COMPARING THE TRANSVERSE DYNAMICS OF THE ESS LINAC SIMULATOR AND THE SPALLATION NEUTRON SOURCE LINAC

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Abstract

The ESS Linac Simulator (ELS) is the model that will be used at the European Spallation Source ERIC in Lund, Sweden, to simulate the transport of the beam envelope during operations. On August 12th 2015, we had the opportunity to use two hours of beam time in the linac of the Spallation Neutron Source in Oak Ridge to benchmark ELS. In this paper we present the results of the transverse dynamics measurements. Such measurements are obtained upon kicking the beam in the medium-energy beam transport (MEBT) and measuring the effect of the oscillation of the beam centroid in 58 beam position monitors (BPMs). The ELS model and these measurements are in agreement with an average discrepancy of 4% in the superconducting section of the accelerator.

INTRODUCTION

During August 2015 the Spallation Neutron Source (SNS) in Oak Ridge, Tenessee, USA, kindly allocated two hours of beam time to test the ESS Linac Simulator [1–3] in their running proton linac. This test was possible because ELS is being developed with an existing framework used for several years at the Spallation Neutron Source in Oak Ridge, Tennessee, USA. The framework is called OpenXAL [4, 5].

The choice of OpenXAL was driven by the need for a framework that can speak the protocol used by the control system, the Experimental Physics and Industrial Control System (EPICS). OpenXAL uses such a protocol because the SNS control system uses EPICS. OpenXAL is entirely made in Java and was extensively tested in a real accelerator. ELS, originally written in C, was ported to Java and integrated in OpenXAL as the main model. Because of the compatibility with SNS, it is now possible to change between machine models in OpenXAL and use the one developed at SNS instead of ELS. This allows us to quickly compare two independent simulators.

The schematic of the linac at the Spallation Neutron Source is in Fig. 1. For the ELS measurements H^- beam

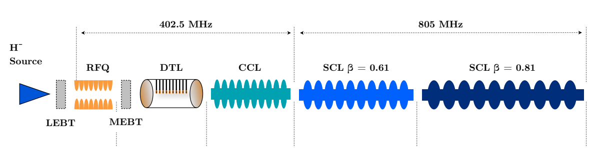

Figure 1: Spallation Neutron Source Linac.

was used with the same characteristics of the SNS production beam but with only 10 micro bunches. The SNS production optics is the result of the mitigation of several issues encountered during the commissioning of the linac, the most notable the Intra Beam Stripping, and summarised in [6].

The main parameters, for the beam and the machine, used for the experiment are summarised in Tab. 1

Table 1: Beam Parameters

Parameter	**Value**
Beam peak current	38 mA
Micro bunches	10
Freq. normal conducting linac	402.5 MHz
Freq. super conducting linac	805 MHz
Horizontal emit.	3.02×10^{-6} m rad
Vertical emit.	3.46×10^{-6} m rad
Longitudinal emit.	3.86×10^{-6} m rad
Top energy	1 GeV

The measurement evaluated the capability of ELS in predicting the transverse dynamics of the linear elements of SNS. Another set of measurements for the test of the longitudinal dynamics was performed and explained in [7]. To understand if these dynamics are correct, the beam was deviated from its centred trajectory using a kicker dipole in the early part of the accelerator (in the MEBT, see Fig. 1). The coherent shift induced by the kick moves the centroid of the beam along a trajectory that will oscillate around the axis of symmetry of the accelerator. The amplitude of the displacement can be calculated as function of the Twiss parameters, the beam energy and the angle of kick with the Eq. 1 [8].

$$\Delta\xi(s) = \theta_\xi \sqrt{\frac{\beta_r(0)\gamma_r(0)}{\beta_r(s)\gamma_r(s)}\beta(0)\beta(s)} \sin[\phi(s) - \phi(0)] \quad (1)$$

where ξ is either x or y if the kick is in the horizontal or vertical plane; β_r and γ_r are the relativistic factors; while β is the betatronic function and ϕ is the phase advance. The index 0 denotes the position of the kicker with the index s that of the position in the accelerator downstream. In this way, if we know the angle of kick θ, we should be able to predict the displacement of the beam since ELS should provide the correct values for energy and Twiss functions, yielding, respectively, the relativistic factors and the betatron and phase advance functions.

