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DETERMINATION OF THE PHASE OF WAKEFIELD DRIVEN BY A SELF-MODULATED PROTON BUNCH IN PLASMA

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Abstract

The phase of wakefield driven by a self-modulated proton bunch depends on the type of seeding method and by the beam-plasma parameters [1]. Particularly when a preceding electron bunch generates seed wakefield, the proton bunch modulation is strongly affected by the seed bunch dynamics along with the plasma. Intrinsic wakefield dephasing from self-modulation of proton bunch can lead to complex evolution of the bunch and wakefield, making it difficult to design an experimental setup for witness beam injection. Using the particle-in-cell code FBPIC [2], we investigate in detail the trends of seed electron and driver proton bunch parameter sensitivity to the phase of wakefield in time in the proton bunch frame. We focus on the parameters affecting the phase of the wakefield through the beam's radial dynamics, such as beam emittance, radial size, energy, and beam to plasma density ratio. Parameter variations are compared to those in the case of the phase of wakefield driven by a non-evolving seed bunch.

INTRODUCTION

Plasma wakefield acceleration experiments at CERN (Advanced WAKEfield Experiment, AWAKE) rely on self-seeded modulation of a long proton bunch [3] to drive wakefields in plasma. In Run 1 experiments, the self-modulation of proton bunch was seeded by a sharp, relativistic ionization front in a Rubidium vapor [4]. The ionization front was placed near the middle of the proton bunch to seed the self-modulation process, i.e., to make it reproducible from event to event.

As a result, the proton bunch self-modulates with the period of plasma wavelength and can resonantly drive plasma wakefield to amplitude on the order of the nonrelativistic plasma wave breaking limit. In Run 2 experiments, two plasmas will be used, one to modulate the drive proton bunch and one to accelerate an externally injected electron bunch [5]. However, since in this configuration the second plasma is preionized, the front half of proton bunch left unmodulated by the relativistic ionization front seeding process could self-modulate with a random phase in the second plasma. This additional self-modulation could interfere with that from the first plasma and thus with the acceleration process. This undesirable situation can be avoided by modulating the entire proton bunch in the first plasma using a preceding electron bunch as a seed. When the proton bunch is modulated by a preceding electron bunch, the modulation process is decoupled from the seeding method. In principle, increasing the number of degrees of freedom makes it possible to study new aspects of self-modulation.

We first briefly describe the dynamics of the low-energy electron bunch in the overdense plasma ($n_s \ll n_0$, where n_s is the seed bunch and n_0 is the plasma density). In this overdense regime, there is no formal condition to match the bunch to the plasma focusing force and prevent its transverse evolution upon long propagation [6]. In addition, in the case studied here with a low energy bunch, energy loss comparable to the incoming energy leads to significant longitudinal evolution of the bunch. Also, it has been confirmed that the low energy of the bunch (< 20 MeV) significantly affects the evolution of the phase of the seed wakefields. We then study bunch parameters and bunch evolution along the plasma to determine whether wakefields driven by the electron bunch can be suitable to seed the self-modulation process.

For this study we used the particle-in-cell code FBPIC [2]. Simulations were performed using azimuthal mode number m = 0, which describes an axisymmetric system. The resolution of the simulation is $\Delta z = 0.02 k_{pe}^{-1}$, $\Delta r = 0.01 k_{pe}^{-1}$, and $\Delta t = \Delta z/c$ in the laboratory frame with the plasma wave number $k_{pe} = \sqrt{n_0 e^2/\epsilon_0 m_e c^2}$, where $n_0 = 2 \times 10^{14}\ \mathrm{cm^{-3}}$ is the plasma density, e the elementary charge, ϵ_0 the vacuum permittivity, m_e the electron mass, and c the speed of light in vacuum. Electron beam parameters for proton bunch modulation simulation are normalized emittance $\epsilon_{r,s} = 0.8$ mm-mrad, rms length $\sigma_{z,s} = 713\,\mu$m, radius $\sigma_{r,s} = 200\,\mu$m, charge Q_s = 50-200 pC (n_s/n_0 = 3.5-13.5$\times 10^{-3}$), and mean energy $\langle E\rangle_s$ = 5-20 MeV. Proton bunch parameters are normalized emittance $\epsilon_{r,p+} = 2$ mm-mrad, rms length $\sigma_{z,p+} = 6$ cm, radius $\sigma_{r,p+} = 200\,\mu$m, charge $Q_{p+} = 24$ nC for half Gaussian profile ($n_{p+}/n_0 = 4 \times 10^{-2}$), and energy 400 GeV.

LOW ENERGY ELECTRON BEAM DYNAMICS IN OVER-DENSE PLASMA

A short ($k_{pe}\sigma_z \sim 1$) and low energy Gaussian electron bunch in over-dense plasma generates wakefields that depend on ξ and r. For much of the bunch parameters used here, the transverse size of the bunch at the plasma entrance is large, such that the focusing force of the plasma wakefields is much stronger than that which would balance the bunch expansion due to its emittance. Therefore, the bunch strongly focuses over a short distance when entering the plasma, with the focusing increasing the amplitude of the wakefields and the emittance, as well as altering the transverse profile of the bunch. As a result, the transverse position and momentum

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distributions of beam at the minimum radial size are not Gaussian [6], they are close to Cauchy or Bennett distributions [7]. The bunch can then propagate over some distance with these new distribution and parameters.

