A MULTIBUNCH PLASMA WAKEFIELD ACCELERATOR

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Abstract

We investigate a plasma wakefield acceleration scheme where a train of electron microbunches feeds into a high density plasma. When the microbunch train enters such a plasma that has a corresponding plasma wavelength equal to the microbunch separation distance, a strong wakefield is expected to be resonantly driven to an amplitude that is at least one order of magnitude higher than that using an unbunched beam. PIC simulations have been performed using the beamline parameters of the Brookhaven National Laboratory Accelerator Test Facility operating in the configuration of the STELLA inverse free electron laser (IFEL) experiment. A 65 MeV electron beam is modulated by a 10.6 μm CO_2 laser beam via an IFEL interaction. This produces a train of ~90 microbunches separated by the laser wavelength. In this paper, we present both a simple theoretical treatment and simulation results that demonstrate promising results for the multibunch technique as a plasma-based accelerator.

INTRODUCTION

In this paper, we investigate a multibunch plasma wakefield acceleration (PWFA) scheme. First we develop a fully relativistic, 1D nonlinear fluid theory that describes the evolution of the wakefield and the plasma wakes for an arbitrary excitation. Then we explain the experimental setup used to detect and measure acceleration effects at the Brookhaven National Laboratory Accelerator Test Facility (ATF), where the bunching of the electron beam (*e*-beam) is achieved when the electrons drift after being energy modulated by a CO_2 laser field interacting inside a magnetic undulator through the inverse free electron laser (IFEL) effect. We also present numerical results and PIC simulations of the expected energy exchange for the upcoming experiments.

THEORETICAL BACKGROUND

Various schemes of plasma-based wakefield accelerators have been theoretically studied and experimentally tested in the past. Beam-driven experiments have primarily focused in the single bunch regime, while laser-driven experiments have been using either single or multiple pulses (e.g., laser beat-wave accelerators).

A technique that has not been thoroughly investigated before utilizes a train of short-length microbunches to excite a strong wakefield in a plasma. When the plasma density is tuned such that the corresponding plasma wavelength matches the separation between the microbunches, then nonlinear electrostatic plasma waves are excited and a strong wakefield will develop. Its peak amplitude depends on the pulse length of the microbunches, the peak of the microbunch density as compared to the background density and the total charge of the multibunched *e*-beam.

1D Nonlinear Equations

When the *e*-beam spot size is much larger than the plasma wavelength, the wakefields can be described accurately with a 1D model [1]. Considering a fluid mechanics description, the equations that describe the interaction between the cold collisionless plasma and the relativistic *e*-beam are (CGS units):

$$\nabla \cdot \vec{E} = -4\pi e\left(n_e - n_i + n_b\right)$$

$$\frac{\partial \vec{p}}{\partial t} + \vec{v}\nabla \cdot \vec{p} = -e\vec{E} - e\frac{\vec{v}}{c}\times\vec{B}$$

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \left(n_e \vec{v}\right) = 0$$

Here n_e is the electron plasma density, n_i the ion plasma density, n_b the *e*-beam density profile, $\vec{v}$ and $\vec{p}$ the velocity and momentum of the electrons, and $\vec{E}$ and $\vec{B}$ the total electromagnetic fields in the plasma. Reducing the equations to 1D and considering the moving frame of the relativistic beam $\xi = z - ct$ ($v_{ph} \cong c$) we can derive a differential equation for the plasma electron density:

$$\frac{d^2 n_e}{d\xi^2} = \frac{3}{2n_e - n_0}\left(\frac{dn_e}{d\xi}\right)^2 - \left(2\frac{n_e}{n_0} - 1\right)^{3/2}\frac{\omega_p^2}{c^2}\left(n_e - n_0 + n_b\right) \cong$$

$$\cong -\frac{\omega_p^2}{c^2}\left(n_e - n_0 + n_b\right)$$

$$E_z = \frac{mc^2}{n_0 e}\frac{1}{\left(2\frac{n_e}{n_0} - 1\right)^{3/2}}\frac{dn_e}{d\xi}$$

The harmonic oscillator approximation is valid if the peak *e*-beam density is weak compared to the plasma density ($n_b << n_0$). If the excitation is a series of microbunches, then the buildup of the wakefield is due to an externally driven oscillator where the excitation frequency should be matched to the plasma frequency. If we assume a Gaussian distribution of the *e*-beam density for each microbunch, then the (sufficiently weak) peak *e*-beam amplitude and, therefore, the peak wakefield amplitude will be proportional to the charge of the *e*-beam and the length of the plasma, and inversely proportional to the longitudinal spot size (σ_z) of each microbunch.

