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SELF-MODULATION OF LONG PARTICLE BUNCHES IN PLASMAS AT SLAC

P. Muggli*, Max Planck Institute for Physics, Munich, Germany
J. Vieira, L. O. Silva, GoLP/Instituto de Plasmas e Fusão Nuclear, IST, Lisbon
W.B. Mori, University of California, Los Angeles, CA 90095, USA
Y. Fang, University of Southern California, Los Angeles, CA 90089, USA
M.J. Hogan, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA

Abstract

Long ($\sigma_z \sim 500\ \mu\mathrm{m}$) SLAC electron and positron bunches sent into dense plasmas ($n_e = 0.6 - 2.3 \times 10^{17}\ \mathrm{cm}^{-3}$) are subject to a transverse two-stream instability called the self-modulation instability or SMI. We use numerical simulations to show that when the SMI saturates, the wakefield excitation reaches the nonlinear regime of the plasma wakefield accelerator (PWFA). We show that defocused particles lead to changes in the transverse bunch size downstream from the plasma. Measurement of that size change is an indirect observation of the SMI occurrence. We also show that the initial plasma ramp expected in the experiment does not significantly change the SMI growth or the peak wakefield amplitude.

INTRODUCTION

The self-modulation of long (when compared to the relativistic plasma wave period) particle bunches in dense plasmas [1] has attracted much attention recently. This interest comes two reasons. First this is a new beam/plasma interaction regime with interesting physics to study. Second, this scheme has the potential to resonantly drive plasma wakefields to large amplitude and is therefore interesting for acceleration of a trailing electron bunch at high gradient ($> 1\ \mathrm{GeV/m}$). Experiments to test and use this plasma wakefield excitation scheme have been proposed to CERN [2] and are in a concept development process. With the assumed 450 GeV proton bunches from the SPS, the instability develops and saturates in $\approx 5\ m$ of plasma at a density in the $n_e = 10^{14} - 10^{14}\ \mathrm{cm}^{-3}$ range. In addition, because of compatibility with LHC operation, these experiments are expected to take place after 2015.

The self-modulation instability (SMI) is driven by the transverse component of the wakefields. For relativistic bunches longitudinal dephasing scales with the particles relativistic factor γ: $\frac{\Delta L}{L} \cong \frac{1}{\gamma^2}\frac{\Delta\gamma}{\gamma}$ (for $\Delta\gamma << \gamma$) and is usually negligible when compared to a wave period over typical meter-scale plasma lengths. However, in the transverse dimension, the motion of the particles is not relativistic (determined by the bunch geometric emittance ϵ: $\langle v_\perp^2\rangle^{1/2} \propto \frac{\epsilon}{\sigma_r}$, σ_r the bunch rms transverse waist size), and upon propagation even weak transverse focusing forces in the linear regime can lead to significant modulation of the particles transverse momentum and thus bunch radius. The instability is driven by the initial transverse wakefields excited by the bunch when entering the plasma. These wakefields have a small amplitude, especially for a long Gaussian bunch. The modulation therefore has the same period as the relativistic plasma wave. The (de)focused $z-$slices of the bunch see their density (de)increase (wakefield amplitude proportional to bunch density in the linear regime) and therefore drive (weaker) stronger wakefields. The bunch density becomes transversely modulated and the long, self-modulated bunch resonantly drives the wakefields to large amplitudes. The initial wakefield amplitude can be increased, and the SMI seeded, for example by exciting wakefields with a preceding charged particle bunch or laser pulse, by giving the bunch a sharp rise time [3], or by creating a co-propagating ionization front.

* muggli@mppmu.mpg.de

SMI WITH SLAC BUNCHES

Plasma wakefield experiments with single, ultra-relativistic electron and positron bunches have been performed at SLAC [4]. These experiments were performed at plasma densities such that the rms bunch length σ_z is approximately matched to the relativistic plasma wave period, i.e., $k_{pe}\sigma_z \cong \sqrt{2}$, where $k_{pe} = \omega_{pe}/c$ is the electron plasma wave number and $\omega_{pe} = \left(n_e e^2/\epsilon_0 m_e\right)^{1/2}$the electron plasma angular frequency. Early experiments were performed with *long* bunches $\sigma_z \cong 500\mu\mathrm{m}$ and *low* plasma densities $n_e = 0 - 5 \times 10^{14}\ \mathrm{cm}^{-3}$ [5], while later experiments were performed with *ultra-short* bunches $\sigma_z \cong 20\mu\mathrm{m}$ and correspondingly *high* plasma densities $n_e = 0.6 - 3 \times 10^{17}\ \mathrm{cm}^{-3}$ [6]. It is clear that the *long* bunches are long when compared to the plasma period in the *high* density plasma: $\lambda_{pe} = 2\pi c/\omega_{pe} = 11.1\ \mu\mathrm{m}$ for $n_e = 2.3 \times 10^{17}\ \mathrm{cm}^{-3}$ (see Table 1). A collimation technique [7] will be used to produce a two-bunch train for PWFA experiments [8]. This technique can be used to shape bunches to seed the SMI. Energy and transverse size bunch diagnostics have been developed for these experiments. In addition, a pre-ionized, high-density plasma source will also be available. All these experimental conditions make it very attractive to test the SMI of lepton bunches at SLAC-FACET [9].

