NUMERICAL MODELING OF THE E-209 SELF-MODULATION EXPERIMENT AT SLAC - FACET*

L. D. Amorim[†], J. Vieira, L. O. Silva,
Instituto de Plasmas e Fusão Nuclear (IPFN) Instituto Superior Técnico
P. Muggli, Max-Planck Institute fuer Physics (MPI)

Abstract

The E-209 experiment currently running at SLAC-FACET used a long electron bunch (~ 5 times the plasma wavelength) to drive plasma wakefields through the self-modulation instability. In this work we present and analyze numerical simulation results performed with the particle-in-cell (PIC) code OSIRIS. The results show that SMI saturates after 5cm of propagation in the plasma and that the maximum acceleration wakefields, 15 − 20GV/m, are sustained over a 1m long plasma. Electron bunch energy loss of 4GeV was observed in the simulations.

INTRODUCTION

Plasma-based accelerators are capable of sustaining higher acceleration gradients than conventional accelerators [1]. beam-driven plasma wakefield accelerators rely on the energy transfer from a relativistic charged electron [2] or positron [3] bunch to the particles to accelerate through the excitation of a plasma wave with wavelength λ_{pe}. Recently the use of short (shorter than λ_{pe}) proton bunches to drive plasma wakefields in the highly non-linear regime was proposed [4] in the so called proton driven plrasma wakefield acceleration(PDPWFA). Numerical simulations of PDPWFA hindicate that proton bunches are good candidates for electron acceleration up to the energy frontier [4].

However, the length of the available proton bunches at CERN (or Fermilab) is much larger than λ_{pe}. As a result they can not be used to drive plasma wakefields in the strongly non-linear regime associated with higher acceleration gradients [5]. Compressing the available proton bunches to resonantly excite non linear wakefields is technically very demanding. Nevertheless, such long proton bunches when propagating in plasmas undergo the self-modulation instability (SMI) where they are split into a train of shorter bunches separated by $\approx \lambda_{pe}$ that can in turn resonantly drive large amplitude wakefields [6]. The potential of the self-modulated PDPWFA has lead to the proposal of an experiment (the AWAKE experiment) that will be performed at CERN in the next 2-4 years [7].

Key physics of electron and positron bunch SMI, similar to that of AWAKE, is currently being studied at SLAC - FACET in the E-209 experiment [8, 9]. In this experiment the SMI signature will be explored by analyzing the electron bunch energy gain and energy loss and the halo formation and by observing the radial modulation period through coherent transition radiation (CTR) interferometry [10, 11].

In the present work the electron beam and plasma configuration similar to the first E-209 experimental run was simulated and analyzed. The simulations were performed using the fully relativistic particle-in-cell code OSIRIS [12, 13]. We show that SMI occurs in the conditions of the experiment and that SMI saturates over the first 5cm of the bunch propagation in the plasma. We also show that the SMI can drive 20GeV/m wakefields sustained over the full plasma length. In addition 4GeV energy loss were observed in the simulations with a final self-modulated electron bunch with energies ranging from 16 to 20GeV in a quasi uniform way.

BEAM AND PLASMA SETUP

The simulations were performed in 2D-cylindrical coordinates using a computational box of $940 \times 380 \mu\text{m}^2$ divided into 1010×425 cells with 2×2 plasma and bunch particles per cell. A 20GeV electron bunch with 1.9×10^{10} particles was considered. The longitudinal electron bunch profile, shown in Fig. 1, closely followed the experimental profile and was described by:

$$\frac{n_b}{n_{b0}} = \left[2\exp\left(-\frac{(z-z_1)^2}{2\sigma_{z1}^2}\right) + \exp\left(-\frac{(z-z_2)^2}{2\sigma_{z2}^2}\right)\right]\exp\left(-\frac{r^2}{2\sigma_r^2}\right) \quad (1)$$

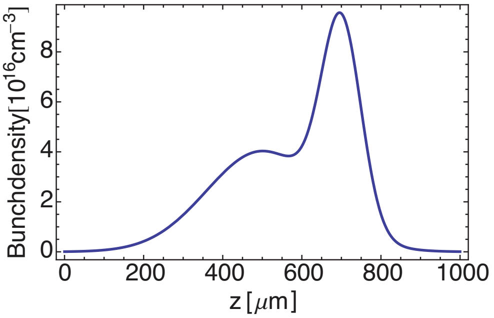

Figure 1: Initial electron bunch profile as given by Eq. 1.

