Beam Physics Note
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BOIS Tuning Strategy: MEBT Corner to HEBT2

Omar Hassan

TRIUMF

Abstract: This beam note presents findings and results from multiple machine development (MDEV) shifts conducted between October and November 2024. These shifts were instrumental in shaping the tuning strategy from the MEBT corner to HEBT2, using a series of predefined sequences. The developed strategy will be utilized in the Bayesian Optimization for Ion Steering (BOIS) control room application.

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

List of Acronyms

ISAC Isotope Separator and Accelerator

RFQ Radio-Frequency Quadrupole

DTL Drift Tube Linac

LEBT Low Energy Beam Transport

MEBT Medium Energy Beam Transport

HEBT High Energy Beam Transport

MCAT Model Coupled Accelerator Tuning

BOIS Bayesian Optimization for Ion Steering

MDEV Machine Development

UCB Upper Confidence Bound

EI Expected Improvement

ECAS Element Command Automated Summary

1 Introduction

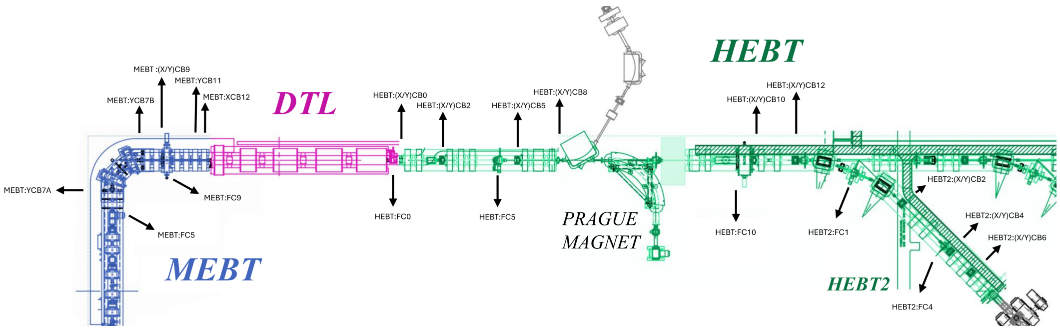

Figure 1: The MEBT and HEBT sections at the ISAC facility, with the relevant steerers and Faraday cups highlighted.

The Isotope Separator and Accelerator (ISAC) facility [1] consists of two post accelerators: the Radio-Frequency Quadrupole (RFQ) [2] and Drift Tube Linac (DTL) [3]. These combine to provide stable and rare isotope beam across three different energy regimes:

- Low Energy Beam Transport (LEBT): 2.04 keV/u
- Medium Energy Beam Transport (MEBT): 153 keV/u
- High Energy Beam Transport (HEBT): 1.53 MeV/u

By utilizing knowledge of the beam dynamics at ISAC and a speedy beam envelope code (`TRANSOPTR` [4]), several control room applications have been developed to augment the operators' capabilities and minimize tuning times to experiments. One critical application is Model Coupled Accelerator Tuning (MCAT) [5] which sets optical elements such as quadrupoles and dipoles to a design tune. As the initial conditions of the beam are unknown (emittance, etc.), beam centroid corrections are required using the steering elements (see figure 1). Bayesian Optimization for Ion Steering (BOIS) [6] is another control room application which finds the steerer values that minimize beam losses as beam propagates to the experiment, with most previous tests being performed in the low energy section.

This beam note is the first in a series to discuss major upgrades to the operational tuning strategy which will be used for the BOIS control room application. There were four different beam configurations over the 2 month testing period, focusing on the medium and high energy sections. Discussions about the found optimal tuning strategies from the MEBT corner to HEBT2 are carried out, including results from the machine development (MDEV) shifts. The time taken to tune is shown with suggested changes for faster optimizations. Lastly, plans for future work are laid out to address either pre-existing issues or issues found during these tests.

