Simulations of Two-Bunch Plasma Wake Field Accelerator Experiments at FACET

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Abstract. Simulation results of possible upcoming Plasma Wake Field Accelrator (PWFA) experiments at FACET are presented. In a two bunches scenario the second (accelerated) electron bunch can have multi-GeV energy gain and a small energy spread after less than 1 meter propagation in a Cs plasma column.

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INTRODUCTION

Recent experiments at SLAC [1] demonstrated that PWFA could be manipulated with an accelerating gradient of $\sim 52 GeV/m$ over meter-long scale. In those experiments the form of plasma wake fields are always attributed to a so-called "Blow-Out" regime [2, 3] in which the drive beam traveling through the plasma is strong enough (always with intense beam current) to expell all the plasma electrons close to it and leaves a bubble-like column around the drive beam only with ions. The expelled plasma electrons will form into a thin sheath around the ion column and finally be dragged back by the ions (Fig. 1). The maximum radius of the bubble is directly related to the square root

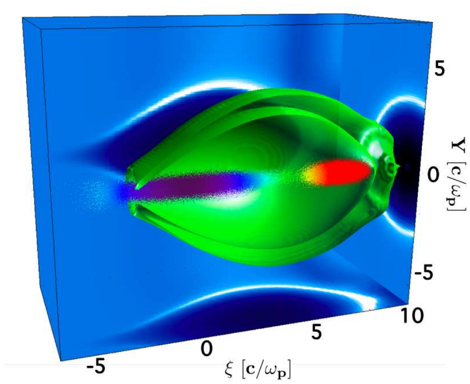
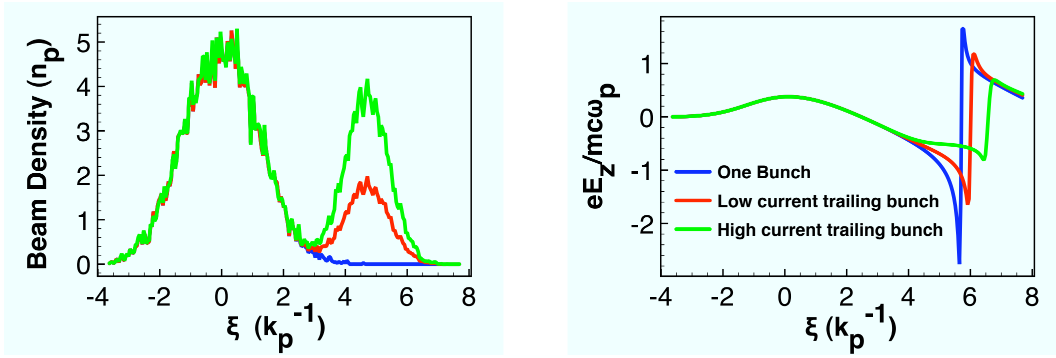


FIGURE 1. Illustration plot of a two-bunch PWFA in the "Blow-Out" regime. This plot is a combination of (a) the plot of cross-section of the plasma electron density (three blue plots on the walls), (b) three dimensional contour surface of the plasma electron density (green surfaces which stand for the inside and outside surfaces of the plasma electron sheath around the bubble) and (c) the beam particles (plotted as colored dots: the color of blue represent low energy and the color of red represent high energy). The two bunches are moving from right to the left.

of the peak current of the drive beam and the length of the bubble is approximately equal to the plasma wave length. The fields inside the bubble are favorable for accelerating particle beams because the accelerating field is transversely uniform and the focusing field is longitudinally uniform and radially linear, which means when the particle beam is accelerated inside the bubble the transverse emittance of the beam can be conserved and the transverse motion of beam particles will not lead to any energy spread. However, the energy spread will still be induced due to the non-uniformity



(a) (b)

FIGURE 2. Plasma wake fields with different beam loads. (a) Lineouts of different longitudinal beam profiles; (b) Lineouts of E_z along the axis. The two bunches are moving from right to the left.

of the accelerating field along the longitudinal direction. As a result Ref.[1] shows that the electron beam has an almost 100% energy spread which is surely not what we expect from a real high energy particle accelerator. Nevertheless, a locally uniform accelerating field can be obtained if we load a second electron beam (which has a proper beam current) appropriately inside the plasma wake of the first beam (Fig. 2). This second bunch also needs to have a high initial energy as the first beam so that the phase slipping between the accelerated beam and the wake field of the first beam can be ignored during the acceleration process in the plasma. Through this way the energy spread of the second bunch will be significantly decreased.

