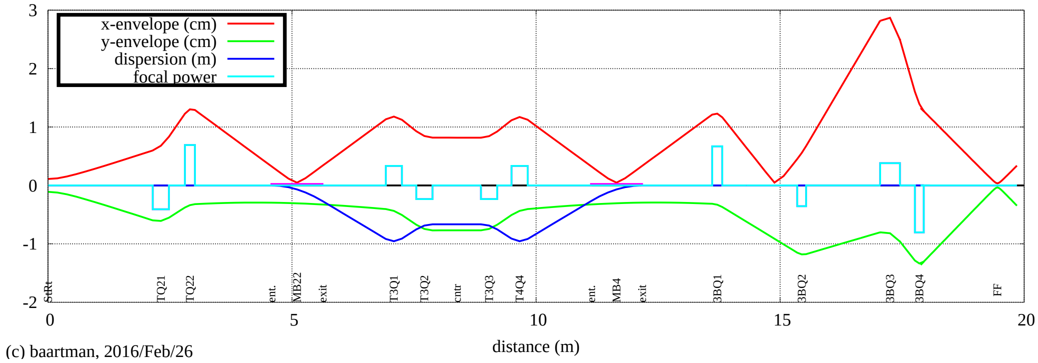

Figure 2: Envelopes and dispersion for Round Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 4.0\,$cm. Final spot diameter $= 2\sqrt{0.04{\rm m} \times 3.0\mu{\rm m}} = 0.69$mm. This is a Strong focus case.

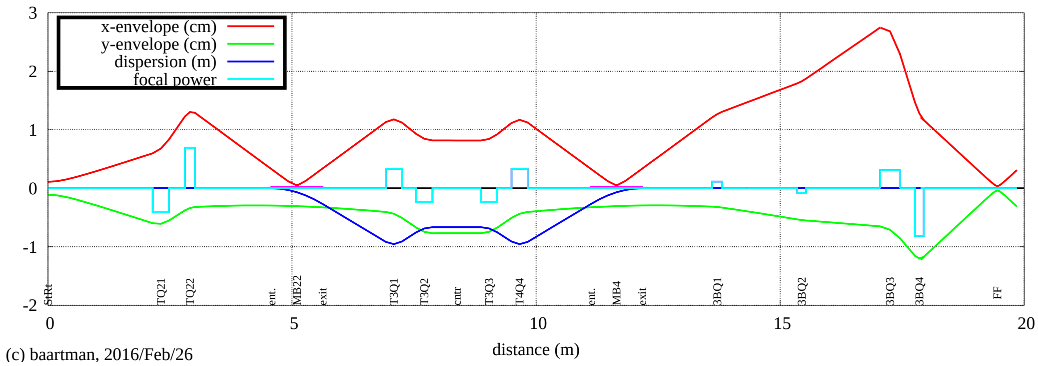

Figure 3: Envelopes and dispersion for Round Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 5.0\,$cm. Final spot diameter $= 2\sqrt{0.05{\rm m} \times 3.0\mu{\rm m}} = 0.77$mm. This is a Weak focus case.

