WITNESS BUNCH ACCELERATION IN A MULTI-BUNCH PWFA*

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Abstract

We present initial experimental results showing the excitation of plasma wakefields by a train of two drive bunches. These wakefields are experienced by a trailing witness bunch that gains energy while retaining a finite energy spread. These well controlled plasma wakefield accelerator (PWFA) experiments are important to test the theory of the PWFA and serve as a testbed for techniques that will be used in high energy experiments.

INTRODUCTION

The beam-driven, plasma-based accelerator known as the plasma wakefield accelerator [1] has made remarkable progress over the last ten years. The acceleration of 42 GeV electrons by another 42 GeV was demonstrated recently [2]. The acceleration of positron bunches in plasmas was also demonstrated in the same experiments [3]. In these experiments, the plasma wake was driven by a single, ultra-relativistic particle bunch that covered all the phase of one accelerator period. This resulted in a large, continuous energy spread (on the order of 84 GeV in the case of [2]) from the maximum energy loss to the maximum energy gain. In addition, in the electron bunch case, the transformer ratio extracted from energy gain and loss measurements was around 1.6 [4]. The transformer ratio R is defined as the ratio between the maximum accelerating field to the maximum decelerating field within the drive bunch (or bunch train). The value of R is important because the maximum energy (per particle) that can be transferred from the particles losing energy to those gaining energy is RE_0, where E_0 is the energy of the incoming particles. For a single, symmetric bunch $R \leq 2$ [5]. It is clear that for the PWFA to be relevant to a future linear collider it must be able to accelerate a high quality particle bunch, and not only trailing particles as in past experiments. In addition, the length of such a plasma-based linear collider is determined (among other parameters and for a fixed energy) by the energy gain in each plasma section.

Conceptually, the acceleration of a bunch with a finite energy spread is trivial. Indeed, when the particles in the PWFA are ultra-relativistic, the particles are frozen in time with respect to each along their propagation direction. In other words, no dephasing occurs between the particles, or between the particles and the wakefield (in absence of parasitic effects such as head erosion [6]). Therefore, two bunches injected into the plasma with a fixed distance will remain at the fixed distance. The parameters of the first bunch, the drive bunch, can be chosen to drive large amplitude wakefields: high charge, length shorter and transverse size smaller than the relativistic plasma wavelength. The second bunch, the witness bunch, is also short and small, and carries less charge than the drive bunch. It can in theory be tailored for optimum beam loading to reach high extraction efficiency and narrow final energy spread [7]. Such a bunch train can either be produced by two independent injectors with optimum control of all the parameters, or be tailored out of a single incoming bunch. We recently demonstrated a simple masking technique that can be used to tailor in time an electron bunch train for PWFA or other applications [8]. This technique can not only be used to produce a drive/witness bunch train, but also a train of equidistant drive bunches followed by a witness bunch at the proper distance for acceleration in the wakefield. With this train, two important results can in principle be obtained. First, since there is now a witness bunch following one or multiple drive bunches, acceleration of a bunch with a finite energy spread can in principle be achieved. Second, by using a drive train with multiple bunches the energy gained by the accelerated bunch can be much larger ($>> 2$) than the energy of the drive bunch train [9]. Note that this effect was recently demonstrated in a dielectric loaded accelerator operating at a frequency much lower than typical PWFAs, where the bunch generation process is well relaxed [10].

EXPERIMENT

The experiment is performed at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). The incoming electron bunch is produced by an S-band linac. The bunch typically carries a charge of $\approx 500\ pC$ in $\approx 5.5\ ps$ at 59 MeV, has a low normalized emittance of $\approx 1\ mm-mrad$ and can be focused to less than 100 μm at the entrance of the plasma. The plasma is created in a H_2-puffed capillary discharge. The capillary is 2 cm-long and has a diameter of 1 mm. The backing gas pressure is $\approx 100\ Torr$. The applied voltage is 15 kV and results in a $\approx 100\ ns$ long, $\approx 700\ A$ current pulse. The plasma density is measured as a function of time with a resolution of $\approx 20\ ns$ through the Stark broadening of the H_α hydrogen line at $\approx 656\ nm$ [11]. The plasma density is measured in the $\approx 7\times10^{18} - \approx 10^{17}\ cm^{-3}$ range. We observe that after the discharge current pulse, the density decays exponentially with a time constant of $\approx 444\ ns$. We use this exponential extrapolation to obtain the density at lower values. Therefore, the plasma density is varied by changing the delay between the capillary discharge time

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and the bunch arrival time. The energy of the bunch after the capillary is measured by a calibrated magnetic spectrometer. After each event with a given plasma density, an event without plasma is recorded with the next available bunch train in order to both compare the two events and insure that the incoming train conditions remain similar.

