ACCELERATION OF AN ELECTRON BUNCH WITH NARROW ENERGY SPREAD IN A PWFA

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Abstract

We show preliminary results of a plasma wakefield accelerator (PWFA) experiment driven by a train of equidistant drive bunches followed by a witness bunch. Characteristics of the resonant excitation of wakefields are observed.

INTRODUCTION

The first plasma wakefield accelerator (PWFA) experiments was performed more than 20 years ago [1], and recently the energy of 42 GeV electrons was doubled over a plasma distance of only 85 cm, corresponding to an accelerating gradient of 50 GeV/m [2]. The first experiment was performed with a drive bunch (DB) followed by a witness bunch (WB) with a variable delay, while in the second experiment a single bunch drove and experienced the wakefield. We have developed a masking method to produce a train of bunches with sub-picosecond spacing and individual bunch length [3]. This method also allows for the tailoring of the bunch train for a particular application. In particular, the spacing, bunch length, number of bunches and charge (or current) in each bunch can be controlled through the mask and the beam parameters. We have shown that bunch trains suitable for PWFA experiments can be produced [4,5]. Such a train consists of a number of DBs separated by a distance Δz, and have DBs length smaller than $\Delta z/2$. The drive train is followed by a WB distant by $\Delta z'=1.5\Delta z$ from the last DB. The plasma density can then in principle be adjusted so that the wavelength of the relativistic plasma wave $\lambda_{pe}=2\pi c/\omega_{pe}$ ($\omega_{pe}=(n_e e^2/\varepsilon_0 m_e)^{1/2}$ is the plasma pulsation) is equal to the DB spacing Δz. In this case, and in the linear theory of the PWFA, the wakefield driven by each bunch adds in phase with that driven by the other ones. The DB train therefore resonantly drives the plasma wake to a large amplitude. The witness with spacing $\Delta z'$ is then in the accelerating phase of the wake and can gain large amounts of energy. When the WB length is much shorter than λ_{pe} it exits the plasma with a narrow energy spread. Large amplitude wakefields and production of accelerated bunches with a narrow energy spread are essential characteristics for a future plasma-based linear collider or PWFA-LC.

BUNCH TRAIN FORMATION

The bunch train formation is described in details in references 3 and 4 and is not repeated here. Suffice it to say that for the present experiments, coherent transition radiation (CTR) interferometry measurements indicate that the distance between the drive bunches is between 350 μm and 400 μm. The resonant excitation of wakefields ($\Delta z=\lambda_{pe}$) is expected at a density around $n_e=10^{16}$ cm^{-3}. Note that shorter spacing, requiring larger plasma density and therefore leading to larger wakefield amplitude can also be obtained [3]. The number of drive bunches is three. Each bunch contains approximately 30 pC. The bunches are focused to a transverse size of $\approx$100 μm, and their density is therefore in the 10^{13} cm^{-3} range. The wakefields are therefore driven in their linear regime [6,7] for the densities used here ($>10^{14}$ cm^{-3}).

PLASMA SOURCE

The plasma is produced in an H_2-puffed capillary discharge [8]. The capillary is 2 cm long, and its diameter is 1 mm. The backing pressure is between 40 and 100 Torr. The plasma density is measured using Stark broadening of the H_α line at 656 nm. The plasma light is collected by optical fibers directly imbedded into the capillary body. A voltage of 10 kV is applied to the capillary resulting in a half-cycle current pulse of $\approx$700 A with a width of $\approx$200 ns. The plasma light intensity and the plasma density peak slightly later than the discharge current. The measured plasma density reaches a few time 10^{18} cm^{-3}, and then decays exponentially with a time constant of around 400 ns. However, the plasma light becomes weak and the H_α line width becomes too narrow to be measured below $\approx 8\times10^{16}$ cm^{-3}. For lower plasma densities (and later time) the exponential decay constant is used to obtain $n_e(t)$. The plasma density is adjusted for the PWFA interaction by varying the delay between the capillary discharge trigger and the beam arrival time.

