Beam Physics Note
TRI-BN-21-07
March 11, 2021

Status of Model Coupled Accelerator Tuning at ISAC-I

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TRIUMF

Abstract: This document is intended as an overview of the current status of development of model coupled accelerator tuning (MCAT) at ISAC. The TRANSOPTR model of the linac is briefly presented. Thanks to python wrapping of TRANSOPTR's executable, the end to end model can be used for sequential tune optimization of the accelerator, using only starting beam distributions at designated locations in the machine.

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TRANSOPTR [1, 2] (optr) now simulates OLIS-HEBT [3, 4][1,2], including RFQ [6, 7] and DTL [8]

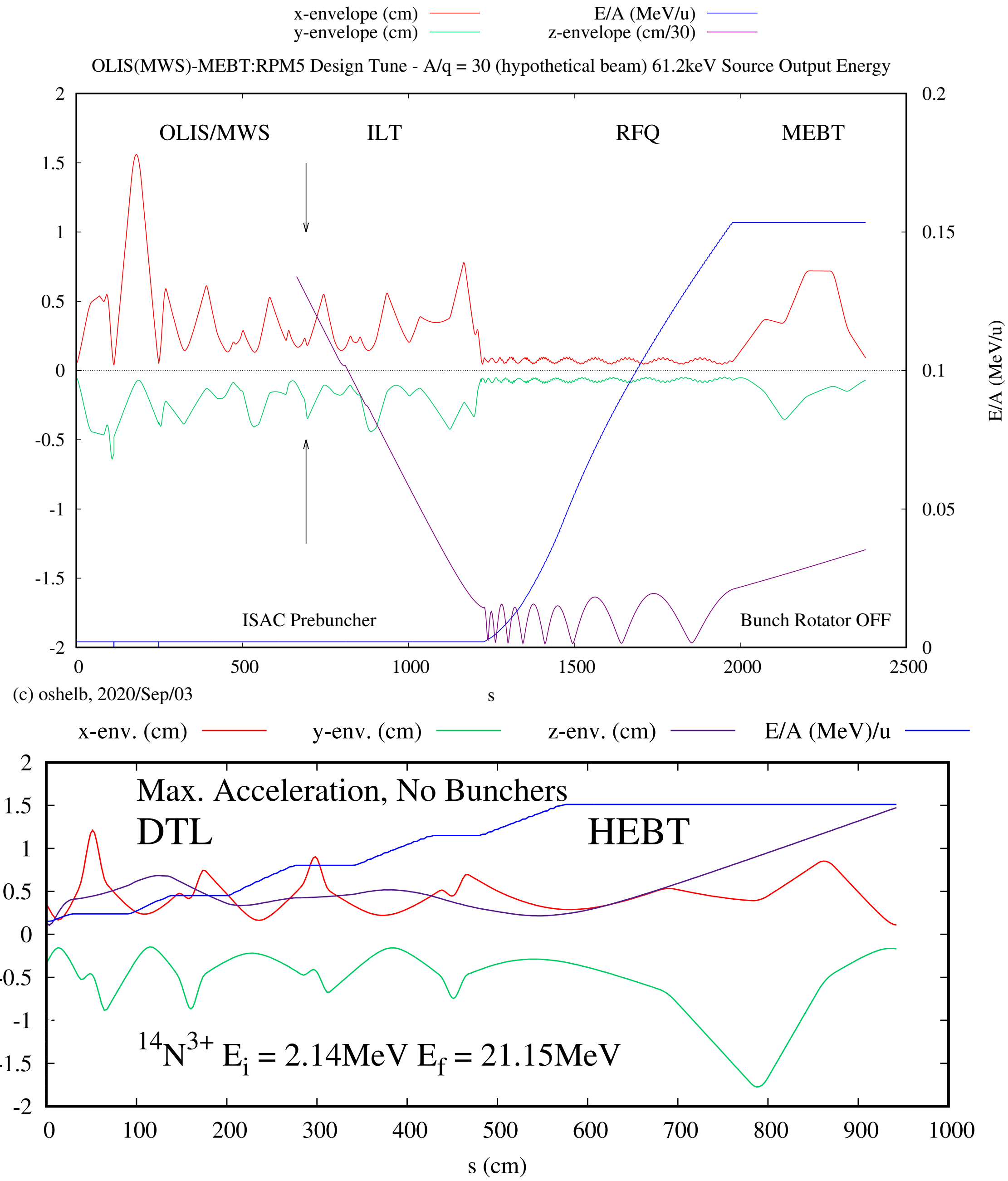


Figure 1: **Top:** OLIS (mws) to MEBT:FC5 composite 2rms envelope. **ISAC-prebunching not yet implemented, reserved for later. Can tune through RFQ without it.** **Bottom:** ISAC-DTL simulation for full E/A acceleration.

[1] These citations also contain documentation on the original tunes that were used at ISAC, mainly in the code Trace3D.

[2] Note that the ISAC-II beamlines are implemented and documented in [5]. Implementation of the SCRF in TRANSOPTR is carried out by S. Kiy, TRIUMF Beam Delivery Grp.

Aside: Tuning the ISAC-Prebuncher & RFQ On-Line

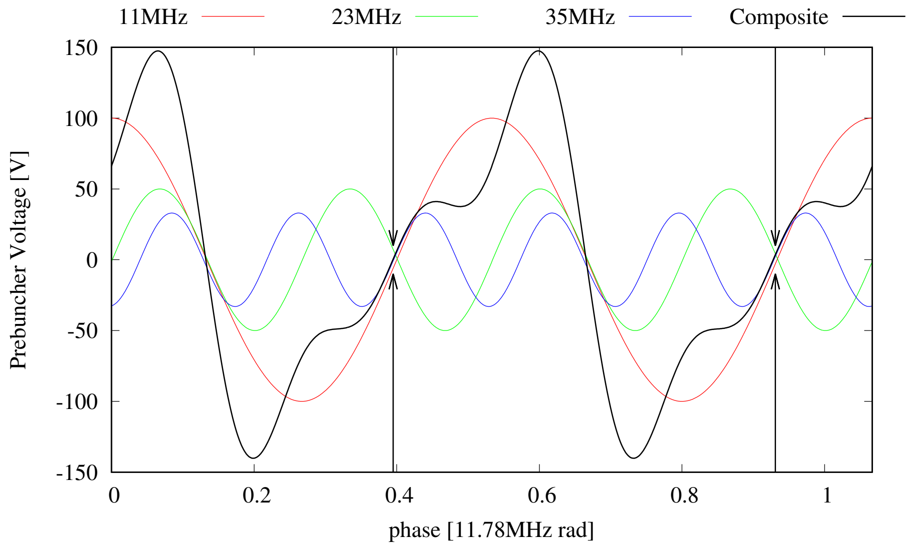


Figure 2: The prebuncher operates on an up to 400 V peak-to-peak waveform to induce a longitudinal density modulation. In practice, the OLIS to MEBT tune from Fig. 1 is first established with the prebuncher off. Once the RFQ has been configured, the composite waveform shown in the figure is tuned by operators manually for transmission. New prebuncher electronics (installed 2019) render this process more reproducible.

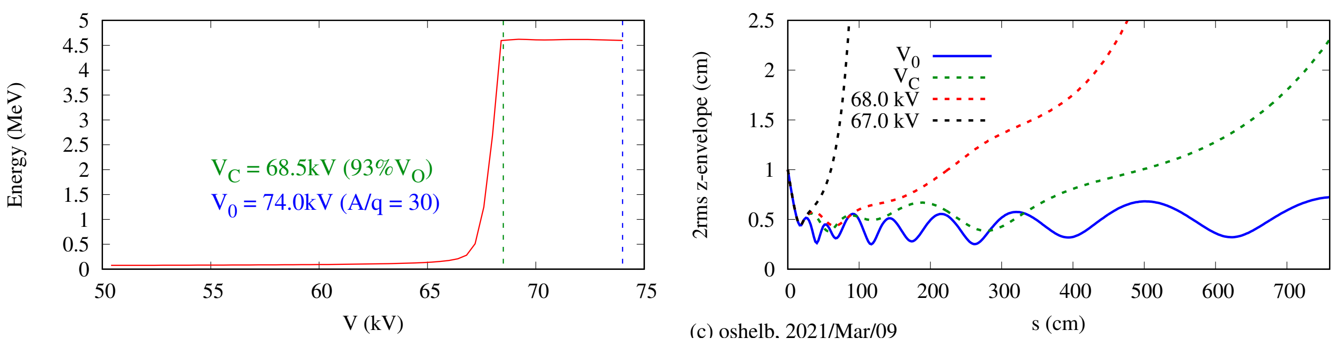


Figure 3: Operationally, the RFQ amplitude can be found using the cutoff test. The operator ramps down the RFQ voltage until transmission through the linac hits zero. The vane voltage producing this condition is divided by 0.9, producing the correct RFQ amplitude for optimum acceleration. This behavior is known from on-line tuning, has been simulated in `PARMTEQ` [9] and is also present in `TRANSOPTR`, shown above for an A/q=30 beam. On the left, the energy vs. vane voltage relationship is shown. To the right, the longitudinal (z) envelopes for the same A/q, at various voltages, demonstrate the loss of longitudinal bunch coherence with diminishing voltage, a proxy for transmission loss through the linac.

