Beam Physics Note
TRI-BN-23-26
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Updates of the e-LINAC RF Calibration

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Abstract: This work reports the calibration of the amplitude and phase of e-linac RF. Further report on its implementation into HLA is also shown in the appendix.

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1 Objectives

The amplitude and phase of the RF gradient and phase (mainly EINJ and EACA) in e-LINAC have arbitrary inputs in TRANSOPTR "assumed" by the users. This affects the accuracy and the reliability when we want to compare the calculated envelope/tune with the beam profile during real operation. In order to solve this issue, calibration of the RF parameters was performed. This work summarizes the procedure of calibration, as well as the calibrated results with their implementation in hla/acc/env. Note that there were a few measurements taken. This report describes mainly the latest work done in 2023.

2 EINJ calibration

2.1 Beam energy from dipole magnetic field

2.1.1 B-I curve of EMBT:MB5A

Before we begin, the relationship between the magnetic field B and the coil current I of EMBT:MB5A is fitted up to the seventh order and plotted in Fig. 1. For instance, the relationship up to the first-order and third-order are given below (Note that further details can be found in [1, 2]):

$$B/\mathrm{T} = 3.14 \times 10^{-3}(I/\mathrm{A}) - 5.15 \times 10^{-5}$$
$$B/\mathrm{T} = -1.99 \times 10^{-8}(I^3/\mathrm{A}^3) + 3.16 \times 10^{-3}(I/\mathrm{A}) - 2.77 \times 10^{-5} \quad (1)$$

From the non-linear field in Fig. 1, we can see that the third order fit is sufficient to include the hysteresis effect of the magnet up to an accuracy of $\pm 7\,\mathrm{G}$.

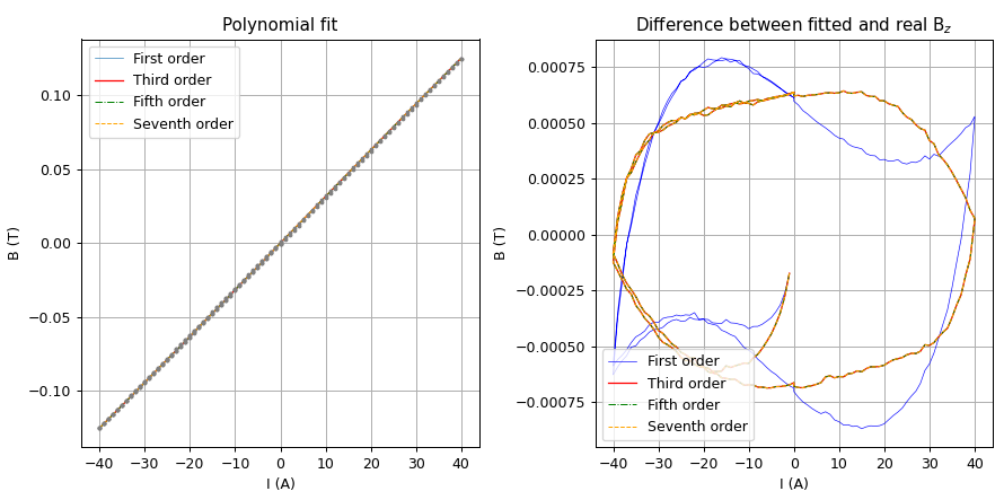


Figure 1: Relationship between the EMBT:MB5A current and the magnetic field

2.1.2 Magnetic rigidity

The magnetic field of the EMBT:MB5A dipole is related to the beam energy by the rigidity:

$$p = qB\rho$$

Taking the arc length of $\Delta\theta = 18$ deg and an effective length of $l = 0.1504$ m

$$\begin{aligned} p &= q \int_l \frac{B}{\Delta\theta} \, ds \\ &= qB \cdot (0.0473/\text{m}) \\ E^2 &= (T + E_0)^2 = (pc)^2 + E_0^2 \\ T + E_0 &= \sqrt{(pc)^2 + E_0^2} \\ T &= \sqrt{(pc)^2 + E_0^2} - E_0 \end{aligned}$$

where $E_0 = 0.511$ MeV and $q = -e$ for an electron beam, T is the kinetic energy, p is the momentum, c is the speed of light.

