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Short note

Simulating the injection of magnetized plasma without electromagnetic precursor wave

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1. Introduction

This note aims to explain how to inject magnetized plasma through an open boundary into the simulation domain of a particle-in-cell simulation. If the magnetic field at the boundary is constant in time, i.e., if magnetized plasma of constant magnetization is injected at a steady rate, this does not present any challenges beyond injecting the particles at a fixed rate and possibly absorbing plasma waves impinging on the wall. If, however, the magnetization or the injection rate changes, a time-varying magnetic field is present. The classical use case for this scenario is a shock front moving through a plasma into the simulation volume.

The time variation in magnetic field obviously produces a curl of the electric field. This new electric field in turn produces a magnetic field of its own. Or in other words, an electromagnetic wave is launched. This effect might be desired in the implementation of antennas that launch electromagnetic radiation into the simulation domain. When injecting magnetized plasma this high frequency effect is undesired and might – depending on the amplitude of the wave – produce unphysical or at least undesired effects in the medium ahead of the injected material. From observations [1–3] it is known that shock waves do not continuously emit electromagnetic radiation ahead of the shock front, which is what should be reproduced in simulations. The goal is, therefore, to find an injection method that is capable of handling time variable magnetic fields at the injection site without launching an electromagnetic precursor wave.

Both antennas and injection of magnetized plasma is often performed by prescribing a current density instead of directly setting the magnetic field. This has the advantage that the resulting magnetic field is automatically divergence free as it is calculated from Ampere's Law.

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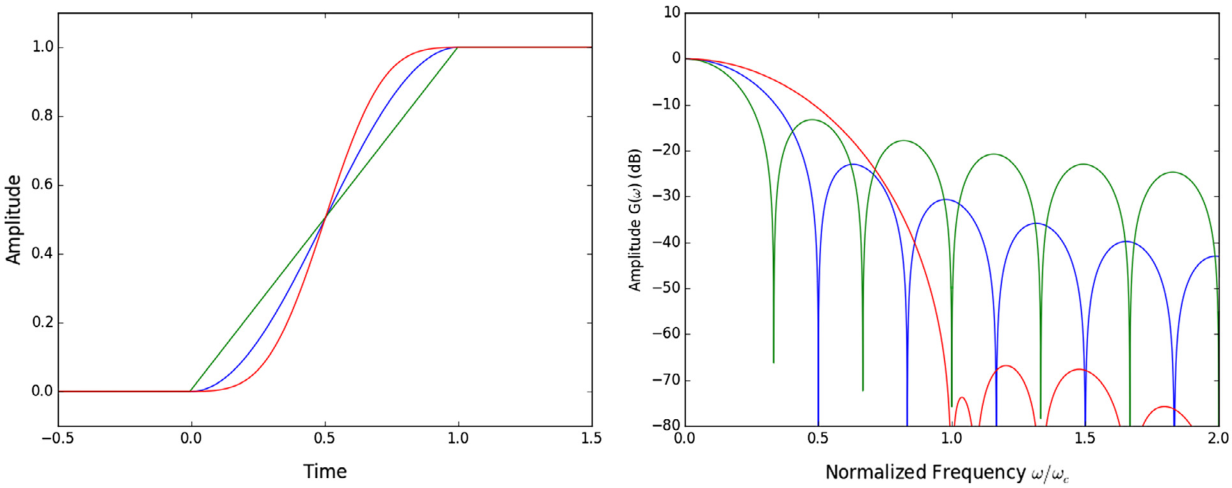

(a) Step Response (b) Spectral Content

Fig. 1. Amplitude over time (step response) and over frequency (frequency spectrum) of different window functions. A linear ramp, that result from passing the injection through a moving average filter and that injects at constant rate is shown in green. The sinusoidal half wave suggested in [4] is shown in blue. The Blackman–Harris window suggested in this work is indicated in red. (Colored lines are available in the web version of this article.)

One example of using a current pulse to push magnetized plasma is given in [4]. The authors there also note that the shape of the current pulse is not arbitrary, but has to be chosen carefully to avoid the generation of a precursor wave. Their choice for the injection profile was a cosine half wave switching smoothly from zero to a desired value and subsequently holding that value constant. Two different period lengths of the cosine are discussed, 8 $\omega_{\mathrm{p,e}}^{-1}$ and 60 $\omega_{\mathrm{p,e}}^{-1}$, where $\omega_{\mathrm{p,e}}$ is the electron plasmafrequency at the initial, uncompressed density. The first case works well as a driver, but still launches a visible electromagnetic wave. The slower injection of the latter case avoids this effect. Additionally, the current is not injected in a single location, but over a finite spatial range of 14 Debye lengths, which helps to reduce high k noise, equivalent to high frequency waves.

Another example of a time variable magnetic field that passes the boundaries of the simulation domain is presented in [5]. In that case, a non-homogeneous magnetic field is considered, combined with a moving simulation domain that tracks a bunch of particles. This application, however, uses an electrostatic plasma model, that is free from electromagnetic waves by construction.

In many other cases only unmagnetized plasma is injected and magnetic fields are only present in the simulation domain through the self-consistent interaction with the ambient plasma. Typical examples can be found in [6] and references therein, especially [7].

All the tests of the injection method presented below in section 2 were performed with the electromagnetic particle-in-cell code ACRONYM [8]. It is a fully-parallelized code for the simulation of collisionless plasma phenomena using standard algorithms of second order accuracy in space and time. Electromagnetic fields are stored in a standard Yee ([9]) grid. Particles are updated using the Boris push [10,11]. The current density that results from the movements of the charge particles is deposited onto the grid using the method of Esirkepov [12]. This deposition, as well as the interpolation of the electromagnetic fields to the particle position, use the second order interpolation using a TSC shape function. The code allows to use any of the different FDTD schemes listed in [13] to calculate the update of the electromagnetic fields. However, for the purpose of this note, only the standard second-order scheme is used, that uses a straightforward approximation of the curl using four terms in the expression for central differences. The open boundary through which the magnetized plasma is injected discards any particles that might reach it from the simulation domain. All incoming waves are absorbed by a perfectly matched layer (PML, see [14]). More precisely, a PML with a complex frequency shift is used, that is implemented using time domain equations following the convolutional PML scheme described in [15].

2. Method

The electric field of the precursor wave is produced by the change in time of the magnetic field. An obvious approach to remove the precursor is thus to feed the injected magnetic field through a low pass filter to remove the steep rise. In more technical terms, the derivative of the magnetic field, is convolved with a digital low pass filter and then running sum of the resulting signal is applied on the boundary. Fig. 1a shows the resulting amplitude of the supplied magnetic field at the boundary of the simulation domain as a function of time.

To see the effective reduction of high frequency components that could propagate through the plasma, it is useful to also plot the frequency dependence of the transfer function of the low pass filter. This is shown in Fig. 1b. Alternatively, this can be seen as the amplitude of the waves launched at the boundary as a function of frequency.