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# TRANSVERSE DYNAMICS AND SOFTWARE INTEGRATION OF THE ESS LOW ENERGY BEAM TRANSPORT

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## Abstract

The first part of the ESS linac, also called front-end, comprising the Ion Source and the Low Energy Beam Transport (LEBT) section, will be installed and commissioned in 2018. The LEBT is used to focus and correct the proton beam trajectory and clean the head and tail of the proton pulse from the flat top before entering the RFQ. During the ion source and LEBT commissioning a full beam characterization at the RFQ entrance interface is planned. It is thus important to have an application in the control room able to display quantities measured by the diagnostic devices and also to quickly run a simulation including not only centre of mass dynamics but also envelope. This paper presents the efforts in modelling the LEBT elements, as accurately as possible, and implementing the dynamics calculation and integration with diagnostics tools. The final result is a Java FX GUI based on the OpenXAL library.

## INTRODUCTION

The European Spallation Source ERIC project is already well into construction phase. The linear accelerator (linac) will provide an unprecedented proton beam power of 5 MW, with a proton beam current of 62.5 mA and a 2 GeV beam energy on target with a duty factor of 4%. The linac is superconducting which allows for the long pulse length of 2.86 ms, and a 14 Hz pulse repetition rate.

Commissioning of the front-end of the warm linac should start still in 2018 and it is important that the dynamics of the proton beam is understood. The aim of this section is to capture the diverging beam from the ion source and transport a focused and aligned beam straight into the narrow opening of the Radio Frequency Quadrupole (RFQ). Models for the LEBT elements were bench-marked, the beam trajectory and envelope evolution were compared to Tracewin [1] envelope and particle simulations and are show in the next section. A user interface based on the OpenXAL [2] library, and also presented in this paper, was created in order to guide the operator and the commissioning team on how to adjust the parameters to reach a successful transport and matched beam at the RFQ.

## LEBT LATTICE

The first part of the accelerator, right after the ion source, is a 2.5 meter section called LEBT. For the commissioning a tank was added after the collimator in order to allow a second set of measurements of emittance and position, as show in Fig. 1. This section is equipped with two solenoids and two pairs of horizontal and vertical steerers located inside of

Table 1: Expected Beam Parameters at the Entrance of the LEBT [3]

Parameters	Value	Unit
Emittance $\epsilon_x$	0.1223	$\pi$ .mm.mrad
$\alpha_x$	-3.303	-
$\beta_x$	0.397	m
Emittance $\epsilon_y$	0.1217	$\pi$ .mm.mrad
$\alpha_y$	-3.285	-
$\beta_y$	0.392	m
Beam Current	74	mA
Space Charge Compensation	0.95	-
Kinetic Energy	75	keV

each solenoid. The input beam parameters for the LEBT, expected from the Ion Source [3], are listed in Table 1.

## Trajectory Simulations

For the solenoids we decided to use a field map element [4]. The field profile of the LEBT solenoids is very narrow and with no clear flat-top, as show in Fig. 2, which makes the implementation of a hard-edge model approximation inaccurate. Figure 3 shows a comparison of the trajectory calculation for both cases.

Due to limitations regarding superposition of field map elements in OpenXAL, the steerers could not be included as such, and another solution was needed. The field on axis for both steerers is show in Fig 2, it is important to observe that the field profile is almost as long as the solenoid field. Note also that the horizontal field is weaker than the vertical for the same current of 120A, this is due to the fact that the horizontal winding is on top of the vertical one, further away from the beam pipe center. In Fig. 4 a comparison of the proton beam trajectory after passing through a vertical

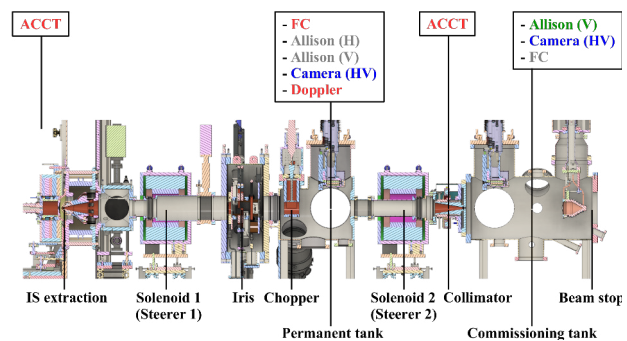


Figure 1: Schematics of the Ion Source, LEBT and the commissioning tank.

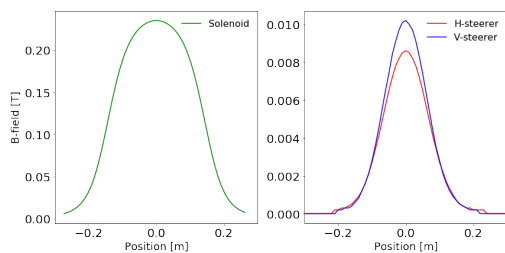


Figure 2: Field profile on axis for the solenoid and steerers. The fieldmap for the solenoid has no flat-top part and thus results in a ill-defined hard-edge approximation. The steerer's filed-map for maximum current (120 A) is almost as long as the solenoid map indicating that the thin lens approximation is probably a bad choice.

