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

P. Muggli∗, O. Reimann, Max Planck Institute for Physics, Munich, Germany
S.J. Gessner, M. Hogan, S.Z. Li, M.D. Litos, SLAC National Accelerator Laboratory, Menlo Park, USA
K. Marsh, W. Mori, C. Joshi, N. Vafaeei-Najafabadi, University of California, Los Angeles, USA
E. Adli, V.K. Berglyd Olsen, University of Oslo, Oslo, Norway

Abstract
We briefly describe the E209 experiment to be performed at SLAC FACET. We show how evidence of 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 autocorrelation trace.

INTRODUCTION
Large amplitude plasma wakefields are most efficiently driven by relativistic, charged particle bunches about one electron plasma wavelength (λpe) long: σz ≡ λpe/(√2π) [1] in a scheme known as the plasma wakefield accelerator (PWFA) [2]. The wakefield amplitude increases with decreasing beam size (σz, σr) and correspondingly increasing plasma density (ne): EWB ∼ n2/3 e [3], as long as the bunch charge remains in a σzσr2 ∼ λ3 pe volume. These dependencies favor short bunches and dense plasmas to reach large wakefield amplitudes, as was the case for example in the SLAC experiments (σz ≡ 20 µm, σr ≡ 10 µm, Ne− ≡ 2 × 1010) that yielded 42 GeV energy gain in only 85 cm of plasma with ne ≡ 2.7 × 1017 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 (σz ≡ 10 cm) proton bunches carrying 6 kJ (400 GeV, SPS) or 112 kJ (7 TeV, LHC, both with 1011 p+) are routinely produced at CERN. When propagating in high-density plasmas, i.e. such that λpe(∼ 10σ3 e/2) ≪ σz, these bunches are subject to the self-modulation instability (SMI) [5]. The SMI originates from the low level transverse wakefields (W⊥, focusing/defocusing) driven by the long bunch that periodically modulate its density (n⊥), thereby feeding back onto the wakefields (Ez,W⊥ ∼ n⊥/n⊥e). The SMI transforms a long bunch into a train of shorter bunches separated by ∼ λpe that can resonantly drive wakefields to large amplitude. An experiment known as A22 Plasma Wakefield Acceleration [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 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.

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.

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A22 Plasma Wakefield Acceleration
since $1/\gamma \sim 1/40000$. This issue is addressed in another paper in these Proceedings [14].

**BUNCH FIELDS AND CTR SIGNAL**

![Image of bunch density profile](image1.png)

**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 $n_e = 8 \times 10^{16} \text{ cm}^{-3}$. The bunch has an energy of 20.35 GeV, is $\approx 600 \mu$m-long, contains $\approx 1.9 \times 10^{10}$ electrons and is focused to $\sigma_r \approx 40 \mu$m radius near the entrance of the plasma. Note that $E_z$ reaches $\approx 900$ 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 the autocorrelation 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 $\lambda_{pe} \approx 118 \mu$m. These traces illustrate that the signal that is expected when/if SMI occurs. The appearance of the peaks in the autocorrelation trace is also visible on its Fourier spectrum (Fig. 5). This simple example shows that the expected peaks in the autocorrelation trace appear, even though the bunch profile may be far from Gaussian or square. We note that experimentally the autocorrelations 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...
The amplitude of the modulation (on the autocorrelation signal) effectswere observed before [13, 16]. They may affect transmissivity/reflectivity, detector frequency response, etc.) interferometry (finite CTR foil size, diffraction, materials response and filtering of the various elements used for the CTR make the signal noisy. We also note that the frequency response is not attempting to retrieve the un-modulated bunch profile.

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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REFERENCES