Beam Physics Note
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Investigations into the HEBT & HEBT2 Beamlines with Multi-Objective BOIS

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TRIUMF

Abstract: The first online test for multi-objective optimization was carried out during the MDEV shift on 22/09/2024. Single-objective tests proved that getting high transmission into DRAGON is difficult, where a lack of proper understanding of the HEBT/HEBT2 beamlines was apparent. This beam note goes over the MDEV results and provides some analysis of these beamlines using TRANSOPTR.

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1 Introduction

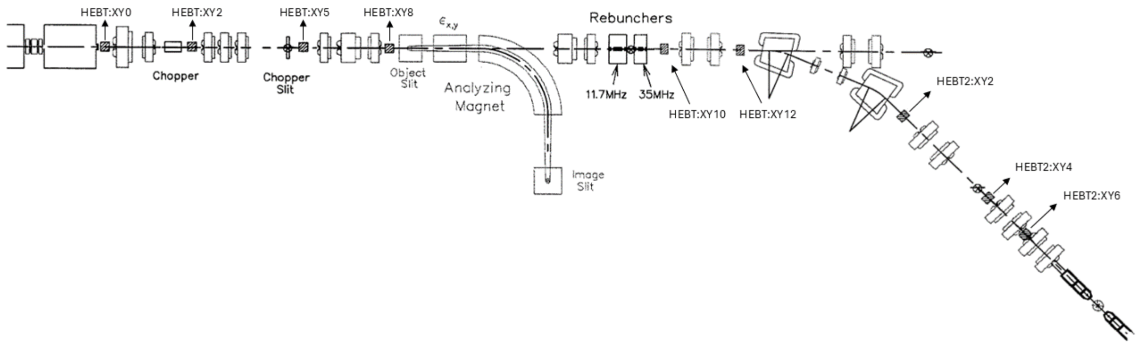

Figure 1: Beamline diagram from HEBT to HEBT2.

The multi-objective Bayesian optimization problem has been previously motivated with the development of the Wobbler [1]. This approach would allow for the simultaneous optimization of beam transmission & centeredness. This is a novel approach for TRIUMF which has immediate application to the DRAGON experiment, where testing is primarily done.

From hereon I will be talking about steerer pairs for the sake of brevity, e.g. HEBT:XCB0 and HEBT:YCB0 will be referred to as HEBT:XY0 as displayed in figure 1.

The primary goal of this beam note is to discuss the MDEV [2] shift where the multi-objective approach was tested. Following that there is an analysis using TRANSOPTR of the HEBT & HEBT2 beamlines [3] to study the impact of the steerers on the beam envelopes and centroids.

2 Machine Development Results

MDEV shift took place on 22/09/2024. Snapshot #8137, beam properties and conditions at HEBT:

Species	7Li
Energy (keV/u)	461
Charge state	2+

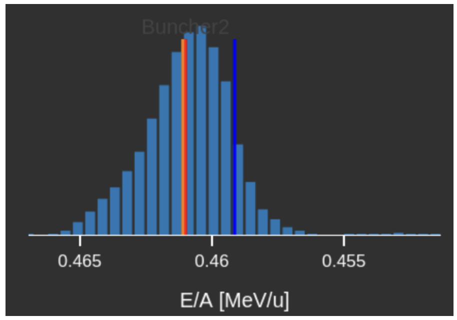

Figure 2: Energy spectrum, y axis in arbitrary units. 1) Red line is the buncher's design energy. 2) Blue line is central energy of the HEBT1 dipole magnet (reference trajectory). 3) Orange line is the centroid, computed in MCAT.

Transmission from HEBT:FC5 to HEBT2:FC4 was 84.1%.

I attempted to solve both the single and multi objective problems. Both of these problems presented various issues, but the results do provide significant insight into the difficulty of optimizing the high energy lines.

2.1 Single-Objective

There were a few runs of single objective to get beam to DRA:FC1. This proved to be much more tricky than expected. BOIS was unable to get high tranmission in the limited testing that was performed. Even though none of the tests ran to completion, the EI acquisition function typically finds high transmission very quickly. BOIS achieved $\sim$14% transmission from HEBT:FC5 to HEBT2:FC4. The second section from HEBT2:FC4 to DRA:FC1 was even more surprising, a brief detour:

The EI acquisition function was incorrectly implemented to highly favor exploration especially when finding a very good solution: the hyperparameter controlling the exploration-exploitation balance was scaled by the best solution. This means that when one gets an improperly scaled hyperparameter leaning towards exploration, but it is doubly problematic as this favors exploration even more as better solutions are found. This issue was simply fixed by implementing the standard EI function without any scaling. Another issue that was found was the implementation of boundBOIS, which bounded too strongly in HEBT.

