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3D TRACKING METHODS IN A GEANT4 ENVIRONMENT THROUGH ELECTROSTATIC BEAMLINES*

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Abstract

Due to the relatively infrequent use of electrostatic beamline elements compared with their magnetic counterparts, there are few particle tracking codes which allow for the straightforward implementation of such beamlines. In this contribution, we present 3D tracking methods for beamlines containing electrostatic elements utilising a modified version of the Geant4 based tracking code 'G4beamline'.

In 2020 transfer lines will begin transporting extremely low energy (100 keV) antiproton beams from the Extra Low Energy Antiproton (ELENA) ring to the antimatter experiments at CERN. Electrostatic bending and focusing elements have been chosen for the beamlines due to their mass independence and focusing efficiency in the low energy regime. These beamlines form the basis of our model which is benchmarked against simplified tracking simulations. Realistic beam distributions obtained via tracking around ELENA in the presence of collective effects and electron cooling will be propagated along the optimised 3D transfer model to achieve the best beam quality possible for the experiments.

INTRODUCTION

This year ELENA will supply its first antiprotons to the new experiment GBAR [1] at the Antiproton Decelerator (AD) hall. It will be connected to the rest of the experiments with electrostatic transfer lines [2] by 2020. Electrostatic elements are less common than magnetic in such a large configuration, however, as the field of low energy antimatter physics grows with new facilities such as FLAIR [3] [4], their use is becoming more widespread.

The main goal of this study is to develop and test new tools and methods for highly realistic and detailed particle tracking simulations, particularly in the case of low energy ion transportation. Here, we set out to create a 3D model of the electrostatic transport line from ELENA to the ALPHA experiment [5] since we may benchmark our new methods against pre-existing simulations, help to determine and optimise beam parameters at the experiment, and eventually compare simulation results with beamline performance.

As opposed to particle tracking codes such as MAD-X [6] which use pre-determined transport matrices for propagation through optical elements, particles in these simulations are optically influenced by the electrostatic and magnetic fields they encounter. They are propagated through a physical 3D environment where they may be subject to additional forces and effects based on the physics package in use. The simulation may then take into account many combined factors including inhomogeneous and fringe fields, stray magnetic fields, residual gasses, heating effects on electrodes, space charge effects and more.

SIMULATION ENVIRONMENT

The simulation was constructed and performed within Geant4 based particle tracking code G4beamline [7]. There are several features which make it the most desirable software within which to base the simulations.

G4beamline allows the user to construct particle accelerators and transport lines from pre-defined beamline elements and externally generated field maps. Users may also define fields within the program based on vectors or equations. Particle beams may also be defined within the code, or externally generated beam distributions may be read in, allowing maximum flexibility.

Additionally, Geant4 contains physics lists capable of accurately simulating low energy hadron behaviour [8]. Finally, G4beamline is equipped to calculate useful accelerator physics quantities, such as the emittance and beta functions of a beamline. This allows for the user to optically tune elements and lattices.

ELECTROSTATIC QUADRUPOLES - SOURCE CODE MODIFICATION

G4beamline allows for the implementation of generic magnetic quadrupole elements with a simple one line command, *genericquad*. The elements are composed of two components: A pipe-like structure which acts as a limiting aperture, optionally removing particles who are incident on its surface; and a quadrupole shaped magnetic field (including fringe fields), whose gradient may be determined by the user.

As mentioned previously, all ELENA transfer lines elements are electrostatic. For this study it is sufficient to represent the quadrupoles by standard field shapes and instead implement the bespoke bending elements as externally generated field maps. Further studies into the exact design of the quadrupoles could be performed and their field maps added at a later stage.

In order to allow for easy implementation of the electrostatic quadrupoles, a modification of the G4beamline source code was made. The *genericquad* quadrupole class was edited to accept two new commands for both magnetic and electrostatic quadrupole placement, *genericquadM* and *genericquadE*, respectively. The field distribution in *genericquadE* was taken from *genericquadM* replacing magnetic components with electrostatic ones, thus creating a field akin to a skew electrostatic quadrupole. Placement of a *generic-*

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quadE element within any beamline must therefore include a rotation of 45° along the direction of beam propagation for standard quadrupole behaviour.

The modified code was compiled, and two identical beams were run through a series of *genericquadM* and a series of rotated *genericquadE* elements. The field gradients for both types of quadrupoles were set such that equivalent elements in both series had the same focusing strength, k. The magnetic and electrostatic field gradients, G_M and G_E respectively, were calculated from k, in G4beamline input units (Tm^{-1}, MVm^{-1}) using:

$$G_M = \frac{kp}{c \times 10^{-9}}, \quad G_E = \frac{G_M v}{10^6}, \tag{1}$$

where p is the momentum of the particles in the beam, c is the speed of light in vacuum and v is the velocity of the beam particles.

