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BEAM DYNAMICS SIMULATION WITH AN UPDATED MODEL FOR THE ESS ION SOURCE AND LOW ENERGY BEAM TRANSPORT

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Abstract

Beam dynamics simulation of the ion source (IS) and low energy beam transport (LEBT) of the European Spallation Source (ESS) Linac is conducted with TraceWin and IBSimu code. TraceWin allows multi-particle tracking based on a particle-in-cell space-charge solver and is the standard simulation tool of the whole ESS Linac. IBSimu is based on a Vlasov solver and allows to simulate beam extraction from plasma as well as the beam transport in the LEBT. In preparation for beam commissioning of the IS and LEBT in the ESS Linac tunnel, which started in September 2018 and is ongoing as of the time of writing this paper, the simulation models of the IS and LEBT in these two codes were updated. This paper reports the effort for these updates, including particle distribution out of the IS, electromagnetic field map of the LEBT solenoid, more realistic aperture structure in the LEBT, as well as updated LEBT solenoids scan simulation.

INTRODUCTION

The European Spallation Source (ESS), currently under construction in Lund, Sweden, will be the world's most powerful neutron source. It is driven by a proton linac at 62.5 mA, with 2.86 ms long pulses at 14 Hz. The first section of the proton linac (IS and LEBT) have been commissioned first at INFN-LNS and at ESS in late 2018 and the first half of 2019 [1–3]. Front-end and target main beam parameters are summarized in Table 1.

In the LEBT, two solenoids focus the beam that is transported to the next section, the RFQ, where it will be bunched and accelerated to 3.6 MeV. As tuning and initial operation requires lower power than the nominal 5 MW, an iris is installed in LEBT to adjust the peak current. Matching to the RFQ is sensitive to beam parameters and machine conditions, in particular the level of space charge compensation (SCC). The goal of the IS-LEBT commissioning is to establish optimal candidates of beam modes to transport to the RFQ, once installed.

Multi-particle tracking simulations are performed to support the commissioning activities. Such simulations have previously shown that matching from the LEBT to the RFQ can be achieved by identifying the region of high transmission, as it coincides with the region of minimum transverse and longitudinal emittance growth. In this paper we verify that this matching method is valid also for the updated model, which includes an improved IS particle distribution, new field maps as well as a more detailed aperture description in the LEBT.

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Table 1: Beam Parameters at IS and Target

Parameter	**Unit**	**IS**	**Target**
Kinetic energy	MeV	0.075	2000
Pulse current (total)	mA	~85	62.5
Pulse current (proton)	mA	~70	62.5
Proton fraction	%	~80	100
Pulse length	ms	~6	2.86
Pulse repetition rate	Hz	14	14

UPDATES IN SIMULATION

IS Output Distribution

For simulations of the beam extraction and transport in LEBT, IBSimu code [4] has been used [3, 5]. In the very beginning of the off-site beam commissioning of the IS and LEBT at INFN-LNS, ~100 mA of current was extracted. LEBT transport simulations corresponding to this condition were presented in [3]. Due to indications of a large initial divergence for this condition, later during the off-site beam commissioning, the extraction system was moved closer to the plasma surface by 1 mm and the extracted current was also reduced to ~83 mA [6]; these changes made the beam envelope after the first solenoid more parallel to the beam axis. Our IBSimu simulation has been also updated by reflecting these changes. Figure 1 shows the old (left) and new (right) horizontal phase space distribution of the proton beam from IBSimu at the lattice interface of the IS and LEBT, 70 mm downstream of the plasma surface. For the new distribution, the total extracted current is 83 mA, of which 70.8 mA are protons. The emittance (RMS normalized) ε_N and Twiss parameters are $\varepsilon_N = 0.135\,\pi$ mm mrad, $\beta = 1.09$ mm/π mrad, and $\alpha = -11.50$ for the old and $\varepsilon_N = 0.144\,\pi$ mm mrad, $\beta = 0.44$ mm/π mrad, and $\alpha = -4.23$ for the new. This new distribution is used as the input of the LEBT simulations conducted using the TraceWin code [7] in later sections.

