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NEW RFQ AND FIELD MAP MODEL FOR THE ESS LINAC SIMULATOR

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Abstract

The Java ESS Linac Simulator (JELS) is an extension of the Open XAL online model that is a fundamental part of the accelerator control system. The model is used by high-level physics applications for commissioning, tuning, and machine development activities at the European Spallation Source (ESS).

This paper summarizes the upgrades done to JELS during the last year. An RFQ model is under development. The RFQ was the only element of the linac missing in the online model. The electromagnetic field map model has been refactored to ease implementation of new elements (rf cavities and magnets), and to allow the superposition of more than one field map and other elements. Further improvements have also been done in the treatment of corrector magnets and space charge for continuous beam in the Low-Energy Beam Transport (LEBT). Finally, the machine description can now include arbitrary aperture definitions.

INTRODUCTION

Open XAL is a framework to develop high-level physics applications that was initially developed at SNS [1]. Later it became open-source and a collaboration between several laboratories started. ESS is part of the collaboration and is participating actively in the development of the core and applications [2].

Open XAL includes and online model that can be used for fast simulations of the accelerator beam dynamics. At ESS, we have extended the online model to match our requirements. This extended model is know as Java ESS Linac Simulator (JELS). The main modifications include 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.

This paper focus on some of the latest changes of the model, including the improvement of the field map elements and the addition of a simplified model of the RFQ.

RFQ

Our goal is to be able to perform end-to-end simulations of the full ESS linac using JELS in Open XAL. In the past we have been able to simulate all the way from the exit of the RFQ to the target [3].

Thanks to the recent implementation of an algorithm to compute space-charge effect for DC beams [4] and the magnetic field map model, we can now accurately simulate the Low-Energy Beam Transport (LEBT) section of the ESS linac.

The only section of the accelerator that is still missing in our model is the RFQ. As a proof of concept, we developed a model based on the classical two-term potential function (see e.g. [5]). We started from the simplest model because we are concerned about the computation speed, since JELS is mainly used in Open XAL as an online model.

In cylindrical coordinates, the two-term electric potential function of an RFQ cell is

$$U(r,\theta,z) = \frac{V}{2}\left(A_0\, r^2 \cos(2\theta) + A_{10}\, I_0(kr)\cos(kr)\right), \quad (1)$$

where A_0 and A_{10} are constants defined by the cell geometry, $k = 2\pi/L$, L is the cell length, and I_0 is the modified Bessel function of the first kind and order 0.

Figure 1 shows the results of our model compared to a simulation run using TraceWin [6], a commercial multiparticle tracking and envelope code. Unfortunately, it is clear that the accuracy of the model using the two-term potential is not sufficient and a more precise model is needed.

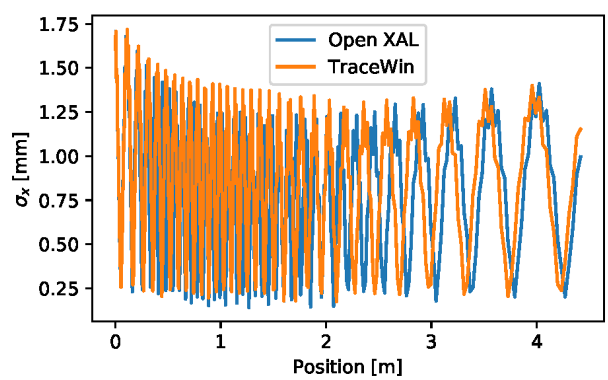

Figure 1: Horizontal beam size in the ESS RFQ simulated using Open XAL (blue) and TraceWin (orange). Initial beam kinetic energy 74.6 keV and no space charge.