This two-bunch PWFA scheme will be an important part of the upcoming experiments at FACET (Facilities for Accelerator Science and Experimental Test Beams) at SLAC [4] for demonstrating a high energy gain acceleration through PWFA with a narrow energy spread. The two bunches are produced from a single bunch by placing a mask in the middle of the last chicane (for compressing the bunch) on the beamline. Before the last chicane the single bunch has already been added an energy spread which is correlated to the longitudinal (or temporal) distribution of the bunch. In the middle of the chicane the dispersion of the bunch will be correlated to its energy spread as well as the longitudinal distribution of the bunch. When the bunch passes through the mask the dispersion space of the bunch will be modified by the mask resulting in a modulation of the longitudinal distribution of the bunch after it gets out of the chicane. In this way a single bunch will finally turn into two bunches with a separation between them.

With given beams parameters we can change the plasma parameters to optimize the acceleration. In this paper we will firstly talk about the plasma source used in the two-bunch PWFA experiments. And then PIC simulation results based on the possible parameters of two bunches from FACET will be presented.

PLASMA GENERATION IN THE TWO-BUNCH PWFA

In order to obtain a high energy gain through PWFA a meter long plasma with density around $10^{16}\ cm^{-3}$ is always needed. A convenient way to generate such a plasma may be using the self electric field of the drive beam to ionize a neutral gas. The ionization rate given by the ADK model [5] is

$$w(s^{-1}) \approx 1.52\times\ 10^{15}\frac{4^{n^*}\xi_i[eV]}{n^*\Gamma(2n^*)}\left(\frac{20.5\xi^{3/2}[eV]}{E[GV/m]}\right)^{2n^*-1}\cdot\exp\left(-\frac{6.83\xi_i^{3/2}[eV]}{E[GV/m]}\right),$$

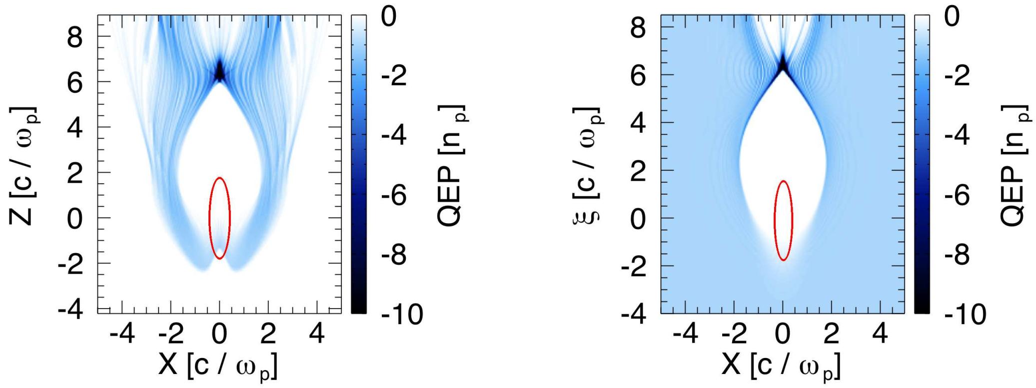
where ξ_i is the ionization energy and $n^* = 3.69Z/\xi_i^{1/2}[eV]$ is called the effective principal quantum number. In the same transit time Δt (the time the atom or ion staying in the field) the ionization fraction $(w(s^{-1})\cdot\Delta t)$ will reach 100% when the electric field is greater than a certain value. Table 1 shows these critical values of different atoms and ions. The lower the ionization energy is the lower the critical electric field of the fully ionization will be.