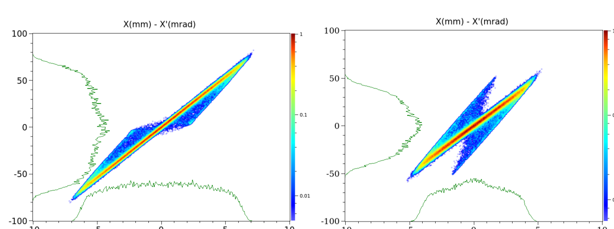

Figure 1: Old (left) and new (right) IS distributions from the IBSimu code.

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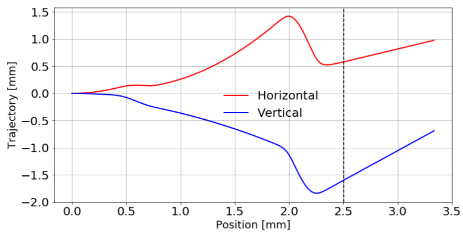

Figure 2: Beam trajectory under the influence of the Earth magnetic field. The black vertical dashed line marks the interface LEBT-RFQ.

LEBT Model Updates

In order to improve the accuracy of simulations of the LEBT, solenoid field maps were provided from an updated model in Radia [8, 9].

For a low energy beam, as in the LEBT, the magnetic field of the Earth has a strong effect on its trajectory. A survey data shows that the local field in Lund points downwards with an intensity of 47 µT [10]. Using this data a field map was created covering the entire length of the LEBT and the commissioning tank, superimposed to all its elements. Without the influence of the magnets the Earth's field can bend the beam up to 4 mm at the LEBT-RFQ interface in the horizontal plane. Figure 2 shows the trajectory once the solenoids are set to 235 mT and 220 mT, respectively, and no steerers are used.

The aperture geometry of LEBT in our model is updated (Fig. 3). The updates include i) aperture transitions within the solenoids, around 0.5 m and 2 m, due to connections of different types of beam pipes, ii) modeling of three pairs of blades making a hexagonal shape as well as the entrance aperture of 80 mm diameter for the iris, iii) an update of the chopper diameter from 70 mm to 80 mm, and iv) modeling of the collimator before the RFQ interface.

NOMINAL SOLENOIDS SETTING

The standard technique to find the strengths of the two solenoids, which provide a matched beam at the LEBT-RFQ interface, is to scan both and find the values maximizing the transmission through the RFQ. Such a simple technique is possible since the solenoids' setting for the maximum transmission coincides with the one for the minimum emittance growth. To find the optimum solenoids' values as well as the corresponding Twiss parameters at the LEBT-RFQ interface for the updated simulation setup, described in the previous

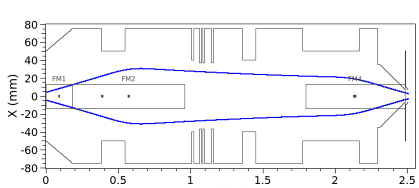

Figure 3: Update LEBT aperture geometry, together with 2×RMS beam envelope.

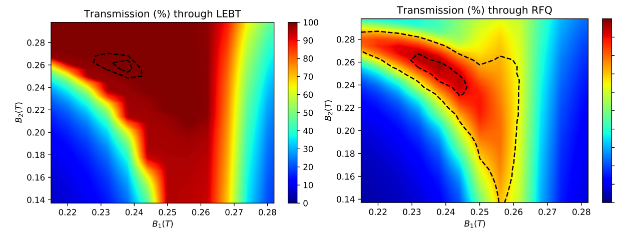

Figure 4: Transmission through the LEBT (left), with dashed lines showing 25% and 50% mismatch. Transmitted particles through the LEBT and RFQ (right), with dashed lines showing the contour of the transverse emittance at 0.15 and 0.25 π mm mrad.

section, we simulate the solenoid scan looking at RFQ transmission values. Tracking simulations are performed with TraceWin for the LEBT and Toutatis code [11] for the RFQ, where 1×10^5 macro-particles are tracked for each solenoid setting using the updated input distribution. In the LEBT space-charge forces are calculated every millimeter with the 2D PICNIR routine with (16, 32) mesh size in (r, z). SCC in the LEBT is set to 95%.