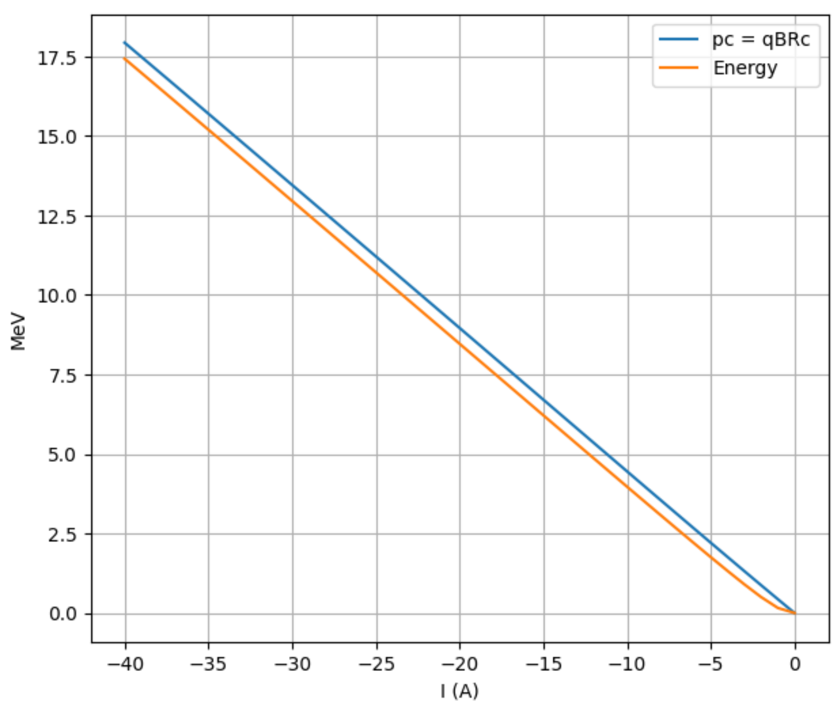


Figure 2: Relationship between the energy (or momentum) and the EMBT:MB5A dipole current.

2.2 Gradient

2.2.1 Procedures and Methods

1. The buncher was set to be off. EINJ phase was set to the point with the maximum beam brightness observed on EMBT:VS5B.

2. Buncher was turned on. It was set to the bunching phase by ensuring the same position (no energy gain from the buncher) on EMBT:VS5B as before it was turned on. Buncher phase setpoint = 81 ; Phase readback on VVM = -94.4.

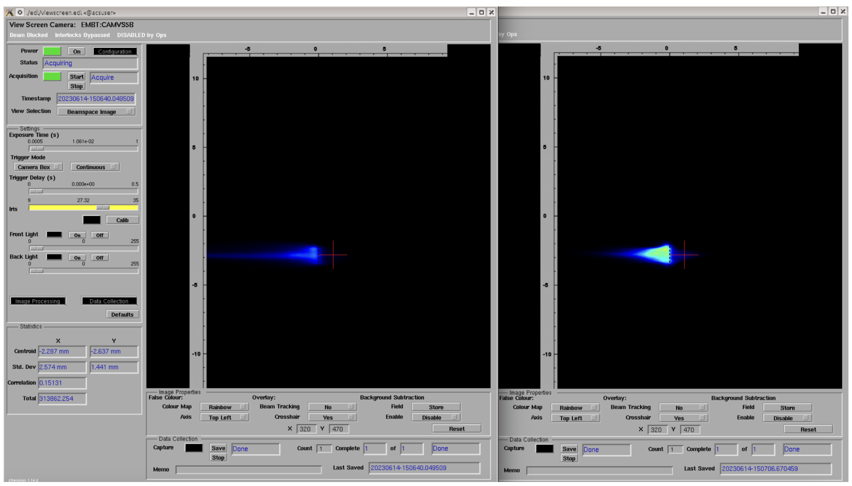


Figure 3: EMBT:VS5B beam image before starting the calibration. LHS shows the image when the buncher was off, while the RHS shows the beam when the buncher was turned on and set to the bunching phase. The error is determined from the approximate horizontal beam radius of about ± 2 mm, i.e. corresponds to $\sim 1.3\%$ for a typical dispersion of about 1.5 mm/% at EMBT:VS5B.

3. The EINJ phase was changed by ± 10 to check its effect on the beam. The maximum energy gain (EMBT:MB5A at max amplitude) is confirmed when the EINJ phase setpoint is -27 and phase readback on VVM is 174.

4. Ensure the horizontal edge of the beam is centered at EMBT:VS5B for max energy.

5. EINJ setpoint was changed from 540 up to a maximum of 900 with a step of 40. For each change, the beam was re-centered by adjusting the dipole (ref: EMBT:MB5A current around ~ -21.5 A at ~ 9.25 MeV).

6. The EMBT:MB5A dipole current, EINJ setpoint and VVM readback were all recorded.

2.2.2 EINJ VVM-bvol vs EMBT:MB5A coil current

Then, the EINJ VVM-bvol and the EMBT:MB5A coil current is also plotted and fitted in Fig. 4. Comparison with the previous measurements is also shown.

