**Beam Physics Note**
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# Replacement of SEBT3B:Q1 and SEBT3A:Q2 Danfysik L5 type quads with L1 types.

Spencer Kiy

TRIUMF

**Abstract:** As part of the planned completion of BL4N from the cyclotron to ARIEL Proton Target West (APTW), four Danfysik L5 type quads are desired. To minimize cost of the BL4N completion, an objective was set to identify and re-purpose L5 quads from elsewhere on site. As of Feb. 2025 two such quads exist in the ISAC-II Experimental Hall, SEBT3B:Q1 and SEBT3A:Q2. This report assesses the effects of replacing these quads with Danfysik L1 type quads.

4004 Wesbrook Mall, Vancouver, B.C. Canada V6T 2A3 · Tel: 604 222-1047 · www.triumf.ca

# 1 Introduction

# 2 Focal Strength

As noted by Baartman in the Appendix of [1], the integrated gradient (at nominal/full power) of a DanFysik L1 is actually 5% higher than a DanFysik L5, and thus the choice of an L1 instead of an L5 has no detrimental effect on the available focusing power at these locations in the beamlines. The question then becomes just whether or not the smaller aperture of the L1s is sufficient to avoid loss of ions on the beam pipe.

# 3 Aperture Size for Given Optics

The longest possible path for radioactive ions in the ISAC and ARIEL facilities is on the order of 150 to 200 metres. Radioactive ions are very expensive to produce and difficult to extract from a target so once extracted it is preferable to avoid losing ions for unnecessary reasons, when the cost to do so is relatively small (compared to construction of target stations and production and operation of targets in these stations). A useful goal used by Baartman [2] is to limit losses to less than 0.1% per metre of beamline. This would keep overall transport efficiency above 80% for a 200 m beamline (ignoring losses such as charge breeding efficiency, capture in the ISAC RFQ, and stripping efficiencies in foils).

From the post ISAC-II linac beamline to the SEBT3B target location there are 22 quads spaced over approximately 33 m. So the loss is limited to less than 0.1% per quad to ensure the loss per metre is below 0.1%. Assuming a centered gaussian distribution, keeping the aperture/beam pipe at 3.3 sigma or further accomplishes this.

However, in reality the beam may be off centre at times, and so a more detailed consideration follows for the two cases (SEBT3B:Q1 and SEBT3A:Q1).

**SEBT3B:Q1**

The various options for optics to EMMA through the SEBT3 and SEBT3B sections described by Baartman [1] for a beam with an emittance of 3 $\mu$m [1] result in 2rms beam sizes at SEBT3B:Q1 ranging from 6.5/3.4 mm (x/y, for the 'matched' beam start at SEBT:RPM20, shown below in Figure 1) to 12.8/2.9 mm (x/y, for the 'round' beam start at SEBT:RPM20, shown below in Figure 2).

[1] This number was used as an upper limit in many design studies for ISAC-II, and is a valid upper limit based on recent operational experience in 2024. Horizontal and vertical emittance measured at SEBT:EMIT18 in 2024 varied from 1.3 to 2.9 $\mu$m.

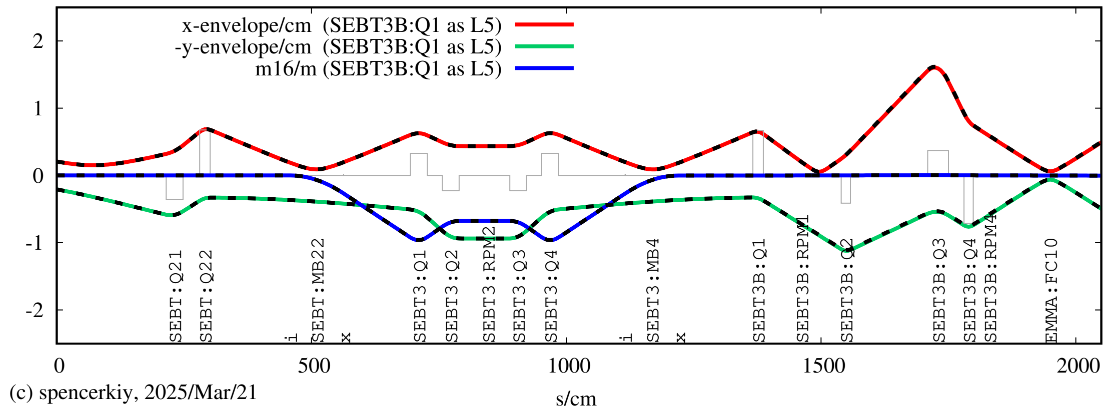


Figure 1: SEBT to SEBT3B envelopes and dispersion for **matched** beam start with 3 μm emittance. The envelopes with an L1 at SEBT3B:Q1 are shown as black dashed lines over top of the envelopes with the existing L5.