Calculated transmission as a function of the two solenoid field strengths, B_1 and B_2, through the LEBT and RFQ is presented in Fig. 4. The transmission through LEBT and RFQ, is maximized for $B_1 = 237.5$ mT and $B_2 = 259.5$ mT. The total transmission is 98.2%, of which 1% are unaccelerated particles that remain at 75 keV. The transmission of accelerated particles above the threshold of 3.2 MeV is thus 97.2%. For a proton current of 70.8 mA out of the IS, 69.5 mA is transported to the end of the RFQ. It is confirmed that the optimal transmission through the LEBT and RFQ coincides with the minimal emittances under the simulated condition, giving 0.14 π mm mrad (transverse) and 0.26 π mm mrad (longitudinal). The Twiss parameters at the exit of the LEBT for this new optimal solenoids setting are $\beta = 0.17$ mm/π mrad and $\alpha = 1.7$.

IRIS APERTURE

The impact of the aperture of the iris blades on beam dynamics in the LEBT is studied, using the same parameters as described in the previous section. The mismatch factor is calculated at the exit of the LEBT with respect to the matched Twiss parameters ($\alpha = 1.7$ and $\beta = 0.17$ mm/π mrad) (Fig. 5). Apart from the transmission, beam parameters at the RFQ are negligibly affected by changing iris aperture from 37 mm to 22 mm. With a 22 mm aperture 54 mA is transported through the RFQ and the mismatch is 1%. As a result, the linac can be tuned using the iris to reduce the beam current.

SENSITIVITY STUDY

Initial Emittance and SCC

Certain machine and source conditions, in particular initial beam parameters out of the IS and SCC in the LEBT, are

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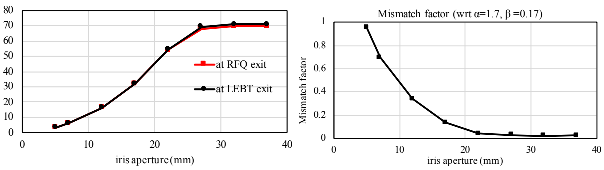

Figure 5: Output current and mismatch factor at the LEBT exit with respect to the iris aperture radius.

challenging to control and yet may change the condition for matching. Hence, based on a report from the off-site beam commissioning [3], we tested the sensitivity of the matched condition against slightly pessimistic conditions of a higher initial emittance of 0.25 π mm mrad and a lower SCC level of 90%.

For the higher initial emittance, the domain of full transmission through the LEBT is reduced, but still reaches 100% (Fig. 6 top left). The SCC level also impacts the beam dynamics, but the shift for the matched solenoids strengths is smaller than the one caused by the larger initial emittance (Fig. 6 top right). The combined effects of the larger initial emittance and lower SCC on the transmission through the LEBT and combined LEBT+RFQ are seen in bottom left and right in Fig. 6. Compared to the original $B_1 = 237.5$ mT and $B_2 = 259.5$ mT the new matched solenoids strengths are different by a few percent: $B_1 = 244$ mT and $B_2 = 250$ mT. The maximum transmission through the RFQ is reduced by 5%, resulting in a total transmission of 93.1%.