`Python` wrapping of `TRANSOPTR` allows writing of procedural tune optimization software [10].

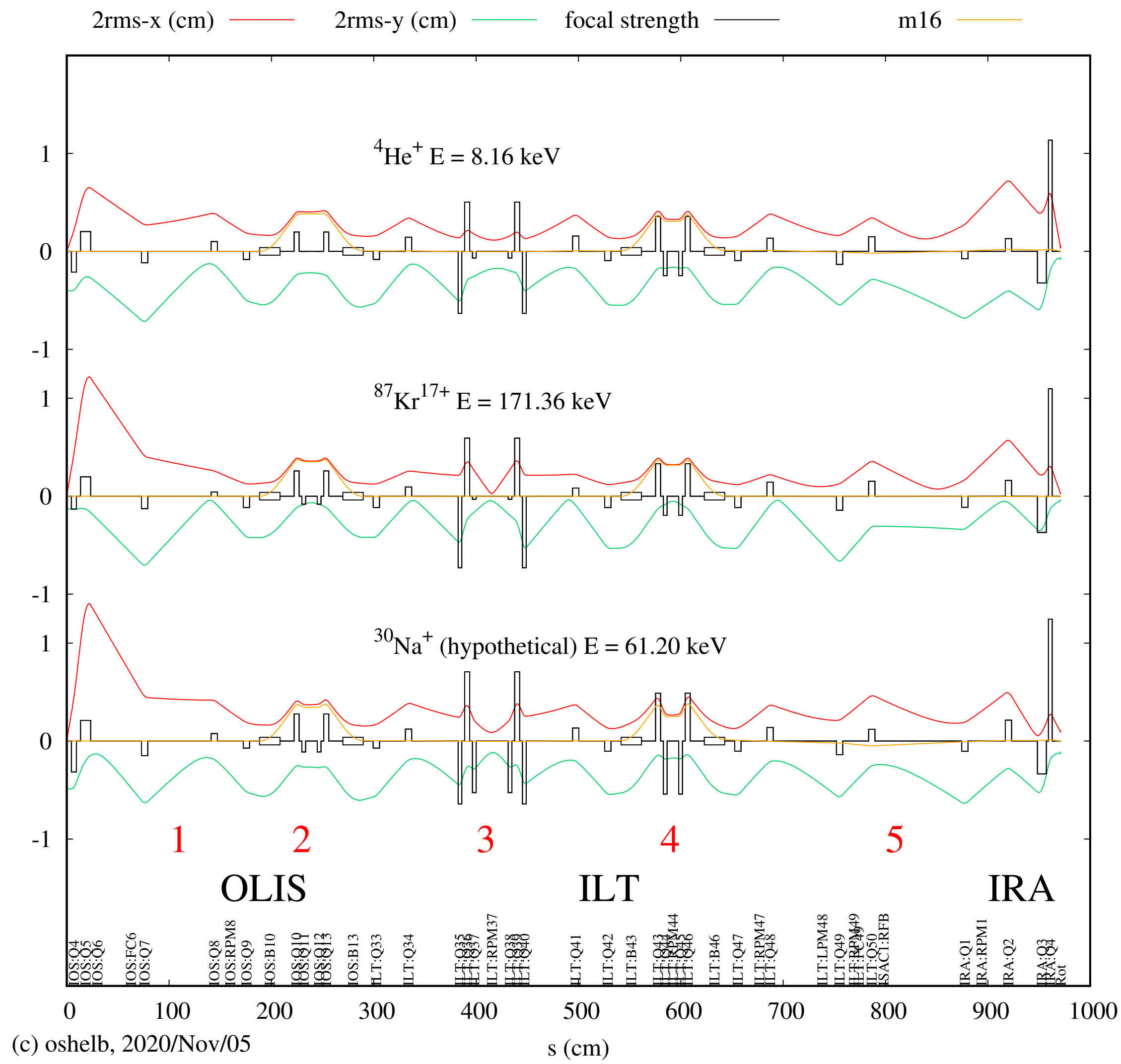


Figure 4: `MCATSequencer`, written in `python`, calls upon `TRANSOPTR` to perform long sequential tune optimizations, provided pre-coded constraints to the σ-matrix. This software is intended to demonstrate the advantage of cutting up tune optimizations into small subsections of 4-6 optimization variables, such as quadrupole voltages. Tune optimizations shown here take approximately 60 seconds start to end. Also shown in this image is the variable prebuncher spot focus at ILT:RPM37, which can be defined via `MCATSequencer` prior to tune optimization.

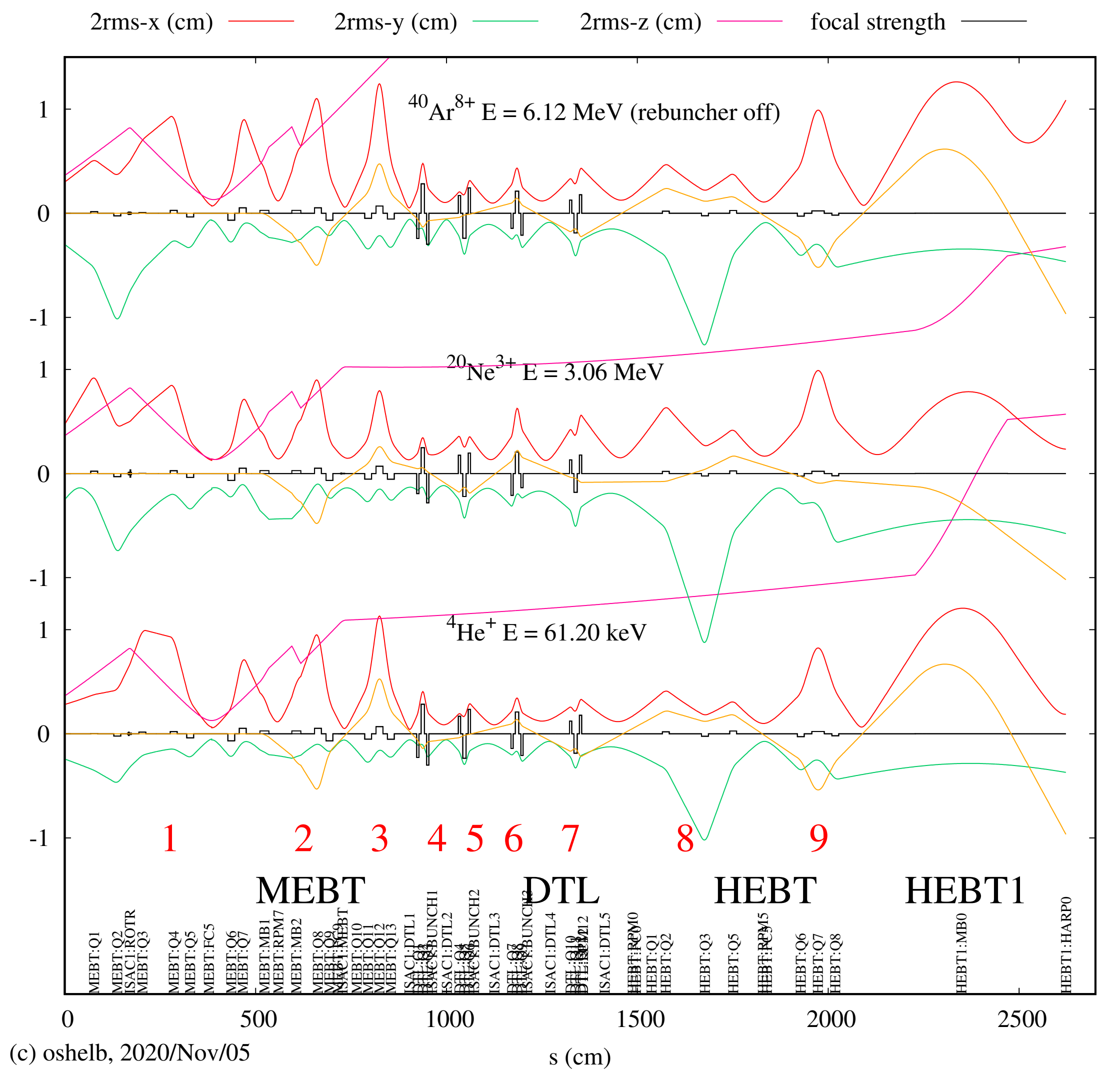


Figure 5: `MCATSequencer` can also perform tune optimizations for the MEBT-DTL-HEBT section, notably including the setting of ISAC-DTL RF cavities amplitude and phase. **These examples show drifting (E/A = 0.153 MeV/u) optimizations through the DTL, which operators establish prior to enabling RF acceleration.**