2 Tuning Sequences

While it is possible to tune the entirety of the elements from MEBT:FC9 to HEBT2:FC4, this would be a large parameter space of 25+ elements, whereas Bayesian optimization is typically best suited for smaller dimensional problems [7]. To tackle this issue, the larger problem is split into several smaller problems, each having an overlap with the previous sequences. These sequences are chosen according to the availability of diagnostics and the typical operator tuning procedure. These sequences contain all steering elements, some sequences include quadrupoles to account for the modelling uncertainties, where the determined bounds for BOIS are $\pm(10-15)\%$ of the MCAT value. The sequences tuned are:

Sequence 1 (MEBT:FC9 to HEBT:FC5, 14 elements):
MEBT:Q6, MEBT:Q7, MEBT:YCB7A, MEBT:YCB7B, MEBT:Q8, MEBT:Q9, MEBT:XCB9, MEBT:YCB9, MEBT:Q10, MEBT:Q11, MEBT:YCB11, MEBT:Q12, MEBT:XCB12, MEBT:Q13.

Sequence 2 (HEBT:FC0 to HEBT:FC5, 4 elements):
HEBT:XCB0, HEBT:YCB0, HEBT:XCB2, HEBT:YCB2

Sequence 3 (HEBT:FC5 to HEBT:FC10, 6 elements):
HEBT:XCB2, HEBT:YCB2, HEBT:XCB5, HEBT:YCB5, HEBT:XCB8, HEBT:YCB8

Sequence 4 (HEBT:FC10 to HEBT2:FC1, 6 elements):
HEBT:XCB8, HEBT:YCB8, HEBT:XCB10, HEBT:YCB10, HEBT:XCB12, HEBT:YCB12

Sequence 5 (HEBT2:FC1 to HEBT2:FC4, 4 elements):
HEBT:XCB12, HEBT:YCB12, HEBT2:XCB2, HEBT2:YCB2

Most of these sequences are fixed, however it is possible to combine sequences 2 and 3 into one problem in the future. Note that these sequences overlap each other, where typically the last two elements of the previous sequence are included in the next sequence. This allows for more flexibility as the beam can enter the interface of the sequence at different points, essentially allowing the boundary conditions to change.

3 Results

3.1 October 14-15, 2024

The beam configuration was $^{84}\mathrm{Kr}^{15+}$ at 461 keV/u. This MDEV shift was focused on testing different sequences and optimizing across the MEBT corner. The objective is to maximize the current transmission as measured from one Faraday cup to the next.

3.1.1 MEBT Corner

The initial snapshot is #8303. Most of the optimizations were performed using the Upper Confidence Bound (UCB) [8] acquisition function where the exploration vs exploitation hyperparameter (β) was kept at $\beta = 3$. The initial tests excluded all quadrupoles, which proved ineffective. The primary issue with the MEBT corner quadrupoles is the discrepancy between the optimal tune determined by MCAT and the design tune. Further investigation suggests that this mismatch is likely due to inaccuracies in the effective lengths of the MEBT corner quadrupoles [9].