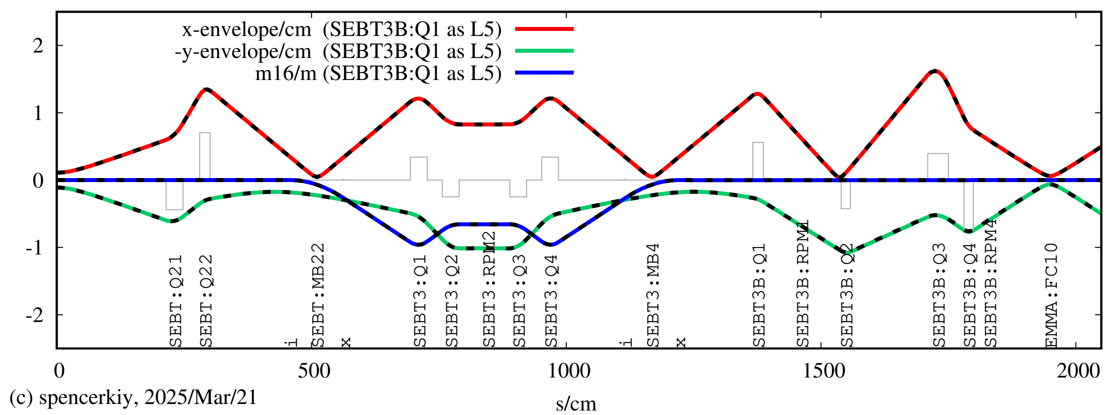


Figure 2: SEBT to SEBT3B envelopes and dispersion for **round** beam start with 3 μm emittance. The envelopes with an L1 at SEBT3B:Q1 are shown as black dashed lines over top of the envelopes with the existing L5.

To assess the aperture size on a mis-aligned beam, an assumed maximum offset of the beam centroid from the optical axis of 0.5 cm was applied in both horizontal and vertical directions. Using the simulated 2rms beam sizes at SEBT3B:Q1, a gaussian distribution was assumed and used to generate $10^5$ random ion positions that were then compared to the beam pipe. This was done for both the matched and round beam starts, and are shown below in Figure 3.

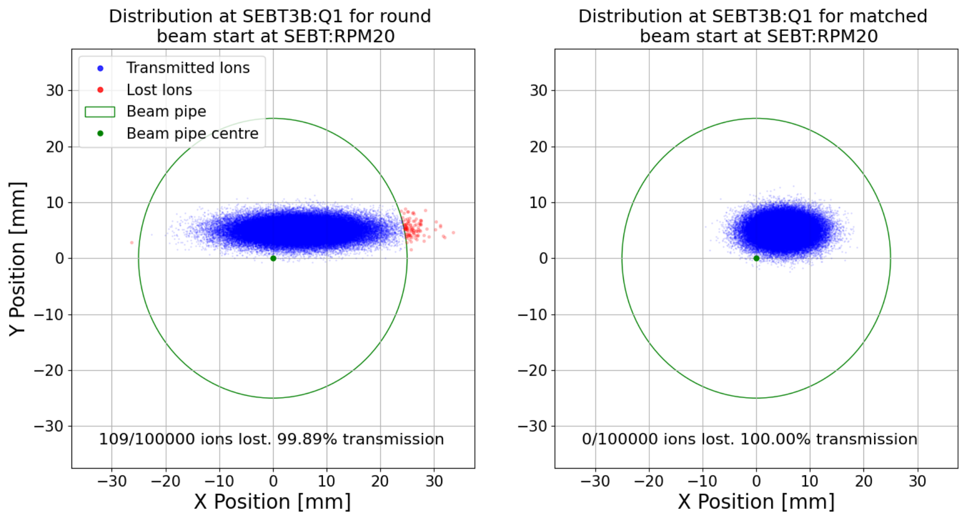


Figure 3: Beam spot at SEBT3B:Q1 assuming a gaussian distribution, for 3 μm emittance, for maximum centroid error of 5 mm in both X and Y, for two tunes: round beam start (above left) and matched beam start (above right) at SEBT:RPM20. Note that marker diameters for lost ions are artificially increased by a factor of 5 for better visibility.

