TRIUMF Beam Physics Note
TRI-BN-17-20
January 22, 2018

Envelope calculations on the Ion Beam Injection and Extraction of CANREB EBIS

Matthew Pereira Wilson

TRIUMF

Abstract: An electron beam ion source (EBIS) is being developed for the production of highly charged ions in the CANREB (CANadian Rare isotope facility with Electron Beam ion source) project at TRIUMF. The multiple tunable electrodes of the CANREB EBIS, coupled with the necessity of directing both an electron beam and an ion beam of varying charge, impose a challenging task for the optimization of the beam optics. With this in mind, beam envelope simulations have been performed to determine the acceptance of the CANREB EBIS and the emittance of the extracted ion beam. The electric field of the different EBIS electrodes were modelled using finite element analysis software and the envelope simulations were executed using beam envelope code TRANSOPTR. Preliminary results show TRANSOPTR as a viable candidate for the tuning of the CANREB EBIS.

4004 Wesbrook Mall, Vancouver, B.C. Canada V6T 2A3 Tel: 604 222-1047 Fax: 604 222-1074
www.triumf.ca

Contents

1 Introduction

The CANREB project at TRIUMF is designed to produce pure, highly charged, radioactive isotopes for acceleration and research in nuclear physics. The main component of the CANREB project is an Electron Beam Ion Source (EBIS) that is designed to increase the charge to mass ratio of the radioactive isotope beam. An EBIS uses a magnetically compressed electron beam to increase the charge of the injected ions through successive electron impact ionization. The setup of the CANREB EBIS poses a very interesting challenge for the optimization of this process, since the same section of beam line has to transport a high intensity electron beam, and a pulsed ion beam that is singly charged on injection and +n charged on extraction. It also has to ensure the overlap between the beams at the EBIS centre is maximized. With the purpose of tuning the CANREB EBIS electrode potentials, the beam simulations were performed with a beam envelope tracking code that offers a quick and efficient tool for optimizing the beam envelope size. The optimized beam envelope was then used to estimate the CANREB EBIS acceptance of the injected beam and determine the emittance of the extracted beam.

1.1 Abbreviations

- ARIEL: Advanced Rare IsotopE Laboratory
- CANREB: CANadian Rare isotope facility with Electron Beam ion source
- ISAC: Isotope Separator and ACcelerator facility
- HRS: High Resolution mass Separator
- RFQ: Radio Frequency Quadrupole
- PDT: Pulsed Drift Tube
- EBIS: Electron Beam Ion Source
- NIS: NIer-Spectrometer
- LEBT: Low Energy Beam Transport

2 LEBT beam line

The CANREB EBIS is located along the ARIEL Low Energy Beam Transport (LEBT) line[1]. By the time singly charged ions reach the LEBT line, they have been mass selected to 1/200,000 resolution by the High Resolution mass Separator (HRS)[2]. The beam is then thermally cooled and bunched at the Radio Frequency Quadrupole (RFQ) buncher, and at the Pulsed Drift Tube (PDT) its kinetic energy is reduced from 60 qkeV to 14 qkeV.

Beam envelope simulations of the CANREB EBIS were performed from the entrance of the PDT to the centre of the EBIS trap electrode, and from the centre of the EBIS trap electrode to the end of the LEBT matching section. The matching section of the LEBT line is common to both injected and extract ions from the EBIS. Between the PDT and the EBIS, there are four einzel lenses, of which two belong to the matching section. Optics belonging to the matching section transport singly charged ions on injection and +n charged ions on extraction.

Down stream of the EBIS there is a Nier-spectrometer for mass to charge ratio selection. Schematic view is given in Figure 1 of the LEBT line.