Tuning the second section reintroduced this hyper-exploration error despite using the same β value of 10 and the corrected implementation of EI (leading to our study of envelopes and centroids in section 3):

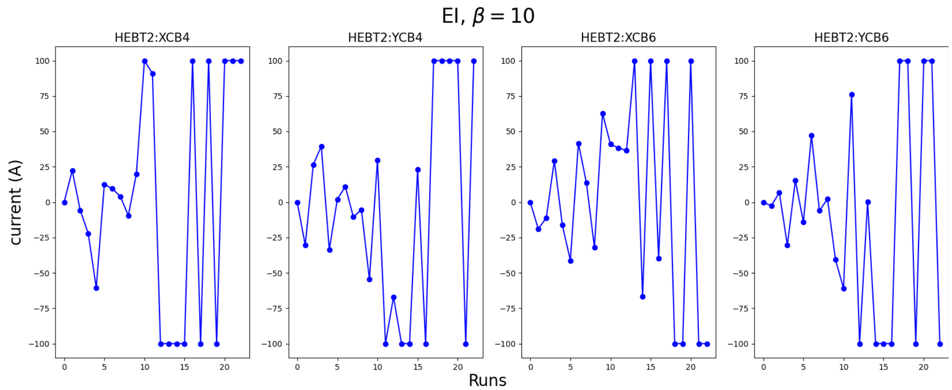

Figure 3: The explored input space for the second section.

Adjusting to $\beta = 5$ still leaned heavily towards exploration, but it had less of a tendency to explore extreme values. The best transmission BOIS was able to get from HEBT2:FC4 to DRA:FC1 was ∼25% with using UCB at $\beta = 3$. Again no run was completed however this is still a surprising result. There is a clear gap in our understanding of the HEBT/HEBT2 beamlines, motivating the need for the analysis done in section 3.

Possible explanations include issues where the beamline doesn't run as designed, such as the disabled quadrupole HEBT:Q4 [4] and the quadrupoles' power in the HEBT2 bend [5]. Besides that, the HEBT section is quite large at ~ 1500 cm. Splitting this section into several subsections would likely produce more favorable results.

2.2 Multi-Objective

With the present diagnostic options, the wobbler is a completely destructive technique, it is important to find an effective procedure which preserves the measurements of the current transmission. The procedure used for this shift is one where the current is measured while the wobbler runs for a full period, then centeredness is determined using the following formula:

$$c = \max\left(1 - (\sigma_x^2 + \sigma_y^2), -20\right), \tag{1}$$

where $\sigma_{x,y}^2$ corresponds to the variance of the x,y centroids. This formula was done to preserve the nonlinear relationship of the centeredness, e.g. a beam off axis by 1 mm is considered a well centered beam. However this approach is flawed as it is both unnecessary and improperly scaled (not scaled by the harp dimensions). Since the primary goal of the multi-objective approach is to find the Pareto front, altering the objective function used is unnecessary as all solutions along the Pareto front are explored in any case.

Another issue is that the harp (DRA:PROFCH) is a partially intercepting device consisting of parallel thin metal wires, meaning it only offers a proxy for the beam current and is prone to saturation issues. The two options are measuring the downstream Faraday cup (DRA:FCCH) or integrating over the harp. Although a third option worth considering is combining both of these measurements to get a more accurate estimate of the current.

Figure 4 shows the explored input space and the objective values over time. The current was measured by integrating over the harp. An assumption was made that current and centeredness are independent objectives. The Expected HyperVolume Improvement (EHVI) acquisition function was used, which can be considered as a generalization of EI for multiple objectives. A full explanation of the technical aspect of the multi-objective approach will be addressed in a future beam note. The current shown is comparable to the solutions found in the single objective problem, which is the severe limitation in any analysis that may be performed on this data.

An important note to make is that multi-objective is a very time consuming problem to solve, alternative approaches should be explored. One alternative is solving two separate single-objective problems instead of the multi-objective one, this approach assumes that centering the beam will not significantly impact the transmission.

The conclusion of this MDEV shift is that we need to have a better understanding of the HEBT/HEBT2