SIMULATION RESULTS

We study the long bunch/dense plasma interaction [10] using the particle in cell (PIC) code OSIRIS [11]. The code

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has been successfully benchmarked against other codes and against experimental results [12, 13, 14]. However, accurately simulating the propagation of a bunch many plasma wavelengths long in an instability regime and over long plasma distances remains computationally challenging and costly. Simulations results presented here therefore assume 2D cylindrically symmetry. The parameters considered here for the SLAC bunch and plasma are listed in Table 1. We consider the case of a bunch with a sharp (compared to a plasma period) rise time. This fast rise time seeds the SMI [3], and simulations indicate that this seeding mitigates the growth of the competing transverse hose instability, at least over a meter-scale plasma length. The position of the sharp rise time along the bunch can be varied. When near the peak of the bunch, maximum initial wakefields can be driven ($\sim 4\% E_{WB}$, where $E_{WB} = \frac{m_e c \omega_{pe}}{e}$, the cold plasma wavebreaking field) but less charge remains to drive them than when the rise time is placed earlier in the bunch. An optimum may exist that drive the largest wakefields while at the same time suppressing the hose instability. This can be easily studied experimentally.

Table 1: Beam and plasma parameters. Same value in both cases indicated by *.

$n_e[\mathrm{cm}^{-3}]$	6×10^{16}	2.3×10^{17}
$c/\omega_{pe}[\mu\mathrm{m}]$	21.7	11.1
$\sigma_r[\mu\mathrm{m}]$, $[c/\omega_{pe}]$	10, 0.5	*
$\sigma_z[\mu\mathrm{m}]$, $[c/\omega_{pe}]$	500, 23	*
γ_0	4×10^4	*
N_{part}	2×10^{10}	*
$n_b[\mathrm{cm}^{-3}]$	2.5×10^{16}	*
n_b/n_0	0.41	0.1
$\epsilon_N[\mathrm{mm} \cdot \mathrm{mrad}]$	50	*
$L^{\mathrm{plasma}}[m]$, $[c/\omega_{pe}]$	$1, 4.6 \times 10^4$	$1, 9 \times 10^4$

Simulation results show very interesting features for the case of the SLAC electron and positron bunches [10]:

- The instability grows and saturates only over approximately 5 cm (see Fig. 1)
- The wakefield amplitude reaches near wave breaking amplitudes ($E_z \sim E_{WB}$)
- The positron bunch is strongly defocused in the non-linear regime and few particles remain after 1 m of plasma
- Multi-GeV energy loss and gain by the drive particles can be reached over $1\ m$ of plasma
- The occurrence of SMI translates into increase of the beam transverse size downstream from the plasma

Figure 2 shows the electron bunch and plasma density after $1\ m$ of propagation in the 6×10^{16} cm^{-3} plasma. The individual bunches are clearly visible, and they each reside in a *bubble* empty of plasma electrons, a situation typical of the non-linear regime of the PWFA. The number of self-modulated bunches is $N \sim 15$, and the plasma density variation requirements to resonantly excite wakefields along the plasma are relatively easy to satisfy: $\delta n/n_e \sim 1/N$. The electrons that are *missing* have been defocused and have essentially left the simulation box, as shown on Fig. 3. This figure shows the bunch radial density at each position along the plasma. A significant number of electrons leave the bunch near the instability saturation point ($z \cong 5$ cm), with a maximum angle of the order of 3 mrad. Bunch electrons are continuously lost, although at a smaller rate once the instability has saturated and the PWFA has reached the non-linear regime (in this case, see Fig. 2). The relative number of lost electrons is about 23 %.

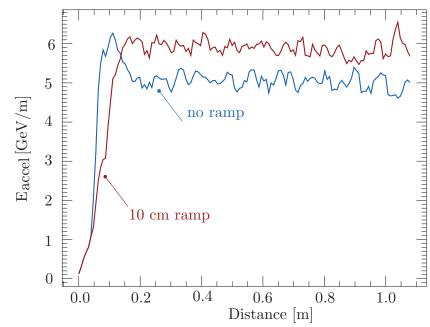

Figure 1: Maximum longitudinal electric field E_{accel} along the bunch as a function of propagation distance z for the case of a step function plasma density (blue line) and a plasma density profile with a continuous ramp at the entrance (red line), as measured in the experiment [4]. In both cases the plasma density is $n_e = 6 \times 10^{16}$ cm^{-3}.

