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TRANSOPTR Implementation of ISAC-II

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Abstract: The linear envelope code TRANSOPTR now includes, via the High-Level Applications (HLA) /acc database, the ISAC-II Superconducting-High Energy Beam Transport (SEBT) sections. This notably includes transport optics to the TIGRESS, EMMA and IRIS experiments, now available on the TRIUMF-HLA interface. Further, an on-axis electric field map for the DSB Buncher, computed with Opera2D for TRANSOPTR use, is presented. The source material for the implementation and its details are presented, in addition to a benchmark comparison with the code trace3D, used up to this point to perform the envelope optics computations used to produce ISAC-II tunes.

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1 Introduction and Background

The ISAC-II facility, shown in Figure 1, provides TRIUMF users with the highest energy postaccelerated radioisotope beams, following acceleration in the Superconducting Linear accelerator (SCL). As such, the facility houses several key nuclear physics experiments including nuclear spectroscopy, high-precision mass measurements and the investigation of halo nuclei. For an effective and successful beam delivery, heavy ion beams accelerated to energies beyond 10 AMeV must meet the requirements demanded by these precision experiments. Of particular concern during experiment beamtime is the establishment of a well-defined transverse focus into a variety of experimental apparatus, in addition to precise beam energies and energy stability.

The constantly changing requested beam energies, compositions, intensities, mass-to-charge ratios and transverse focussing requirements render ISAC-II high energy beam tuning notoriously time consuming and intensive, particularly from the operational standpoint. Further challenges are encountered when one considers the inherent complexity of the SCL, which may require periodic retuning due to unforseen events. Notable example include cryogenic cavity instabilities which require cavity re-phasing, or target/ion-source issues which may shift isotope contamination ratios. In both these examples, it may be necessary to change ISAC-II beam energy, or even isotope mass-to-charge ratio to meet strict experimental beam property requirements.

Much as for the ISAC-I HEBT system, up until the present, tunes have been computed and analyzed with the optics code `Trace-3D`, in which segments of the transport optics are sequentially and individually simulated. Beam transport element setpoints representing `Trace-3D` computed values are then recorded on a set of spreadsheets by the Beam Physics group and provided to RIB Operations, which then manually phases the SCL. During SCL setup in preparation for delivery, depending upon the requested beam energy, operators must then periodically and manually adjust the transport optics in the SEBT sections, as the accelerator is brought up to the requisite state. As such, delivery to ISAC-II is reserved for the final stages of operator training, rendering the pool of fully trained individuals small. Thus, ISAC-II beam delivery is generally time consuming, particularly when responding to unforseen challenges.

This note will discuss the implementation of the SEBT transport optics and RF to `TRANSOPTR` in addition to a benchmark comparison to the aforementioned `Trace-3D` implementation. In addition, the `Opera2D` computed on-axis electric field mapping for the DSB Buncher will be presented. As was the case for both MEBT and HEBT implementations [1] [2], the comparison made herein is not intended as a test or commentary on either model's performance, but rather as a demonstration of the ability of the present `TRANSOPTR` implementation to reproduce and ultimately supplant the previous model for use in the computation and analysis of ISAC high energy tunes.

2 High-Level Application Implementation

Under the TRIUMF High-Level Applications (HLA) framework [3], the traditional `TRANSOPTR` element sequence stack `sy.f` is automatically generated through a python wrapper routine, which reads in the requisite sequence of elements from a central database. This database, known as the `/acc` database, formatted in `xml`, contains a sequential ordering of all transport, diagnostic and accelerating elements present along a given beamline segment. Within the database, groups of elements are broken down into sequences, which consist of the smallest possible number of sequential elements which define a unique path.

While the sequence `xml` files contain the locations of all elements present in the beamline, including steering elements, beam diagnostics and aperture constrictions, for the purposes of the present note, these will be omitted from discussion, in favor of beamline optical elements such as quadrupoles and RF cavities. The rationale for doing so is that both diagnostics and steerers are not used in TRANSOPTR, which assumes an on-axis beam at all times and locations along the beampath. This is not to say that diagnostic locations are unimportant. On the contrary, knowing their precise location is crucial to predict measured beam envelope behavior. However, given that they do not affect the envelope TRANSOPTR, in the present note their presence is implicitely acknowledged but not explicitely discussed. Consequently, the focus will be placed on ion-optical elements such as quadrupoles, bending magnets and RF cavities.

3 ISAC-II Sequences and Source Material

All dimensions for the layout of the DSB and SEBT beamline were obtained from the TRIUMF Design Office. The present section details each sequence which was implemented for ISAC-II, along with the associated drawings from which element positions were measured. While the `/acc` database contains definitions of all elements represented in the design drawings, including diagnostics and vacuum elements, such as isolation valves, the sequences as presented herein will only list optical beamline elements, such as quadrupoles, magnetic dipoles and RF cavities. Further note that x and y steerers are also present in the database, but presently have no effect in TRANSOPTR, which assumes zero-value centroids for the beam distribution along the optical path.

The position S along the optical path for all sequences is referenced to the start of sequence marker, with the sequence ending at the end of sequence marker. Each sequence's ending point is made to precisely overlap with the beginning of the following one. In cases where the sequence measurements had to be extracted from more than one design drawing, this will be indicated in the sequence table. All sequence element locations are referenced to the design drawing shown immediately above to the element in question, where the drawing number, a link to the figure and the start and end (x,y) coordinates used for measurements are specified.

Figure 1: Overview of the ISAC-II facility. The DTL and part of the HEBT section may be seen at the bottom right, including the branching into the ISAC-II DSB transfer line. In the figure, the superconducting linac (SCL) defines the lower vertical segment immediately following DSB, while the SEBT transport lines define the upper vertical segment. ISAC-II High energy experiments are located at the top, with from right to left the SEBT1, SEBT2 SEBT3A and SEBT3B lines, respectively.

3.1 Sequence dsb_db0

The first sequence involved in transport to ISAC-II is known as the S-Bend transfer section, designated DSB. The section features 4 magnetic dipole benders, DSB:MB0, MB2, MB14 and MB16, interspersed with 16 magnetic quadrupoles. The section may accomodate beams with a ridigity up to $B\rho$ = 1.22 T-m with a design energy of 1.5MeV/u [4]. DTL output beams are steered and matched into the SCL, with a longitudinal match provided by the 35MHz DSB Buncher, whose on-axis field simulation is shown in Section 4.

sequence dsb_db0			
Start IHE0281D.dwg (x,y)		End IHE0281D.dwg (x,y)	
(1403.5516mm,6007.5647mm)		(20407.7996mm,5544.9802mm)	
Design Drawing		Figure 2	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	marker	0.000	0.000
DSB:MB0	mb	665.391	956.374
DSB:Q1	MQuad	2083.519	180.000
DSB:Q2	MQuad	2721.343	180.000
DSB:MB2	mb	4137.525	956.374
DSB:Q3	MQuad	5680.275	325.000
DSB:Q4	MQuad	6132.777	180.000
DSB:Q5	MQuad	7812.777	180.000
DSB:Q6	MQuad	8292.777	180.000
DSB:Q7	MQuad	11112.777	180.000
DSB:Q8	MQuad	11592.777	180.000
DSB:Buncher	linac	12229.826	390.423
DSB:Q9	MQuad	12872.777	180.000
DSB:Q10	MQuad	13352.777	180.000
DSB:Q11	MQuad	14392.777	180.000
DSB:Q12	MQuad	14959.992	180.000
DSB:Q13	MQuad	16539.992	180.000
DSB:Q14	MQuad	16919.992	180.000
DSB:MB14	mb	18868.233	956.374
DSB:Q15	MQuad	20336.421	180.000
DSB:Q16	MQuad	20841.421	180.000
DSB:MB16	mb	22309.618	956.374
SCB:Q1	MQuad	24257.805	180.000
SCB:Q2	MQuad	24637.805	180.000
end sequence	marker	25581.6492	0.000

Table 1: Sequence dsb_db0, showing source design drawing (.dwg file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. Note: design drawing IHE0281D.dwg uses millimeters as reference units, unlike many of the other ISAC-I drawings. The TRANSOPTR element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table.

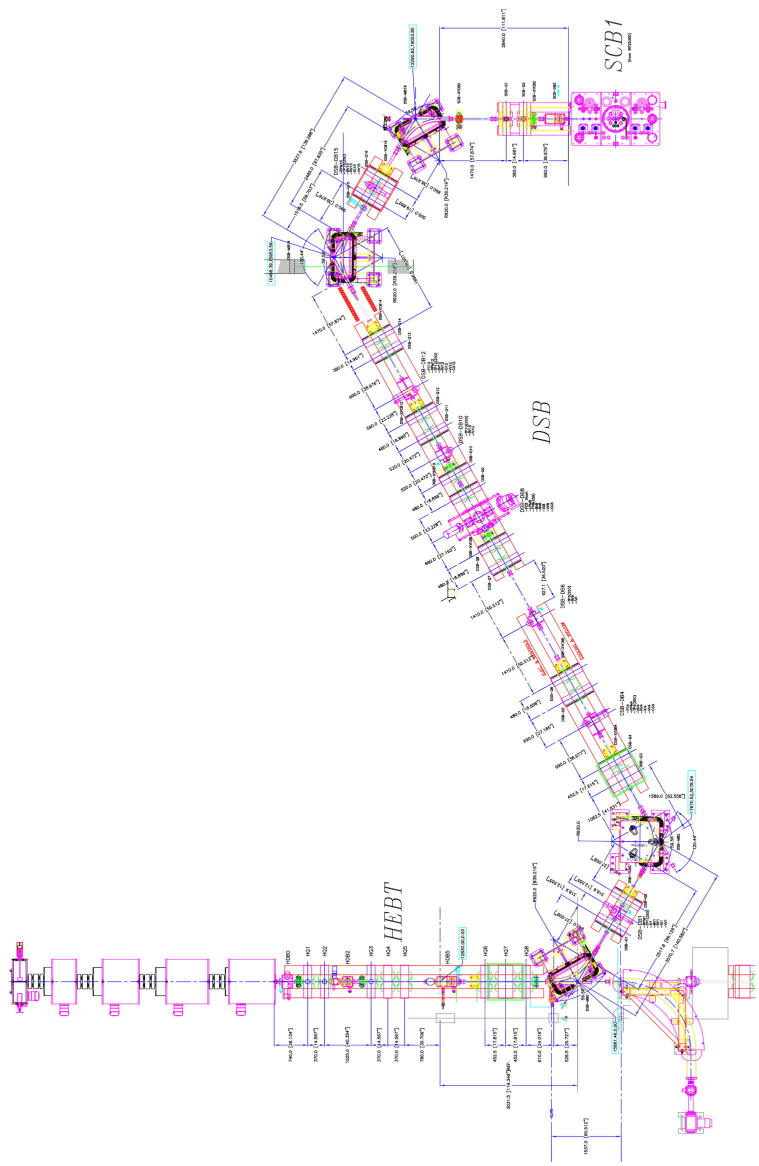


Figure 2: Design drawing `IHE0281D.dwg`, showing an overview of sequence `dsb_db0`, spanning DSB:MB0 to SCB:Q2. The DTL is visible at the bottom left, with the beam propagation direction running from bottom left to right through the HEBT section (sequence `hebt_db0` in [2]). The DSB:MB0 is visible at the bottom center of the figure. When delivering to ISAC-II, beam propagates through the DSB transfer line section, after deflection by DSB:MB0, from bottom to top, before being deflected laterally into the SCL, by the last two DSB dipoles.

3.2 Sequence sebt_db8

High energy SCL beam enters the SEBT line at 0° with an energy ranging from ∼1.5 to 10 MeV/u. The sequence ends at SEBT:IV22, inside the ISAC-II experimental hall.

sequence sebt_db8			
Start IHE0486D.dwg (x,y)		End IHE0486D.dwg (x,y)	
(44.7119",103.9787")		(369.3457",103.9787")	
Design Drawing		Figure 3	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	marker	0.000	0.000
SEBT:Q9	MQuad	930.709	325.000
SEBT:Q10	MQuad	1525.704	325.000
SEBT:NIM10	marker	2035.477	0.000
SEBT:FTM10	marker	2541.301	0.000
SEBT:Q11	MQuad	3140.710	325.000
SEBT:Q12	MQuad	3735.705	325.000
SEBT:FTM12	marker	4725.452	0.000
SEBT:Q13	MQuad	5380.707	180.000
SEBT:Q14	MQuad	5975.702	180.000
SEBT:Q15	MQuad	7650.702	180.000
SEBT:Q16	MQuad	8245.697	180.000
Start IHE0487D.dwg (x,y)		End IHE0487D.dwg (x,y)	
(29.75089",103.9787")		(355.9134",103.9787")	
Design Drawing		Figure 4	
SEBT:EMIT18:SLIT	marker	9402.221	0.000
SEBT:Q17	MQuad	9920.697	325.000
SEBT:Q18	MQuad	10515.692	325.000
SEBT:EMIT18:HARP	marker	11002.221	0.000
SEBT:NIM18	marker	11466.394	0.000
SEBT:Q19	MQuad	12190.692	325.000
SEBT:Q20	MQuad	12785.687	325.000
SEBT:STRP20A	marker	13212.017	0.000
SEBT:SID20	marker	13306.886	0.000
SEBT:FC20	marker	13540.637	0.000
SEBT:FTM20	marker	13786.278	0.000
SEBT:BB20	marker	15152.919	0.000
SEBT:Q21	MQuad	15935.687	330.000
SEBT:Q22	MQuad	16525.920	200.000
Start IHE0571D.dwg (x,y)		End IHE0571D.dwg (x,y)	
(248.253",144.882")		(305.390",144.882")	
Design Drawing		Figure 5	
end sequence	marker	17977.1995	0.000

Table 2: Sequence sebt_db8, showing source design drawings (.dwg file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. The TRANSOPTR element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table.

