



Realistic 3D implementation of electrostatic elements for low energy machines

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Abstract

Novel antimatter experiments at CERN require high intensity, low energy (<100 keV) antiproton beams. Each experiment has a set of desirable beam parameters. To achieve this, and obtain the greatest efficiency, transfer lines will be based on electrostatic optics. Unfortunately, only a small amount of simulation codes allow realistic and flexible implementation of such elements. In this contribution, methods for accurately creating and tracking through electrostatic optical elements are presented, utilising a combination of a modified version of G4Beamline (Roberts and Kaplan 2007) and finite element methods (FEM). To validate our approaches the transfer line from the ELENA (Chohan et al. 2014) ring to the ALPHA experiment was chosen as a basis for particle tracking studies. A range of approaches to modelling the electrostatic elements were explored, ranging from simple field expressions, to the complex field maps used in the final model. An investigation into the achievable beam quality at ALPHA is presented.

Keywords ELENA · G4Beamline · Antimatter · Electrostatic optics

1 Introduction

In the modern field of accelerator physics, where ions are typically in the relativistic regime, magnetic bends and quadrupoles are more efficient than electrostatic ones. With comparatively less focus on low energy accelerator physics, the usage of electrostatic optical elements [3, 4] is more uncommon. However in the new era of extra low energy (<100 keV) antimatter physics, brought in by new facilities such as FLAIR [5] or ELENA, their use will become more prevalent.

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The main objective of this study is the improvement of existing tools and development of new methods for fast but realistic and thorough particle tracking simulations comparable with models in FEM software. Here we implement a 3D model of the electrostatic transport line from ELENA to the ALPHA experiment [6] 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 real measurements of beamlines which will become operational at the end of 2020.

As opposed to particle tracking codes such as MAD-X [7], particles in these simulations are propagated through a physical 3D environment where they may be subject to additional forces and effects based on surrounding conditions. At such a low energy scale, even small electrostatic field imperfections will have a significant impact on the orbit and quality of the beam. Hence, the simulation should take into account many combined factors including parameterized shapes of inhomogeneous and fringe fields, stray magnetic fields, residual gasses, heating effects on electrodes, space charge effects and other additional scattering and collective effects.

2 Simulation environment

G4Beamline was chosen as the main working environment for the realization of our goals. As a Geant4 based tool it allows 3D particle tracking through matter and EM fields. The code simplicity and flexibility make it a very robust software on which to base the simulations. The implementation of the fields allows and enables the use of an electric or combined electromagnetic variant. These fields can also vary with time.

Generated 6D beam distribution can propagate through voxelized 3D media by analyzing the factors limiting the particle movement and applying the relevant physics processes for each step. Primarily, EM fields are the main source of restraint in the beam transport line. In order to propagate the created distribution inside dipoles or quadrupoles, the equation of motion of the particle in the field is integrated. In general, this is done using a Runge-Kutta method for the integration of ordinary differential equations.

Additionally, the Geant4 environment contains numerous physical models or manually prepared physics lists that may be based on new measurements, which makes accurately simulating low energy hadron behaviour possible [8].

3 Electrostatic quadrupoles—source code modification

The implementation of generic magnetic quadrupole elements is possible with a simple one-line command, *genericquad* and includes a wide set of parameters to make the model more realistic. The transverse field shape of a magnetic quadrupole is described by filling each voxel in its aperture with x and y components of the field: $B_x = G_B y$, $B_y = G_B x$; where $G_B = \frac{B_T}{r}$ is flux density gradient, r is the radius of quadrupole aperture and B_T is magnetic flux density at the pole tip.

In order to allow for easy implementation of the electrostatic quadrupoles, a modification of the G4Beamline source code was made. The quadrupole class was edited to accept G_E , an electric field strength gradient, as a new parameter for electrostatic quadrupole placement as well. Electrostatic field components were defined in the following way: $E_x = -G_E x$, $E_y = G_E y$;

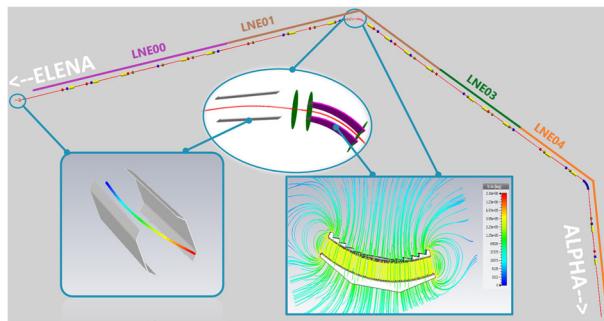


Fig. 1 The full transfer line from ELENA (left) to ALPHA (right) with antiproton beam tracks (red line). Bending elements are highlighted and CST models with field lines shown

The field gradients for both sets of quadrupoles were set such that both sets had the same focusing strength, k . The magnetic and electrostatic field gradients, G_B and G_E respectively, were calculated from k , in G4Beamline input units (Tm^{-1} , MVm^{-1}) using:

$$G_B = \frac{kp}{c \times 10^{-9}}, \quad G_E = \frac{G_B v}{10^6}, \quad (1)$$

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.

