# Numerical Study of Electron Bunch Seeded Proton Bunch Self-Modulation

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## Introduction

The Advanced WAKEfield Experiment (AWAKE) at CERN uses the self-modulation (SM) process of a long proton bunch for plasma-based electron acceleration [1]. In the first experimental run, Rubidium vapor was ionized by a laser pulse propagating near the longitudinal center of a long proton bunch. The sharp onset in plasma density in the middle of the proton bunch provides a seed for SM, causing the proton bunch to be split into many micro-bunches, leading to an increase in wakefield amplitude along the bunch and along the plasma. An alternative method to seed SM in future experiments is to use a short electron bunch [2]. This decouples the seed wakefield from the proton bunch parameters, allowing for more flexible control of the seeding process. In this work, we use Particle-In-Cell code FBPIC [3] to investigate the mechanism of electron bunch seeded proton bunch SM.

Simulations were performed using azimuthal mode number $m = 0$, which describes an axisymmetric system. The resolution of the simulation is $\Delta z = 0.02k_{pe}^{-1}$, $\Delta r = 0.01k_{pe}^{-1}$, and $\Delta t = \Delta z/c$ in the laboratory frame with the plasma wave number $k_{pe} = \sqrt{n_0 e^2/\varepsilon_0 m_e c^2}$, where $n_0 = 2\times10^{14}\mathrm{cm}^{-3}$ is the plasma density, e the elementary charge, $\varepsilon_0$ the vacuum permittivity, $m_e$ the electron mass, and c the speed of light in vacuum. The simulation window is moving at the speed of light. Electron bunch parameters for proton bunch SM simulations are: normalized emittance $\varepsilon_{n,s} = 0.7$ mm-mrad, rms length $\sigma_{z,s}/c = 2$ ps, radius $\sigma_{r,s} = 200\ \mu$m, charge $Q_s = 150$ pC ($n_s/n_0 = 1.25\times10^{-2}$, where $n_s$ is the electron bunch density), and mean energy $\langle E\rangle_s = 18$ MeV. Proton bunch parameters are: normalized emittance $\varepsilon_{n,p+} = 2$ mm-mrad, rms length $\sigma_{z,p+}/c = 200$ ps, radius $\sigma_{r,p+} = 200\ \mu$m, charge $Q_{p+} = 24$ nC for half Gaussian profile ($n_{p+}/n_0 = 4\times10^{-2}$, where $n_{p+}$ is the proton bunch density), and energy 400 GeV.

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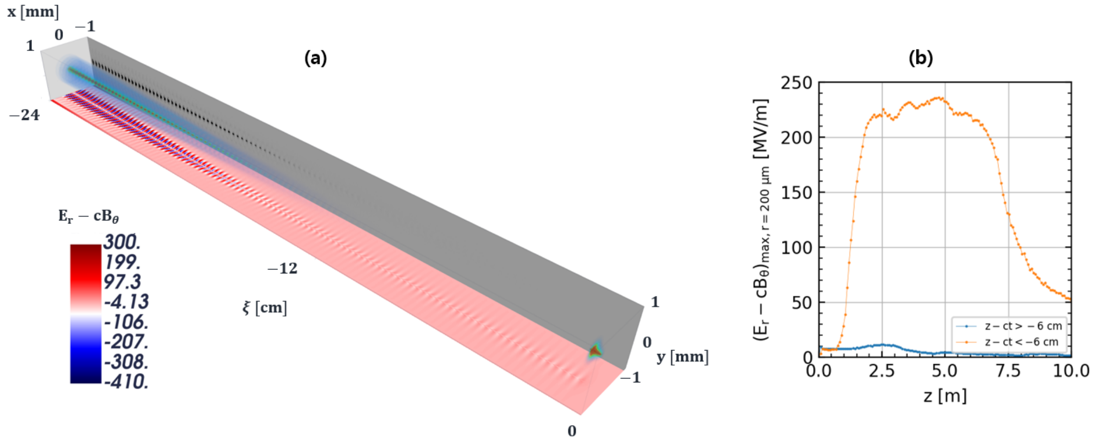


Figure 1: (a) 3D volumetric plot of a long proton bunch density modulated behind a short seed electron bunch in plasma at $z = 3$ m with the projection on $y\xi$ plane at $x = -1$ mm (color-gray) and the transverse wakefield $E_r - cB_\theta$ on $x\xi$ plane at $y = -1$ mm (color-red and blue) and (b) the transverse wakefield amplitude evaluated at $r = 200$ $\mu$m in seed electron bunch ($\xi = z - ct > -6$ cm) and modulated proton bunch ($\xi = z - ct < -6$ cm) dominant regions, respectively.