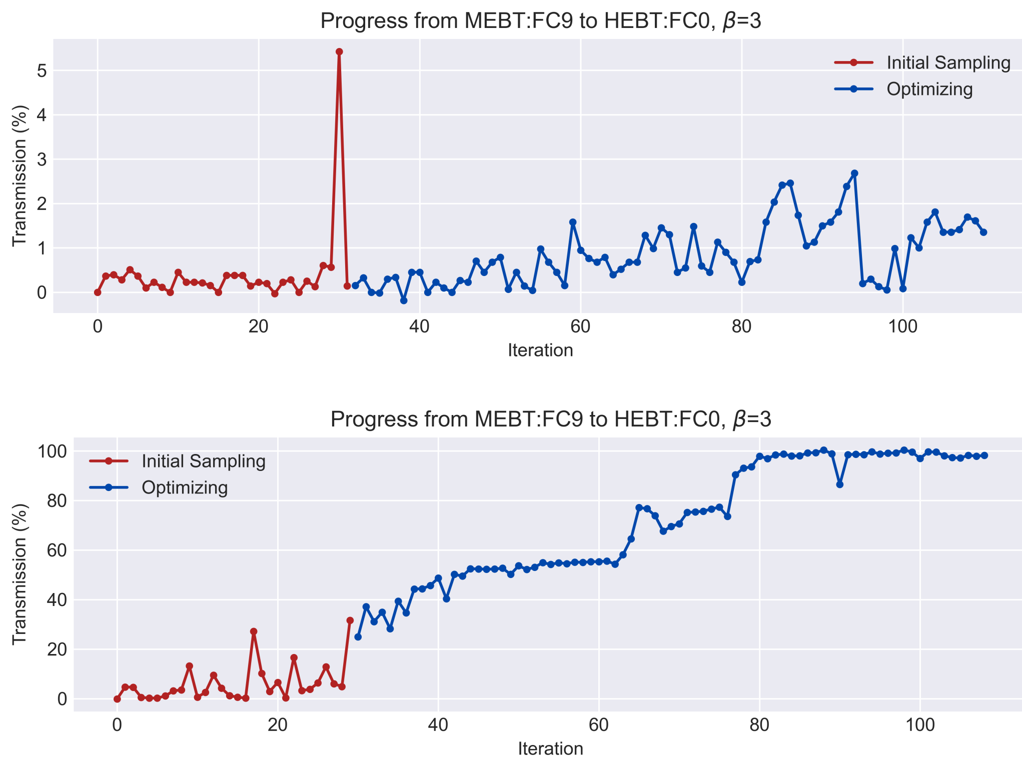

Figure 2: **Top:** Optimization with unbounded quadrupole values. **Bottom:** Bounding quadrupoles to $\pm 10\%$ of the MCAT value.

Figure 2 shows the relevant tests where quadrupoles were included in the optimizations, keeping the quadrupoles unbounded was unsuccessful yielding a current transmission of 5%. Bounding the quadrupoles to $\pm 10\%$ of the MCAT value yielded a transmission of 100%. It is then best to fine tune the MCAT value, this minimizes the input space leading to easier convergence. Final snapshot is #8315.