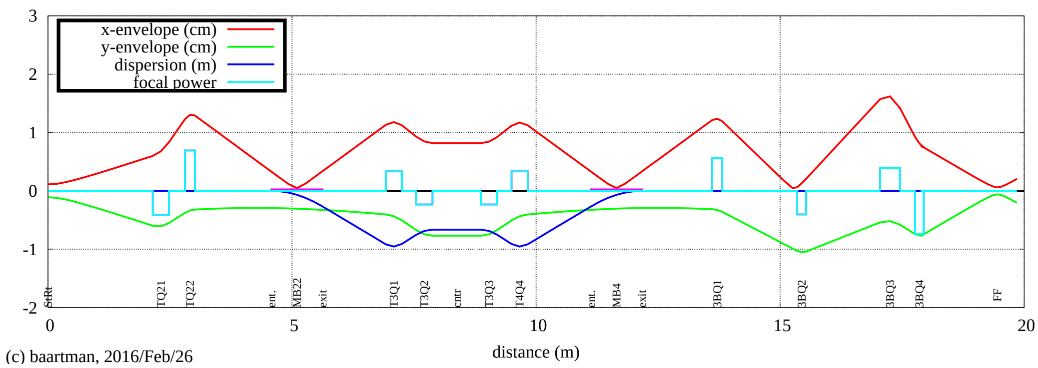

Figure 4: Envelopes and dispersion for Round Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 12.5\,$cm. Final spot diameter $= 2\sqrt{0.125{\rm m} \times 3.0\mu{\rm m}} = 1.22$mm. This is a Strong focus case.

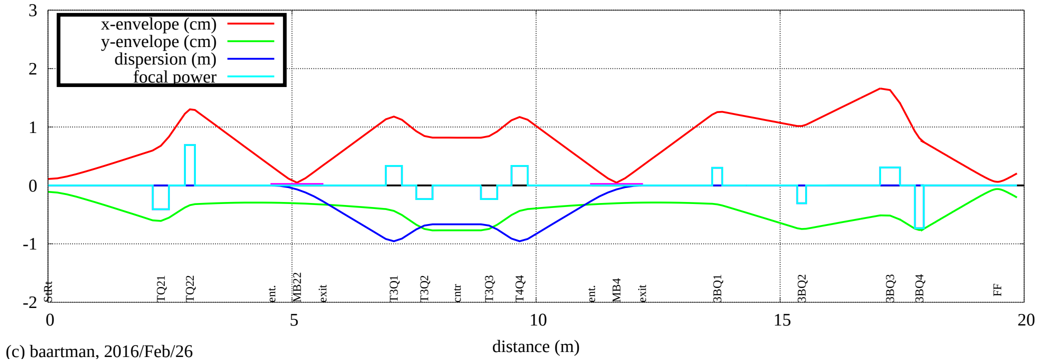

Figure 5: Envelopes and dispersion for Round Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 12.5\,$cm. Final spot diameter $= 2\sqrt{0.125\text{m} \times 3.0\mu\text{m}} = 1.22$mm. This is a Weak focus case.

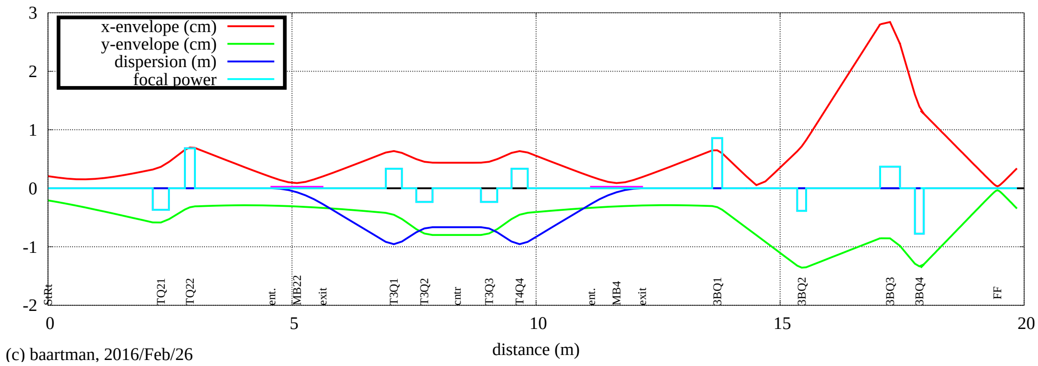

Figure 6: Envelopes and dispersion for Matched Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 4.0\,$cm. Final spot diameter $= 2\sqrt{0.04\text{m} \times 3.0\mu\text{m}} = 0.69$mm. This is a Strong focus case.

