BENCHMARKING OF THE ESS LEBT IN TraceWin AND IBSimu

Ø. Midttun*[1], University of Bergen, Bergen, Norway
Y. Levinsen, R. Miyamoto, C. Plostinar, ESS, Lund, Sweden
[1]also at ESS, Lund, Sweden

Abstract

The modeling of the proton beam in the ESS accelerator starts with a beam distribution as an input to the TraceWin code currently used as the simulation tool. This input is typically a Gaussian distribution, a distribution from other codes, or data from an emittance measurement. The starting point of these simulations is therefore located somewhere along the Low Energy Beam Transport (LEBT) close to the ion source. In this paper, we propose to use IBSimu to model the beam extraction from the ion source, which provides an input beam distribution to TraceWin. IBSimu is a computer simulation package for ion optics, plasma extraction, and space charge dominated ion beam transport. We also present a benchmarking of the beam tracking through the LEBT using both these tools, and propose a transition interface to handover the beam distribution from IBSimu to TraceWin.

INTRODUCTION

This paper presents the modeling of the ion source and Low Energy Beam Transport (LEBT) for the European Spallation Source (ESS) proton accelerator. We used two simulation codes to model this part of the accelerator lattice: IBSimu for the beam extraction from a plasma and particle tracking at low energy [1], and TraceWin for particle tracking at low energy [2]. The method consisted of simulating the beam extraction from the ion source plasma with IBSimu, which gave an output beam distribution at a specific location. TraceWin then used this distribution as an input to track the particle trajectories through the LEBT. We chose to handover the beam distribution at the lattice interface between the ion source and the LEBT (ISRC-LEBT), defined as 70 mm downstream of the inner wall of the plasma chamber.

SIMULATION SET-UP

The ion source for the ESS proton accelerator is a microwave discharge ion source [3]. Because this type of ion source is symmetric around the beam axis, we chose a cylindrical symmetric simulation of the beam extraction to save computing time with respect to a full 3D model. For all simulations described in this paper, we chose a set of plasma parameters as input to IBSimu that were kept constant. These were the plasma potential ($\Phi = 20$ V), the transverse ion temperature ($T_t = 1$ eV), the electron temperature ($T_e = 10$ eV), and the initial ion energy ($E_0 = 10$ eV). The simulations used a rectangular mesh with a step size of 0.4 mm, and the particles were distributed over approximately 80,000 trajectories. We included two ion species in the simulations: 80 % of H^+,

* oystein.midttun@esss.se

and 20 % of H_2^+. Each trajectory in cylindrical symmetry simulations corresponds to a ring in 3D, and has a different current according to the radius. In TraceWin, particle trajectories have equal currents, and the beam distributions were therefore converted to match this format. Each input beam distribution to TraceWin contained a total of 200,000 particles.

To compare the two simulation tools, we tracked the same beam distribution through the LEBT with IBSimu and TraceWin. Figure 1 shows output images from the two simulation codes. Both codes included a space charge compensation of 95 % effective in the region between the two electron repellers. The first repeller sits in the extraction column close to the ion source plasma chamber, and protects the ion source from back streaming electrons. The second repeller is located close to the RFQ entrance to prevent electrons from entering. The repellers also help keeping electrons in the beam, and thus maintaining a high degree of space charge compensation. The value of the space charge compensation is an approximation based on experiences with a similar LEBT from IFMIF/EVEDA [4].

COMPARISON OF IBSIMU AND TRACEWIN

This study compared the output from the two simulation codes by tracking a single beam distribution through the LEBT, and varying the magnetic field strength of the two solenoids. The input beam consisted of 73.4 mA of protons, and 18.3 mA of H_2^+. These values were chosen to be close to the anticipated ion source proton current of 74 mA, and proton fraction larger than 75 %. Figure 2 compares the simulated current transported to the RFQ. The solenoid magnetic field along the beam axis was scanned from 0.12 T to 0.3 T, with a step size of 0.05 T.

