

# SELF-MODULATION AND HOSING INSTABILITY OF SLAC ELECTRON AND POSITRON BUNCHES IN PLASMAS

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## Abstract

We describe through particle-in-cell simulations some of the key physics of the upcoming E-209 self-modulation experiment at SLAC-FACET. We show that that uncompressed SLAC-FACET electron bunches can drive non-linear plasma waves in the blowout regime capable of reaching large accelerating gradients comparable to those driven by compressed bunches. Large amplitude accelerating gradients can be sustained over meter long plasmas, without hosing growth. Since in the blowout, most of the longitudinal wakefield phase is defocusing for positrons, uncompressed positron bunches at SLAC-FACET drive lower acceleration gradients. The acceleration of externally injected electron and positron bunches is also briefly described.

1 m long plasmas with  $n_0 \sim 10^{17} \text{ cm}^{-3}$ . Although they are much shorter than CERN SPS proton bunches, uncompressed lepton bunches at SLAC-FACET are in the conditions of the self-modulation instability (i.e.  $\sigma_{\parallel} \gg \lambda_p$ , and  $\sigma_{\perp} \simeq c/\omega_p$ ). In addition, bunches with short rise times (i.e. shorter than  $\lambda_p$ ) can also be produced to seed the self-modulation instability. Signatures for the self-modulation instability can be measured down-stream from the plasma using several available diagnostics (e.g. OTR, CTR, energy spectrometer, etc).

## INTRODUCTION

The proton driven plasma wakefield accelerator [1] uses short proton bunches, with length comparable to the plasma skin depth, i.e.  $\sigma_{\parallel} \sim c/\omega_p$ , where  $c$  is speed of light,  $\omega_p$  the plasma frequency, to drive strongly non-linear wakefields in the blowout regime. Numerical simulations show that compressed LHC-CERN proton bunches could excite 1 GeV/m acceleration gradients leading to the acceleration of 600 GeV electrons in 600 m plasmas. Currently available proton bunches, however, are  $\sigma_{\parallel} = 10 \text{ cm}$  long and encompass several tens of plasma wavelength ( $\lambda_p$ ) in low density plasmas with  $n_0 = 10^{14} - 10^{15} \text{ cm}^{-3}$ . Thus, although not suited to excite non-linear plasma waves, these bunches can still drive large amplitude wakefields through the self-modulation instability [2]. This configuration will be explored at CERN using Super Proton Synchrotron (SPS) proton bunches in experiments to occur within the next 3-5 years [3].

Key physics of the future experiment at CERN (e.g. self-modulation, hosing, ion motion, role of plasma density uniformity, etc) will be tested with currently available electron and positron bunches [4] at SLAC-FACET in the E-209 experiment [5]. This experiment, illustrated schematically in Fig. 1, consists in the propagation of uncompressed 20 GeV SLAC electron or positron bunches, with length  $\sigma_{\parallel} = 500 \mu\text{m}$  and width  $\sigma_{\perp} \sim 10 \mu\text{m}$ , in

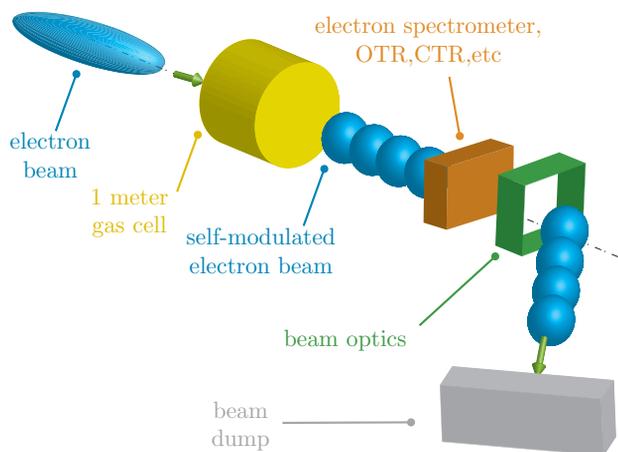


Figure 1: Schematic illustration of the E-209 experiment at SLAC-FACET. The experiment will measure the self-modulation of uncompressed electron (or positron) bunches after a 1 meter-long plasma. Measurements will be performed with several available diagnostics, including OTR to measure the change in transverse size downstream the plasma, CTR to measure the modulation periodicity, spectrometer to measure energy variations, etc.

In these proceedings we describe simulation results in conditions of the E-209 experiment using the massively parallel, fully relativistic particle-in-cell code Osiris [6]. We show the evolution of maximum acceleration gradients as a function of propagation distance for both electrons and positrons. Differences between the self-modulation by positively and negatively charged bunches are also analyzed. Acceleration of external electron and positron bunches in the wake of self-modulated electron bunches is also briefly described. We show that seeding the SMI with half-cut

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bunches provides stable acceleration gradients over a propagation distance long when compared to the SMI saturation length.