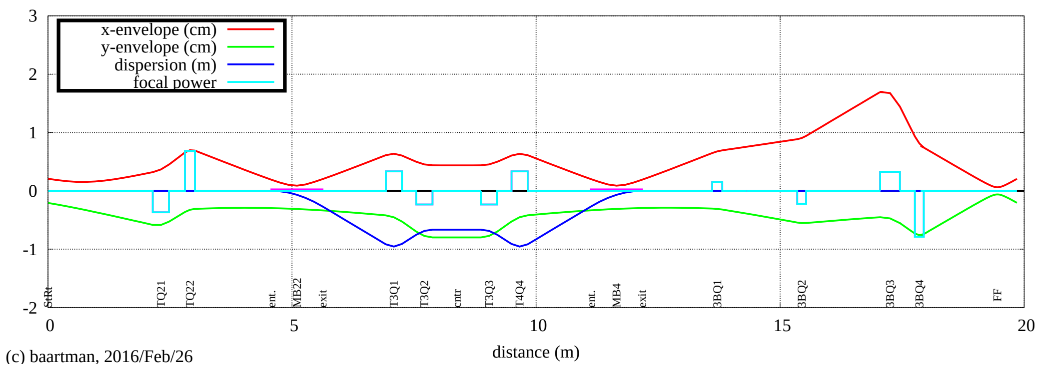

Figure 7: Envelopes and dispersion for Matched Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 12.5\,$cm. Final spot diameter $= 2\sqrt{0.125\text{m} \times 3.0\mu\text{m}} = 1.22$mm. This is a Weak focus case.

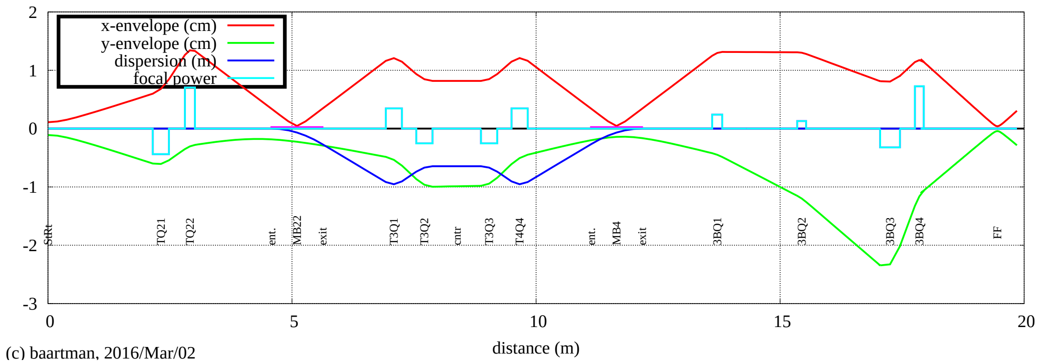

Figure 8: Envelopes and dispersion for Round Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 5.0\,$cm. Final spot diameter $= 2\sqrt{0.05{\rm m} \times 3.0\mu{\rm m}} = 0.77$mm. This is a reverse polarity case.

