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PRELIMINARY SIMULATIONS OF PLASMA WAKEFIELD ACCELERATOR EXPERIMENTS AT FACET*

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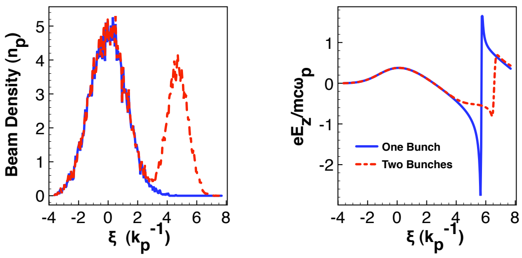
Abstract

Recent experiments at SLAC have demonstrated that a single electron beam driven Plasma Wakefield Accelerator (PWFA) can be produced with an accelerating gradient of 52 GeV/m over a meter-long scale [1]. If another electron bunch is properly loaded into such a wakefield, it will obtain a high energy in a short distance as well have a small energy spread. Such a PWFA experiment with two bunches will be performed in FACET, which is a new facility at SLAC [4]. Numerical simulations using QuickPIC show that with possible beam parameters in FACET the first electron bunch (with less current than that in the FFTB experiment) can still produce a meter-long plasma column with a density of $5 \times 10^{16} cm^{-3}$ via field ionization when we use a gas with a lower ionization energy. And the second electron bunch can have an energy gain on the order of 10 GeV with a very narrow energy spread. If a pre-ionized plasma is used instead of the neutral gas, the energy gain of the second bunch can be enhanced to 30 GeV.

INTRODUCTION

The experiments on the former FFTB facility at SLAC [1] have demonstrated that PWFA can have an accelerating gradient of 52 GeV/m over a distance about one meter long. In those experiments, the plasma wakefield is driven by a single 42 GeV electron bunch. This beam's intensity is strong enough to ionize a Li gas and excite a nonlinear wakefield in the field-ionized plasma. The wakefield is in a so-called "Blow-Out" regime [2, 3], in which all the plasma electrons close to the drive beam are pushed away by the drive beam's field and finally pulled back by the plasma ions. The expelled plasma electrons will form a thin sheath around a bubble-like cavity filled with only ions. The drive beam is just enclosed inside the cavity and feels a longitudinally uniform and radially linear focusing force (which can conserve the transverse emittance of the beam). The longitudinal electric field inside the bubble only depends on the longitudinal position and is transversely uniform, which ensures that transverse motion of the drive beam will not induce additional energy spread. In the single drive beam PWFA, most of the drive beam feels a decelerating field and only the rear part is accelerated. These particles in the rear locate in a large regime of the wakefield's phase and thereby feel different accelerating forces. This produces a large energy spread (almost 100%) in the final spectrum of the beam [1]. However, a locally uniform accelerating field can be obtained if a second electron beam is loaded properly inside the bubble (Fig. 1). In this way, the second electron beam will be accelerated under a much flatter field while the first beam is decelerated. And the energy spread of the second beam will be very small. To demonstrate that both a high energy gain and a narrow energy spread can be obtained in the PWFA, such a two-bunch scheme is proposed for a new facility FACET (Facilities for Accelerator Science and Experimental Test Beams) at SLAC [4].



(a) (b)

Figure 1: Plasma wakefields with different beam loads. (a) Lineouts of longitudinal beam profiles; (b) Lineouts of E_z along the axis. The beams are moving from right to the left.

QuickPIC [5] will be used for modeling these new PWFA experiments. This code has several significant improvements since we used it for modeling the experiments on FFTB. In this paper, we will first talk about the developments in QuickPIC. And then some preliminary simulation results of two-bunch PWFA will be presented.

CODE DEVELOPMENT

QuickPIC is a 3D parallel quasi-static Particle-In-Cell (PIC) code, which is developed with the UPIC framework [6]. This code provides a more efficient way of modeling the plasma based accelerator compared with full PIC codes (such as OSIRIS [7]). Recently we have made three significant improvements on the code. First, multiple ionization based on the Ammosov-Delone-Krainov (ADK) model [8] is implemented into the ionization package in QuickPIC. This is necessary for simulating the experiments using field-ionized plasma source. Different from former experiments, multiple ionization may be an important issue in the future experiments because we may use Cs as a plasma source instead of Li (which is used before) and Cs

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has a much lower threshold of second ionization. The new ionization package will help to study the influence caused by that. Second, the pipelining algorithm is enabled in the ionization package. For a well scaled parallel code, the total time the simulation takes will decrease when you using more processors. The pipelining algorithm will make the code scale to more processors. So that we can shorten the simulation time by applying more processors for a single simulation. Third, a new iteration method is used to speed up the code even more. By solving a different set of fields' equations, the new method gives an accurate solution after a single iteration (the code needs between 2 to 7 iterations before, depending on the intensity of the drive beam). As a result, the computing time is at least shortened by a factor of 2.