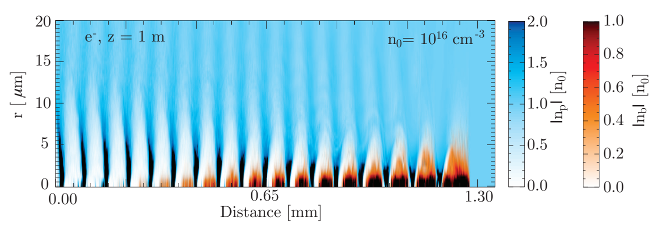

Figure 2: Plasma electron density (blue colors) and electron bunch density (red colors) after $1\ m$ of propagation in the 6×10^{16} cm^{-3} plasma. The multiple plasma bubbles surrounding the SMI-formed bunches are clearly visible. The bunch has a sharp rise time at the peak of its density.

Most simulations are performed with the case of a constant plasma density profile. However, with the metal vapor plasma source that is planned for the experiments with the SLAC beam, the plasma density longitudinal profile is that of the metal vapor. This profile has been measured experimentally [4], and has a *Gaussian-like* initial ramp of length about 10 cm. This realistic profile has been included in the simulations and its effect on the accelerating field amplitude can be seen in Fig. 1. Figure 1 shows that the effect is negligible, with the possible benefit of a slightly larger peak field after the SMI saturation. Note that at the lowest of the two densities considered here, the peak accelerating wakefield amplitude ($E_{accel} \sim 6\ GV/m$) is significantly lower than at the higher density ($E_{accel} > 30\ GV/m$, [10]). This is due to the lower plasma density ($E_{WB} \sim n_e^{1/2}$), and to the fact that the bunch and plasma are shorter in term of plasma periods. The presence of the ramp also has a negligible effect on the energy spectrum of the bunch electrons at the plasma exit.

Figure 4 shows the bunch time integrated transverse size, a distance $1\ m$ downstream from the plasma exit, as could be observed, for example with optical transition radiation (OTR) with and without plasma. Without plasma, the beam simply diverges because of its emittance over a vacuum propagation distance of $2\ m$. The bunch transverse profile remains Gaussian. With the plasma, the occurrence of the SMI leads to defocusing of some of the bunch electrons. In addition, the ones in the focusing phase of the wakefields see their emittance grow due to the radially nonlinear focusing fields existing while the SMI develops. The bunch profiles appears to be much broader, with long wings. Measuring this profile change would therefore be an indirect evidence of the occurrence of the SMI.

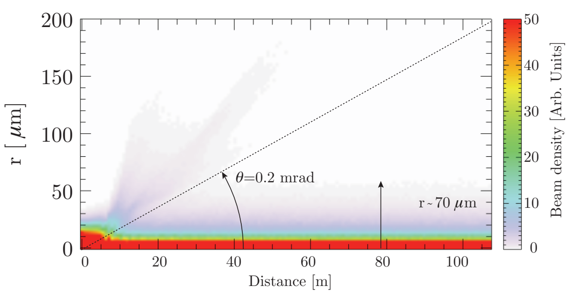

Figure 3: Electron bunch density along the $1\ m$ plasma. Defocused electrons leaving the wakefields are visible thanks to the saturated color table.

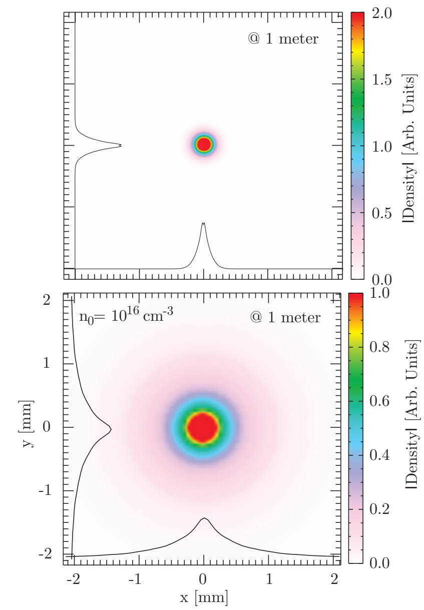

Figure 4: Electron bunch transverse density $1\ m$ downstream from the plasma exit without plasma (top image, $2\ m$ of vacuum propagation) with the $1\ m$-long, $6 \times 10^{16}\ \mathrm{cm}^{-3}$ density plasma (bottom image, $1\ m$ of vacuum propagation after the plasma). The effect of SMI on the transverse beam size is clearly visible.

CONCLUSIONS

We have demonstrated through numerical simulations that the nonlinear regime of the PWFA is reached when the SMI of long SLAC electron bunches occurs. We have also shown that beam transverse size measurements downstream from the plasma show the occurrence of the SMI. We expect to perform SMI experiments with the long SLAC bunches in 2013. These experiments will show for the first time that large amplitude plasma wakefields can be resonantly driven and sustained over long plasma distances leading to large energy gain and loss even by the drive bunch electrons. Further simulation results can be found in Ref. [10].

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