The round beam start is the tune that has most often been used historically, and results in an approximate 0.1% loss at SEBT3B:Q1 under these assumptions. The matched beam start (the preferred tune since 2024) is far within the beam pipe still and results in no beam loss at SEBT3B:Q1. Notably, with either tune, under worst case conditions, the approximated beam loss is at or within the acceptable margins noted in the previous section.

**SEBT3A:Q2**

In terms of aperture size, Baartman already recommended [1] that SEBT3A:Q2 could have the current L5 replaced with an L8. The Danfysik L8s have a comparable focusing strength to the L1 and L5, but have an even smaller aperture than the L1 at 4.25 cm diameter rather than the more standard 5.2 cm diameter L1s in ISAC.

This report does not access the L8 option further and rather focuses on the L1 for two reasons: 1) The offered spare quads at TRIUMF at this moment are L1 and L2 types and 2) With the tunes considered here, the losses from an L8 would slightly exceed the acceptable 0.1% margin.

The analagous tunes to the SEBT3B tunes above are shown below for SEBT3A. The 'matched' beam start at SEBT:RPM20, shown in Figure 4 results in 2rms sizes of 3.0/11.5 mm (x/y) at SEBT3A:Q2, while the 'round' beam start, shown in Figure 5, results in 2rms sizes of 1.3/10.6 mm (x/y) at SEBT3A:Q2. Not shown here is a weak focus tune that results in 2rms sized of 9.3/5.4 mm (x/y) at SEBT3A:Q2.

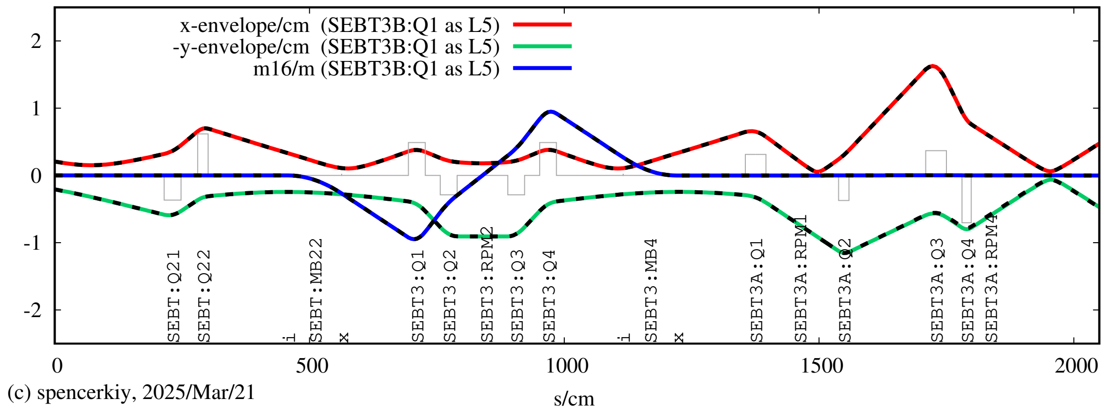


Figure 4: SEBT to SEBT3A envelopes and dispersion for **matched** beam start with 3 $\mu$m emittance. The envelopes with an L1 at SEBT3A:Q2 are shown as black dashed lines over top of the envelopes with the existing L5.

