ELECTRON BUNCH SELF-MODULATION IN A LONG PLASMA AT SLAC FACET

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Abstract

We briefly describe the E209 experiment to be performed at SLAC FACET. We show how evidence of the the radial modulation of the electron bunch resulting from the occurrence of the self-modulation instability is expected to appear on a coherent transition radiation autocorellation trace.

INTRODUCTION

Large amplitude plasma wakefields are most efficiently driven by relativistic, charged particle bunches about one electron plasma wavelength (λ_{pe}) long: $\sigma_z \cong \lambda_{pe}/(\sqrt{2}\pi)$ [1] in a scheme known as the plasma wakefield accelerator (PWFA) [2]. The wakefield amplitude increases with decreasing beam size (σ_z, σ_r) and correspondingly increasing plasma density (n_e): $E_{WB} \sim n_e^{1/2}$ [3], as long as the bunch charge remains in a $\sigma_z\sigma_r^2 \sim \lambda_{pe}^3$ volume. These dependencies favor short bunches and dense plasmas to reach large wakefield amplitudes, as was the case for example in the SLAC experiments ($\sigma_z \cong$20 μm, $\sigma_r \cong$10 μm, $N_{e^-} \cong 2 \times 10^{10}$) that yielded 42 GeV energy gain in only 85 cm of plasma with $n_e = 2.7 \times 10^{17}\ cm^{-3}$ [4]. However, this SLAC bunch carries only about 144 J, thereby limiting to that amount the possible energy transfer from the drive to a witness bunch.

Long ($\sigma_z \cong$10 cm) proton bunches carrying 6 kJ (400 GeV, SPS) or 112 kJ (7 TeV, LHC, both with $10^{11} p^+$) are routinely produced at CERN. When propagating in high-density plasmas, i.e. such that $\lambda_{pe}(\propto n_e^{-1/2}) << \sigma_z$, these bunches are subject to the self-modulation instability (SMI) [5]. The SMI originates from the low level transverse wakefields ($W_\perp$, focusing/defocusing) driven by the long bunch that periodically modulate its density (n_b), thereby feeding back onto the wakefields ($E_z, W_\perp \sim n_b/n_e$). The SMI transforms a long bunch into a train of shorter bunches separated by $\sim \lambda_{pe}$ that can resonantly drive wakefields to large amplitude. An experiment known as *AWAKE* [6] has recently been approved by CERN to test electron acceleration in a SMI-driven PWFA. We proposed another experiment [7] using electron (e^-) and positron (e^+) bunches available at SLAC-FACET to test the physics of SMI. This experiment is known as E209. It takes advantage of the long bunches used in earlier PWFA experiments [8] and of the high-density, m-long plasmas now available for short bunch experiments [9]. Note also that the effect of the longitudinal wakefields on the energy spectrum of a bunch 1-5 plasma wavelengths-long 60 MeV electron bunch was observed as evidence of seed for the SMI [10].

Simulation results [7] indicate that with high plasma density ($n_e = 2.7 \times 10^{17}\ cm^{-3}$) and a long ($\sigma_z \cong$500 μm, and $\sigma_r \cong$10 μm, $N_{e^-,e^+} \cong 2 \times 10^{10}$) and a half-cut bunch to seed the SMI, initial wakefields of ~0.5G V/m grow to over 20 GV/m (both with electrons and positrons) and saturate after only $\sim 5\ cm$ of plasma. However, the peak amplitude values are not maintained (see Fig. 3 of [7]) but lower values (>15, e^- and >7 GV/m, e^+) are sustained over the remaining ~95 cm of plasma. In these proposed experiments there are no externally injected particles to sample the wakefields and their amplitude can only be inferred from energy gain/loss by the drive bunch particles.

DETECTING SMI OCCURRENCE

Experimentally, the occurrence of SMI can be evidenced with three diagnostics. First the energy gain/loss by drive bunch particle is larger than that given by the initial wakefields amplitude (no SMI gain) multiplied by the plasma length. An imaging magnetic spectrometer capable of measuring sub-GeV energy change in the bunch energy spectrum is available at FACET.

Second, the creation of a halo of defocused particles around a more focused bunch train core can in principle be observed using time-integrated transverse images of the bunch using optical transition radiation. This diagnostic has been used with e^- [11] to evidence beam betatron oscillations and e^+ [12] to emphasize the difference in plasma focusing fields for the two particle species.