ENERGY MEASUREMENTS

The bunch energies are measured downstream from the plasma with a magnetic spectrometer. The electrons are dispersed in energy by a dipole magnet and imaged using four quadrupoles. The electrons then hit a phosphor screen and the light is imaged onto a 12-bit CCD camera. Energy spectra are obtained successively with and without plasma for two consecutive bunch trains, i.e., about 670 ms apart. It is assumed that the spectrum of the bunch without the plasma is representative of the spectrum of the beam entering the plasma so that PWFA interaction information can be extracted. The energy scale and linearity are obtained by varying the current in the spectrometer dipole and recording the beam position on the CCD image. A typical calibration is shown in Fig. 1

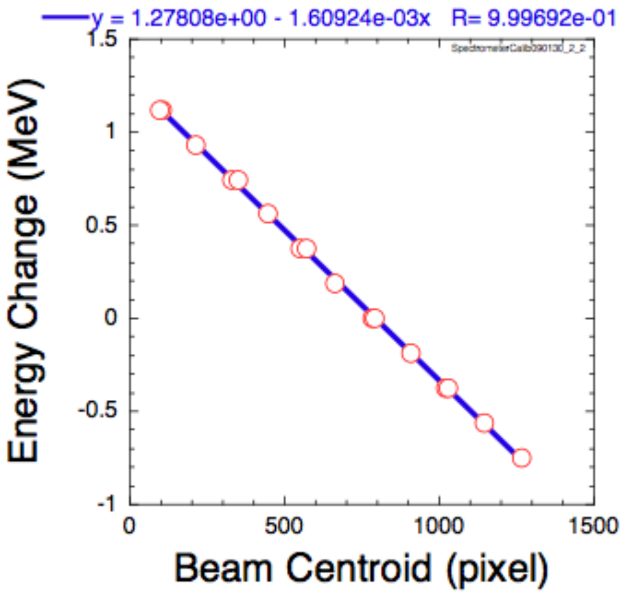

Figure 1: Typical calibration of the spectrometer obtained by scanning the current in the spectrometer dipole. The incoming average beam energy is ≈59 MeV.

PWFA INTERACTION

For the measurements presented here, the number of drive bunches is fixed at three. At resonance the DBs are all expected to lose energy while the WB gains energy. This results in an overlap in energy that can therefore mask the true origin of the particles that gain energy. It would be therefore advantageous to have the witness bunch energy to be the highest in the incoming train. The beam phase space can be rotated using an X-band harmonic cavity. Plans exist to install such a cavity at ATF.

RESONANT PWFA INTERACTION

Once the beam and mask parameters are chosen, the spacing between bunches are determined. In this case the bunches length is approximately half their spacing ($\sigma_z \approx \Delta z$). When the plasma density is such that $\Delta z \approx \lambda_{pe}$, the wakefields add in phase and a maximum energy loss by the DBS should be observed. At the same time, the WB should gain energy at the maximum rate. Figure 2 shows two consecutive beam energy spectra acquired with the plasma off, and with the plasma on and a density close to the resonant value. Large energy loss is clearly visible. The bunch structure is also lost because the energy change due to the resonant PWFA interaction is much larger than the initial energy separation between bunches.

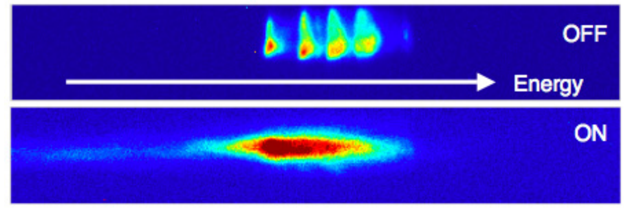

Figure 2: Top: beam energy spectrum obtained with plasma off, showing the three equidistant drive bunches (Δz or ΔE) at high energy and the WB at low energy with a spacing $\Delta z'=1.5\Delta z$ or $\Delta E'=\Delta z \Delta E$. Bottom: energy spectrum with a resonant plasma density ($\lambda_{pe}(n_e) \approx \Delta z$). Large energy loss is observed and possible energy gain is also visible on the enhanced image. Because of the large energy loss the bunch structure is washed out. The energy loss is of the order 1 MeV over 2 cm of plasma. The incoming average beam energy is ≈59 MeV.

