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DC BEAM SPACE-CHARGE MODELING FOR OPENXAL*

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Abstract

Open XAL is an open source multi-purpose accelerator physics software platform based on a pure Java open source development environment used for creating accelerator physics applications, scripts and services. Currently, the software has been used with an ellipsoidal (bunched) beam to account for space-charge effects. Applications developed so far for ESS, such as the Virtual Machine for the ESS Low Energy Beam Transport (LEBT) section, would profit from a DC beam description. In this paper, the space-charge component for a continuous beam is derived taking into account beams with different transverse charge distributions (uniform, Gaussian, etc). The implementation in OpenXAL and a comparison with other simulation codes is also presented.

INTRODUCTION

A continuous (DC) beam model was derived and implemented in OpenXAL followed by benchmarking. After the benchmarking, a GUI was developed in JavaFX within which the possibility to choose between a DC and a bunched beam model for the beam simulation was implemented. The results of the physical model of the beam and the developed GUI will be used in the ESS control room in the near future during commissioning and operations.

THE DC BEAM

The Space Charge Effect

The space charge effect contributes to the transverse expansion of low-energy beams but is negligible for high-energy beams, as described in [1]. The space charge component was re-derived using the same procedure as described in [2, 3], such that it could be easily implemented in OpenXAL.

Using K, a dimensionless variable referred to as the generalized beam perveance [2], the expressions for the space charge effect on the beam are [4]

$$\frac{1}{f_{sc,x}} = \frac{2K}{x_0(x_0+y_0)} D_{DC}, \tag{1}$$

$$\frac{1}{f_{sc,y}} = \frac{2K}{y_0(x_0+y_0)} D_{DC} \tag{2}$$

with the form-factor D_{DC} being purely numerical and depending only of the beam transverse distribution. The values for four different beam distribution profiles for a DC beam are shown in Table 1. Those values match those calculated in [3].

Table 1: The Functional Λ for Symmetric Beam Profiles

Shape description:	**F(s)**	**D_{DC}(F)**
Uniform	$\begin{cases} C & \text{for } s \leq 1, \\ 0 & \text{for } s > 1. \end{cases}$	1
Gaussian	$Ce^{-s/2\sigma^2}$	0.977
Hollow	$Cse^{-s/2\sigma^2}$	0.987
Parabolic	$\begin{cases} C(1-s) & \text{for } s \leq 1, \\ 0 & \text{for } s > 1. \end{cases}$	0.996

In OpenXAL the space charge matrix kick, generalized for a 2D format, over a step-size Δz can be written as

$$M_{\mathrm{SC,\,2D}}(\Delta z) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ \Delta z f_{sc,x}^{-1} & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \Delta z f_{sc,y}^{-1} & 1 \end{pmatrix}. \tag{3}$$

Implementation

In order to implement the DC beam into OpenXAL, and since the beam trajectory does not depend on linear space charge effects, the Java class in which the beam envelope is calculated has to be modified. This class, in OpenXAL, is called *EnvelopeTrackerBase*. It is, amongst all, responsible for calculating the space charge kick over every element's slices. [5].

The function responsible for calculating the space charge kick was modified in order to test if the beam calculated was bunched or dc it efficient and required minimal changes of the core of the code, and is benchmarked in the next section. It is possible now to set the DC beam flag directly via the input XML file was and also when the Tracker in called within the program, setting *useDCBeam* as *True*.

BENCHMARK RESULTS

The DC beam model was benchmarked in a series of tests with the beam transport code TraceWin [6] as reference in order to conclude whether the implementation was correctly done. In TraceWin, the simulated beam is referred to as a CW (DC wave) which, in this case, is a DC beam. During the benchmarking, the magnets are simulated using the same lattice: Drift (1 m), magnet (0.5 m), and drift (1.0 m). The 1.0 m drift matrix is defined as M_D. Initial conditions of the beam's trajectory during the simulations ([mm] units for the positions and [mrad] units for the angles) is defined in Table 2, the initial Twiss parameters in Table 3, the simulations' magnet properties are defined in Table 4 and the kinetic energy of the particles is 74.7 keV.