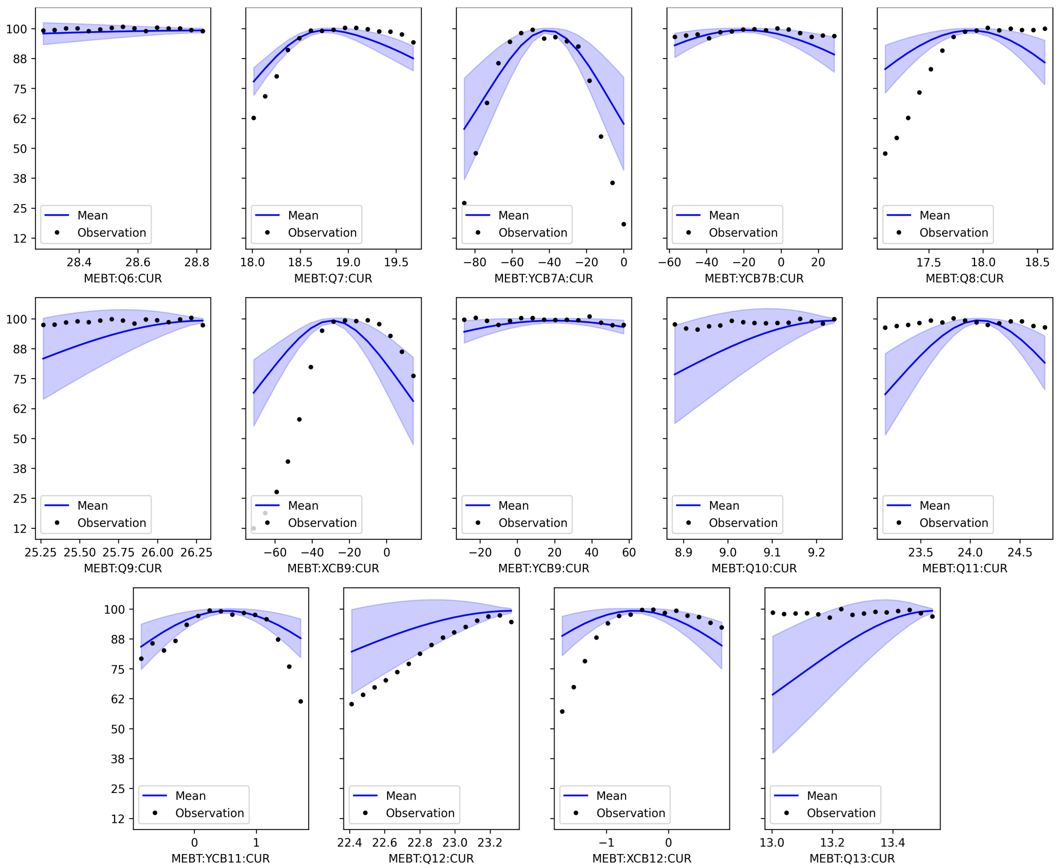

Figure 3: Fit vs Scans of the bounded quadrupole optimization problem.

Figure 3 shows the 1 dimensional posterior scans for all the elements. Predictions for both quadrupoles and steerers are both mostly within the uncertainty. These scans need improvement and will be rewritten in the future, see section 4.

Notes: 1) RIB operator noticed MEBT:YCB7A tripped, it repeatedly tripped during the tests. 2) Current at MEBT:FC0 dropped from 6.2nA at start of testing to 5.5nA.

3.1.2 HEBT to HEBT2

The Initial snapshot was #8293. Sequential optimization was utilized with sequences 2-5. Tests were carried out using both Expected Improvement (EI) [10] and UCB, EI generally converges faster but is less consistent. Running BOIS with EI and $\beta = 10$ works for sequence 2, however sequence 2 is a very easy sequence to optimize where maximum transmission is found immediately in the random sampling stage (before an acquisition function is even used). A more interesting sequence to test is sequence 3 which fails with significant over-exploration. Figure 4 shows the explored input space for two β values when using EI. As a result of this over-exploration, transmission was at a minimum ($\approx 1 - 5\%$). This issue was later found to be with `BoTorch` [11], we previously used was version 0.11.3, upgrading to version 0.13 fixed this issue. A future beam note will discuss these acquisition functions and the issues encountered in detail.