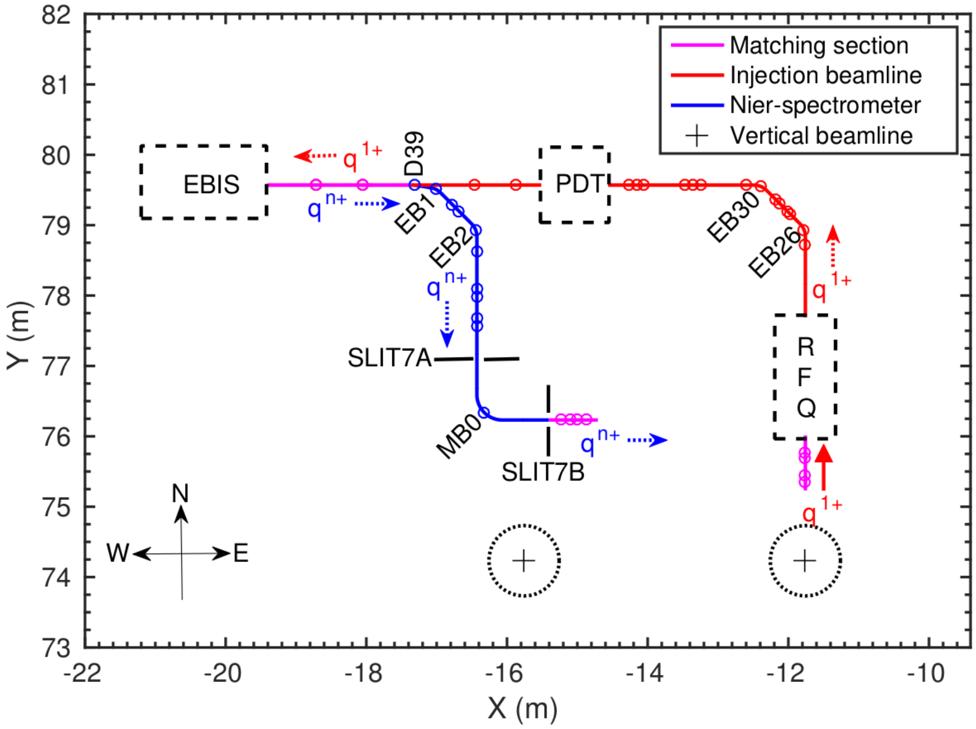

Figure 1: Schematic of the LEBT beam line[1]

3 Electrostatic Field Modeling

In order to perform the beam envelope calculation along the LEBT beam line, the electromagnetic properties of the different beam optical elements must be known to a good degree of resolution. The electrostatic properties of the PDT, einzel lenses and EBIS were modeled using OPERA-TOSCA electrostatic model. The magnetostatic properties of the EBIS were obtained by Heidelberg University in their development of the CANREB EBIS[3] .

3.1 Pulsed Drift Tube

The CANREB PDT is used to reduce the kinetic energy of the bunched beam leaving the RFQ, so as to match the design injection energy of the EBIS. To recreate the PDTs mode of operation in TRANSOPTR, the along axis potential used starts at a far edge of the PDT OPERA model, where the potential is 0 kV and ends at the physical centre of the PDT, where the potential is maximum. In TRANSOPTR, this emulates the device being turned off when the bunch is at the centre. See figure 2 for geometry used in OPERA simulation and figure 3 for resulting along axis potential with PDT at 46 kV.

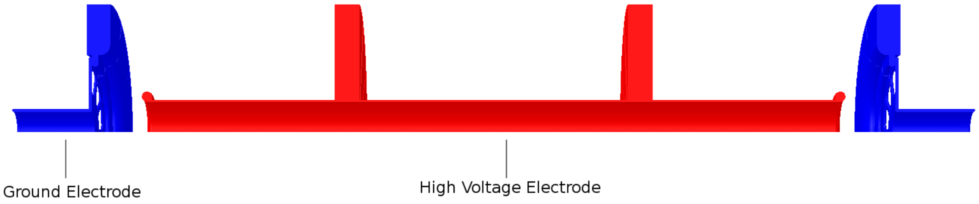

Figure 2: One Quarter of the PDT geometry in finite element analysis software (Opera)

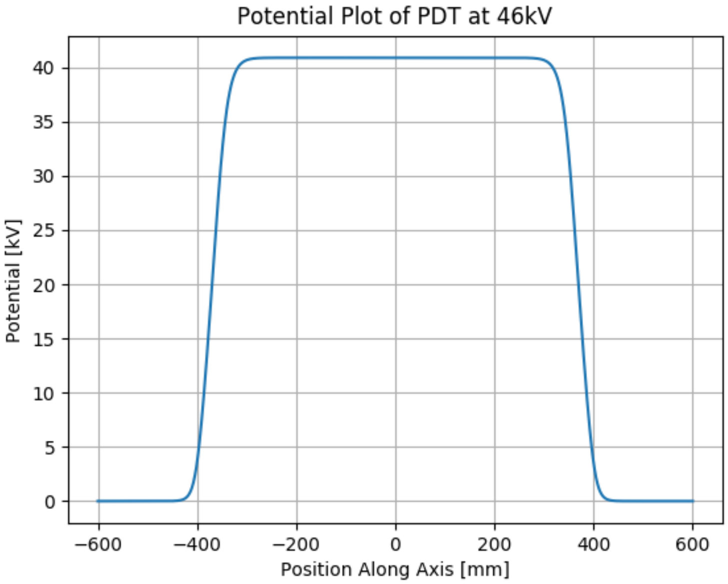

Figure 3: Along axis potential of the PDT

3.2 Einzel Lens

Einzel lenses are simple optical instruments that allow for the refocusing of the beam. For further reading on the physics of the einzel lens and charged particle optics see reference[4]. See figure 4 for geometry used in Opera simulation and figure 5 for resulting along axis potential of the einzel lens at −10 kV. The four einzel lenses in the LEBT beam line have identical geometries.