The simulation parameters can be found in Table 1.

The peak bunch density used in the simulations is $n_{b0} = 6.4 \times 10^{15}\text{cm}^{-3}$, which is much lower than the initial uniform background electron plasma density that is given by $n_{p0} = 8 \times 10^{16} \approx 12.5\ n_{b0}$. The plasma wavelength is 118μm. The bunch total length is of about $500 - 600\mu\text{m} \approx 4 - 5 \times$

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[†] ligia.diana.amorim@ist.utl.pt

Table 1: Values of the Parameters of the Profile specified in Eq. 1 used in the Simulation.

σ_{z1}	σ_{z2}	σ_r	z_1	z_2
50μm $2.7\lambda_{pe}$	140μm $7.5\lambda_{pe}$	30μm $1.5\lambda_{pe}$	700μm $37.2\lambda_{pe}$	500μm $26.6\lambda_{pe}$

λ_{pe}, thus it is sufficient for self-modulation to occur. The simulated plasma total length is 1m.

SIMULATION RESULTS

The simulations used a moving window traveling at the speed of light, c, moving in the direction of the beam. Figure 2 shows the self-modulated electron (blue) and plasma (green) density at the end of the simulation. The direction of propagation is to the right of the plot. The wake bubbles can be seen in Fig. 2 as well as the four self-modulated bunches that fit inside those bubbles.

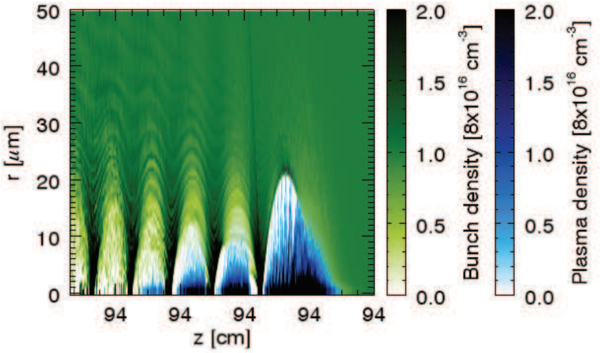

Figure 2: Final electron bunch (blue) and plasma densities (green). Color scales represent densities normalized to n_0.

Simulations show that the portions of the bunch propagating in the defocusing field regions are pushed away from the propagation axis. The portions that remain in focusing regions are focused towards the axis throughout the propagation in the plasma, i.e. the bunch becomes self-modulated though the SMI.

The evolution of the accelerating wakefield as a function of the propagation distance can be found in Fig. 3. It follows the curves found in SMI numerical studies [8]. The SMI grows and saturates over the first $\approx$ 5cm of the electron bunch propagation in the plasma, reaching maximum accelerating field values close to 20GeV. After the saturation of the SMI the fields decrease slightly by $\approx$ 5GV/m and remain approximately constant (15 ± 2GV/m) during the remainder of the propagation in the 1m long plasma.

We note that the wave breaking field is $E_0 = m_e c\omega_{pe}/e \approx 27$GV/m. Thus, wake excitation in this simulation occurred in mildly non linear regime. It has been shown that the Hosing instability, where the bunch centroid undergoes unstable oscillations [8, 14] can be mitigated after SMI saturates in linear regime [15]. A more detailed study of the competition between SMI and Hosing in this regime will nevertheless be addressed in a future publication.