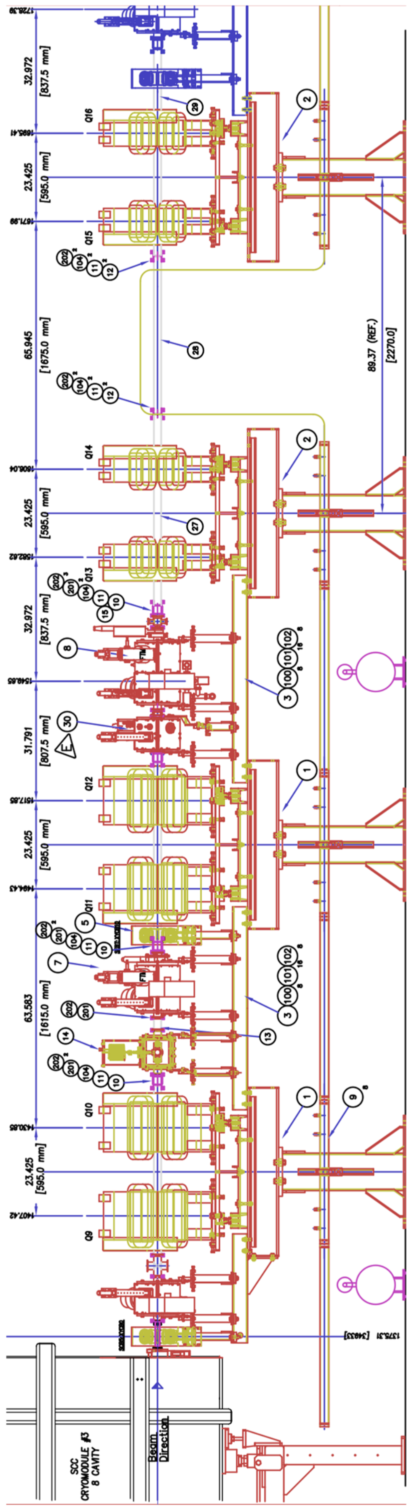


Figure 3: Design drawing `IHE0486D.dwg`, showing an overview of the first third of sequence `sebt_db8`, spanning SEBT:Q9 to SEBT:Q16. The outer edge of the final SCL cryomodule, SCC3, is visible at the bottom, with the beam propagation direction running from bottom to top.

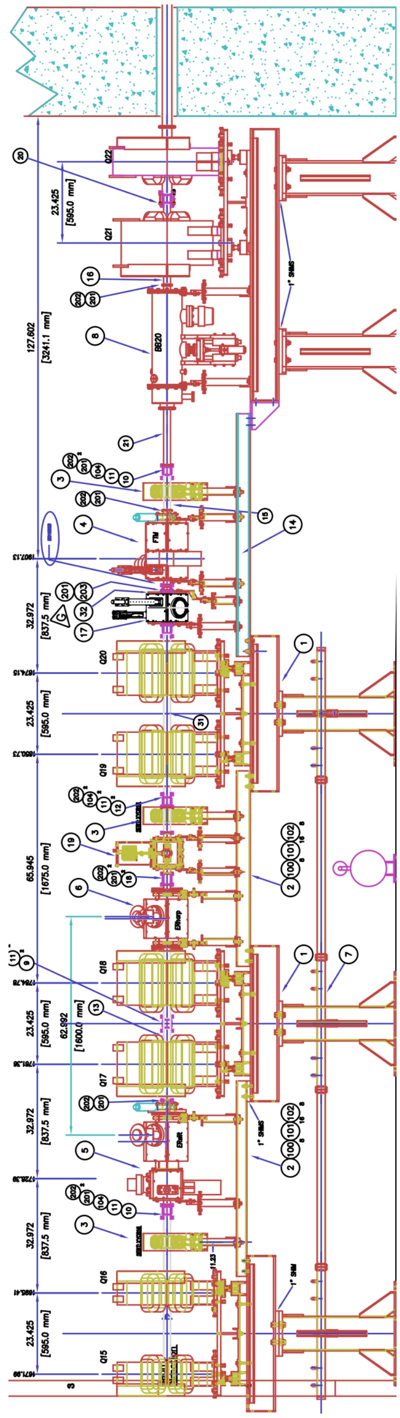


Figure 4: Design drawing `IHE0487D.dwg`, showing an overview of the second third of sequence `sebt_db8`, spanning SEBT:Q17 to SEBT:Q22. The ISAC-II vault wall is visible at the top, with the beam propagation direction running from bottom to top.

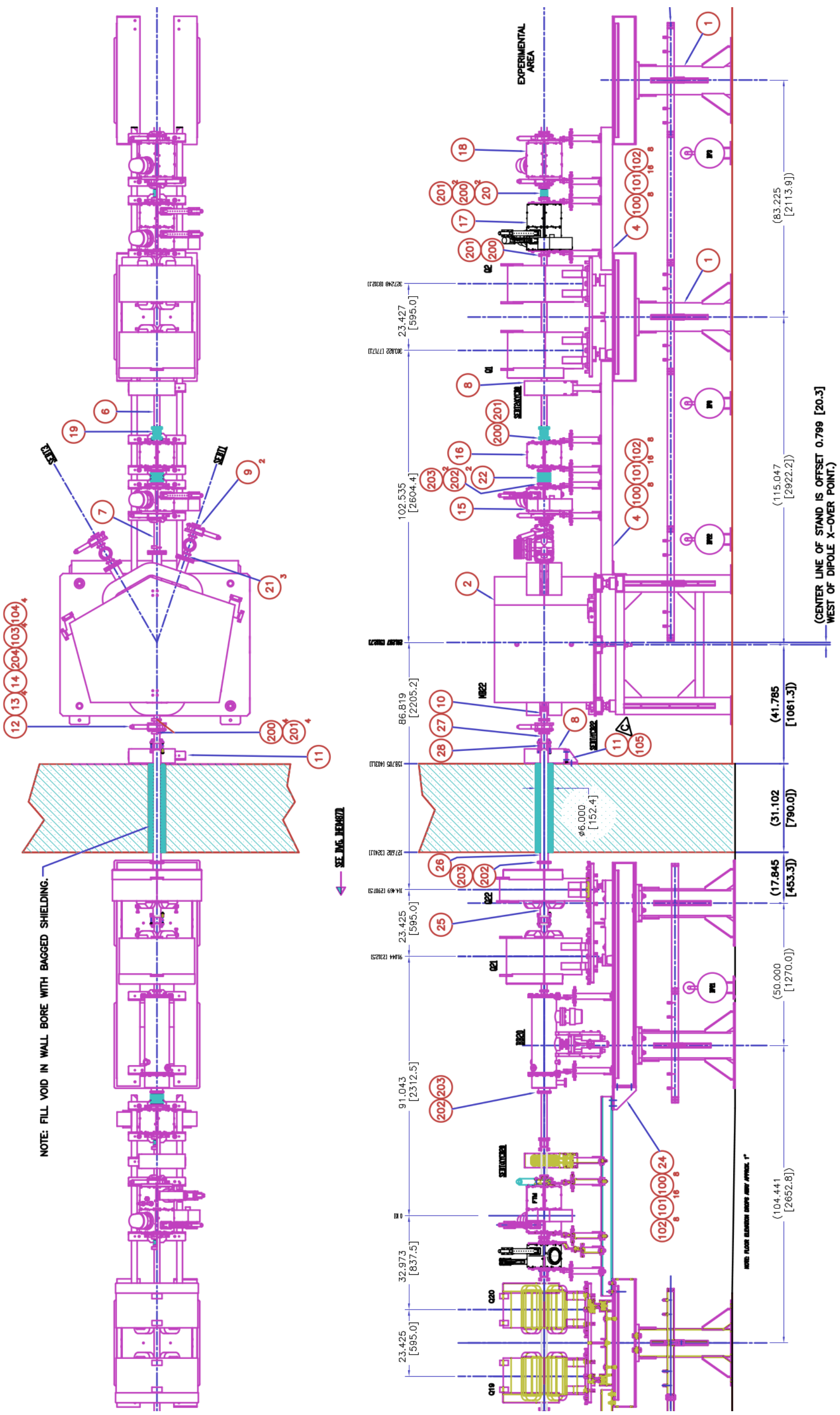


Figure 5: Design drawing `IHE0571D.dwg`, showing an overview of the final third of sequence `sebt_db8`, spanning SEBT:Q22 to the end-of-sequence point, defined as SEBT:IV22. The ISAC-II vault wall is visible at the center, with the beam propagation direction running from bottom to top.

3.3 Sequence `sebt1_db0`

The SEBT1 beamline begins with lateral deflection through SEBT:MB22 and consists of a straight beamline segment allowing for beam transport into a now disused vacuum/experiment chamber, known as HERACLES. In practice, and as of writing this note, the SEBT1 line is used as a general purpose experiment station, with custom apparatus periodically being installed beyond SEBT1 diagnostic box 3, beyond SEBT1:IV4. As such, the `/acc` database sequence is defined up to the isolation valve, with an added drift distance until the location of the next diagnostic box, roughly 1.7m downstream. Experimental chambers generally occupy the aforementioned drift space, and as such it allows for the computation of customized experiment beam focusses.

To avoid confusion, all elements beyond this point, while physically present and operational, have been omitted. Should a need arise to deliver down the final SEBT1 line, this can be added at a later time to the `/acc` database.

sequence `sebt1_db0`			
Start `IHE0571D.dwg` (x,y)		End `IHE0571D.dwg` (x,y)	
(305.390”,144.882”)		(335.073”,144.882”)	
Design Drawing		Figure 5	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	`marker`	0.000	0.000
SEBT:MB22	`mb`	753.948	1062.600
Start `IHE2887D.dwg` (x,y)		End `IHE2887D.dwg` (x,y)	
(64.426”,217.428”)		(358.584”,217.428”)	
Design Drawing		Figure 6	
SEBT1:SCD0	`marker`	3733.368	0.000
SEBT1:Q1	`MQuad`	4487.875	325.000
SEBT1:Q2	`MQuad`	5148.275	406.400
SEBT1:Q3	`MQuad`	5808.675	325.000
SEBT1:IV4	`marker`	6530.594	0.000
end sequence	`marker`	8225.561	0.000

Table 3: Sequence `sebt_db8`, showing source design drawings (`.dwg` file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. The `TRANSOPTR` element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table. For reference, commonly used or referred to non-optical devices, such as the flight-time monitors (FTM) are displayed herein as markers.

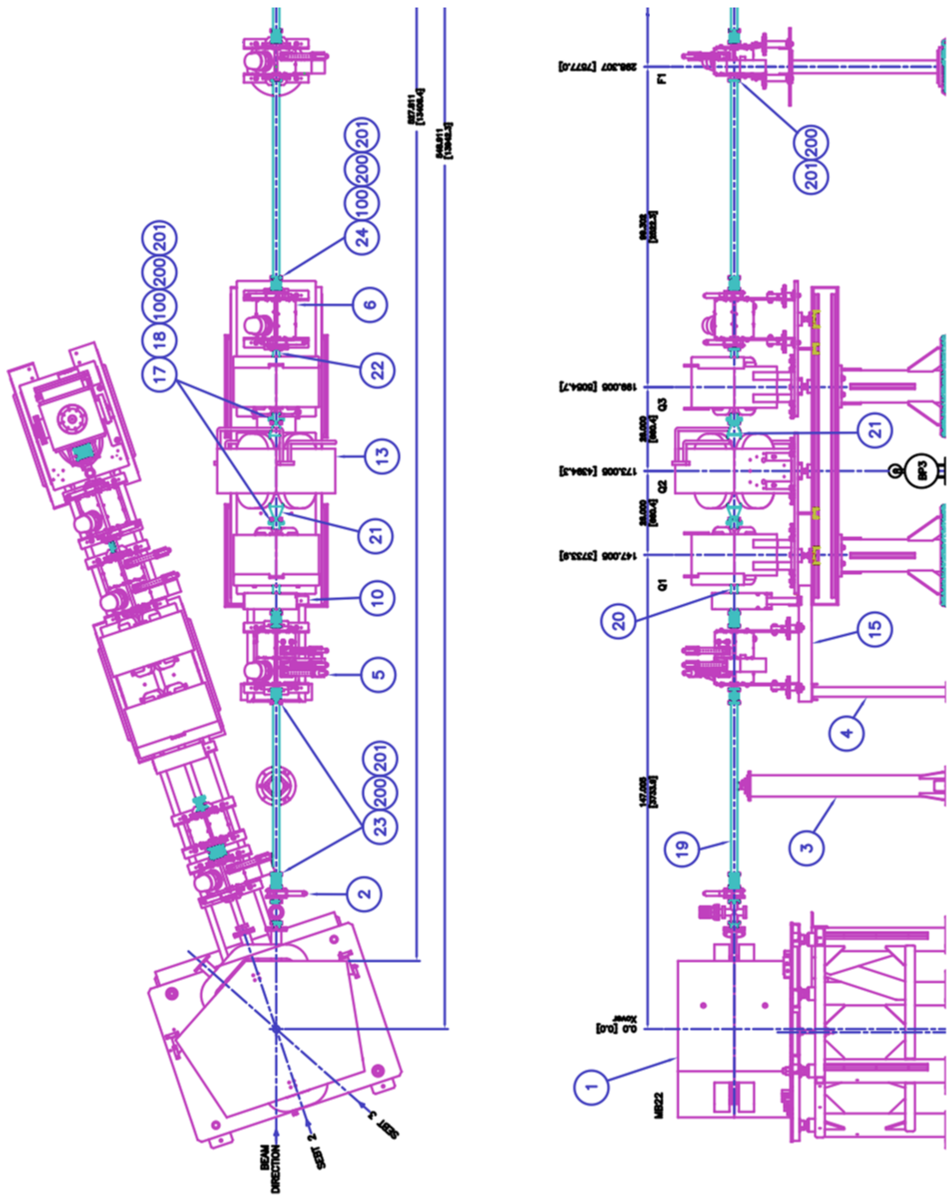


Figure 6: Design drawing `IHE2887D.dwg`, showing an overview of the sequence `sebt1_db0`, spanning SEBT:MB22 to the end-of-sequence point, defined as a 1.695m drift beyond the centerpoint of SEBT1:IV4, corresponding to the vacuum flange attachment of the next diagnostic box after SEBT1:IV4. The beam propagation direction runs from bottom to top. Note: All beamline elements located beyond this point, corresponding to the final diagnostic box at the top of the figure, are excluded as they are not presently in use. If needed, they may be added as a supplemental sequence.

3.4 Sequence `sebt2_db0`

The 0° SEBT2 line is defined when SEBT:MB22 is off and degaussed by operations, enabling delivery to the IRIS experiment, located beyond isolation valve SEBT2:IV3. To enable computations of arbitrary experiment beam delivery conditions, a 1m drift is added beyond the valve until the end of sequence point.

sequence `sebt2_db0`			
Start `IHE0571D.dwg` (x,y)		End `IHE0571D.dwg` (x,y)	
(305.390”,144.882”)		(551.4211”,144.882”)	
Design Drawing		Figure 5	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	`marker`	0.000	0.000
SEBT:MB22	`marker`	753.948	0.000
SEBT2:Q1	`MQuad`	3358.286	325.000
SEBT2:Q2	`MQuad`	3953.332	325.000
SEBT2:FC2	`marker`	4402.988	0.000
SEBT2:SID2	`marker`	4561.408	0.000
SEBT2:IV2	`marker`	4866.665	0.000
SEBT2:IV3	`marker`	5249.189	0.000
end sequence	`marker`	6248.189	0.000

Table 4: Sequence `sebt2_db0`, showing source design drawings (`.dwg` file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. The `TRANSOPTR` element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table. For reference, commonly used or referred to non-optical devices, such as the SEBT2 beam diagnostics and isolation valves are displayed herein as markers.

