MEASURING THE SELF-MODULATION INSTABILITY OF ELECTRON AND POSITRON BUNCHES IN PLASMAS∗

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Abstract

We briefly describe some of the features of the E209 experiment at SLAC-FACET. The experiment aims at studying the physics of the self-modulation instability of long electron and positron bunches in dense plasmas. Encouraging initial results were obtained so far. Further experiments will take place soon.

INTRODUCTION

The E209 experiment at SLAC-FACET uses the well instrumented PWFA facility to study the self-modulation instability (SMI) of long charged particle bunches in m-long, dense plasmas [1]. In this context, bunches are considered as long when their duration is many periods of the electron plasma wave (τ ≳ 2π/ωpe ~ n_e0^1/2) or their length many wavelengths of the wave (L ≳ λpe ~ n_e0^−1/2). Here n_e0 is the plasma electron density, ωpe = (n_e0e^2/ε0m_p)^1/2 is the electron (angular) plasma frequency and λpe = 2πc/ωpe.

In the FACET case the electron (e−) or positron (e+) bunch can be between 1.0 and 1.5 mm and the plasma density in the 10^16 to 10^17 cm^−3 range (335 ≳ λpe ≳ 34 μm). This means that the particle bunch can be the equivalent of a few tens of plasma wavelengths long.

The SMI develops because of the positive feedback between the transverse wakefields alternating from focusing to defocusing over a plasma wavelength and the bunch density increasing/decreasing as a result. Transverse bunch slices of larger/lower density drive stronger/weaker wakefields, closing the feedback loop. The instability typically grows and saturates over a few (5 – 10) centimeters with the E209 beam and plasma parameters. The resulting periodic modulation of the bunch density due to the radial change can then resonantly drive wakefields over long plasma distances.

SMI OCCURRENCE

The occurrence of the SMI has (at least) three observable effects on the bunch.

1. The driving of wakefields leads to energy loss (and gain) by the drive bunch particles. This can in principle be measured at FACET with the imaging magnetic spectrometer that has an energy resolution on the order of 0.4% of the incoming particles energy, or better than 100 MeV around the 20 GeV bunch energy [2].

2. The transverse profile of the bunch is modified by the SMI occurrence when observed downstream of the plasma. At that location and without plasma the bunch has typically transverse Gaussian profiles with different rms sizes due to the different emittances in the horizontal and vertical planes (ε_N,ε_y = 50, 5 mm-mrad). When the SMI occurs the transverse profile is expected to have a focused core surrounded by a halo consisting of the defocused particles. This situation has already been observed with e+ bunches approximately λpe-long. In this case the halo originates from the non-linear nature of the focusing fields [3]. This is observed by imaging onto a CCD camera the backward optical transition radiation (OTR) emitted by the bunch when traversing a thin titanium foil placed at 45° with respect to the beam axis. Note that because the OTR wavelength (400-800 nm) is much shorter that the characteristic longitudinal and transverse size of the bunch, this radiation is emitted incoherently.

3. The coherent transition radiation (CTR) emitted by the bunch when traversing another thin titanium foil carries information about the bunch density modulation. Since the modulation is periodic with period ≃ λpe, the wavelength spectrum of the radiation should exhibit a peak at ≃ λpe. The spectrum of the radiation can be obtained using Fourier transform infrared (FTIR) spectroscopy. The CTR is sent through an interferometer and the interferometer signal recorded as a function of the delay or path length difference (PLD) between the two arms of the interferometer. The interferometer signal is then Fourier transformed and one can show that

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3: Alternative Particle Sources and Acceleration Techniques

A22 - Plasma Wakefield Acceleration
the spectrum of the interferometer signal is the same as that of the incoming signal. This method is often used as a diagnostic to retrieve the bunch longitudinal profile (see for example [4]), but less commonly to derive information about the bunch radius since transverse imaging diagnostics can be obtained using for example optical transition radiation (OTR) or wire scanners. However, the bunch form factor is tridimensional and thus carries information about the bunch radius (see for example [5]) and the dependency has been measured with a single bunch [6]. Occurrence of SMI, i.e., of periodic radial modulation, is thus expected to appear as a peak at the modulation wavelength. Information about the modulation depth and the number of periods along the bunch can in principle be retrieved from the peak amplitude, its width and possible harmonics. However, the zeroth order information is in the wavelength of the modulation.