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Table 2: Initial Conditions of the Simulated Beam

x_0	x'_0	y_0	y'_0	z_0	z'_0
1	3	2	4	0	0

Table 3: Initial Twiss Parameters of the DC Beam

Plane:	**x**	**y**	$\mathbf{z_{DC}}$
α	−3.2288082	−3.227559	0.0
β	0.38607772	0.38580933	1.0
ε	1.03040028E-5	1.03040028E-5	1.0

Table 4: Simulated Magnets' Properties

Magnet:	**Length: [m]**	**Magnetic field: [T]**
Quadrupole	0.5	0.15
HE solenoid	0.5	0.235

Quadrupole Simulation

Since the DC beam model was implemented in OpenXAL by only changing the beam envelope part of the Tracker, the beam trajectory is expected to remain the same. This was confirmed by looking at the difference between the beam trajectory results from TraceWin and OpenXAL, and with this confirmation, only the beam envelope results are shown and discussed. The beam simulations for the quadrupole magnet was carried out with the initial conditions defined in Table 2 and Table 3 through the lattice $M = M_D M_{QP} M_D$, where M_{QP} is the matrix of the quadrupole with properties defined in Table 4. The results from TraceWin and OpenXAL agree with only computational floating point error differences, suggesting that the DC model implementation was properly executed.

Hard-Edge Solenoid Simulation

The lattice of this simulation is $M = M_D M_{HE} M_D$ where M_{HE} is the hard-edge solenoid magnet matrix (HE solenoid in Table 4). The solenoid magnet both focuses and rotates the beam, reflected by the right part of Figure 1 showing the beam envelope decrease in both transverse planes.

As can be seen in Figure 1, the solenoid magnet efficiently focuses the beam in both transverse planes at the same time. The left plot shows that the difference between the DC beam implementation in OpenXAL and the TraceWin CW beam model reference is negligible, limited to only computational floating point error differences.

SIMULATION OF THE LEBT SECTION

The DC beam model was already suggested as a further development of OpenXAL in [7], in which the bunched beam was manipulated to resemble a DC beam by using very large longitudinal beam emittance and a fitting parameter in order to re-normalize the current density. Therefore, an

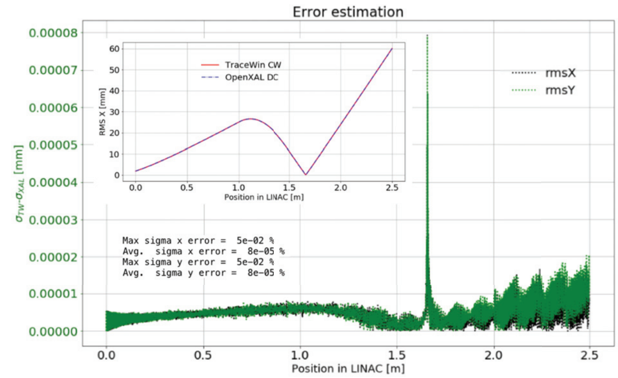

Figure 1: Simulation of a 10 mA DC beam through a hard-edge solenoid magnet. The main figure shows the absolute value of the difference between the beam envelope results from TraceWin and OpenXAL, whilst the inlet shows the absolute values of the horizontal beam envelope.

evaluation is made of how well the DC and the bunched beam models from OpenXAL perform for a 74 mA 74.7 keV beam through the LEBT section of the ESS proton Linac in comparison with TraceWin and multi-particle (Partran) simulations with 300,000 particles.

As can be seen in Table 5, the two beam models in OpenXAL (DC and 3D/bunched) use identical parameters for the transverse plane. The only difference is for the longitudinal (z) plane, for which the bunched beam needs input data. The reason for the values shown in Table 5 is that the bunched beam was optimized to mimic the DC beam, which with a large β-value and large longitudinal emittance created a very long bunch and minimize the space charge effect in the longitudinal plane.

Table 5: Initial Twiss Parameters of the Bunched Beam

Plane:	**x**	**y**	$\mathbf{z_{3D}}$
α	−3.2288082	−3.227559	0.0
β	0.38607772	0.38580933	110.0
ε	1.03040028E-5	1.03040028E-5	1E-6

Using the Twiss parameters from Table 3 and Table 5 as initial conditions for the beam simulations for the DC and the bunched beam, the proton beam is simulated through the LEBT section of the ESS proton Linac. The simulation sequence consists of two solenoids (modeled by fieldmaps [8], and can be described by the matrix

$$M_{\text{LEBT}} = M_{D1} M_{Sol1} M_{D2} M_{Sol2} M_{D3}$$

where M_{D1}, M_{D2} and M_{D3} are three drift segments' matrices of length 0.3354 m, 0.9534 m and 0.1263 m, resp., and M_{Sol1} and M_{Sol2} are fieldmap solenoid magnets defined in Table 6 as FM sol. 1 and FM sol. 2, resp. The fieldmap used was the outcome from Radia simulations of the real solenoid magnets in the LEBT-section [9]. Since the benchmark reference, TraceWin, integrates fieldmaps differently

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than OpenXAL, difficulties arise when assessing whether a difference is coming from the integration methods or from the DC beam model. The simulation results can be seen in Figure 2.