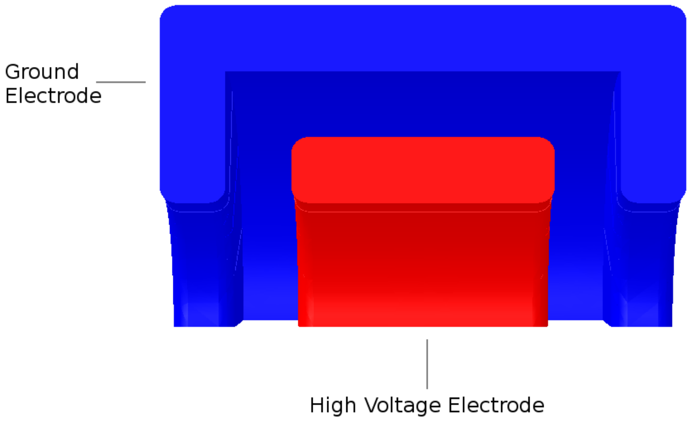

Figure 4: One Quarter of the Einzel Lens geometry in finite element analysis software (Opera)

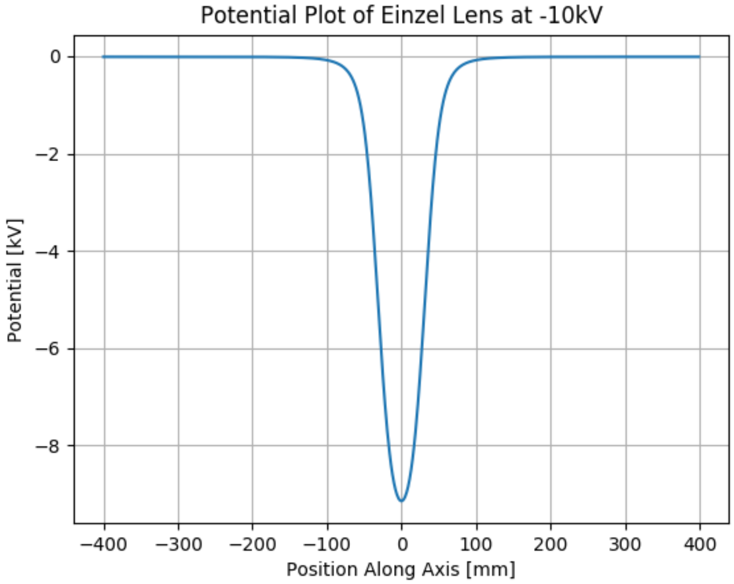

Figure 5: Along axis potential of the Einzel Lens

3.3 Electron Beam Ion Source

The CANREB EBIS is composed of four distinct sections: a collector, a sikler lens, the EBIS trap electrodes and an electron gun. Schematic shown in figure 6 does not include the electron gun since its electrostatic properties are outside the scope of the ion beam simulations. See figure 7 for the along axis potentials of the EBIS electrodes, where the x=0 position is the centre of the EBIS trap.

The electron beam is generated to the left of the EBIS trap electrodes (see figure 6). The electron beam passes through the EBIS trap and sikler lens and is dumped inside the collector. The ion beam's injection and extraction paths are the same, so once the ion beam is inside the EBIS, it only travels inside the collector, sikler lens and EBIS drift tubes up to and including the trap. It remains trapped until the desired charge state is reached and it is then ejected the same way it came in. The ion beam never travels left of the EBIS trap electrode. Figures 8, 9 and 10 illustrate the trapping of the ion beam and the changes that occur to the EBIS electrode potentials. The electron beam has not been represented in the illustrations, but its action is present in all stages.

