SIMULATIONS OF PLASMA WAKEFIELD ACCELERATION WITH XOOPIC*

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Abstract

We present 2-D cylindrical particle-in-cell simulations of the E-157 beam wakefield experiment at SLAC, in which a 30 GeV electron beam passes through 1 m of preionized Li (lithium) plasma. Plasma electrons are blown out from the axis in the wake of the electron beam, driving a strong axial electric field, E_z of order 1 GV/m, in the small region where the plasma electrons fall back to the cylindrical axis. We also simulate wakefield accelerators with much higher plasma density and a 50 GeV drive beam. Electron impact ionization of the background neutral Li is found to be significant only for plasma densities of order 10^{17} cm^{-3} or larger. Other collisional processes are also considered.

1 INTRODUCTION

The plasma wakefield accelerator (PWFA) concept is being demonstrated experimentally at the Stanford Linear Accelerator Center in the E-157 experiment,[1,2,3] which has been simulated with the PIC (particle-in-cell) code OSIRIS.[4,5] The purpose of the E-157 experiment is to demonstrate the generation of high fields by showing that particles in the tail of the 30 GeV driving bunch are accelerated by approximately 600 MeV over the course of a meter. A scaled-up version of the E-157 experiment could be used as an "afterburner" for the Stanford Linear Collider to boost the electron beam energy by 100 GeV or more.[6,7,8,9]

The E-157 experiment uses a laser to pre-ionize a Li plasma for the driving electron bunch; however, it is also possible for the driving bunch to both produce the plasma via electron-impact ionization and also generate the plasma wakefield. This "self-modulated" PWFA concept is one of the experiments being considered as part of ORION, a proposed advanced accelerator facility at SLAC.[10] Modeling a self-modulated beam wakefield accelerator requires relativistic scattering models and electron-impact ionization cross-sections. The plasma electrons driven radially outward in forming the wake will also ionize the background neutral gas via electron-impact ionization.

The XOOPIC[11] code started as a pioneering effort to apply object oriented techniques to plasma simulation codes and is written in C++. Applications have ranged from high pressure discharges to relativistic microwave devices. XOOPIC uses MPI (message passing interface) for massively parallel, SMP (symmetric multiprocessor) and distributed architectures, demonstrating linear speed up with as many as 16 processors. We have recently modified XOOPIC for use in simulating plasma-based accelerators: parallel moving-window, launching of laser pulses, generalized beam emitters, and porting the code to the Cray T3E.

2 MODELING E-157 WITH XOOPIC

We have modeled E-157 with XOOPIC and found agreement with previous[4] work. The simulation region, in 2-D cylindrical geometry, is 0.9 mm in r by 5.4 mm in z, with the corresponding number of grid points n_r=32 and n_z=192, for a total of 6144 cells. With 4 macro-particles per cell representing the plasma electrons, there are 24,576 plasma particles. The 30 GeV electron beam is represented by 9 macro-particles per cell, and the beam covers 8 by 64 grids (initially) for 4608 beam particles. The grid size is dz=dr=28 μm. The time step, chosen to satisfy the Courant condition, is $dt=.5*dz/c=4.69\times10^{-14}$ s. Thus, it requires 71,400 time steps to propagate the beam through the 1 m Li plasma.

The plasma density is taken to be 2.1×10^{14} cm^{-3}, which implies an electron plasma frequency of $\omega_p=8.2\times10^{11}$ s^{-1}. Thus, $\omega_p*dt=0.04$ and the electron plasma frequency is being resolved, which is required for stability in a time-explicit PIC code. The Li plasma is assumed to be cold, but very little numerical heating is observed, because the moving window algorithm "sweeps" the electrons through at the speed of light.

Figure 1 shows the initial 30 GeV beam in cylindrical coordinates, with r on the vertical axis and z on the horizontal axis, and dimensions in m. Figure 2 shows the plasma wake. The structure of the wake is independent of the beam radius. Figure 3 shows the accelerating field generated by the wake in V/m. With higher resolution, the peak field on axis is greater than 1 GV/m.