3.5 Sequence sebt3_db0

The SEBT3 line, defined with SEBT:MB22 on, transports SCL beams up to another switchyard defined by SEBT3:MB4, from which there are three possible destinations, covered by sequences sebt3_db4, sebt3a_db0 and sebt3b_db0. As such, the present sequence is defined up to isolation valve SEBT:IV4, immediately preceeding SEBT3:MB4.

sequence sebt3_db0			
Start IHE0571D.dwg (x,y)		End IHE0571D.dwg (x,y)	
(305.390”,144.882”)		(551.4211”,144.882”)	
Design Drawing		Figure 5	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	marker	0.000	0.000
SEBT:MB22	mb	753.948	1047.200
Start IHE0545D.dwg (x,y)		End IHE0545D.dwg (x,y)	
(5.013’,9.865’)		(24.153’,9.865’)	
Design Drawing		Figure 7	
SEBT3:Q1	MQuad	2752.522	330.000
SEBT3:Q2	MQuad	3377.362	330.000
SEBT3:FC2	marker	4193.616	0.000
SEBT3:Q3	MQuad	4702.327	330.000
SEBT3:Q4	MQuad	5327.472	330.000
end sequence	marker	6587.820	0.000

Table 5: Sequence sebt3_db0, showing source design drawings (.dwg file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. Note: drawing IHE0545D.dwg, as provided by the TRIUMF Design Office, while it lists drawing units in inches, the as-provided drawing’s digital measurement units are feet. As such, the reference start and end coordinates are presented in feet. The TRANSOPTR element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table. For reference, SEBT3:FC2 has been included.

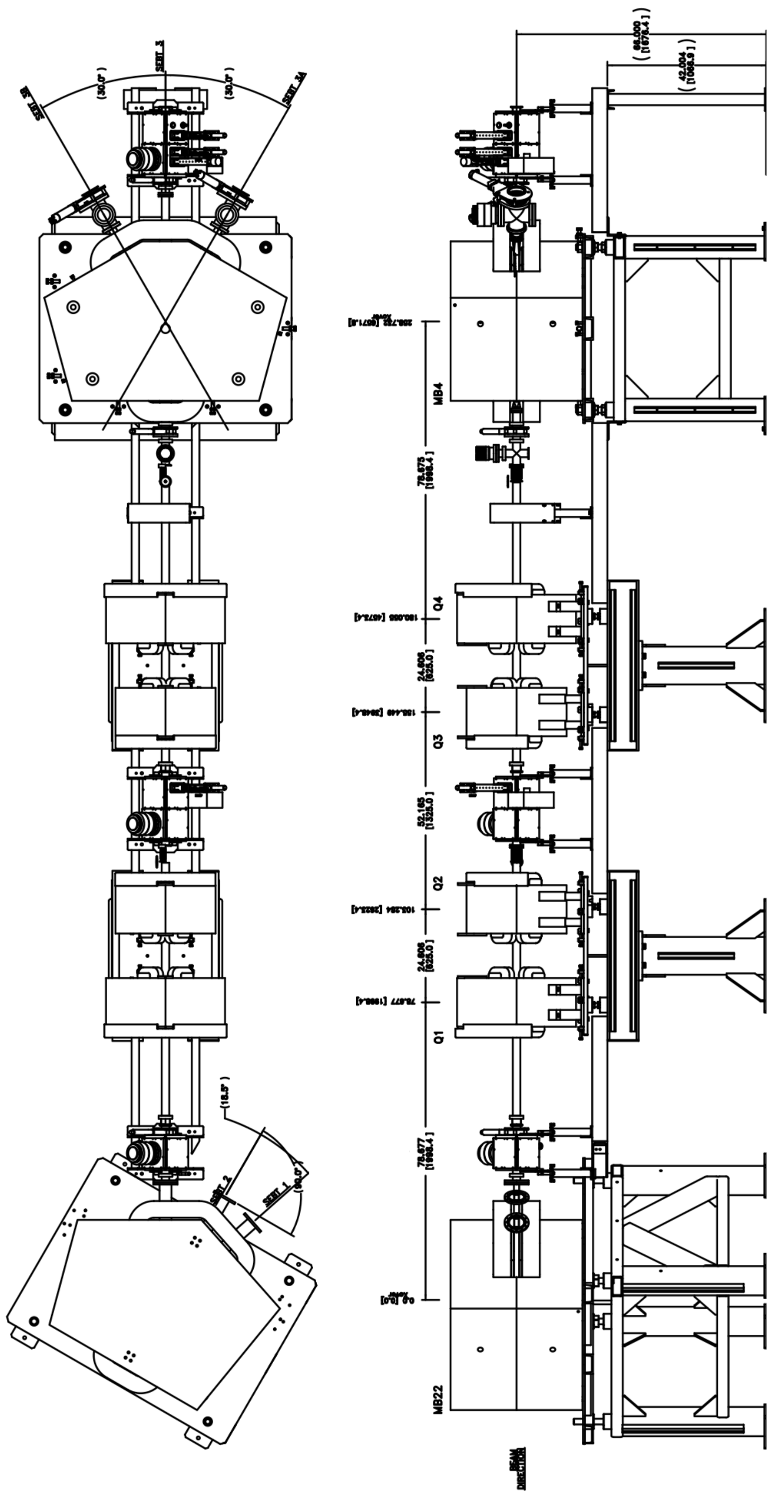


Figure 7: Design drawing `IHE0545D.dwg`, showing an overview of the sequence `sebt3_db0`, spanning SEBT:MB22 to the end-of-sequence point, defined as the centerpoint of SEBT3:IV4, upstream of the dipole magnet SEBT3:MB4. The beam propagation direction runs from bottom to top.

3.6 Sequence sebt3_db4

Defined when SEBT3:MB4 is degaussed by operations and powered off, this sequence corresponds to a 0° path with respect to the SEBT3 line, defined previously in sebt3_db0. The section is used by ISAC-II experiments, notably TIGRESS, for particle identification via a TBragg detector, located at the end of the SEBT3 line. The present sequence therefore ends at the vacuum flange immediately preceeding the TBragg detector.

sequence sebt3_db4			
Start IHE0545D.dwg (x,y)		End IHE0545D.dwg (x,y)	
(24.153',9.865')		(31.309',9.865')	
Design Drawing		Figure 7	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	marker	0.000	0.000
SEBT3:MB4	marker	737.921	0.000
SEBT3:RPM5	marker	1784.299	0.000
SEBT3:FC5	marker	1874.825	0.000
end sequence	marker	2181.150	0.000

Table 6: Sequence sebt3_db4, showing source design drawings (.dwg file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. Note: drawing IHE0545D.dwg, as provided by the TRIUMF Design Office, while it lists drawing units in inches, the as-provided drawing's digital measurement units are feet. As such, the reference start and end coordinates are presented in feet. The TRANSOPTR element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table. For reference, SEBT3 diagnostics have been included.

3.7 Sequence `sebt3a_db0`

Defined when SEBT3:MB4 deflects beam into the SEBT3A line, this sequence defines final beam transport up to the TIGRESS experiment. The sequence ends one meter beyond the isolation valve SEBT3A:IV4, allowing for computations of drifts into and focussing for the TIGRESS experiment chamber.

sequence `sebt3a_db0`			
Start `IHE0545D.dwg` (x,y)		End `IHE0545D.dwg` (x,y)	
(24.153',9.865')		(26.574',9.865')	
Design Drawing		Figure 7	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	`marker`	0.000	0.000
SEBT3:MB4	`mb`	737.921	1047.200
Start `IHE0544D.dwg` (x,y)		End `IHE0544D.dwg` (x,y)	
(5.626',9.768')		(31.198',9.768')	
Design Drawing		Figure 8	
SEBT3A:Q1	`MQuad`	2813.609	406.400
SEBT3A:RPM1	`marker`	3678.631	0.000
SEBT3A:Q2	`MQuad`	4543.654	205.000
SEBT3A:Q3	`MQuad`	6354.470	406.000
SEBT3A:Q4	`MQuad`	6954.622	180.000
SEBT3A:FC4	`marker`	7281.367	0.000
SEBT3A:SID4	`marker`	7362.444	0.000
SEBT3A:IV4	`marker`	7532.218	0.000
end sequence	`marker`	8532.218	0.000

Table 7: Sequence `sebt3a_db0`, showing source design drawings (`.dwg` file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. Note: drawings `IHE0545.dwg` and `IHE0544.dwg`, as provided by the TRIUMF Design Office, while listing drawing units in inches, the as-provided drawings digital measurement units are feet. As such, the reference start and end coordinates are presented in feet. The `TRANSOPTR` element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table. For reference, commonly used SEBT3A diagnostics have been included.

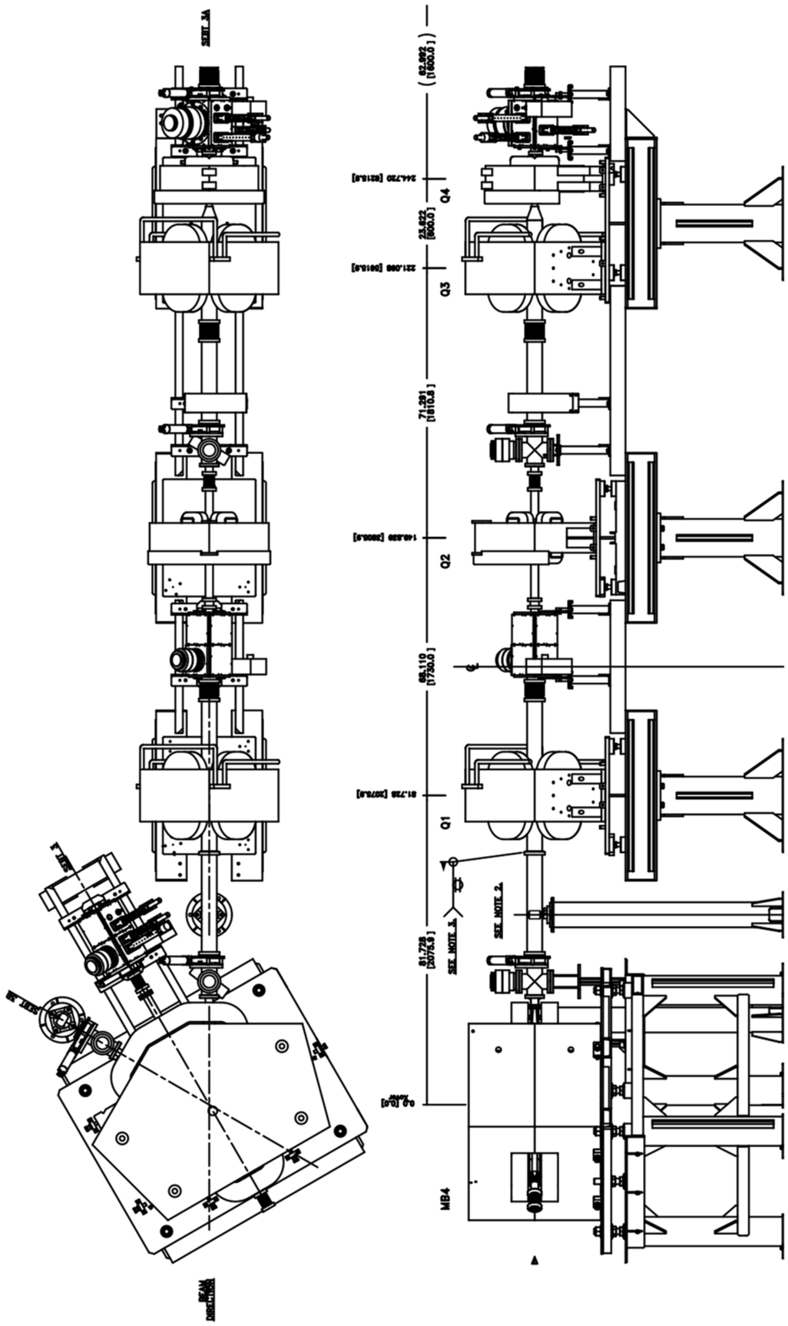


Figure 8: Design drawing `IHE0544D.dwg`, showing an overview of the sequence `sebt3a_db0`, spanning SEBT3:MB4 to the end-of-sequence point, defined one meter beyond the centerpoint of SEBT3A:IV4, representing a drift into the TIGRESS experiment. The beam propagation direction runs from bottom to top.

3.8 Sequence sebt3b_db0

EMMA, the newest experiment station at ISAC-II, is serviced by the SEBT3B beamline, defined when SEBT3:MB4 deflects beam from SEBT3. The sequence is defined 2m past EMMA:APT10, an experiment aperture intended for final alignment into the EMMA apparatus.

sequence sebt3b_db0			
Start IHE0545D.dwg (x,y)		End IHE0545D.dwg (x,y)	
(24.153',9.865')		(26.574',9.865')	
Design Drawing		Figure 7	
Element Name	Element Type	Position S[mm]	Length L[mm]
start sequence	marker	0.000	0.000
SEBT3:MB4	mb	737.921	1047.200
Start IHE2886D.dwg (x,y)		End IHE2886D.dwg (x,y)	
(92.591",140.859")		(479.0762",140.859")	
Design Drawing		Figure 9	
SEBT3B:Q1	MQuad	2822.423	200.000
SEBT3B:Q2	MQuad	4543.831	180.000
SEBT3B:Q3	MQuad	6354.648	406.400
SEBT3B:Q4	MQuad	6954.647	180.000
SEBT3B:FC4	marker	7478.293	0.000
EMMA:APT10	marker	8554.6438	180.000
end sequence	marker	8532.218	0.000

Table 8: Sequence sebt3b_db0, showing source design drawings (.dwg file) with reference start and end coordinates from which elements and their positions along the optical axis, S in millimeters were extracted. Note: drawing IHE0545.dwg, as provided by the TRIUMF Design Office, while listing drawing units in inches, the as-provided drawings digital measurement units are feet. As such, the reference start and end coordinates are presented in feet. The TRANSOPTR element (subroutine) type, in addition to the element length are also displayed. All element positions are referenced to the drawing listed above their respective location in the table. For reference, commonly used SEBT3B/EMMA beamline diagnostics and elements have been included.