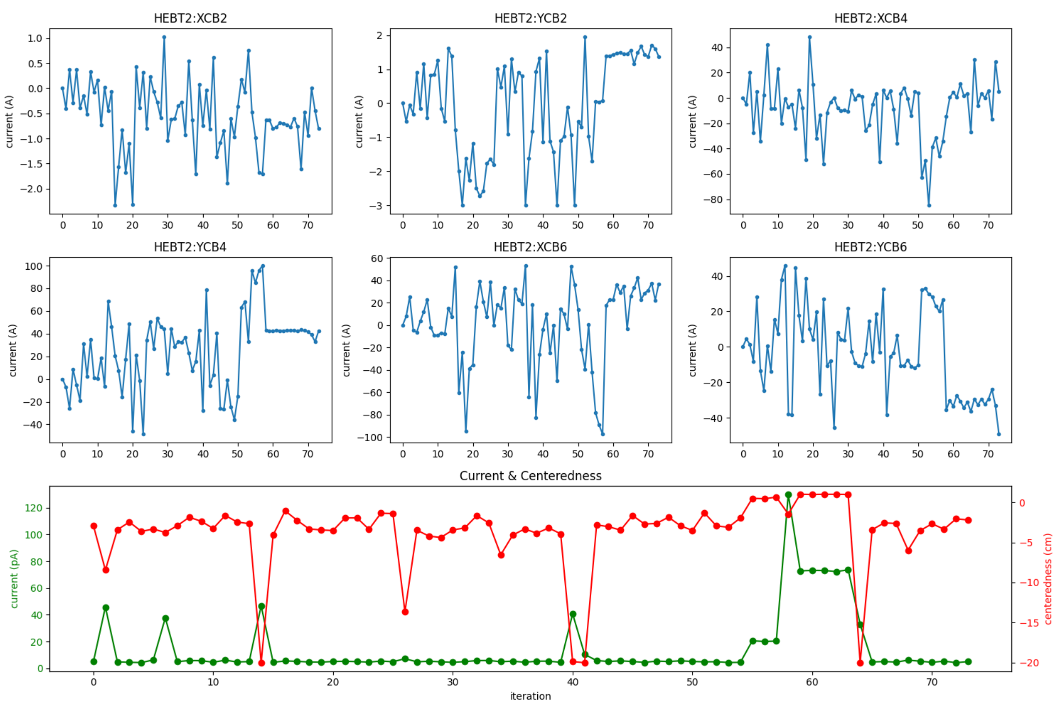

Figure 4: The explored input space and the objectives for the multi-objective problem.

beamlines, only when the single-objective problem is fully addressed can we properly approach the multi-objective problem.

3 TRANSOPTR Simulations

Following the results of the MDEV shift, we can start with analysis of TRANSOPTR simulations from the HEBT beamline to DRAGON. We pick a previous run, snapshot #6679, with beam properties and conditions at HEBT:

Species	15N
Energy (keV/u)	477
Charge state	3+

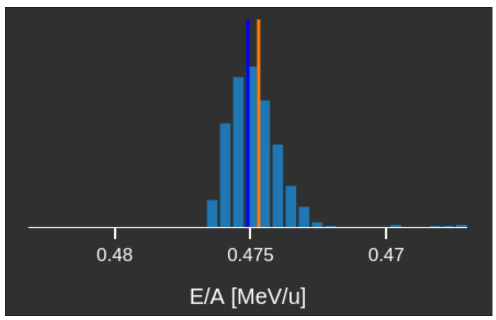

Figure 5: Energy spectrum, y axis in arbitrary units. 1) Red line is the buncher's design energy. 2) Blue line is central energy of the HEBT1 dipole magnet (reference trajectory). 3) Orange line is the centroid, computed in MCAT.

Transmission from HEBT:FC5 to HEBT2:FC4 was 87.5%, and from HEBT2:FC4 to DRA:FC1 was 90.9%. The operator tunes from this snapshot for the quadrupoles and dipoles are used for our TRANSOPTR inputs. This allows us to study how changing these steerers affect the beam envelopes and centroids.

I first ran a few simulations to observe the effect of a 1 mrad deflection in both the x and y directions using the GENSHIFT subroutine [6]. This deflection is applied to each of the steerers individually. The corresponding effects on both the beam envelopes and centroids can be observed in figure 6. The dotted grey lines approximate the apertures, this is a more extreme example where size excursions can be observed. Also note that the default DTL injection distribution is used, which has a larger emittance. The primary beam loss occurs in the long drift section from around s = 1200 cm to s = 2400 cm.

