ELECTRON AND POSITRON BUNCH SELF-MODULATION EXPERIMENTS AT SLAC-FACET*

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Abstract

We describe some of the measurements that will be performed to study the physics of the self-modulation instability of electron and positron bunches. These measurements will be performed at SLAC-FACET in the E209 experiment. The effect of the SMI on the drive bunch itself (electron or positron) will be studied. Differences between electron and positron bunches are expected since the wakefields are driven into the nonlinear regime.

INTRODUCTION

It was recently proposed to use the self-modulation instability (SMI) of long charged particle bunches in dense plasmas to drive large amplitude (~1 GV/m) accelerating wakefields [1]. Using the SMI is a method to produce a train of short bunches out of long bunches available today. Long bunches are interesting for driving wakefields and possibly accelerating particles because they can cary large amounts of energy, between 6 and 110 kJ for the p^+ bunches produced by the CERN SPS or LHC with $\sigma_z \cong$10-12 cm. Short bunches are desirable because the maximum amplitude of the accelerating field scales as $E_{WB} = \left(2\pi m_e c^2/e\right)/\lambda_{pe}$ and wakefields are most efficiently driven by bunches with $\sigma_z \cong \lambda_{pe}$, therefore $E_{max} \propto 1/\sigma_z$. Since $\lambda_{pe} = 2\pi c/\omega_{pe} = 2\pi c/\left(n_{e0}e^2/\epsilon_0 m_e\right)^{1/2}$, shorter bunches also require larger plasma densities n_{e0}.

We proposed to use the long e^- and e^+ bunches the SLAC linac produced for early plasma wakefield accelerator (PWFA) experiments ($\sigma_z \cong$500-700 μm) [2, 3, 4] and the high density plasma available for current experiments $n_{e0} \cong 10^{16}$-10^{17} cm^{-3} [5] to test some of the SMI physics [6].

Theory and simulations predict that as long as the wakefields are in the linear regime, the SMI of positively and negatively charged particle bunches are identical (all other parameters being the same). The wakefields are in the linear regime as long as $E_z \approx (\delta n_e/n_{e0}) E_{WB} \ll E_{WB}$, i.e., the electron density perturbation δn_e that sustains the wakefields satisfies $\delta n_e \ll n_{e0}$. But the nonlinear wakefield regime with $\delta n_e \sim n_{e0}$ is interesting because the accelerating field can reach the wave breaking field amplitude. In this regime the wakefields become anharmonic and in general more favorable for propagation and acceleration of negatively charged bunches. This is due to the pure ion column (focusing for electrons, defocusing for positrons, for example) occupying most of the phase of the wakefields. This regime is often referred to as the blowout or bubble regime. While the wakefields driven by the (long) unmodulated bunch are in the linear regime ($\delta n_{e0} \cong n_{b0} \ll n_{e0}$, see Table 1), the self-modulation and the ensuing resonant wakefield excitation drives the wakefields into the nonlinear regime. As a result, different quantitative outcomes are expected when changing only the sign of the drive bunch charge.

With the beam and plasma parameters available at SLAC-FACET many of the physics aspects of the SMI, including the asymmetry between negatively and positively charged drive bunches can be studied [6]. We outline here some of the measurements currently planned in experiment tentatively scheduled for this Fall and beyond.

PLANNED MEASUREMENTS

The experiment aims at observing as many of the characteristics of the SMI as possible with the FACET infrastructure. The nominal parameters for the beam and plasma are given in Table 1. However, these parameters will be varied over as large a range as possible depending on the setup that will be available at the time of the experiments.

Table 1: E209 Experiment Parameters

Parameter & Symbol	Value
Bunch population, N_b	<2× 10^{10}
Length, σ_z	500 μm
Radius, σ_r	>30 μm
Density, n_{b0}	<2.8 × 10^{15} cm^{-3}
Energy, W_b	20 GeV
Plasma density, n_{e0}	1-30 × 10^{16} cm^{-3}
Wavelength, λ_{pe}	334-61 μm
Frequency, f_{pe}	0.9-5 THz
Length, L_{plasma}	1 m
Relative bunch density, n_b/n_{e0}	0.1-0.003
Bunch length, $k_{pe}\sigma_z$	3.5-51
Bunch radius, $k_{pe}\sigma_r$	0.6-3
Plasma length, $k_{pe}L_{plasma}$	19,000-103,000

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Energy Gain/Loss

The first evidence that SMI has occurred can be obtained by comparing the energy spectrum of the bunch downstream from the plasma location with and without plasma. Without plasma the energy spectrum is that of the incoming bunch, i.e., around 20 GeV and with a correlated energy spread on the order of 1%. The imaging magnetic spectrometer has an energy range from ∼11 GeV to >60 GeV with sub-GeV resolution, reaching ∼100 MeV for the nominal energy [7]. With the plasma, but without occurrence of SMI, the maximum energy gain and loss would be given by the longitudinal wakefields amplitude driven the long bunch multiplied by the plasma length. This amplitude can be calculated from 2D linear theory [8]. The longitudinal field amplitude far behind a symmetric Gaussian current profile distribution bunch with N particles is: $E_{\pm} \cong \frac{e}{4\pi\epsilon_0} N_b k_{pe}^2 e^{\frac{-k_{pe}^2\sigma_z^2}{2}}$, where $k_{pe} = 2\pi/\lambda_{pe}$. Note that this expression is valid for narrow bunches ($k_{pe}\sigma_r \ll 1$, σ_r the rms Gaussian bunch radius), and it overestimates the fields driven in the $k_{pe}\sigma_r \sim 1$ bunches of these experiments. With the parameters of Table 1 (n_{e0}=10^{16} cm^{-3}), this amplitude is ≅630 MV/m. Therefore, for the case of a 1 m-long plasma, the energy gain/loss would be less than 0.63 GeV, much lower than the one predicted by simulations when SMI occurs (>5 GeV both for electrons and positrons, see Fig. 5 in [6]). The wakefield amplitude and thus the energy gain are even smaller at larger plasma density (larger $k_{pe}\sigma_r$). Even the product of the post-saturation amplitude (>7 GV/m, see Fig. 3 in [6]) with a 1 m plasma length leads to multi-GeV gain and loss.