### Electron bunch seeded proton bunch modulation

In Fig. 1(a), an electron bunch precedes a long proton bunch in a pre-ionized, over-dense plasma. The low energy electron bunch rapidly evolves at the entrance of the plasma [4], generating transverse wakefield with amplitude $\sim 10$ MV/m [blue curve in Fig. 1(b)] within $\sim 3$ m of propagation distance in the plasma. This wakefield driven by the electron bunch seeds the SM of the proton bunch. When the proton bunch self-modulates, the amplitude of the wakefield along the proton bunch increases rapidly [orange curve in Fig. 1(b)]. The increase of SM wakefield amplitude continues until the nonlinear behavior of the SM process causes the phase shift of SM wakefield [5].

### Uniqueness of the phase of the proton bunch SM

Figure 2 shows the evolution of the longitudinal electric field $E_z$, on the bunch axis, along $\xi = z - ct$. Within $z < 2$ m, $E_z$ has approximately a single wavelength in the entire the simulation window in Fig. 2. After the propagation distance $z \sim 3$ m, the seed wakefield significantly decreases and becomes too small to contribute to the SM growth in Fig. 2(e). As SM grows, the phase of $E_z$ shifts backwards along $\xi$. Even though the amount of phase shift varies along $\xi$, we can see that the phase of SM wakefield near the center of the proton bunch originates from the initial seed wakefield [see Fig. 2(b)].

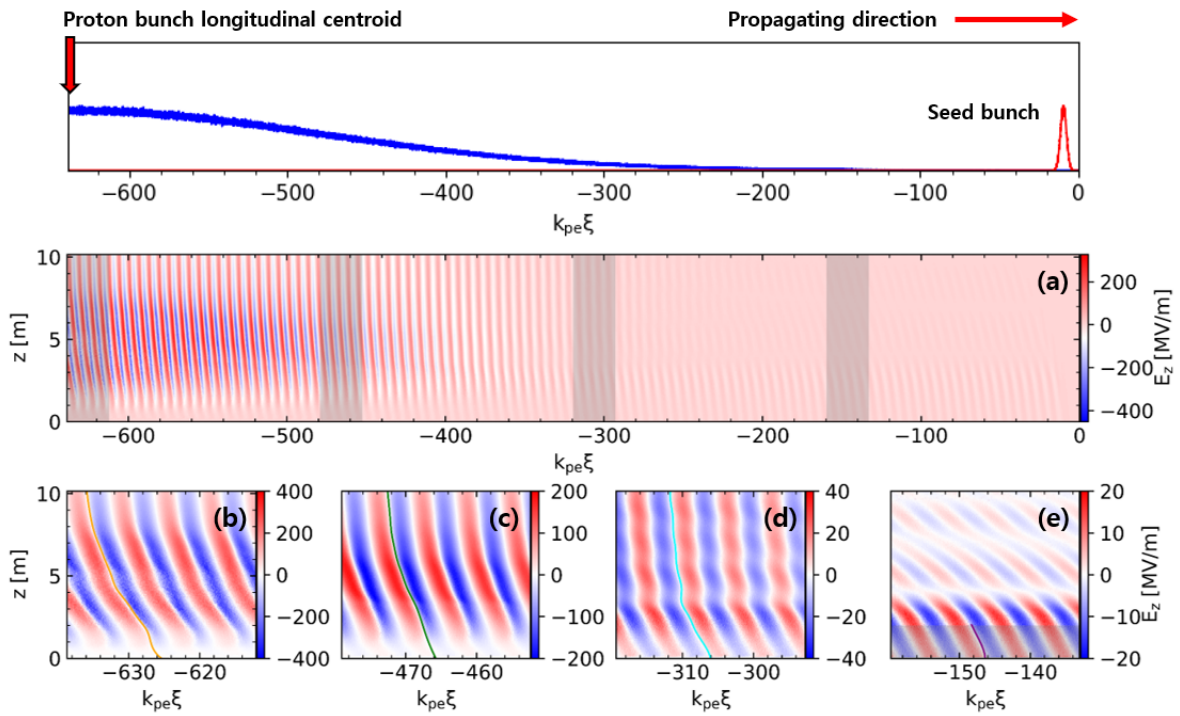


Figure 2: Evolution of longitudinal wakefield amplitude and phase during the growth of proton bunch modulation. (a) Waterfall plot of longitudinal wakefield in entire simulation box. [(b)-(e)] Waterfall plots of longitudinal wakefield in shaded regions of (a).

