Analysis of electron bunch energy spectra after meter scale over-dense plasma

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Introduction

The proton-driven plasma wakefield acceleration experiment AWAKE uses the self-modulation (SM) mechanism of a long proton bunch in an over-dense plasma to drive large amplitude wakefields [1]. In order to seed SM and control its phase, the use of a short and low energy electron bunch that precedes the long proton bunch in the plasma to seed self-modulation has been studied experimentally [2]. The seeding of SM depends on wakefields driven by the electron bunch. We study in numerical simulations the evolution of the seed electron bunch along the plasma. In particular, we produce energy spectra of the electron bunch that will be compared to the ones measured in the experiments. We use parameters close to the experimental ones. The electron bunch loses a significant fraction of its energy driving seed wakefields [3]. As a result, the electron bunch parameters strongly evolve along the plasma and electrons can be lost both along the plasma and along transport to the energy spectrometer. We find that a bunch with larger charge leads to more energy loss by bunch particles, which implies larger amplitude of the seed wakefields. The electron bunch energy spectrum after the 10 m plasma is estimated using particle-in-cell simulations [4]. We want to use simulation results to reverse-engineer the process in laboratory and to verify our understanding of electron beam seeding experiments by comparing them with experimental results.

Transverse dynamics of the electron bunch in over-dense plasma

The resolution of axisymmetric simulations is $\Delta z = 0.02k_{pe}^{-1}$, $\Delta r = 0.005k_{pe}^{-1}$, and $\Delta t = \Delta z/c$ in the laboratory frame with the plasma wave number $k_{pe} = \sqrt{n_{pe}e^2/\varepsilon_0 m_e c^2}$, $n_{pe} = 1\times10^{14}\,\mathrm{cm}^{-3}$ 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. The simulation window with sizes $R_w = 2/k_{pe}$ and $L_w = 100/k_{pe}$ is moving at c.

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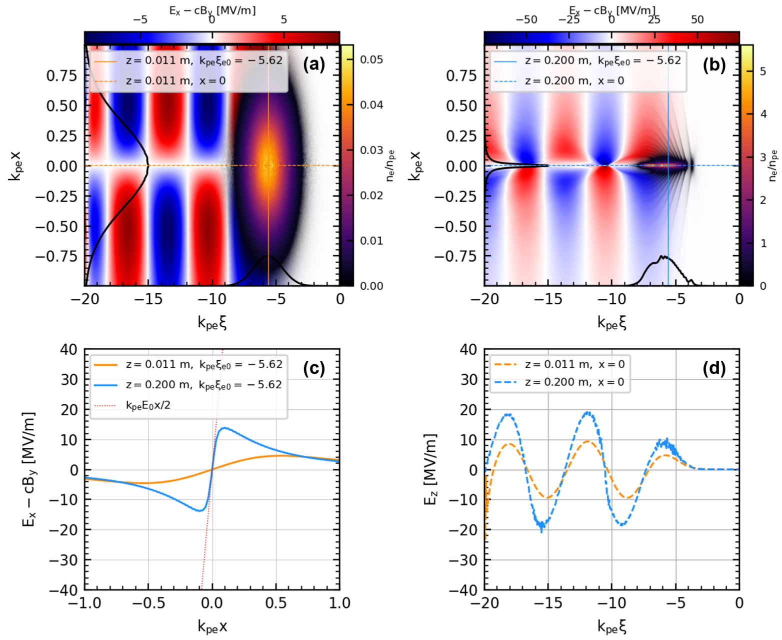

Figure 1: Electron bunch density and wakefields before ($z \approx 1$ cm) and after ($z \approx 20$ cm) beam evolution near the plasma entrance. Side colorbars Figs (a) and (b): electron bunch density normalized to n_{pe}. Top colorbars Figs (a) and (b): transverse plasma wakefields driven by the electron bunch. Black curves Figs (a) and (b): projected beam number densities, arbitrary unit. (c) Transverse and (d) longitudinal wakefields (orange curve) before and (blue curve) after beam evolution. Transverse/longitudinal wakefields curves taken through bunch center.

