NUMERICAL STUDIES OF SELF MODULATION INSTABILITY IN THE BEAM-DRIVEN PLASMA WAKEFIELD EXPERIMENTS*

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Abstract

Proton beam-driven plasma wake-field acceleration has been proposed as a way to bring electrons to TeV energy range in a single plasma section. When a long proton bunch propagates into the plasma, this bunch splits into many small bunches. This phenomenon is known as a Self-Modulation Instability (SMI), and its characteristics depend on the ratio of bunch length and plasma wavelength. In this study, we first introduce a Particle-In-Cell (PIC) code WARP, focusing on the basis of parallel version structure. Through numerical simulations using the WARP, we investigate the characteristics of the SMI and propose possible experimental setup at the Injector Test Facility (ITF) of Pohang Accelerator Laboratory (PAL). Also, we present dependencies of the witness beam quality on both the driver beam and plasma parameters.

INTRODUCTION

Plasma based advanced accelerator by laser and particle beams has made significant progress over the past years. The energy scale of this acceleration realized till now is in the GeV regime about electrons. Thus, the producing and manipulation of TeV electron bunch in a single Plasma Wake-Field Accelerator (PWFA) is our interest. To excite plasma wave, a short proton bunch of scale in the plasma wavelength $\lambda_p = 2\pi c/\omega_p$ is required. But all the available proton bunches in TeV regime and with small energy spreads are much longer, usually tens of centimeters long. If the long driver is modulated to the scale we want at the plasma, we can accelerate electrons up to TeV energy regime. That is Self-Modulation Instability (SMI). However, driving some stable and strong plasma wave is not an easy work. When a long proton bunch propagates into plasma, the beam suffers from hose instability and two-stream instability, not only SMI. Especially, hose instability plays a role disturbing development of SMI. Therefore, the studies of aspect of competition between SMI and hose instability and how radius evolution of driver beam based on SMI is related with transverse two stream instability are necessary. In this paper, we introduce the study on electron-driven plasma wake-field. This study is performed with Particle-In-Cell code WARP originally developed by the heavy ion fusion group at LBNL and LLNL in US. Caring for ITF of PAL, the concepts in this paper were covered.

MAIN CONCEPTS

Beam-driven plasma wake-field is in other words, so called PWFA. To understand PWFA of a long electron or proton bunch, a few concepts of beam-plasma interaction will be described briefly.

Ponderomotive Force

A ponderomotive force is a nonlinear force that a charged particle experiences in an inhomogeneous oscillating electromagnetic field. The ponderomotive force F_p is expressed by $F_p = -(e^2/4m\omega^2)\nabla(E^2)$. This equation means that a charged particle in an inhomogeneous oscillating field not only oscillates at the frequency of ω of the field, but is also accelerated by F_p toward the weak field direction. By this force, the charged particle beams propagating into plasmas make plasma waves (or ion cavities). However, in this paper, this is not explicitly covered again.

Self-Modulation Instability

Once plasma wave is excited by the beam, the self-modulation of the long electron (or proton) bunch essentially occurs due to the action of the transverse wakefields on the bunch itself. This self-modulation splits the long beam into short bunches of the length of scale λ_p. The bunch train with this process will resonantly drive the plasma wake-field. This is different from the case caused by the electrostatic two-stream instability.

Hose Instability

The propagation of a long charged particle beam in plasmas may suffer from the hose instability in the limit $n_b \ll n_e$. It can severely affect and destroy the wakefield. But, for the stable excitation of plasma wave without wave-breaking, above limitation is required in both electron and proton driven cases. Therefore, controlling the hose instability is one of our key-words. To do that, two techniques, pre-seeding the self-modulation and shaping the axisymmetric divers, are suggested.

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SIMULATION

As remarked above, for a non-axisymmetric ($\partial_\theta \neq 0$) and gently rising beam density profile in the course of time, hose instability can be observed as shown in Fig. 1(c). In the simulation result Fig 1(b), the driver beam is focused with transverse size $\sim\sigma_r/3$. If the beam has step function-like head, effect of its non-axisymmetric geometry is not crucial especially for the short propagation distance.

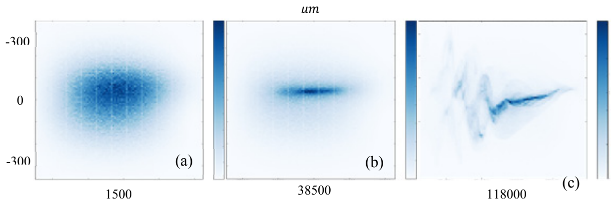

Figure 1: Three pictures from left to right are in sequence of the propagation time t.

In the study of SMI, aspect of competition between hose instability and SMI is very important. Because both of two phenomena are developed as increasing propagation time, the ratio of growth rates for the two instabilities should be considered [1]. To circumvent this problem and resonantly excite the wake, the beam profile must contain Fourier components close to the plasma frequency. Therefore, the length of curving head ΔL is necessarily less than λ_p [2]. The strongest wake-fields occur when $\Delta L = 0$. This is one of methods for pre-seeding of SMI.