In the Linac, the transversal dynamics are also affected by the presence of the space-charge force. These measurements are not capable to evaluate the space-charge because the oscillation created by the kicker is coherent and not affected by the beam current.

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MEASUREMENT

Two corrector kickers in the MEBT section were used to generate the displacement of the centroid of the beam: the MEBT_Mag:DCH01 for the kick in the horizontal plane and the MEBT_Mag:DCV01 for the vertical plane. Both magnets sits at 0.128 m from the beginning of the MEBT section and are long 0.061 m.

The scan of the magnets were performed independently, which means that when a kicker was powered, the other was switched off in order to minimise the coupling between the two oscillations. The applied field to the kickers ranged from −0.005 T to 0.008 T in 13 steps in both planes while the displacement of the centroid was measured in the 58 beam position monitors (BPMs) installed in the accelerator. The horizontal and vertical trajectories of the beam, with the two correctors switched off, as showed in Fig. 2, were measured and subtracted as reference from the other measurements obtained during the scan of the magnets.

The results of the scan in the two planes, after the subtraction of the references, are shown in Fig. 3.

Figure 2: Reference trajectories measured with MEBT_Mag:DCH01 and MEBT_Mag:DCV01 switched off.

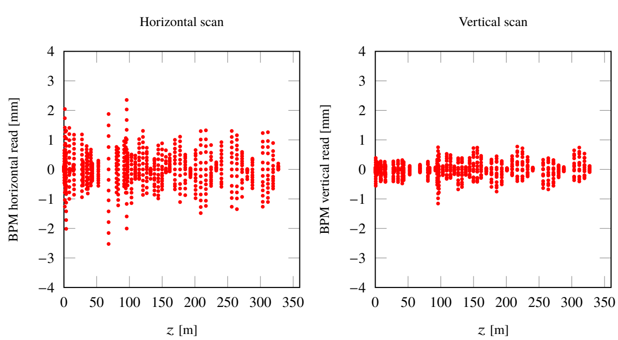

Figure 3: Displacement of the beam centroid measured in the BPMs during the scan of the horizontal (left) and vertical (right) kickers. Each column of dots is the reading of a BPM and each dot in the column represent one of the 13 magnetic fields between −0.005 T and 0.008 T used during the scan.

As preliminary observation we can see that the kickers generate an oscillation compatible with what we expect from a reasonable betatronic oscillation. The amplitude scales linearly with the angle produced by the kicker, as expected from Eq. 1.

The comparison between measurements and ELS model is done splitting the accelerator in two sections: the normal conducting section (the first 95 meters of the accelerator) and the superconducting section (the remaining 230 meters of the machine). The normal conducting section uses the optics contained by default in the OpenXAL distribution file provided with the SNS lattice, and also the initial conditions of the beam are obtained from the production file of the OpenXAL distribution. The model is able to reproduce the beam orbit well for all the 13 different values of the magnetic field for both horizontal and vertical correctors. The ELS model vs. measurement for the normal conducting section of the accelerator in the case of the correctors powered at 0.006 T is shown in Fig. 4. The rapid oscillation in the normal conducting section does not allow a sampling with the 24 (plus 2 not functioning) BPMs good enough to have a numerical comparison, nevertheless a qualitative comparison shows that the model is capable to predict the oscillation.

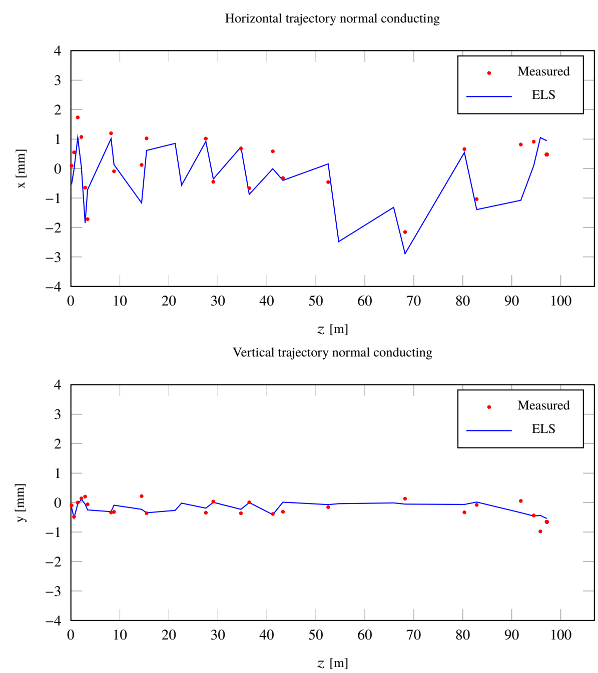

Figure 4: Comparison of ELS-predicted and measured response to kicker-generated oscillations in the normal conducting sections of SNS when the applied magnetic field to the corrector was 0.006 T.