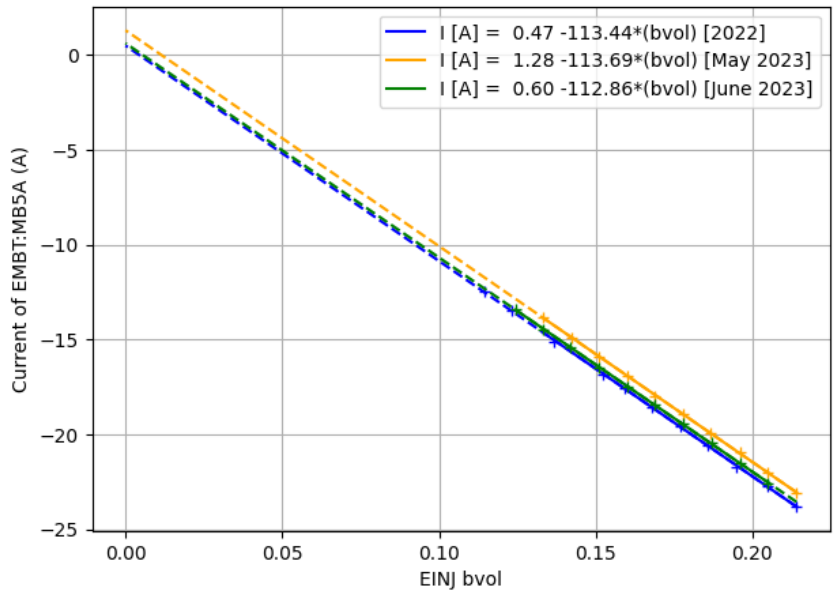
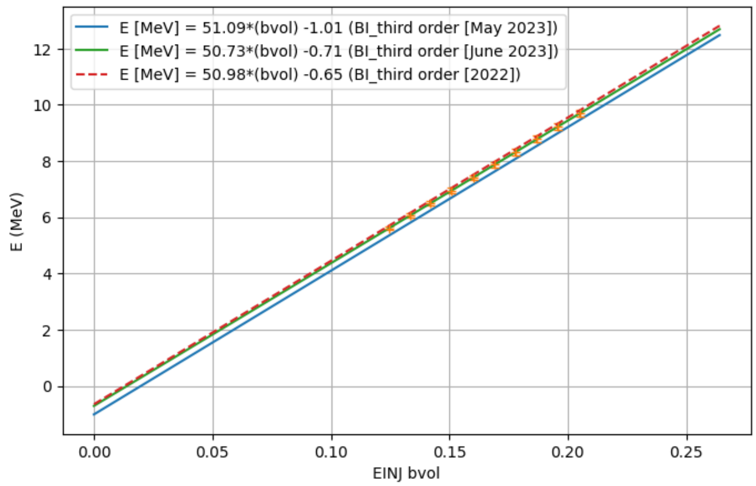


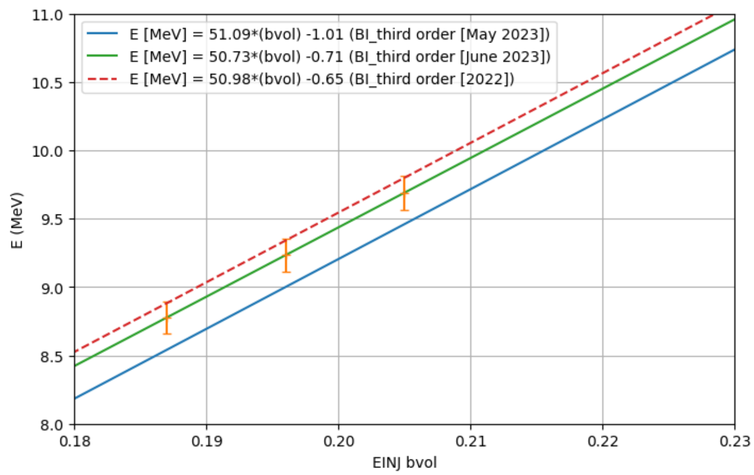
Figure 4: Relationship between the EMBT:MB5A current and the EINJ:VVM:BVOL.

2.2.3 EINJ VVM-bvol vs Energy

Using the third order of B-I relationship in 1 and Fig. 4, the relationship between the EINJ:VVM:BVOL and the beam energy is determined and shown in Fig.5. The comparison with previous measurement is also shown in Fig. 5. Further analysis of the work can refer to [2].



(a) Comparison of linear fit with previous calibration



(b) Zoomed-in around the typical range

Figure 5: Dependence of the beam energy on the EINJ:VVM:BVOL (Note: Error bar accounts for the ±1.3% of energy for measurement taken in June 2023).