The peak accelerating field overlaps the tail of the beam. Figure 4 shows the resulting acceleration of beam particles after 1m of propagation through the Li plasma. The vertical axis is $p_z=\gamma v_z$ in units of m/s.

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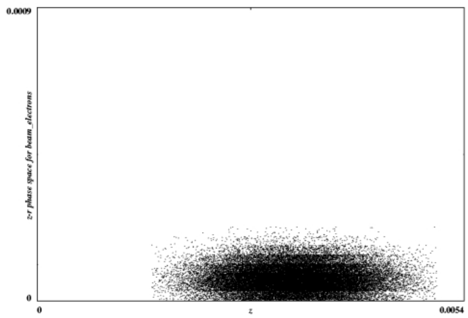

Figure 1: Initial distribution of the 30 GeV beam.

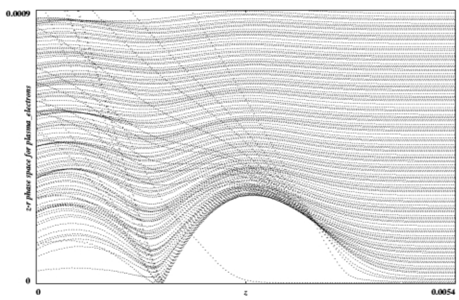

Figure 2: Plasma wake.

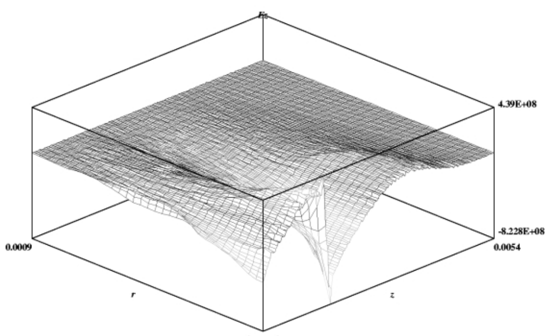

Figure 3: Longitudinal electric field.

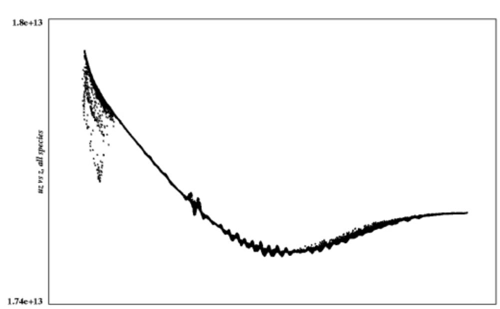

Figure 4: z-P_z phase space of beam at 1 m.

3 MODELING PARTICLE COLLISIONS

XOOPIC uses the null collision method[12] for MCC (Monte Carlo collision) treatment of electron-impact excitation and ionization and for electron-neutral elastic scattering. MCC models for Ar, Ne, He and H have been used for some time, and we recently added an ionization model for Li, using cross sections from the literature.[13] However, the cross section and scattering models assume the impact energy is nonrelativistic.

The bulk of the blown-out plasma electrons in the wake are nonrelativistic, but a significant fraction are not. Modeling collisional effects involving the drive beam must, of course, be fully relativistic. Electron-neutral collision cross sections $\sigma(E)$ fall from their maximum like $ln(E)/E$ for impact energies E<200KeV. Relativistic effects break this scaling, leading to a minimum in $\sigma(E)$ for E~1MeV, followed by logarithmic growth, which eventually saturates at a density dependent energy (the Fermi plateau).[14]

A fitting function for impact ionization cross sections has been developed,[15] using the ionization energy and two adjustable parameters, capturing both low-energy and relativistic behavior (but not the Fermi plateau). The fitting parameters are determined largely by data for higher energies, which has been published for a number of gasses[16] (although not Li). Fitting functions have also been developed for the energy distribution of the secondary electrons,[17] and the angular distribution for relativistic scattering is well known.[14]

Figure 5 shows electron-impact cross-sections for Li, for 1 eV < E < 30 GeV. The solid red line is for ionization of neutral Li (ejecting the outer electron from the 2s shell). The lower line (solid, long dashes) is for subsequent ionization of the Li^+. The cross section for ionizing neutral Li by ejecting an inner electron from the 1s shell is roughly the same magnitude as the double ionization cross section. The fitting parameters were determined, not from data, but by requiring agreement with nonrelativistic results in the regime E~200 KeV, where both models should hold, so there is considerable uncertainty for E in the GeV range.