A comparison of the transverse beta functions, $\beta_{x,y}$, calculated from the RMS beam width and the input beam emittance was made. For both sets of 7 quadrupoles each, the beta functions were almost identical and well within what would be considered sufficient to benchmark the new electrostatic models against their magnetic counterparts.

ELECTROSTATIC BENDING ELEMENTS

A range of approaches to modelling the electrostatic elements were explored and compared.

Field Expressions

The simple way to create user-defined fields in G4beamline is based on determining the electrostatic components E_x, E_y, E_z by expressions via the *fieldexpr* command. Expressions for the field components can use cartesian coordinates $\{x, y, z\}$ for a box field shape or cylindrical coordinates $\{z, r\}$ for a cylinder shape including the possibility of dependence on time for both systems. Expressions can use almost all operators available in C programming language.

To begin with a simple approximation of the fast deflector [9] field, E, was created using the following expressions:

$$E_x = E\cos\theta, \; E_y = 0, \; E_z = E\sin\theta\,, \tag{2}$$

where θ is the angle between the centre line of the element and the z axis. This creates a field perpendicular to the electrodes. The main limits of this approach are the simplified field shapes and absence of a link with the real geometry of the elements, however it works as a fast and simple approximation during the beamline construction phase.

Finite Element Methods

To improve the accuracy of the simulation, realistic fields including fringe effects and inhomogeneities and due to geometrical factors were generated using finite element software. Fortunately, G4beamline allows the import of external field maps utilizing the *fieldmap* command. However, only very restricted grid formats for maps with a constant step in $\{x, y, z\}$ or $\{z, r\}$ are accepted.

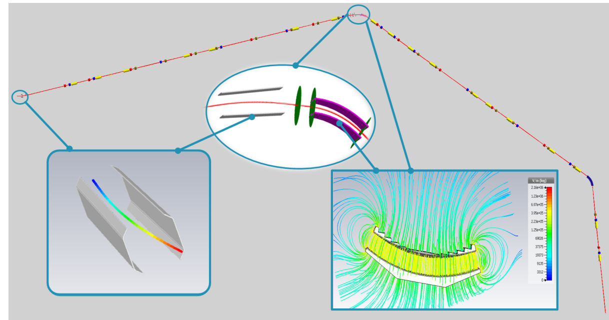

Figure 1: The full transfer line from ELENA (left) to ALPHA (right) with antiproton beam tracks (red line). Bending elements are highlighted and CST models and field maps shown.

Firstly, CAD models of all bending elements from the electrostatic transfer line were created. They were based on drawings from the CERN EDMS database [9], and consisted primarily of the electrodes used to generate the bending fields.

The models were imported to ANSYS Workbench Electric [10] and field maps were generated according to nominal operation voltages. However, meshes of such complicated geometries are not output to a grid with constant step size and converting them was found to be both computationally cumbersome and inaccurate. The models were saved for future thermomechanical studies.

New field maps were obtained using the same models in CST Studio [11], Fig. 1. The field maps were found to have nominal values of field gradient at the centre of the elements. Additionally, output field maps could be generated in a G4beamline compatible format, removing an intermediate step and approximations.

INPUT BEAMS

Using a MAD-X model of the transfer lines [12], the Twiss parameters $\alpha_{x,y}$ and $\beta_{x,y}$ at the extraction point from ELENA were calculated. Using these parameters and transverse emittances of $\epsilon_{x,y} = 1$ mm mrad, a Gaussian beam of 10,000 macroparticles was generated in the input format used by G4beamline. This beam was used during the construction and tuning phase of the simulation.

As shown in previous studies [13] the electron cooling process in ELENA is expected to create a bi-Gaussian transverse beam distribution. Additionally, an emittance-momentum correlation may further complicate the transverse beam profile. Beam distributions which contain both of these effects can be generated, taking specific parameters from simulations, and tracked through the G4beamline simulation.

A new algorithm for analysing data taken by the scraper system in ELENA gives a detailed description of the beam, including a term to describe the magnitude of the emittance-momentum correlation [14]. The data can be reconstructed to generate a beam distribution, and then tracked along the transfer lines model, to optimise ahead of installation in 2020.