2.3 Phase

2.3.1 Procedures and Methods

1. Similar to the calibration of EINJ amplitude, before starting the calibration for EINJ phase, buncher was set to be off. EINJ was estimated for maximum energy gain by obtaining the maximum brightness on EMBT:VS5B.

2. Buncher was set to bunching phase by ensuring the same max position on EMBT:VS5B as before it was turned on. Buncher phase setpoint = 68 ; Buncher phase readback on VVM = -78.

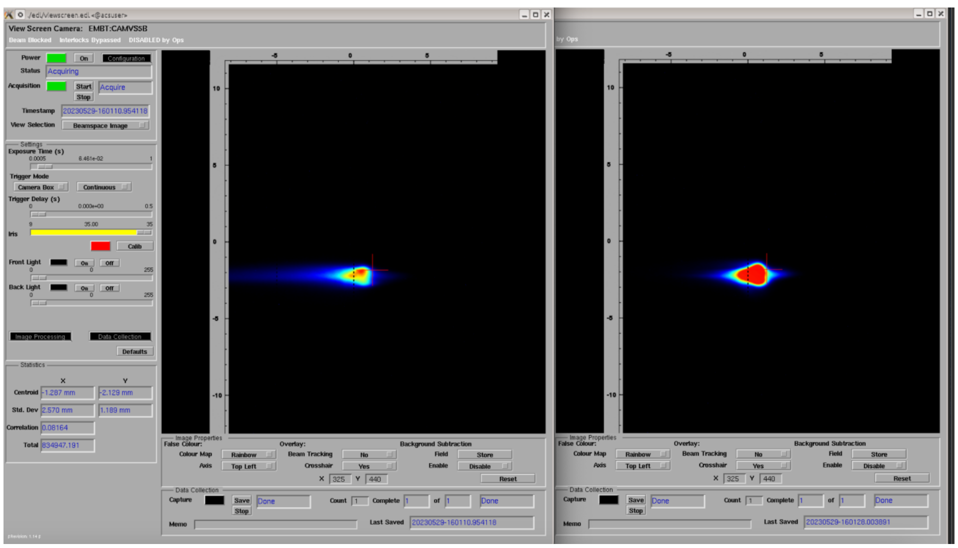


Figure 6: Confirming the buncher is at the bunching phase. LHS shows the beam on EMBT:VS5B without buncher being turned on, while the RHS shows the beam when the buncher is turned on and placed at the bunching phase.

3. The EINJ phase was re-optimized for maximum energy. All the VVM readback and setpoint were recorded.

4. The EINJ phase was changed by ± 20. The beam is re-centered on the viewscreen by adjusting the EMBT:MB5A coil current. The buncher setpoint was optimized for a properly bunched beam. The corresponding readback and setpoint were all recorded.

5. Step 4 was repeated for ± 40 of EINJ phase.

2.3.2 Results

Similar simulation was done by TRANSOPTR using the input code given in Appendix A. The EINJ:VVM:PHASE to Energy plot is compared with the TRANSOPTR model. The result is shown in Fig. 7.

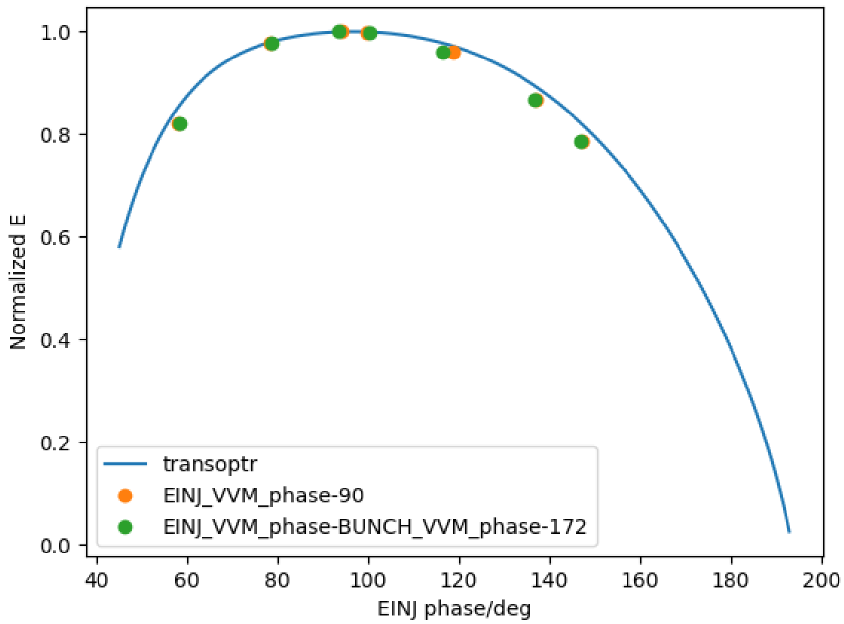


Figure 7: The plot of EINJ phase vs TRANSOPTR simulations. The orange points are fitted data using (VVM:EINJ:PHASE-90). The green points are fitted data using (VVM:EINJ:PHASE-VVM:BUNCHER:PHASE-172). The input of TRANSOPTR used to generate the fit is attached in Appendix A.

