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LATEST DEVELOPMENTS AND UPDATES OF THE ESS LINAC SIMULATOR

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Abstract

A fast and accurate online model is required for optimal commissioning and reliable operation of the high-power proton linac at the European Spallation Source. The Open XAL framework, initially developed at SNS, is used at ESS for the development of high-level physics applications. The online model we use, the Java ESS Linac Simulator (JELS), extends the Open XAL model with several features.

This paper describes the latest updates carried out to JELS. Two new elements have been implemented: a solenoid field map for the LEBT and a DTL Tank element that automatically calculates each gap phase. All calculations are now done in the laboratory frame, in agreement with Open XAL convention. A thorough benchmark of the model against TraceWin, which is the tool used for the lattice design, is also presented.

INTRODUCTION

Open XAL is a framework to develop high-level physics applications that was initially developed at SNS and then transformed into a collaborative project between several laboratories [1]. ESS is an active contributor to the project, both to its core and by developing new applications [2].

One of the central parts of Open XAL is its online modelling capabilities. Although the model delivered in the suite covers most of the elements typically found in an accelerator, in some situations it requires some customization to adapt to the specific needs. In our case, the extension is known as the Java ESS Linac Simulator (JELS) and it includes field map integrators for rf cavities and magnets, a different transit-time factor definition for rf cavities, a new model for bending magnets, and some specific beam instrumentation.

In this paper we describe the latest changes to the model, as well as the addition of new elements.

MODEL UPDATE

The main modification that was required in our online model was to change the system of reference. Open XAL performs all calculations in the laboratory frame of reference, but we were previously using the beam frame of reference. For that reason, most elements required modifications to their transfer matrices, as well as the space-charge calculation, to be consistent with Open XAL main distribution. In addition, new elements were added and an extensive benchmarking was carried out.

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FIELD MAPS

For elements with strong nonlinearities, a single matrix representation might not provide enough accuracy. In the ESS linac, that is the situation for the solenoid magnets in the LEBT, dominated by fringe fields, and for the superconducting cavities.

The approach used in our model is to numerically integrate field maps for the corresponding elements, although a new technique is currently being investigated to avoid numerical integration and to treat nonlinearities for rf cavities [3].

In general, the motion of a charged particle under the influence of an electromagnetic field is described by the Lorentz force as

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \frac{\vec{p}}{\gamma\, m} \times \vec{B}\right), \tag{1}$$

where $\vec{p}$ is the particle momentum, q its charge, m its mass, $\vec{E}$ the electric field, $\vec{B}$ the magnetic field, and γ the Lorentz factor.

In most practical situations, we use the paraxial approximation. In Cartesian coordinates, the equations of motion become

$$\begin{aligned}
\frac{d^2x}{ds^2} &\simeq \frac{q}{\gamma\,\beta^2\, m\, c^2}\left[E_x - E_z\frac{dx}{ds} + \beta\, c\left(\frac{dy}{ds}B_z - B_y\right)\right],\\
\frac{d^2y}{ds^2} &\simeq \frac{q}{\gamma\,\beta^2\, m\, c^2}\left[E_y - E_z\frac{dy}{ds} + \beta\, c\left(B_x - \frac{dx}{ds}B_z\right)\right],\\
\frac{d^2z}{ds^2} &\simeq \frac{q}{\gamma\,\beta^2\, m\, c^2}\left[E_z + E_x\frac{dx}{ds} + E_y\frac{dy}{ds}\right],
\end{aligned} \tag{2}$$

where c is the speed of light and β the relativistic beta.

Then the electric and magnetic fields are expanded to the first order, as shown below for the x coordinate of the electric field:

$$E_x(x,y,z) \simeq E_{x0} + \frac{dE_x}{dx}x + \frac{dE_x}{dy}y + \frac{dE_x}{dz}z + \dots \tag{3}$$

And finally we solve the equations of motion using a first order integrator. For example, for the x coordinate:

$$\begin{aligned}
x[n+1] &= x[n] + \Delta s\, x'[n],\\
x'[n+1] &= x'[n] + \Delta s\, x''[n],
\end{aligned} \tag{4}$$

where Δs is the integration step size.

Two implementations for the solenoid field map were developed. In one of them, the field is described using two components, radial and longitudinal, assuming cylindrical symmetry. The other implementation uses a representation of the field in a 3D Cartesian coordinate system. Both models have been successfully benchmarked against TraceWin [4], as shown in Fig. 1. For a more extensive study, see [5, 6].