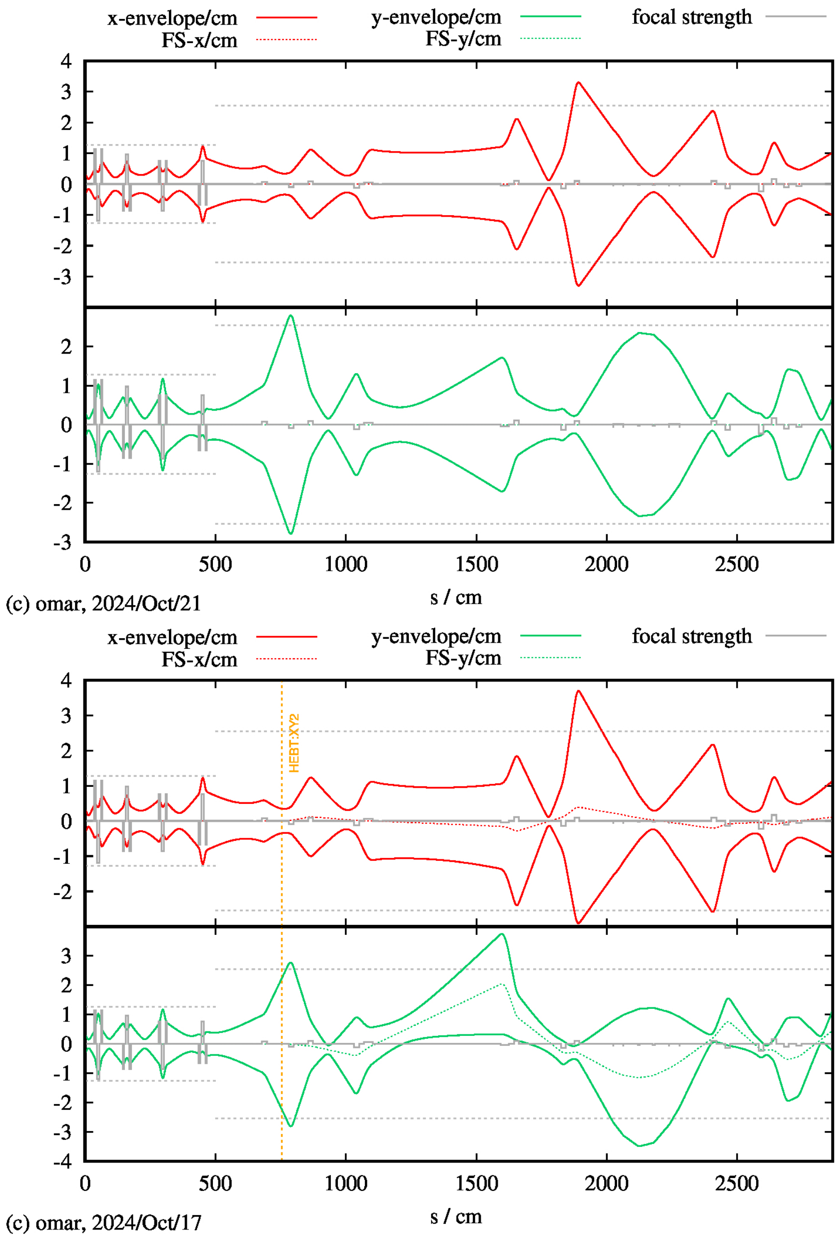

Figure 6: Top: full beam envelopes without deflections. Bottom: full beam envelopes after applying a 1 mrad deflection, applied in both x and y following the HEBT:XY2 steerer pair. FS-x/y refers to the Frenet-Serret x/y centroids respectively. TRANSOPTR also assumes that the dipoles are set to the correct rigidity.

This beamline was shown to induce chromatic couplings downstream of the HEBT2 bend in a report from 2023 [5]. A chromatic beam smears out the foci of each quadrupole due to the transverse-longitudinal couplings, which causes the emergence of a halo. This makes the beam more difficult to control through optical components. Adjusting the lattice in HEBT/HEBT2 would be required to render the bend doubly achromatic. This would simplify tuning and likely lead to better transmission into the DRAGON experiment.

Another way to observe the effects of the individual steerers on the beam centroids is by observing the extent of their deflective power, i.e. how much they can deflect the beam in both x and y. This is determined by running 100 TRANSOPTR simulations for each steerer pair, with varying x and y momentum kicks.

Figure 7 shows the deflective power of the steerer pairs. This plot depends on various factors such as the A/q and the beam energy, and it is related to the matrix elements m_{12} & m_{34}. The steerer pairs HEBT:XY2 and HEBT:XY8 have the largest deflective power in one dimension and significant impact on the other. HEBT:XY10 and HEBT:XY12 have the weakest deflective power and only in one dimension (y and x respectively).