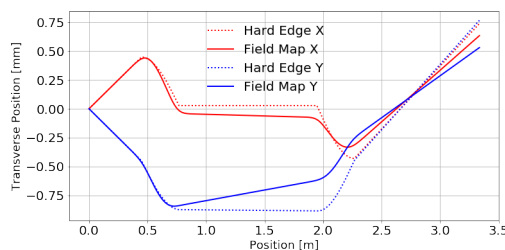


Figure 3: Comparison of a trajectory simulation with the solenoids as field-map elements and using a hard-edge model. The initial conditions are those in Table 1 and initial angles of 3 mrad and -3 mrad in the horizontal and vertical planes respectively.

steerer while the solenoid field is set to the maximum (400 mT) is shown and it is clear that a thin lens approximation is not good enough. For comparison, the trajectory calculated splitting the steerers into 3 thin lenses is also shown in Fig. 4

Figure 5 shows the angular kick error of the steerers once the solenoid field is taken into account and all the relative errors are calculated with respect to Tracewin simulations using field-maps for both solenoids and steerers. The plots show the error in Polar coordinates instead of Cartesian since the solenoid mixes the coordinates in the two planes and thus  $r = (x^2 + y^2)^{1/2}$  and  $\phi = \arg(x + iy)$  was used. When going from a thin lens approximation to splitting the steerers in 3 thin kicks there is a reduction in the error by a factor of 2. Increasing the number of kicks from 3 to 5 the improvement is around 1-2% and the increased complexity does not justify the gain. To achieve a better accuracy in the trajectory simulations with the simplest solution, keeping the trajectory differences between Tracewin and OpenXAL below 10%, we decided to split each steerer in 3 thin lens elements located at the center and at half-max field.

### Envelope Simulations

OpenXAL is only designed to work with bunched beams, but in the LEBT the proton beam is rather continuous, since it is the first section after the proton extraction. The energy of 75 keV is far from relativistic, which means that the space

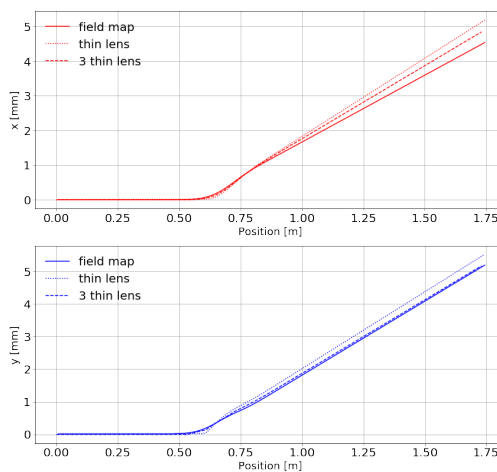


Figure 4: Simulation of a beam trajectory through a solenoid at maximum field (400 mT) and a vertical steerer (20 mT peak field). For the steerer 3 different models were used: field maps, thins lens and 3 lens approximation.

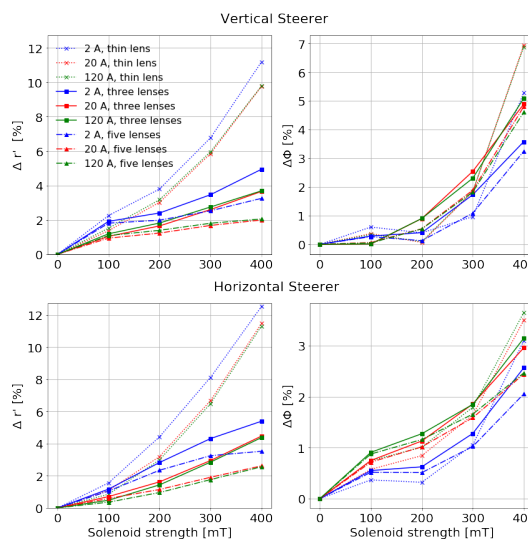


Figure 5: Angular error for the steerer kick using 3 different models: thins lens and 3 and 5 lens approximation. The steerer's strengths are 2, 20 and 100% of the maximum field and the solenoid strength was scanned from 0 to 400 mT. The errors are evaluated in polar coordinates since the solenoid mixes the trajectory in the two cartesian planes. All errors are with respect to tracewin calculations using the field-maps for the steerers and solenoid.

charge has a strong impact on the beam. Without a continuous beam option, the longitudinal emittance and total current of the beam were re-scaled in order to resemble that of a continuous beam. Here once again TraceWin was used for bench-marking the results obtained with OpenXAL.

