ION TRANSPORT OPTIMISATION AT THE LOW ENERGY BRANCH

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Abstract

In majority of the accelerator beamlines, the goal is to achieve the highest possible desired beam throughput. When the beamline consists of only a few optical elements, beam transport optimisation can be achieved by adjusting a few knobs by an experienced operator. But when the beamline operates in a variety of regimes spanning the entire periodic table at various ion energies, the versatility makes beam transport optimisation challenging even for experienced operators. In this proceeding, we present the scaling formulas for optimizing ion transport through the Low Energy Branch (LEB) based on first-order transfer matrix formalisem and describe how we determine the optimal settings for the LEB optical elements.

INTRODUCTION

The Low Energy Branch (LEB) [1] at the Micro Analytical Center (MIC) [2] supplies a variety of high current (up to 50 µA) ion beams, ranging from light (e.g. H, He, C, B, ^{15}N), mid-mass (e.g. Si) to heavy (Ag, W, Pb, Bi) ion beams in the energy range of 100 eV up to 30 keV to different experimental stations.

The LEB consists of electrostatics steerers to correct for beamline misalignment in the $x-y$ plane and move the beam to desired location on the target, the dipole magnet to select the desired m/q ratio, and Einzel lens for focusing the beam. To verify ion transport three Faraday Cup (FC) detectors are used. For full layout of the ion optical components see Fig. 1.

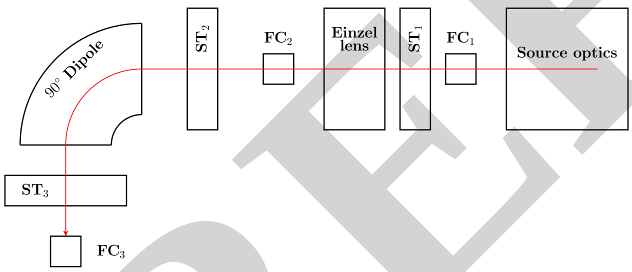

Figure 1: Beam optics elements of the LEB, ST stands for electrostatic $x-y$ steerer.

TRANSPORT OPTIMISATION

When optimising transport through an ion beamline we need to go through several levels of optimisation:

I. Choose the optical elements needed for beam manipulation given desired energy range, mass range and beam currents.

II. Determine the dimensions of optical elements.

III. After the assembly determine the beam element misalignment, imperfections, power supply instabilities.

IV. Determine the parameter ranges that the optical elements will operate in.

V. Maximise the beam current through the beamline by taking into account the beam phase space and all points above.

Steps I and II were performed and completed during the design phase of the LEB. In step II we relied on phase space measurements of the beam exiting the accelerator sources to constrain the design parameters of the optical elements in the LEB. Step III is still underway.

In the upcoming chapters, we cover the optimisation steps IV and V. We use $^4He^+$ beam as a tool for calibration of optics, determination of misalignment and optics scaling factors.

LEVEL IV. OPTIMISATION

At this stage of optimisation we want to determine in what parameter ranges we will operate the components, starting with the dipole magnet.

90-degree Dipole magnet

LEB has a Danfysik 90-degree dipole magnet with bending radius of $\rho = 240$ mm, exit and entrance angles of 26.6°, and a pole gap of 25 mm. The magnet can operate with coil currents of up to 52 A, but is operated with currents of up to 50 A to avoid overheating.

The current needed to bend the ion of interest (m, q) with specific energy kinetic energy E_k is given by:

$$I_{\text{dipole}} = \frac{D}{\rho}\sqrt{\frac{m * E_k}{q^2}}. \quad (1)$$

The scaling constant D was obtained via calibration using pure $^4He^+$ beam at 20 keV, for which the dipole had to be set to $I_{\text{dipole}} = 9.2$ A, giving us $D = 257.148$ A mm $e_0/\sqrt{\text{keV amu}}$.