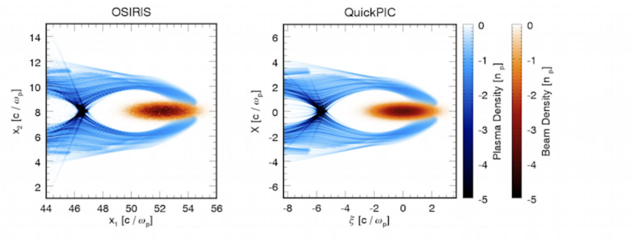


Figure 2: Plasma density from simulations using OSIRIS and QuickPIC. The r.m.s. spot size of the electron drive beam is $\sigma_r = 10\ \mu m$; the r.m.s. beam length of is $\sigma_z = 34.1\ \mu m$; the particle number of the beam is $N = 9.57 \times 10^9$ and the initial energy of each beam is $E = 23\ GeV$ and the plasma density is $5.0 \times 10^{16}\ cm^{-3}$.

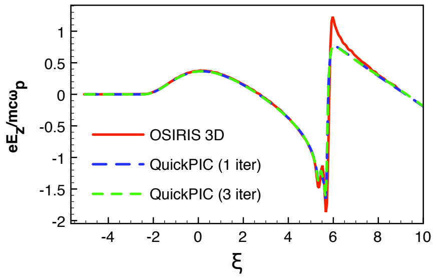


Figure 3: Longitudinal electric field (on axis) from simulations using OSIRIS and QuickPIC

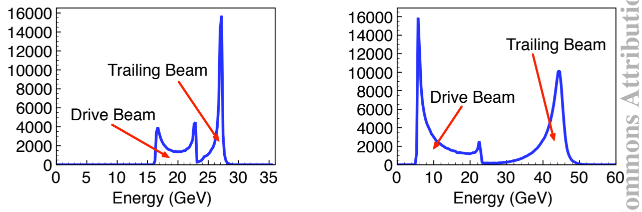
For benchmarking the code, we simulate the wakefield driven by a single electron beam in a field-ionized plasma by using OSIRIS 3D and QuickPIC. The simulation results (Fig. 2 and 3) show excellent agreement with each other.

SIMULATIONS OF TWO-BUNCH PWFA

In this section, we use QuickPIC to simulate two electron beams traveling through a neutral gas. The r.m.s. spot size of each electron beam is $\sigma_{r1} = \sigma_{r2} = 10\ \mu m$; the r.m.s. beam length of each beam is now $\sigma_{z1} = 34.1\ \mu m$, $\sigma_{z2} = 19.3\ \mu m$; the transverse r.m.s. normalized emittance of each beam is now $\epsilon_{x1,2} = \epsilon_{y1,2} = 100\ mm \cdot mrad$; the particle number of each beam is $N_1 = 9.57 \times 10^9$, $N_2 = 4.33 \times 10^9$; the distance between two beam centers is now 130 μm and the initial energy of each beam is still $E_{01} = E_{02} = 23\ GeV$. These initial electron beams' parameters are obtained from the overall simulation of FACET beamline. Considering the drive beam (the first electron beam) has a smaller current than the former experiments, we chose Cs gas as the plasma source instead of Li (which was used in the previous experiments [1]), because Cs has a lower ionization threshold than Li. The plasma density is carefully chose to keep the second beam's energy spread small. There are two optimal plasma densities, which are $3.7 \times 10^{16}\ cm^{-3}$ and $5.0 \times 10^{16}\ cm^{-3}$, can be used for this case.

Lower Plasma Density

With a lower plasma density, the "bubble" of the wakefield is long enough to contain both two beams. Fig. shows snapshots of plasma and beams densities when two beams getting to different distances in the neutral gas. The plasma can be only generated in the area close to the drive beam. The radius of the plasma column has to be bigger than that of the bubble in order to keep the plasma wakefield well formed. The head of the drive beam will spread out because the ionized plasma cannot provide a strong enough focusing force. As a result, the self field around the beam head will be weakened and the ionization front will move backwards and finally disappears. As shown in Fig. 4 the drive beam can no longer ionize the neutral gas after $88cm$ propagation. Fig. 5 (a) is the final energy spectrum of both two beams. The trailing beam has a 5 GeV energy gain and the energy spread is less than 3%. But the drive beam is still 15 GeV when the plasma wake terminates, which means the drive beam's head erosion is too severe so the wake amplitude decreases before the drive beam's energy is used. If we can slow down the drive beam's head erosion, the beams can propagate a longer distance, which can also make the second bunch gain more energy. Because the spreading rate of the beam head is proportional to the beam emittance, one way to slower the head erosion is to decrease the emittance of the drive beam. Another way is to use a preformed plasma. Fig. 5 (b) shows the final en-



(a) (b)

Figure 5: Energy spectra of both two beams: (a) In a field ionized plasma; (b) In a preformed plasma. The numbers on the y axis are reference values with arbitrary units.