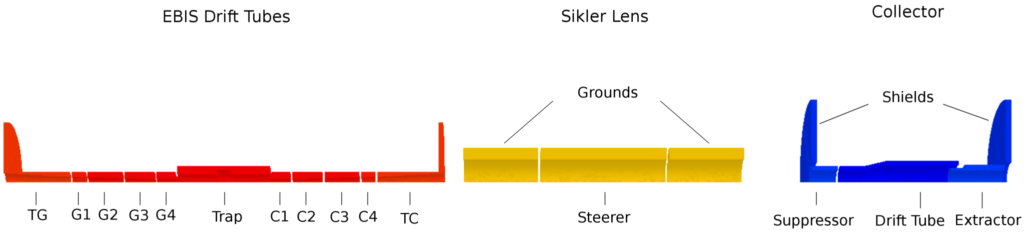

Figure 6: EBIS geometry in finite element analysis software (Opera)

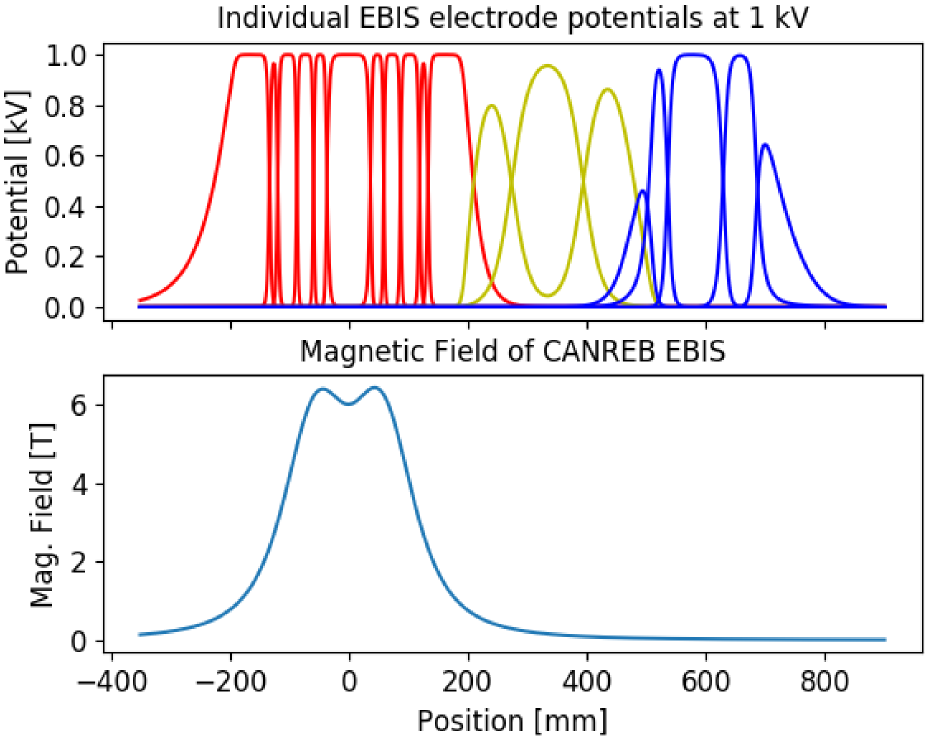

Figure 7: CANREB EBIS along axis potentials

4 Electron Beam

The charge breeding process of the EBIS is dependent on the overlap between the ion and electron beams at the centre of the EBIS trap. To provide an optimization goal for the ion beam envelope simulations, the radius and acceptance of the electron beam at the centre of the EBIS trap were analytically calculated. The electron beams space charge potential was also calculated so that its effect may be included in the ion beam simulations at a later date.

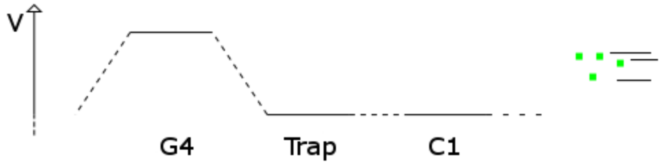

Figure 8: Schematic of the EBIS trapping mechanism - Injection

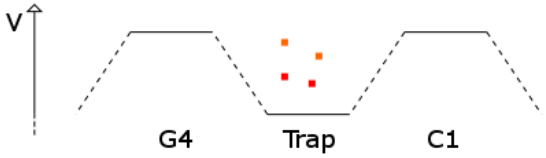

Figure 9: Schematic of the EBIS trapping mechanism - Charge State Breeding

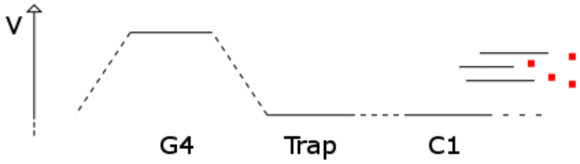

Figure 10: Schematic of the EBIS trapping mechanism - Extraction

4.1 Radius

The calculation of the electron beam's radius was performed using Herrman's theorem[5]. This approach takes into consideration the thermal and non-laminar motion of the electrons, as well as properties derived from the cathode[6]. The Herrmann radius $\mathrm{r_e}$ contains 80% of the electron beam's total current and is given by,

$$r_e = r_b\sqrt{\frac{1}{2}+\frac{1}{2}\sqrt{1+4\Big(\frac{8kT_c r_c^2 m_e}{e^2 r_b^4 B^2}+\frac{B_c^2+r_c^4}{B^2 r_b^4}\Big)}} \tag{1}$$