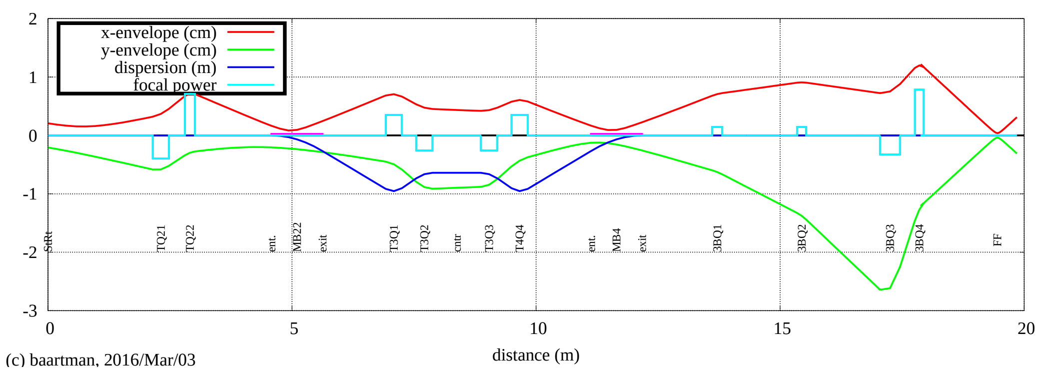

Figure 9: Envelopes and dispersion for Matched Beam start, with emittance $\epsilon_{x,y} = 3.0\,\mu$m, $\beta_{\rm FF} = 5.0\,$cm. Final spot diameter $= 2\sqrt{0.05{\rm m} \times 3.0\mu{\rm m}} = 0.77$mm. This is a reverse polarity case.

dispersion itself has to cross through zero at the symmetry point. As well, we tune a double waist at the symmetry point. This amounts to 3 conditions. We use Q21, Q22 and the 2 quads SEBT3:Q1,Q2 to achieve this.

From MB4 to EMMA, there are 4 quadrupoles to match to a round, very tight focus at the EMMA target. The focus is very small, < 1 mm diameter for a beam emittance of $3\,\mu$m, so special attention must be paid to reduce aberrations.

In order to focus to such a small spot, the beam must be quite large on the next-to-last quadrupole; an aperture of roughly 10 cm is required. This is larger than our largest of the surplus (from Chalk River) DanFysik quadrupoles, so for this one quad, we use a TRIUMF standard 4Q14/8.

The beam envelope for various final $\beta_{x,y}$ are shown in Figures 2-7. There are two possibilities for starting beam at SEBT:DB20: a "Round Beam" with $\beta_{x,y} = 40$ cm, and a "Matched Beam" that is matched to the periodic focusing upstream of this point. This latter case is referred to as the "multi-charge" tune as it is essential for transporting more than one charge state at a time[8]. However, it also has the desirable feature that it minimizes chromatic effects[1]. So far, in 10 years of running, only the Round Beam has been used.

Tunes are shown in Table 3. These read directly in quadrupole currents and should be good to about $\pm 1\%$. The B-I curves were fitted from Doug Evans' data[4]. Also fitted were the Enge functions and fringe field effects, but these are small in first order.