To evaluate the beam transmission in the LEBT, we considered both the transmission of the proton beam current, and the matching of the emittance and Twiss parameters – combined into the so-called mismatch parameter, M – at the RFQ entrance. The emittance at the exit of the RFQ is approximately equal to $\varepsilon(1 + M)$, where ε is the normalized rms emittance at the RFQ entrance and M is the mismatch parameter. M is expressed as

$$M = \left\{ 1 + \frac{\Delta_M + [\Delta_M(\Delta_M + 4)]^{1/2}}{2} \right\}^{1/2} - 1, \quad (1)$$

where $\Delta_M = (\Delta\alpha)^2 - \Delta\gamma\Delta\beta$ [5]. For the calculation of M, we used the anticipated values of α: 1.02, and β: 0.11 m, at the RFQ entrance. The contour in Fig. 2 indicates the
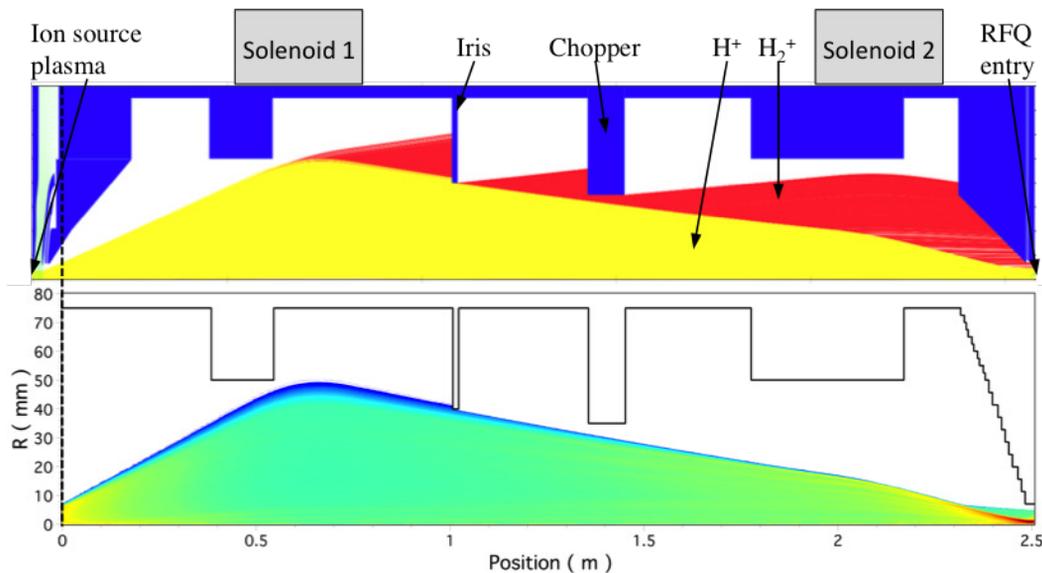
Figure 1: Top: output image from an IBSimu simulation. The protons (yellow) and H_2^+ (red) are extracted from the plasma on the left hand side, and tracked though the two-solenoid LEBT to the RFQ. Bottom: output image from TraceWin containing only the protons. The dotted line indicates the location of the ISRC-LEBT lattice interface, where the TraceWin simulation starts. We observe that the aperture reductions of the iris and the chopper force a strong focus from the first solenoid to transport a high fraction of the proton beam.
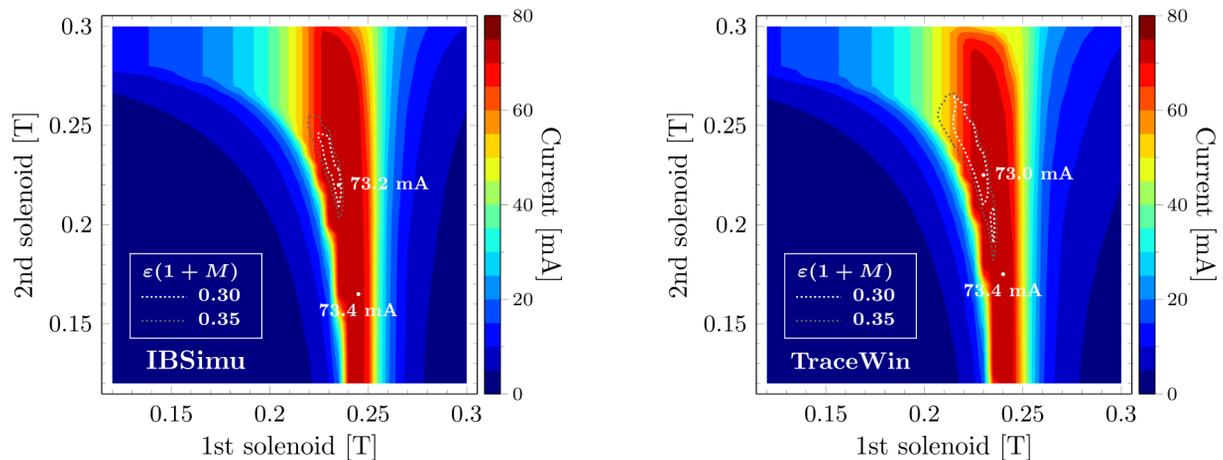
Figure 2: Proton beam current at the RFQ entrance as a function of the magnetic field of the two solenoids. The two beam currents corresponds to the maximum transmitted beam current, and the transmitted beam current for the minimum value of $\varepsilon(1 + M)$ (inside the contour).