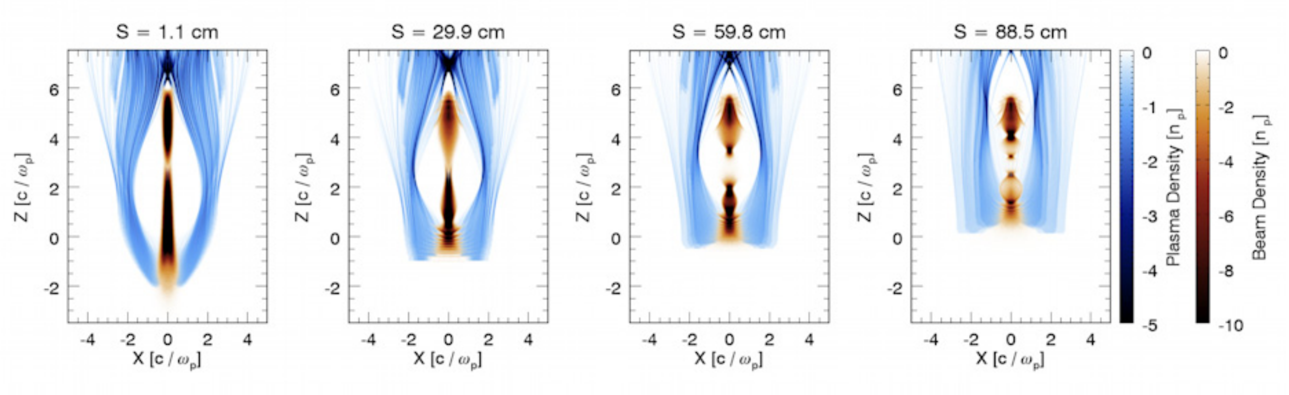
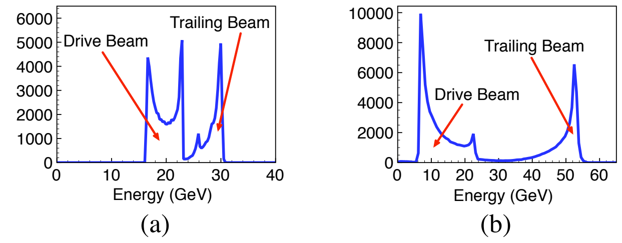


Figure 4: Snapshots of the ionized plasma density and beams charge densities at different propagation distances. The beams are traveling downwards

ergy spectrum from the QuickPIC simulation with the same beam parameters but a preformed plasma. The acceleration distance is enhanced to 230 cm and the energy gain of the trailing beam is around 20 GeV while the energy spread is still very small.

Higher Plasma Density

With a higher plasma density, the length of the ”bubble” will be shorter. So that the rear part of the trailing beam will fall out of the first bucket and feels a decelerating field and a defocusing force as well. This will result in a broader energy spread on the second beam. But the accelerating gradient is larger than that in the lower density plasma. So the trailing beam finally has an energy gain of 7 GeV (shown in Fig. 6 (a)) after 76 cm propagation in the plasma. When switching to the preformed plasma, the energy gain (shown in Fig. 6 (b)) can reach 30 GeV after 143 cm propagation in the plasma.



(a) (b)

Figure 6: Energy spectra of both two beams: (a) In a field ionized plasma; (b) In a preformed plasma. The numbers on the y axis are reference values with arbitrary units.

SUMMARY

In the blow-out regime of PWFA, if a second electron beam is appropriately loaded into the wake field driven by the first beam, the accelerating field felt by the second beam can be locally uniform and finally leads to a narrow energy spread. Such two-bunch PWFA configuration is proposed in the new facility FACET at SLAC. We are using QuickPIC for the numerical simulation on those experiments and other related issues. QuickPIC has been significantly improved and has become faster and more accurate for modeling the PWFA for both preformed plasma and field-ionized plasma. With possible FACET two beams parameters, simulation results show that the trailing beam can be accelerated in the wake field to an energy gain on the order of 10 GeV with a less than 3% energy spread. The energy gain is limited by the head erosion of the drive beam when using a field-ionized plasma. If a preformed plasma is used, the energy gain can reach to 30 GeV while the energy spread is still small.

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