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Warp simulations for capture and control of laser-accelerated proton beams

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Abstract. The capture of laser-accelerated proton beams accompanied by co-moving electrons via a solenoid field has been studied with particle-in-cell simulations. The main advantages of the Warp simulation suite that was used, relative to envelope or tracking codes, are the possibility of including all source parameters energy resolved, adding electrons as second species and considering the non-negligible space-charge forces and electrostatic self-fields. It was observed that the influence of the electrons is of vital importance. The magnetic effect on the electrons outbalances the space-charge force. Hence, the electrons are forced onto the beam axis and attract protons. Besides the energy dependent proton density increase on axis, the change in the particle spectrum is also important for future applications. Protons are accelerated/decelerated slightly, electrons highly. 2/3 of all electrons get lost directly at the source and 27% of all protons hit the inner wall of the solenoid.

1. Introduction

Ion acceleration from high-intensity, short-pulse laser irradiated thin foils [1, 2] has attracted much attention during the past decade. The emitted ion and, in particular, proton pulses contain large particle numbers (exceeding 10^{12} particles) with energies in the multi-MeV range and are tightly confined in time (<ps) and space (source radius a few micrometers). The generation of these high-current beams is a promising new area of research and has motivated pursuit of applications such as tabletop proton sources or preaccelerators.

Requirements for an injector are controllability, reproducibility and a narrow (quasi-monoenergetic) energy. However, the source provides a divergent beam with an exponential energy spectrum that exhibits a sharp cutoff at its maximum energy [3]. The laser and plasma physics group of the TU Darmstadt, in collaboration with GSI Helmholtzzentrum für Schwerionenforschung and LBNL/LLNL, is studying possibilities for transport and RF capture into conventional accelerator structures. The first experiments were carried out at the PHELIX laser system [4].

The results indicate the need for theoretical characterization. The effect of external magnetic fields on the expanding proton beam, current neutralized by co-moving electrons, is not investigated up to now. Emerging space charge issues due to charge separation and the self-fields of the proton beam have a significant influence on the proton beam transport, because the intense beam behaves as a non-neutral plasma. Therefore, any analysis of beam dynamics needs to include the electrostatic self-fields of the beam. Such an analysis is an ideal application for the particle-in-cell (PIC) simulation technique which has been heavily used for neutral plasma simulations. It became evident that the Warp simulation code, developed by the LLNL/LBNL Heavy Ion Fusion group, is the perfect tool to analyze this beam behavior. Warp [5] is used to optimize the experimental setup as well as the ion optics to transport the proton beam. These controllable beams will simplify isochoric heating of samples. They will also enable fundamental studies in FI research, using a proton ignitor beam that comes to be separated spatially from the plasma that created by the initial laser-matter interaction.

2. Simulation setup

The Warp suite of simulation codes was developed to study high current ion beams for application in heavy-ion driven inertial confinement fusion. Therefore, high current beams are necessary. Warp implies the dominant space-charge forces and the electrostatic self-fields of the beam. The code combines the PIC technique (uses the Lorentz equation of motion to advance in time simulation particles) with a description of the accelerator “lattice” of elements. The effects of the space-charge are included by a global solution of Poisson’s equation, giving the electrostatic potential, at each time step. The macro-particles are advanced in time using a combination of the “leap frog” and “isochronous leap frog” methods.

2.1. Proton beam parameters

In comparison to other simulation code, Warp can import user-specific particle source parameters. Hence, proton beam parameters like energy distribution, envelope opening angle, source size and transverse emittance could be included energy resolved. The reference beam was recorded at the Phelix laser system, delivering 130 J in 700 fs at intensities about 4.5×10^{19} W/cm^2. The protons follow an exponential energy distribution from 2.3 MeV to a cut-off energy at 28.7 MeV and have an integrated particle number of 8×10^{12}. The opening angle decreases from 54° full angle to 10° for increasing proton energy. The proton source size diameter follows a parabolic behavior with its maximum at 480 μm. And the transverse RMS emittance decreases from 1.6 to 1.0 mm-mrad for increasing proton energy.

