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IMPLEMENTATION OF NOVEL ACCELERATION FUNCTIONALITY IN BDSIM

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Abstract

Beam Delivery Simulation (BDSIM) is a Geant4 based accelerator tracking code which includes interactions of particles with material. BDSIM has become an important code in the accelerator community to simulate dense beam lines and beam losses. Since laser and beam driven plasma wakefield acceleration (LWFA/PWFA) is a promising acceleration method with more users creating their own bespoke Geant4 simulation we found it important to include LWFA/PWFA related capability in BDSIM. This requires the addition of new beamline elements that are commonly used in plasma acceleration experiments. A gas volume (typically a capillary) where the LWFA/PWFA takes place and a beam mask to create a separate drive beam and a witness beam. In some of those elements, the particle beam interacts with gas so ideal gas calculations are required if we want different options to input the gas properties. Biasing can specifically be applied to the gas material in those elements. Simulating the interactions between the beam and a plasma is not done in BDSIM. An external software like Wake-T is used to compute the fields and the particles data. BDSIM can now read the output HDF5 files to reconstruct the fields inside the gas capillary or use the particle data as a bunch definition for the beginning of a beamline. Some results explaining how to make a LWFA/PWFA simulation are presented.

INTRODUCTION

BDSIM [1] is a simulation tool that can be used for particle tracking in an accelerator beamline as well as interaction between particles and materials.

Ideal Gas Calculations

The materials in BDSIM are defined by the mass density ρ and the composition of said material. The total molar mass $\overline{A}$ is then defined as

$$\overline{A} = \sum_i x_i A_i, \tag{1}$$

where A_i is the molar mass of the different species in the material and x_i the fraction of each of those species.

If the material is a gas we can apply the ideal gas law written as

$$PV = nRT, \tag{2}$$

where P is the pressure, V is the material volume, n is the total number of moles, R the ideal gas constant and T the temperature.

Since the mass of the material can be express as

$$m = \frac{A}{\mathcal{N}_\mathrm{A}} = \frac{nA}{N}, \tag{3}$$

where N is the total number of atoms, we can re-write using Equation 2 the mass density as

$$\rho = \frac{mN}{V} = \frac{P\overline{A}}{RT}. \tag{4}$$

BDSIM (hence Geant4 [2]) only cares about the mass density ρ and the molar mass $\overline{A}$ of material to figure out the cross section of the interactions. But with a gas we can compute its pressure if we know the temperature and vice-versa. This open up other ways to define a gas material in BDSIM. Assuming we know the the composition of our gas (i.e. we know $\overline{A}$) then we only need two of the three values between ρ, P and T.

In the same way, we can use the mole density

$$d = \frac{n}{V}, \tag{5}$$

or the number density

$$D = \frac{N}{V}, \tag{6}$$

as alternatives to define a gas material in BDSIM. The densities d and D are then converted into the mass density ρ to do the calculations, allowing for more flexible inputs for a gas material. In the perspective of advanced acceleration in BDSIM, alternative methods to define gas materials should help users with different conventions.

Logical Volume Biasing

On any beamline element in BDSIM it is possible to apply some biasing, usually cross section biasing. This biasing could be apply to the vacuum part of an element, a material part of an element, or both. Since PWFA [3] and LWFA [4] in BDSIM will feature interactions between the particle beam and some gas elements, we found useful the addition of a more localised biasing. Using a new element parameter one can now apply some biasing to a given logical volume inside the element.

NEW ELEMENTS

Beam driven and laser driven plasma wakefield acceleration (PWFA/LWFA) both consist on exiting a plasma cell in order to accelerate a particle bunch. In the former the

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plasma is exited by another particle bunch and in the later it is by a laser.

Simulations of PWFA/LWFA requires specific beamline elements. External geometry can be provided to BDSIM in order to define and place those elements in the beamline. But to facilitate the use of BDSIM for advanced acceleration, we made the addition of two commonly used elements: a beam mask and a gas capillary.

Beam Mask

In PWFA, the plasma is exited by a drive bunch. The perturbation it generates is then used to accelerate a witness bunch. To create both the drive and the witness bunch, one method is to use a beam mask like in Fig. 1.