We produce a train of equidistant drive bunches with period $\Delta z = 480\ \mu m$. The period is adjustable through the bunch correlated energy spread and the mask spacing. The number of bunches in the train is selected to be two (see Fig. 1(a)) by using a slit in conjunction with the mask [8]. By opening the slit a witness bunch is added that follows the drive train at a distance $\Delta z' = 746\ \mu m \cong \frac{3}{2}\Delta z$. The spacing between the bunches are measured using coherent transition radiation (CTR) interferometry. The various filtering processes (diffraction, transmission, detection) prevent the direct measurements of the individual bunch length. The slits in the mask that allow electrons through are $\frac{1}{2}\Delta z$-wide, suggesting that the length of the bunches is also $\frac{1}{2}\Delta z$ and that their profile is square. However, calculations suggest that the bunches have a more smooth time structure with charge in between the square pattern [8]. Each bunch carries about 30 pC, which means that each bunch density n_b is $\approx 1\times10^{13}\ cm^{-3}$. As will be seen later, this places the PWFA in the linear regime since $n_b << n_e$.

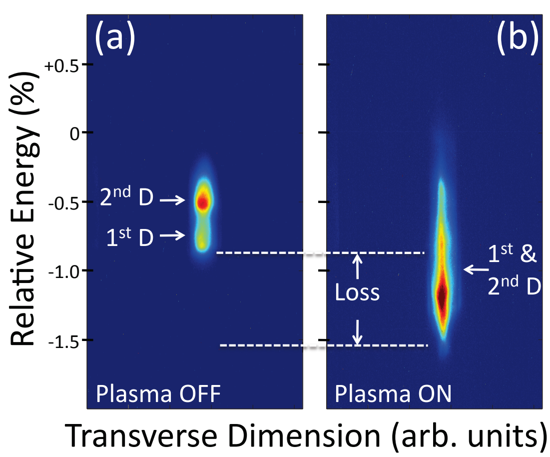

Figure 1: Images of the bunch train with two drive bunches (no witness bunch) dispersed in energy in the vertical direction, with (a) the plasma off, and (b) a plasma density of $\approx 8\times10^{15}\ cm^{-3}$.

The masking technique produces a train with a correlated energy chirp. The sign of the chirp is chosen such that the witness bunch enters the plasma with the largest energy. In this case, when the plasma density is tuned so that the relativistic plasma wavelength ($\lambda_{pe} = 2\pi c/\omega_{pe}$) is equal to the drive bunch train period (Δz), the train resonantly excites the wakefields and the drive bunches losing energy and the witness bunch gaining energy do not overlap on the energy spectrum image (see Fig. 2). Here $\omega_{pe} = \left(n_e e^2/\epsilon_0 m_e\right)^{1/2}$ is the electron plasma angular frequency in a plasma of density n_e. The spectrometer images without plasma (see Fig. 1(a) and 2(a)) suggest that the drive bunches overlap in energy. This is indeed not the case at the mask. However, when the train travels through the dipole magnet placed after the mask, which brings the dispersion back to zero, emission of coherent synchrotron radiation (CSR) occurs. As a result the energy spectrum of the bunch is modified; the bunches lose energy to CSR and their spectrum broadens [12], resulting in the image of the train of Fig. 1(a) and 2(a). It is important to note that this change in energy does not modify the bunch train time structure since the relative dephasing between particles with the energies of the plasma off spectra is small compared to their initial time difference ($|\Delta L| \cong \left(|\Delta\gamma|/\gamma^3\right)L \cong 1\ \mu m << \Delta z$ for $L \cong 10\ m$, $\gamma = 117$, and $\Delta\gamma = 0.2$.