For these experiments the plasma will be created by laser-ionization of an alkaline metal vapor [9]. The laser pulse is focused to a line along the beam propagation axis by an axicon lens. The axicon maps the radial intensity of the laser pulse onto position along the line focus. Therefore, the plasma length can in principle be varied by changing the transverse size of the laser pulse on the axicon, for example by an iris. Variation of the plasma length could provide information about variations of the longitudinal wakefields along the plasma, or even, with short enough plasma length, about the growth of the SMI itself.

Note that since the energy gain and loss are much larger than the incoming energy content of the bunch, no evidence of the periodic structure of the wakefields is expected in the energy spectra. This is unlike what was observed in experiments at BNL-ATF with a 50 pC, 60 MeV electron bunch and a 2 cm-long plasma [10]. Note also that unlike in experiments planed for example at CERN, in these experiments the plasma length (∼1 m) is much larger than the saturation length of the SMI (∼5-10 cm). Also, the expected energy gain and loss can be comparable to the bunch incoming energy. Therefore, energy change by drive bunch particles is a suitable diagnostic for SMI occurrence.

Transverse Modulation

Of course, the SMI occurs because of the transverse wakefields. The observation of the effect of the longitudinal wakefields, although the goal of particle acceleration experiments, is only indirect evidence of SMI development. The longitudinally periodic modulation of the bunch density is the result of local focusing and defocusing. Transition radiation [11] is often used to characterize the time structure of charged particle bunches. While incoherent optical transition radiation (OTR) carries direct information about the bunch time structure it is difficult to measure in the plasma frequency range of these experiments (∼1-5 THz). The information contained in the long wavelength, coherent range of transition radiation (or CTR) can be measured using interferometry. In this case the information is contained in the transverse, bunch radius dependent form factor. The effect of this bunch factor has been observed at lower energy at the FLASH facility [12]. While the effect of radial modulation tends to be suppressed for high-energy bunches that emit CTR essentially in the forward direction (peak angle at $\sim 1/\gamma$, γ the particles' relativistic factor), this effect has previously been observed at FACET [13].

Therefore, CTR interferometry should reveal the time structure of the bunch when SMI occurs. With a typical Mach-Zender interferometer arrangement, the periodicity is expected with a path length difference $\Delta z \cong \lambda_{pe}/2$. Note that the interferometer trace will be obtained from multiple SMI events with parameters as similar as possible. Although the amplitude of the modulation and its phase along the bunch may vary, its periodicity should remain essentially constant, as long as the plasma density is reproducible. The metal vapor is produced in a system with a long thermal time constant (minutes) [14]. The laser ionization is a threshold process rather insensitive to the small shot-to-shot laser intensity variations expected. These variations should therefore not impede the SMI period determination.

Seeding and Hose Instability

An important topic is that of the seeding of the SMI. The SMI can be seeded to reduce the plasma length for it to reach saturation at the same maximizing the length available for acceleration with a fixed plasma length. In addition, the seeding should allow for the fixing of the phase of the wakefields along the drive bunch. Without seeding, the SMI grows from noise and the phase of the SMI wakefield is random with respect to position along the bunch. The position of the seed (short laser pulse or particle bunch, ionizing laser pulse, sharp bunch leading edge) determines the wakefields starting point. A witness bunch to be accelerated can then be injected into the optimum accelerating and focusing phase of the wakefields once their zero is fixed.

Another important issue is the mitigation of the competing transverse hose instability (HI) [15]. This instability competes with SMI and could destroy the drive bunch before SMI or acceleration can occur. This effect has been

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illustrated for the case of a proton bunch in Ref. [16]. Calculations and simulations indicate that seeding the SMI allows it to win over the HI, at least under some circumstances and plasma length [6, 17].

A notch collimator method is available at FACET to produce a drive/witness bunch train for PWFA experiments [5, 18]. This method will be used to create a sharp (when compared to λ_{pe}) leading edge at various positions along the bunch. The effect of seeding on energy gain and hosing will be studied.

Varying Parameters

The development of the SMI and of the HI depend on the initial beam and plasma parameters. The effect of the bunch charge species, population, radius, as well as of the plasma density and length on all the above measurements will be studied in details.

SUMMARY

The E209 experiment was proposed to SLAC FACET to study the physics of SMI thanks to the available long ($\sim$500 μm) particle bunches (electron/positron), source of dense plasma (n_{e0}=10^{16}-10^{17} cm^{-3}), seeding mechanism (notch collimator) and diagnostics: large range, good resolution energy spectrometer, OTR, CTR, etc. The effects of SMI onto the drive bunch only will be measured, no particles will be injected in the wakefields to be accelerated. These experiments are scheduled for the Fall 2013 and beyond.

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