## SELF-MODULATION OF UNCOMPRESSED SLAC-FACET LEPTON BUNCHES

We start by describing the general features of self-modulated wakefields driven by uncompressed SLAC-FACET electrons and positron drivers. Simulations use a moving window that propagates at  $c$ . Background plasma ions are immobile in order to avoid deleterious effects associated with the ion motion [7]. Simulation domain is divided into cells with dimensions  $k_p \Delta z = k_p \Delta x_{\perp} = 0.0375$ , where  $\Delta z$  and  $\Delta x_{\perp}$  are the longitudinal and transverse grid cell size, and where  $k_p = \omega_p/c$  is the plasma wavenumber. In the simulations, the bunch density profile is:

$$\frac{n_b}{n_0} = \frac{1}{2} \frac{n_{b0}}{n_0} \left[ 1 + \cos \left( \sqrt{\frac{\pi}{2}} \frac{\xi - \xi_0}{\sigma_{\parallel}} \right) \right] \exp \left( -\frac{x_{\perp}^2}{2\sigma_{\perp}^2} \right), \quad (1)$$

for  $0 < \xi - \xi_0 < \sigma_{\parallel} \sqrt{2\pi}$  (i.e. bunch with sharp rise to seed the SMI [8]) where  $n_{b0}/n_0$  is the peak beam density normalized to the background plasma density,  $\xi = z - ct$  is the distance to the head of the bunch,  $z$  the propagation distance,  $t$  the time, and  $\xi_0$  the initial position of the center of the bunch. For SLAC-FACET  $n_{b0}/n_0 = 0.05 - 0.1$ ,  $\sigma_{\parallel} = (100 - 200) c/\omega_p$ ,  $\sigma_{\perp} \sim (1 - 2)c/\omega_p$ .

Figure 2 shows the evolution of the accelerating gradients as a function of the propagation distance for SLAC-FACET. Simulations show that these bunches can drive strong wakefields in the blowout regime with accelerating gradients in excess of 20 GeV/m for electrons and 10 GeV/m for positrons. Before non-linear excitation regimes, for  $z < 5$  cm, positrons and electrons generate similar wakefields, in agreement with linear wakefield theory. For longer propagation distances, near the saturation of the self-modulation instability, for  $z > 5$  cm, both positrons and electrons can drive plasma waves in the blowout regime. However most of the transverse blowout wakefields are defocusing for positrons. Thus, a significant fraction of positrons defocus, decreasing the number of particles available to drive the wake and leading to lower accelerating gradients in comparison to the electron bunch scenario. These results suggest that the linear regime has advantages over the non-linear regime in future self-modulation experiments with positively charged bunches.

The drive bunch can accelerate and decelerate in its own wakefields. Simulations show that electrons can gain up to 7 GeV and lose up to 14 GeV after propagation in a one meter long plasma (1% energy level). Positrons can also gain up to 7 GeV and lose 8 GeV over the same propagation distance (1% energy level).

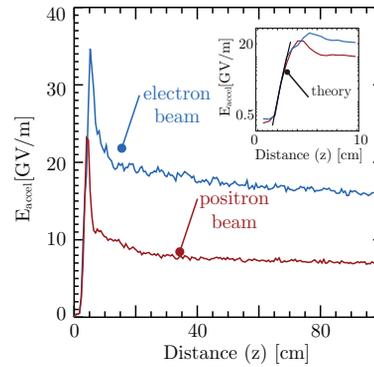


Figure 2: 2D cylindrically symmetric Osiris simulation results of the evolution of maximum accelerating gradients during self-modulation of SLAC-FACET uncompressed electrons (blue) and positron (red) bunches. The inset shows a comparison for the maximum accelerating fields between simulations and self-modulation instability linear theory.

## ACCELERATION OF EXTERNAL ELECTRON AND POSITRON BUNCHES

Self-modulated wakefields can also be used to accelerate externally injected electron or positrons bunches. We considered the acceleration of test electron and positron bunches in the wake of a self-modulated electron bunch. The test electron/positron density profile is similar to the driving bunch (cf. Eq. (1)). Test electrons are injected at the plasma entrance and propagate through the plasma region where the wakefield phase velocity has strong variations due to the growth of self-modulation [5, 9, 10]. Despite complicated to describe because of these strong wakefield phase velocity variations, trapping of some of the externally injected particles occurs nevertheless. The majority of the trapped electrons are accelerated within the first plasma waves, even though electrons at the back reached higher energies. Figure 3a shows the evolution of the maximum electron energy as a function of the propagation distance. Figure 3b illustrates the corresponding final energy spectrum. The electron spectrum shows a continuous energy distribution up to 5 GeV (injection energy of 300 MeV). Other injection mechanisms could provide for lower energy spreads (e.g. side injection after the saturation of the SMI [9]).