Where $\mathrm{r_b}$ is the Brillouin radius[7],

$$r_b = \sqrt{\frac{2m_e I_e}{\pi\epsilon_0 v_e e B^2}} \tag{2}$$

Variable Name		Value
Intensity	$\mathrm{I_e}$	0.5 A
Magnetic Field at Trap	B	6 T
Magnetic Field at Cathode	$\mathrm{B_c}$	0.0021 T
Electron Energy	E	1.6 kV
Cathode Temperature	$\mathrm{T_c}$	1200 K
Radius of Cathode	$\mathrm{r_c}$	3.175 mm
Radius of Trap	$\mathrm{r_{trap}}$	10.1 mm

Table 1: Variable names and values used for calculation of electron beam radius and space charge at trap

The electron beam radius at the centre of the trap was determine to be 0.0619 mm using the values shown in table 1.

4.2 Space Charge

The calculation of the electron beam space charged was done by modeling the beam as an infinite cylinder of uniform charge density. Applying Gauss' Law to derive the space charge potential,

$$\frac{Q}{\epsilon_0} = \oiint \boldsymbol{E} \cdot \hat{n} dS \tag{3}$$

We derive the radial component of the electric field to be,

$$E_r(r) = \begin{cases} \dfrac{I_e}{2\pi\epsilon_0 v_e}\dfrac{r}{r_e^2}, & r < r_e \\ \dfrac{I_e}{2\pi\epsilon_0 v_e}\dfrac{1}{r}, & r \geq r_e \end{cases} \tag{4}$$

Taking the gradient of $\mathrm{E_r}$ and applying the boundary condition that the potential be zero at the surface of the electrodes[6],

$$V_e(r) = \begin{cases} \dfrac{I_e}{4\pi\epsilon_0 v_e}\Big[\Big(\dfrac{r}{r_e}\Big)^2 + 2\ln\Big(\dfrac{r_e}{r_{trap}}\Big) - 1\Big], & r < r_e \\ \dfrac{I_e}{2\pi\epsilon_0 v_e}\ln\Big(\dfrac{r_e}{r_{trap}}\Big), & r \geq r_e \end{cases} \tag{5}$$

Using equation 5 and the values in table 1, we obtain the following space charge potential at the centre of the trap 11,

4.3 Acceptance

In order to minimize the charge breeding time of the EBIS, the overlap between the ion and electron beams need to be maximized. Knowing the

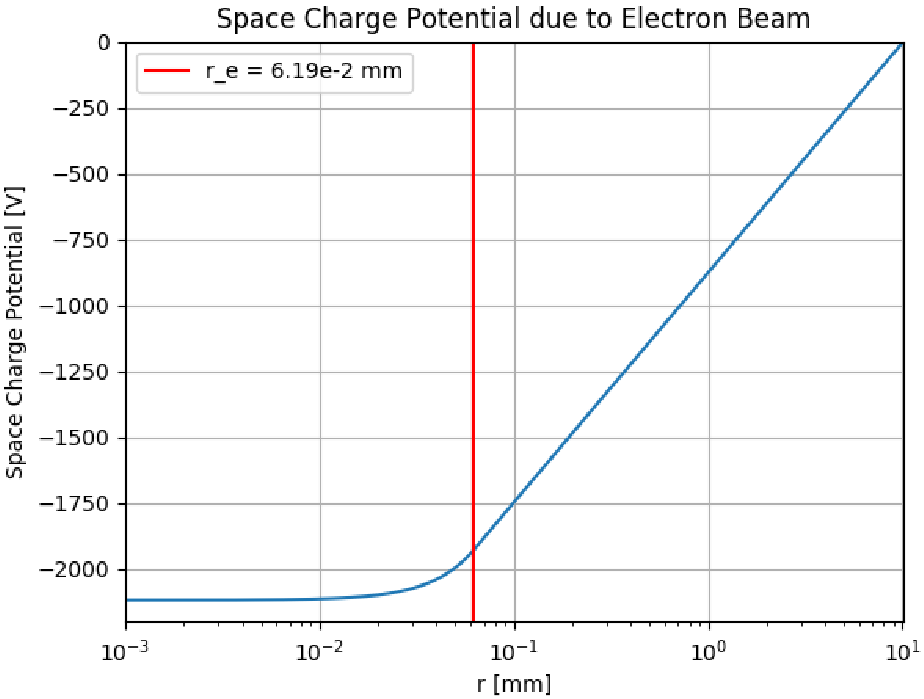

Figure 11: Off Axis Space Charge Potential of Electron Beam

transverse phase-space acceptance of the electron beam at the trap gives us the normalized phase-space area in which the ion beam should be contained[8]. The transverse phase-space acceptance of the electron beam is given by[9],