2.2. Particle source and external field

The protons are injected before the first time step with the *inverse transform sampling* method. Limited by the computation capacity and the length of a run, the simulation particle number is set to 10^6. Additionally, co-moving electrons ($v_e = v_p \rightarrow 1.2$ keV $< E_e <$ 15.7 keV) are injected as separate species but with the same beam parameters. For the first simulations the electrons with energies > 15.7 keV will be neglected. By setting up a volume source, the plasma frequency can be resolved with an acceptable simulation time step of 0.1 ps. At later time during expansion, the density is low enough to go to 1 ps time steps. A solenoid field with 8.6 T magnetic field strength has been included. Its field is obtained from the analytic field profile of a cylindrical current sheet. The off-axis field is given by multipole expansion. The solenoid dimensions are 72 mm in length with a front and a back 6 mm insulator flange. The inner radius of the coil is 22 mm and the distance to the source is 17 mm.

2.3. Simulation grid

The simulation grid for the field solver is defined by resolving the Debye length. A rough initial estimate yields to 0.5 mm per grid cell in radial direction and 1 mm in beam direction (cylinder symmetry). The boundary condition for the particles is set to absorbing and the potential vanishes.

3. Simulation results

3.1. Beam neutrality

Before studying the influence of the solenoid on the proton beam, Warp has to guarantee the beam neutrality. For this case, a simulation without solenoid field was done. During the first 400 ps the co-moving electrons neutralize the proton beam. Shortly after that, a potential in the order of some mV appears due to numerical heating. At 800 ps the potential builds up to 1 V and when the beam hits the solenoid inner wall it adds up to 100 V. In conclusion, the neutrality at the beginning is enough for the simulation setup, because the existing magnetic field affects the beam neutrality already during the first time steps.

3.2. Proton and electron beam expansion

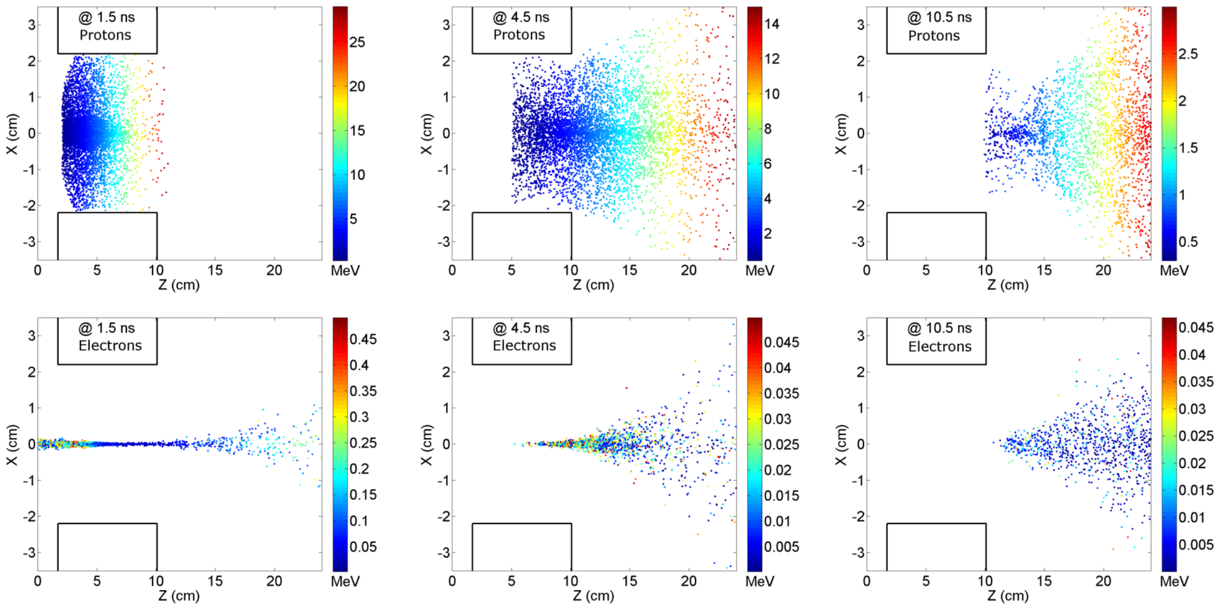

Figure 1. Snapshots of the proton (top) and electron (bottom) expansion for 3 different time steps: 1.5, 4.5 and 10.5 ns. The color scales for the particle energy (between 1.25 MeV and 29.5 MeV) were adjusted separately for a better illustration.