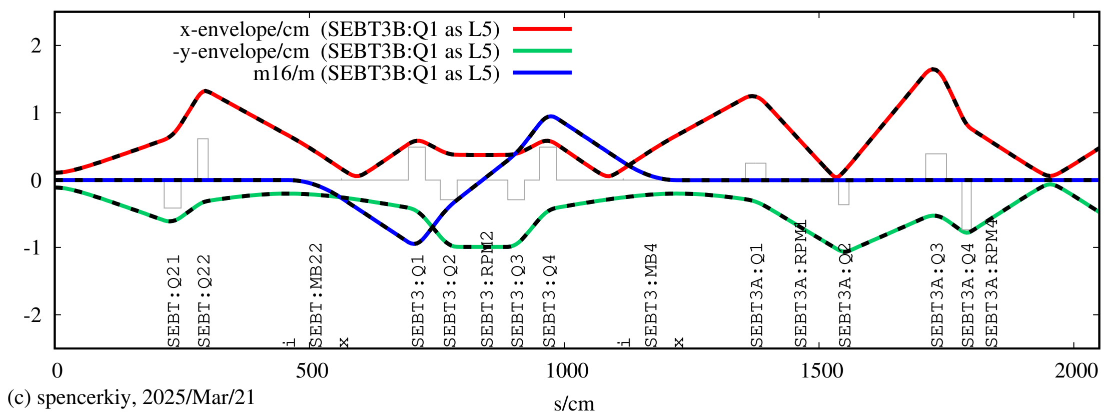


Figure 5: SEBT to SEBT3A envelopes and dispersion for **round** beam start with 3 $\mu$m emittance. The envelopes with an L1 at SEBT3A:Q2 are shown as black dashed lines over top of the envelopes with the existing L5.

The same methodology is then repeated here for SEBT3A:Q2. An assumed maximum offset of the beam centroid from the optical axis of 0.5 cm was applied in both horizontal and vertical directions.

Using the simulated 2rms beam sizes at SEBT3A:Q2, a gaussian distribution was assumed and used to generate $10^5$ random ion positions that were then compared to the beam pipe. This was done for both the matched and round beam starts, and are shown below in Figure 6.

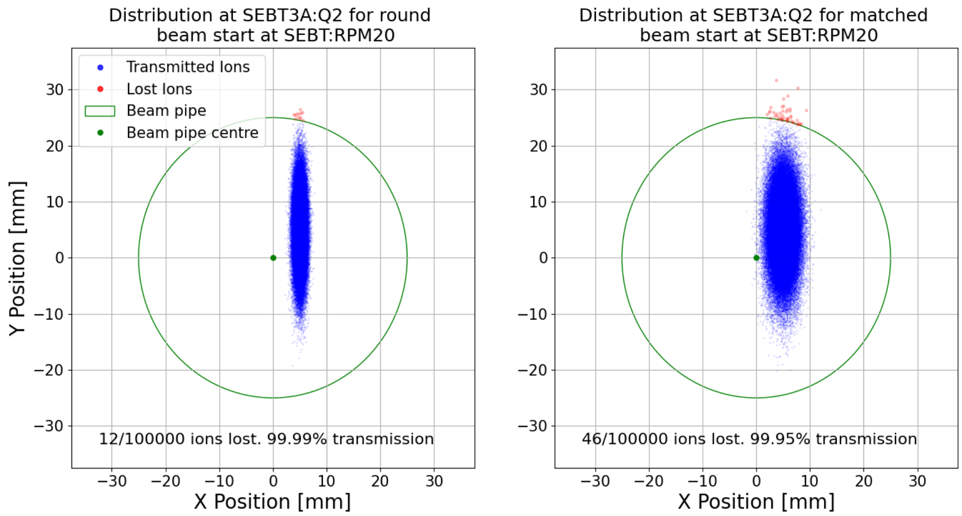


Figure 6: Beam spot at SEBT3A:Q2 assuming a gaussian distribution, for 3 µm emittance, for maximum centroid error of 5 mm in both X and Y, for two tunes: round beam start (above left) and matched beam start (above right) at SEBT:RPM20. Note that marker diameters for lost ions are artificially increased by a factor of 5 for better visibility.

The round beam start is the tune that has most often been used historically, and results in an approximate 0.01% loss at SEBT3A:Q2 under these assumptions. The preferred tune since 2024, the matched beam start, results in an approximate 0.03% loss. Notably, with either tune, under worst case conditions, the approximated beam loss is within acceptable margins.

# 4 Experience and Current State of SEBT3 and SEBT3B Beamlines

As already noted, in 2024, the preferred operational tune to SEBT3B-EMMA (and that implented in MCAT [3]) is now the matched beam start (as opposed to the round beam start). This tune (Figure 1) results in a smaller horizontal 2rms beam size at SEBT3B:Q1, giving a much wider buffer to a 52 mm aperture quadrupole and beam pipe.

Further, it was noted years ago that a mistake was made during the design or installation of the SEBT beamlines - the beam pipe at four installed quadrupoles[2] with apertures larger than the standard 52 mm **does not widen to the size of the quad aperture** (Figure 7). As larger aperture quadrupoles are used to accomodate larger beam sizes, this defeats the purpose of using them.