The TRANSOPTR-DTL has been calibrated with beam

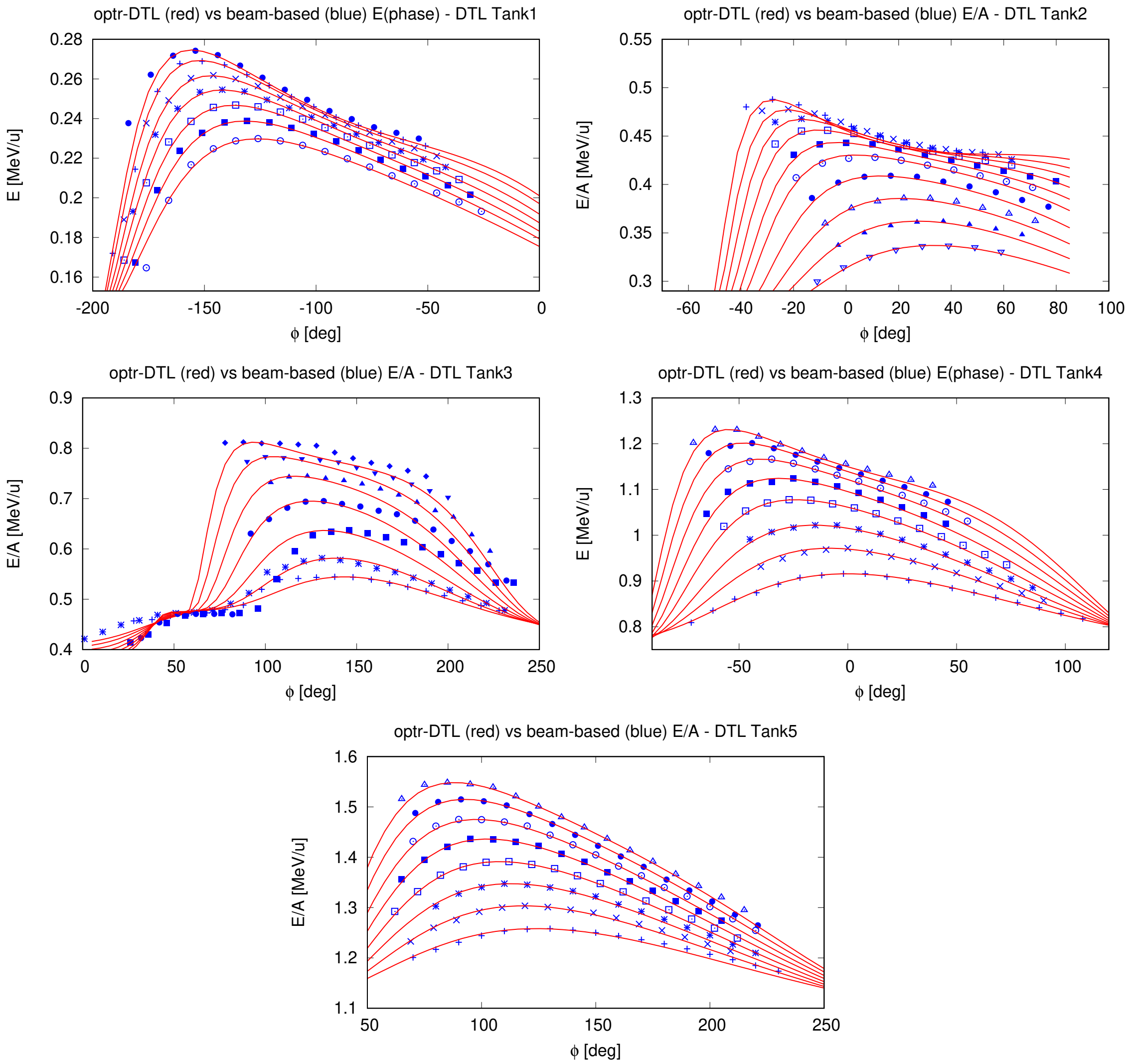


Figure 6: Beam based testing using a $^{16}O^{4+}$ beam were performed for the ISAC-DTL. These TRANSOPTR simulations of longitudinal acceleration are based upon Opera-2D static electric field maps of the ISAC-DTL [8]. As a refinement, a CST-MWS simulation of the linac is being performed in collaboration with IAP-Frankfurt. Measurement credit: T. Angus, S. Kiy, J. Lewis, S. D. Rädel and O. Shelbaya

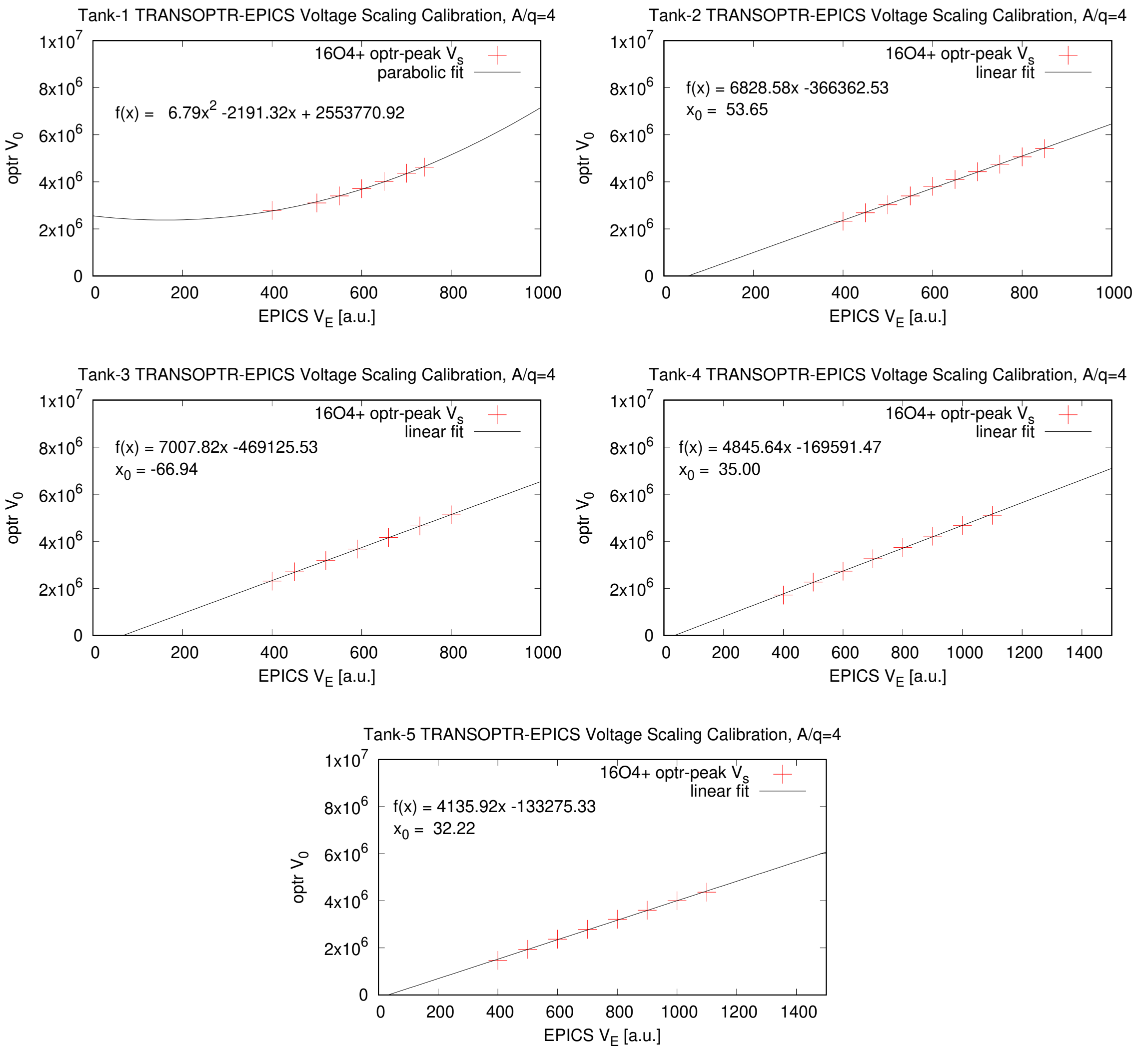
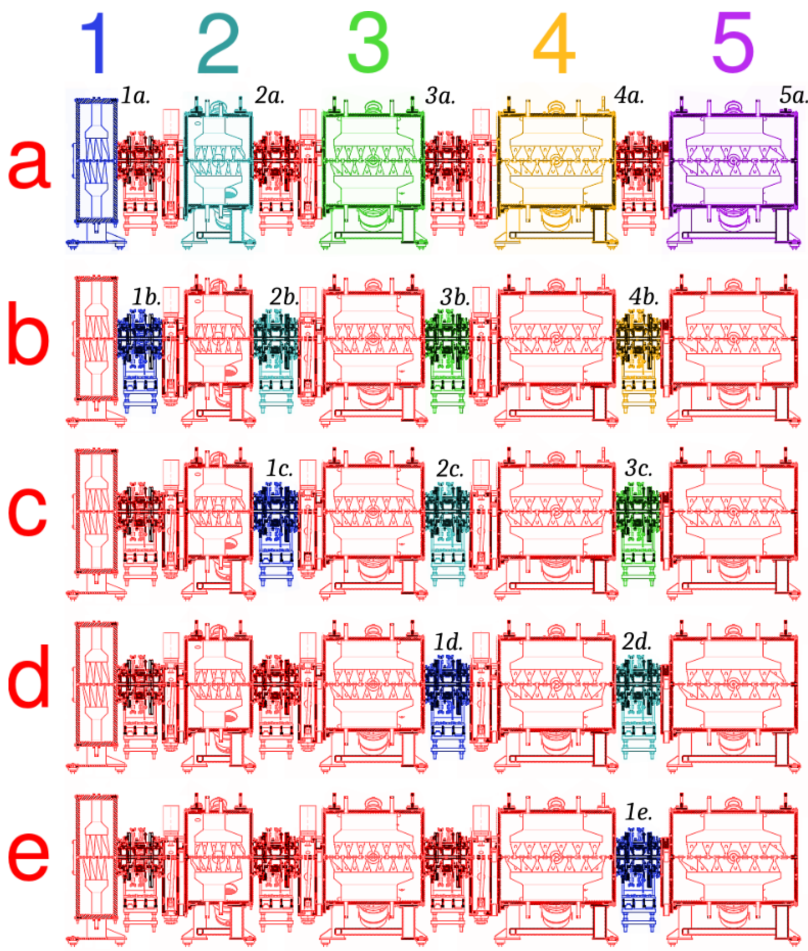