Figure 1 shows the evolution of beam radial rms size (left) and transverse wakefield amplitude evaluated at r =200 µm (right) for different initial normalized emittances. The lowest emittance bunch (1 mm-mrad, blue line), the most mismatched one, quickly pinches (~10 cm) and generates the highest wakefield amplitude (~8-15 MV/m) that is sustained over a longer distance (~1.5 m) than higher emittance bunches, and thus less mismatched bunches, do. Only the highest emittance bunch (27 mm-mrad, red line) diverges immediately.

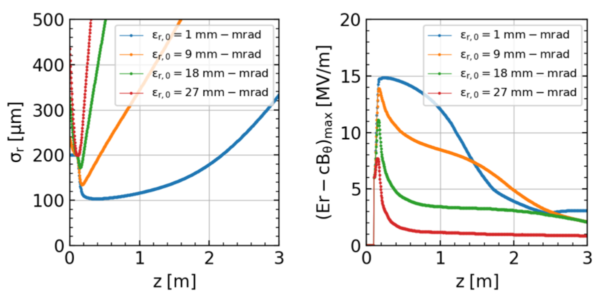

Figure 1: Evolution of the beam rms radius (left) and of the transverse wakefield amplitude evaluated at r = 200 µm (right) driven behind the seed electron beam with different initial transverse emittances. Plasma starts at z = 0.1 m. Plasma density: $n_0 = 2 \times 10^{14}$ cm^{-3}.

Figure 2 shows the evolution of bunch length (left) and transverse wakefield (right) for bunches with different initial rms lengths. We keep the initial bunch density constant, thus the bunch charge changes with its length. The change in the amplitude of the wakefields is due to significant dephasing of bunch particles due to energy loss leading to significant slow down from their initial velocities. Figure 2 shows that the longitudinal evolution of a low energy electron bunch along the plasma is minimum when it is such that $k_{pe}\sigma_z = \sqrt{2}$ (orange line). The bottom Fig. 2 show the corresponding evolution of the longitudinal wakefields behind the electron bunch as a function of distance in the plasma. These confirm that the evolution of the phase of the wakefields all along the plasma is minimum for the case of $k_{pe}\sigma_z = \sqrt{2}$.

Figure 3 shows the mean longitudinal position (left) and transverse wakefield amplitude (right) along the propagation distance z for bunches with different initial energies. Increasing the bunch initial energy corresponds to decreasing the effect of energy loss on the velocities of the particles. Therefore, even though the highest energy bunch (160 MeV, green line) drives large wakefield amplitudes over a longer distance than the lower energy ones, the effect of dephasisng is much less than in those cases.

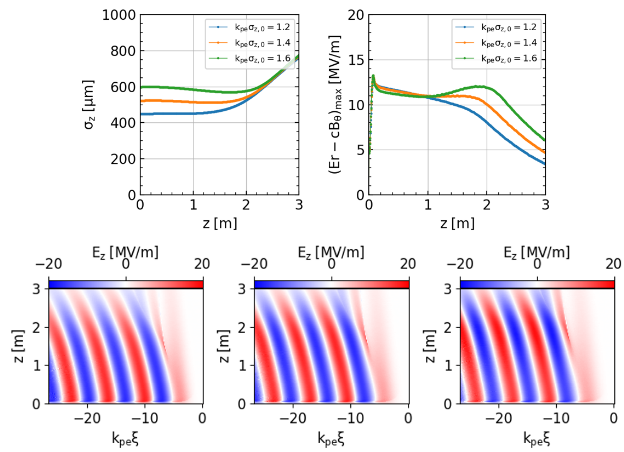

Figure 2: Top: evolution of the bunch mean position (left) and of the transverse wakefield amplitude evaluated at r = 200 µm (right) driven behind the seed electron beam with different initial lengths with $k_{pe} \approx 1.2$ (blue), 1.4 (orange), and 1.6 (green line). Bottom: corresponding evolution of longitudinal wakefields on axis for the three initial bunch lengths. The seed electron beam is initially centered at $k_{pe}\xi \approx$ -3.5, -4.2, and -4.8 in each case. Plasma starts at z = 0. Plasma density: $n_0 = 2 \times 10^{14}$ cm^{-3}.