SIMULATION RESULTS

Experimental Considerations

The choice of the simulation parameters is based on the experimental configuration of the ATF. The first half of the setup that generates the microbunched *e*-beam is similar to the STELLA IFEL experiment [2]. A 65 MeV, 350 pC, 1 mm long *e*-beam with a spot size of 25 μm is energy modulated via an IFEL interaction with a 10.6 μm CO_2 laser inside a magnetic undulator. When the energy modulation (proportional to the electric field of the laser beam) reaches ~1 % FWHM, then the *e*-beam is allowed to drift in free space for a distance of 254 cm. At the end of the drift space, a series of ~90 microbunches, each 1 μm long, are formed, which are then fed into a high density (10^{19} cm^{-3}) 3 mm long plasma created in a capillary discharge.

Wakefield Evolution and Energy Gain

We used the Particle-in-Cell code Osiris to simulate the beam-plasma interaction in 2D according to the above experimental parameters. Figure 1 shows the buildup of the wakefield as the microbunches enter the plasma. Both the theory and the simulation agree that a peak wakefield of about 0.02 or 60 MV/cm builds up after the *e*-beam propagates 1 mm inside the plasma. The tail of the *e*-beam (whose shape resembles the ATF *e*-beam) has only a few electrons and does not contribute much to the total wakefield.

Figure 2 shows the simulated phase space of the *e*-beam after the exit of the 3 mm long plasma in both the longitudinal and transverse directions. The maximum energy gain reaches 21 MeV, which is approximately equal to the peak wakefield amplitude multiplied by the plasma length. This implies that the maximally accelerated electrons originate from the tail of the beam.

Note that the electrons at the peaks of the distribution are the ones that are most decelerated in order to create the wakefield, and the particles that are actually accelerated are the background residual electrons between the microbunches. This indicates a tradeoff exists between the maximum wakefield that can be built and the total number of particles that will "see" this wave and accelerate. This is because increasing the amount of charge within each microbunch to enhance the wakefield formation would also reduce the number of background electrons.

CONCLUSIONS

Theoretical and simulated results indicate that resonantly exciting a high-density plasma with a multibunched *e*-beam can generate a strong wakefield and hence accelerate electrons to high energies. The upcoming experiments at the ATF are oriented towards the goal of verifying these concepts.

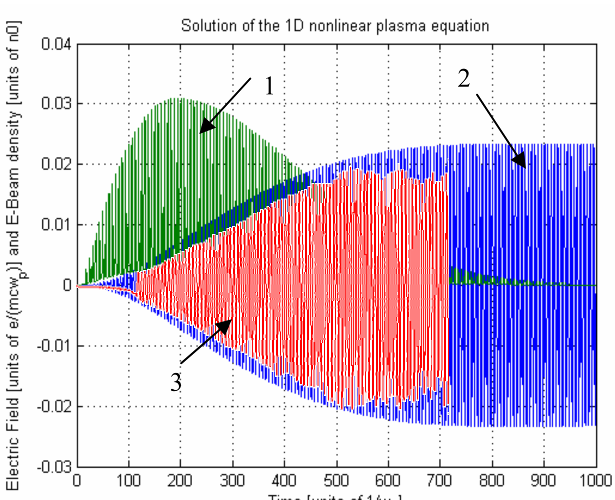

Figure 1: The electron beam density x100 (1), the theoretical wakefield (2) and simulated wakefield (3) after 1mm of propagation in the plasma.

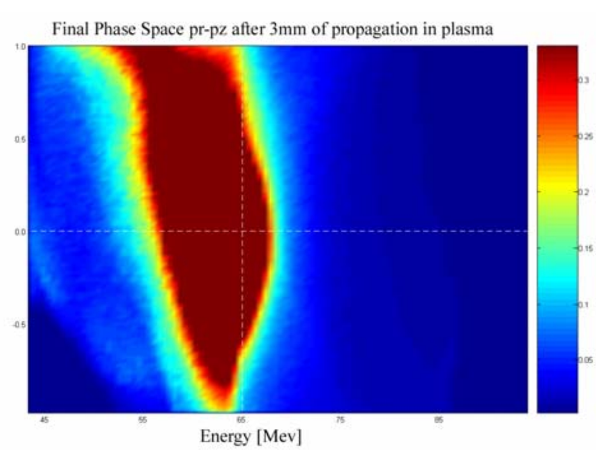

Figure 2: The final phase space of the beam after the exit of the 3mm long plasma. The density is in units of the plasma density, the horizontal axis in MeV and the vertical in units of mc.

REFERENCES

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[2] W. D. Kimura, *et al*., "Detailed Experimental Results for Laser Acceleration Staging", Phys. Rev. ST Accel. Beams **4**, 101301 (2001).