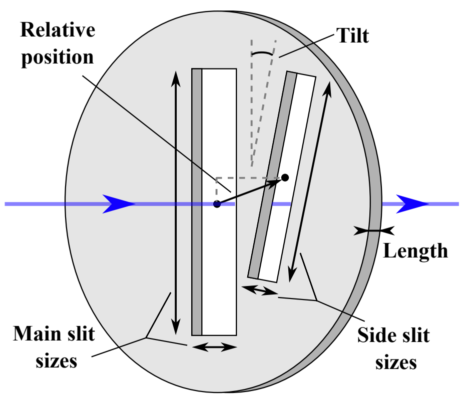

Figure 1: Schematics of the beam mask in BDSIM. The main slit is always centered on the beam axis, represented in blue. The side slit can be moved and tilted with respect to the main one.

Usually placed in a dispersive section, this beam mask act as a set of collimators that extract different sections of the particle bunch as shown in Fig. 2.

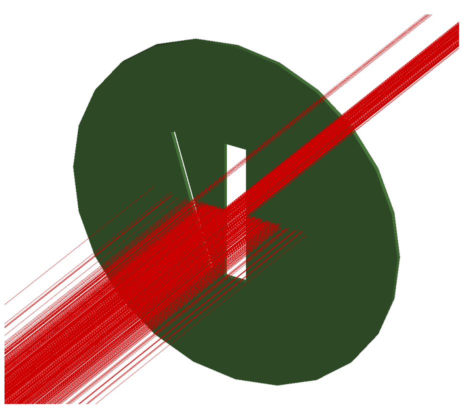

Figure 2: Example of the beam mask element used in a BDSIM simulation. Electrons in red travels from left to right.

The two output bunches will have a difference in energy. At the end of the dispersive section, it will translate to an arrival time difference. This makes the first arriving bunch the drive bunch and the second one the witness bunch.

The beam mask is a destructive element that will produce some background particles. A histogram of the particles energy can be found in Fig. 3.

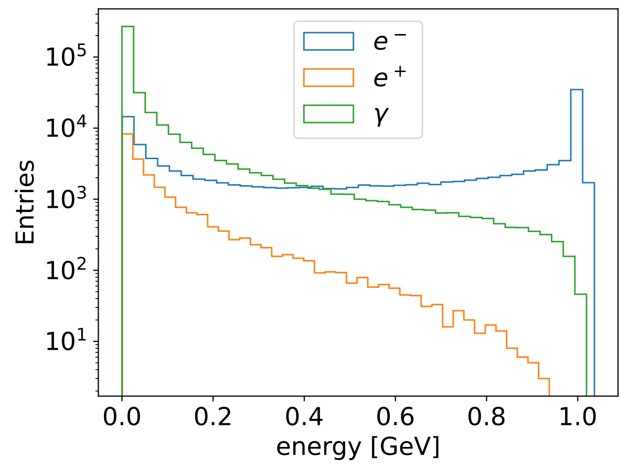

Figure 3: Energy histogram of a 1 GeV electron beam after the beam mask.

Gas Capillary

For both PWFA and LWFA, the acceleration usually take place in a gas capillary. A cylinder of gas, surrounded by a capillary material, is turned into a plasma using end electrodes as described in Fig. 4.

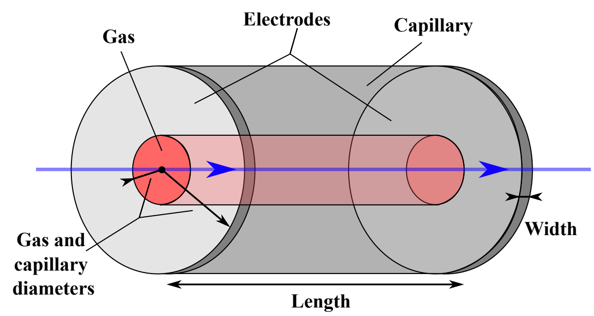

Figure 4: Schematics of the gas capillary in BDSIM. The cylinder of gas, centered on the beam axis, is surrounded by a capillary. On each sides there is an electrode matching the capillary section. Both the gas, capillary and electrodes materials can be defined by the user.

The drive bunch passing through the gas will induce a characteristic electromagnetic field to accelerate the witness bunch.