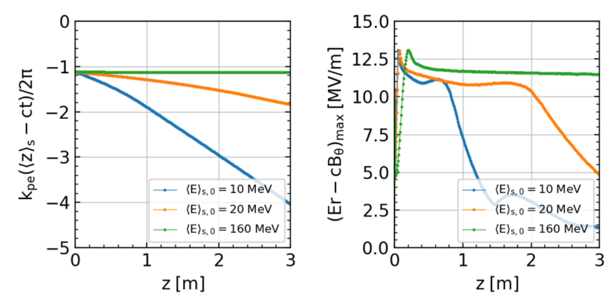

Figure 3: Initial energy dependence of seed electron bunch longitudinal centroid (left) and its wakefield amplitude (right) evaluated at r =200 µm. Plasma starts at z = 0. Plasma density: $n_0 = 2 \times 10^{14}$ cm^{-3}.

SSM PHASE EVOLUTION WITH BEAM-PLASMA PARAMETERS

In our study, the proton bunch modulation is seeded by transverse wakefields driven by a preceding, low energy (< 20 MeV) electron bunch in an overdense plasma. In this section, we show how sensitive the phase of proton bunch modulation is to the initial energy, charge and length of the seed bunch. The top Fig. 4 shows the general geometry. The seed electron bunch is placed $4\sigma_{z,p+}$ away from the proton bunch longitudinal center at $k_{pe}\xi \approx -638$. We plot on the figures below the longitudinal wakefields to illustrate their phase in a $-638 \lesssim k_{pe}\xi \lesssim -479$ (-24 cm $< \xi < -18$ cm) range, near the proton bunch peak and after 10 m of plasma. In each case, the plot consists of five simulations for five values of the parameter that is varied. The first such figures

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shows that, as the seed electron bunch energy is lowered, the phase of the wakefields shifts backwards more. This is caused by the stronger evolution of the lower energy bunch along the plasma, as shown above. Over the 5-20 MeV energy range, the phase difference is almost π. The amplitude of the wakefields also generally decreases with seed bunch energy. The "No seed" case, without electron bunch corresponds to the wakefields seeded in the simulation by the small proton bunch density step at its beginning.

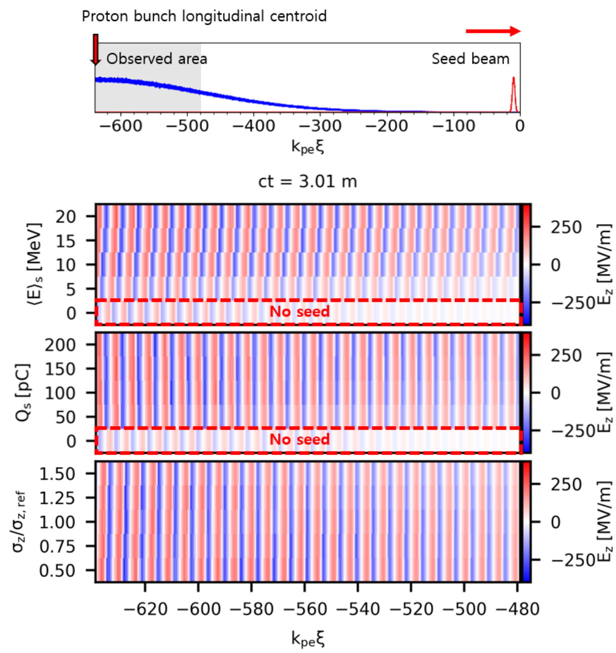

Figure 4: Phases of SSM at the longitudinal centroid of proton bunch by scanning seed beam initial energy (the second row), charge (the third row), and length (the fourth row). The seed electron beam is initially centered at $k_{pe}\xi \approx -4.7$. Plasma density: $n_0 = 2 \times 10^{14}$ cm^{-3}.

The middle figure shows that the phase of the wakefields is quite insensitive to the charge of the seed bunch (over this range). The "No seed" case shows that electron bunch seeding does occur though, since its phase is different from those with electron bunch.

The bottom figure shows that the phase is quite insensitive to the seed bunch length. Even though the length of seed bunch changes with propagation distance with different initial lengths, the evolution of the phase of the wakefields caused by the evolution of the bunch length is not significant. Here, we note that transition between the seeded self-modulation (SSM) and the self-modulation instability (SMI) was not observed in low energy (5 MeV) and charge (50 pC) seed beam cases, which could be different in the experiment because the noise levels are different (much lower in simulations).

CONCLUSION

The proton bunch modulation in plasma can be seeded by a preceding short electron bunch. In order to determine conditions of electron bunch seeding, we studied the dynamics of a low-energy seed electron bunch. A finite energy Gaussian electron beam cannot be radially matched to linear wakefields in over-dense plasma. The seed wakefield driven by the electron bunch sharply increase above amplitude previously reported to seed the self-modulation process (SSM) [1]. We found that with this low energy bunch (< 20 MeV), seed wakefields are driven over less than 3 m. The phase evolution of seed wakefields in the proton bunch frame is mostly affected by the initial seed beam energy. The phase of SSM observed near the peak of the proton bunch, where we expect wakefields to reach their maximum amplitude, are also mostly affected by the initial seed beam energy. The other parameter variations, that could reflect variations in experiments, such as charge and length, did not significantly contribute to variations in phase of the SSM.

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