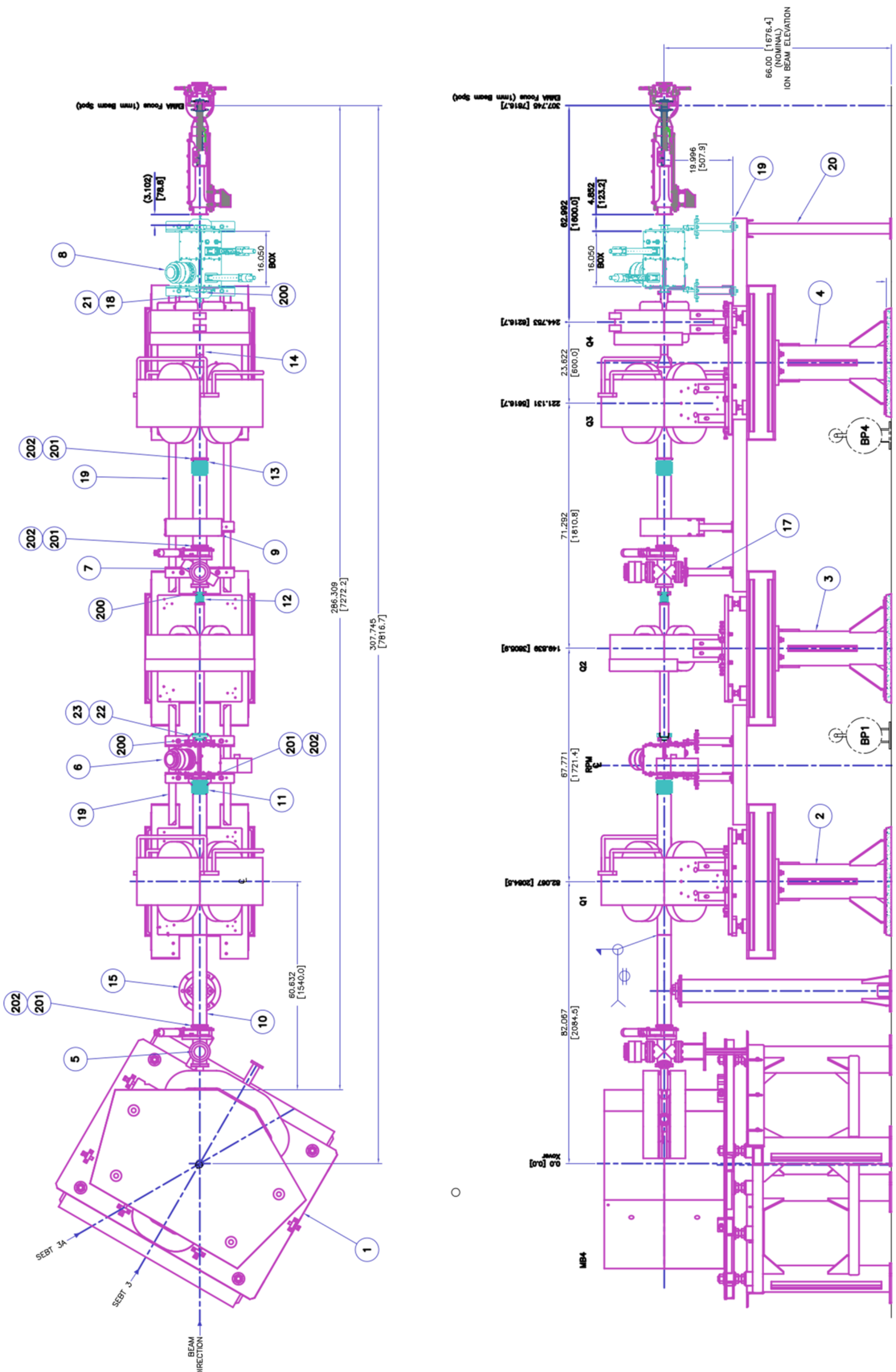


Figure 9: Design drawing `IHE2886D.dwg`, showing an overview of the sequence `sebt3b_db0`, spanning SEBT3:MB4 to the end-of-sequence point, defined two meters beyond the centerpoint of the EMMA aperture (EMMA:APT10), representing a drift into the EMMA experiment. The beam propagation direction runs from bottom to top.

4 DSB RF Cavity Simulation

TRANSOPTR accelerating (or bunching) simulations rely upon calls to the subroutine `linac`, which itself expects as input a handfull of cavity design parameters. These include the RF phase setting of the cavity and the operating frequency in MHz. As is outlined in Reference [5], for the case of axially symmetric RF accelerating geometries, the F-matrix representing the cavity effects upon the moments of the beam distribution may be expressed as:

$$\mathbf{F_R}(s) = \begin{pmatrix} 0 & \frac{1}{P_0} & 0 & 0 & 0 & 0 \\ \mathcal{A}(s) & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{P_0} & 0 & 0 \\ 0 & 0 & \mathcal{A}(s) & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{\beta'}{\beta} & \frac{1}{\gamma^2 P_0} \\ 0 & 0 & 0 & 0 & \mathcal{B}(s) & -\frac{\beta'}{\beta} \end{pmatrix} \tag{1}$$

with the functions:

$$\mathcal{A}(s) = -\frac{q}{2\beta c}\left(\mathcal{E}'(s)C - \mathcal{E}(s)S\frac{\omega\beta}{c}\right) \tag{2}$$

$$\mathcal{B}(s) = \frac{q\mathcal{E}(s)\omega S}{\beta^2 c^2} \tag{3}$$

where the parameters $S = \sin(\omega t_0 + \theta)$ and $C = \cos(\omega t_0 + \theta)$ and $\mathcal{E}(s)$ & $\mathcal{E}'(s)$ is the on-axis electric field and its derivative with respect to s, the distance along the optical axis. Providing this field mapping is therefore indispensible for implementing the envelope simulation.

4.1 Opera2D DSB Buncher Simulation

The sole RF element encountered during beam transfer to ISAC-II is the DSB Buncher, which is used to accomplish a time focus at the entrace of the SCL. The room-temperature, two-gap resonator for the DSB Buncher is shown in Figure 10. It is noted that the DSB Buncher is nearly identical in design to the HEBT-35MHz buncher shown in [2]. The extracted physical dimensions used for the Opera2D simulation are shown in Table 9. The resulting simulation of $\mathcal{E}(s)$ is shown in Figure 11, which has been added to the /acc database for TRANSOPTR simulations.

Parameter	Value [in]
Start	0.0000
ground tube end	4.2920
tube 1 start	5.7095
tube 1 end	9.6465
ground tube start	11.0640
ground tube end	15.3710
aperture radius	0.3937
radial tube thickness	0.5906
inner-tube rounding radius	0.1875
outer tube rounding radius	0.3750
full field-map length	15.3710

Table 9: Physical dimensions extracted from drawing `IRF1351D.dwg` for the 35MHz DSB buncher.

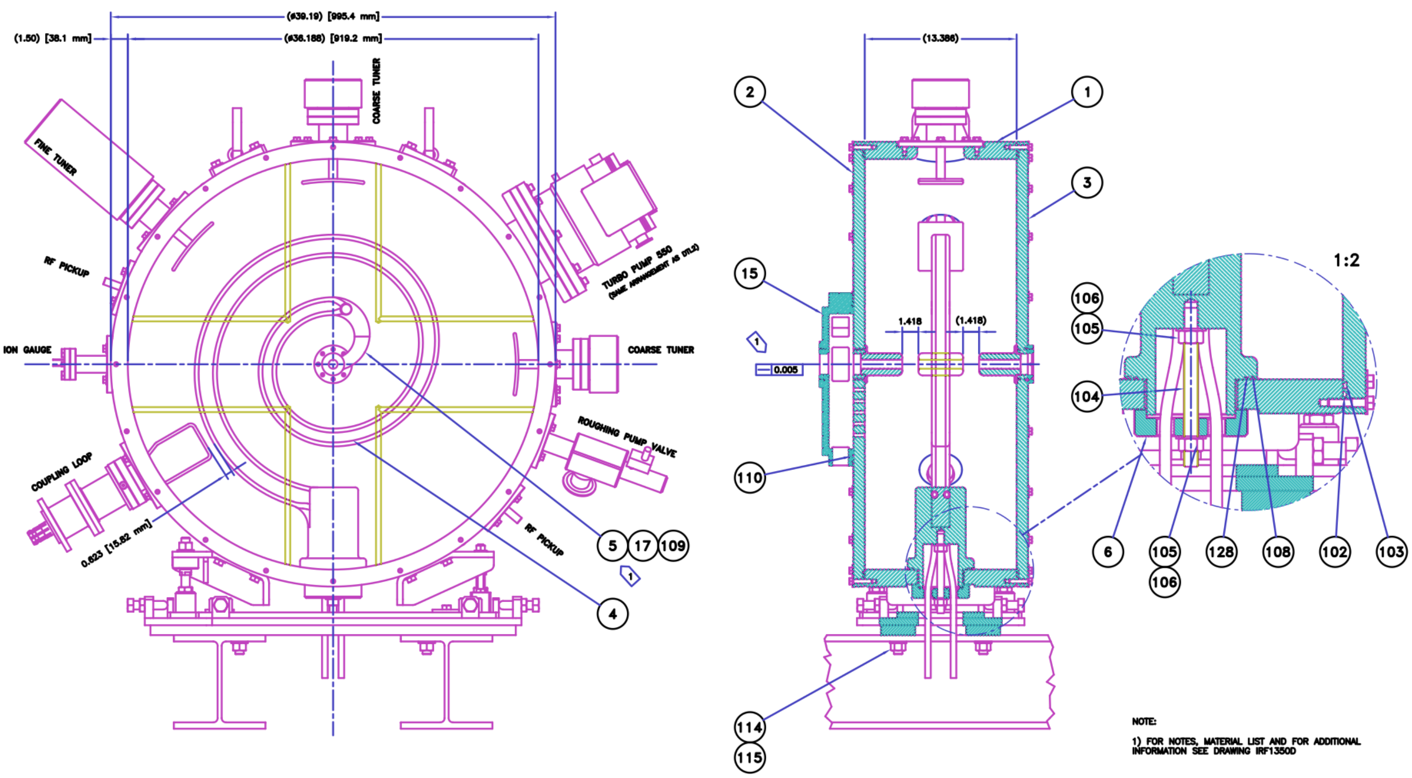


Figure 10: Design drawing `IRF3151D.dwg`, showing interior detail for the DSB Buncher. Obtained from the TRIUMF Design Office.

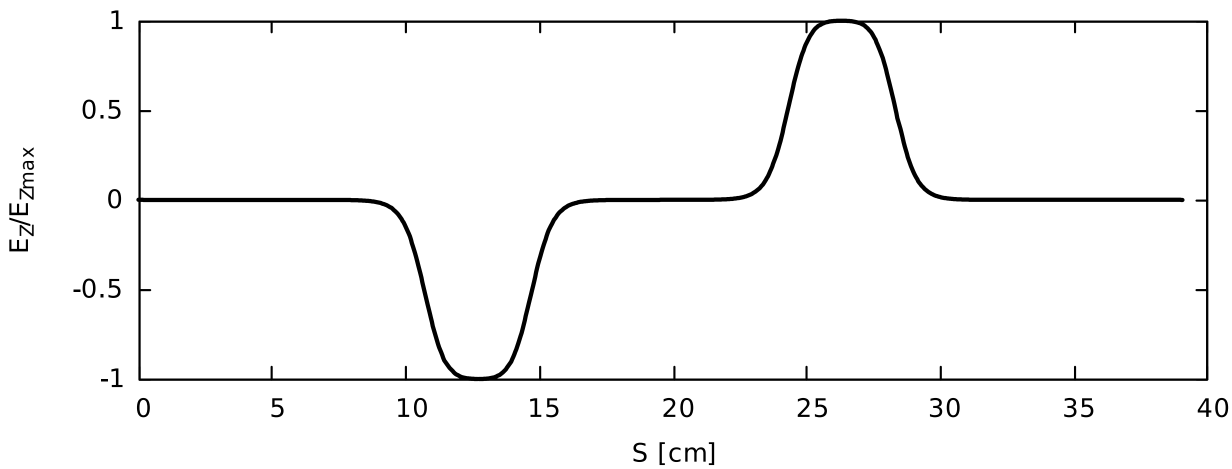


Figure 11: `Opera2D` simulated normalized on-axis electric field for the 35MHz DSB Buncher, using parameters specified in Table 9.

5 `Trace-3D` Simulations

The `Trace-3D` implementation for the SEBT beamlines are segmented into groups roughly mirroring the sequences defined in the `/acc` database, as specified in Table 10. Additionally, the table features beam parameters used for the original simulations. The ensemble of simulations shown in Table 10 and the listed figures represent the tune computation and analysis tools which were used for the ISAC-II high energy sections up until 2019.

Figure ref.	subsequence elements	m[MeV/c^2]	E [MeV]	Q
Figure 12	HEBT:Q6 to SCB:Q2 (DSB)	27944.33	45.00	5
Figure 13	SEBT:Q9 to SEBT:Q20	27944.83	246.00	10
Figure 14	SEBT:Q21 to TUDA-II (SEBT1)	27945.00	246.00	10
Figure 15	SEBT:Q21 to IRIS (SEBT2)	27944.83	246.00	10
Figure 16	SEBT:Q21 to TIGRESS (SEBT3A)	27945.00	246.00	10
Figure 17	SEBT2:Q21 to TBragg (SEBT3-straight)	27945.00	246.00	10
Figure 18	SEBT:Q21 to EMMA (SEBT3B)	27945.00	246.00	10

Table 10: Listing of `Trace-3D` SEBT simulations, as used by the TRIUMF Beam Physics group to compute ISAC-II high energy tunes, with associated figures showing original simulation outputs. Input particle mass, energy and charge state are also listed, as they were on the original `.t3d` files.