With just the geometry, the particle bunch will interact with the plasma as though it was a regular gas material with the density ρ and molar mass $\overline{A}$ define by the user. This interaction can be seen in Fig. 5.

As the beam travel inside the gas, the production of secondary particle decrease its energy. A example histogram of the energy loss along the beam axis can be found in Fig. 6.

On top of the gas capillary geometry, an electromagnetic field can then be applied in order to simulate the acceleration of the particles.

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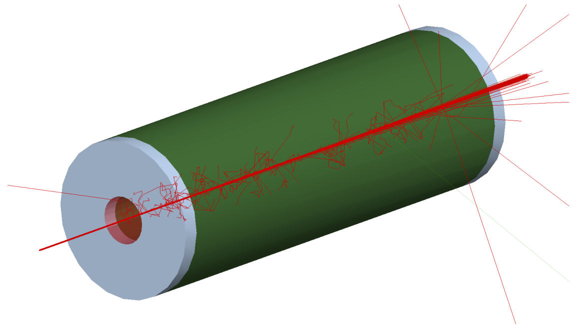

Figure 5: Example of the gas capillary element used in a BDSIM simulation. Electrons in red travels from left to right.

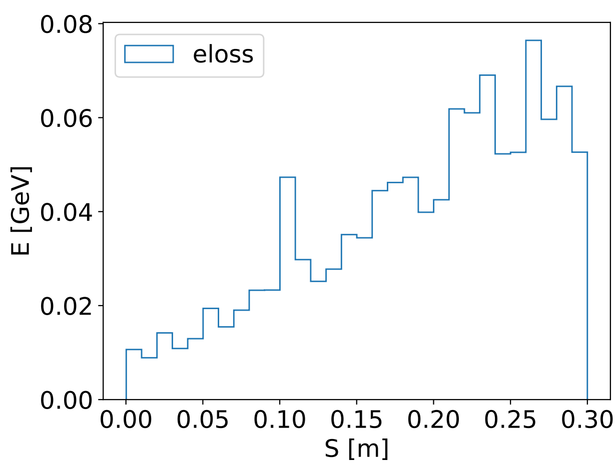

Figure 6: Energy loss in gas capillary.

FIELDS

A good accuracy on the electromagnetic field perceived by the witness bunch is crucial if we want a realistic simulation of the acceleration. It is not planed for BDSIM to have its own plasma calculations. The preferred method is then to use external software to compute the field and apply them to the gas capillary element described above.

Wake-T

There is a variety of software that could be used to calculate the field. To develop the advanced acceleration interfaces we used Wake-T [5] as our example.

Wake-T is one of the quickest plasma acceleration software because it comes with two main approximations. The first one consider that the problem is symmetric around the beam axis so we only need to compute the fields for one (r, z) plane. The second one assume a relativistic beam going in the plasma meaning the field variations along time are negligible. A static field at peak intensity is a correct approximation for the witness bunch.

By defining both the a drive bunch, a witness bunch and a plasma cell, Wake-T computes the electromagnetic field seen by the witness as well as the position and momentum of this bunch after the acceleration.

Even if Wake-T is not the sole tool for plasma acceleration, its output is written in HDF5 files like a lot of plasma acceleration software. So a BDSIM functionality to read HDF5 is essential.

HDF5 Loader

A new class was added in BDSIM in order to read an HDF5 file. In this class, functions are built to extract each component of both the electric and magnetic field. In addition, there are functions that can extract the position and momentum data of the witness bunch after the acceleration. This can be use a bunch definition in BDSIM for a beamline starting just after a PWFA/LWFA stage.

SUMMARY

Advanced acceleration capabilities in BDSIM required the addition of two new beamline element, a beam mask and a gas capillary. The plasma volume in the latter is treated as an ideal gas. Defining this gas in BDSIM is facilitate by internal ideal gas calculation, allowing for multiple input possibilities for the user. Interactions in a specific volume of an element, like the gas in the gas capillary, can now be biased independently from the rest of the element. BDSIM does not compute the PWFA/LWFA electromagnetic fields in the gas capillary. It should rely on external software and apply static field on the element afterwards. A class was added to read fields data as well as bunches data from HDF5 files.

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