The sign of the VVM phase is also checked by the change in the X-envelope. Fig. 8 shows the change of σ_x with EINJ phase simulated by TRANSOPTR. As seen, σ_x decreases when phase is increased up to +30 deg. Beyond +30 deg, σ_x increases significantly as most particles are likely not be in the accelerating phase. On the other hand, σ_x increases when the EINJ phase is reduced from the max.

Similar behaviour is observed at EMBT:VS5B as shown in Fig. 9. When the EINJ phase is changed by -10 deg, it shows an elongated beam in X, while it shows a smaller beamsize in X when the phase is changed by +10 deg. This consistency proves that the sign of EINJ phase recorded by VVM:EINJ:PHASE is the same with the one simulated by TRANSOPTR, i.e. VVM:EINJ:PHASE is correlated to EINJ phase in TRANSOPTR by:

$$\text{TRANSOPTR:EINJ:PHASE} = \text{VVM:EINJ:PHASE} - 90/\text{deg} \tag{2}$$

However, as the phase of EGUN is not known, the VVM:EINJ:PHASE is subject to change daily. In that case, the input from epics to be load into TRANSOPTR in eqn. 3 will also fluctuate from day to day incorrectly. To solve this, the relative phase between

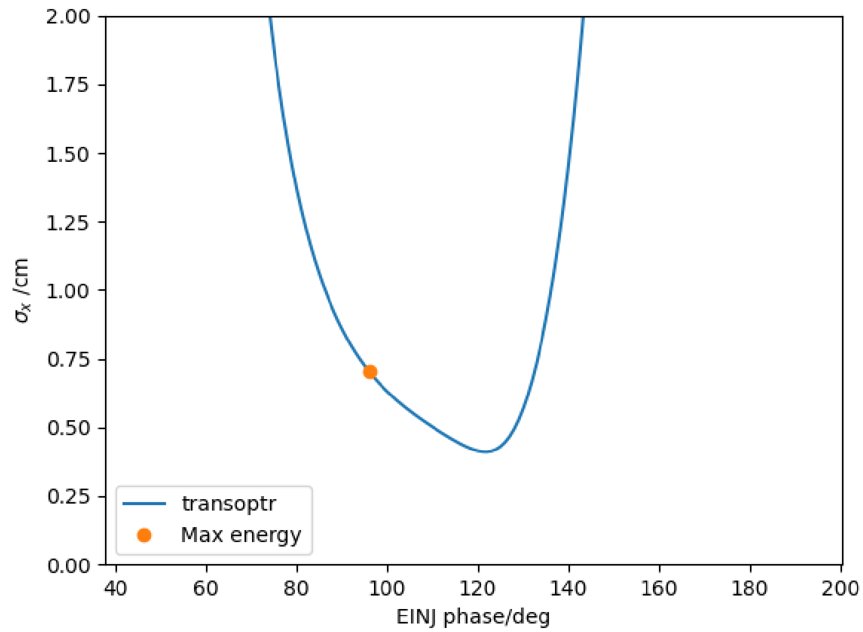


Figure 8: TRANSOPTR calculations of EINJ phase VS σ_x at EMBT:VS5B. The orange point (96 deg) corresponds to the phase with the highest energy gain. σ_x decreases when phase is increased up to +30 deg, while σ_x increases when the EINJ phase is reduced from the max. energy (Note: The input for TRANSOPTR is attached in Appendix A).