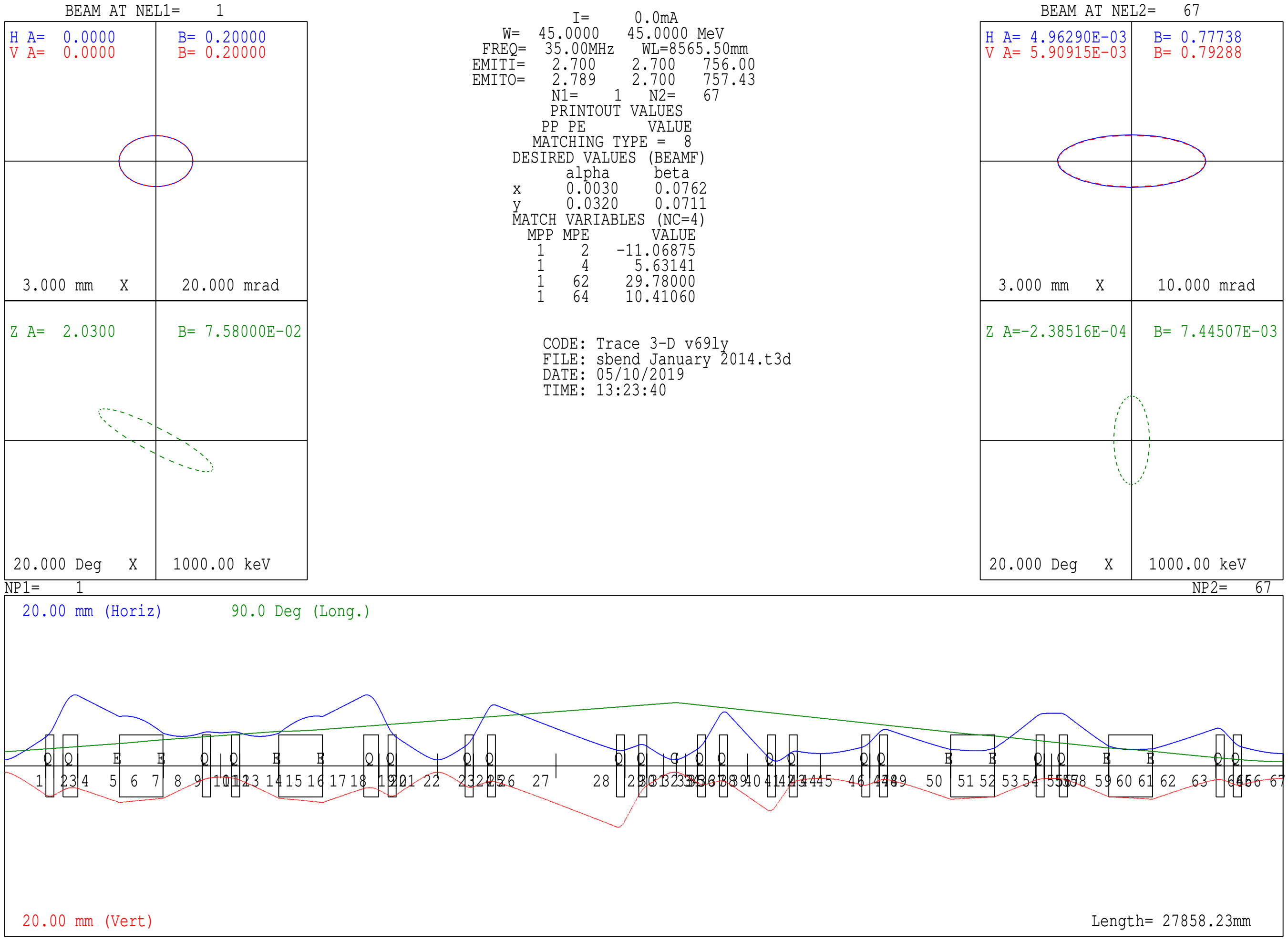


Figure 12: `Trace-3D` envelope simulation of element-sequence spanning HEBT:Q6 to SCB:Q2. The horizontal envelope and its parameters are shown in blue, vertical in red and longitudinal in green. The input beam ellipses containing $4\epsilon_{RMS}$ are shown on the left hand side, with A and B representing the Twiss parameters α and β, while the output distributions are on the right hand side. The input and output beam emittances are visible in the top center, labeled EMITI and EMITO, respectively, and have units of mm*mrad for transverse and deg*keV for longitudinal. The beam envelopes are shown at the bottom, following the same color convention. The location and lengths of quadrupoles are represented by the squares labeled Q. Drifts are represented by a black horizontal line at the lower graph midplane. Finally, the numbers on the lower graph, spanning 1 to 11, sequentially label all elements called in the simulation. Quadrupole gradients are shown in Table 11.

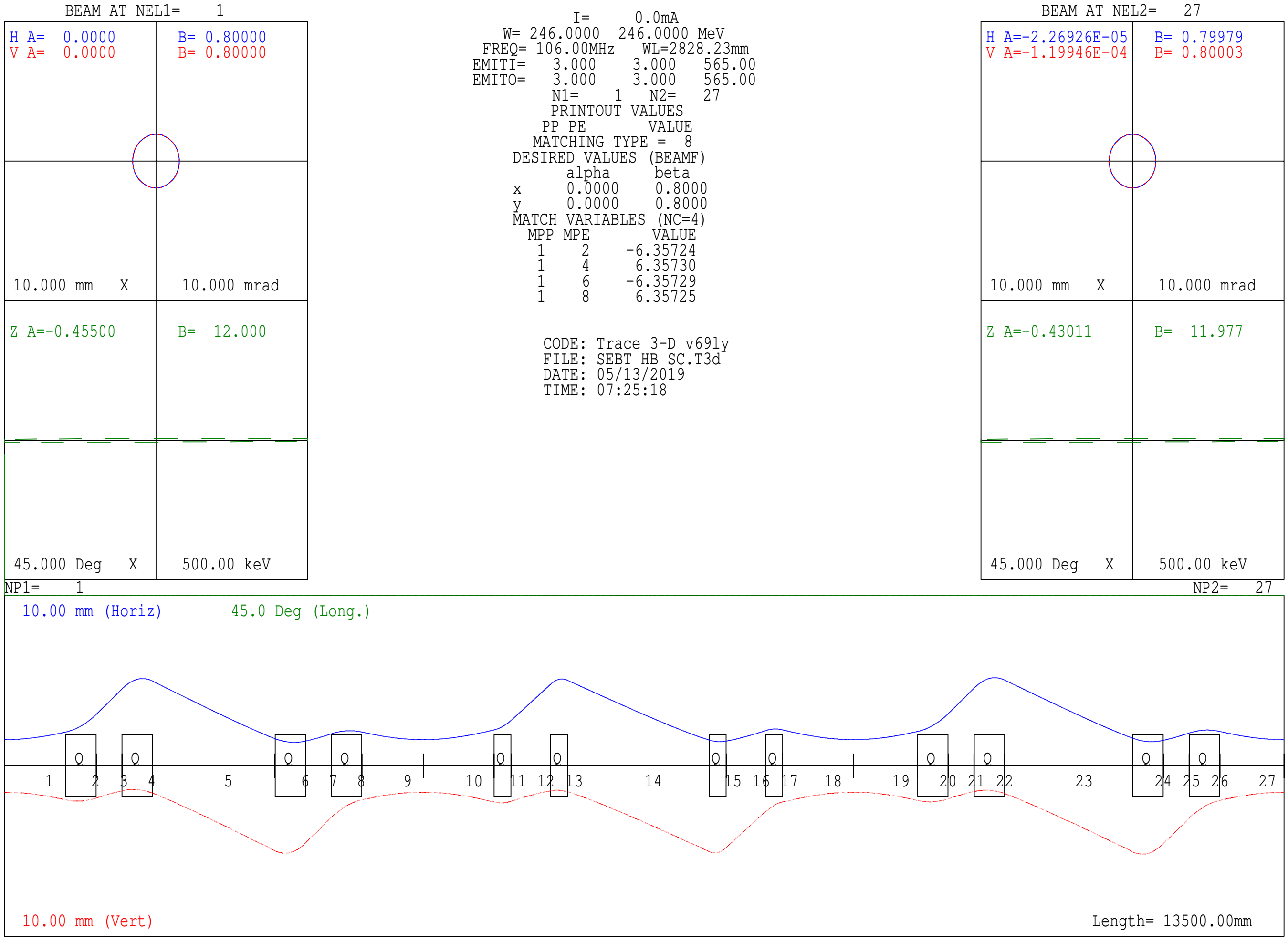


Figure 13: `Trace-3D` envelope simulation of element-sequence spanning SEBT:Q9 to SEBT:Q20. The horizontal envelope and its parameters are shown in blue, vertical in red and longitudinal in green. The input beam ellipses containing 4ϵ_{RMS} are shown on the left hand side, with A and B representing the Twiss parameters α and β, while the output distributions are on the right hand side. The input and output beam emittances are visible in the top center, labeled EMITI and EMITO, respectively, and have units of mm*mrad for transverse and deg*keV for longitudinal. The beam envelopes are shown at the bottom, following the same color convention. The location and lengths of quadrupoles are represented by the squares labeled Q. Drifts are represented by a black horizontal line at the lower graph midplane. Finally, the numbers on the lower graph, spanning 1 to 11, sequentially label all elements called in the simulation. Quadrupole gradients are shown in Table 12.

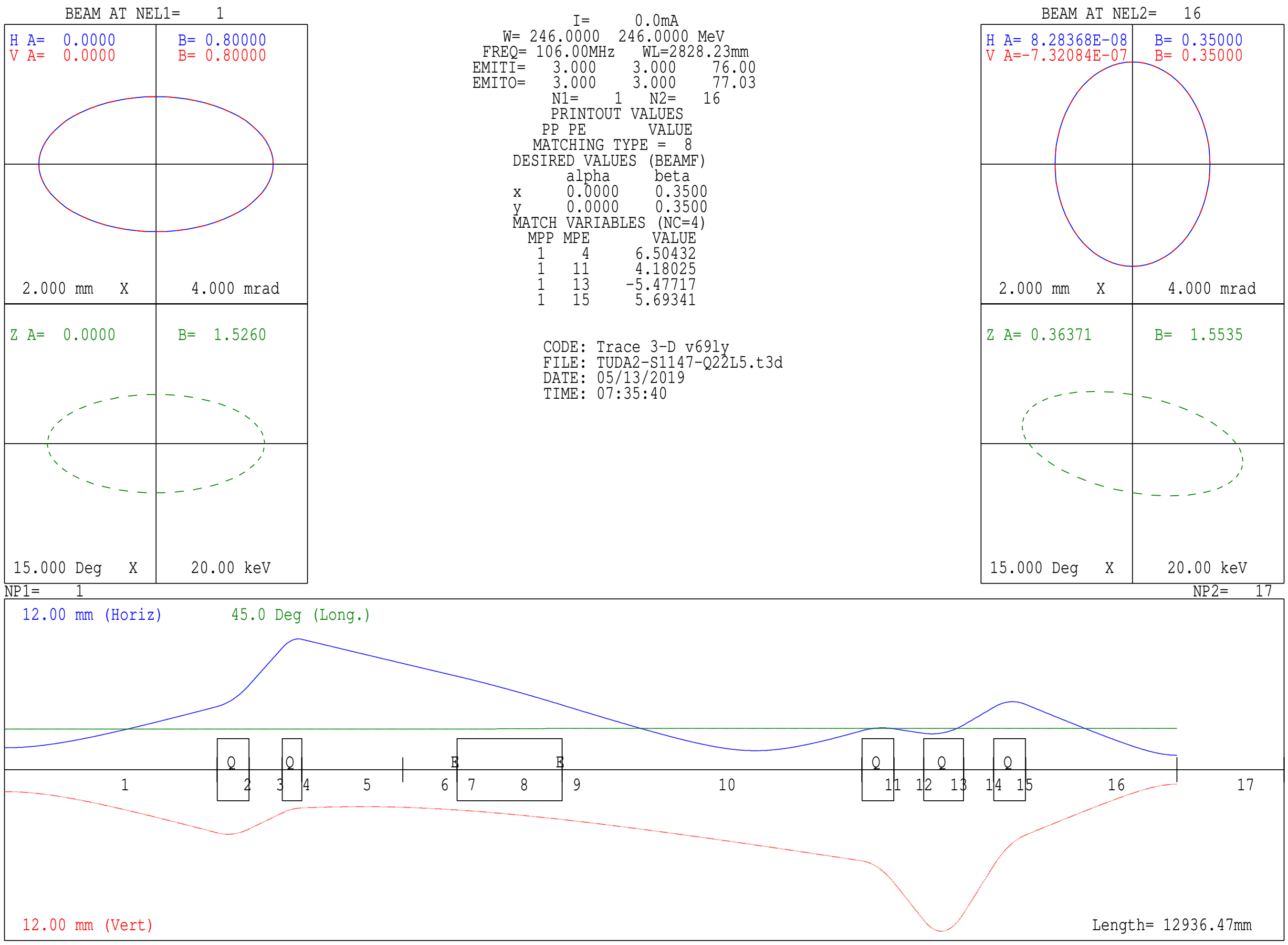


Figure 14: `Trace-3D` envelope simulation of element-sequence spanning SEBT:Q21 to the TUDA-II experimental chamber (SEBT1). The horizontal envelope and its parameters are shown in blue, vertical in red and longitudinal in green. The input beam ellipses containing $4\epsilon_{RMS}$ are shown on the left hand side, with A and B representing the Twiss parameters α and β, while the output distributions are on the right hand side. The input and output beam emittances are visible in the top center, labeled EMITI and EMITO, respectively, and have units of mm*mrad for transverse and deg*keV for longitudinal. The beam envelopes are shown at the bottom, following the same color convention. The location and lengths of quadrupoles are represented by the squares labeled Q. Drifts are represented by a black horizontal line at the lower graph midplane. Finally, the numbers on the lower graph, spanning 1 to 11, sequentially label all elements called in the simulation. Quadrupole gradients are shown in Table 13.