$$\alpha = \pi\gamma\frac{r_e}{c}\sqrt{\frac{Q_{inj}e}{m_{ion}}}\left(Br_e\sqrt{\frac{Q_{inj}e}{m_{ion}}} + \sqrt{\frac{Q_{inj}eB^2r_e^2}{4m_{ion}} + \frac{\rho_l}{2\pi\epsilon_0}}\right) \tag{6}$$

Where ρ_l is the charge per metre of the electron beam and γ is the relativistic gamma factor. Using values from table 2, the electron beam acceptance was determined to be 44.29 mm mrad.

Where v_e was calculated using,

$$v_e = \sqrt{\frac{2E}{m}} \tag{7}$$

and ρ_l,

$$\rho_l = \frac{1}{\pi r^2 v_e}. \tag{8}$$

Variable Name		Value
Herrman Radius of Electron Beam	r_e	$6.19 \times 10^{-5}\,\mathrm{m}$
Speed of Electrons	v_e	$2.37 \times 10^{7}\,\mathrm{m\,s^{-1}}$
Charge of injected ion	Q_{inj}	+1
Mass of ion	m_{ion}	133 u
Magnetic Field at trap	B	6 T

Table 2: Variable names and values used to calculate electron beam acceptance

5 TRANSOPTR Simulations

5.1 AXEnZ subroutine

A new subroutine was required to perform the beam envelope calculations of the CANREB EBIS in TRANSOPTR. AXEnZ loads the multiple electrode potentials in parallel and assembles them into a single array. From there, the subroutine calls AXEZ for the first order beam envelope calculation.

5.2 Variables

The simulations were performed for a Cesium ion beam of 133 u. The beam envelope simulation required the tuning of 15 electrode potentials. The optimization of these potentials was done using TRANSOPTRs fitting subroutine which varied the applied potential to each electrode. The desired beam envelope is matched to the CANREB EBIS entrance and achieves maximum overlap with the electron beam at the EBIS trap centre. The optimization of the beam envelope was done in such a way that the electrode potentials would remained the same between the injection and extraction. Another major consideration when limiting TRANSOPTR in the optimization of the beam envelope was the beam energy at the centre of the EBIS trap. When in operation, the ion beam energy at the trap needs to be negligible when compared to that of the electron beam. With this in mind, the trap's potential was set so that the incoming ion beam would have at most 0.1 qkeV when trapped. The power source limitations, and hence the optimization range limiting TRANSOPTR, was obtained from the CANREB EBIS High Voltage design note[10]. Table 3 shows the optimization intervals TRANSOPTR explored and the resulting optimal electrode potentials.

Electrode Name	Potential Range [kV]	Optimal Potential [kV]
Einzel Lenses 38 & 39	0 to 15	6.78
Einzel Lenses 40 & 41	0 to 15	8.63
Trap Platform	0 to 15	10.89
E-gun Platform	0 to 20	0
Trap	0 to 3	3
C1	0 to 3	3
C2	0 to 3	2.912
C3	0 to 3	2.916
C4	0 to 3	2.625
TC	0 to 3	2.245
Sikler Ground	0 to 0.06	0.06
Sikler Steerer	0 to 0.06	0.06
Coll. Extractor	-6 to 0	0
Coll. Shields	0 to 1.6	0
Coll. Drift	0 to 0.06	0
Coll. Suppressor	-3 to 0	0