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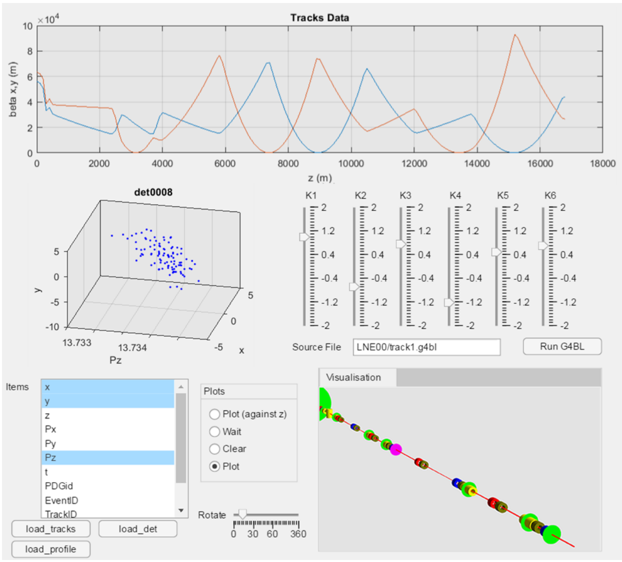

Figure 2: Screenshot of the GUI being developed for use in tuning and optimising the beamline.

BEAMLINE CONSTRUCTION AND TUNING

Beamline Construction

The beamline was constructed seperately in four sections named LNE00, LNE01, LNE03 and LNE04, and then assembled fully later. LNE00 is the extraction line from ELENA and begins with a fast deflector which would actually be situated inside the ELENA ring itself. This first section was the lattice used to test the modified quadrupoles. LNE04 contains the final bend of the line and extends until the designated handover point to ALPHA.

Beamlines were constructed of only the components necessary for having an effect on the beam, marking specific element placement or for simulation analysis: Quadrupoles, bending element field maps, solid materials to represent electrode positions and virtual detectors between sections and at BPM positions. Additional to virtual detectors, hollow cylinders were added to mark detector chamber lengths and to introduce the associated apertures.

Tuning and Optimisation GUI

Because the bending elements in this simulation contain asymmetrical fields and fringe field effects, the design gradient is only appropriate as a guide value. The bending elements were tuned using G4beamline's *tune* command. Using a reference particle the *tune* command runs multiple iterations until it finds a solution within a specified error.

Unfortunately, the field strength of quadrupoles is not a tunable property so alternative solutions for optimising the optics of the lattice had to be found. G4beamline comes packaged with a script for utilising numerical minimization techniques, however for the purpose of tuning a complicated beamline to several constraints and with many free variables, the code is not sufficient.

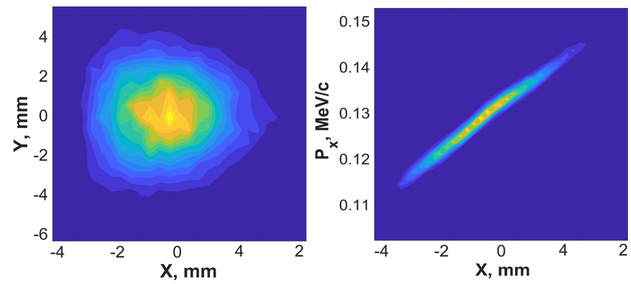

Figure 3: Beam profile and phase space plots.

Work on a GUI to solve this problem is in progress (Fig. 2). The main function of the GUI will be to utilise external libraries to optimise lattice parameters whilst running numerous iterations of the simulation. Currently, the GUI allows the user to control the strengths of quadrupoles manually using sliders, run the simulation, and can instantly display important beam and lattice properties when simulations are complete.

RESULTS

So far, quadrupoles in LNE00 and half of LNE01 (before the bend to ATRAP) have been optically matched. All bending elements have been optimised to the correct bending angle. When the beam is run through the entire line with these parameters zero particles are lost despite no quadrupole tuning for the majority of the line.

Beam profiles at the end of LNE01 (Fig. 3) show that despite some distortions due to bending elements, the beam is being transported properly through the beamline.

OUTLOOK

A fully working model of the transport line from ELENA to the ALPHA experiment has been constructed. It is currently being optically matched and is already capable of transporting a matched Gaussian beam along its entire length. In parallel to tuning and optimisation, a GUI interface and tuning software are being developed to aid these and future similar simulations.

The next step will be to complete the tuning of the beamline, and ascertain beam properties at ALPHA. Additionally, dynamic aperture and other error tolerance studies may be performed. A range of settings to optimise for different beam properties at the hand over point will be determined.

Future goals for the simulation include the tracking of more realistic beam profiles from external simulations such as BETACOOL and the injection of beams based on real data taken from ELENA. Thermomechanical effects on electrodes and the impact of stray magnetic fields will also be investigated. Additionally, the beamline can be expanded to the other experiments at the AD hall, for the purpose of tailoring beam quality to each experiment. The software and methods developed will then provide a comprehensive simulation toolkit for the optimisation of low energy beamlines.

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