3.1 Aberrations

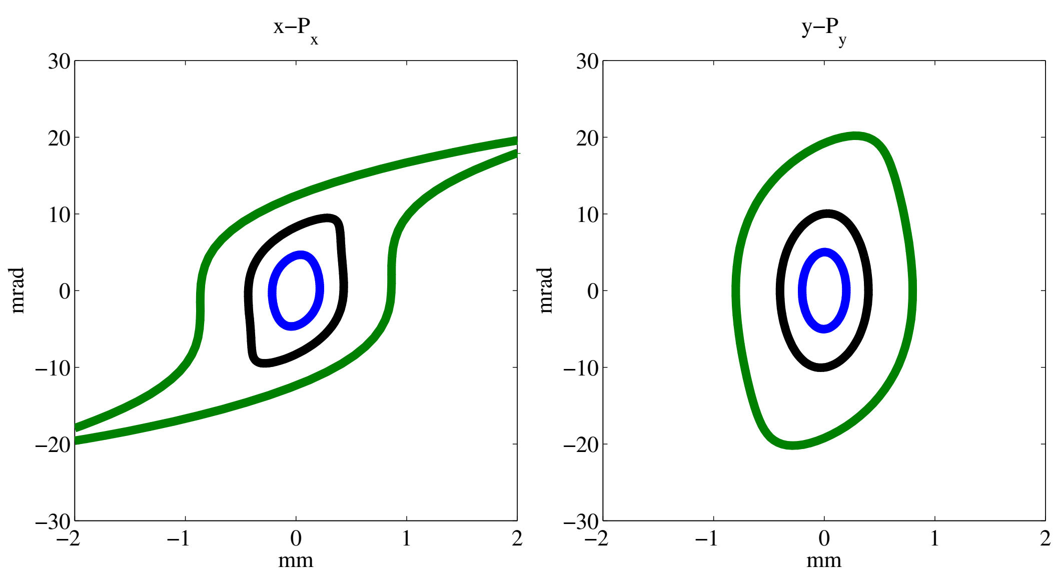

Figure 10: Emittance boundaries at 1μm (blue), 4μm (black), 16μm (green), for the $\beta_{\rm FF} = 4.0$ cm Strong tune. Left is Horizontal, right is Vertical.

The optics achieves smallest possible $\beta_{x,y}$ of 4 cm. Thus if emittance i.e. largest phase space amplitude is $3\,\mu$m, spot diameter is 0.69 mm. Except for the cubic aberrations in the horizontal plane,

Table 3: EMMA tunes for matched beam start (upper), and Round Beam start (lower). These are the quad currents in Amps, assuming the existing quad types of Table 2, and recommended quad types of Table 1. The sign convention is that Positive currents are Horizintally focusing for positive ions.

Matched Beam	SEBT		SEBT3	
	Q21	Q22	Q1	Q2
	-26.0	$+111.5$	$+53.5$	-16.5

		SEBT3B			
Tune Type	β_{FF}	Q1	Q2	Q3	Q4
Strong	4.0	$+144.6$	-27.3	$+267.0$	-55.6
	5.0	$+135.6$	-27.8	$+267.1$	-54.8
	6.25	$+127.5$	-28.2	$+267.4$	-54.0
	12.5	$+108.5$	-29.5	$+268.2$	-50.7
	25.0	$+96.1$	-30.5	$+268.2$	-46.0
Weak	12.5	$+23.8$	-15.8	$+234.8$	-56.5
	25.0	$+44.0$	-23.9	$+226.8$	-49.5

Round Beam	SEBT		SEBT3	
	Q21	Q22	Q1	Q2
	-28.9	$+112.9$	$+53.5$	-16.5

		SEBT3B			
Tune Type	β_{FF}	Q1	Q2	Q3	Q4
Strong	4.0	$+109.2$	-25.1	$+276.0$	-58.1
	5.0	$+104.9$	-25.8	$+277.3$	-57.0
	6.25	$+101.3$	-26.6	$+278.5$	-56.5
	12.5	$+91.6$	-28.6	$+283.8$	-53.0
	25.0	$+85.3$	-30.2	$+290.2$	-48.6
Weak	5.0	$+18.4$	-5.5	$+220.7$	-58.5
	6.25	$+31.3$	-12.6	$+226.6$	-57.7
	12.5	$+48.5$	-21.5	$+221.1$	-52.3
	25.0	$+57.4$	-25.6	$+202.1$	-44.6

emittance up to $6.25\,\mu$m would still allow a 1 mm diameter spot. However, as shown in Figure 10, the maximum emittance is $4\,\mu$m.

The dominant source of nonlinearity is SEBT3B:Q3. The beam must be centred to within a mm or so horizontally through Q3. During setup, this can be checked by varying this quad by a small amount and adjusting the steerer until the quad no longer steers beam on target.

3.2 Reverse Polarity case

The EMMA experiment prefers the horizontal rather than vertical to be the higher quality[3], so a tune with SEBT3B reversed polarities was attempted. This was successful, but a disadvantage is that SEBT3B:Q1 becomes redundant with Q2; so to achieve the final focus, the achromatic section must be tuned along with SEBT3B quads. In effect, the two sections SEBT3 and SEBT3B lose their individual character. The reverse polarity envelopes are shown in Figs. 8,9, and the aberration effect in Fig. 11. The smallest $\beta_{x,y}$ is 5 cm, and only a "Weak" tune is possible. However, overall, this tune might be more robust and certainly has smaller aberration in the horizontal plane.