Figure 3(a) shows the evolution of the phase of the longitudinal electric field. As it was roughly shown in Figs. 2[(b)-(e)], the phase shifts are approximately equal within $\mathrm{z} = 2$ m. Since the effect of SM growth accumulate in $\xi = \mathrm{z} - \mathrm{ct}$ and ct, we can see that the phase shift of $\mathrm{E_z}$ is most significant at $\xi \sim -4\sigma_{\mathrm{z,p+}}$ in Fig. 3(a). Figure 3(b) shows the evolution of the phase velocity of the longitudinal electric field. In the seed wakefield dominant region (purple curve, $\xi \sim -\sigma_{\mathrm{z,p+}}$), the phase velocity is initially determined by the propagation velocity of the low energy seed bunch. While the SM is growing, the phase velocity is mostly slower than the speed of light, even after the seed wakefield contribution becomes negligible. At $\xi \sim -2\sigma_{\mathrm{z,p+}}$ and $\mathrm{z} > 3$ m where the seed and SM wakefield contributions are comparable and interfering with each other, the phase velocity is observed as partially superluminal.

## Conclusion

The proton bunch self-modulation in plasma can be seeded by a preceding short electron bunch. In our study, the low energy seed electron bunch is rapidly focused, generating linear plasma wakefield with amplitude above the threshold for phase-reproducible proton bunch self-modulation [6]. The phase of the proton bunch self-modulation is initially determined with a given single-frequency seed wakefield. As the self-modulation grows, the phase from the seed

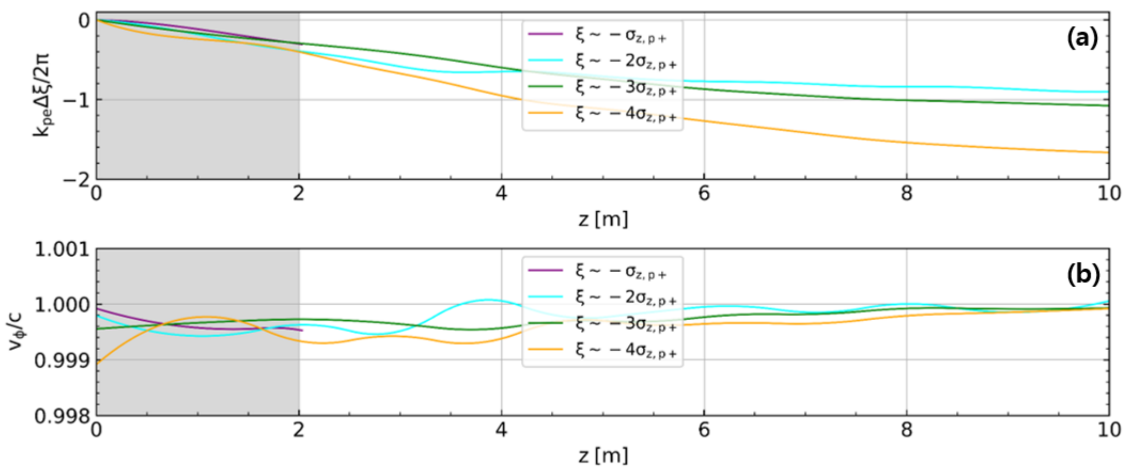


Figure 3: Evolution of longitudinal wakefield phase and phase velocity during the growth of proton bunch modulation. (a) Phase shift of longitudinal wakefield in shaded regions of Fig. 2(a). (b) Phase velocity of longitudinal wakefield in shaded regions of Fig. 2(a). The phase and phase velocity at $\xi \sim -\sigma_{z,p+}$ are well defined and shown only within $0 < z < 2$ m (shaded regions).

wakefield continuously shifts in $\xi$ and ct. We will further study the suitable conditions for seeding of the SM of the proton bunch, in close cooperation with the experimental program.

## References


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