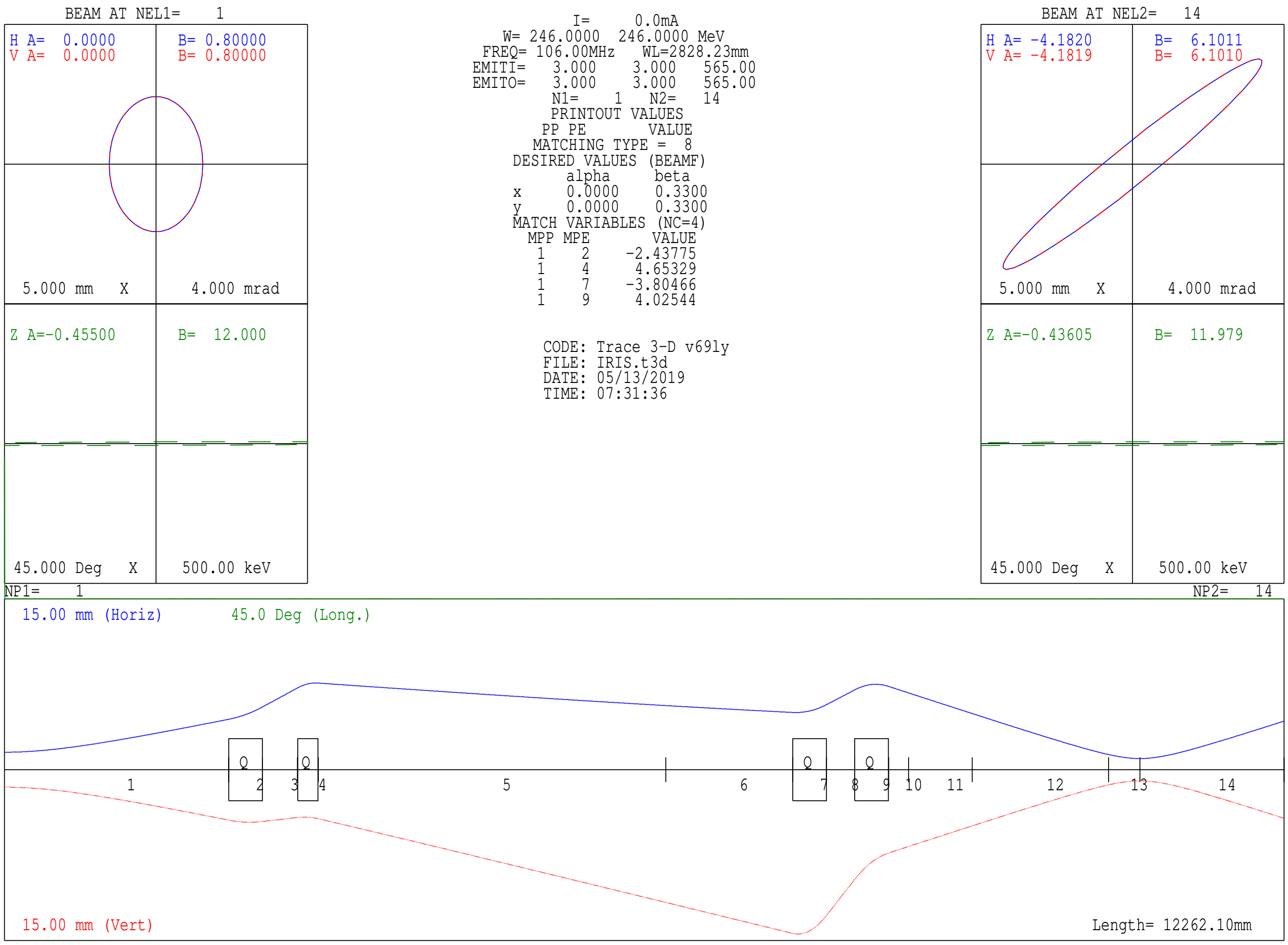


Figure 15: `Trace-3D` envelope simulation of element-sequence spanning SEBT:Q21 to the IRIS experimental chamber (SEBT2). The horizontal envelope and its parameters are shown in blue, vertical in red and longitudinal in green. The input beam ellipses containing $4\epsilon_{RMS}$ are shown on the left hand side, with A and B representing the Twiss parameters α and β, while the output distributions are on the right hand side. The input and output beam emittances are visible in the top center, labeled EMITI and EMITO, respectively, and have units of mm*mrad for transverse and deg*keV for longitudinal. The beam envelopes are shown at the bottom, following the same color convention. The location and lengths of quadrupoles are represented by the squares labeled Q. Drifts are represented by a black horizontal line at the lower graph midplane. Finally, the numbers on the lower graph, spanning 1 to 11, sequentially label all elements called in the simulation. Quadrupole gradients are shown in Table 14.

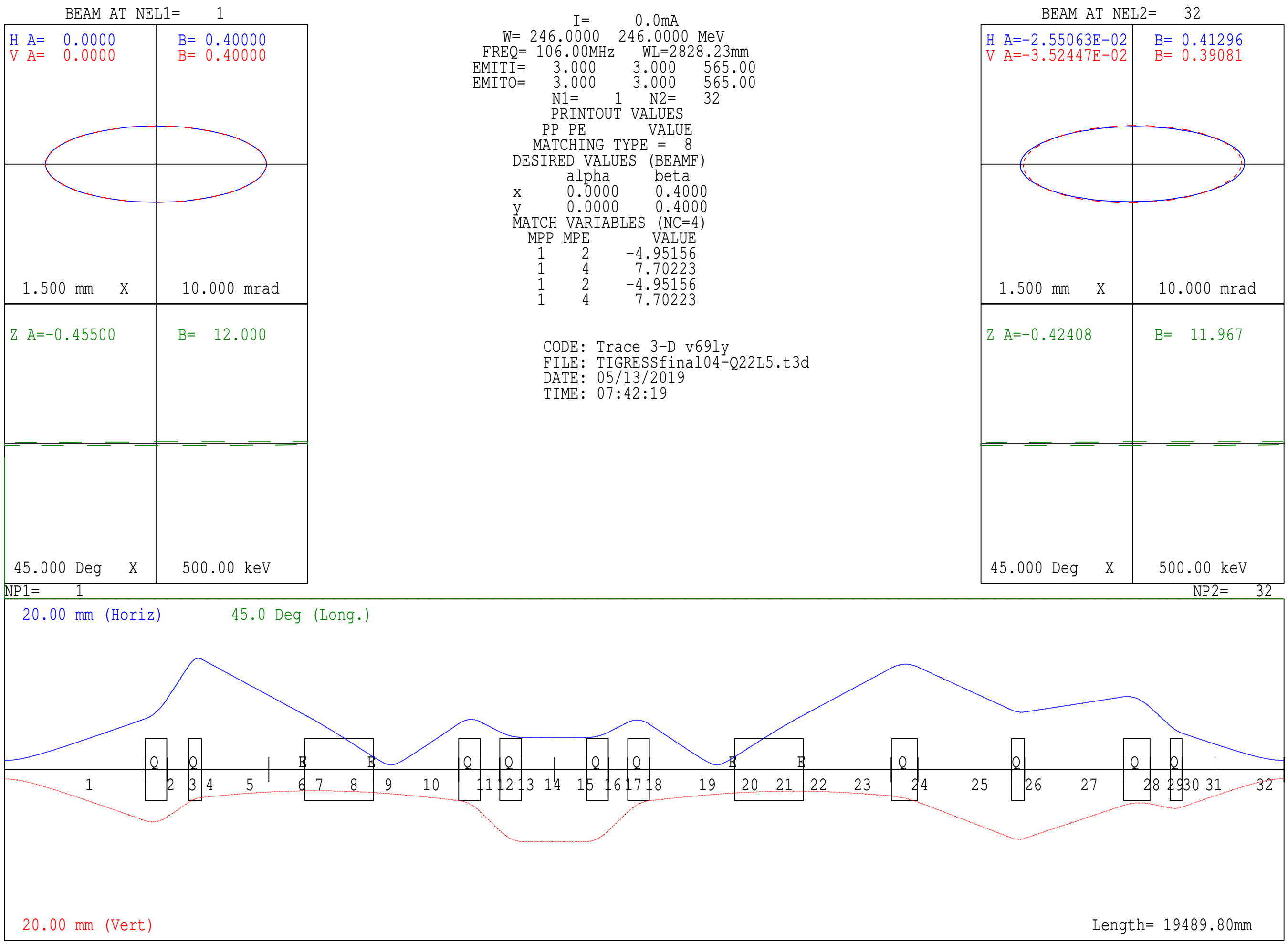


Figure 16: `Trace-3D` envelope simulation of element-sequence spanning SEBT:Q21 to the TIGRESS experimental chamber (SEBT3A). The horizontal envelope and its parameters are shown in blue, vertical in red and longitudinal in green. The input beam ellipses containing $4\epsilon_{RMS}$ are shown on the left hand side, with A and B representing the Twiss parameters α and β, while the output distributions are on the right hand side. The input and output beam emittances are visible in the top center, labeled EMITI and EMITO, respectively, and have units of mm*mrad for transverse and deg*keV for longitudinal. The beam envelopes are shown at the bottom, following the same color convention. The location and lengths of quadrupoles are represented by the squares labeled Q. Drifts are represented by a black horizontal line at the lower graph midplane. Finally, the numbers on the lower graph, spanning 1 to 11, sequentially label all elements called in the simulation. Quadrupole gradients are shown in Table 15.

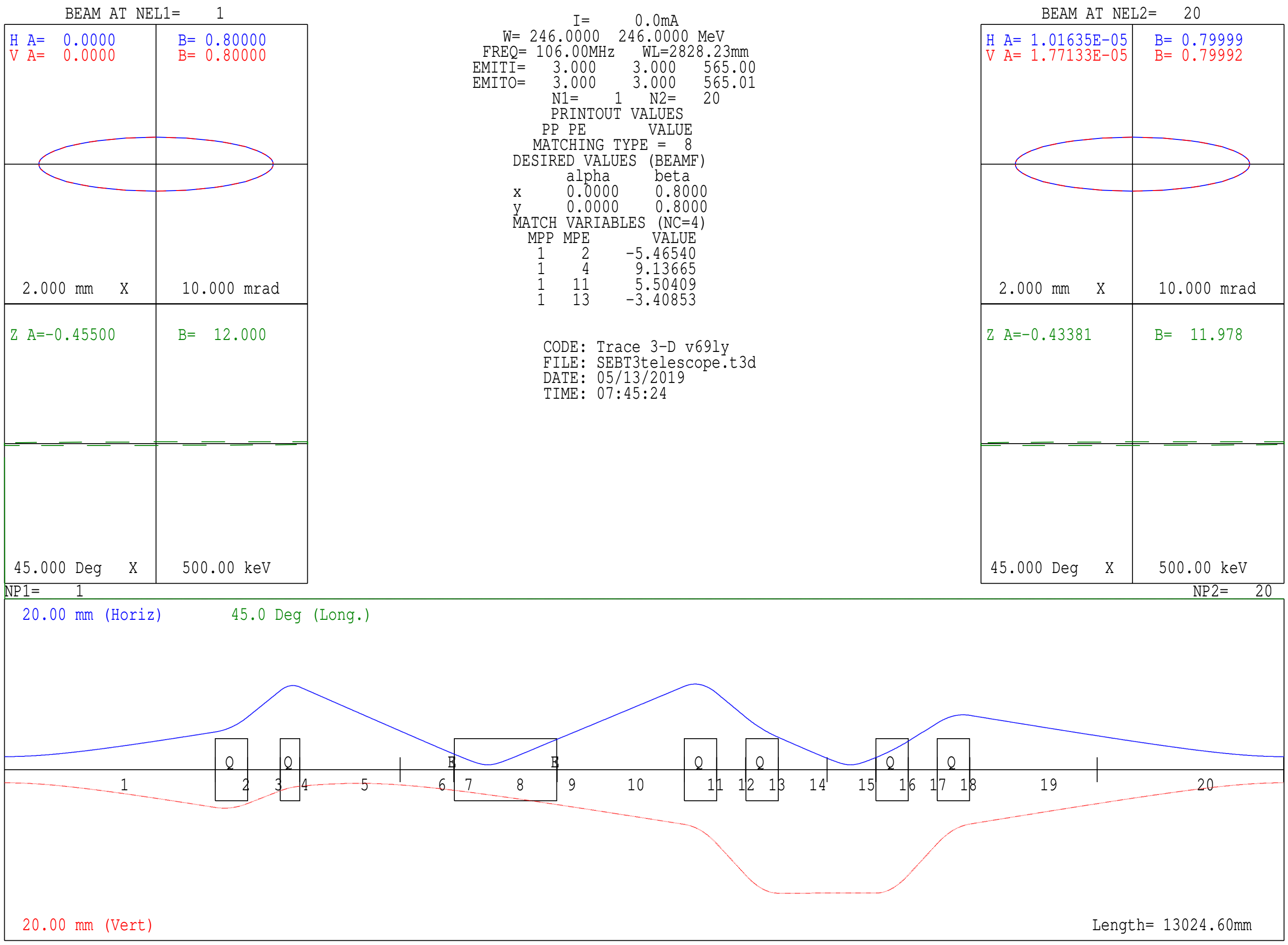


Figure 17: `Trace-3D` envelope simulation of element-sequence spanning SEBT:Q21 to the TBragg detector (SEBT3-straight). The horizontal envelope and its parameters are shown in blue, vertical in red and longitudinal in green. The input beam ellipses containing $4\epsilon_{RMS}$ are shown on the left hand side, with A and B representing the Twiss parameters α and β, while the output distributions are on the right hand side. The input and output beam emittances are visible in the top center, labeled EMITI and EMITO, respectively, and have units of mm*mrad for transverse and deg*keV for longitudinal. The beam envelopes are shown at the bottom, following the same color convention. The location and lengths of quadrupoles are represented by the squares labeled Q. Drifts are represented by a black horizontal line at the lower graph midplane. Finally, the numbers on the lower graph, spanning 1 to 11, sequentially label all elements called in the simulation. Quadrupole gradients are shown in Table 16.