If the beam is strong enough a fully ionized plasma column will be generated around this beam when it is traveling in a neutral gas. With the same drive beam the lower the ionization threshold of the neutral gas is the bigger the radius of the plasma column will be. Fig. 3 shows the "Blow-Out" plasma wakes in a field ionized plasma and a preformed

TABLE 1. Critical electric field of several types of gases [5].

Atom/Ion	$\xi_i(eV)$	**Z**	n^*	$E_{cric}(GV/m)$
H	13.6	1	1.00	75.3
He	24.5	1	0.746	182
He^+	54.4	2	1.00	602
Li	5.39	1	1.59	18.7
Li^+	75.5	2	0.848	985
Cs	3.89	1	1.87	11.5
Cs^+	25.1	2	1.47	189

plasma. In a field ionized plasma the radius of the plasma column should be bigger than the maximum bubble radius of the plasma wake in order to maintain the plasma wake in a good shape for providing a well acceleration condition. This can be achieved by using a plasma with higher density (which can decrease the bubble radius of the plasma wake) or lower ionization threshold (which can increase the radius of the ionization column). For the parameters in FACET two-bunch PWFA experiments the gas of Cs is preferred instead of the gas of Li used in the former single bunch PWFA experiments [1] because Cs has a lower ionization threshold than Li.



(a) (b)

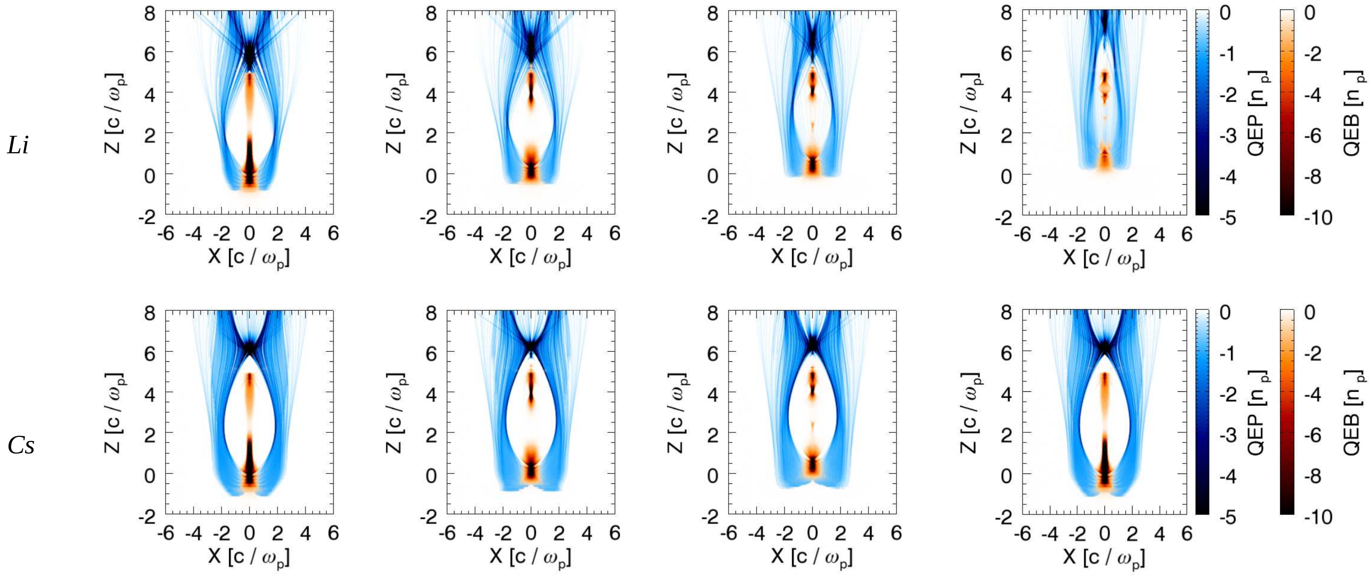
FIGURE 3. Snapshot of plasma electron density of the wake exited by a single electron beam (the red line is the beam density contour) in (a) Field ionized plasma and (b) Preformed plasma. The drive beam is moving downwards.