LOW DENSITY PWFA INTERACTION

At low plasma density the plasma wavelength is much longer than the bunch length and than their spacing. One therefore expects that all bunches (DBs and WB) would lose energy with an amount of energy loss that increases along the bunch train. Figure 3 shows two spectra with plasma off and with low plasma density. As expected, all bunches lose energy, and the amount of energy loss increases from the first DB (at the highest incoming energy) to the last and WB (at the lowest incoming energy).

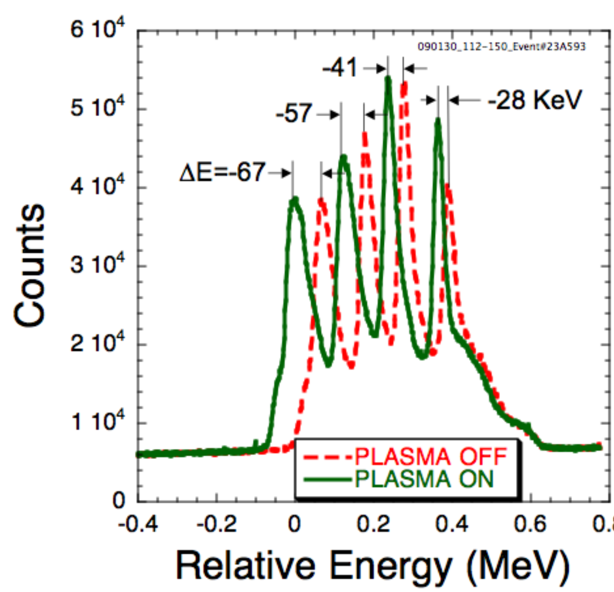

Figure 3: Energy spectra with the plasma off (dashed, red line) and with a low plasma density (green, solid line). The relative energy losses (ΔE) are indicated for each bunch. The incoming average beam energy is ≈59 MeV.

DISCUSSION

The preliminary PWFA interaction results presented show for the first time the resonant excitation of plasma wakefields by a train of drive bunches. Large energy loss is observed, accompanied with possible energy gain. At low density all bunches lose energy at a rate increasing from the front to the back of the train. This is exactly the behavior expected from linear PWFA theory. A number of other measurements would support the theory. For example, at low density larger wakefields, and therefore larger energy loss, are expected from the bunch without the train structure. At low density (λ_{pe}>>Δz) the envelope of the solid bunch or of the bunch train drives the wake. However, the bunch train carries about half the charge of the solid bunch. This can be easily verified by pulling the mask out of the beam path, and by recording the energy spectrum with and without plasma. On the contrary, at resonance ($\lambda_{pe}\approx\Delta z$), only the bunch train carries modulation at the plasma wavelength. Therefore, much larger (resonant) wakefields are expected with the mask than without, because the wakefield amplitude increases with plasma density, even though the bunch train carries about half the charge. The stability of the bunch spacing from event to event is also critical for these measurements. The bunch spacing is proportional to the bunch correlated energy spread or chirp $\Delta E/E_0$ [3,4]. Variations in the phase of the linac rf wave with respect to the arrival time of the bunch modifies $\Delta E/E_0$ and also Δz and $\Delta z'$. The CTR energy emitted by the bunch train is inversely proportional to the bunch length. Therefore, an online measurement of the CTR energy could be used to monitor the variations in Δz and $\Delta z'$. However, any foil placed in the path of the beam spoils its emittance. Preservation of the low emittance is necessary for good imaging of the spectrometer. Edge ration may be a possible means to monitor the bunch spacing while measuring the PWFA interaction. Another possibility would be to use electro-optic measurement of the bunch train electric field to monitor the exact bunch spacing on an event-to-event basis. The implementation of such a diagnostic at ATF is currently being investigated.

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