PLASMA WAKEFIELD ACCELERATORS USING MULTIPLE ELECTRON BUNCHES

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Abstract

For 70 years particle acceleration schemes have been based on the same technology which places particles onto rf electric fields inside metallic cavities. However, since the accelerating gradients cannot be increased arbitrarily due to limiting effects such as wall breakdown, in order to reach higher energies today's accelerators require km-long structures that have become very expensive to build, and therefore novel accelerating techniques are needed to push the energy frontier further. Plasmas do not suffer from those limitations since they are gases that are already broken down into electrons and ions. In addition, the collective behavior of the particles in plasmas allows for generated accelerating electric fields that are orders of magnitude larger than those available in conventional accelerators. As plasma acceleration technologies mature, one of the main future challenges is to monoenergetically accelerate a second trailing bunch by multiplying its energy in an efficient manner, so that it can potentially be used in a future particle collider. The work presented here analyzes the use of multiple electron bunches in order to enhance certain plasma acceleration schemes.

INTRODUCTION

In the plasma wakefield accelerator (PWFA), a relativistic electron beam is fed into a plasma and excites electron oscillations which support wakefields that can be orders of magnitude higher than those utilized in present conventional accelerator structures [1], thus providing a promising technology for the design of a future particle collider. One of the most crucial challenges is to accelerate a trailing bunch in a high-gradient wakefield driven by a preceding bunch, and demonstrate the energy transfer between the two bunches. This work was presented in detail in [2], and here we summarize these experimental results. In addition, we compare the two-bunch interaction to the effects observed when the drive bunch is blocked, and only the witness bunch decelerates in the plasma. The beam loading efficiency is also extracted.

In addition, of interest here are schemes where multiple electron bunches are used to drive the wakefield in the plasma, due to the possibility of multiplying the energy of an incoming trailing beam in a single PWFA stage. This can occur at a given plasma density if the number of particles in each bunch along with the bunch positions is tuned appropriately, as was theoretically explored previously in reference [3] in the linear regime. Here we further scrutinize some of these schemes by evaluating the tradeoffs between their field gradient and efficiency. We find that if the number of particles per bunch as well as the placement of the bunches can be tuned, the 1D driving efficiency can approach 85% or higher. The methods suggested here can be directly implemented using the recently demonstrated method to create desirable short bunches with sub-picosecond spacing [4].

WITNESS BUNCH ACCELERATION

In the experiment that was performed at the Accelerator Test Facility (ATF) of the Brookhaven National Laboratory, two subpicosecond electron bunches with ≈0.5 nC total charge, that where created during a break-up procedure in the chicane and dog-leg dipoles of the accelerator, were fed into a high-density plasma. By tuning the plasma density of a capillary discharge, the bunches could sample different phases of the plasma wave, and the transition from deceleration to acceleration could be controlled, demonstrating accelerating gradients of up to 150 MV/m for the witness bunch [2].

The left-hand side column in Figure 1 shows the experimental energy spectra recorded when the plasma density was set to 1×10^{16} cm^{-3}, therefore setting the plasma wavelength to $\lambda_p = 334\mu m$. The witness bunch in this case mainly gained ≈0.9 MeV in energy [Figure 1(a)]. The simulation illustrates that the observed peak in the energy spectrum around 59 MeV resulted from the superposition of both accelerated electrons from the witness bunch and decelerated electrons from the drive bunch (which only lost energy) [Figure 1(b-c)]. Some residual charge of the drive bunch was recorded around 60.5 MeV, probably reflecting the non-Gaussian initial energy distribution in the experiment.

In order to confirm that the witness bunch was indeed affected by the drive bunch, the higher-energy bunch was partially blocked by closing a slit located at the dispersion plane inside the dog-leg. Side-by-side comparison of the double-bunch and single-bunch interaction is shown in Figure 1. When the plasma density remained at 1×10^{16} cm^{-3}, the witness bunch had an average energy loss of ≈1 MeV [Figure 1(d)]. Since the witness bunch lost 1 MeV due to its own wake and gained 0.9 MeV in the presence of the drive bunch, we conclude that the net energy shift due to the drive bunch was 1.9 MeV, corresponding to a ≈315 MV/m unloaded accelerating wakefield amplitude driven by the first bunch. This value agrees with the numerical calculation and therefore the beam-loading efficiency is estimated approximately $\eta_b = 1 - 150^2/315^2 = 77\%$ for this interaction.

MULTIBUNCH DRIVING SCHEMES

In this section we examine three different multibunch driving schemes: One that maximizes the wakefield amplitude, one that maximizes the transformer ratio and one that maximizes the driving efficiency of the system.