For the operation of the beamline we are interested in the maximal kinetic energy that can be bent with the dipole for different ion beams of interest: $^4He^+ = 590.73$ keV, $^{14}N^+ = 168.78$ keV, $^{28}Si^+ = 84.39$ keV, $^{120}Sn^+ = 19.69$ keV and $^{208}Pb^+ = 11.36$ keV. The dipole coil current constrains the maximal energy of ions we can transport for masses above 110 amu to 20 keV or below, despite the fact

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that the source extraction voltage can accelerate ions up to 30 kV for all masses.

Einzel lens

The next component of the beamline is the einzel lens used to focus the beam (see Fig. 2 and 3). The einzel lens cylinders have equal length and diameter $2r, L_E = 81$ mm and are $g = 8.1$ mm apart. For the focal length of our lens we use the approximation (see Ref. [3]):

$$f \approx \frac{4L_E}{V_E/V_{\mathrm{acc}}}, \tag{2}$$

where V_E is the voltage applied to the central cylinder of the einzel lens and V_{acc} the voltage the beam was accelerated with at the ion source.

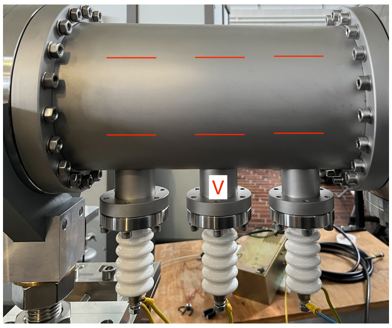

Figure 2: In housed manufactured Einzel lens that can operate in the range of up to 30 kV.

Then, if we re-order the Eq. (2) we can obtain the optimal voltage of the einzel lens at which we focus the beam at the desired distance $L_2 = f$:

$$V_E = \frac{4L_E}{L_2} V_{\mathrm{acc}}. \tag{3}$$

This gives us for the ^{4}He$^+$ beam at 10 keV on the second FC_2 ($L = 900$ mm after the einzel lens) the value of 3.6 kV. As will be shown later the optimum is off, but of right order of magnitude.

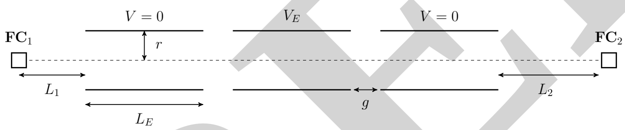

Figure 3: The setup of the einzel lens and the LEB Faraday cups 1 and 2, along with corresponding lens voltages and dimensions.

Electrostatic x-y steerer

The next element is the electrostatic $x - y$ steerer constructed from four parallel plates of length L_S positioned a distance d apart (see Fig. 4). The steerer allows us to move the beam in the (x, y) plane by the desired offset $\Delta x, \Delta y$.

To obtain the voltage V_x needed to move the beam for a distance Δx at length L_D after the steerer, we can write the steerer transfer map as:

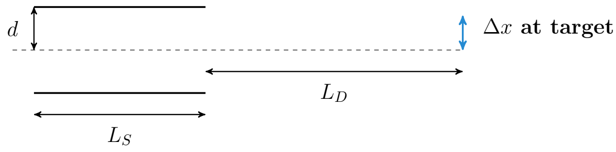

Figure 4: Steerer dimensions and the Δx offset produced on the target.

$$\begin{bmatrix} x \\ x' \end{bmatrix}_f = \begin{bmatrix} 1 & L_S \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ x' \end{bmatrix}_i - \frac{L_S}{2d}\frac{V_x}{V_{\mathrm{acc}}} \begin{bmatrix} \frac{L_S}{2} \\ 1 \end{bmatrix}, \tag{4}$$

and after applying the drift space L_D transfer map:

$$\begin{bmatrix} x \\ x' \end{bmatrix}_f = \begin{bmatrix} 1 & L_S + L_D \\ 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ x' \end{bmatrix}_i - \frac{L_S}{2d}\frac{V_x}{V_{\mathrm{acc}}} \begin{bmatrix} \frac{L_S}{2} + L_D \\ 1 \end{bmatrix}. \tag{5}$$

This yields for the desired $\Delta x = x_f - x_i$ the required steerer voltage of:

$$V_x = V_{\mathrm{acc}} \frac{(L_S + L_D)x'_0 - \Delta x}{L_S + 2L_D} \cdot \frac{4d}{L_S}, \tag{6}$$

providing us with the scaling formula for the last optical element.