Third, the radial modulation period can in principle be observed with coherent transition radiation (CTR) interferometry. Indeed, in general the bunch form factor is tridimensional and contains information both about the longitudinal *and* transverse structure of the bunch. The diagnostic is well known and can either directly yield the bunch structure, as was demonstrated with trains of particle bunches [13], or indirectly by calculating the Fourier transform of the signal. The challenge with high energy bunches is that while the transverse bunch structure information is maximized at large angles away from the bunch propagation direction, CTR emission peaks in a narrow forward angle with opening on the order of $1/\gamma$, γ the particles relativistic factor. With the 20 GeV beam available at FACET this angle is very narrow

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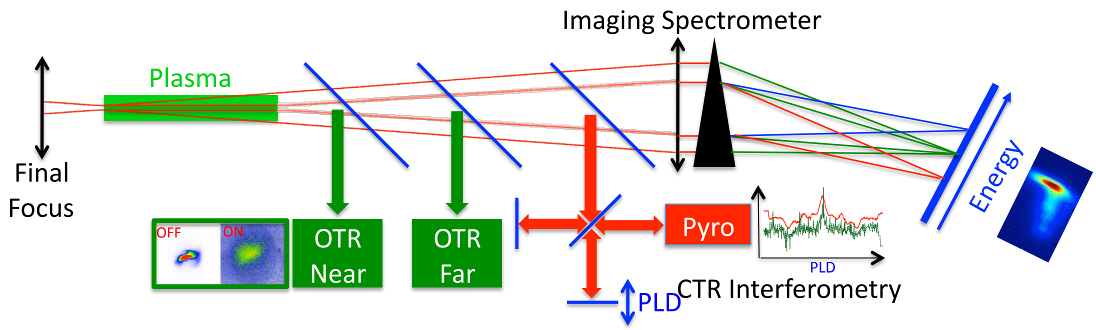

Figure 1: Schematic of the E209 experiment at SLAC FACET. The beam (e^- or e^+) is focused near the entrance of the plasma. The plasma is created by laser photo-ionization of a metallic vapor (lithium) [9] (not shown). The time integrated bunch transverse profile can be recorded ~1 and ~2 m downstream from the plasma exit using optical transition radiation (OTR). Coherent transition radiation (CTR) interferometry is preformed ~3 m downstream from the plasma exit using a Mach-Zender interferometer and a pyro-electric detector. The bunch energy spectrum can be recorded by an imaging magnetic spectrometer. Figure not to scale.

since $1/\gamma \sim 1/40000$. This issue is addressed in another paper in these Proceedings [14].

BUNCH FIELDS AND CTR SIGNAL

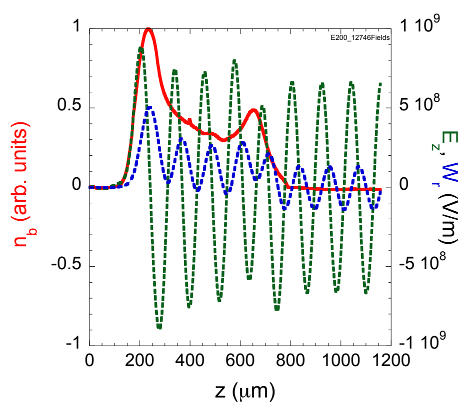

Figure 2: An example of the bunch longitudinal density profile measured recently (red line). The bunch propagates towards the left. The corresponding longitudinal: E_z, green dashed line, and transverse: W_r, blue dashed line, wakefields.

Here we calculate the initial wakefields driven by the bunch and illustrate using a naive model how modulation would affect the CTR interferometry signal. The wakefields can be calculated using 2D linear PWFA theory [15] with the actual bunch profile measured in the experiment. Figure 2 shows an example of the electron bunch longitudinal density profile that was measured using a transverse deflecting cavity. It also shows the corresponding longitudinal (E_z) and transverse (W_r) wakefields driven in a plasma with electron density $n_{e0} = 8 \times 10^{16}\ cm^{-3}$. The bunch has an energy of 20.35 GeV, is ≈600 μm-long, contains ≈ 1.9×10^{10} electrons and is focused to $\sigma_r \cong$40 μm radius near the entrance of the plasma. Note that E_z reaches ≈900 MeV or only about 3% of the wave breaking field. We consider here a naive model where the transverse wakefields lead to a longitudinal modulation of the bunch density, as shown on Fig. 3. Then