Figure 1 shows electron bunch profiles and the wakefields they drive before and after the strong beam evolution, near the entrance of the over-dense plasma. The initial rms bunch length is $\sigma_{\xi,e0} \approx 1.13/k_{pe}$ ($\sigma_{\xi,e0}/c = 2$ ps) which is close to the optimum bunch length $\sigma_{\xi,e0} = \sqrt{2}/k_{pe}$ for plasma wakefields generation. Other initial electron bunch parameters are Q_e =250 pC, ($n_{e0}/n_{pe} \approx 4.2\times10^{-2} \ll 1$), rms radius $\sigma_{r,e0} = 200\ \mu$m, normalized emittance $\varepsilon_N = 1.34$ mm-mrad, and mean energy $\langle E \rangle_{e0} = 18$ MeV. As the bunch is interacting with the plasma, it is focused and the bunch and plasma density perturbations increase. After evolution, the transverse wakefields near the axis is close to $k_{pe}E_0x/2$ [red dotted line in Fig. 1(c)] which typical of the blowout regime [7]. Most bunch particles reside within the linearly increasing wakefields region. Here, $E_0 = k_{pe}m_ec^2/e$ is the non-relativistic wave-breaking field in cold plasma.

Electron bunch over 10 m plasma and its energy spectrum

In Figs. 2[(a)-(d)], we show how the electron bunch parameters and the radial wakefields it generates along the plasma for Q_e = 150, 250, and 800 pC. The initial parameters are: rms radii $\sigma_{r,e0} = 173,\ 200,\ 500\ \mu$m, rms lengths $\sigma_{\xi,e0}/c = 2$ ps, normalized emittances $\varepsilon_N = 1$, 1.34, 3 mm-mrad, respectively. Figure 2(a) shows that with all charges, the bunch rms radial size is drastically reduced near the plasma entrance. When the energy loss of bunch particle is negligible while the bunch evolves transversely, the bunch radial size reaches an equilibrium size with $\sigma_{r,eq} \sim \sigma_{r,e0}/2$ [5]. However, with our parameters, energy loss during that evolution is significant because of the low energy of the particles (18 MeV) and the amplitude of the longitudinal wakefields (>10 MV/m, see Fig. 2(c)). After the abrupt focusing over less than a meter, the bunch rms size quickly increases [Fig. 2(a), solid curves]. This means that a fraction of the particles escape from the wakefields. In order to track and characterize the behavior of bunch particles whose energy spectra we measure in experiments (i.e., reaching the energy spectrometer screen), we select particles that clear an aperture of 10 mm diameter placed at the plasma exit and that reach at the screen ∼6.7 m downstream from the plasma exit, and recalculate the rms size of their distribution (dashed curves in Figs. 2(a) and (b)). The rms radius of these distributions only slowly increases when compared with those with all particles. Since the energy loss of bunch particles leads to dephasing between them, the rms length of both populations constantly increases after ∼1 m for Q_e=800 pC, ∼2 m for Q_e=150 and 250 pC. Figure 2(c), shows that the bunch maximum density also strongly evolves within the first few meters of plasma, evolution directly related to that of the bunch dimensions ($n_{pe} \propto 1/\sigma_{r,e}^2\sigma_{\xi,e}$). Figure 2(d) shows the evolution of the averaged radial wakefields behind the seed bunch, weighted over the radius of the Gaussian proton bunch profile with $\sigma_{r,p} = 200\ \mu$m. We use this calculation to characterize the seeding of the SM of the proton bunch [6].

The integrated effect of the wakefields, including their strong transverse and longitudinal evolution of the bunch along the 10 m-long plasma, is reflected in the energy spectrum of the electron bunch. Energy spectra before and after electrons pass the aperture at the plasma exit are shown in Figs. 2(e) and (f). Since the bunch duration was not measured in the experiment, we vary the bunch rms duration from 1 to 10 ps. The high energy (∼18 MeV) particles that diverge early along propagation and do not generate wakefields are blocked by the 10 mm diameter aperture at the plasma exit. The figures show that the minimum energy reached by particles generally increases with shorter bunch durations (for all charges) and generally increases with bunch charge (for all durations).