Figure 6 shows the comparison of envelope simulations using TraceWin and OpenXAL and also the result of a particle tracking for the expected initial conditions in the LEBT (see Table 1). The differences between the averaged rms values, for the envelope mode simulations, are below 5%

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except for the region where the beam size goes below 2 mm, in this case the differences can be as large as 40% (see Fig. 7). A series of simulations for a range of initial emittance values (between 0.055 and 0.33 mm.mrad), currents (31.25, 61.5 and 80 mA) and solenoids strengths (default optics, over-focused and under-focused) were performed in order to evaluate the re-scaling factors. We settled to use  $\sigma_{z0} = 105$  mm and a scaling factor of  $I_{xal} = 35 \times I_{cw}$  for the current which kept the average differences for the calculated rms values along the LEBT and commissioning tank under 10%. Figure 8 shows the evolution of the longitudinal beam size using the input parameters from Table 1. For all other simulated cases the longitudinal beam size blow-up due to space charge was always below 5%.

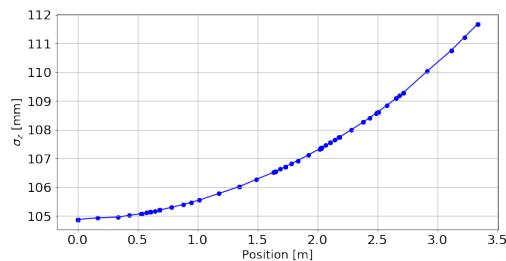


Figure 8: Rms longitudinal beam size along the LEBT and commissioning tank for envelope simulations using OpenXAL. The longitudinal beam size was increased in order to better simulate a continuous beam. The space charge blow-up is below 5%.

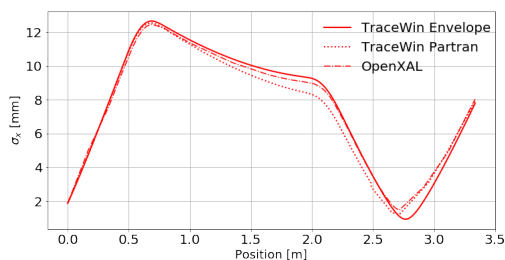


Figure 6: Rms beam size along the LEBT and commissioning tank for envelope simulations using TraceWin and OpenXAL and multi-particle simulation in Tracewin. Initial conditions as listed in Table 1.

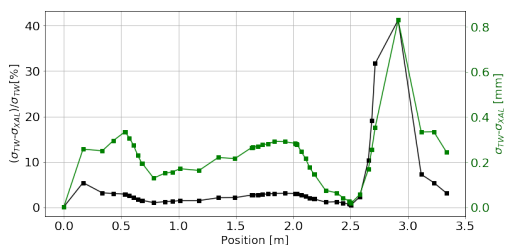


Figure 7: Example of error calculation for the transverse rms size values obtained from simulations in OpenXAL and Tracewin, for the same conditions as show in Fig. 6. The average error is below 5% and significant discrepancies are only observed once the rms values goes below 2 mm, where errors of up to 40% were calculated.

## THE GUI INTERFACE

All the implementations described in the previous section were gathered and a full description of the Ion Source and LEBT lattice was translated to a XML input file for OpenXAL. The JavaFX GUI is show in Fig 9. The application allows the user to interact with the main elements of the LEBT and commissioning tank, like solenoids and steerers and shows the simulated trajectory and envelope for the live machine conditions. The readings from Non-invasive Profile Monitors (NPMs, marked as Cameras in Fig 1) can be added to the trajectory and envelope plots. Using the drop

down menu on the bottom right of Fig. 9 it is possible to use the readings from the Allison Scanners or NPMs and, from its position, propagate trajectory and envelope further. It is also possible to match the initial conditions (position and/or twiss parameters) in the LEBT based on their readings. The current monitors, Faraday Cup (FC) and Beam Current Monitor (ACCT), readings can be used in the model as the initial current value.

## CONCLUSION

The model for the main elements in the LEBT (solenoids and steerers) was bench-marked and included in the OpenXAL lattice. The trajectory and envelope differences, when compared to Tracewin simulation of a CW beam, are below 10%. A JavaFX GUI interface where the user can check the the model against real measurements and also interact with the main elements and diagnostics in the LEBT and commissioning tank was developed and should be used soon during commissioning and further in operations.



Figure 9: JavaFX GUI interface. The plots show the trajectory (top chart) and envelope (bottom chart) together with NPM readings.

## REFERENCES

- [1] D. Uriot and N. Pichoff, "Status of TraceWin Code," presented at the 15th Int. Particle Accelerator Conf. (IPAC'15), Richmond, VA, USA, May 2015, paper MOPWA008.
- [2] Open XAL website, <http://openxal.github.io>.
- [3] Ø. Midttun *et. al.*, "Measurements and simulations of the beam extraction from the ESS proton source," presented at the 17th Int. Conference on Ion Sources, Geneva, Switzerland, October 2017.
- [4] J. F. Esteban Müller and E. Laface, "Latest developments and updates of the ESS Linac Simulator," presented at the 18th Int. Particle Accelerator Conf. (IPAC'18), Vancouver, Canada, May 2018, paper WEPAF086, this conference.