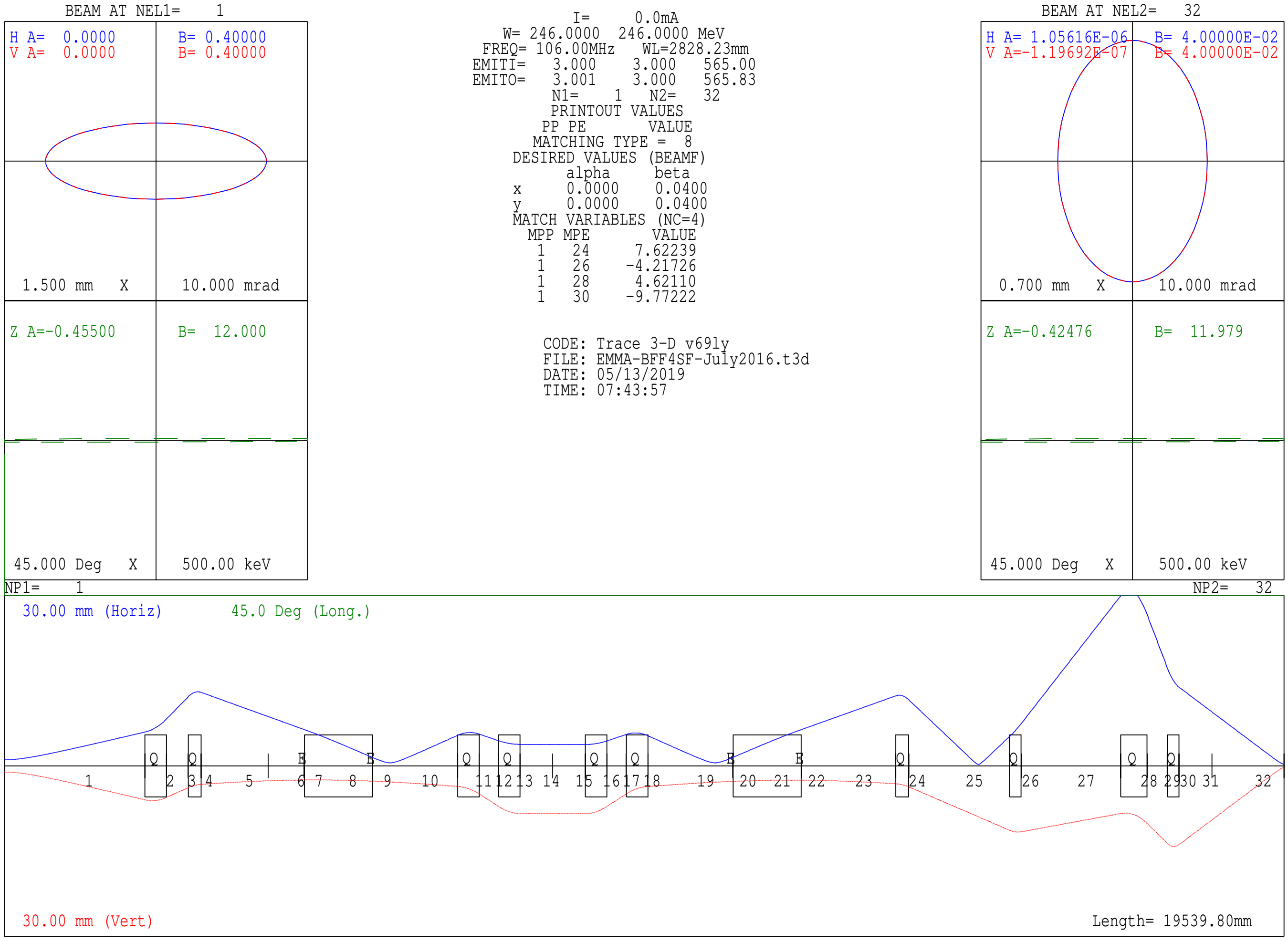


Figure 18: `Trace-3D` envelope simulation of element-sequence spanning SEBT:Q21 to the EMMA experimental chamber (SEBT3B). The horizontal envelope and its parameters are shown in blue, vertical in red and longitudinal in green. The input beam ellipses containing 4ϵ_{RMS} are shown on the left hand side, with A and B representing the Twiss parameters α and β, while the output distributions are on the right hand side. The input and output beam emittances are visible in the top center, labeled EMITI and EMITO, respectively, and have units of mm*mrad for transverse and deg*keV for longitudinal. The beam envelopes are shown at the bottom, following the same color convention. The location and lengths of quadrupoles are represented by the squares labeled Q. Drifts are represented by a black horizontal line at the lower graph midplane. Finally, the numbers on the lower graph, spanning 1 to 11, sequentially label all elements called in the simulation. Quadrupole gradients are shown in Table 17.

5.1 Magnet Parameters and Fields

The envelope simulations outlined in Table 10 each possess a set of magnetic field settings. Since the majority of elements described in the original simulations are quadrupoles, and since trace also assumes on-axis beams (without steerers), only the quadrupole magnetic field gradients are listed herein, for the record. These are the output `Trace-3D` quadrupole gradient values produced by the simulation, in T/m, corresponding to the simulation parameters shown in Table 10. It is noted that `TRANSOPTR` expects pole tip fields, not field gradients. Finally, the grouping of elements listed below corresponds to `Trace-3D` element sequences, which largely overlaps with, but does not exactly correspond to, the `/acc` database sequences. More information about ISAC HE quadrupoles may be found in [6].

Magnet	Aperture [cm]	Gradient [T/m]
DSB:Q1	2.6	4.4998
DSB:Q2	2.6	4.4998
DSB:Q3	2.6	5.6314
DSB:Q4	2.6	−11.0687
DSB:Q5	2.6	−13.2135
DSB:Q6	2.6	10.0949
DSB:Q7	2.6	−10.0949
DSB:Q8	2.6	13.2135
DSB:Q9	2.6	−13.5247
DSB:Q10	2.6	14.2040
DSB:Q11	2.6	−13.1102
DSB:Q12	2.6	19.1738
DSB:Q13	2.6	−9.9150
DSB:Q14	2.6	10.4106
DSB:Q15	2.6	4.1805
DSB:Q16	2.6	4.1805
SCB:Q1	2.6	10.4106
SCB:Q2	2.6	−9.9150

Table 11: DSB Quadrupole settings for `Trace-3D` simulation shown in Figure 12, as defined the original `.t3d` file. Beam parameters are listed in Table 10.

Magnet	Aperture [cm]	Gradient [T/m]
SEBT:Q9	2.6	−6.3572
SEBT:Q10	2.6	6.3572
SEBT:Q11	2.6	−6.3572
SEBT:Q12	2.6	6.3572
SEBT:Q13	2.6	−10.5028
SEBT:Q14	2.6	10.5028
SEBT:Q15	2.6	−10.5031
SEBT:Q16	2.6	10.5032
SEBT:Q17	2.6	−6.2323
SEBT:Q18	2.6	6.2322
SEBT:Q19	2.6	−6.2321
SEBT:Q20	2.6	6.2321

Table 12: SEBT Quadrupole settings for `Trace-3D` simulation shown in Figure 13, as defined the original `.t3d` file. Beam parameters are listed in Table 10. Note the trace sequence does not include SEBT:Q21 and Q22, while they are part of `sebt_db0` in the `/acc` database.

Magnet	Aperture [cm]	Gradient [T/m]
SEBT:Q21	2.6	−4.5000
SEBT:Q22	3.5509	6.5043
SEBT1:Q1	2.6	4.1803
SEBT1:Q2	5.158 74	−5.4772
SEBT1:Q3	2.6	5.6934

Table 13: SEBT1 Quadrupole settings for `Trace-3D` simulation shown in Figure 14, as defined the original `.t3d` file. Beam parameters are listed in Table 10. Note the trace sequence includes SEBT:Q21 and Q22, while they are part of `sebt_db0` in the `/acc` database.

Magnet	Aperture [cm]	Gradient [T/m]
SEBT:Q21	2.6	−2.4378
SEBT:Q22	3.5509	4.6533
SEBT2:Q1	2.6	−3.8047
SEBT2:Q2	5.158 74	4.0254

Table 14: SEBT2 (IRIS) Quadrupole settings for `Trace-3D` simulation shown in Figure 15, as defined the original `.t3d` file. Beam parameters are listed in Table 10. Note the trace sequence includes SEBT:Q21 and Q22, while they are part of `sebt_db0` in the `/acc` database.

Magnet	Aperture [cm]	Gradient [T/m]
SEBT:Q21	2.6	−4.9516
SEBT:Q22	3.5509	7.7022
SEBT3:Q1	3.5509	5.9527
SEBT3:Q2	2.6	−3.5113
SEBT3:Q3	2.6	−3.5113
SEBT3:Q4	3.5509	5.9527
SEBT3A:Q1	5.158 74	1.9083
SEBT3A:Q2	3.5509	−4.1391
SEBT3A:Q3	5.158 74	3.0689
SEBT3A:Q4	2.125 98	−6.5446

Table 15: SEBT3A (TIGRESS) Quadrupole settings for `Trace-3D` simulation shown in Figure 16, as defined the original `.t3d` file. Beam parameters are listed in Table 10. Note the trace sequence starts at SEBT:Q21, going all the way to TIGRESS. In the `/acc` database, this corresponds to sequential sequences.

Magnet	Aperture [cm]	Gradient [T/m]
SEBT:Q21	2.6	−5.4654
SEBT:Q22	3.5509	9.1367
SEBT3:Q1	3.5509	5.5041
SEBT3:Q2	2.6	−3.4085
SEBT3:Q3	2.6	−3.4085
SEBT3:Q4	3.5509	5.5041

Table 16: SEBT3-Straight (TBragg) Quadrupole settings for `Trace-3D` simulation shown in Figure 17, as defined the original `.t3d` file. Beam parameters are listed in Table 10. Note the trace sequence starts at SEBT:Q21, going all the way to TIGRESS. In the `/acc` database, this corresponds to sequential sequences.

Magnet	Aperture [cm]	Gradient [T/m]
SEBT:Q21	2.6	−4.9516
SEBT:Q22	3.5509	7.7022
SEBT3:Q1	3.5509	5.9527
SEBT3:Q2	2.6	−3.5113
SEBT3:Q3	2.6	−3.5113
SEBT3:Q4	3.5509	5.9527
SEBT3B:Q1	3.5509	7.6224
SEBT3B:Q2	2.6	−4.2173
SEBT3B:Q3	5.158 74	4.6211
SEBT3B:Q4	2.6	−9.7722

Table 17: SEBT3B (EMMA) Quadrupole settings for `Trace-3D` simulation shown in Figure 18, as defined the original `.t3d` file. Beam parameters are listed in Table 10. Note the trace sequence starts at SEBT:Q21, going all the way to TIGRESS. In the `/acc` database, this corresponds to sequential sequences.

6 `TRANSOPTR` Implementation of the ISAC-II Beamlines

Segments of the ISAC-II transport system, corresponding to the original `Trace-3D` simulations in Section 5 were generated using the `/acc` database sequences described in Section 2. The magnetic field gradients listed in Section 5.1 were converted to pole-tip fields, thanks to the listed magnet apertures, and provided to `TRANSOPTR`, enabling the generation of envelopes for comparison with trace.

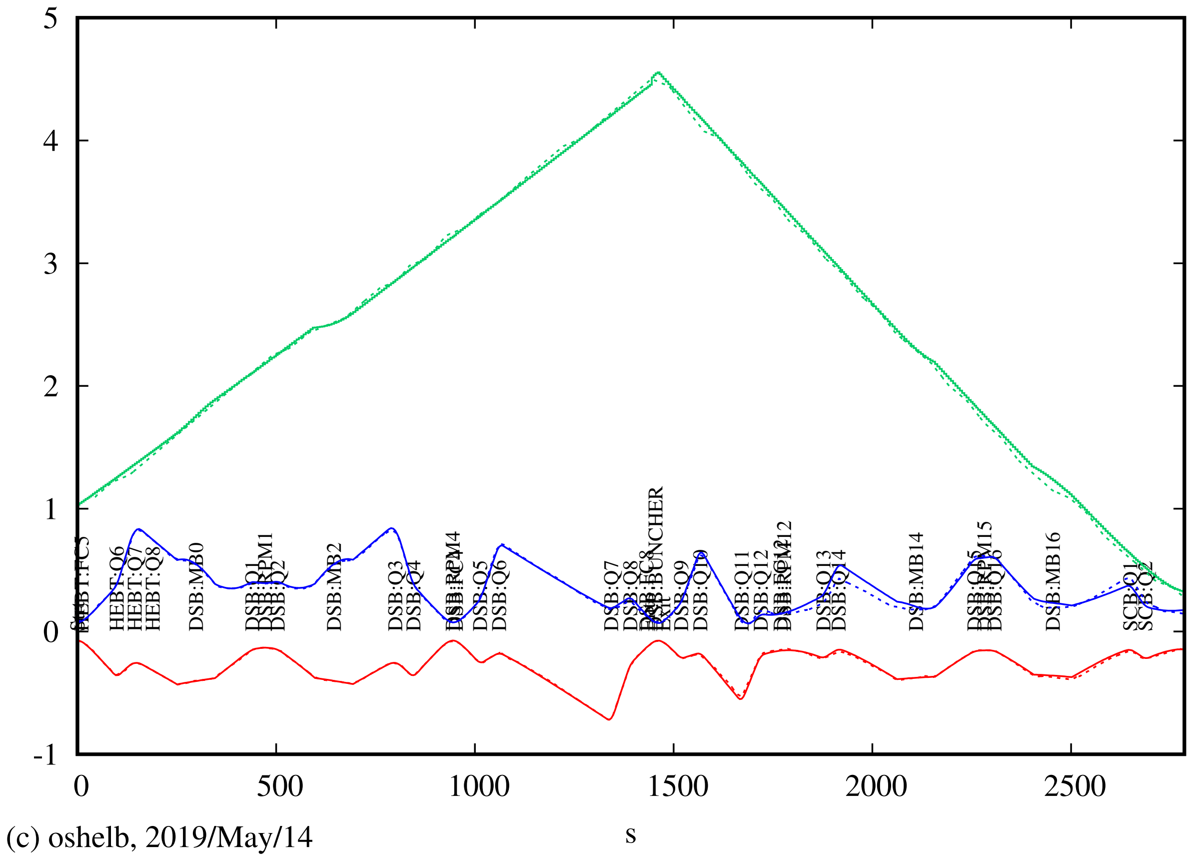
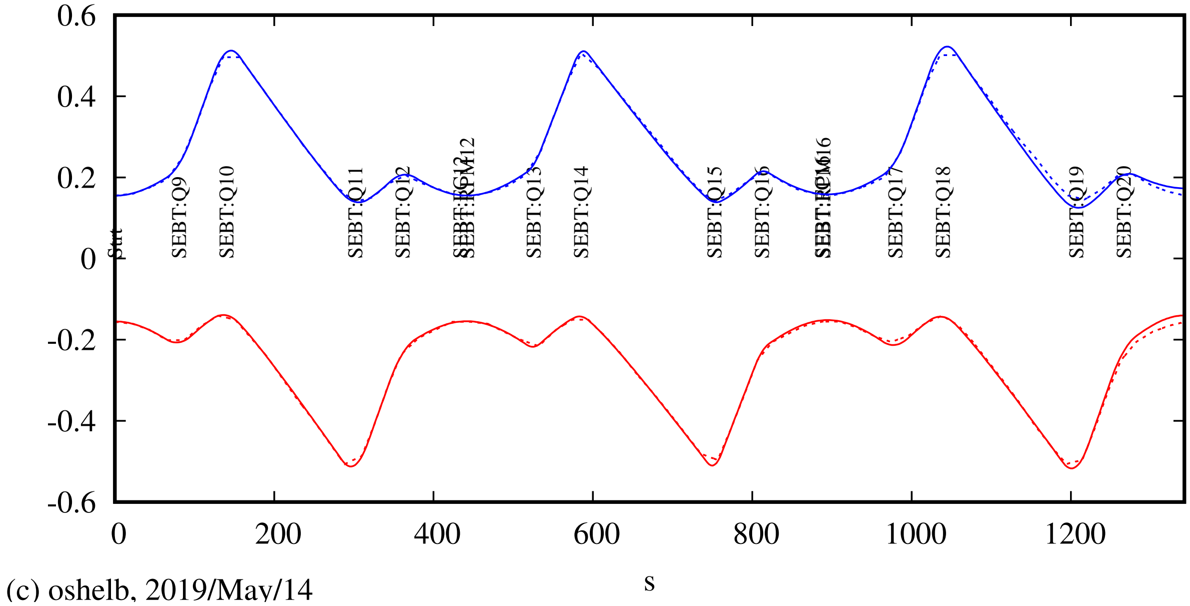


Figure 19: `TRANSOPTR` envelope simulation (solid lines), overlayed with the `Trace-3D` envelope (dashed lines), for the elements spanning HEBT:Q6 to SCB:Q2, representing the DSB line. The horizontal envelopes are shown in blue, vertical in red and longitudinal in green. Element names, as represented in the `/acc` database `TRANSOPTR` sequences are shown vertically at the graph midplanes. All axis dimensions are in cm.