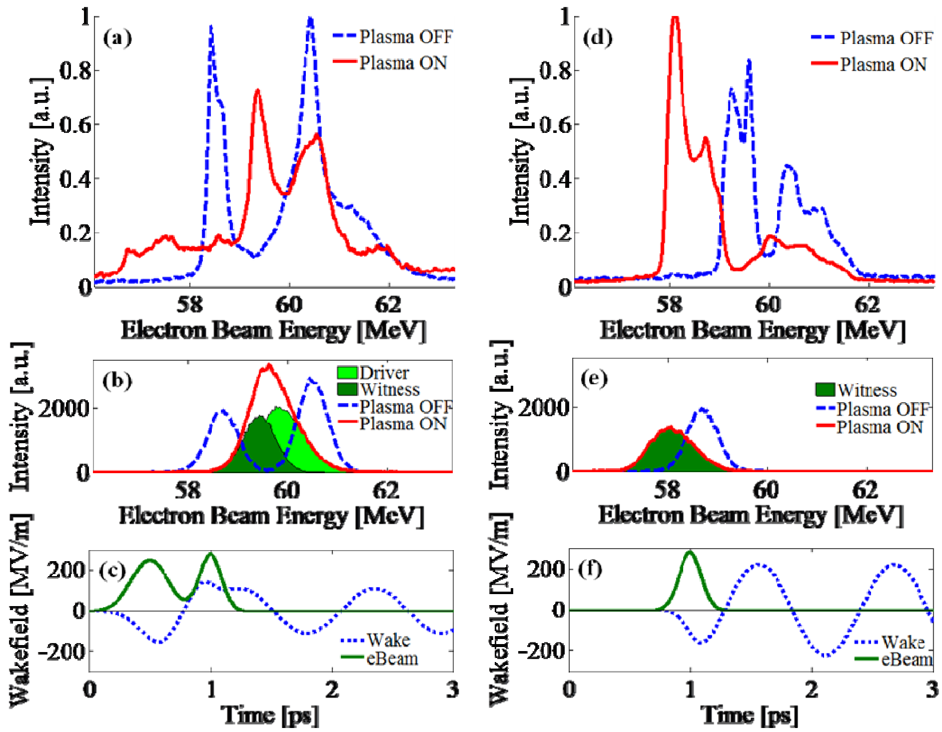

Figure 1: Experimental and simulated energy spectra after the 6 mm-long capillary discharge at 1×10^{16} cm^{-3} plasma density for the double-bunch beam (left column), and for the witness bunch only (right column): (a), (d): experimental energy profiles; (b), (e): simulated energy profiles; (c), (f): simulated plasma wakefield and position of the bunches inside the wake.

An example of a PWFA under a maximum wakefield setup is presented in Figure 2 (top panel) where the on-axis beam density and wakefield of a 5+1 bunch system (5x30 pC drive bunches and 1 witness bunch) is shown. In this example $k_p w = \pi$, and the bunches are separated by 250 µm at 1.8×10^{16} cm^{-3} plasma density ($\lambda_p = 250\,\mu m$). The reason why the transformer ratio and the efficiency are not enhanced is because the last bunch feels the almost full decelerating field, while the early bunches feel a smaller decelerating field. In this example the transformer ratio is $R = 1.1$ and the efficiency is only 13%. In order to increase the transformer ratio, each bunch needs to feel the exact same decelerating field.

Figure 2 (middle panel) illustrates an example where a ramped bunch train of 4 drive bunches is fed into the same plasma. The bunches are separated by 1.5 plasma wavelengths apart and have a total charge of 500 pC, while their charges scale as $31pC\times[1:3:5:7]$. The transformer ratio is 7.9 and the 1D driving efficiency of the system is 64%, equal to the efficiency of a single bunch.

Several things need to be pointed out in this scheme. Although the total wakefield increases linearly with the number of bunches, similar to the maximum wakefield scheme, this occurs here by supplying quadratically more charge (as opposed to linearly more). The total wakefield amplitude per total unit charge put into the system scales inversely proportional with the number of bunches in the ramped bunch train scheme described here. In addition, from an energy perspective, each particle is depositing into the plasma as much energy as the particles in the first bunch do, and the rest of its energy is being transferred to the following bunch in the train to prevent it from decelerating faster. In this way all the particles deposit their energy at the same rate (on average along the bunch), and the last bunch in the train releases this net energy into the plasma.

Note that the efficiency of the system is limited by the efficiency of a single bunch, which is achieved when the charge in each bunch is adjusted properly such that the wakefield under each bunch is the same. Even so, the variation of the wakefield inside each individual bunch sets an upper bound for the efficiency. This limit can be overcome (at the slight expense of the transformer ratio) if the positions and number of particles per bunch are fine-tuned, as we will show in the following.

Gaussian, square and other realistically-shaped bunches have maximum single bunch efficiencies around 60% - 70%, depending on their width relative to the plasma density. This is the maximum fraction of their energy that can be transferred to the plasma. Even if the transformer ratio is maximized, the efficiency is never larger than the single bunch efficiency for those setups.