Figure 7: Calibrations obtained between EPICS RF cavity scaling factor and TRANSOPTR on-axis electric field scaling parameter, using the same $^{16}O^{4+}$ beam shown in Fig. 6. **These calibrations now mean we can perform TRANSOPTR tune optimizations that will return an RF cavity amplitude that can directly be input to the control system. As there is growing evidence of phase instabilities and a non one-to-one correspondence between RF degrees and physical degrees (400° RF $\sim$ 360° optr), phasing will have to be done manually on-line.**

Spectral Autofocusing of the ISAC-DTL



Cavity	E/A [MeV/u]	MCAT-sequence
Tank-1	0.253	*1a,1b,1c,1d,1e*
Tank-2	0.461	*1a,1b,2a,2b,2c,2d*
Tank-3	0.781	*1a,1b,2a,2b,3a,3b,3c*
Tank-4	1.150	*1a,1b,2a,2b,3a,3b,4a,4b*
Tank-5	1.530	*1a,1b,2a,2b,3a,3b,4a,4b,5a*

Figure 8: **The ISAC-DTL model can be automatically focused at any point in its output energy spectrum using `MCAT`.** Here, the ISAC-DTL autofocusing procedure that is executed by `MCATSequencer` is graphically shown. In the plot, as in life, color implies energy. DTL output E/A is achieved by sequential `MCAT` execution as shown in the table above. Each labeled step represents a `TRANSOPTR` optimization, which is enabled thanks to pre-coded constraints built into the model. Specifically, these are located in the `acc/-XML` repository (gitlab.triumf.ca/hla/acc) and are included in the `TRANSOPTR` file `sy.f` at execution. Intermediate energies are achieved by detuning the last necessary tank, with all previous tanks configured to design, again using optr's optimizer. Devices in red are untouched by `MCATSequencer`. Downstream optics are also optimized after the fact.

Modelling Summary

1. There is now an end-to-end `TRANSOPTR` model of the ISAC-I linac, starting at OLIS.
2. Development of `TRANSOPTR` has added an RFQ capability
3. The ISAC-DTL implementation in `TRANSOPTR` has had its output energy versus phase response been verified with beam
4. Development of `python` wrapped software (`MCATSequencer`) allows for start-to-end machine tune optimizations.
5. This notably includes an energy independent automatic transverse focusing procedure for the ISAC-DTL.

Quadrupole Scan Tomography

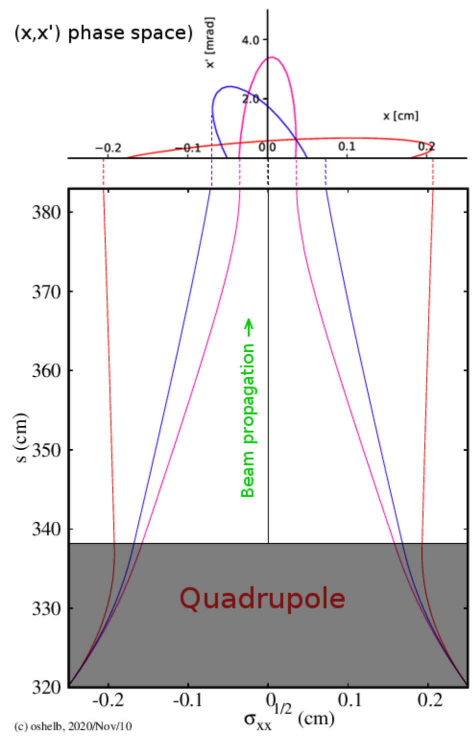


Figure 9: Scanning a quadrupole on a position monitor (RPM/LPM) allows for the use of a tomographic reconstruction method (Maximum Entropy Tomography/MENT) [11] to reconstruct the beam distribution on-line, at the entrance location of the quadrupole. This means we can carry out emittance measurements where dedicated emittance rigs are unavailable.

Quadrupole scans at OLIS

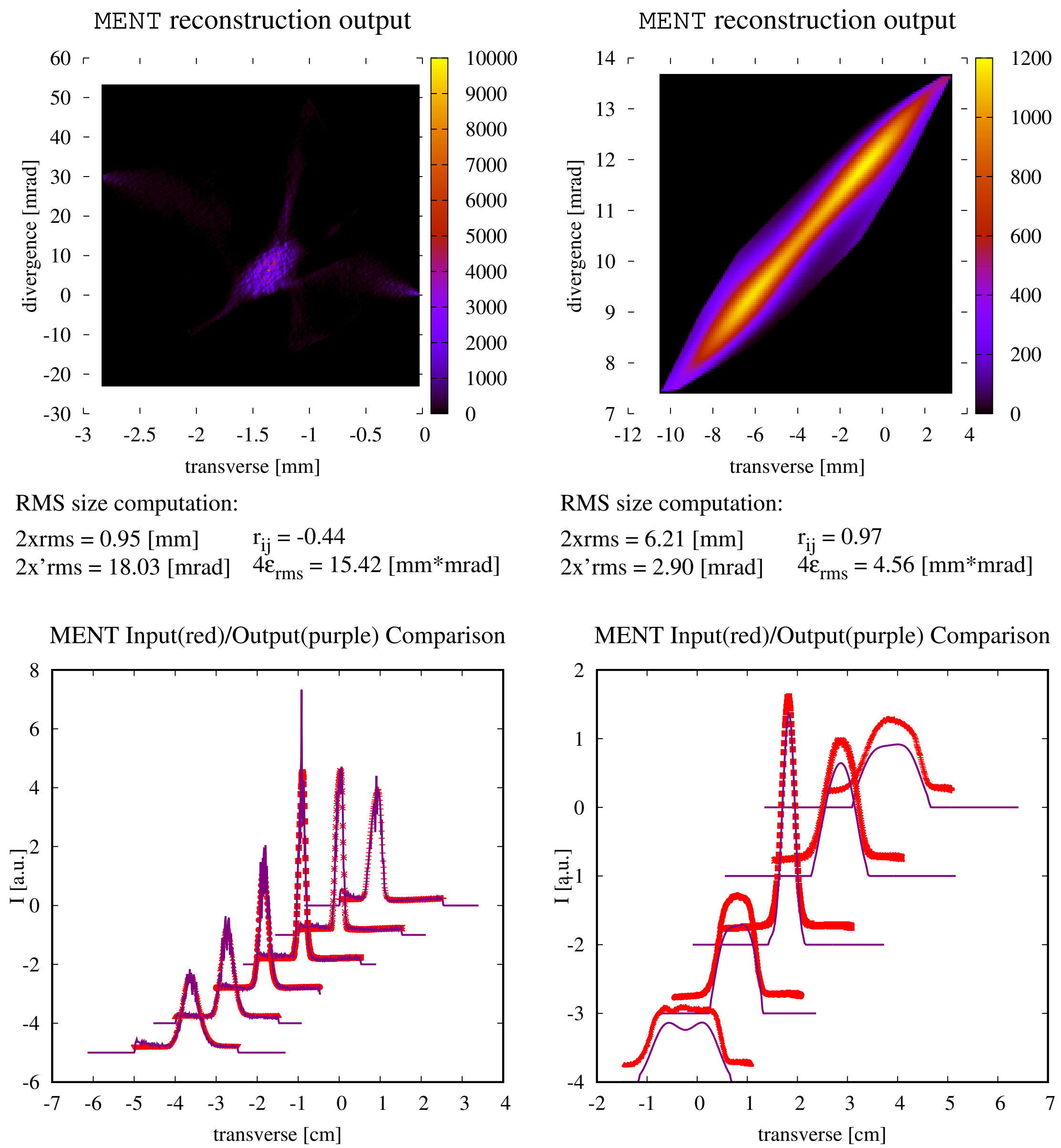


Figure 10: OLIS quadrupole scans of IOS:Q7 on IOS:RPM8, producing the x-transverse distribution at IOS:MCOL3A. **These examples have been chosen since they show two of the main challenges with such measurements. On the left, the input RPM data includes noise on either side of the peak. MENT interprets this as additional structure during the tomographic procedure, resulting in the appearance of filaments in the reconstruction. These act to broaden the 2rms distribution and contaminate the extraction of starting beam parameters. On the right, the MENT algorithm has improperly converged on the fit data, which usually implies that transmission has been lost during the quadrupole scan. When this is encountered on-line, corrective steering must be performed to ensure the entire quadrupole scan can be done with minimal centroid displacement on the RPM.**