[2] SEBT3:Q1, SEBT3:Q4, SEBT3A:Q2, and SEBT3B:Q1

So in fact, the SEBT beamlines have been operating in effect with smaller 52 mm apertures at SEBT3B:Q1 and SEBT3A:Q2 since day one. Beam delivery through these sections has been successful for various tunes, demonstrating that we can operate without issue with these smaller apertures at these quads.

Figure 7: A DanFysik L5 (7.2 mm aperture) at SEBT3B:Q1, with the standard ISAC high energy beam pipe size, showing a noticeable gap between the pole tip and beam pipe.

## 5 Power Supplies

The current required to obtain the envelopes in Figures 1, 2, 4, and 5 are summarized below in Table 1. Voltage required is estimated using Doug Evans' quad measurement data for a 1982 L5, and a 1982 L1.

| | L5 Current [A] | L5 Voltage [V] | L1 Current [A] | L1 Voltage [V] |
|---|---|---|---|---|
| SEBT3B:Q1 (round start) | 91.0 | 14.1 | 45.0 | 17.1 |
| SEBT3B:Q1 (matched start) | 109 | 16.9 | 54.2 | 20.6 |
| SEBT3A:Q2 (round start) | 58.8 | 9.1 | 29.0 | 11.0 |
| SEBT3A:Q2 (matched start) | 60.0 | 9.3 | 29.8 | 11.3 |

Table 1: Current and voltage required for L1 and L5 type quads at SEBT3A:Q2 and SEBT3B:Q1 locations. Note all 4 cases are for 'strong focus' tunes as shown in Figures 1, 2, 4, and 5. These values are for a beam rigidity of 2.5 T-m.

Note that the current and voltage requirements for the L1s above are within the capabilities of the power supplies which are already installed, summarized in Table 2. Nonetheless, power supplies group should review if it would be beneficial to swap out the power supplies for the 33 V 85 A supplies which are more commonly used for L1s.

| | Current [A] | Voltage [V] | EPICS limit [A] |
|---|---|---|---|
| SEBT3B:Q1 | 170 | 30 | 170 |
| SEBT3A:Q2 | 200 | 30 | 200 |

Table 2: Summary of power supplies currently installed for SEBT3B:Q1 and SEBT3A:Q2.

# 6 Other Considerations

It is worth noting that the following will be required to accomodate the impact of this change on the ISAC-II Linac and Beamlines Facility.

- A work request must be submitted (this is a change to a commissioned system) by the group(s) who want to remove the L5 quads.
- A short re-commissioning both with and without beam will be required prior to experiments once the replacement is complete.
- The power supplies in use and requirements for L1s should be reviewed by the High Current Power Supplies Group.
- Changes to EPICS to accomodate the change (at a minimum, changing limits of PVs for clarity, possible further changes if supplies are swapped out).
- Requires update of ACC, MCAT, and any other models looking at this beamline section.
- The new L1s must be measured at the magnet test scan before installation.
- Careful scheduling will be required to avoid impact on ISAC-II experiments in the 2025 beam delivery schedule. It is preferred for this to occur after all experiments on SEBT3B and SEBT3A are finished for the 2025 beam delivery year.

# 7 Conclusion

Replacement of SEBT3B:Q1 and SEBT3A:Q2 quadrupoles from Danfysik L5 types to Danfysik L1 types have been shown to have no detrimental impact to the SEBT optics design.

1. The integrated focal strength of L1s are indeed higher than that of the L5s.

2. There is over eight years of empirical data showing 52 mm diameter apertures at the locations of these quads are acceptable.

3. The various options for beam optics in the SEBT3A and SEBT3B sections have been shown to result in losses below the desired 0.1% level, even in the event of significant beam misalignment of 5 mm in both x and y.

## References

[1] Richard Baartman. Optics to EMMA. Technical Report TRI-BN-16-03, TRIUMF, 2016.

[2] Richard Baartman. Vacuum Requirements in ISAC for ISAC2. Technical Report TRI-DN-98-07, TRIUMF, 1998.

[3] Olivier Shelbaya. Model Coupled Accelerator Tuning (PhD thesis). Technical Report TRI-BN-23-04, TRIUMF, UVic Dept. of Physics & Astronomy, 2023. https://dspace.library.uvic.ca/handle/1828/14804.