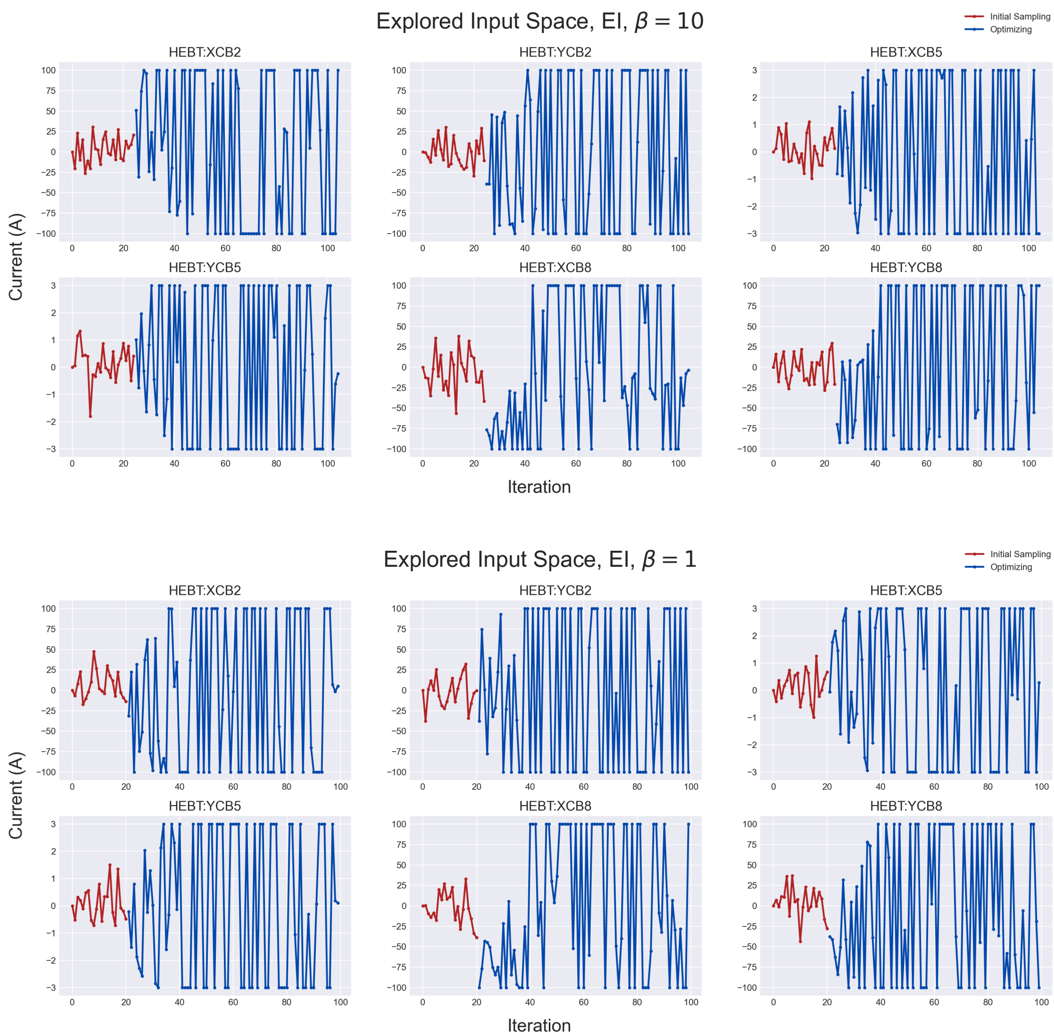

Figure 4: Explored input space during optimization for EI. **Top:** $\beta = 10$. **Bottom:** $\beta = 1$

I resolved to using UCB with $\beta = 3$ as it is the most reliable configuration we have, this yielded good transmission at about 93%. Figure 5 shows the expected input space exploration.

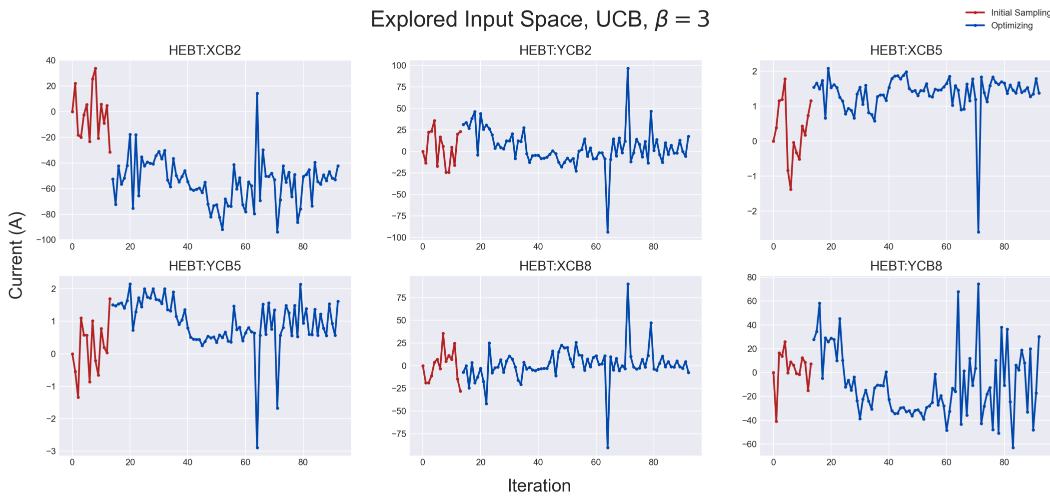

Figure 5: Explored input space during optimization for UCB with $\beta = 3$.