Future Steps

We are planning to improve the RFQ model by using the more accurate eight-term potential:

$$\begin{aligned} U(r,\theta,z) = \frac{V}{2}\Bigg[& A_{01}\left(\frac{r}{r_0}\right)^2 \cos 2\theta + A_{03}\left(\frac{r}{r_0}\right)^6 \cos 6\theta \\ & + A_{10} I_0(kr)\cos kz + A_{30} I_0(3kr)\cos 3kz \\ & + (A_{12} I_4(kr)\cos kz + A_{32} I_0(3kr)\cos 3kz)\cos 4\theta \\ & + (A_{21} I_2(2kr)\cos 2\theta + A_{23} I_6(2kr)\cos 6\theta)\cos 2kz \Bigg]. \end{aligned} \quad (2)$$

The calculation of the 8 coefficients requires to solve the Laplace equation numerically and fit the coefficients. Since this can be computationally expensive for an online model, we plan to use an external program to precalculate the coefficients and reduce computation time.

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Space charge strongly affects the dynamics in the RFQ and has to be taking into consideration in the model. In this regime, the envelope model that we use in Open XAL might not be accurate enough. If that is the case, we can consider implementing a multiparticle tracker together with a PIC code or another space-charge solver (e.g. [7]). That can considerably slow down the simulations, but since it would only be used for the RFQ, it might be acceptable.

FIELD MAPS

Previous versions of JELS already included 3 different types of field maps: a 1D model for rf cavities (only amplitude along z), a 2D model for magnets (assuming cylindrical symmetry), and a 3D magnetic field map.

That implementation had nevertheless two main limitations. The first one is that the field maps were treated as thick elements, therefore it was not possible to superpose two field maps or a field map and other thick element. The second issue is that the implementation of new field map elements required to write three classes with a large fraction of boilerplate code. It was required a class for the Standard Machine Format (SMF) object, representing the physical element; an attribute bucket class, which was used to define the parameters of the device; and a model class, which defines the physics of the element.

For these reasons, the field map classes were refactored to allow superposition of field maps, simplify the development of new field map elements and reduce the amount of boiler-plate code needed. The new implementation is more complex, but new elements can be added easily by writing only a single class.

Implementation

As for any other accelerator device, the field map implementation is divided in the machine description (SMF) and the physics model.

On the SMF side, we included a new FieldMap attribute bucket[1] that groups all the properties related to the field maps. Field maps should use this bucket together with another one describing the device, for example, a MagnetBucket.

Then, two generic devices has been included:

- RfFieldMap, that extends RfGap. This device is used for rf cavities.
- MagFieldMap, that extends Electromagnet and can be used for any type of magnet.

These are the classes that should be used in the element mapping definition.

The most important class here is FieldMap[2]. The class implements methods to read field map files in the same format as TraceWin and abstract methods to calculate the fields. This is the only one that has to be extended when developing a new field map element, and the abstract methods should implement the logic to understand the field map files.

Finally, the FieldMapFactory class uses the information from the FieldMapBucket to chose which class derived from FieldMap should be used.

On the model side, there are two implementations for rf elements and two for magnetic fields. One of them uses thin elements, which have the advantage that can be superposed to other elements; and the other one uses thick elements, that are faster. The user can decide which class to use for each device.

All the model elements use FieldMapPoint objects generated by the SMF FieldMap classes, which describe the electromagnetic field at a given point, and the transfer matrix is calculated using the FieldMapIntegrator[3] class, that is developed in the next section.

Field Map Integrator

The class FieldMapIntegrator implements a first order integrator for generic electromagnetic field maps.

The equations of motion are derived from the Lorentz force, which describes the motion of a charged particle under the influence of an electromagnetic field as

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \frac{\vec{p}}{\gamma\, m} \times \vec{B}\right), \tag{3}$$

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.