Conclusions

The self-modulation of a proton bunch in plasma can be seeded by wakefields driven by a preceding short electron bunch. The low-energy seed electron bunch is rapidly focused and the amplitude of the wakefields it drives dramatically increases at the beginning of the plasma. Because the energy loss along the plasma is comparable to the initial energy of the bunch particles,

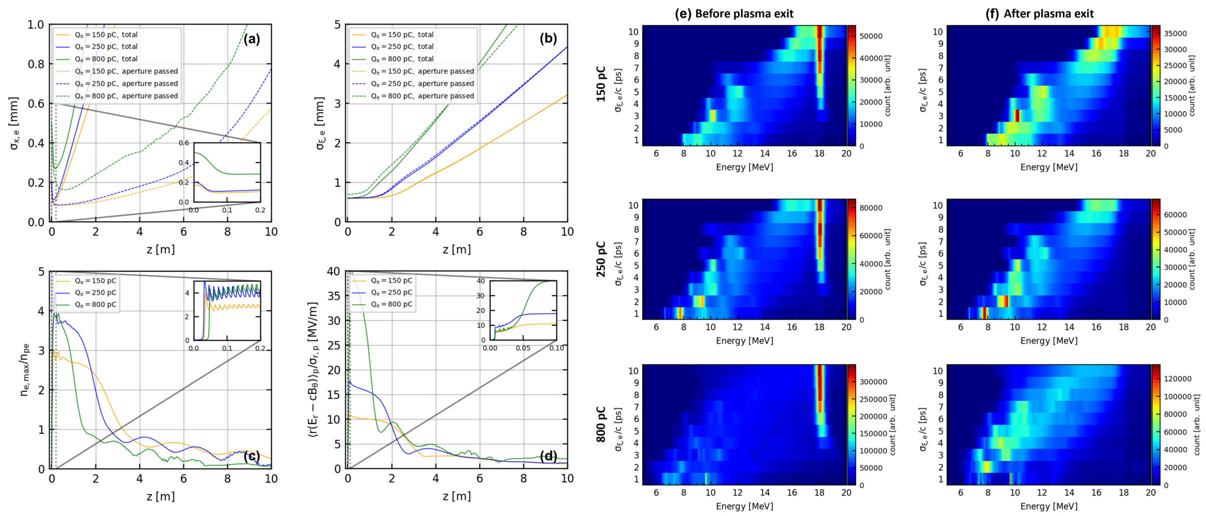

Figure 2: (a)-(d): Evolution of electron bunch parameters and of wakefields it drives over 10 m of plasma for initial bunch charges $Q_e = 150$, 250, and 800 pC, initial rms bunch duration $\sigma_{\xi,e0}/c = 2$ ps. (a) Bunch rms radius of (solid curves) whole bunch, and (dashed curves) distribution clearing the aperture at the end of the plasma. (b) Same as (a) for bunch rms length. (c) Bunch maximum density. (e) Average transverse wakefields amplitude behind the electron bunch weighted over the radius of the Gaussian radial profile of the $\sigma_{r,p} = 200\ \mu$m proton bunch (no proton bunch in the simulations). Electron bunch energy spectra (e) before and (f) after the aperture at the end of the plasma, for bunches with various rms durations and three charges.

some electrons transversely leave the wakefields early along the plasma and some dephase and re-absorb energy from wakefields. As a result, the electron bunch drives seed wakefields with large amplitude (>10 MV/m in this case) over a few meters of the plasma. Simulated energy spectra show that the maximum energy loss by electrons increases with larger bunch charge, as expected. We also generate energy spectra for electron bunches with various initial durations. We plan to compare these spectra to those obtained in experiments to attempts to determine the amplitude of seed wakefields that were sufficient to seed the SM of the 400 GeV proton bunch that was demonstrated in experiments [2].

References

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