SIMULATION RESULTS

Two cases are presented in this section. The initial electron beams parameters of these two cases are both based on the overall simulation of the entire FACET system. QUICKPIC [6] with ionization module is used to modeling the process of the two electron bunches traveling through the neutral gas. For each case we are using optimal plasma density which is properly chosen to minimize the energy spread of the accelerated bunch.

Case I

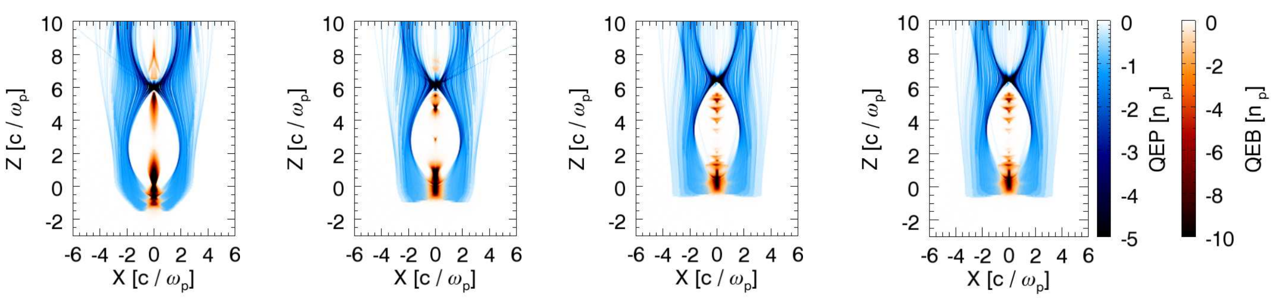
In this case the r.m.s. spot size of each electron beam is $\sigma_{r1} = \sigma_{r2} = 10\ \mu m$ (1 stands for the drive beam, 2 stands for the trailing beam); the r.m.s. beam length of each beam is $\sigma_{z1} = 18\ \mu m$, $\sigma_{z2} = 25\ \mu m$; the transverse r.m.s. normalized emittance of each beam is $\varepsilon_{x1,2} = \varepsilon_{y1,2} = 50\ mm \cdot mrad$; the particle number of each beam is $N_1 = 6.7 \times 10^9$, $N_2 = 2.3 \times 10^9$; the distance between two beam centers is 115 μm; the initial energy of each beam is $E_{01} = E_{02} = 23\ GeV$.



(a) $s = 14.3\ cm$ (b) $s = 30.9\ cm$ (c) $s = 47.5\ cm$ (d) $s = 64.2\ cm$

FIGURE 4. Snapshots of plasma electron charge density (in blue) and beams charge densities (in brown) at different propagation distances. The plots of first row are simulation results using Li and second row are results using Cs. The beams are moving downwards.

Fig. 4 shows the difference between using Li and using Cs. The initial plasma density is $5.0 \times 10^{16}\ cm^{-3}$ in both cases. In the gas of Li the ionized plasma column is not big enough to keep the plasma wake in a good shape. The drive beam almost burns out after traveling 64.18 *cm* in Li while in Cs the drive beam is still good at the same distance, which means the drive beam can propagate longer in the gas of Cs. Therefore the acceleration length and final energy gain of the second electron bunch will be increased when using Cs instead of Li.



(a) $s = 5.0\ cm$ (b) $s = 35.2\ cm$ (c) $s = 65.3\ cm$ (d) $s = 95.6\ cm$

FIGURE 5. Snapshots of plasma electron charge density (blue) and beams charge densities (brown) at different propagation distances when using Cs with the density of $7 \times 10^{16}\ cm^{-3}$. The beams are moving downwards.