Due to the higher charge to mass ratio of the electrons compared to the protons, the electrons rotate on a much smaller radius in the magnetic field. The Larmor radius is given by $r_L = \sqrt{2E_{kin}m_e}/eB$ and is < 0.5 mm at the source position (B = 1.4 T) for the energy range of the co-moving electrons. Hence, most of the electrons get immediately bent down to the beam axis, the electron density increases and the expansion is not neutral anymore. Electrons are decelerated and accelerated (up to 1.25 MeV), not only forwards but also backwards because of the negative potential growth on axis. The magnetic effect outbalances the space-charge force. The electrons are not pulled back by the positive proton potential and the protons are attracted to the beam axis. This proton density increase can be observed for a wide range of energies, see figure 1. When the beam leaves the solenoid and the field attenuates (0.3 T 5 cm behind the solenoid), the electrons start to expand and follow the protons. Additionally, a proton beam waist and an over-focusing can be seen (simulation time of 10.5 ns in figure 1).

3.3. Proton and electron energy distribution

Figure 2 shows the proton and electron energy distribution for three different times: the initial distribution, the lost particles and the spectrum behind the solenoid. The acceleration/deceleration for the electrons is explicitly pointed out by the spectrum description. But the maximum electron energy given above of 1.25 MeV does not appear in the spectrum, because this kinetic energy was generated and reduced during the expansion. A very important observation is the loss of 66% of all electrons already during the first time steps. They are decelerated, pushed backwards and absorbed at z=0, the boundary of the simulation box. Thus it appears that the guaranteed beam neutrality is enough for the first picoseconds and finally the expansion is dominated by a positive potential. But still 2/3 of all electrons are sufficient to generate a high enough negative potential on axis to attract the protons.

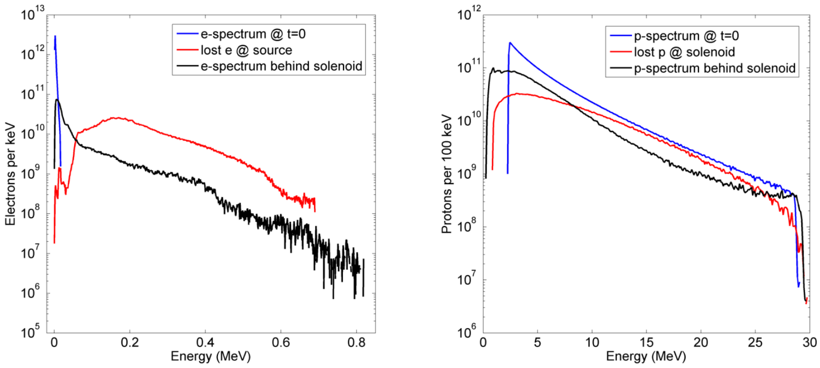

Figure 2. Electron (left) and proton (right) spectra: initial distribution, lost particles and spectrum behind solenoid.

As well as the electrons, the protons get slightly accelerated and decelerated. But there are no proton return currents. All lost protons are absorbed at the inner wall of the solenoid illustrated by the dip in the proton transmission spectrum. An overall proton transmission of 63% could be observed. But it is not possible to calculate an energy dependent transmission because of the acceleration/deceleration, the protons per energy interval jump.

3.4. Proton beam collimation

A first review shows only a proton density increase on axis, not really a collimation. The proton beam waist (figure 1) could be an evidence for beam collimation at an energy of around 0.8 MeV (envelope simulations without space charge effects predict 2.5 MeV). By checking the RMS or edge radius of each proton energy, no constant radius can be observed. Additionally, the radial velocity component decreases only slightly. However, for collimation it has to be close to zero. That is also the reason, why the beam waist increases for later times. The recent simulation data are still subject to further analysis and results will be published elsewhere.

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