Table 3: Physical limits on the electrode's potentials and their optimized value

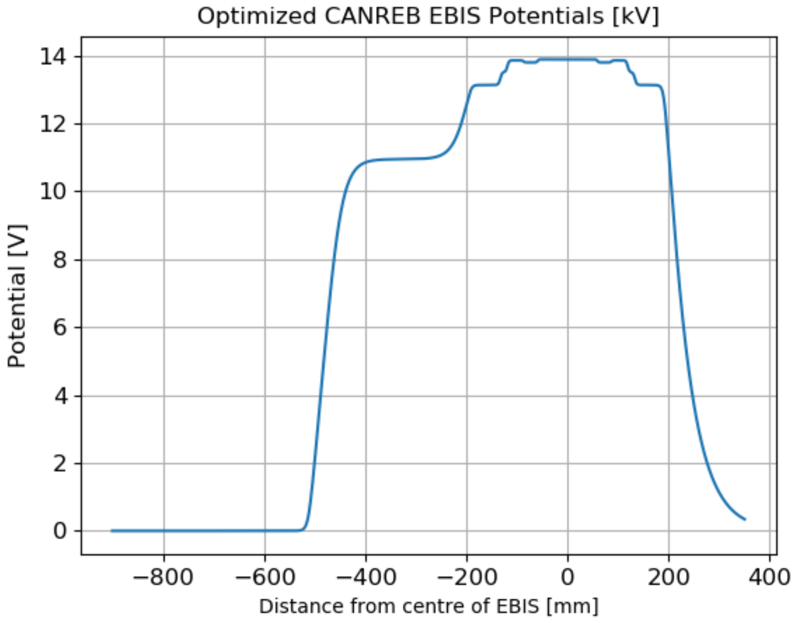

Figure 12: CANREB EBIS along axis potential optimized for 14 qkeV Cesium beam

5.3 Simulations

5.3.1 Injection

The injection simulation begin at the entrance of the PDT with a singly charged ion beam of 16 µm emittance and 60 qkeV of kinetic energy. The result of the optimized injection simulation is shown in figure 13, where the entrance of the PDT is marked as StRt, and the centre of the EBIS trap is labeled TRAP. The singly charged cesium beam is slowed down inside the PDT to 14 qkeV. Once the optimized injection beam envelope was achieved, the beam emittance was incrementally increased until the beam envelope touched the EBIS drift tubes. The critical emittance at which this happened was determined to be the CANREB EBIS acceptance, around 40 µm. This value is consistent with the analytic calculation of the electron beam acceptance of 44 µm.

5.3.2 Extraction

In order to ensure that the electrode potentials that achieved the desired injection beam envelope would also work on the extracted beam, envelope simulations were performed on the beam leaving the CANREB EBIS. The extraction beam envelope is shown in figure 14. The extraction simulation begins from the EBIS trap centre with the horizontal and vertical envelope sizes and emittances carried over from the injection simulation. However, the charge state was increased from +1 to +19. Other effects of the charge breeding process were not included at this stage. The starting point of the simulation was TRAP (on the left) and its end at PM39. The emittance of the extracted ion beam was 3 µm for an injected ion beam of 16 µm.

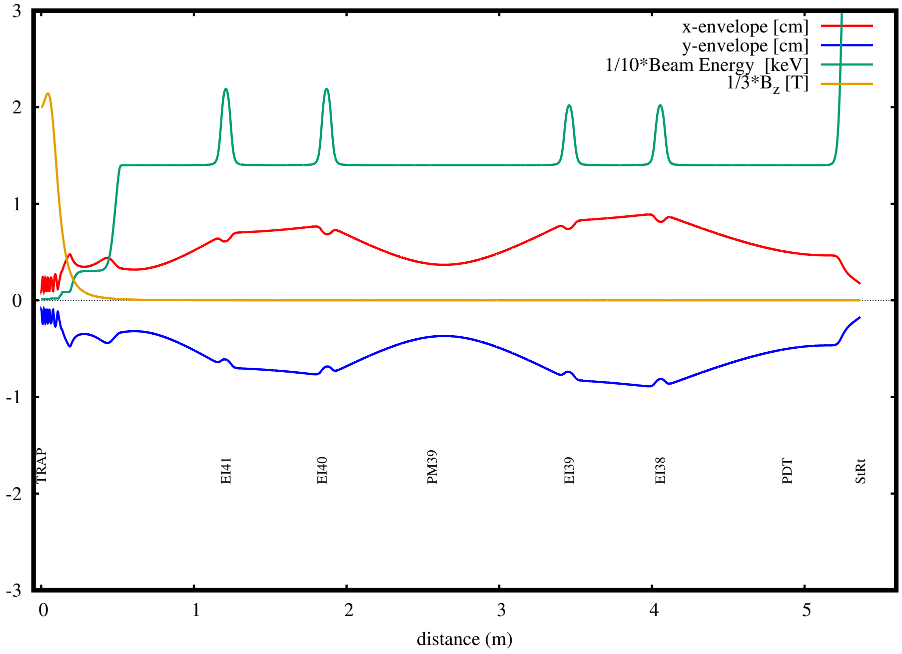

Figure 13: TRANSOPTR beam envelope calculation from PDT entrance to EBIS - Injection

