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

P. Muggli†, O. Reimann
Max Planck Institute for Physics, Munich, Germany
L.D. Amorim, N.C. Lopes, L.O. Silva, J.M. Vieira
Instituto Superior Tecnico, Lisbon
J. Allen, S.J. Gessner, M. Hogan, S.Z. Green, M.D. Litos, B.D. O'Shea, V. Yakimenko
SLAC, Menlo Park, California, USA
G. Andonian, C. Joshi, K. Marsh, W. Mori, N. Vafaei-Najafabadi, O. Williams
UCLA, Los Angeles, USA
E. Adli, C. A. Lindstrom, V. B. Olsen
University of Oslo, Norway

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 ($\tau \gg 2\pi/\omega_{pe} \sim n_{e0}^{-1/2}$) or their length many wavelengths of the wave ($L \gg \lambda_{pe} \sim n_{e0}^{-1/2}$). Here n_{e0} is the plasma electron density, $\omega_{pe} = \left(n_{e0}e^2/\epsilon_0 m_e\right)^{1/2}$ is the electron (angular) plasma frequency and $\lambda_{pe} = 2\pi c/\omega_{pe}$. 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^{18} cm^{-3} range ($335 \geq \lambda_{pe} \geq 34\,\mu$m). 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 ($\epsilon_{Nx,y} = 50, 5$ 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 λ_{pe}-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^o 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 $\cong \lambda_{pe}$, the wavelength spectrum of the radiation should exhibit a peak at $\cong \lambda_{pe}$. 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

---

* Work at SLAC is supported by DOE contract DE-AC02- 76SF00515. The authors would like to acknowledge the contributions of J. Yocky and N. Lipkowitz. No useful beam would be available for E209 without them.

† muggli@mpp.mpg.de

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.

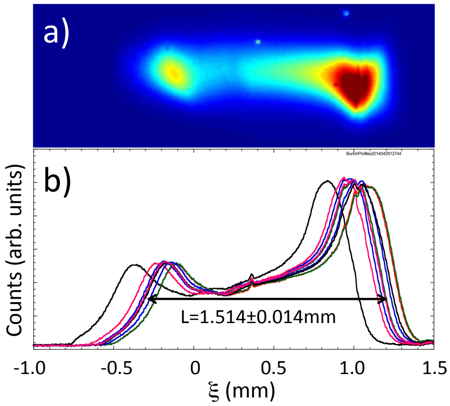

Figure 1: a) Typical image of the bunch when dispersed transversely, i.e. in time, by the deflecting cavity. The deflection direction is in the horizontal plane in this case. b) Ten consecutive bunch profiles obtained in each case by summing images such as that in a) along the no-deflection direction. 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^o. For example when operating at more than the value known as $+90^o$ the front of the bunch will be deflected the most and the back the least, as shown on Fig. 2. Note that at $\pm 90^o$ there is no net deflection (and thus the ambiguity) and that the 0^o case is obtained with the cavity off to avoid large global deflection. Figure 3 shows that when the measurement was made the deflection was towards the lower side of the image, and thus comparing with Fig. 2 the measurement was as in case b). Therefore the weaker feature of the *two-hump* bunch is the front. Note that the feedback system that keeps the beam pointing at the middle of the screen for the 0 and $\pm 90^o$ was turned off for these measurements.

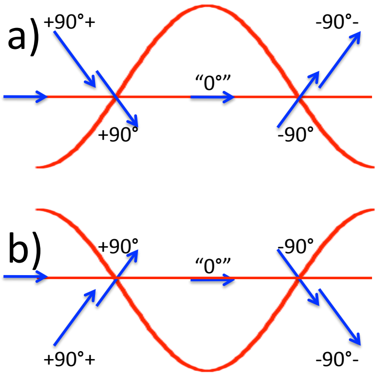

Figure 2: Illustration of the transverse cavity deflecting electric field (red lines) on the incoming electron bunch. The blue arrows represent the bunch deflection at the various phases of the cavity field with respect to the bunch (fixed), in terms of phase. Two cases are illustrated because the absolute phase or the cavity field with respect to the bunch is not known, only its relative value is. In the experiment the 0^o image is obtained with the cavity field off (no deflection). In case a) the peak field deflects the electron bunch upwards and downwards in case b) for relative phase larger than 90^o.