Is it then possible to use multiple drive bunches to obtain a total system efficiency that is larger than the individual bunch efficiency, without a need to specially shape the bunches? The counter-intuitive answer is yes! This is achieved by placing the bunches at those phases of the wakefields such that the total wakefield under each bunch is most flat (thereby depositing energy more efficiently), even if the wakefield is not exactly the same between bunches. Notice in the middle panel of Figure 2 for example, there are particles inside each bunch that experience an almost zero wakefield (near the edges), while other particles near the center of the bunches experience the full decelerating field. This can be avoided if the bunches are placed earlier in the wakefield such that they sample both a portion of the decelerating phase of the wakefield and a portion of the accelerating phase as well, with the number of particles per bunch is adjusted accordingly. Such an example using 4 drive bunches is shown in the bottom panel of Figure 2.

In this scenario the bunches are equidistant and separated by 1.28 plasma wavelengths apart, and the total charge is 300 pC and scales as $17.5pC\times[1:2.70:5.20:8.22]$ in each bunch. Those optimal values are found numerically by running an optimization routine for the efficiency as a function of the bunch separation and the bunch charges. Further enhancements (few %) can be achieved if the restriction for equidistant bunches is lifted. The 1D driving efficiency of the plasma accelerator shown here is 84%, while the transformer ratio is 5.14 (instead of the theoretical maximum of 8 for 4 bunches).

It is interesting to observe the physics of this interaction. In contrast to the maximum transformer ratio scheme of the previous section, the wake under each bunch is not identical anymore. The first bunch experiences a weaker decelerating wakefield for example. However this is allowed here because from an energy perspective the first bunch is not as important as the later bunches that carry more energy and affect the efficiency more significantly. In essence, the first bunch jump-starts the wake such that the second bunch will sample a more flat portion of it. Shorter bunches increase the efficiency further as they sample narrower portions of the sinusoidal wakes.

SUMMARY

We have presented experimental results that demonstrate the high-gradient acceleration of a trailing witness bunch in a two-bunch PWFA experiment. Also, we show the tradeoffs between maximizing the wakefield amplitude, the transformer ratio, or the driving efficiency of the system. Considering that a future PWFA collider will require the maximum possible efficiency out of the system in order to achieve optimum operation, the schemes described here could have a great impact when operating in the linear regime.

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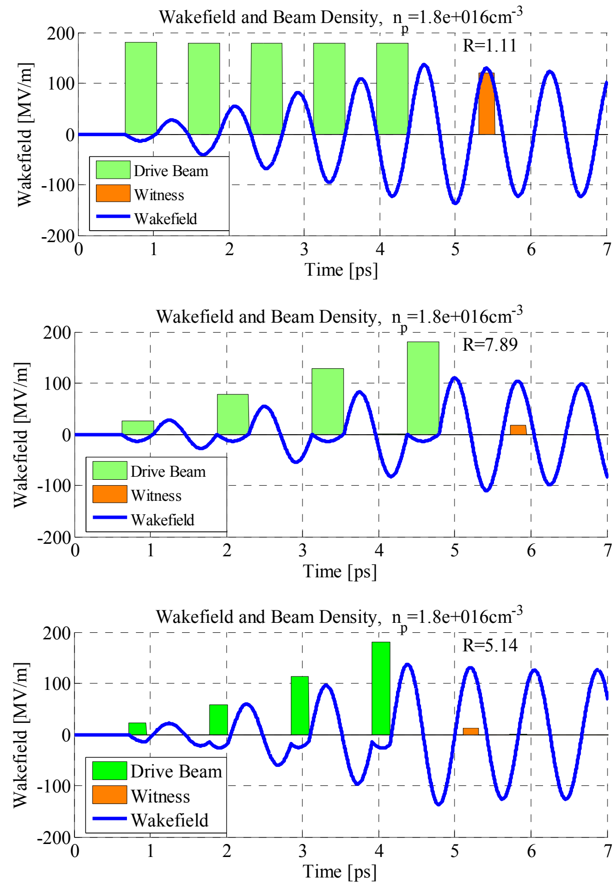

Figure 2: Examples of multibunch plasma accelerators with a witness bunch. Top panel: maximum wakefield setup. The bunches are identical with $k_p w = \pi$ and are separated by one plasma wavelength apart. The driving efficiency of this system is 13%. Middle Panel: maximum transformer ratio setup. The bunches are identical with $k_p w = \pi$ and are separated by 1.5 plasma wavelengths apart. The total charge is 500 pC and in each bunch is increased linearly. The driving efficiency of this system is 64%. Bottom panel: maximum efficiency setup. The bunches are identical with $k_p w = 0.56\pi$ and are separated by 1.28 plasma wavelengths apart. The charge in each bunch is $17.5pC\times[1:2.70:5.20:8.22]$. The driving efficiency of this system is 84%. In these examples $\lambda_p = 250\mu m$ and $\sigma_r = 100\mu m$.

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