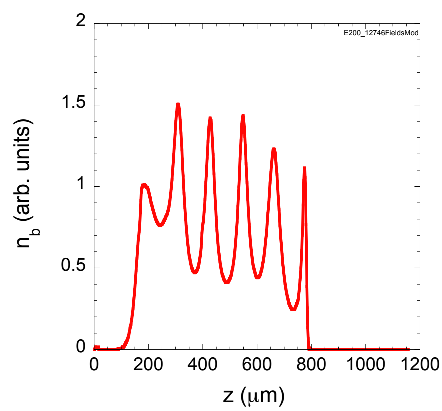

Figure 3: Bunch density profile obtained by assuming that the transverse wakefields lead to the longitudinal profile given by: $n_b = n_{b0}/(W_r/max(W_r) + 0.3)$. The bunch propagates towards the left.

the autocorellation trace for the un-modulated bunch profile of Fig. 2 and for the calculated model profile of Fig. 3 can simply be calculated. The results are shown on Fig. 4. The trace for the modulated bunch clearly shows the appearance of peaks with the periodicity of the modulation, corresponding to the period of the wakefields which is also the plasma wavelength $\lambda_{pe} \cong 118\ \mu m$. These traces illustrate that the signal that is expected when/if SMI occurs. The appearance of the peaks in the autocorellation trace is also visible on its Fourier spectrum (Fig. 5). This simple example shows that the expected peaks in the autocorellation trace appear, even though the bunch profile may be far from Gaussian or square. We note that experimentally the autocorellations traces are built of many beam-plasma interaction events (unlike the calculations above) and are affected by variations in the experimental parameters. The plasma density (and therefore the plasma period) are not expected to vary since the plasma is obtained by laser ionization [9] (threshold process) of a metal vapor whose density only changes with a thermal

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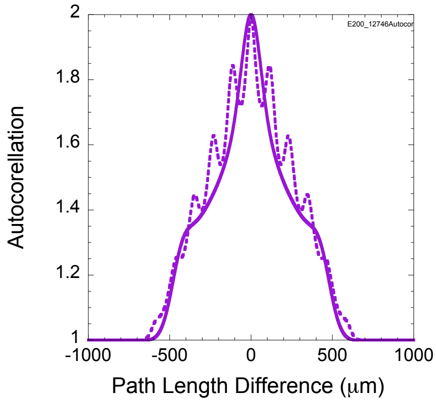

Figure 4: Calculated autocorellation traces for the un-modulated bunch profile of Fig. 2 (continuous line) and for the calculated model profile of Fig. 3 (dashed line).

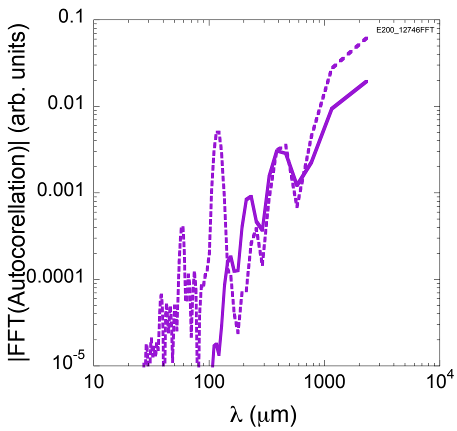

Figure 5: Fourier spectra of the autocorellation traces for the un-modulated bunch profile (continuous line) and for the calculated model profile (dashed line) of Fig. 4. Both traces are normalized to 2.

time constant (many minutes). The signal amplitude (or the CTR energy) can vary depending on the bunch radial modulation depth, the bunch initial charge and radius and the phase of the modulation within the bunch. The effect of the phase of the modulation along the bunch does not prevent the autocorellation measurement since for each event CTR at wavelength λ only interferes with itself, regardless of its absolute phase. However, the other effects will certainly make the signal noisy. We also note that the frequency response and filtering of the various elements used for the CTR interferometry (finite CTR foil size, diffraction, materials transmissivity/reflectivity, detector frequency response, etc.) will also modify the measured traces. However, these additional effects were observed before [13, 16]. They may affect the amplitude of the modulation (on the autocorellation signal), but as long as the period ($\approx \lambda_{pe}$) we are seeking to observed is not suppressed the signal can be visible. We are not attempting to retrieve the un-modulated bunch profile.

Figure 2 suggests that the rise length of the bunch is comparable to the plasma wavelength. This may suggest further influence on the SMI development, as observed in simulations [17].

SUMMARY

The E209 experiment at SLAC-FACET aims at studying the self-modulation instability of long electron and positron bunches in plasmas. We will use three diagnostics to evidence the occurrence of SMI. We evaluate the initial wakefields driven by the electron bunch with a measured longitudinal profile. We use a simple model to illustrate the signal expected from CTR interferometry when SMI occurs. All experimental results will be compared to numerical simulation results, such as those obtained in the proposal phase of this experiment [7].

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