LEVEL V. OPTIMISATION

In the final step of the optimisation we take into account the lens optimal parameters and the properties of the phase space. For ^{4}He$^+$ beam at LEB, the beam size and divergence were measured to be : $(\sigma_x, \sigma_y) = (3.5, 3.5)$ mm and $(\sigma'_x, \sigma'_y) = (2.5, 2.5)$ mrad.

We model the beam by using a bi-gaussian distribution (see Ref. [4]):

$$f(x, x') = \frac{1}{2\pi\sigma_x\sigma_{x'}} \exp\left(-\frac{1}{2}\left[\frac{\mu_x^2}{\sigma_x^2} + \frac{\mu_{x'}^2}{\sigma_{x'}^2}\right]\right), \tag{7}$$

and equivalently for the (y, y') plane. The current on the Faraday cup is then defined as:

$$I_{FC} = \int_{-r_{FC}}^{r_{FC}} \int_{-r'_{FC}}^{r'_{FC}} f(x, x') f(y, y') \mathrm{d}x\mathrm{d}x'\mathrm{d}y\mathrm{d}y', \tag{8}$$

with $r_{FC} = 5$ mm the radius of the Faraday cup entrance and $r'_{FC} = r_{FC}/d_{FC} = 10$ mrad the maximal angle of the beam that can enter the Faraday cup (since r'_{FC} is far larger than the 2.5 mrad divergence of our beam all angles are detected). In radial coordinates the I_{FC} can be written as:

$$I_{FC} = 2\pi\sigma_r\left(1 - \exp\left[-\frac{r_{FC}^2}{2\sigma_r^2}\right]\right)\sigma_{r'}\left(1 - \exp\left[-\frac{{r'_{FC}}^2}{2\sigma_{r'}^2}\right]\right), \tag{9}$$

where $\sigma_r(a), \sigma'_r(a)$ depend on the parameters a of the beamline as the beam is passed through different optical elements.

One option would be to use the current on the FC to find the optimal lens parameter via $\frac{\partial I_{FC}}{\partial a} = 0$, but the resulting optimisation formulas are complicated and cannot be solved exactly. The alternative is to look at the statistical momenta of the beam: $\mu(a), \sigma(a)$ and look for optima on the level of those.

90-degree Dipole Magnet

With the transfer map for phase-space there is no need for a parameter optimisation beyond the correct current I_{dipole} for (E_k, q, m) of the beam.

Einzel Lens

We are interested if the phase space has the effect on the estimated optimal voltage V_E for the einzel lens.

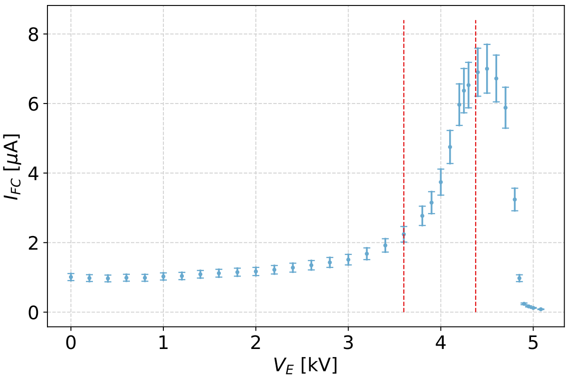

Figure 5: Comparison of the measured current with the predicted optimal parameter for the einzel lens voltage. A detailed description of this experiment can be found in Ref. [5]. The first red line corresponds to the optimum predicted via (Eq. (3)) $V_E = 3.6$ kV and the second line to the prediction of (Eq. (15)) $V_E = 4.38$ kV.