region containing the minimum values of $\varepsilon(1 + M)$, referred to as the effective emittance. When minimizing the effective emittance, the proton beam calculated by IBSimu contained a current of 73.2 mA within an effective emittance of 0.24 mm mrad, and the proton beam calculated by TraceWin contained a current of 73.0 mA within an effective emittance of 0.18 mm mrad.

When we look at the comparison of beam tracking in Fig. 2, IBSimu and TraceWin provide similar results. Both plots have identical shapes, which resemble the typical "banana-shaped" matched region. The optimal setting of solenoid 1 is, however, quite narrow. Only the values close to the optimal set point provides high beam current trans-

mission. The reason is that at weak focusing, a large part of the beam is lost between the solenoids, on the apertures of the iris and the chopper. Once solenoid 1 is set properly, it focuses the beam towards the RFQ entrance, as shown in Fig. 1. At this setting, solenoid 2 has less effect on the beam, and can be changed more freely.

The difference seen in Fig. 2 originates from the method of calculating the beam space charge. IBSimu tracks all ion species through the electric (and magnetic) fields, and adds the space charge of the beam to the calculation of Poisson's equation in the next simulation iteration. This process continues until the solution converges. TraceWin can import two particle species for the tracking. However, when it per-

forms the calculation, the two species are tracked separately, and their respective space charge is not affecting the other specie. This hypothesis was confirmed when looking at the phase-space plot at the LEBT-RFQ lattice interface. With 95 % space charge compensation, the output ellipses from the two codes were differently tilted, whereas with 100 % space charge compensation, the ellipses' shapes were identical. Based on this observation, we believe that IBSimu generates a more realistic simulation in the case of a low energy beam containing different ion species.

LEBT TRANSMISSION AND RFQ MATCHING

In this case, we studied the transmission of beams with varying current though the LEBT. IBSimu provided the different particle distributions that were imported into TraceWin at the ISRC-LEBT lattice interface. TraceWin then tracked each distribution through the LEBT as a function of the magnetic field of the two solenoids. Figure 3 shows the transmitted proton current and the effective emittance as a function of the input proton current. The plot includes two different ways of optimization: one for maximized transmitted current, and one for minimized effective emittance. The minimum effective emittance was found on the grid of the solenoid scan with no interpolation between the set points. This approximation might have induced an error on the results.