Then, using the paraxial approximation, the equations of motion in Cartesian coordinates become

$$\begin{aligned} \frac{d^2x}{ds^2} &\simeq \frac{q}{\gamma\,\beta^2\,m\,c^2}\left[E_x - E_z\frac{dx}{ds} + \beta\,c\left(\frac{dy}{ds}B_z - B_y\right)\right], \\ \frac{d^2y}{ds^2} &\simeq \frac{q}{\gamma\,\beta^2\,m\,c^2}\left[E_y - E_z\frac{dy}{ds} + \beta\,c\left(B_x - \frac{dx}{ds}B_z\right)\right], \\ \frac{d^2z}{ds^2} &\simeq \frac{q}{\gamma\,\beta^2\,m\,c^2}\left[E_z + E_x\frac{dx}{ds} + E_y\frac{dy}{ds}\right], \end{aligned} \tag{4}$$

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

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

$$E_x(x,y,z) \simeq E_{x0} + \frac{dE_x}{dx}x + \frac{dE_x}{dy}y + \frac{dE_x}{dz}z + \ldots \tag{5}$$

And finally we use a drift-kick-drift model to integrate the equations of motion.

Examples

The new field map model has been tested and benchmarked against TraceWin. Here we show some of the results.

The rf field map model has been verified for the different cavities used in the ESS linac. Figure 2 shows a simulation

[1] xal.extension.jels.smf.attr.FieldMapBucket
[2] xal.extension.jels.smf.impl.FieldMap
[3] xal.extension.jels.model.elem.FieldMapIntegrator

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of the medium-β section (36 cavities) using this model and compared with TraceWin. The results of the two codes match very well. This test has been successfully repeated for all the sections of the ESS linac.

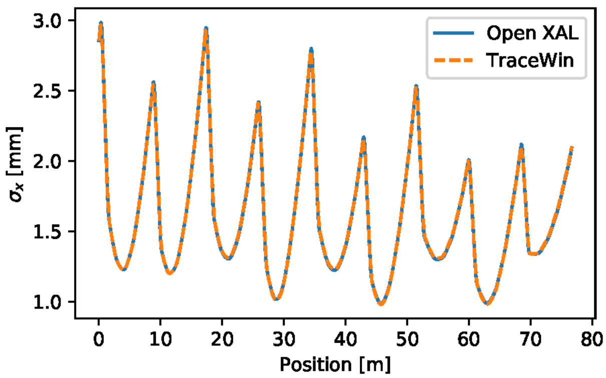

Figure 2: Horizontal beam size in the medium-β section (MBL) of the ESS linac simulated using Open XAL (blue) and TraceWin (orange). Initial beam kinetic energy 216.5 MeV and no space charge.

Another test was carried out using the magnetic field map model for the solenoid magnets used in the LEBT. A comparison with results from TraceWin are shown on Fig. 3 and a good agreement is observed.

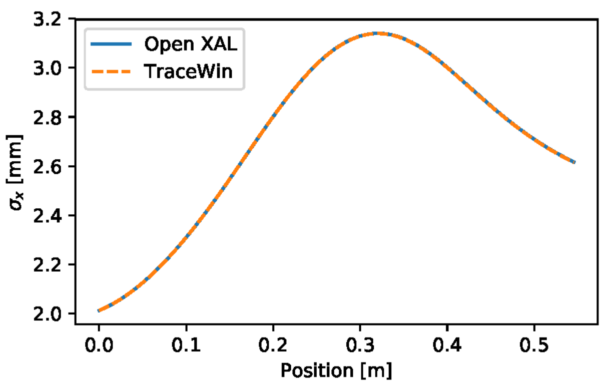

Figure 3: Horizontal beam size in a LEBT solenoid magnet simulated using Open XAL (blue) and TraceWin (orange). Beam kinetic energy 75 keV and no space charge.

OTHER IMPROVEMENTS

Several other changes have been done to our model and are summarized in [2]. They include a new algorithm to simulate DC beams with space charge, a new feature to split long corrector magnets in several kicks for better accuracy, a more flexible aperture definition for the accelerator devices, improvement of the treatment of misalignments, and simplification of some of the existing elements.

In addition, more unit tests have been defined to verify the model and they are executed by the continuous integration.

SUMMARY

This paper presented some of the improvements and new developments to the Open XAL online model done at ESS. The field map elements have been refined and refactored to allow an easier development of electromagnetic devices including the overlapping of the fields of different accelerator components. We started to build a new model for the RFQ based on two-term electric potential that will be extended in the eight-term potential to improve the accuracy.

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