MCAT with `TRANSOPTR` On-Line at IOS-RFQ

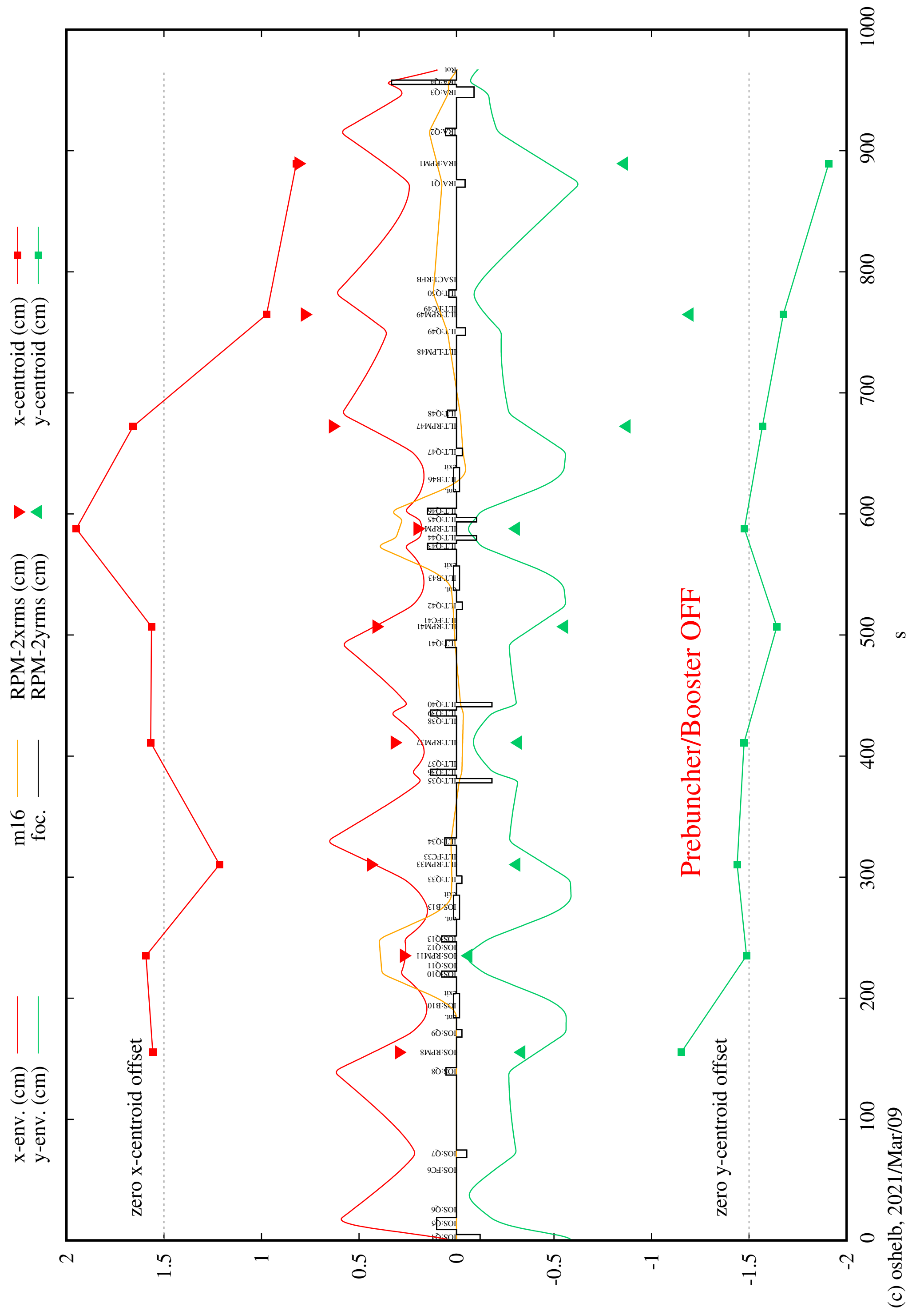


Figure 11: MCAT practice run at OLIS (MCAT#3, Nov 18, 2020). The measured on-line beam distribution at IOS:MCOL3A is fed to `MCATSequencer`, which computes the ILT tune, using the constraints upon the beam matrix that are encoded in the `acc/` database. RPMs are scanned along the line and their 2rms (x, y) sizes and beam centroid offsets are plotted. **Note increasing error with 2rms size, evidencing a mismatch condition. Also observe strong steering (centroid offsets), which was necessary to obtain high transmission ($>$90%).**

Observation 1: **Beams from OLIS do not appear to conform to our (Beam Physics Group) assumptions. Moreover, since there are no beam position monitors prior to IOS:RPM8, there are little signals to optimize other than transmission around the dipole (IOS:MB). This often leads to abnormal/anomalous configurations for the source [12]. Additionally, consistent y-steering into and out of the dipole suggests a potential dipole or beamline misalignment at OLIS.**

Observation 2: **There is a strong and persistent need for both vertical and horizontal steering out of OLIS, in particular at the locations of IOS:XCB8 and IOS:YCB9.**

Observation 3: **Configuring the spherical benders (IOS:B10, B13, ILT:B43, B46) to their theoretical setpoints generally produces below optimal transmission through the ILT line. It is frequently found that the spherical benders must be operated at 100 to 200 volts above their predicted setpoints. It is also observed that there has been no inspection of the alignment of the bender electrodes proper for several years.**

Observation 4: **There is a strong need for vertical corrective steering in the ILT section, particularly in the prebuncher line. This can be understood as a consequence of the prebuncher's aperture constraint, though it also evidences that we generally have off-axis beams by the time we exit the OLIS line.**

Observation 5: **From the location of ILT:RPM37 (prebuncher) onward, a mismatch consistently appears in the measured on-line tune. This has been seen on several MCAT beam development occasions thus far. Though some of this can be attributed to the tomographic procedure, the agreement with IOS:RPM8, RPM11 and ILT:RPM33 suggests a beam that is under control until the exit from the first achromatic bend. The optics of the ILT section should be scrutinized and inspected for things like missing skimmer electrodes, improper or poorly grounded connections, or any other abnormality. The dual triplets around the prebuncher appear to be the initiation location of this mismatch.**

Observation 6: **A further mismatch is consistently observable beyond the second achromatic bend. In particular, beam behavior on-line around quadrupoles ILT:Q47, Q48, Q49, Q50, IRA:Q1, up to IRA:RPM1 does not agree with the model. These should be scrutinized. The behavior appears distinct from the suspected issues around the prebuncher.**

Observation 7: **The above listed observations render injection in the ISAC-RFQ from a model computed tune unpracticable. Manual tuning is instead required.**