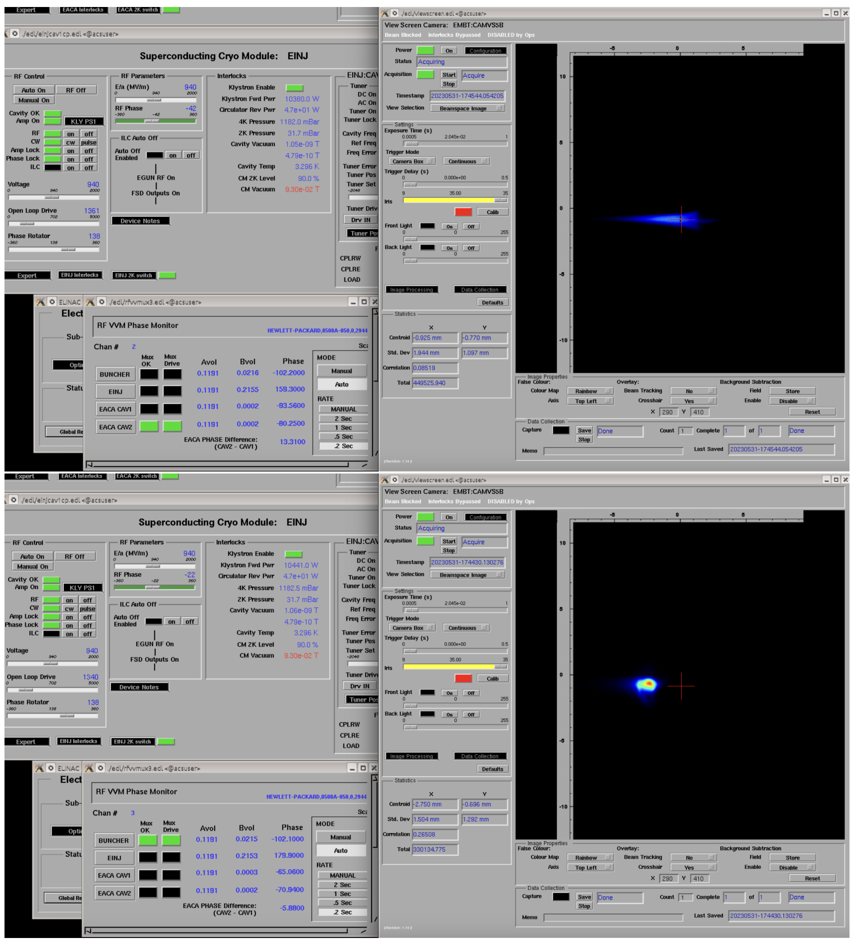


Figure 9: The beam enveloped observed at EMBT:VS5B when the EINJ phase is changed by -10 deg (top) and +10 deg (bottom).

VVM:EINJ:PHASE and VVM:BUNCHER:PHASE is used instead:

$$\text{TRANSOPTR:EINJ:PHASE} = \text{VVM:EINJ:PHASE} - \text{VVM:BUNCHER:PHASE} - 172/\text{deg} \quad (3)$$

2.3.3 The effect of EINJ phase change

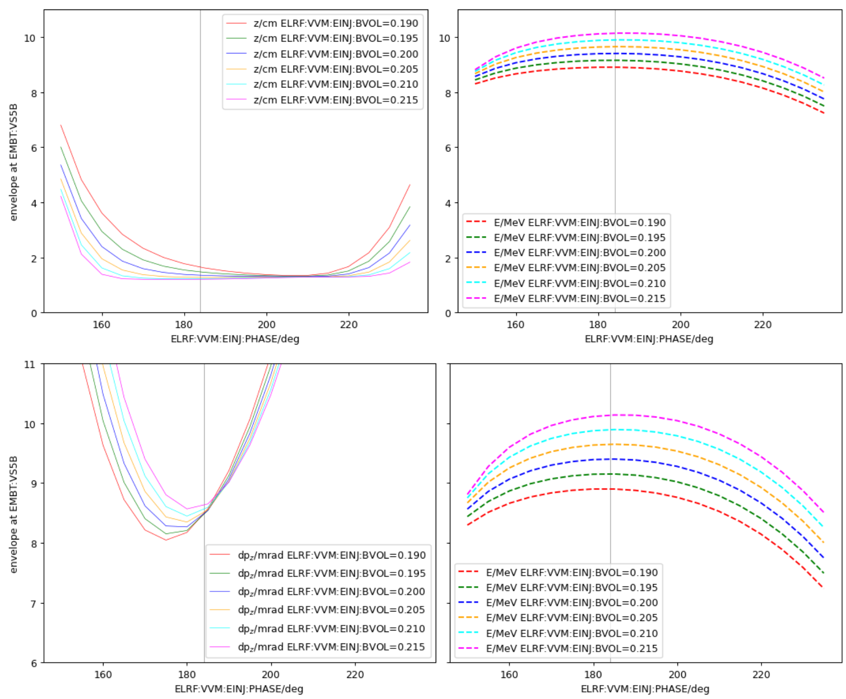


Figure 10: The change of the longitudinal size (σ_z) and the momentum spread ($\sigma_{z'}$) simulated by TRANSOPTR.