For the parameters of Case I there is not an ideal plasma density which can be used to generate a narrow energy spread of the accelerated beam since the second bunch does not have a strong enough beam current (similar as the second case shown in Fig. 2). Fig. 5 shows snapshots of plasma and electron beams densities when the gas of Cs with density of $7 \times 10^{16}\ cm^{-3}$. The drive beam can travel almost 1 meter inside the plasma before the plasma wake terminate. Fig. 6 shows the energy spectrum of the trailing beam at the final point. Since the rear part of the trailing beam locates outside the bubble this part will feel a decelerating field in the wake. As a result a peak with energy loss appears in the spectrum. The accelerated part of the trailing beam has a peak energy of 37 *GeV* and the maximum energy gain is around 20 *GeV*. The energy spread is around 35% (FWHM value) which is not good enough. If keeping increasing the plasma density, fewer particles in the trailing beam will get accelerated and the energy spread of these beam particles will approach 100%.

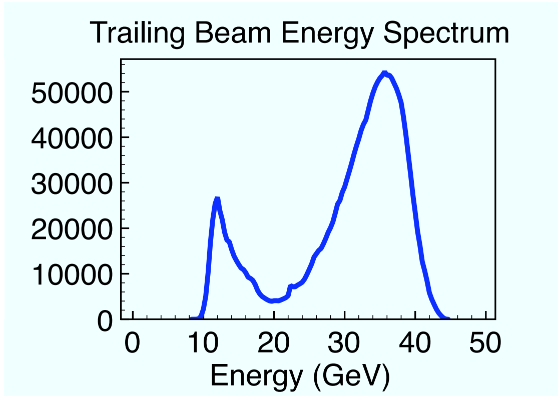
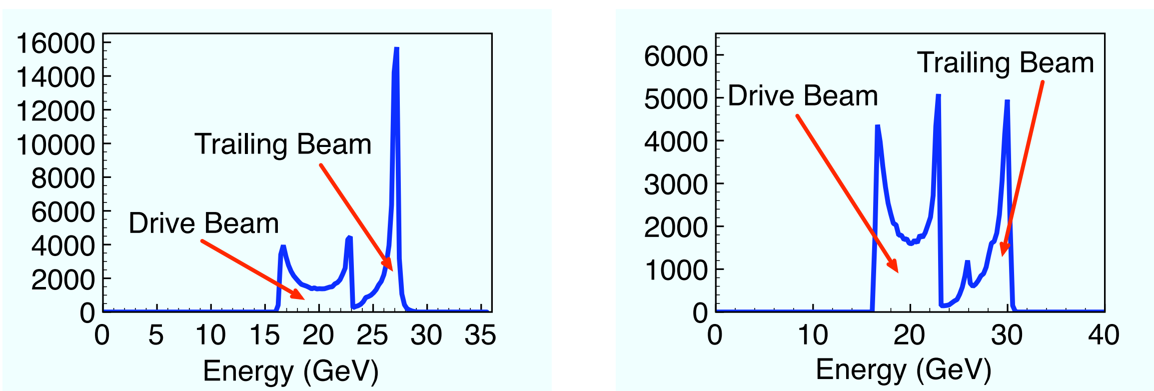


FIGURE 6. The energy spectrum of the trailing beam at $s = 95.6\ cm$. The numbers on the y axis are reference values without unit.

Case II

In this case the r.m.s. spot size of each electron beam is $\sigma_{r1} = \sigma_{r2} = 10\ \mu m$ (1 stands for the drive beam, 2 stands for the trailing beam); the r.m.s. beam length of each beam is $\sigma_{z1} = 34.1\ \mu m$, $\sigma_{z2} = 19.3\ \mu m$; the transverse r.m.s. normalized emittance of each beam is $\varepsilon_{x1,2} = \varepsilon_{y1,2} = 100\ mm \cdot mrad$; 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 130 μm; the initial energy of each beam is $E_{01} = E_{02} = 23\ GeV$.



(a) (b)

FIGURE 7. The energy spectrums of both two beams at (a) $s = 88.6\ cm$ with plasma density of $3.7 \times 10^{16}\ cm^{-3}$ and (b) $s = 76.2\ cm$ with plasma density of $5.0 \times 10^{16}\ cm^{-3}$. The numbers on the y axis are reference values without unit.