Table 4: "Reverse Polarity" EMMA tunes for matched beam start (upper), and Round Beam start (lower). These are the quad currents in Amps, assuming the existing quad types of Table 2, and recommended quad types of Table 1. The sign convention is that Positive currents are Horizintally focusing for positive ions.

		SEBT		SEBT3	
Matched Beam		Q21	Q22	Q1	Q2
		-27.7	$+113.4$	$+55.8$	-18.3
		SEBT3B			
Tune Type	β_{FF}	Q1	Q2	Q3	Q4
Reverse	5.0	$+19.0$	$+13.0$	-238.4	$+55.6$
		SEBT		SEBT3	
Round Beam		Q21	Q22	Q1	Q2
		-31.0	$+115.2$	$+55.3$	-17.9
		SEBT3B			
Tune Type	β_{FF}	Q1	Q2	Q3	Q4
Reverse	5.0	$+38.7$	$+9.1$	-232.1	$+51.8$

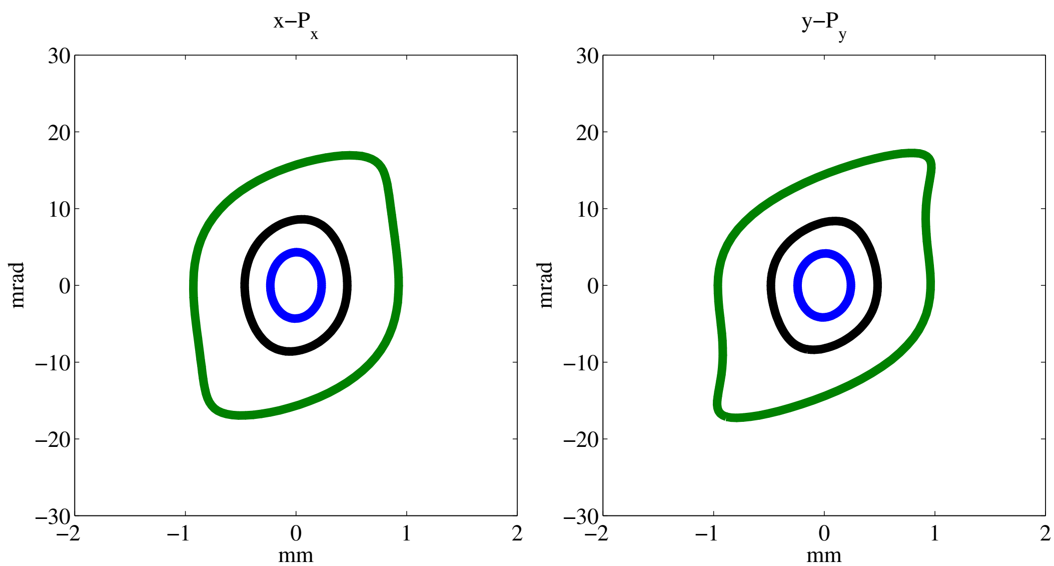

Figure 11: Emittance boundaries at 1μm (blue), 4μm (black), 16μm (green), for the $\beta_{\mathrm{FF}} = 5.0\,$cm reversed polarity tune. Left is Horizontal, right is Vertical.

3.3 Tolerances (ripple)

Figure 12 shows the effect of a 0.2% error in quad strength. It is clear from this that both the settability and the ripple on SEBT3B:Q3 must be below the 0.1% level.