The rest of the sections were optimized using UCB, see figure 6. Total tuning time was ≈ 42 mins, however this will be cut down in the future, the maximum transmission is often found very early on so early stoppage needs to be implemented. Final snapshot was #8294.

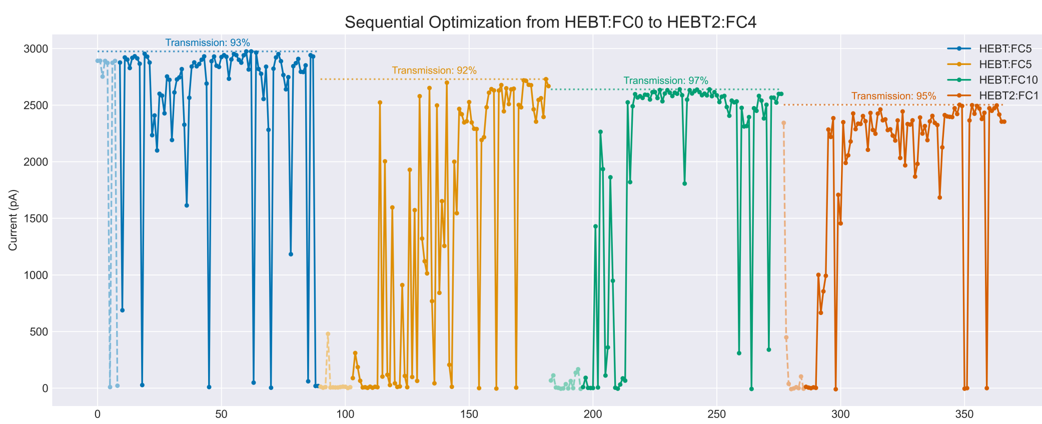

Figure 6: Sequential optimization from HEBT:FC0 to HEBT2:FC4. This covers sequences 2-5, best transmission is shown for each sequence.

3.1.3 Combining Sequences 2-5

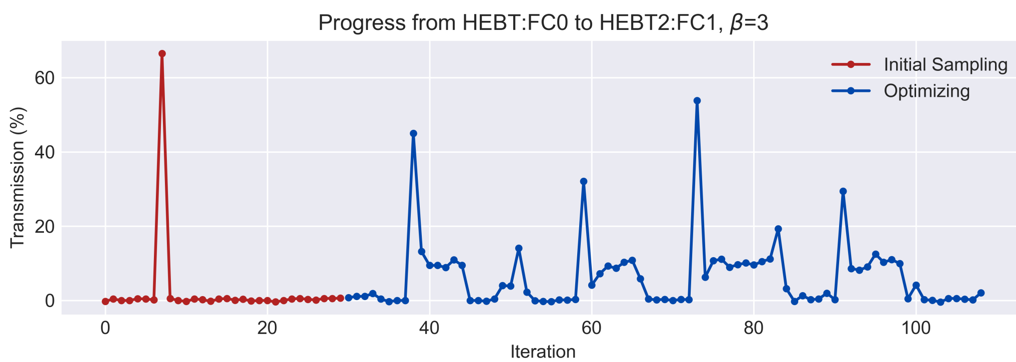

Figure 7: Optimization problem where sequences 2-5 are combined.

To showcase the inefficacy of tuning long stretches of the beamline in one go, a test was conducted where sequences 2-5 were combined into a single optimization problem (14 elements). Figure 7 showcases the progress, what immediately stands out is the lack of improvement over time. The best point reached in sampling is never surpassed, final transmission from HEBT:FC5 to HEBT2:FC4 is 68% which is far below the sequential method (86%). Final snapshot is #8296.