Parameters for the driver beams are used for the two cases, which are Super Proton Synchrotron (SPS) beam [3] at CERN (1) and half-cut Gaussian beam (2) profiles as follows.

$$n_{b,SPS} = \frac{N_b}{2\sigma_r^2\sigma_z(2\pi)^{\frac{3}{2}}} e^{-\frac{r^2}{2\sigma_r^2}} \left[1 + \cos\left(\sqrt{\frac{\pi}{2}}\frac{z}{\sigma_z}\right)\right],$$

$$-\sigma_z\sqrt{2\pi} < z < 0\,, \tag{1}$$

$$n_{b,Gaussian} = \frac{N_b}{\sigma_r^2\sigma_z(2\pi)^{\frac{3}{2}}} e^{-\left(\frac{r^2}{2\sigma_r^2}+\frac{z^2}{2\sigma_z^2}\right)},$$

$$-3\sigma_z < z < 0\,, \tag{2}$$

with $\sigma_z = 960\ \mu m, \sigma_r = 120\ \mu m$, and $N_b = 3.12 \times 10^8$.

For the rigorous analysis, initial beam energy spread should be considered, because in the case of actual experimental setup, driver beam has initial energy spread. The energy spread of the driver beam allows SMI to be considered as the energy modulation. It can be a phase reference for injection of witness beam [2]. However, present available script of WARP do not contain that. It will be developed soon. Figure 2 shows differences between two cases of SPS and half-cut Gaussian. Figure 1(a) shows the tail half of SPS beam. Density modulation of the beam is apparently observed. Figure 1(b) shows half-cut Gaussian beam. Self-modulated beam is also observed, but it is not obvious as comparing with SPS beam case. In the both two cases, the length of plasmas from the entrance to the exit is 5 cm long. The size of the moving window is 500 μm wide and 2.4 mm long.

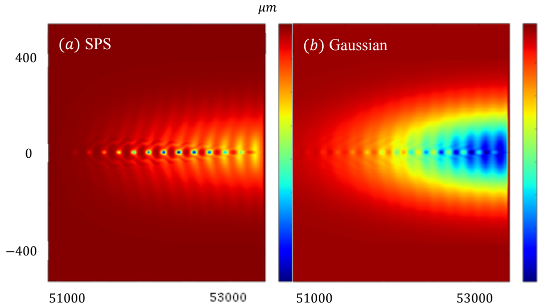

Figure 2: SMI from two beam profiles of SPS (a) and half-cut Gaussian (b). Other parameters of two pictures are same.

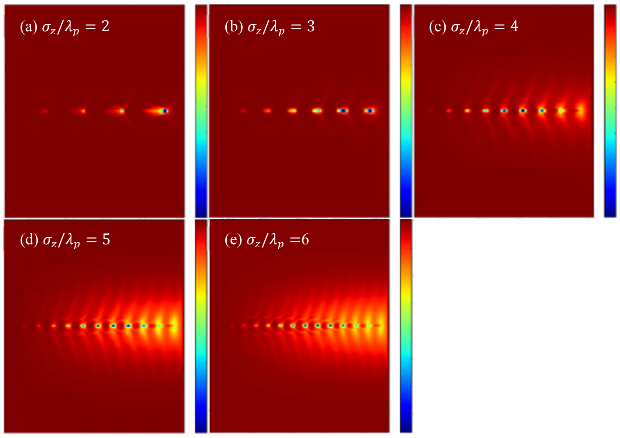

Figure 3: The number of (relatively strong) wake periods within the bunch is varied between ~2 and ~6 by varying the plasma density n_p from 4.8×10^{15} (a) to 4.3×10^{17}(e) cm^{-3} for SPS beam profile. All the parameters without n_p are same as Fig. 2(a).

Utilizing Euler variables $\xi = \beta_0 ct - z$, self-modulation instability grows spatially as increasing ξ and temporally as increasing t as shown in Fig. 4. Similarly for a long proton bunch driver, analytical approach of SMI tell us the same result [1].

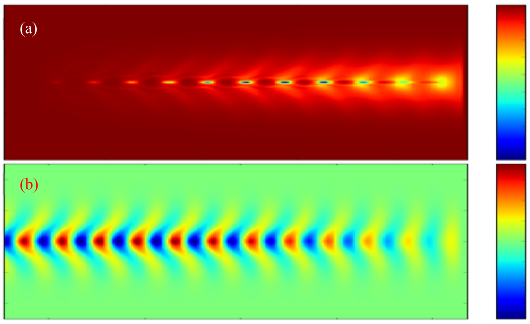

Figure 4: Modulated beam density profile (a) and longitudinal wake-field E_z.

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