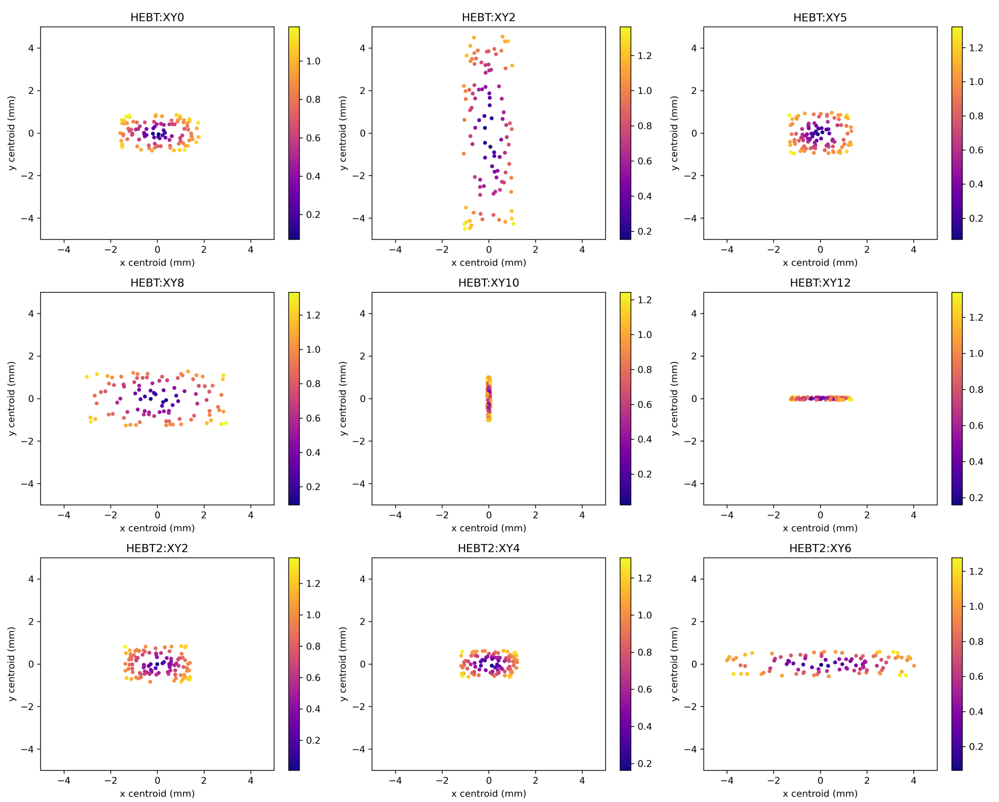

Figure 7: x vs y centroids for 100 TRANSOPTR runs for each steerer. The colour bar shows the total x and y deflections by adding them in quadrature.

4 Future work

For the future, we would like to:

- Utilize only the important steerers, as opposed to using all the available steerers.
- Break down the tuning into smaller subsections.
- Fix boundBOIS for HEBT.
- Stress test EI under different β values, especially in HEBT2.
- Further test multi-objective optimization with many optimizations, including summing up the currents from the harp and the FC.
- During a discussion with Oliver Kester & Olivier Shelbaya, Olivier brought up and suggested that we take action on HEBT:Q4 and the HEBT2 bend section quadrupoles.

5 Acknowledgements

Thanks to John Mossman & Luis Enrique Charon for assisting during MDEV. Credit to Olivier Shelbaya for assistance with the TRANSOPTR analysis, and credit to Wojtek Fedorko for his help with creating the multi-objective procedure.

6 Appendix

The full beam envelopes for each steerer pair, 1 mrad deflection in both x and y for each steerer:

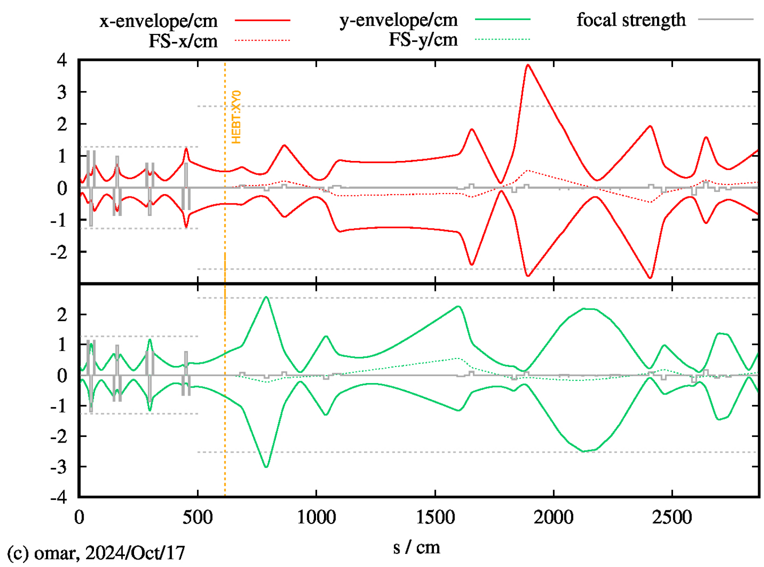

Figure 8: HEBT:XY0

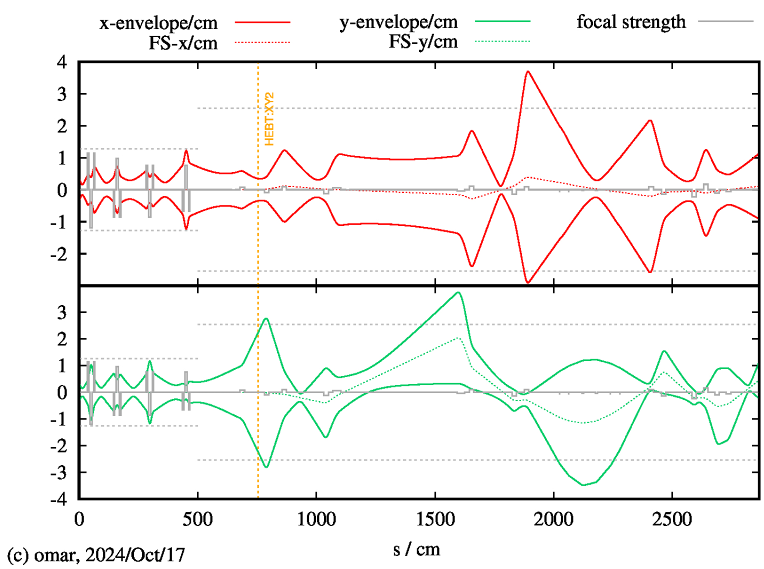

Figure 9: HEBT:XY2

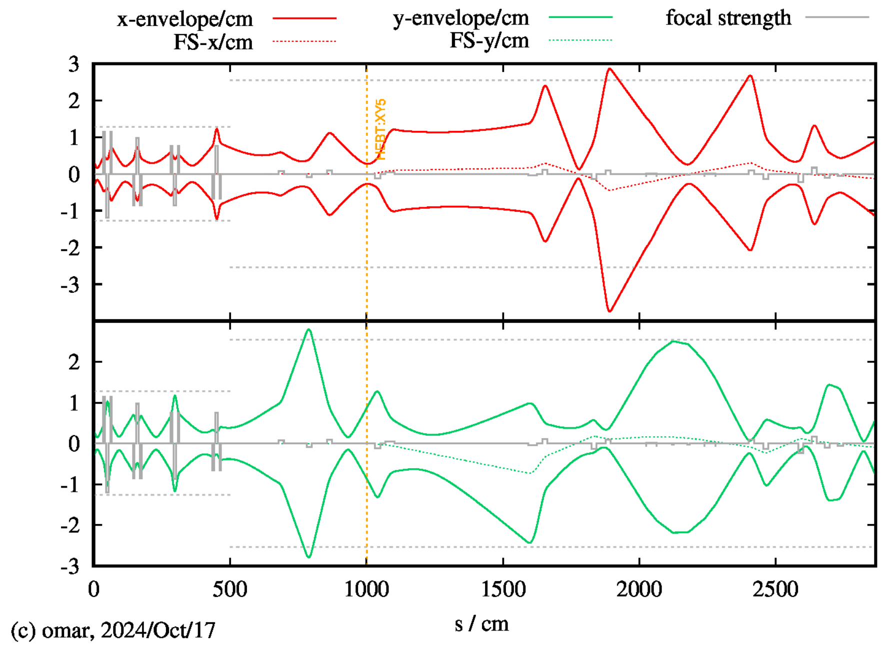

Figure 10: HEBT:XY5

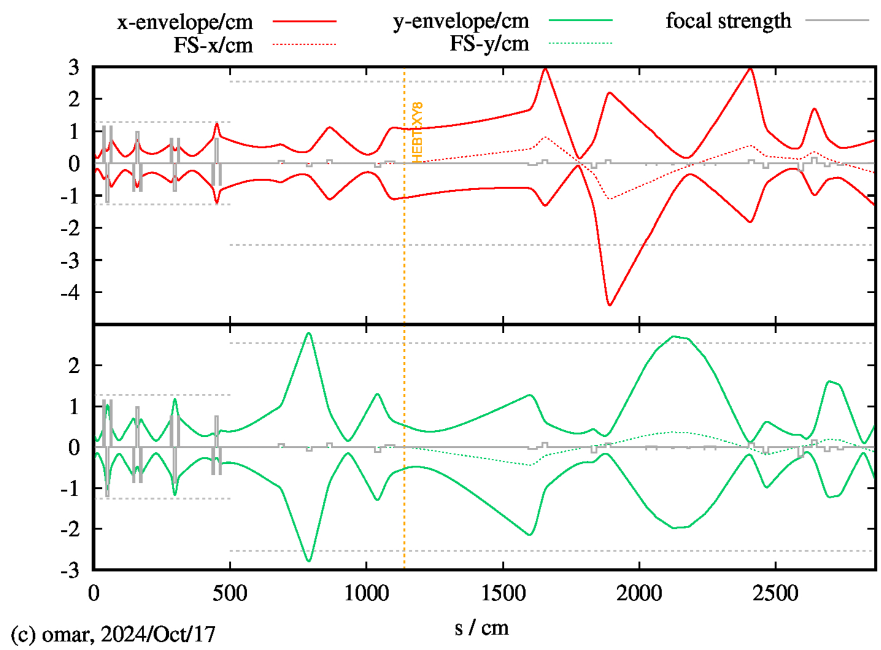

Figure 11: HEBT:XY8