Figure 1: a) Typical image of the bunch when dispersed transversely, i.e. in time, by the deflecting cavity. The deflection direction is in the horizontal plane in this case. b) Ten consecutive bunch profiles obtained in each case by summing images such as that in a) along the no-deflection direction. The bunch length $L$ (FWHM) is about 1.5 mm.

**BUNCH CHARACTERIZATION**

At FACET the linac is setup to compress the ±6 mm bunch exiting the damping ring to ±20 µm in three compression stages [7]. In order to produce the long bunch for the SMI experiments the compressor voltage is lowered and the first compression is only partial. The bunch experiences no further compression along the rest of the linac. The bunch longitudinal profile is determined using a deflecting, X-band RF cavity [8]. Figure 1 shows a typical image of the deflected bunch exhibiting a two-hump profile, as well as multiple profiles acquired successively. The bunch length (FWHM) is on the order of 1.5 mm and rather stable. However, the profile is ambiguous regrading its front/back since the absolute phase of the deflecting RF wave with respect to the bunch arrival time is unknown and may vary from day to day. The bunch front/back can be determined unambiguously by adjusting the phase of the RF in the deflecting cavity to values larger than 90°.

The bunch profiles of Fig. 1 b) show that the bunch as a relatively long rise length when compared the the expected plasma wavelength (< 340 µm). A long rise length is not efficient at seeding the instability and has a significant impact on its growth [9].

Note that long electron and positron bunches delivered by the linac have similar characteristics. The positron bunch population is usually lower ($\pm 1.8 \times 10^{10} \text{e}^+/$bunch) than the electron bunch one ($\pm 2.0 \times 10^{11} \text{e}^/\text{bunch}$). In both cases the initial energy is 20.35 GeV and the bunch is focused at the plasma entrance to a transverse size on the order of 40 µm.

**CTR DIAGNOSTIC**

A thin metallic foil placed in the path of the beam ~2 m downstream from the plasma exit is used as radiator for CTR. The forward CTR is collected by a 2 inch diameter, 15 cm focal length, off-axis parabola (OAP) with an ±4 mm diam-
Preliminary experimental results indicate the presence of peaks in the Fourier spectrum of the CTR interferometric trace at the expected wavelength both for electron and positron bunches. The modulation wavelength scales with plasma wavelength, as expected. OTR images show the formation of a charge core surrounded by a halo, also as expected from the SMI development with electron and positron bunches. Significant energy loss was observed with electron bunches in a lithium plasma, whereas with other plasmas no significant energy loss (or gain) was observed. The too small to measure energy loss in argon and hydrogen plasmas may be due to the small plasma radius that is on the order of the incoming bunch radius and plasma skin depth at the plasma densities explored \((1 - 10 \times 10^{16} \text{ cm}^{-3})\). Another concern is the transverse size of the bunch at the CTR screen. That size must be smaller than the modulation wavelength for fully coherent radiation to be emitted. We are considering moving the CTR diagnostic either closer to the plasma or in the imaging plane of the magnetic spectrometer. In this case CTR measurements would be taken with the spectrometer dipole magnet turned off.

**SUMMARY**

The E209 experiment aims at studying the physics of the self-modulation instability of electron and positron bunches in dense plasmas. It uses the well developed experimental apparatus available at SLAC FACET. Initial results show clear signs of the occurrence of SMI, both with electron and positron bunches. More detailed experiments will be conducted soon. The development of SMI with positively charged bunches is relevant to the AWAKE experiment at CERN that will use a long \((\sigma_z \approx 12 \text{ cm})\) to drive wakefields in a plasma with \(\lambda_{pe} \approx 1.2 \text{ mm}\) [12].

**REFERENCES**