MCAT: MEBT & DTL Drift

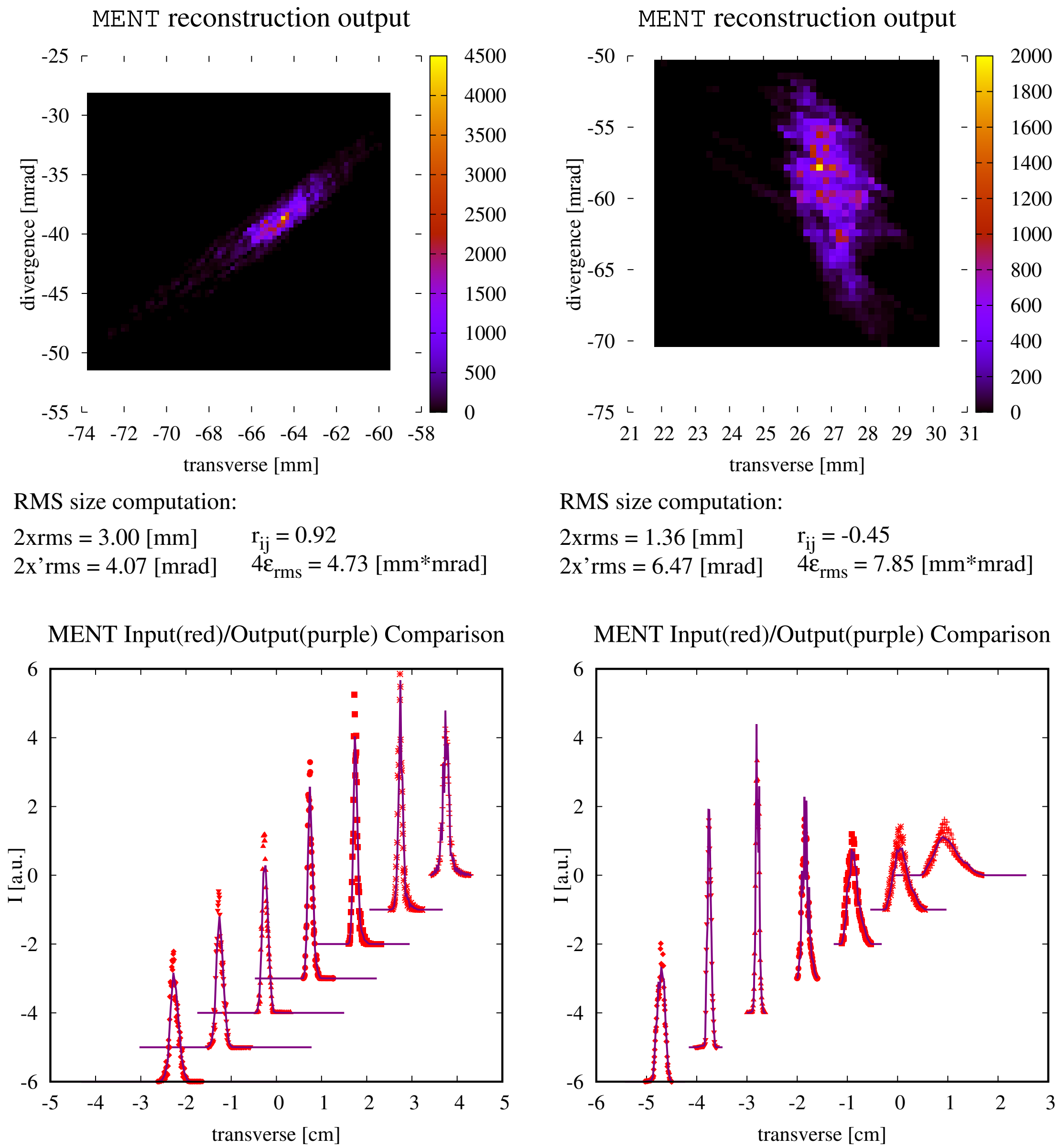


Figure 12: Quadrupole MEBT:Q5 is scanned on MEBT:RPM5. The tomographic reconstruction is configured as to produce the $\boldsymbol{\sigma}$-matrix for (x, Px) and (y, Py) at the exit of the ISAC-RFQ, at a point chosen to overlap the historic start point of `Trace3D` simulations [3].

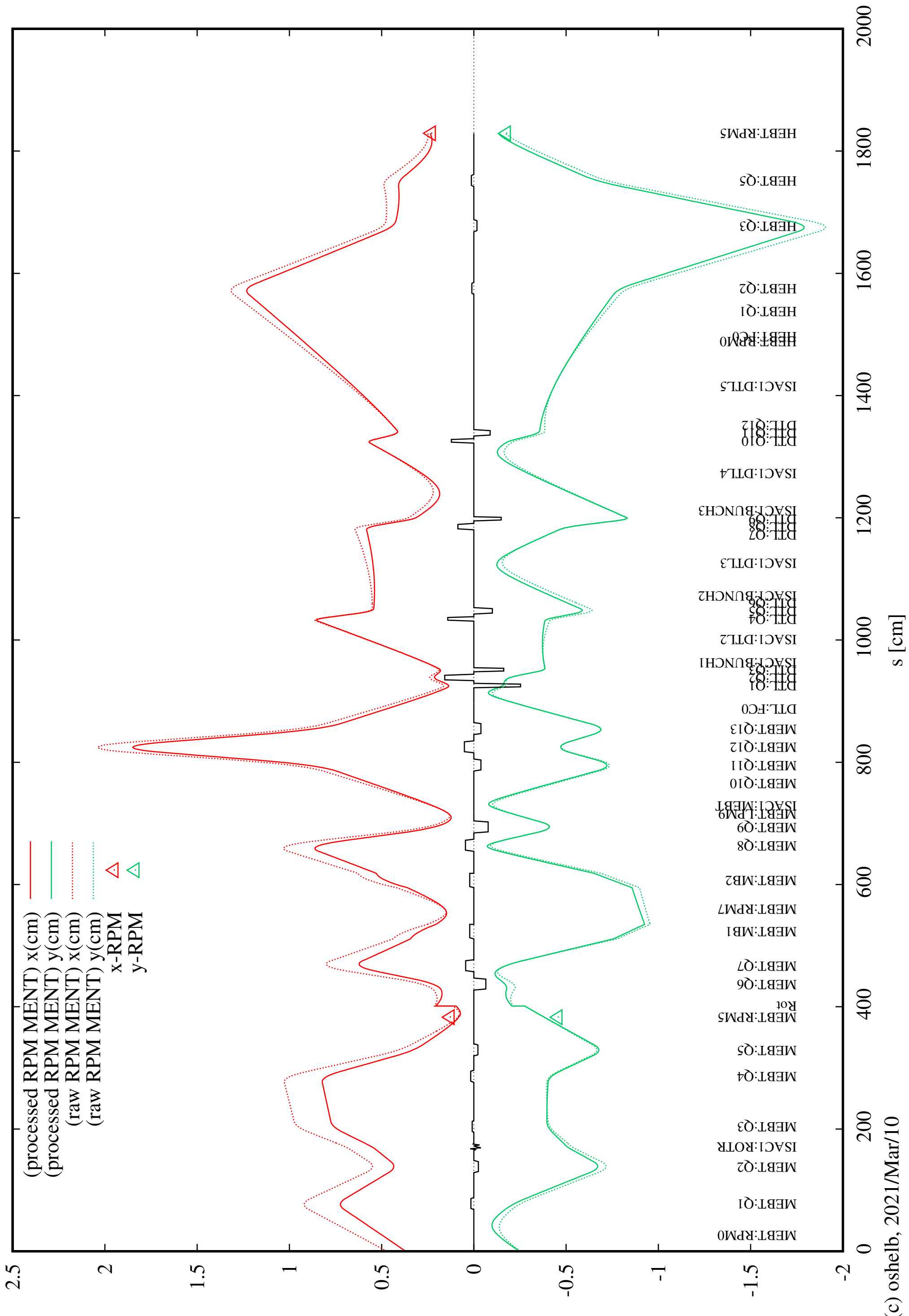


Figure 13: The reconstructed distribution from Fig. 12 was used in the `TRANSOPTR` model to simulate drifting through the DTL using an operational tune and was compared with a beam profile measurement at HEBT:RPM5. A transmission of 89% was recorded [13].

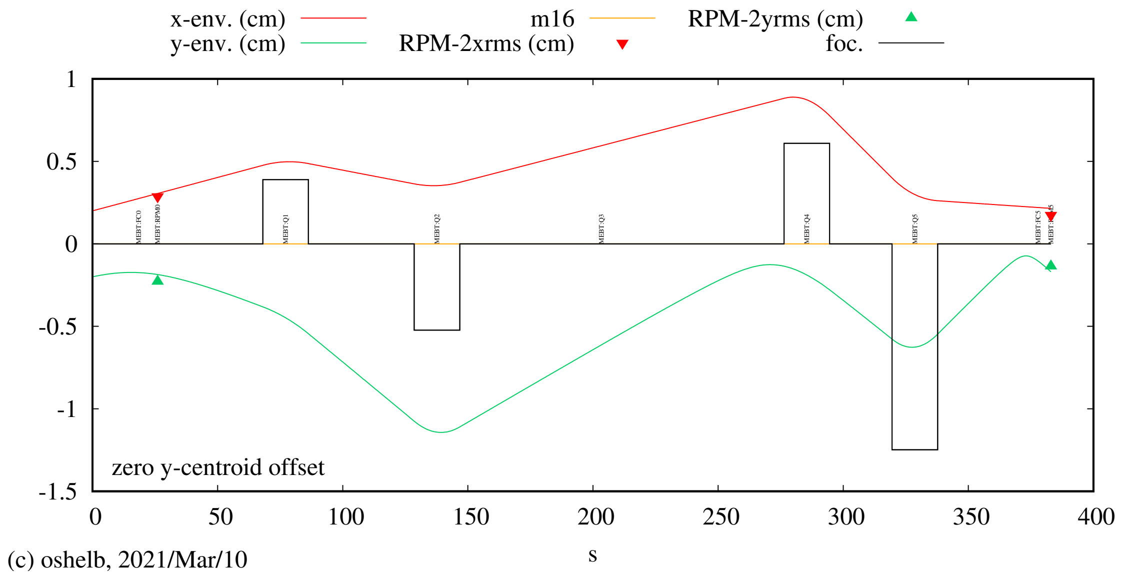


Figure 14: The reconstructed distribution from Fig. 12 was used for an `MCAT` optimization on-line, as a verification of beam control up to MEBT:RPM5.