3 EACA calibration

3.1 Gradient

A simpler calibration was also performed for EACA. The energy before passing the EACA cavity is assumed to be about 9.1 MeV, and the contribution from both EACA1 and EACA2 are assumed to be the same. Also, the linear relationship between the EHAT:MB4 dipole current and the beam energy is taken as T=0.235(I/A)+0.013 MeV. Using the actual VVM data from both EACA1 and EACA2 during the high-power beam delivery in June 2023, we estimated the relationship between bvol and the beam energy is given as eq. 4. The plot is shown in Fig. 12.

$$T = 15.3 \times (\text{bvol}) + 9.1\,\text{MeV} \quad (4)$$

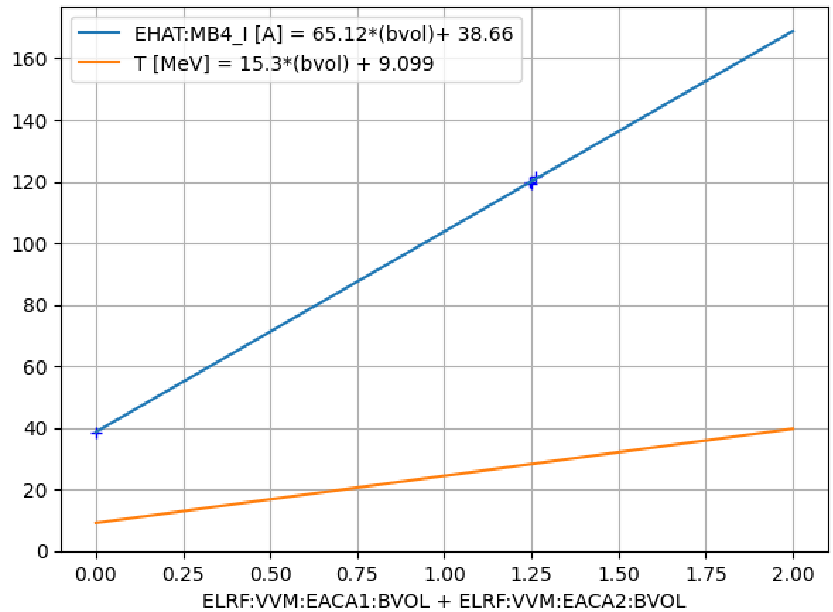


Figure 11: Relationship between the coil current of EHAT:MB4 and the beam energy (T) to ELRF:VVM:EACA1:BVOL+ELRF:VVM:EACA2:BVOL.

3.2 Phase

On the other hand, the phase difference between the two EACA and buncher as picked up by the ELRF:VVM is also calibrated. As calculated by TRANSOPTR, the maximum energy gain occurs at the phase of EACA1=-22 deg and EACA2=-156 deg respectively. From the data we used to run beam in June 2023 (we are assuming the energy is maximum at the operational EACA phase), the average phase difference between EACA1 and buncher ($\Delta\phi_1$) and the average phase difference between EACA2 and buncher ($\Delta\phi_2$) are about -76.4 deg and 130 deg respectively. Therefore, the calibrated phase input for TRANSOPTR from the phase picked up by VVM is given as

$$\begin{aligned}
\text{TRANSOPTR:EACA1:PHASE} &= \text{VVM:EACA1:PHASE} - \text{VVM:BUNCHER:PHASE} \\
&- (-76.4 \text{ deg} + 22 \text{ deg}) \\
&= \text{VVM:EACA1:PHASE} - \text{VVM:BUNCHER:PHASE} \\
&+ 54.4 \text{ deg} \\
\text{TRANSOPTR:EACA2:PHASE} &= \text{VVM:EACA2:PHASE} - \text{VVM:BUNCHER:PHASE} \\
&- (130 \text{ deg} + 156 \text{ deg}) \\
&= \text{VVM:EACA2:PHASE} - \text{VVM:BUNCHER:PHASE} \\
&- 286.8 \text{ deg}
\end{aligned}$$