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 ($\cong 1.8 \times 10^{10}$ e^+/bunch) than the electron bunch one ($\cong 2.0 \times 10^{10}$ e^-/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-

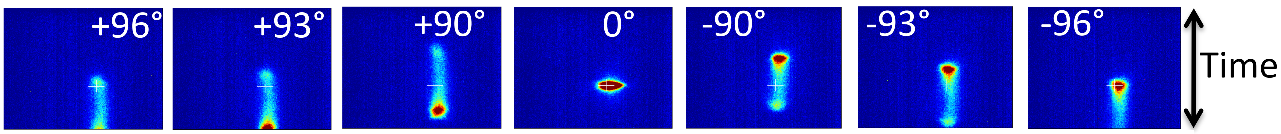

Figure 3: Images of the bunch for seven different phases of the deflecting cavity with respect to the bunch. Only the 0 (cavity off), +90 and -90^o are used for the bunch length measurement. The $\pm 93^o$ and $\pm 96^o$ images are used to remove the ambiguity between the front and back of the bunch. In this case the weaker hump of the bunch is the head, as determined from Fig. 2 b). For these images the deflection direction is vertical (as indicated by "Time").

eter hole to allow for the particle beam free passage. The collimated CTR is sent to a Michelson interferometer with two pyro-electric detectors (pyros). The first one, placed behind the fixed, semi-transparent mirror serves as a reference or normalizing measurement. The second one is placed in the output beam path and records the interference signal. The radiation is focused on both pyros by additional OAPs. The peak signal amplitude is recorded for each relative delay between the two interferometer arms (or PLD) by a gated analog to digital converter.

The data is acquired at a 10 Hz particle beam rate and a 5 Hz laser beam rate. The laser creates the plasma by field-ionization of an alkali metal vapor (lithium) or of a gas (hydrogen or argon) [10]. With this alternate laser ON/OFF, the data sets with and without plasma can be acquired quickly and simultaneously, minimizing the possible effects of laser and particle beam parameters drift (pointing, etc.). The CTR optical line and detectors have transfer and response functions that are wavelength dependent (finite foil size, diffraction, absorption, resonances in the pyros, etc). However, as long as the wavelength of the radiation corresponding to the radial modulation period can be identified, the effect of those wavelength dependent effects can be essentially ignored. The data from the interferometer is then Fourier transformed to look for a peak at the modulation wavelength ($\cong \lambda_{pe}$). Harmonics of the modulation period can also be expected since numerical simulations indicate strong modulation of the bunch radius [11].

PRELIMINARY RESULTS

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 ($1 - 10 \times 10^{16}\,\mathrm{cm}^{-3}$). 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 developement of SMI with positively charged bunches is relevant to the AWAKE experiment at CERN that will use a long ($\sigma_z \cong 12\,\mathrm{cm}$) to drive wakefields in a plasma with $\lambda_{pe} \cong 1.2\,\mathrm{mm}$ [12].

REFERENCES

[1] J. Vieira *et al.*, Phys. Plasmas **19**, 063105 (2012).

[2] E. Adli *et al.*, Nucl. Instr. and Meth. in Phys. Res. A **783**, 35 (2015).

[3] P. Muggli *et al.*, Phys. Rev. Lett. **101**, 055001 (2008).

[4] P. Muggli *et al.*, Phys. Rev. Lett. **101**, 054801 (2008), Phys. Rev. ST Accel. Beams 13, 052803 (2010).

[5] S. Casalbuoni *et al.*, TESLA Report 2005-15 (2005).

[6] O. Grimm *et al.*, EPAC'08 Proceedings, 113 (2008).

[7] M.J. Hogan *et al.*, New J. Phys. **12**, 055030 (2010).

[8] R. Akre *et al.*, Proceedings PAC 2001, p. 2353.

[9] J. Vieira et al., Plasma Phys. Control. Fusion **56**, 084014 (2014).

[10] S.Z. Green *et al.*, Plasma Phys. Control. Fusion **56**, 084011 (2014).

[11] L.D. Amorim and J. Vieira, private communication.

[12] AWAKE Collaboration, Plasma Phys. Control. Fusion 56 084013 (2014).