The longitudinal field shape difference between electrostatic and magnetic quadrupoles was also taken into account. The current G4Beamline magnetic model is based on the standard description by an Enge function [9] with six parameters $a_1 \dots a_6$. The same method is applicable to electrostatic version of elements, fitting the six parameters to match fields obtained through realistic FEM simulations.

$$Enge(z) = \frac{1}{1 + \exp(a_1 + a_2(z/D) + \dots + a_6(z/D)^5)}, \quad (2)$$

where z is the distance perpendicular to the effective field boundary and D is the full aperture of the particle optical element.

4 Electrostatic bending elements

The realistic fields including fringe effects fields and inhomogeneities due to geometrical factors were generated using finite element software. Firstly, CAD models of all bending elements from the electrostatic transfer line were created. They were based on drawings from the CERN CDD database [10] and consisted primarily of the electrodes used to generate the bending fields. The size and shape of field maps completely depend on the CAD models used. Thus, for comparison with previous simulations in other tracking codes, all simplifications should be taken into account. Furthermore, the models were imported to CST Studio [11] and field maps were generated according to nominal operating voltages, Fig. 1. The field maps were found to have nominal values of field gradient at the center of the elements. Thereafter output field maps could be generated in a G4Beamline compatible 3D grid format. At this stage, an optimal field map resolution was chosen according to the difference in computational times and tracking output, meaning that the value of the integrated field was not changing significantly after some point. In addition, CAD models

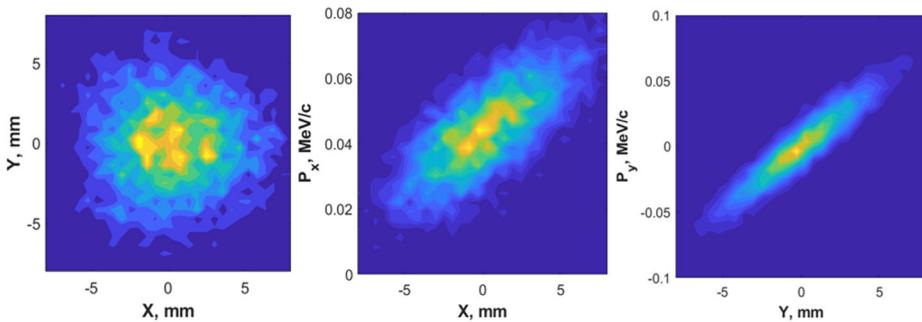


Fig. 2 Beam profile and transverse phase space at the ALPHA experiment, considering nominal beam parameters at extraction from ELENA

can be used for future thermomechanical studies in Ansys Workbench [12] via transfer of spatial distributions of deposited energy to thermal loads.

5 Results

At present, implementation of an electrostatic version of quadrupoles in LNE00, LNE01 and LNE03-04 sections to ALPHA from ELENA transfer line have been tested. The external field maps for bending elements were obtained from FEM simulations. The gradients of all electrostatic bending elements have been optimised to compensate fringe effects and achieve the correct bending angle. Despite the fact that quadrupole tuning for the majority of the line has not been completed and initial parameters were used from the original MAD-X simulation, zero initial particles are lost.

Assuming nominal beam parameters and 100 keV extraction kinetic energy from ELENA, the computed beam distributions at the end of the ALPHA transfer line (Fig. 2) show that despite some imperfections due to the inhomogeneity of 3D fieldmaps, the beam is being transported properly through the beamline.

6 Outlook

A new electrostatic version of the *genericquad* element from G4Beamline has been added to our modified version of the code. The first testing of this element within the transfer line from ELENA to the ALPHA experiment showed great agreement with preceding models of electrostatic quadrupoles and FEM simulations. Future goals for the simulation include the tracking of more realistic beam profiles from external simulation software and the injection of beams based on real data [13]. As mentioned previously, the main source of inhomogeneities is the design of bending or focusing elements. It is hard to avoid fringe field effects completely but it is possible to apply additional corrections for power supplies or positions of the problematic elements. Thus, field maps or their analytical description should be based on real experimental data obtained from novel measurement techniques for electrostatic fields [14]. A further combination of such kind of measurements with beam diagnostic tools will estimate how realistic these methods of simulation are. Thermomechanical effects on electrodes and the impact of stray magnetic fields will also be investigated. Additionally,

the existing model of the beamline can be expanded to the other experiments at the AD hall, for the purpose of tailoring beam quality to each experiment.

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