We observe that the two optimization methods gave similar transmission results for input currents below 73 mA. In this region we achieved close to 100 % proton current transmission. However, the effective emittance increased dramatically with optimization for high beam current transmission. When optimizing for minimum $\varepsilon(1 + M)$, we reached a minimum effective emittance of 0.12 mm mrad for a proton current of 57 mA. For initial proton currents ranging from 57 mA to 73 mA, the minimum effective emittance increased with the beam current to 0.18 mm mrad. For higher input currents, the transmitted current dropped drastically. As the emittace continued to increase – even for a lower transmitted proton current – we can conclude that the ion source should not operate to produce such high beam currents. The higher extracted beam current from the ion source results in a more and more divergent beam. At some point, the increase of the beam losses overcomes the increase of beam current, and less current reaches the RFQ.

CONCLUSION

We compared the particle tracking at low energy with the simulation codes IBSimu and TraceWin. The input ion beams consisted of 80 % protons, and 20 % H_2^+. The codes gave similar results, however, IBSimu has a more realistic tracking method as it includes the space charge from both ion species, whereas TraceWin tracks the ion species separately. TraceWin, on the other hand, is efficient to perform error studies on the beam tracking, and can continue the tracking
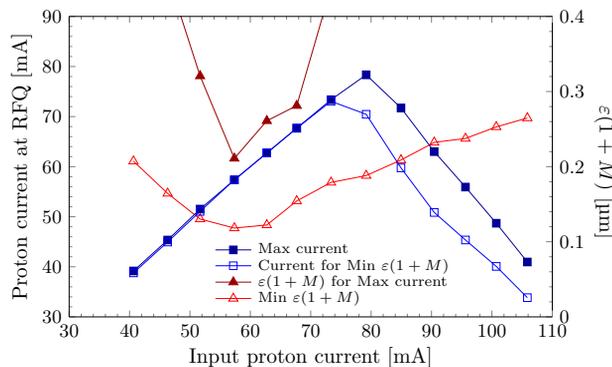
Figure 3: Proton beam current at the RFQ entrance and effective emittance as a function of the initial proton current. IBSimu provided the initial particle distributions, and TraceWin tracked these through the LEBT while varying the magnetic fields of the two solenoids.

through the RFQ. For these reasons, we will probably use both codes in the future for LEBT beam studies.

The IBSimu simulations showed that the LEBT should be able to transport a proton beam of 73 mA within an effective emittance of 0.24 mm mrad. This is acceptable compared with the anticipated values of 74 mA within $\varepsilon = 0.25$ mm mrad. There are, however, many unknowns that needs to be verified through measurement. These are parameters such as space charge compensation degree, fractions of protons, H_2^+ and also H_3^+, and the longitudinal position of the two solenoids.

In this paper, we have demonstrated the capability of two independent simulation codes to model the proton beam in the LEBT. We have also started characterizing the LEBT in preparation for the beam commissioning.

REFERENCES

[1] T. Kalvas, O. Tarvainen, T. Ropponen, O. Steczkiewicz, J. Ärje, and H. Clark, "IBSIMU: A three-dimensional simulation software for charged particle optics", *Review of Scientific Instruments*, vol. 81, no. 2, p. 02B703, 2010.

[2] D. Uriot, and N. Pichoff, "Status of TraceWin Code", in *Proc. of IPAC'15*, Richmond, VA, USA, June 2015, paper MOPWA008, pp. 92-94.

[3] L. Celona *et al.*, "The Prototype of the Proton Injector for the European Spallation Source", in *Proc. of LINAC'14*, Geneva, Switzerland, September 2014, paper THPP085, pp. 1044–1046.

[4] N. Chauvin, O. Delferrière, R. D. Duperrier, R. Gobin, P. A. P. Nghiem, and D. Uriot, "Source and Injector Design for Intense Light Ion Beams Including Space Charge Neutralisation", in *Proc. of LINAC'10*, Tsukuba, Japan, September 2010, paper TH302, pp. 740–744.

[5] R. Miyamoto, "Tracking Based Courant-Snyder Parameter Matching in a Linac with a Strong Space-Charge Force", in *Proc. of LINAC'16*, East-Lansing, MI, USA, September 2016, paper MOPRC013, pp. 88–91.