MODELING SELF-IONIZED PLASMA WAKEFIELD ACCELERATION FOR AFTERBURNER PARAMETERS USING QUICKPIC [∗]

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Abstract

For the parameters envisaged in possible afterburner stages[1] of a plasma wakefield accelerator (PWFA), the self-fields of the particle beam can be intense enough to tunnel ionize some neutral gases. Tunnel ionization has been investigated as a way for the beam itself to create the plasma, and the wakes generated may differ from those generated in pre-ionized plasmas[2],[3]. However, it is not practical to model the whole stage of PWFA with afterburner parameters using the models described in [2] and [3]. Here we describe the addition of a tunnel ionization package using the ADK model into QuickPIC, a highly efficient quasi-static particle in cell (PIC) code which can model a PWFA with afterburner parameters. Comparison between results from OSIRIS (a full PIC code with ionization) and from QuickPIC with the ionization package shows good agreement. Preliminary results using parameters relevant to the E164X experiment and the upcoming E167 experiment at SLAC are shown.

INTRODUCTION

A plasma wakefield accelerator (PWFA) can have accelerating fields on the order of $100GV/m$, and is proposed as a way to double the energy of a future linear collider[1]. In this proposed afterburner concept, meter long high density plasmas ($>10^{16}cm^{-3}$) are needed. This exceeds the current capability of producing plasmas by laser photon-ionization. Fortunately, in the process of pursuing larger accelerating fields by reducing the bunch length, a regime where the space charge of the relativistic beam can ionize low ionization potential neutral gases is also reached ($E_{r\_\max} \propto N/(\sigma_r\sigma_z)$). Using self-ionization as a new plasma source has been investigated using simulations[2][3] and has achieved good results in experiments[4]. However, the plasma wake produced by self-ionized electrons may differ from that of a pre-ionized plasma, and may thus influence the beam dynamics, such as, beam head erosion and the hosing instability, when the beam propagation distance is extended to meters long and hence hundreds of betatron wavelengths. However, it is not practical to use a fully explicit PIC code, such as those in [2] and [3] to model this stage because the maximum time step that can be chosen is restricted by the Courant condition. Fortunately, a novel 3D quasi-static PIC code, QuickPIC has recently been developed [5]. It is fully relativistic, fully nonlinear, fully parallelized, and highly efficient for PWFA research. It gives wakes almost identical to those from OSIRIS (full PIC code in [3]) in pre-ionized cases at savings of at least a factor of 100 in CPU hours. The details of QuickPIC are contained in [5]. Here we describe changes relevant to the ionization package and show some of the preliminary results.

IONIZATION PACKAGE IN QUICKPIC

Due to the quasi-static approximation, fields can be solved locally in 2D slices. Thus, in QuickPIC, a 2D slice of plasma is swept through a 3D beam, getting all the fields around it. These fields are then used to update the beam particles. For the self-ionized case, a neutral slice is used instead. The electrons and ions are generated by integrating the ionization rate from in front of the beam where the electric field (thus the ionization rate) is zero. We use the field ionization rate formula from the ADK model[6], e.g. for Li→Li$^+$,

$$W(s^{-1}) = \frac{3.46\times 10^{21}}{E^{2.18}(GV/m)} \times e^{-\frac{85.5}{E(GV/m)}} ,$$

which corresponds to a full ionization threshold of $6GV/m$ over $20fs$ (bunch duration is $\sim 100fs$).

Since QuickPIC was written as an object-oriented code, it is relatively straightforward to add ionization into it without worrying about the parallelization. However, there are several complications. First, in QuickPIC, the relativistic factor γ and parallel momentum $p_{//}$ for plasma electrons are calculated from $p_\perp$ through a conserved quantity of particles under quasi-static approximation, i.e. $\gamma - p_{//} - \psi = 1$[7], where $\psi = \phi - a_{//}$ is the normalized pseudo-potential (ϕ and a are normalized scalar and vector potentials). Reexamination of the derivation shows that for ionized electrons, it should be written as $\gamma - p_{//} - \psi = 1 - \psi_0$, where ψ_0 is the initial pseudo-potential at the location where these electrons are born; this quantity is in general not zero. Second, when advancing a 2D slice in QuickPIC, an iteration loop which utilizes diffusion equations is used to calculate the potentials and densities. In order for the iteration to converge faster, appropriate 'diffusion coefficients' need to be chosen and they depend on the plasma density[8]. In

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the self-ionized case, we choose these ‘diffusion coefficents’ based on the neutral density. It appears that this simple choice is adequate. Other complications involve reconsideration of the normalization, details of generating particles near the processor boundaries, and in the conversion of units from the 2D part of the code to the 3D part of the code.

BENCHMARK VERSUS OSIRIS

The longitudinal electric fields of the wake obtained from QuickPIC simulations are compared with the OSIRIS field-ionization results. Figure 1(a) is a case where the space charge field of the beam is significantly above lithium's ionization threshold ($E_{r\_\max} = 26GV/m$); and Figure 1(b) is a case where it is near threshold ($E_{r\_\max} = 11.7GV/m$). In Figure 1(a), a parameter scan is presented in order to check the influences of the simulation parameters, such as the number of particles per cell and resolution in z direction. We can see that for these choices of simulation parameters the results change little.