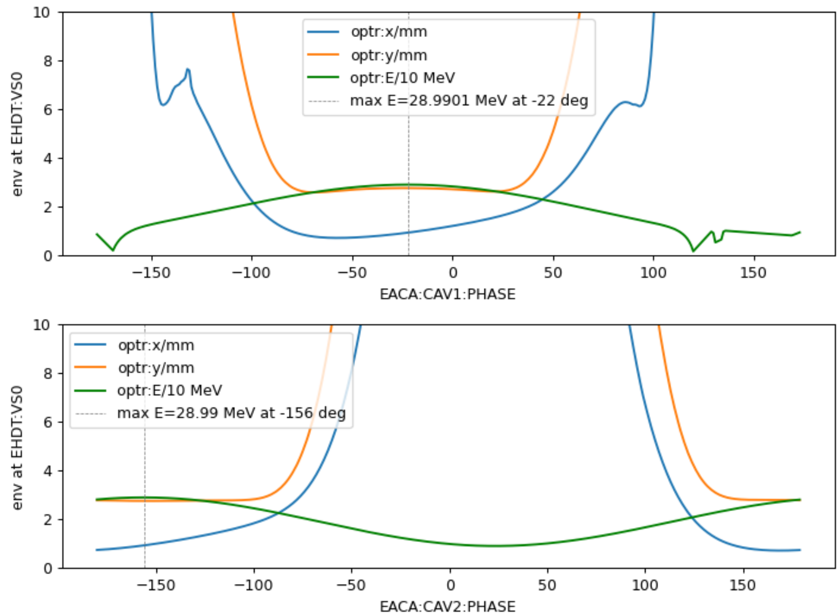


Figure 12: The envelope parameters and energy at EHDT:VS0 as calculated by TRANSOPTR at different EACA phases.

A TRANSOPTR input for EINJ phase calibration

The following TRANSOPTR input was used for elinac/egun-embt-fc6. . (Note that futher information about the LINAC in TRANSOPTR can be found in [3]) .:

```
2e-05 0.0 0.0 0.510999 -1.0 5.4e-13
-1 5 0.01 0.0001
0 0.0 1.0 0.0
0.373 1.06 0.373 1.06 0.014 1.0
1.0 1.0 1.0 1.0 1.0 1.0 1.0 1.0
2
1 2 -0.856 3 4 -0.856
15
3e+05 0.0 3.5e+05 0 ! EGUN:BIAS:VOL V1 V
2.8524 -5.0 5.0 0 ! EGUN:SOL1:CUR B1 A
0.025 0.0 0.05 0 ! ELRF:VVM:BUNCH:BVOL RFA1 V
-77.0 -360.0 360.0 0 ! ELRF:VVM:BUNCH:PHASE RFP1 deg
3.7988 -5.0 5.0 0 ! ELBT:SOL1:CUR B2 A
3.1683 -5.0 5.0 0 ! ELBT:SOL2:CUR B3 A
10.0 0.0 30.0 0 ! EINJ:AMP RFA2 MV
93.45 -360.0 360.0 0 ! EINJ:PHASE RFP2 deg
2.689 -5.0 5.0 0 ! EMBT:Q1:CUR QM1 A
```

-3.601 -5.0 5.0 0 ! EMBT:Q2:CUR QM2 A
2.142 -5.0 5.0 0 ! EMBT:Q3:CUR QM3 A
1.561 -5.0 5.0 0 ! EMBT:Q4:CUR QM4 A
-2.026 -5.0 5.0 0 ! EMBT:Q5:CUR QM5 A
0.0 -5.0 5.0 0 ! EMBT:Q5B:CUR QM6 A
3.52 -5.0 5.0 0 ! EMBT:Q6:CUR QM7 A
0.001 20
10 0.0 0.95 20

B Application in `gitlab.triumf.ca/hla/acc`

B.1 Change in `sequence`

The following changes were made to `elinac/sequence/einj.xml`

```
...
<epics>
<setpoint pv="ELRF:VVM:EINJ:PHASE" unit="deg" min="-180" max="180"/>
<setpoint pv="ELRF:VVM:EINJ:BVOL" unit="V" min="0" max="1"/>
</epics>
<optr freq="1.3*GHz" phase="ELRF:VVM:EINJ:PHASE-90*deg"
scale="(50.63*1e6*ELRF:VVM:EINJ:BVOL-0.78*MV)*2" mapFile="elinac/fieldMap/einj.dat"
nlines="447"/>
...
```

B.2 Change in `tune`

The following changes were made to most of the tune files that pass through EINJ such as `elinac/tune/egun-embt_ fc6_ ref.xml`:

```
...
<set value='0.215*V' pv='ELRF:VVM:EINJ:BVOL' />
<set value='-170*deg' pv='ELRF:VVM:EINJ:PHASE' />
...
```

References

[1] T. Planche (2014). [link].
URL https://beamphys.triumf.ca/~tplanche/magnetic_measurements/e-linac_magnets/dipoles/EMBT/measurements_at_TRIUMF/EMBT_SN0001/data/EMBT_DIPOLE_SN0001_40A_14May28_1334.dat

[2] H. W. Koay (2023). [link].

URL https://triumfoffice365-my.sharepoint.com/:u:/g/personal/hkoay_triumf_ca/ET1k54Tv5qVMhPkA4lO6QOOBBLmSV6biRR_xNuNoC9sz7w?e=C0foGz

[3] R. Baartman, TRIUMF beam physics note TRI-BN-15-0: Linac envelope optics, Tech. rep., TRIUMF (2015).