For a focal length f of the einzel lens, sandwiched between the drift space, L_1 and L_2, we can write the phase space transfer matrix as:

$$M = M_{L_2} M_E M_{L_1} = \begin{bmatrix} 1 - L_2/f & L_2 + L_1(1 - L_2/f) \\ -1/f & 1 - L_1/f \end{bmatrix}. \quad (10)$$

We can obtain the transformation of momentum σ by a linear transformation of the random variable:

$$\sigma_f = M \sigma_i M^T, \quad (11)$$

or, if we write out the $\sigma_{r,f}$ component:

$$\sigma_{r,f}^2 = \left(1 - \frac{L_2}{f(V_E)}\right)^2 \sigma_{r,i}^2 + \left[L_2 + L_1\left(1 - \frac{L_2}{f(V_E)}\right)\right]^2 \sigma_{r,i}^2. \quad (12)$$

By minimising $\sigma_{r,f}^2$ with respect to V_E:

$$\frac{\partial \sigma_{r,f}^2}{\partial V_E} = 0, \quad (13)$$

computing the above derivative we obtain:

$$(\sigma_{r,i}^2 + L_1^2 \sigma_{r',i}^2)\left(1 - \frac{L_2}{4L_E}\frac{V_E}{V_{\text{acc}}}\right) + L_1 L_2 \sigma_{r',i}^2 = 0, \quad (14)$$

solving for V_E we obtain the optimal setting for the Einzel lens voltage:

$$V_E = V_{\text{acc}} \left[\frac{4L_E}{L_2} + \frac{4L_E L_1}{\frac{\sigma_{r,i}^2}{\sigma_{r',i}^2} + L_1^2} \right], \quad (15)$$

where the second term is the correcting factor due to finite beam phase space, with $L_1 = 540$ mm, $L_2 = 900$ mm. The corrected optimal einzel lens voltage V_E is then 4.38 kV which is the value at which the maximum transmission current on FC_2 was indeed obtained (see Fig. 5).

Electrostatic x-y Steerer

In case of the steerer it is enough to look at the shift of the beam center. Using the linear random variable transformation $_f = A_i + \mathbf{b}$ we can rewrite the beam center shift by replacing x_0' and Δx with their average values:

$$V_x = V_{\text{acc}} \frac{(L_S + L_D)\mu_{x_0}' - \Delta\mu_x}{L_S + 2L_D} \cdot \frac{4d}{L_S}, \quad (16)$$

where $\Delta\mu_x = \mu_{x_f} - \mu_{x_i}$.

CONCLUSION

In these proceedings we discussed the process of LEB optics optimisation and how the optimal parameters for the dipole magnet, the einzel lens and the electrostatic steerer can be obtained if beam phase space features are taken into account.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. Primož Pelicon and Dr. Jurij Simčič for all their advice and support during this research. The work at the Jožef Stefan Institute was supported by the Slovenian Research Agency (ARIS) grants P1-0102, P1-0112, I0-0005.

REFERENCES

[1] Z. Brencic *et al.*, “Development of Low Energy Branch at Micro Analytical Centre, Ljubljana, Slovenia”, in *Proc. IPAC’23*, Venice, Italy, May 2023, pp. 5131–5133. doi:10.18429/JACoW-IPAC2023-THPM113

[2] P. Pelicon *et al.*, “A high brightness proton injector for the Tandetron accelerator at Jožef Stefan Institute”, Nucl. Instrum. Methods Phys. Res. B, vol. 332, pp. 229–233, 2014. doi:10.1016/j.nimb.2014.02.067

[3] A. Galejs and P. H. Rose, “Optics of electrostatic accelerator tubes”, in *Focusing of Charged Particles*, vol. 2, A. Septier, Ed. New York, NY, USA: Academic Press, 1967, pp. 297–326. doi:10.1016/B978-0-12-636902-1.50014-7

[4] T. Kalvas, "Beam extraction and transport", in *CAS - CERN Accelerator School: Ion Sources*, Senec, Slovakia, May 29–Jun. 8, 2012, pp. 537–564. doi:10.5170/CERN-2013-007.537

[5] M. Skobe, "Prototype control system for the low energy ion beamline", Master's thesis, Ljubljana, Slovenia, 2025, COBISS.SI-ID 232751875.