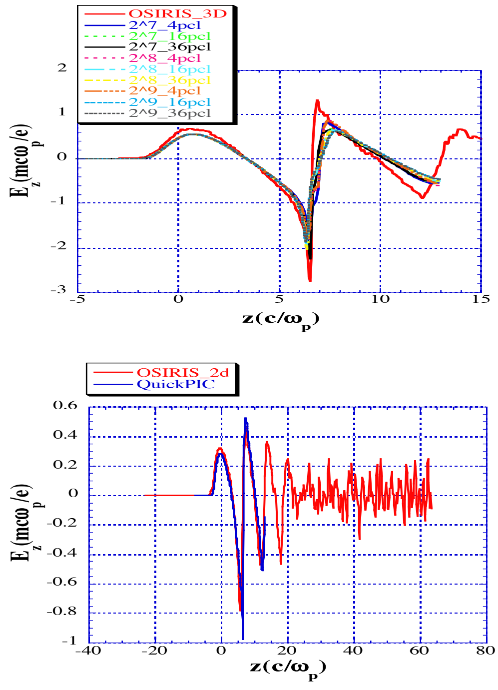

Figure 1. Benchmark of longitudinal electric field for self-ionized lithium plasma wake, $N_b = 2\times10^{10}$ (a) High above threshold, $\sigma_r = 20\mu m$, $\sigma_z = 20\mu m$, ($n_p = 1.25\times10^{17}cm^{-3}$); (b) Just above threshold $\sigma_r = 14.1\mu m$, $\sigma_z = 63\mu m$, ($n_p = 4.2\times10^{16}cm^{-3}$).

The OSIRIS result in (a) is from a 3D simulation and that of (b) is from a 2D simulation. In the past we have shown that for short propagation distances the differences between 2D and 3D in OSIRIS are negligible. In both cases, QuikPIC and OSIRIS agree very well for the first accelerating/decelerating peak.

E164X PARAMETER RESULTS

Simulations are done with parameters relevant to the E164X experiment where ~4GeV energy gain was observed (including the incoming beam energy chirp) [4]. The 28.5GeV beam has 2×10^{10} electrons, same current profile as in [4], transverse rms radius $\sigma_r = 10\mu m$, and normalized emittance in x and y of 50 and $5\,mm\cdot mrad$, respectively. The lithium density rises linearly from 0 to $2.8\times10^{17}cm^{-3}$ in $6.1cm$, keeping this value over $4.8cm$ before it falls linearly to 0 in another $6.1cm$. Figure 2(a) shows the initial beam density at z=0. (b) and (c) are plasma density and E_z at z=8.6cm (flat density region). The useful accelerating field is $\sim 50GV/m$. Figure 3 shows the beam current and average energy at z=16.7cm (near the end of the plasma). The maximum energy gain is $\sim 5GeV$. This agrees well with the experimental results if one includes the energy losses to the beam from betatron radiation of x-rays ($\sim 0.5GeV$ [9]), which is not included in the simulations.

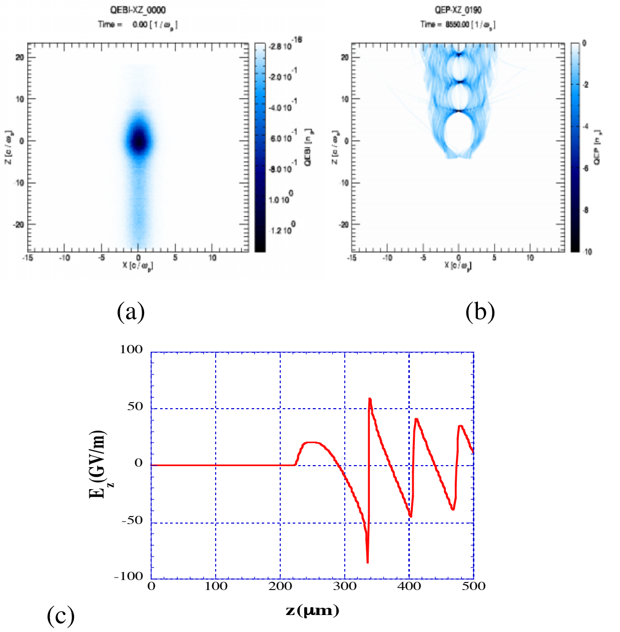

Figure 2. E164X simulation (a) Beam density at z=0; (b) Plasma density at z=8.6cm; and (c) E_z at z=8.6cm.

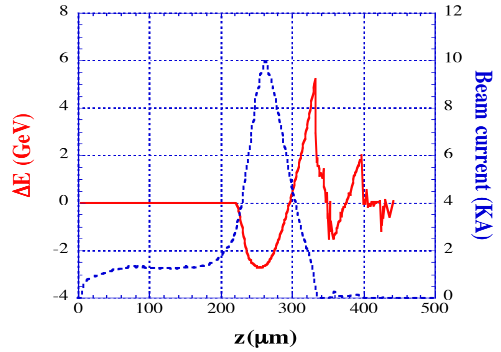

Figure 3. E164X simulation: beam current and energy gain at z=16.7cm .