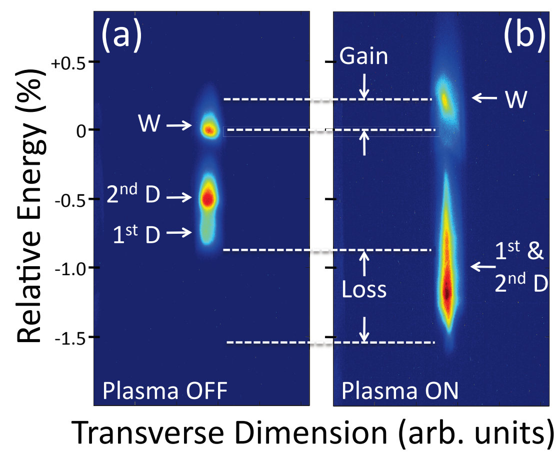

Figure 2: Images of the bunch train with two drive bunches and the witness bunch dispersed in energy in the vertical direction, with (a) the plasma off, and (b) a plasma density of $\approx 8\times10^{15}\ cm^{-3}$.

RESULTS

Figures 1(b) and 2(b) show energy spectra with a plasma density of $\approx 8\times10^{15}\ cm^{-3}$. Note that this density is slightly higher than the predicted value ($\approx 5\times10^{15}\ cm^{-3}$). However, it is at this value that the narrowest witness bunch energy spread is observed.

In the first case, the two drive bunches lose energy. The energy loss from the lowest energy of the plasma off case to that of the plasma on case is $\approx 0.7\%$ corresponding to $\approx 0.42\ MeV$ or 21 MeV/m. The real peak energy loss and gradients are likely larger than these values since the particles that lose energy at the largest rate are expected to be those in the last drive bunch. Few particles seem to gain energy. These are those of the last drive bunch located more than $\Delta z/4$ behind the center of that bunch, due to the limitations of the masking technique [11].

In the second case, with the witness bunch, the energy loss by the drive bunches is very similar, as expected. However, in this case the witness bunch gains energy and retains a finite energy spread. The average energy gain is $\approx 0.2\%$

corresponding to $\approx 0.12\ MeV$ or $6\ MeV/m$. Note that these numbers are small because of the linear character of the interaction.

These spectra were recorded more than 30 minutes apart, yet they show very similar both qualitatively and quantitatively.

The effect of the PWFA on the witness bunch can be obtained by subtracting the images with plasma on and with only two drive bunches (1(b)) from that with the witness bunch (2(b)). These spectra show that the energy spectrum of the witness bunch grows in proportion to its energy gain. This is due to the fact that in this case the witness bunch is not shorter than a half plasma wavelength.

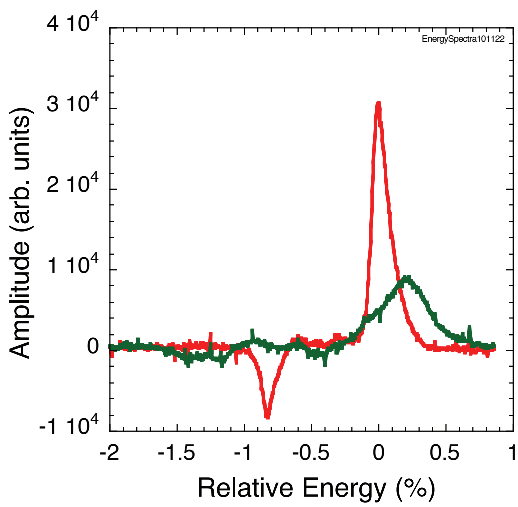

Figure 3: Energy spectra obtained by subtracting the plasma off images (1(a) and 2(a), plasma off, red line) from the plasma on images (1(b) and 2(b), plasma on, green line). The witness bunch charge distribution is centered around the zero relative energy. The negative peak near relative energy -0.8% on the plasma off case corresponds to a slightly different charge distribution between the two images (1(b) and 2(b)). Plasma density of $\approx 8 \times 10^{15}\ cm^{-3}$.

CONCLUSIONS

We show that we can control the bunch train and plasma parameters to observe either only the energy loss by a drive bunch train, or the energy loss by the drive train and the associated energy gain by a trailing witness bunch. Both the plasma and beam parameters are stable and reproducible enough so that these spectra can be compared in a meaningful way, even though they were acquired more than 30 minutes apart. All the bunches in the train have the same charge, leading to large amplitude wakefields. Demonstration of resonant excitation of plasma wakefields will be reported elsewhere. However, to reach a large transformer ratio the charge of the bunches must also be tailored. This is in principle possible with the masking technique used here. Therefore, these experiments represent the first step toward the resonant excitation of plasma wakefields and the generation of large transformer ratios. While the wakefield amplitudes measured here are small, these well controlled experiments are necessary to verify the theory of the PWFA and to test ideas that will be used in high energy experiments [6]. These experiments may also test the issues related to the possibility of a high transformer ratio PWFA in the nonlinear regime.

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