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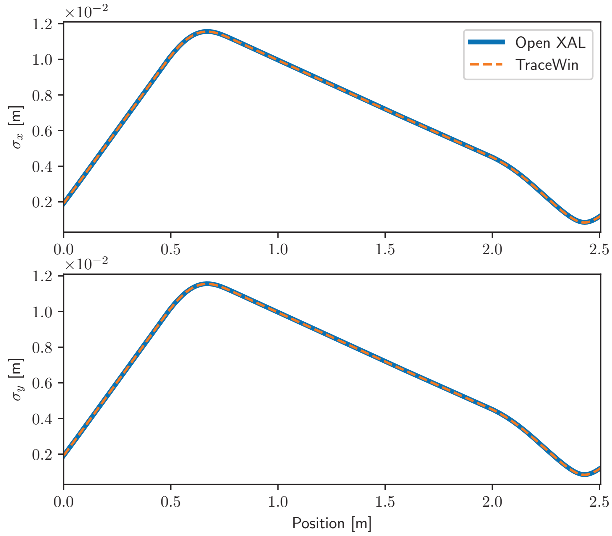

Figure 1: Transverse beam sizes evolution along the LEBT, simulated using Open XAL (blue) and TraceWin (orange).

The previous version of the model included a field map for rf cavities, but it was solving Eqs. (2) analytically [7]. The implementation was modified to compute the solution of Eqs. (2) using a first order integrator as for the solenoids, with a gain in runtime speed of about 30 % and similar accuracy.

DTL TANK

In a DTL tank, all accelerating cells are coupled and therefore the amplitude and phase of the electric field that a particle sees at each gap depends on that in the previous gaps. The phase shift introduced by each gap can be approximated by

$$\Delta\phi \simeq \frac{q\,E_0\,T\,L\,\sin(\phi_s)}{m\,c^2\,\gamma^3\,\beta^2}\frac{k\,T'}{T}, \qquad (5)$$

where E_0 the amplitude of the longitudinal electric field, L the cell length, ϕ_s the synchronous phase, $k = 2\pi/(\beta\lambda)$, λ is the rf wavelength, and T and T' the transit-time factor (TTF) and its derivative, respectively.

Although there is a DTLTank element in the Open XAL model, it uses a polynomial fit for the TTF. At ESS, the DTL was modelled by the beam physics section using the following fit instead:

$$T(\beta_o) = \sum_{n=0}^{\infty} \frac{k}{n!}\left(\frac{\beta_s}{\beta_o} - 1\right)^n \frac{d^n T(\beta)}{d\beta^n}\Big|_{\beta=\beta_o}. \qquad (6)$$

This fit for the TTF was already implemented in Open XAL and used in the ESSRfGap element, but that forced us to define the DTL as a sequence of elements with independent phases and amplitudes. A change of the phase or amplitude of the DTL tank had to be done carefully by modifying all the parameters.

For that reason, a new DTL Tank element that uses the TTF expansion of Eq. (6) was implemented. This allows us to set the amplitude and phase only for the first accelerating gap and all other gaps are calculated accordingly. Figure 2 shows a comparison of the phase for each cell calculated using Open XAL and Eq. (5).

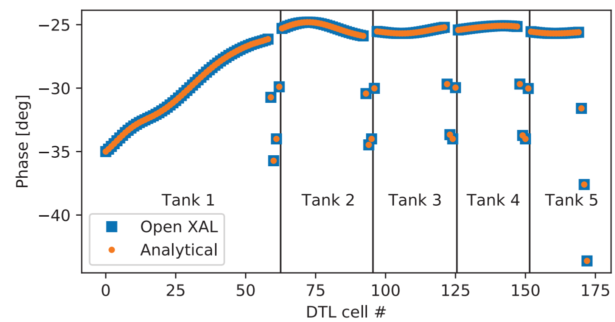

Figure 2: Comparison of the phase for each DTL cell calculated using Open XAL (blue) and analytically (orange).

Finally, the new element was verified using TraceWin. Simulation results of the beam envelope, shown in Fig. 3 for the longitudinal plane, are in perfect agreement.

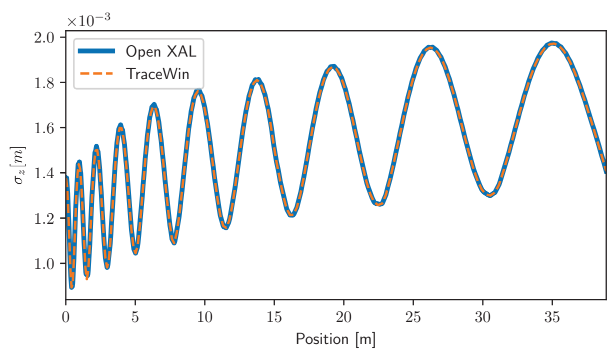

Figure 3: Longitudinal beam size along the DTL section (5 tanks) calculated using Open XAL (blue) and TraceWin (orange).