Trajectory Error

As discussed, beam trajectory errors are expected in the LEBT, even if there is no error in the solenoids. As the beam transport through the RFQ is sensitive to the output

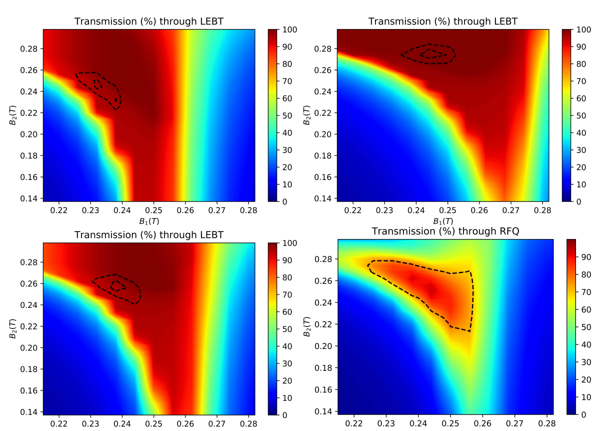

Figure 6: Transmission through the LEBT. Dashed lines show 25% and 50% mismatch for (top left) initial emittance of 0.25 π mm mrad, (top right) SCC level reduced to 90% and (bottom left) initial emittance of 0.25 π mm mrad and SCC reduced to 90%. (bottom right) Transmission through RFQ using a beam with emittance of 0.25 π mm mrad and SCC level of 90% in the LEBT. Dashed line shows the contour of the transverse emittance at 0.25 π mm mrad.

Table 2: Effect of the RFQ Input Trajectory Errors. (Radial error: $dr = [dx^2 + (\alpha dx + \beta dx')^2]^{1/2}$.)

Error	Estimation	1 mm offset	12 mrad offset
Trajectory	Tracking	0.25	0.09
(dr [mm])	Analytic	0.96	1.00
Emittance	Tracking	42	25
($d\varepsilon/\varepsilon$ [%])	Analytic	30	30

beam from the LEBT, the impact of trajectory errors is studied by applying initial offsets in position and angle at the RFQ entrance manually for the LEBT output distribution of the new nominal configuration, described above. We tested a position offset of $dx = 1$ mm and an angle offset of $dx' = 12$ mrad, where the 12 mrad corresponds to the same level of error as 1 mm offset in the normalized phase space according to the relation $dx' = dx\sqrt{1+\alpha^2}/\beta$. The impact of these errors, estimated by both tracking and analytic expressions, is summarized in Table 2. Note that the analytic estimate of the trajectory error (in the normalized coordinates) is based on the standard Courant-Snyder relation $\varepsilon_N/(\pi\beta_R\gamma_R) = \gamma x^2 + 2\alpha x x' + \beta x'^2$, where β_R and γ_R are the Lorentz parameters. The analytic estimate for the emittance growth due to the filamentation effect is based on an expression found in [12]. For the calculations of the normalized coordinates at the RFQ exit, $\beta = 0.283$ mm$/\pi$ mrad and $\alpha = -0.039$, from nominal case are used. As seen in Table 2, the analytic emittance growth and tracking results are fairly close, whereas for the trajectory error the analytic is much larger than the result obtained in the tracking. This indicates that the filamentation effect in the RFQ is strong enough such that the residual trajectory error is nearly wiped out by the time the beam comes out. Note that the emittance growth is also affected by beam losses in the RFQ. The nominal transmission through the RFQ is 97.4%, and is reduced to 93.8% for $dx = 1$ mm and 95.8% for $dx' = 12$ mrad.

CONCLUSION

Results of updated beam dynamics simulations in the IS and LEBT of the ESS proton linac are presented. The model includes the updated particle distribution out of the IS, new field maps for LEBT solenoids and a more realistic aperture structure, including the iris in the LEBT lattice. Optimal solenoids settings in LEBT are identified. The beam mode has satisfactory transmission as well as minimized transverse and longitudinal emittances at the end of the RFQ. Sensitivity to initial emittance and beam conditions such as SCC level and trajectory errors is studied.

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