Table 6: LEBT Magnets

Magnet:	**Length:** [m]	**Magnetic field:** [T]
FM sol. 1	0.5454	0.235
FM sol. 2	0.5454	0.220

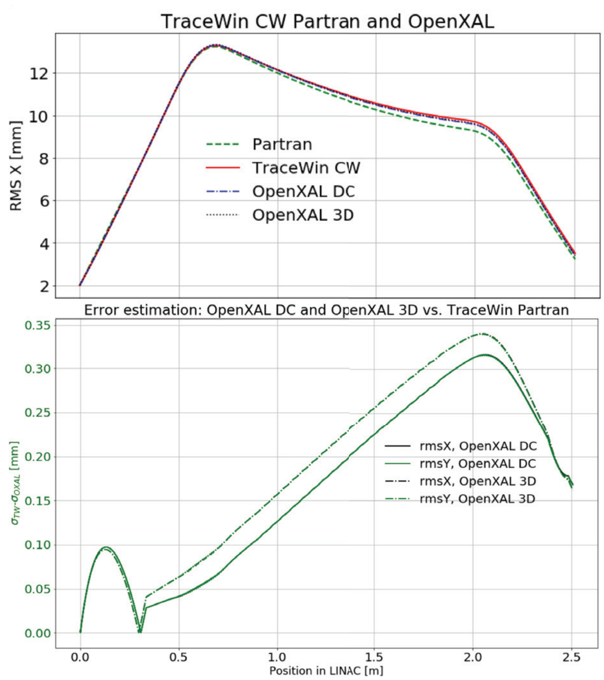

Figure 2: Beam simulation of a 74 mA DC beam through the LEBT section of the ESS proton Linac. The top figure shows the horizontal beam envelope (RMS beam sizes) for the simulations, whilst the bottom figure shows the difference between the beam envelope results from the two OpenXAL beam models and the TraceWin results with Partran.

Figure 2 shows that both beams perform well for both comparisons. Note that only the horizontal beam envelope is shown, which is equivalent with the vertical one (for round beam). The fitting parameter for the bunched beam was optimized to fit the results from the TraceWin envelope simulations.

THE VIRTUAL MACHINE

The high-level physics applications that will be used throughout the commissioning and during operation of the ESS Linac are developed in OpenXAL, an open source Java-based development environment. In the ESS virtual machine (VM), a model of the ESS proton Linac runs live and can be interacted with in similar ways as with the real machine. After implementing the DC beam and a simple, standalone VM application was developed. This application is the first prototype for a future new VM for ESS.

The VM development was started from scratch in order to achieve a structured and simple code, using the application framework for JavaFX Applications which includes a menubar common to all applications [10]. Some of the functionalities of the menubar are: to load and save files, and to load an accelerator and/or accelerator section(s). The VM GUI is lattice and site independent, meaning that any other accelerator facility can, once the proper lattice file has been set up, use it. In Figure 3, the ESS LEBT is set up and simulated.

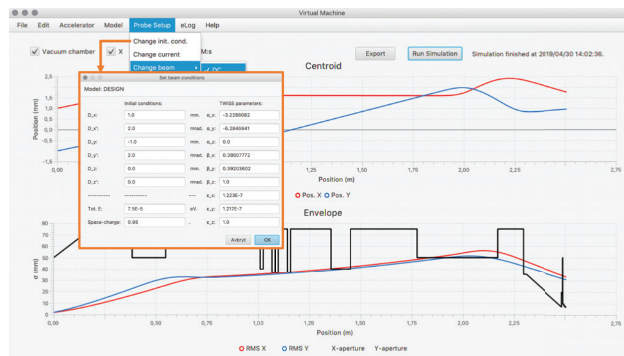

Figure 3: The new OpenXAL VM GUI with the ESS LEBT set up. Functionalities shown are the setting up a beam for simulation and the plots of the simulated DC beam's centroid and envelope functions.

The GUI features include initial parameters set up, such as beam type (DC or bunched), beam current and conditions. The beam can then be simulated with the GUI plotting the beam trajectory and envelope, with the the physical aperture hidden or drawn as a black line. The simulated data can also be exported by pressing the 'Export' button with the plotting data and all initial beam conditions.

CONCLUSIONS

A continuous beam model has implemented in the OpenXAL environment and benchmarked. A new, working GUI has also been successfully developed with JavaFx. The GUI was able to smoothly simulate the accelerator sequence LEBT from the ESS proton Linac. The codes can be found under the OpenXAL open source collaboration page on GitLab, with the ESS site package of OpenXAL reachable on the GitLab collaboration page [5] and with the VM GUI developed under the branch *site.ess.devel.app.virtual-accelerator*.

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