E167 PARAMETER RESULTS

QuickPIC simulations have also been done to model the upcoming E167 experiment, where the neutral lithium column will be elongated with the expectation to see larger energy gain. All parameters used are the same as the E164X simulation, except (1) A gaussian beam similar to the bulk part of the beam in [4] is used ($N_b = 1.87 \times 10^{10}$, $\sigma_r = 10\mu m$, $\sigma_z = 31.2\mu m$); (2) the beam is initially tilted linearly in x-z plane with $\Delta x / \Delta z = 0.011$; (3) the flat region of lithium is now $14.4cm$ long. A QuickPIC simulation for a pre-ionized case is also done for comparison.

Figure 4 shows the phase space density of the beam at z=26.2cm (near end) for the (a) pre-ionized and (b) self-ionized case. The maximum energy gain was 8.8GeV in both cases. In real experiments, this will be smaller due to the energy loss from betatron radiation.

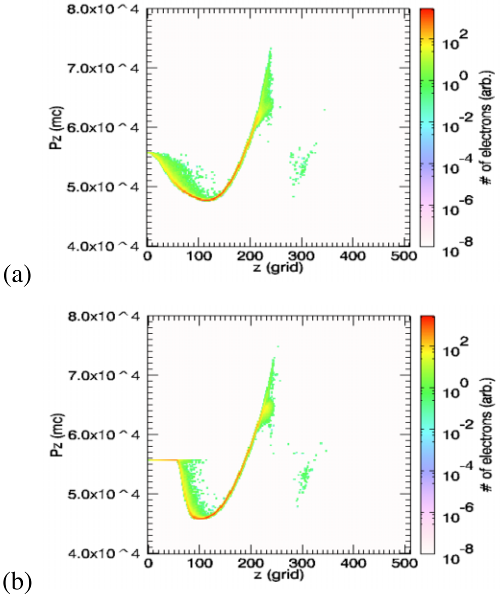

Figure 4. E167 simulation: beam energy at z=26.2cm for (a) pre-ionized case and (b) self-ionized case.

In order to investigate the effects of hosing on beam energy gain, the centroid and rms radius of the beam particles for the slice where maximum energy is achieved (z=230 in Figure 4) are plotted in Figure 5(a) and (b), respectively. From Figure 5(a), we can see that although hosing starts early in time, the amplitude is small so that the beam centroid still resides inside the region of high acceleration, which extends about $10\mu m$ from the axis. However, Figure 5(b) shows the spot size starts to increase after 12cm for the pre-ionized case and after 15cm for the self-ionized case. The number of electrons inside this region can decrease significantly. Thus, although the maximum energy may not be influenced much, the number of high energy particles may decrease. However, from both perspectives, i.e. the amplitude of hosing and the starting point of increased spot size, the self-ionized regime is more favorable than the pre-ionizatied regime.

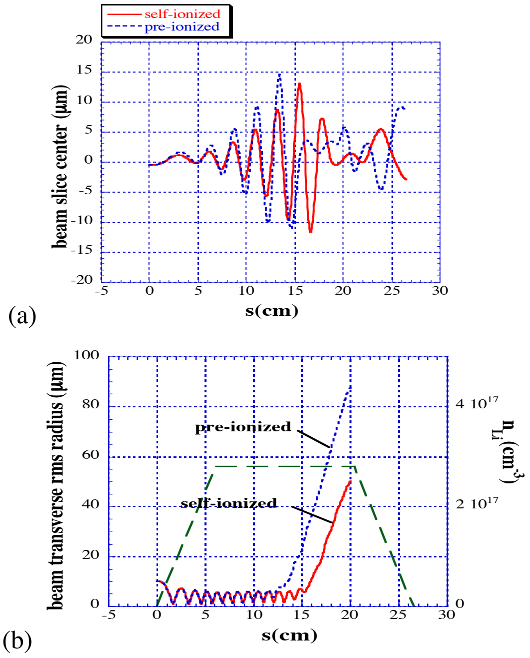

Figure 5 (a) Beam controid and (b) rms radius evolution of particles having maximum energy gain (z=230 in Figure 4).

CONCLUSION

The addition of a field-ionization package in QuickPIC is described. With this package, simulations modeling self-ionized PWFA using afterburner parameters are made possible. Benchmarking shows good agreement of the longitudinal electric field with OSIRIS in both far above and near ionization threshold cases. Preliminary results using E164X parameters shows similar energy gain as observed in the experiment. The maximum energy gain is predicted for the upcoming E167 experiment and effects of hosing on this energy gain are briefly analyzed.

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[9] Estimation based on Lienard formula gives energy radiated by an electron during one betatron oscillation as $7.08 \times 10^{-42} \times \gamma^{2.5} \times n_p (cm^{-3})^{1.5} \times a(\mu m)^2 (GeV)$, where a is the maximum offset. In simulation, there are about 12 envelope oscillations (6 betatron wavelength).

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