BENCHMARK

The ESS linac simulator, the predecessor of our online model, was benchmarked in the past against Tracewin and showed a good agreement [8]. Nevertheless, since that comparison was made, the simulator was integrated in Open XAL and the improvements described in this paper were put in place. Given that TraceWin has also benefited from refinements during this period, a comprehensive benchmark was again required.

All elements implemented in JELS are tested individually against results obtained using TraceWin. Both the transfer matrices and envelope are compared, taking into account that Open XAL uses the coordinate system (x, x', y, y', z, z'), while TraceWin uses (x, x', y, y', z, Δp/p), with

$$z' = \frac{1}{\gamma^2}\frac{\Delta p}{p}. \qquad (7)$$

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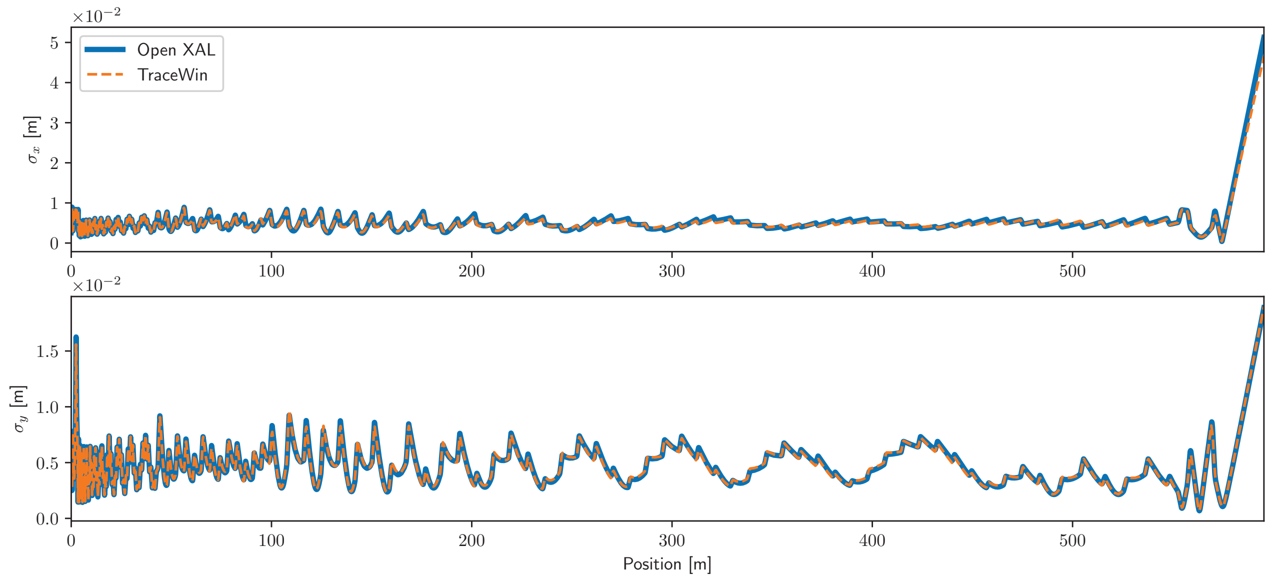

Figure 4: Benchmark of the transverse beam sizes along the full ESS linac between Open XAL (blue) and TraceWin (orange), with space-charge calculation enabled. Nominal proton beam current (62.5 mA) and injection energy (3.62 MeV).

The transfer matrices M and beam covariance matrices σ are therefore related as

$$M_O = \mathrm{diag}(1,1,1,1,1,\gamma_o^{-2})\, M_T\, \mathrm{diag}(1,1,1,1,1,\gamma_i^{2}), \quad (8)$$
$$\sigma_O = \mathrm{diag}(1,1,1,1,1,\gamma_o^{-2})\, \sigma_T\, \mathrm{diag}(1,1,1,1,1,\gamma_i^{-2}), \quad (9)$$

where γ_i is the Lorentz factor at the entrance of the elements and γ_o is at the output, and the matrix subindexes O and T stand for Open XAL and TraceWin, respectively.

These tests are included in the continuous integration, so every new release of the code is verified.

Finally, the full lattice is benchmarked. Figure 4 shows the results of the comparison for the transverse planes, including the space-charge effect. The agreement is good and only small differences can be seen, coming mainly from the algorithms used for field map integration and space-charge, which can be different from those used by TraceWin.

SUMMARY

Latest improvements to the ESS linac online model have been proven to accurately model the whole accelerator, only excluding the RFQ. The model is now consistent with the one shipped with Open XAL regarding the coordinate system.

The new release of the model includes optimized fieldmap integrators for rf cavities and magnets, and a DTL Tank element. It has been benchmarked against other simulation code, TraceWin, and results were in good agreement.

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