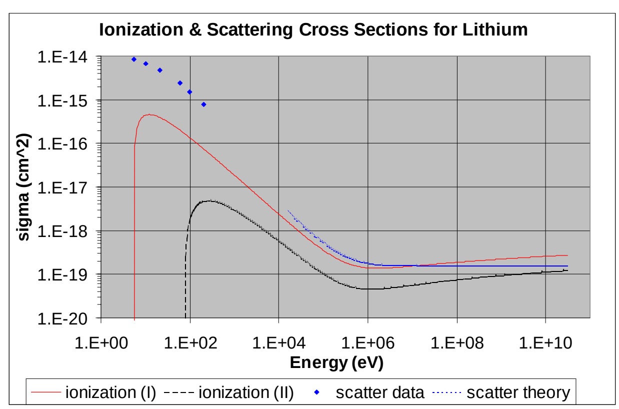

Figure 5: Ionization and scattering cross sections for Li.

The blue points in the upper left of Figure 5 show calculations[18] of the cross section for elastic scattering of electrons on neutral Li. The blue line with short dashes shows the theoretical scattering cross section[14] at high energy. The scattering cross section is 15 times larger than the ionization cross section for E~10 eV, roughly equal at E~10 MeV, and somewhat lower at E~10 GeV.

4 PLASMA AFTERBURNER

Because a large fraction of the plasma electrons in the blow-out region remain nonrelativistic, we have conducted some simulations using the nonrelativistic impact ionization model for Li. The neutral Li background density is assumed to be ten times the plasma density, which corresponds to $2x10^{15}$ cm^{-3} for E-157. Impact ionization is found to be negligible for E-157.

The afterburner parameters recently proposed by Tom Katsouleas,[9] include a Li density that is larger by a factor of 100. Simulations indicate that impact ionization is not completely negligible for this higher density, but that the plasma wake and corresponding accelerating fields are not modified. However, the electron-neutral scattering cross section is much larger, and this scattering might disrupt the wake.

We also modeled the case where the Li density is larger by a factor of 1000 than the density for E-157. In this case, the peak on-axis field behind the drive bunch is not significantly affected, but the trailing wake is disrupted by the additional electrons generated through impact ionization. Figure 6 shows the on-axis electric field both with (blue, dashed) and without (red, solid) ionization effects.

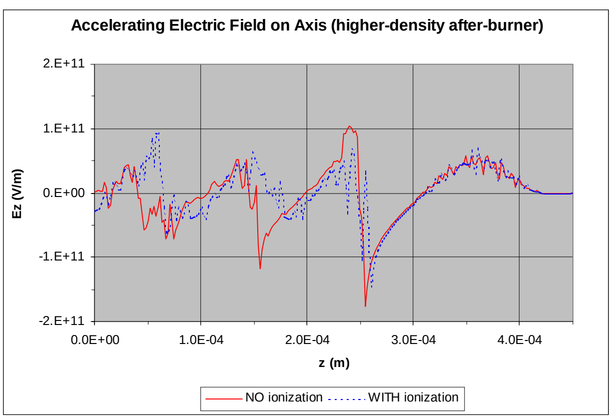

Figure 6: Ez on axis for a very high-density wakefield accelerator, modeled with and without impact ionization.

5 CONCLUSIONS

Electron impact ionization is not relevant to the E-157 experiment. For a plasma afterburner with 100 times greater density, impact ionization is a marginal effect, but electron-neutral scattering may disrupt the wake, unless the plasma is 100% pre-ionized. The plasma wake of a self-modulated wakefield accelerator would likely be disrupted due to impact ionization by the plasma electrons. The version of XOOPIC now under development is a unique tool for modeling these types of problems.

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