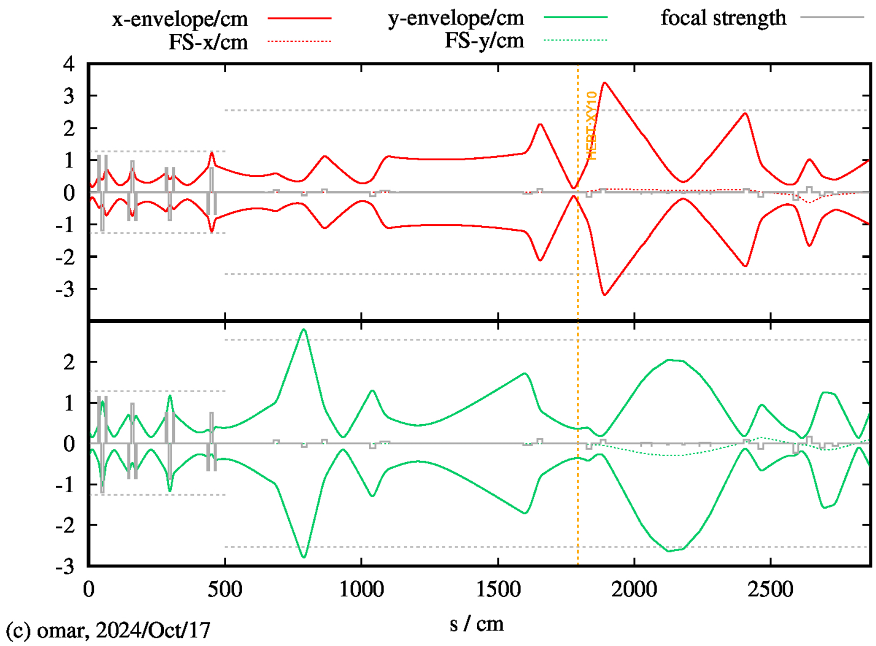

Figure 12: HEBT:XY10

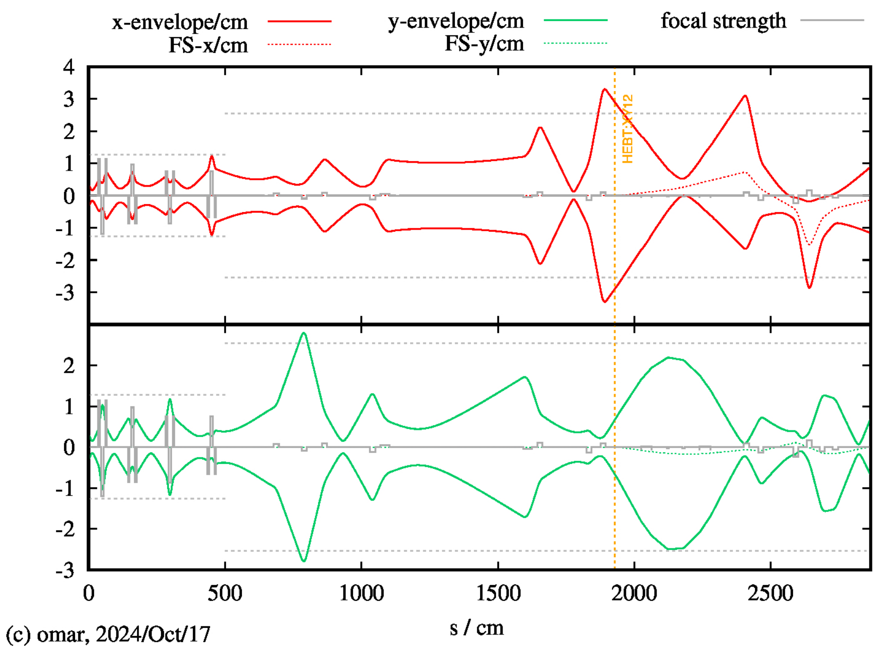

Figure 13: HEBT:XY12

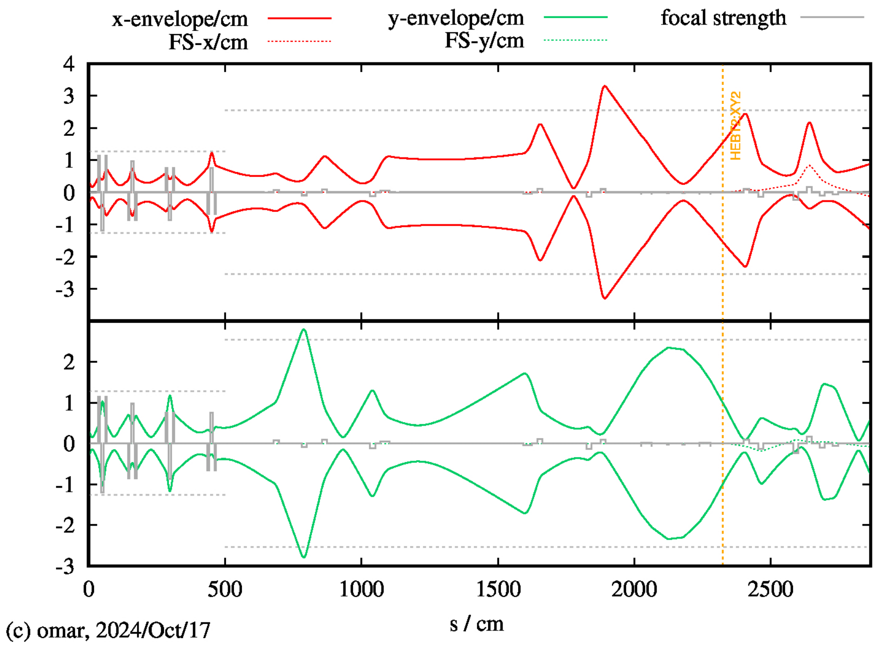

Figure 14: HEBT2:XY2

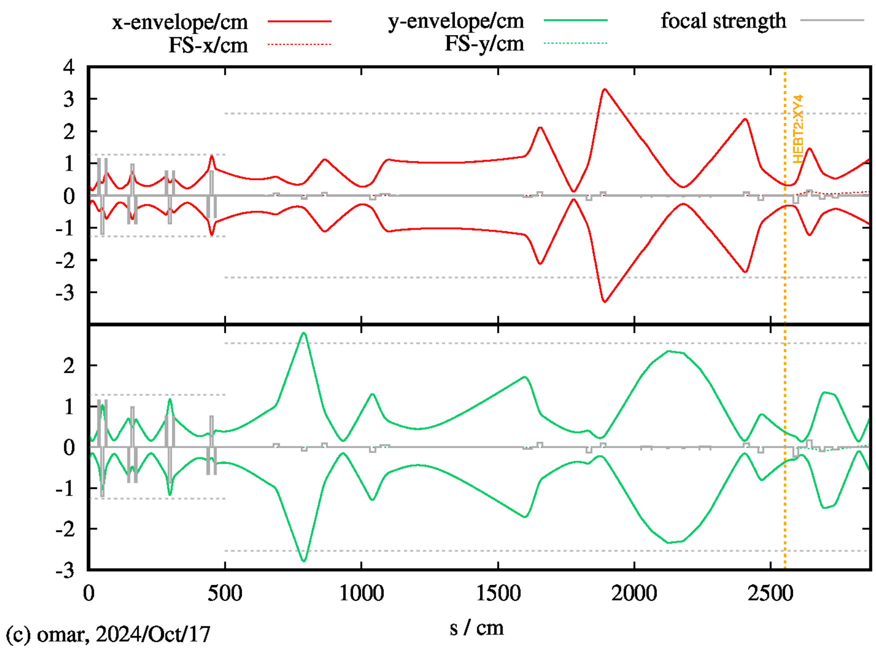

Figure 15: HEBT2:XY4

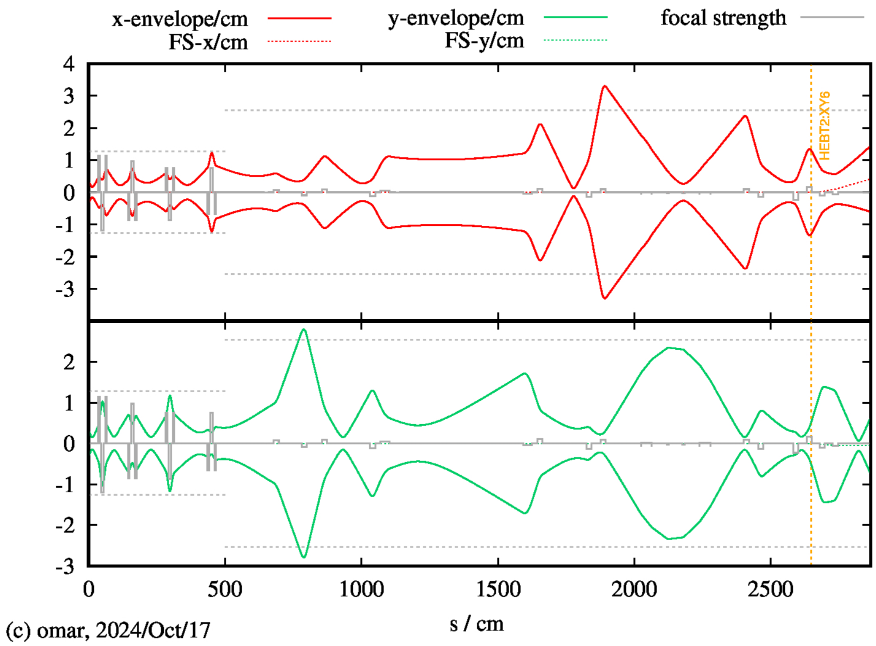

Figure 16: HEBT2:XY6

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[1] O. Hassan, E. Ghelfi, A. Katrusiak. Centering Beam into DRAGON Using the Wobbler. Technical Report TRI-BN-24-20, TRIUMF, 08 2024.

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