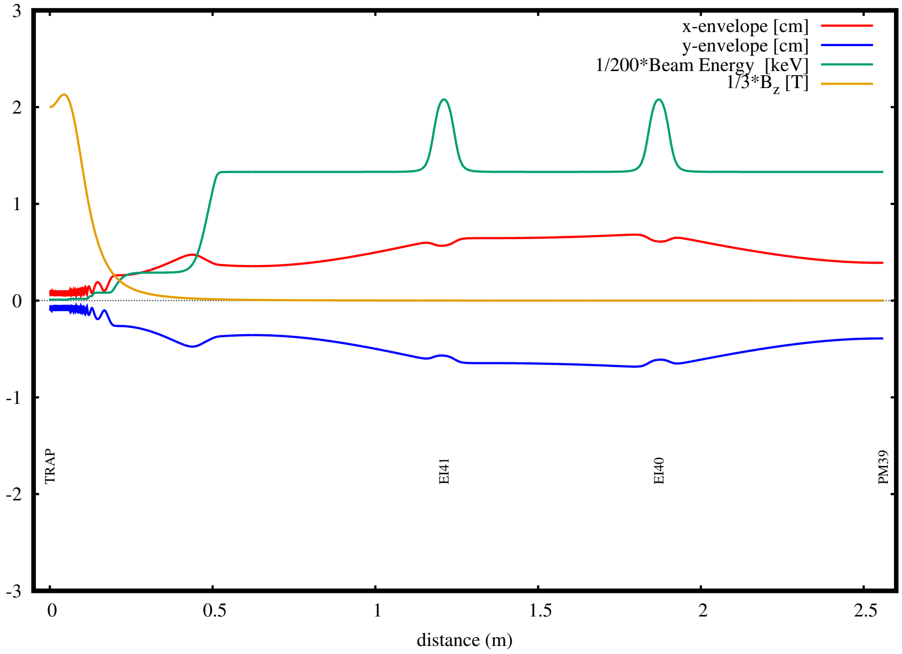

Figure 14: TRANSOPTR beam envelope calculation from EBIS to PM39 marker - Extraction

6 Summary and Outlook

The beam envelope tracking code TRANSOPTR was used to simulate the injection of singly charged cesium 133 u ions into the CANREB EBIS. By determining the radius of the electron beam at the centre of the EBIS trap, it was possible to optimize the ion beam envelope. Using the optimized beam envelope, the acceptance of the CANREB EBIS was calculated to be 40 µm. The emittance of the extracted beam was calculated to be 3 µm, when the injected ion beam had 16 µm emittance and for a charge state change from +1 to +19. This project has created a tool that can now be utilized to other isotopes and different extraction charge states. Future work will include the electron beam space charge potential and its effect on the ion beam. The CANREB EBIS will begin its commissioning phase soon which will allow for the benchmark of the simulation results.

7 Acknowledgments

The author would like to thank Dr. Suresh Saminathan and Dr. Rick Baartman for their guidance and supervision. The author would also like to thank members of the Beam Dynamics group at TRIUMF for their contributions and inputs into the project.

References

[1] Saminathan S. and Baartman R., *Design Note TRI-DN-15-06 Low Energy Beam Transport line for the CANREB Charge State Breeder* Document-116897, Internal report, TRIUMF, Apr., 2017.

[2] J. A. Maloney, R. Baartman, and M. Marchetto, *New design studies for TRIUMFs ARIEL High Resolution Separator*, *Nucl. Instr. Meth.*, vol. 376, pp. 135–139, 2016.

[3] Hubele R. and Crespo J., *Design Note TRI-DN-15-22 CANREB EBIS*, Document-119942, Internal Report, TRIUMF, May 2015

[4] Nolen J.A. and Portillo M., *Charged-particle Optics*, The Optics Encyclopedia, 2007.

[5] Herrmann G., *Optical theory of thermal velocity effects in cylindrical electron beams*, Journal of Applied Physics, 29:127, 1958.

[6] Froese M.W. (2006), *The TITAN Electron Beam Ion Trap: Assembly, Characterization, and First Tests (Master's Thesis)*

[7] Brillouin L., *A theorem of Larmor and its importance for electrons in magnetic fields*, Physical Review, 67:260, 1945.

[8] Wenander F.J.C., *Charge Breeding of Radioactive Ions*, CERN-2013-007, pp.351-380, 2014.

[9] Wenander F., *REXEBIS the Electron Beam Ion Source for the REX-ISOLDE project*, CERN-OPEN-2000-320, 1998.

[10] Graham L., *P310 CANREB EBIS High Voltage Design*, Document-144792, Internal report, TRIUMF, Apr., 2017.