STUDY OF THE ELECTRON SEEDED PROTON 
SELF-MODULATION USING FBPIC

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Abstract

In order to make a full use of the whole proton bunch to drive large amplitude plasma wakefields and suppress the uncontrolled growth of any possible instabilities at the head of the proton bunch, the AWAKE Run 2 experiment plans to use an electron bunch to seed the formation of the proton bunch self-modulation. Additionally, a density step in the plasma channel will be used to freeze the self-modulation process to keep the wakefield amplitude. In this work, numerical simulations performed with FBPIC are used to investigate the electron seeded proton self-modulation and the effect of the plasma density step as well.

INTRODUCTION

The particle beam driven plasma wakefield acceleration (PWFA) has shown the ability to generate ultra-high accelerating gradients (>50 GV/m), which far exceeds those in radio-frequency accelerators [1]. Since effectively exciting plasma waves requires a driver beam with a length on the order of the plasma wavelength \( \lambda_{pe} \), the Advanced Wakefield Experiment (AWAKE) at CERN exploited the seeded self-modulation (SSM) technique to transform a long proton bunch into a train of short bunches, then accelerated an externally injected electron bunch to 2 GeV in the proton driven wakefields [2].

The seeding field of the self-modulation in AWAKE Run 1 is provided by the laser-formed relativistic ionization front (RIF) located in the middle of the proton bunch, which can only seed the controlled self-modulation of protons after the ionization front [3]. Uncontrollable self-modulation instability (SMI) may grow in the front part when the proton bunch with an unmodulated head propagates further in a preformed plasma channel. This effect can be destructive for the wakefield stability and hence the reproducibility of the electron acceleration. Thus in AWAKE Run 2, the electron bunch seeding method, which could lead to self-modulation of the entire bunch, is adopted [3].

Another problem that could prevent the wakefield from growing in the SSM process is the dephasing of plasma wave with respect to (w.r.t) the proton micro bunch [4]. The large phase shift will force a large fraction of those micro bunches into the defocusing phase, which then leads to dramatic proton loss and hence wake amplitude decrease after reaching the peak. By using a plasma profile with a ramped-up density step [5], the SSM process can be slowed down, and the large accelerating gradient can be maintained over longer distance.

The SSM study in previous publications [5, 6] is mainly performed by the quasi-static particle-in-cell (PIC) codes, e.g. LCODE [7], which assumes the beam envelope evolves slowly as it propagates in plasmas. In this proceeding, we use FBPIC [8], a spectral, quasi-3D full PIC code without physical approximations, to take a further look at the electron seeded self-modulation and cross-check it with other results.

CONFIGURATIONS

Typical proton beam and plasma parameters of the AWAKE experiment can be found in [6]. Due to the limitation of computing resource, the RMS length of the proton beam and the number of particles per bunch are scaled down by ten times to \( \sigma_{zp} = 7 \) mm and \( N_p = 3 \times 10^{10} \), respectively. The proton beam has a nominal energy of \( E_{p0} = 400 \) GeV, a relative energy spread of \( \Delta E_{p0}/E_{p0} = 0.035\% \) and a RMS transverse radius of \( \sigma_{rp} = 0.2 \) mm. The baseline parameters of preceding electron beam that is used to drive the seeding wakefields (referred as seed beam hereafter) are beam energy \( E_{e0} = 18 \) MeV, relative energy spread \( \Delta E_{e0}/E_{e0} = 0.1\% \), RMS length \( \sigma_{ze} = 0.3 \) mm, RMS transverse radius \( \sigma_{re} = 0.2 \) mm and charge \( Q_e = 0.5 \) nC. One should notice that the seed beam parameters chosen here can be a bit of different with that in [6], especially the RMS seed beam length \( \sigma_{ze} \). It was chosen to let the whole seed beam reside in the decelerating phase so as to deplete the seed beam and remove it from the plasma much faster [9]. The proton beam and seed beam are represented by \( 10^6 \) and \( 10^5 \) macro-particles in the simulation box, respectively.