3.2 October 20, 2024

3.2.1 Tuning Time Estimates

Table 1: Tuning Times per Sequence

Sequence	# of Elements	Start Time	End Time	Tuning Duration (min)
1	14	6:03	6:12	9
2	4	6:14	6:15	1
3	6	6:16*	6:22	6
4	6	6:23*	6:28	5
5	4	6:29*	6:31	2
Total				28

* Estimated start times, assuming each new sequence begins 1 minute after the previous one ends.

The beam configuration was $^{12}C^{3+}$ [Test 1] at 464 keV/u, and the initial snapshot is #8418. Main goal was to get a time-estimate of BOIS running from sequences 1-5. Manual stoppage when transmission ceases to improve or reaches 90-95% transmission was used. Table 1 shows the tuning times per sequence, with the total tuning time calculated from the initial start time and the final end time. Sequence 1 takes the longest with 9 mins, followed by sequence 3 at 6 mins. Sequence 1 is self explanatory as it is the biggest sequence leading to longer convergence times. Sequence 3 is a bit more of a difficult problem for BOIS to solve, it is useful to understand the beam envelopes in this section to better explain this. This section consists of 4 quadrupoles over ≈ 8 m of beamline, this section then has a long drift where the beam envelopes grow, as shown in Figure 8.

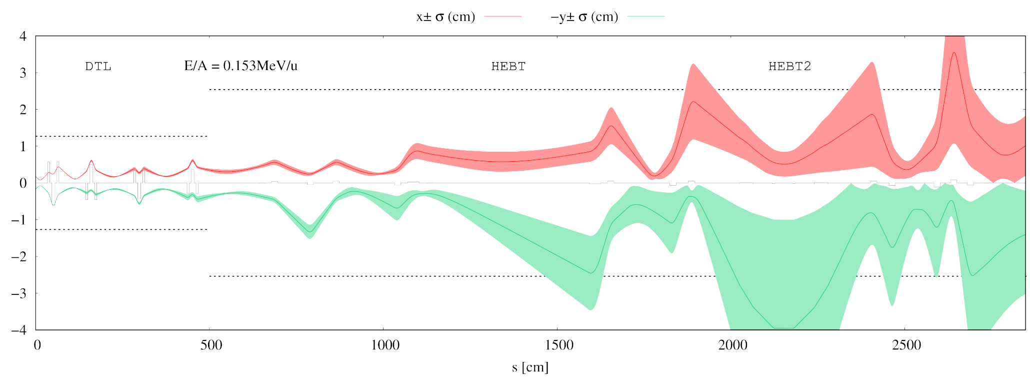

Figure 8: Simulated beam envelopes using `TRANSOPTR` from the DTL to the end of HEBT2. The dotted lines indicate the approximate apertures for each section. A ± 2 mT deviation is applied to the quadrupoles producing the uncertainty. $\Delta p/p$ estimated to be between 0.1% to 1%.

Despite the numerous improvements that can be made to further decrease the tuning time, 28 mins for the MEBT corner to HEBT2 is comparable to what is achieved by operators. As a result of the tuning time and the achieved transmission, BOIS has a great deal of potential to aid the operators during tuning. Final snapshot is #8422.

3.2.2 ECAS

The Element Command Automated Summary Tool (ECAS) is a useful metric for measuring the time taken to tune different sections of the beamline in ISAC [12]. This tool provides the total number of commands over a selected time period using 5 min binning. Figure 9 shows BOIS running from 6 pm till midnight as it was used to tune different sections. This tool still needs some upgrades to have a direct comparison on the tuning times between operators and BOIS on average.