We performed additional simulations using similar test positron bunches. Although most test positrons defocus in the blowout, a small fraction ( $\simeq 1\%$ ) of the initial distribution still accelerates to 5 GeV in less than one meter. Similarly to the test electron case (see Fig. 3) the final energy spectrum was broad.

## STABLE WAKEFIELD GENERATION WITH SEEDED SMI

Simulation results from previous sections were performed in 2D cylindrically symmetric geometry. Al-

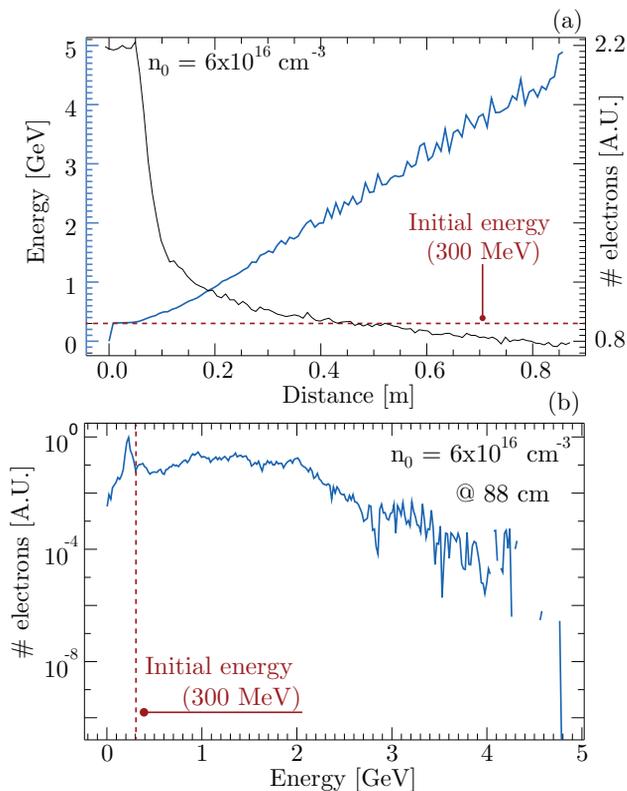


Figure 3: 2D cylindrically symmetric Osiris simulation results of the acceleration of an externally injected test electron beam in the wake driven by an uncompressed SLAC electron bunch. Figure (a) shows the evolution of the maximum energy (blue) and number of test electrons captured (black) as a function of the propagation distance. Figure (b) shows the corresponding test electron energy spectrum after 0.8 m.

though these simulations are useful for understanding self-modulation, they preclude the physics of the hosing instability. However, since hosing and self-modulation instabilities have similar growth rates [11], hosing can lead to beam-breakup preventing excitation of large amplitude wakefields and the acceleration of particles to high energies.

3D simulation results of a self-modulated plasma wakefield accelerator for the early propagation were recently considered for the parameters of SLAC-FACET [5]. However, since full scale 3D simulations of self-modulated plasma wakefield accelerators are computationally demanding, we performed additional simulations in 2D slab geometry (which retains the physics of the hosing instability) for the full 1 meter propagation distance.

Simulations in 2D slab geometry use bunches with short rise times to seed the self-modulation instability while significantly reducing the computational size. In addition, bunch density and bunch dimensions are similar to those of 2D cylindrically symmetric simulations. Fig 4 shows the wakefield after 1 meter of propagation. Stable wakefields are excited throughout the 1 meter plasma. These results

suggest that stable wakefields can be generated in conditions of the E-209 self-modulation experiment at SLAC.

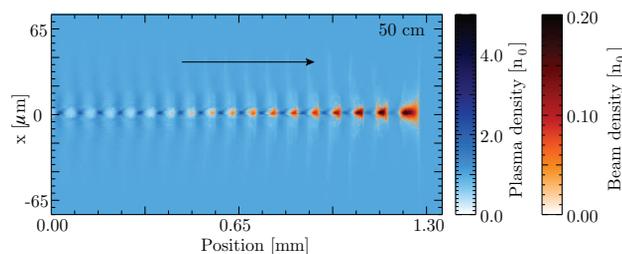


Figure 4: 2D slab geometry Osiris simulation result of a self-modulated plasma wakefield accelerator driven by the uncompressed SLAC-FACET electron bunch after 0.5 m of plasma. Plasma density (blue colors) is superimposed with the electron bunch density (red colors). The bunch propagates from left to right as indicated by the arrow.

## CONCLUSIONS

In these proceedings we presented numerical modeling in the conditions of the E-209 self-modulation experiment at SLAC-FACET. We showed that large acceleration gradients in excess of 20 GeV/m can be excited using uncompressed SLAC-FACET electron bunches. Large wakefields in excess of 10 GeV/m could also be produced by positron bunches. These large accelerating gradients can accelerate particles from the driver or from an externally injected electron or positron bunch. We also showed that bunches with short rise times can be used to generate stable wakefields for long propagation distances.

## ACKNOWLEDGMENT

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