The simulation window moves with a speed close to that of the light (\( c \)) in the beam propagation direction. To ensure transverse physical effects are correctly simulated [10], the radial size \( r_w \) of the longitudinally-axisymmetric simulation box is set as two times \( r_{pe} \), i.e. \( r_w = 3.2 \) mm, as shown in Fig. 1. A transverse grid cell size of \( \Delta r = 4 \) mm, and of \( \Delta z = 8 \mu m \) for the longitudinal grid cells is used to resolve the particle motion and wakefields. The number of plasma particles per cell is set to be 2 along the coordinate \( z \) and 6 along the coordinate \( r \). \( \xi = z - ct \) represents the longitudinal

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coordinate in the simulation window, with \( s = ct \) being the co-moving distance w.r.t the lab frame.

Figure 1: Plasma electron density distribution at \( s = 0.4 \) m.

The simulation study is started with the longitudinally-uniform plasma density profile at first. Figure 2 shows the simulated density of the proton beam (black shade) and the distribution of the electron macro-particles (red dots) of the uniform plasma profile case. While the upper half of Fig. 2 corresponds to the particle distribution at the beginning of the simulation, the lower half represents it at a propagation distance of \( s = 9.2 \) m. Longitudinal plasma profile: Uniform.

Figure 2: Simulation-obtained proton density (black) and electron macroparticle (red) distribution plot at the beginning (up-half, \( s = 0 \) m) and after self-modulation (down-half, \( s = 9.2 \) m). Longitudinal plasma profile: Uniform.

RESULTS

Figure 3: The maximum accelerating gradient for distinct plasma density profiles. The vertical dashed line marks \( s = 0.8 \) m. The insert at the upper-right corner shows the schematic layout of the plasma density step.

Figure 4 shows the evolution map of the longitudinal wakefield \( E_z \) that is measured on the \( z \)-axis along the beam and w.r.t the beam propagation distance \( s \). One obvious feature in Fig. 4 is that the seed wakefield amplitude is soon damped after the seed beam is depleted while the wakefield driven by proton micro-bunches starts to grow and dominate in the back-half of the simulation window (\( \xi < -30 \) mm). However, after reaching the peak at around \( s = 2 \) m, the proton-driven wakefield gets gradually weaker. Along with the change of field amplitude is the phase shift of the zero-field points, which are marked by black lines in Fig. 4. They have been significantly moving towards the beam head after propagating 8 meters in the plasma as a consequence of the micro-bunch destruction. Also due to this phase shift, the partially destroyed micro-bunches first fall into the even stronger focusing region, then to a weaker focusing phase, and finally to the defocusing region, which then forms a positive feedback loop and leads to the continuing process of proton loss and wakefield decay.

One might also notice that at the initial moment (\( s < 1 \) m), there is a phase-mixing region with unusually high field amplitude positioned at \( \xi < -50 \) mm in Fig. 4. This phenomenon is due to the wave-breaking induced by the trajectory crossing of returning plasma electrons, as shown in Fig. 1. These returning plasma electrons were first radially pushed out of the narrow plasma channel by the seed wakefield, then being dragged back by the restoring force due to charge separation [10]. As the singularity point of plasma electrons formed around the axis with the accumulation of returning plasma electrons, the original plasma wave structure breaks at the trajectory crossing point. The wave-breaking...
effect can generate ultra-high defocusing wakefield, which could hamper the growth of the SSM. A detailed study of this effect happening in RIF seeded self-modulation can be found in [10], in which the trajectory crossing can occur several times. However, in our simulations, the re-entry point of returning plasma electrons is behind the main body of proton beam. So the wave-breaking effect does not significantly affect the SSM growth.

CONCLUSION

In this proceeding, we studied the electron-seeded proton self-modulation with the quasi-3D full PIC code FBPI. The simulation results of the scaled-down model proved the validity of this seeding method. By using a proper plasma density profile, one can effectively maintain the final accelerating gradient at a significantly higher level. These results generally agree with those from other codes. However, the ultra-high computing cost prevent us from investigating the full scale problem, for example, the possible effects due to wave-breaking induced by the returning plasma electrons to the SSM of a full length beam. Nevertheless, the available results might be useful as a reference for other simulations.

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