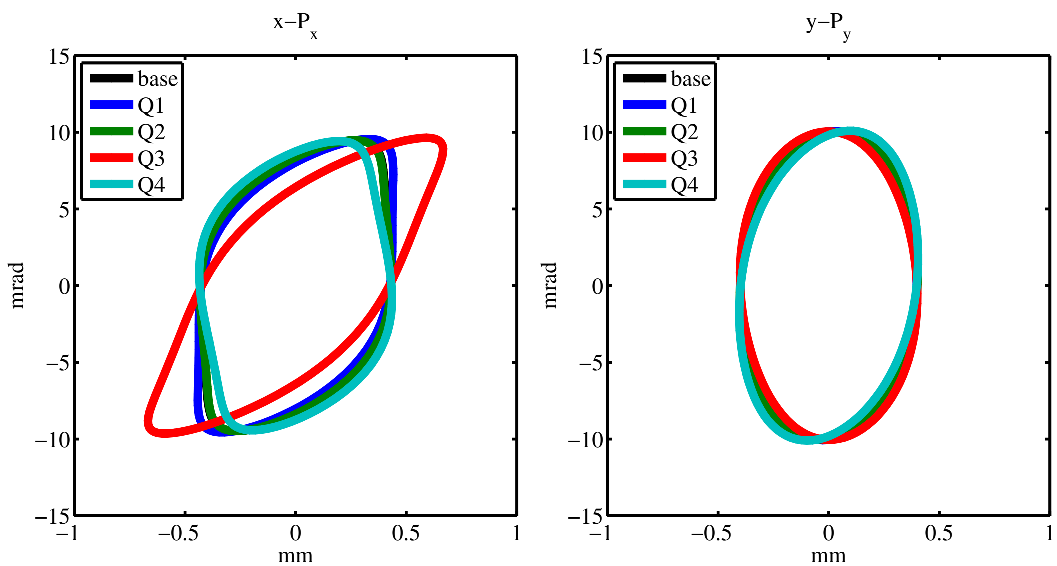

Figure 12: Emittance boundaries at 4μm for the $\beta_{\rm FF} = 4.0\,$cm Strong tune, as each of the 4 quads have a current error of 1 part in 500. Left is Horizontal, right is Vertical. The colour indicates which quad is shifted.

References

[1] R. Baartman. Considerations for ISAC-II Beamlines. Technical Report TRI-DN-05-30, TRIUMF, 2005.

[2] R. Baartman. ISAC-2 switchyard designs. Technical Report TRI-BN-05-03, TRIUMF, 2005.

[3] Barry Davids. private communication. 2016.

[4] Doug Evans. Magnet testing logbooks # 12,13,14. 1997–2006.

[5] Marco Marchetto. private communication. 2015.

[6] G. Stinson. Delivery of singly-charged beams to the ISAC-II experimental area. Technical Report TRI-DNA-05-03, TRIUMF, 2005.

[7] G. Stinson. Specification of quadrupoles for the SEBT, SEBT3, and SEBT3A/B beam lines of ISAC–II. Technical Report TRI-DNA-06-01, TRIUMF, 2006.

[8] R.E. Laxdal Z.H. Peng. A Design Layout for ISAC-II Post-SCLinac Beam Line (HEBT-II). Technical Report TRI-DN-03-19, TRIUMF, 2003.

4 Appendix: Available Quads

Table of maximum characteristics of available quads. “TUDA” quads are those currently installed in ISAC-1 TUDA line.

Quad type	Current/A	Voltage/V	Power/kW	$\int B' ds$/Tesla	Aperture/cm
DanFysik L1	93	27	2.5	5.25	5.2
DanFysik L2	88	37	3.3	9.75	5.2
DanFysik L3	84	12	1.1	7.05	3.0
DanFysik L4	84	15	1.3	9.4	3.0
DanFysik L5	195	30	5.9	5.0	7.2
DanFysik L6	195	40	7.8	8.1	7.2
DanFysik L7	86	28	2.4	13.3	4.25
DanFysik L8	80	22	1.8	6.3	4.25
TUDA Short	250	12	3.0	4.5	8.5
TUDA Long	250	16	4.0	6.75	8.5
4Q14/8	500	13	6.5	6.68	10.3