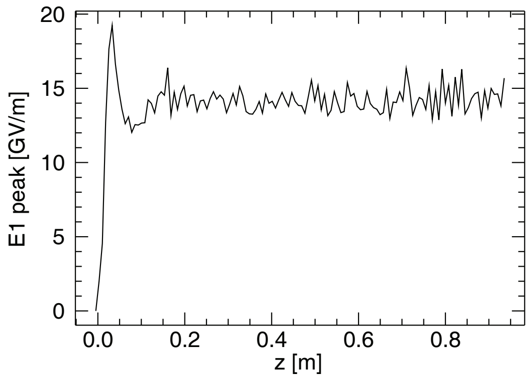

Figure 3: Evolution of the accelerating wakefield as a function of the propagation distance near the axis at $r = 0.75\mu$m.

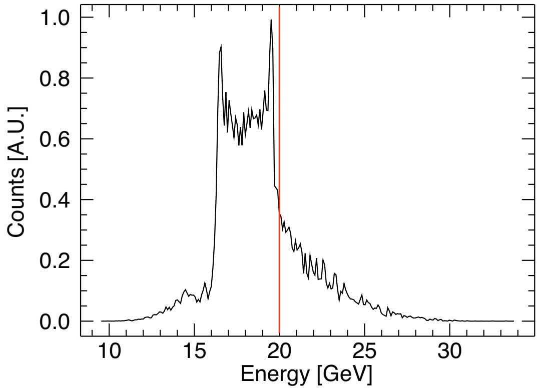

Figure 4: Energy spectrum showing the energy variation after the propagation in the plasma relative to the initial 20GeV of the initial electron bunch.

The final electron bunch energy spectrum is shown in Fig. 4. The two peaks that can be seen in the spectrum are the initial bunch energy 20GeV and the final energy of most of the decelerated particles at 16GeV. The energy gain/loss by the beam electrons ($\approx$ 5GeV) is lower than what could be expected from Fig. 3 which indicates maximum wakefields that would lead to acceleration in the order of the 15GeV/m. This is because the bunch particles do not propagate in regions of maximum accelerating wakefields [16, 17].

Simulations with the same parameters but with positron bunches lead to accelerating wakefields with similar evolution but with half the accelerating field amplitudes. The final modulated bunches are shorter and narrower (see Fig. 5) which indicates that the experimental analysis of the positron bunch self-modulation can be more challenging than the first run of the E-209. The energy spectrum ranges from the 17 to 22 GeV with a central peak-like region at 19.6GeV.

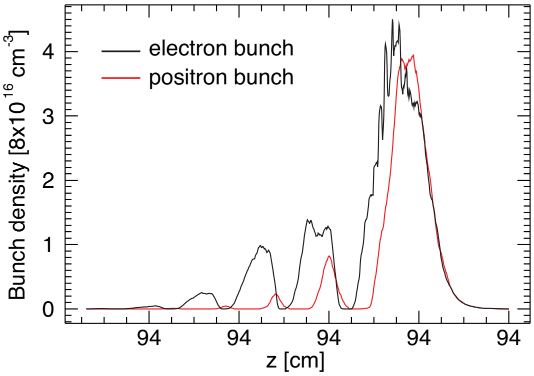

Figure 5: Comparison of the final self-modulated electron (black) and positron (red) bunches.

CONCLUSIONS

The present work has shown that the electron beam configuration (length higher than 4-5 plasma wavelengths) used in the E-209 experiment at SLAC undergoes the self- modulation instability with a saturated state in the mildly non linear plasma wakefield acceleration regime. We found that within the first 5 cm of propagation, the SMI leads to a train of 4 self-modulated bunches separated by λ_p that resonantly drive ≈20GV/m wakefields. The self-modulation saturates the bunch propagated 5cm leading to stable accelerating wakefields that range between 15±2GV/m. The final bunch electrons energy spectrum is a nearly flat-top distribution from 16 to 20GeV.

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