The superconducting section of SNS uses an optics that was modified from the original file contained in OpenXAL. The reason of the change is to increase the size of the beam to minimize the impact of the intra beam stripping effect as described in [6]. The model used in ELS, for the superconducting section, is then instantiated from the dump of the EPICS parameters downloaded from the control system. The magnetic fields of the quadrupoles are immediately available as well as the voltages of the cavities. Some work was required to get the cavity phases matched in the ELS because the phases available from the SNS control system are referred to their master time and not as relative phases as required in the simulation code. Once the phases were reconstructed in the simulator, the model reproduced well the oscillation of the beam for all the 13 different values of the magnetic field for both horizontal and vertical correctors. The ELS model vs. measurement for the superconducting section of the accelerator in the case of the correctors powered at 0.006 T is shown in Fig. 5. The oscillation of the beam in the superconducting section of the accelerator allows a numerical comparison with the model. The relative difference between the data and the model, evaluated in the 32 BPMs as $\frac{1}{32}\sum_{i=1}^{32}\left|\frac{x_{i\,\text{meas}}-x_{i\,\text{ELS}}}{x_{i\,\text{meas}}}\right|$, is within 4% for both x and y planes.

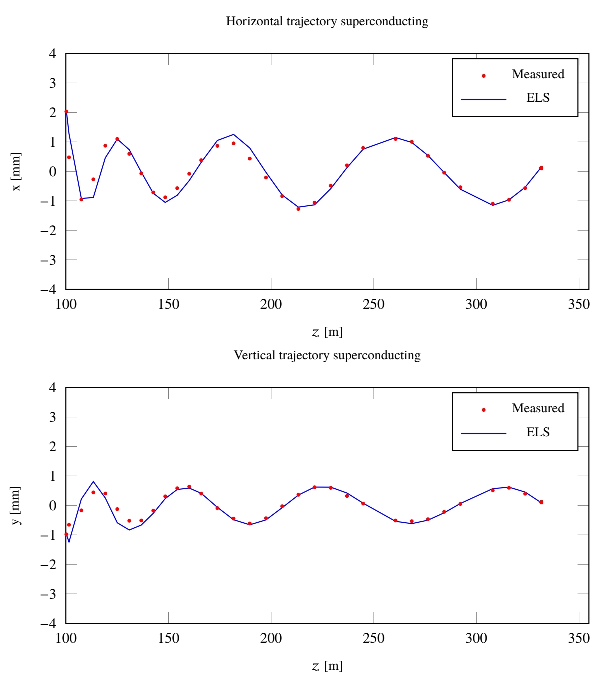

Figure 5: Comparison of ELS-predicted and measured response to kicker-generated oscillations in the superconducting sections of SNS when the applied magnetic field to the corrector was 0.006 T.

A full estimation of the transversal dynamics for an high intensity machine should include also the non-negligible effect of the space charge. The measurement done at SNS involves a coherent shift of the centroid of the beam and, consequently, it does not allow us to evaluate if the space charge model included in the ELS is effective in reproducing a real beam. In order to perform a more accurate quantitative measurements, more information is required such as the calibration of the BPMs, their errors, the precise phase of the superconducting cavities, etc. Nevertheless, the fact that the model is capable of reproducing the frequency of oscillation, the average amplitude, and the angular linear-scaling law, is an indicating that it is predicting the dynamics correctly.

CONLCUSIONS

We benchmarked the transversal dynamics of the ESS Linac Simulator in the H$^-$ linac at the Spallation Neutron Source in a 2 hour machine development time slot in August. The model and the measurements are in good agreement for both horizontal and vertical planes, with a fair qualitative prediction for the normal conducting section and a good numerical estimation for the superconducting section.

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