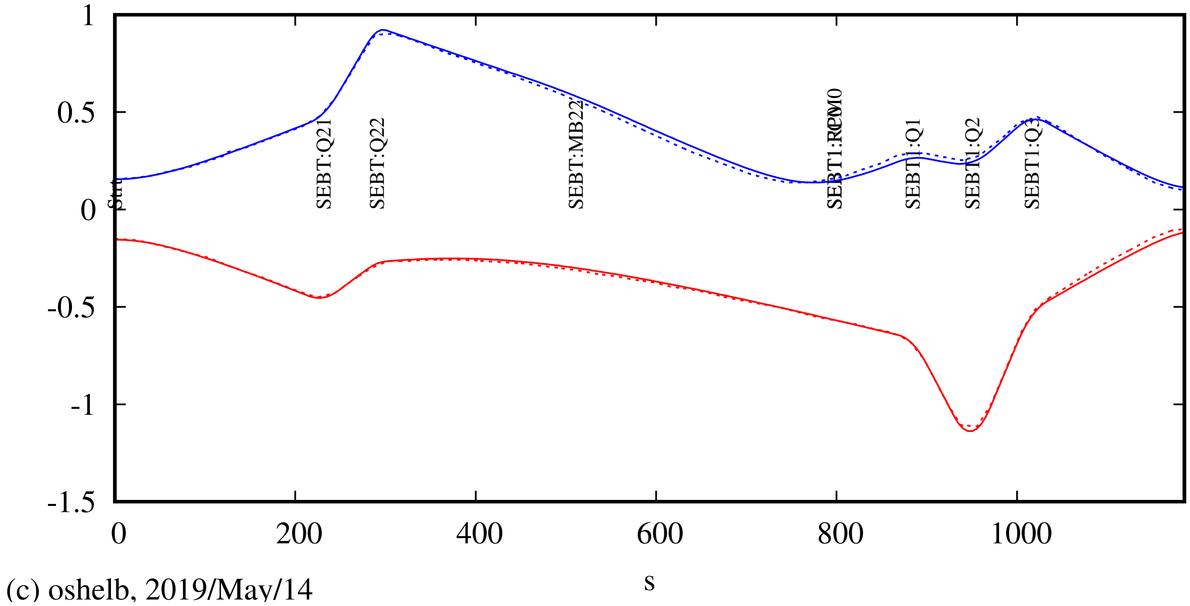
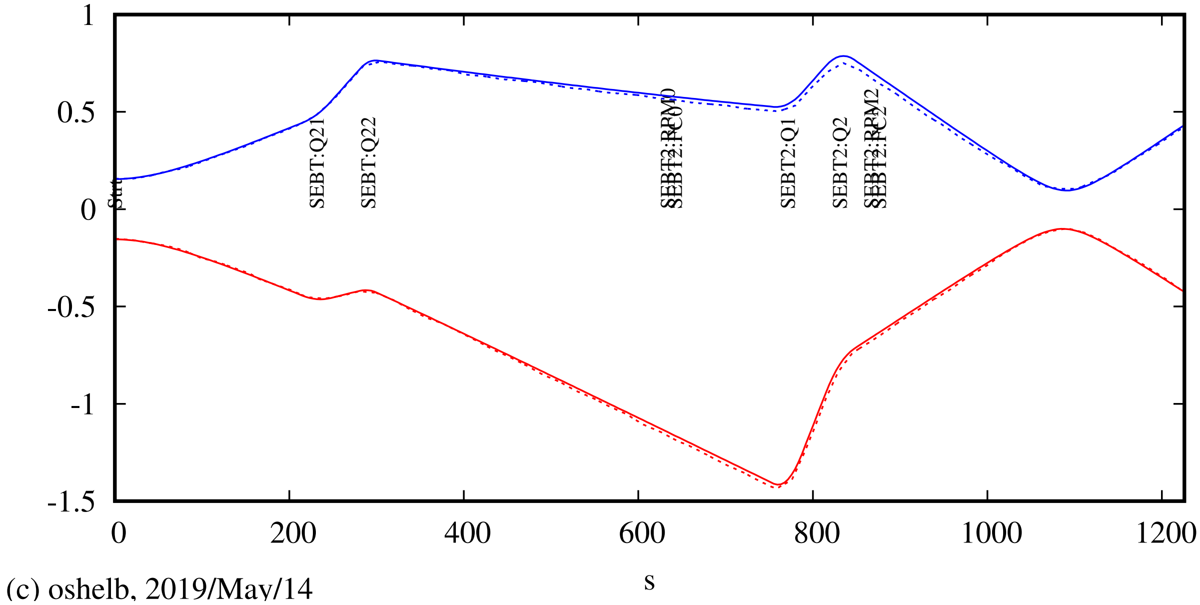


Figure 20: `TRANSOPTR` envelope simulation (solid lines), overlayed with the `Trace-3D` envelope (dashed lines), for the sub-sequences spanning SEBT:Q9 to Q20 (top) and SEBT1 (bottom). The horizontal envelopes are shown in blue, vertical in red and longitudinal in green. Element names, as represented in the `/acc` database `TRANSOPTR` sequences are shown vertically at the graph midplanes. All x and y-axis dimensions are in cm.



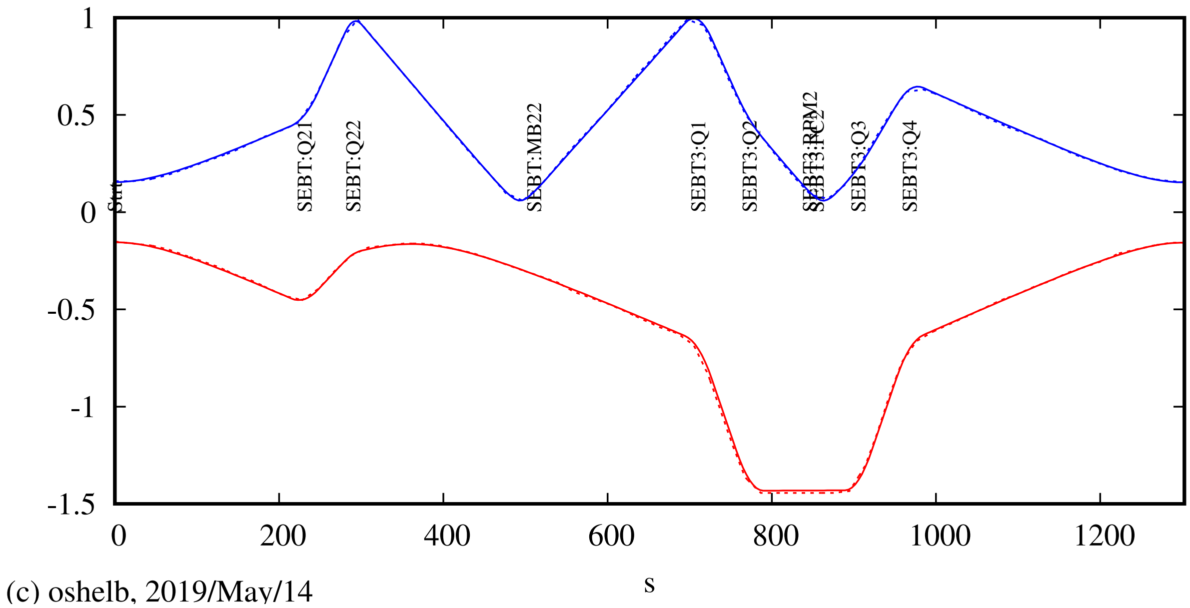
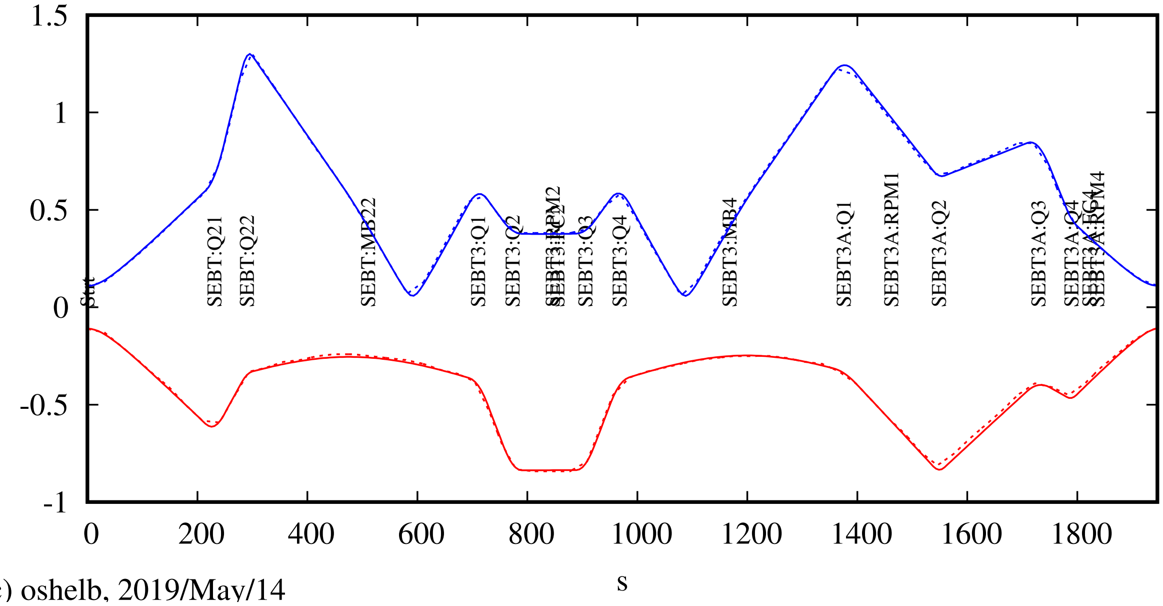


Figure 21: `TRANSOPTR` envelope simulation (solid lines), overlayed with the `Trace-3D` envelope (dashed lines), for the sub-sequences spanning SEBT:Q21 to SEBT2-IRIS (top) and SEBT:Q21 to SEBT3-TBragg (bottom). The horizontal envelopes are shown in blue, vertical in red and longitudinal in green. Element names, as represented in the `/acc` database `TRANSOPTR` sequences are shown vertically at the graph midplanes. All x and y-axis dimensions are in cm.



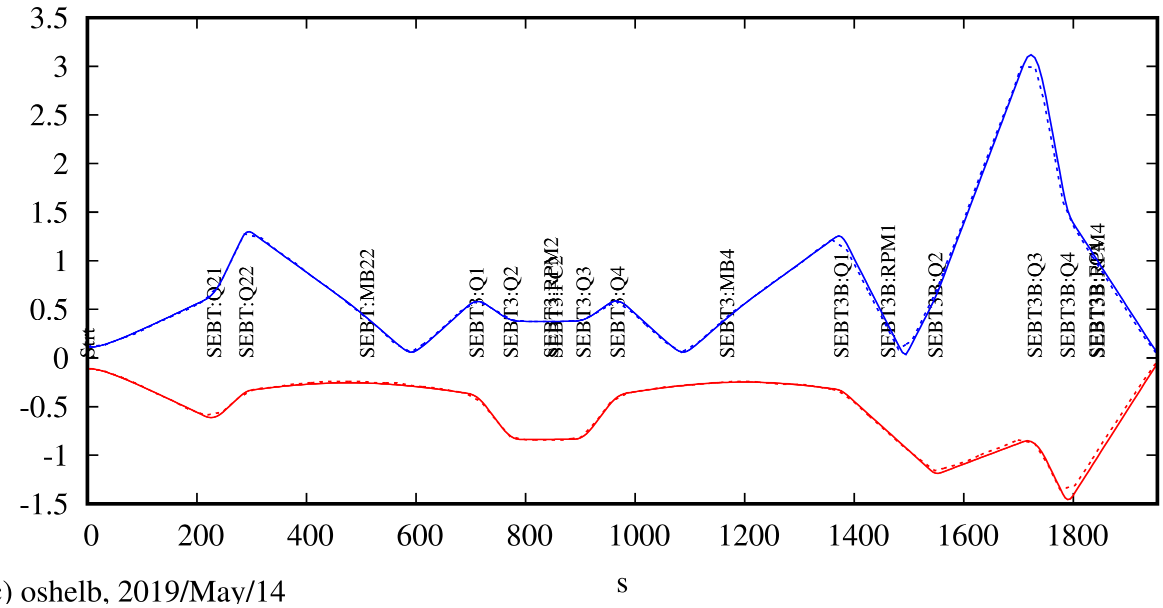


Figure 22: `TRANSOPTR` envelope simulation (solid lines), overlayed with the `Trace-3D` envelope (dashed lines), for the sub-sequences spanning SEBT:Q21 to SEBT3A-TIGRESS (top) and SEBT:Q21 to SEBT3B-EMMA (bottom). The horizontal envelopes are shown in blue, vertical in red and longitudinal in green. Element names, as represented in the `/acc` database `TRANSOPTR` sequences are shown vertically at the graph midplanes. All x and y-axis dimensions are in cm.

7 Conclusion

The TRANSOPTR envelopes in Section 6 agree well with the Trace-3D implementation. While there certainly remains considerable development work ahead, this nevertheless produces confidence that the /acc database implementation of the ISAC-II high energy beamlines produces sensible results.

Together with companion documents [1] and [2], this work now completes initial implementation of the ISAC-I and ISAC-II high energy transport systems and bunching RF cavities. Transport tunes to each experimental station at the ISAC facility may now be computed within the TRANSOPTR framework. This is a critical requirement for an integrated end-to-end model of the ISAC accelerator facility, which will allow for detailed systematic investigations of both tunes and emergent behavior at ISAC. Coupled with the possibility of beam-based feedback into the HLA framework, this paves the way for the development of more sophisticated tuning tools, for both physicsts and operators alike.

Certainly the most powerful aspects of this implementation lies within the /acc database, which now contains element descriptions, including physical dimensions and locations along the optical axis. Thanks to the TRIUMF HLA suite of software, which includes xml2optr[1], a routine to generate TRANSOPTR sy.f stacks automatically, using the database, in addition to saved tune values, long sequences of elements in the ISAC system may be generated with relative ease, without the need for manual beamline definitions. This represents a considerable time savings and indeed a powerful analysis tool for TRIUMF.

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[6] R. Baartman. *B-I Curve fits for TRIUMF Quads*. Technical Report TRI-DN-07-04, TRIUMF, 2007.

[1] Credit: Paul Jung & Thomas Planche