For this case the gas of Cs is used and there are two optimal plasma densities which are $3.7 \times 10^{16}\ cm^{-3}$ and $5.0 \times 10^{16}\ cm^{-3}$. In the case of lower initial plasma density almost the whole trailing beam is located inside the first bubble of the plasma wake while in the higher initial plasma density case the bubble of the plasma wake is not long enough to contain the whole trailing beam so that a part of the trailing beam is not sufficiently accelerated and even decelerated which finally results in the energy spread broadening. Nevertheless, both of two cases still have very small energy spreads which is less than 3% (FWHM value). But the energy gain (5 GeV for low plasma density and 7 GeV for high plasma density) is less than that in Case I. The final energy spectrum (Fig. 7) shows that the drive beam still has a lot of energy when the plasma wake terminates. That is because in the field ionized plasma the plasma wake cannot provide a sufficient focusing force on the head of drive beam. Thus with the same emittance the head of the drive beam will spread out faster in a field ionized plasma than in a preformed plasma. At the same time the ionization front will move backwards due to the weakening of the electric field around the spreading out beam head. Finally the plasma wake will terminate because the drive beam cannot ionize the neutral gas any more even when most of particles in the drive beam do not have adequate energy loss. These will lead to a short acceleration length and low efficiency.

If a preformed plasma is used instead of the field ionized plasma better results will be obtained under the same initial beams parameters. Fig. 8 shows the final energy spectrum of the trailing beam when using the same parameters but the preformed plasma. The acceleration lengths are much longer than those using field ionized plasma. Therefore the energy gain of the trailing beam (~ 20 GeV for low plasma density and ~ 30 GeV for high plasma density) has a prominent growth.

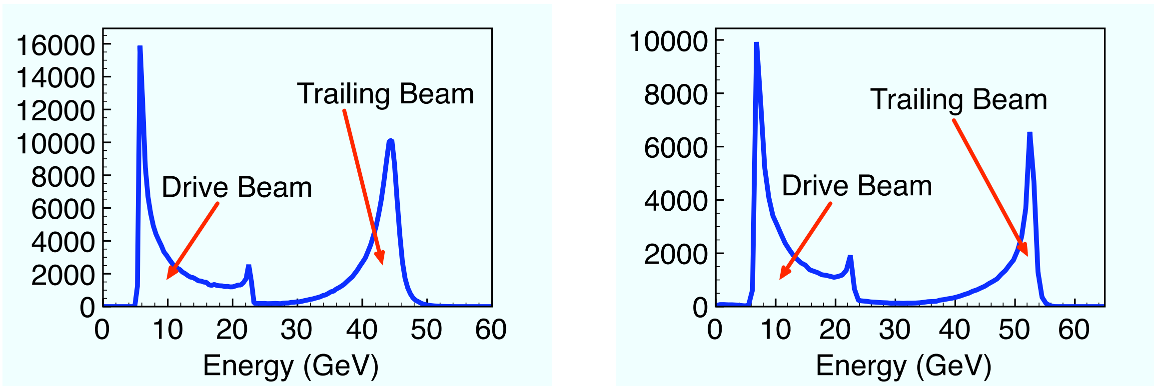


FIGURE 8. The energy spectrums of both two beams at (a) $s = 231.7$ cm with plasma density of 3.7×10^{16} cm^{-3} and (b) $s = 142.8$ cm with plasma density of 5.0×10^{16} cm^{-3} when using preformed plasma. The numbers on the y axis are reference values without unit.

SUMMARY

The two-bunch configuration needed to demonstrate a narrow energy spread at FACET will be crafted by manipulating the electron beam phase space in the dispersion plane. Because the peak current of the drive beam will be on the order of 10 kA, a lower ionization threshold gas will be needed to produce the required plasma density columns over meter scale length. This is accomplished by choosing Cs which has an ionization threshold of 3.9 eV as opposed to previously used Li which has an ionization threshold of 5.4 eV. PIC simulations done using the code QUICKPIC show that the drive beam is able to produce a meter long plasma with density of up to 5×10^{16} cm^{-3} before beam head erosion effects terminate the wake. The appropriately placed trailing beam can be accelerated by the wake to give energy gains on the order of 10 GeV with a narrow energy spread. The energy gain can be increased by propagating the two beams in a pre-ionized plasma.

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