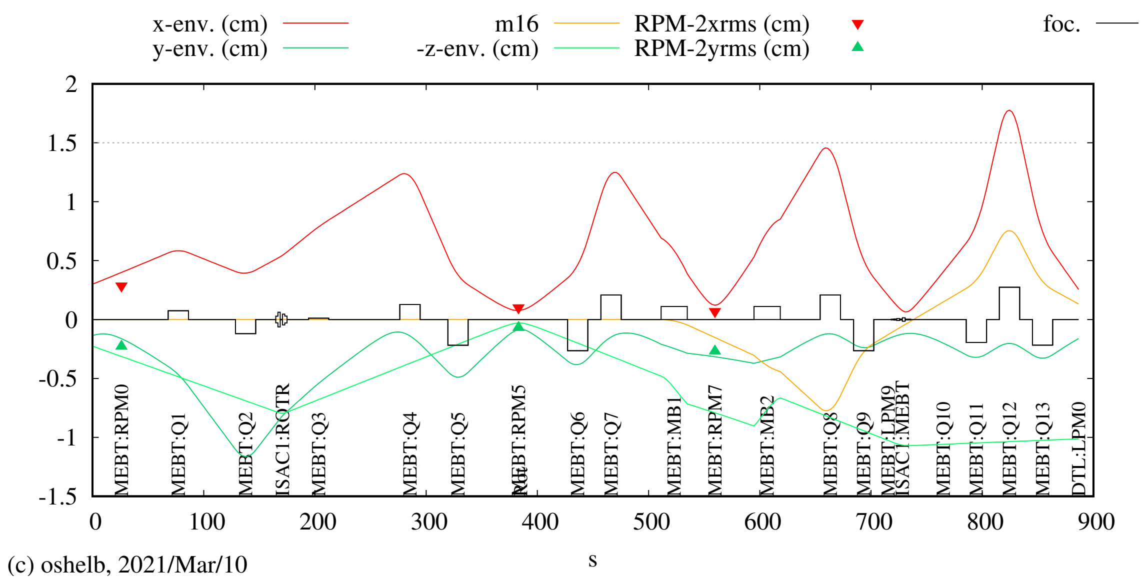


Figure 15: Using the distribution from Fig. 12, `MCAT` was used to optimize the full MEBT line, up to DTL injection. A transmission of 100% was recorded, though heavy steering intervention was required in the line. Difficulties operating LPMs and processing their data precluded beamsize extraction during this particular run, Nov. 11, 2020.

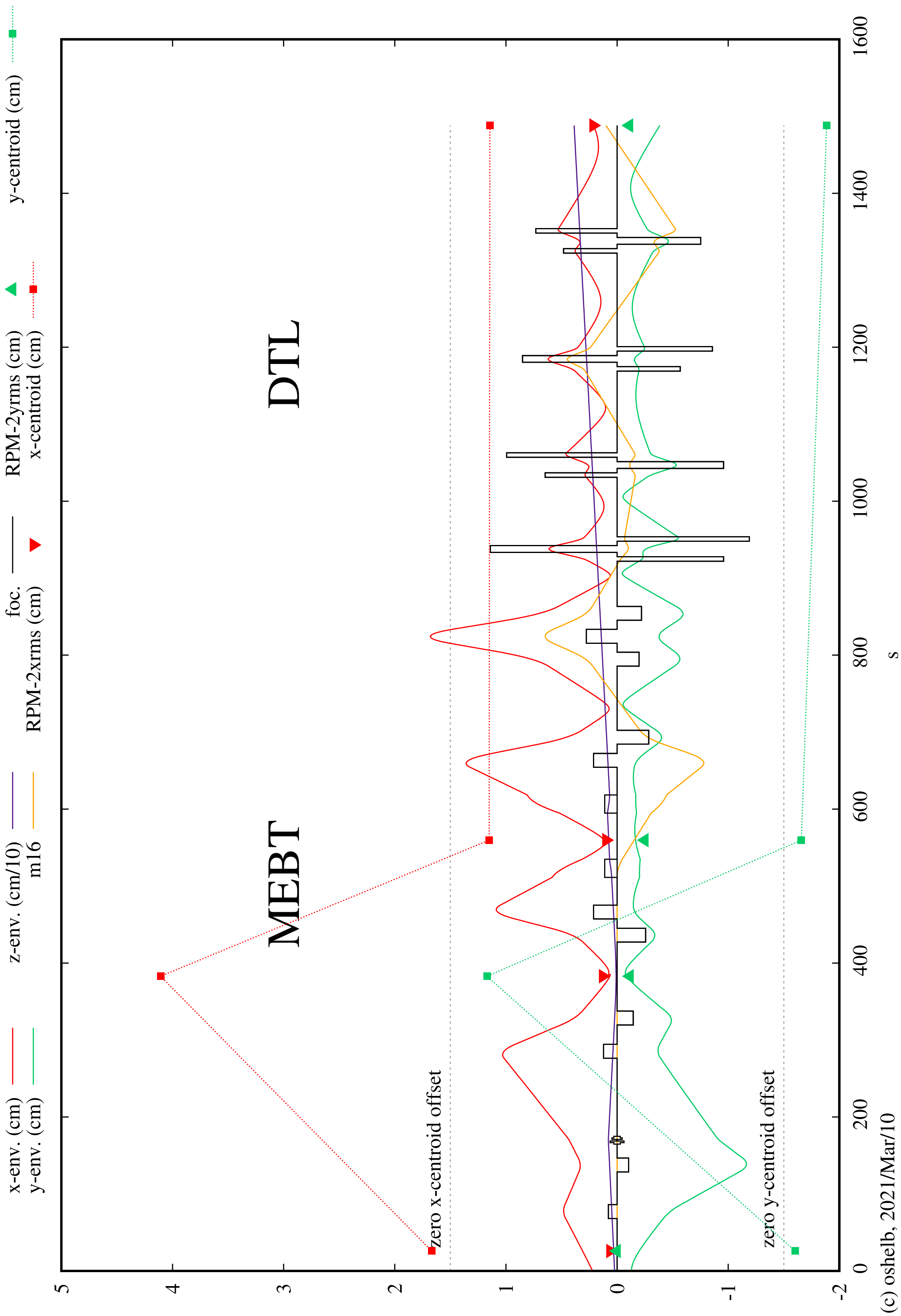


Figure 16: An on-line distribution, similar to that shown in Fig. 12, was used for a full MEBT-DTL-HEBT MCAT optimization. Recorded DTL Transmission was 60%.

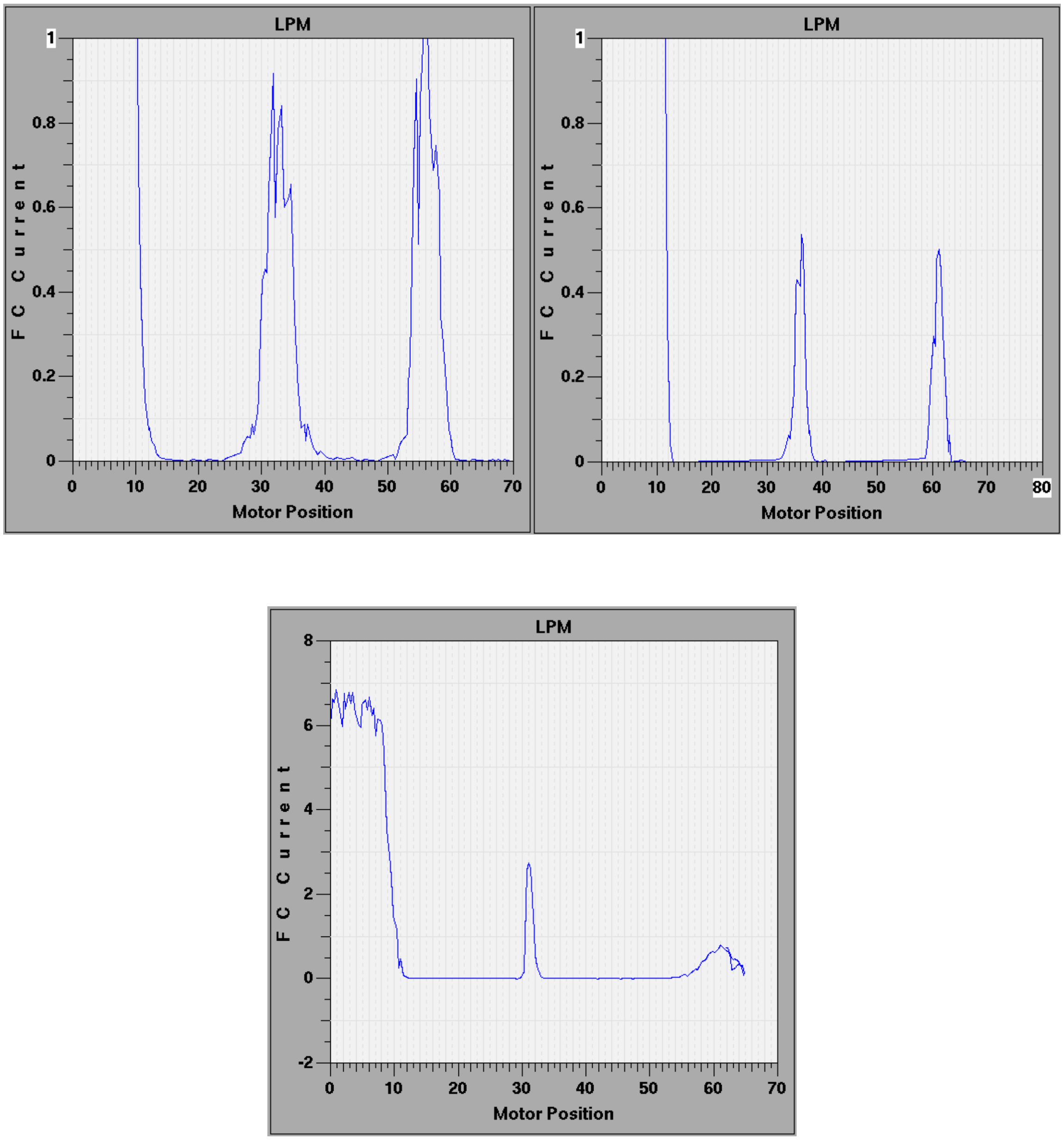


Figure 17: **Top-left:** DTL:LPM0, **Top-right:** DTL:LPM3, **Bottom:** DTL:LPM6. `MCAT`-DTL tunes computed together with the MEBT section frequently lead to profile degradation through the machine, in addition to transmission loss. Extraction of LPM signals is not straightforward from EPICS, so the traces are shown here unnormalized for qualitative inspection. Ongoing development aims to produce an HLA compatible output for LPMs, in collaboration with the Controls Group.