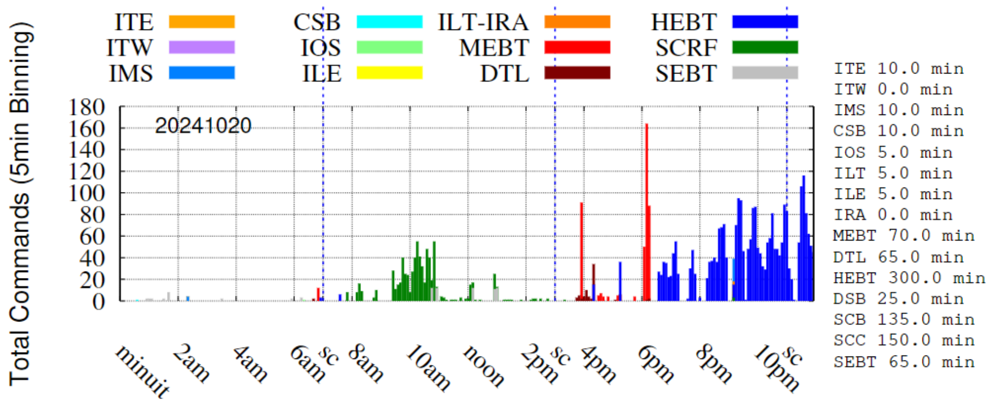

Figure 9: The ECAS plot for $^{12}C^{3+}$ [Test 1].

3.3 November 6, 2024

Beam was $^{12}C^{3+}$ [Test 2] at 464 keV/u, and the initial snapshot is #8554. Ion source had degraded since the last MDEV shift, leading to poor beam quality from the source. Final snapshot is #8561.

3.4 November 20, 2024

Beam was $^{133}Cs^{21+}$ at 254 keV/u, and the initial snapshot is #8728. The ion source was unstable resulting in significant fluctuations of the current at the Faraday cups. Final snapshot is #8738.

3.5 Summary

Table 2: Current transmission across different sequences for various beam configurations.

Species	**Energy (keV/u)**	**Section 1**	**Section 2**	**Section 3**	**Section 4**	**Section 5**
$^{84}Kr^{15+}$	461	100%	93%	91%	97%	95%
$^{12}C^{3+}$ [Test 1]	464	89%	100%	90%	94%	97%
$^{12}C^{3+}$ [Test 2]	464	76%	98%	78%	82%	92%
$^{133}Cs^{21+}$	254	100%	100%	97%	91%	97%

Despite the ion-source issues, BOIS consistently achieves high transmission rates across the medium and high energy sections while maintaining a short tuning time for multiple beam configurations. These results will inform the development of BOIS as a control room application for sections starting at the MEBT corner to HEBT2.

4 Future Work

While this work has been extremely promising, there are several improvements required, some needing MDEV shifts for testing:

- Early stoppage has not yet been implemented in BOIS, this is a relatively easy step that saves a significant amount of time. The idea is to stop the program if either of these two conditions is met: 1) The beam transmission reaches a pre-determined threshold. 2) No improvement in beam transmission after x number of iterations. It is also possible to set a $\beta = 0$ to maximally exploit the best inputs for ∼5 iterations after a condition is met.
- Minimize steering by bounding the inputs, this has been developed with boundBOIS [6], but not extensively tested in the medium to high energy beamlines.
- Include the best input values based on previous runs in the initial sampling stage, which are scaled to match the current beam configuration. Currently, this is a completely random process which calculates test values from the midpoint of the bounds.
- Fit vs Scans will be changed in the future, the current implementation is flawed as it appears to explore in huge steps around the predicted optimal. Furthermore, this is not documented so the reasoning behind the current implementation is missing.
- A study in early January showcased that BOIS performs worse with multi-threading. Run BOIS as a single-threaded task in the future.
- The current as measured on the Faraday cup is averaged over 20 measurements, this is redundant as the wait time between each measurement (0.01s) is far quicker than the response time for the server (0.2s). It is best to average over a smaller number of measurements and provide the proper wait times between the measurements.

5 Acknowledgements

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