Steering in the MEBT Section [14] Since 2000

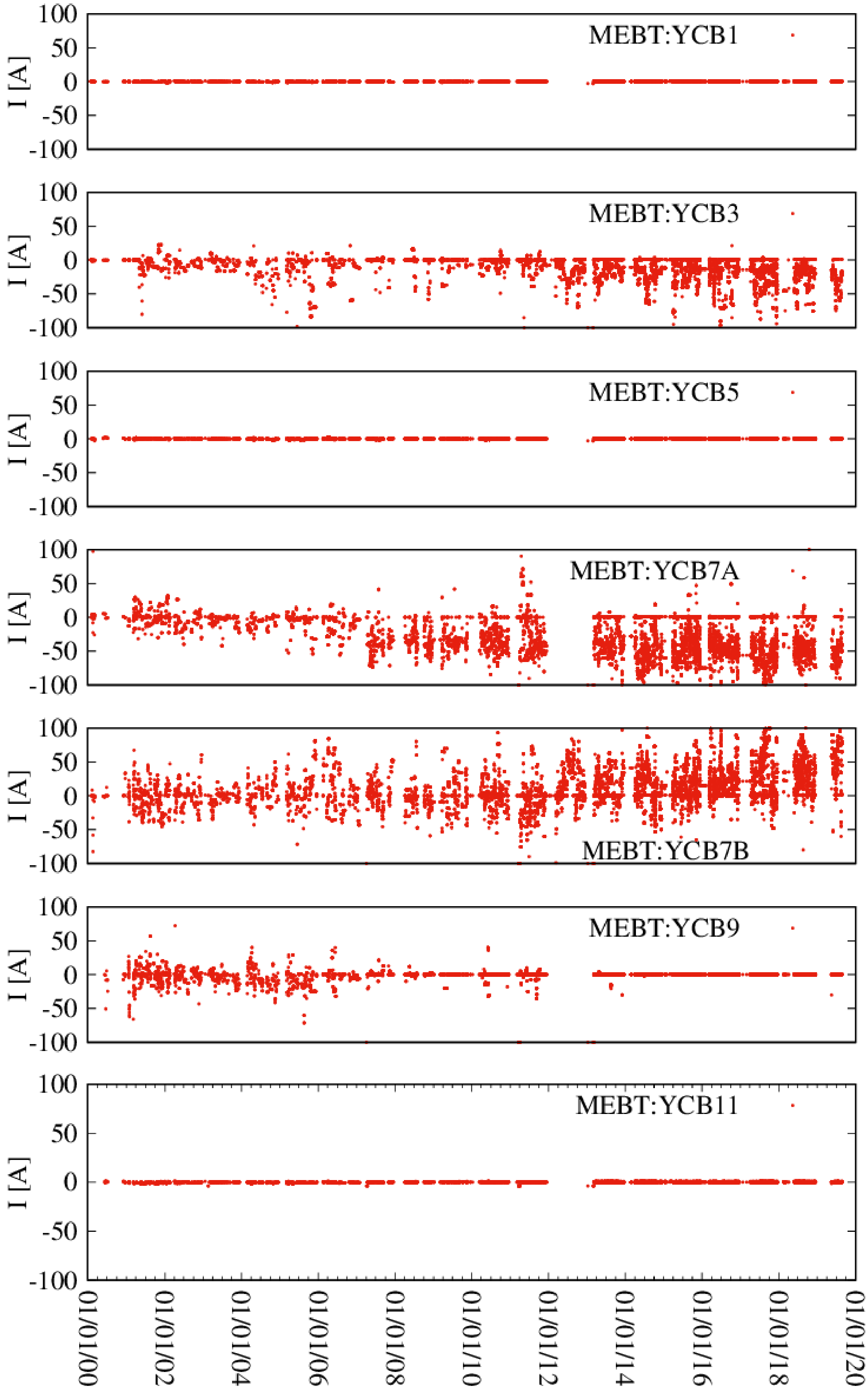


Figure 18: RIB Operations savetune extracted y-steering values, dating back to 2000.

Figure 19: Evidence of floor slab stress and potential shifting in the ISAC-I experimental hall.

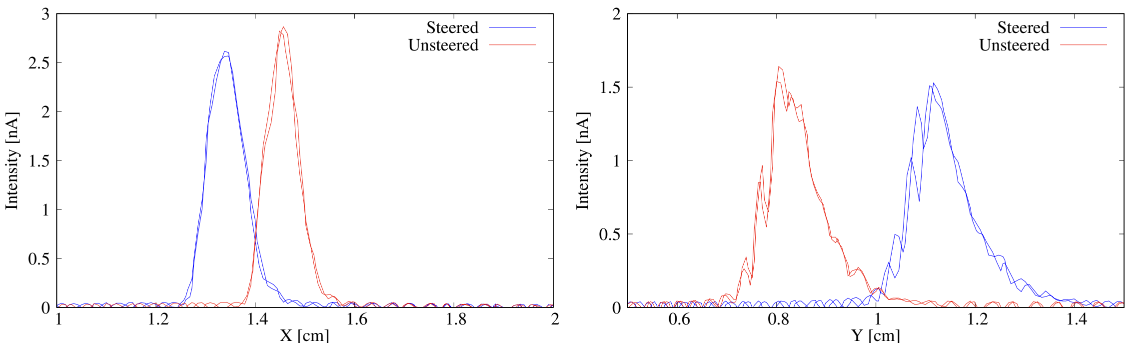


Figure 20: Removal of corrective steering from operational tunes causes a centroid shift on MEBT:RPM5 as shown.

Observation 8: **`MCAT` optimized MEBT tunes produce high transmission, after steering intervention in the line. This generally includes MEBT:YCB7A/7B set to values up to $\pm$100A, the P/S limit.**

Observation 9: **Operationally, the MEBT dipoles are not set to the beam rigidity (Bρ). Instead, they are generally set roughly 10 A above the expected current and both are manually tuned by operators. This manual tuning also involves the use of YCB7A/7B.**

Observation 10: **`MCAT` computed MEBT-DTL-HEBT tunes suffer transmission loss through the (unpowered, E/A = 0.153 MeV/u) DTL, with usually no more than 50% measurable on HEBT:FC5.**

Observation 11: **`MCAT` computed DTL-HEBT drifting tunes which make use of previously saved operational values for MEBT were found to produce between 89 to 92% transmission through the DTL (from MEBT:FC9 to HEBT:FC5) during tests in summer 2020.**

Observation 12: **Operational MEBT tunes make use of manually defined Q1 to Q5 values [15].**

Beam Development Summary

1. Familiarity was gained with using quadrupole scan tomography on-line
2. Extracted tomographic distributions fed TRANSOPTR simulations and optimizations of both the OLIS-RFQ-MEBT, in addition to MEBT-DTL-HEBT sections.
3. Only drifting DTL tunes were performed to investigate transverse envelope issues through DTL.
4. Attempts to compute full MCAT tunes through both ILT and MEBT-DTL produce transmission issues which appear to arise from disagreement between the TRANSOPTR model and the on-line optics.
5. Considerable steering in OLIS, ILT and MEBT appear to suggest beamline axis alignment issues.
6. DTL Transmissions of roughly 60% were obtained for MCAT tunes for MEBT-DTL-HEBT without DTL acceleration and beam profiles in the linac were found to diverge from the expected behavior.
7. Consistent and heavy y-steering around the MEBT dipoles (MB1 and MB2), together with manual tuning of the dipoles away from the beam rigidity value appears to suggest a dipole misalignment issue in MEBT.
8. Obtention of a high DTL transmission ($>$90%) using an operational MEBT tune together with an MCAT computed DTL tune further suggests that on-line detuning of the section compensates for unwanted/unexpected optical effects in MEBT.

Modelling Summary (Repeated)

1. There is now an end-to-end TRANSOPTR model of the ISAC-I linac, starting at OLIS.
2. Development of TRANSOPTR has added an RFQ capability
3. The ISAC-DTL implementation in TRANSOPTR has had its output energy versus phase response been verified with beam
4. Development of `python` wrapped software (`MCATSequencer`) allows for start-to-end machine tune optimizations.
5. This notably includes an energy independent automatic transverse focusing procedure for the ISAC-DTL.

References

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