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Head Erosion with Emittance Growth in PWFA

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Abstract. Head erosion is one of the limiting factors in plasma wakefield acceleration (PWFA). We present a study of head erosion with emittance growth in field-ionized plasma from the PWFA experiments performed at the FACET user facility at SLAC. At FACET, a 20.3 GeV bunch with 1.8×10^{10} electrons is optimized in beam transverse size and combined with a high density lithium plasma for beam-driven plasma wakefield acceleration experiments. A target foil is inserted upstream of the plasma source to increase the bunch emittance through multiple scattering. Its effect on beam-plasma interaction is observed with an energy spectrometer after a vertical bend magnet. Results from the first experiments show that increasing the emittance has suppressed vapor field-ionization and plasma wakefields excitation. Plans for the future are presented.

Keywords: plasma wakefield acceleration, head erosion, emittance, field-ionized PWFA.
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INTRODUCTION

In plasma wakefield acceleration (PWFA), the benefits of having high gradient, low energy spread, and emittance preservation of the accelerating beam have made it an attractive choice for advanced accelerator of the future. In particular, PWFA with plasma field-ionized by the bunch itself has the advantage of producing high accelerating gradients, on the order of 10 GeV/m, without timing or alignment issues between the bunch and the plasma. In the PWFA experimental program at FACET we aim at addressing any critical physics issues for realizing a single module of a plasma-based accelerator for a future linear collider. One of the important issues is bunch head erosion that has been shown to be one of the limiting factors for energy gain in a PWFA driven by a relatively large emittance bunch [1].

In field-ionized PWFA the head of the bunch travels in a neutral gas and expands along its vacuum trajectory as the space charge field of the bunch ionizes the gas or vapor. Then the space charge force of the beam expels plasma electrons, creating an ion channel that exerts a restoring force to pull electrons back on the propagation axis. This focusing provided by the ion column allows the bunch electrons to propagate over long distances without expansion. However, the particles in the front of the bunch are not focused and the bunch density and electric field decrease locally. This phenomenon, illustrated in Figure 1, leads to bunch head erosion and causes the ionization front to slip further back from the head of the bunch. Because it takes additional time to ionize the plasma, head erosion is more pronounced and significant in field-ionized PWFA than pre-ionized PWFA.

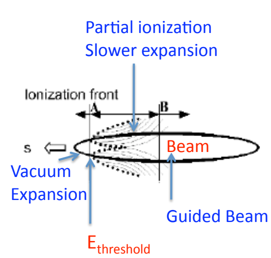

FIGURE 1. An illustration of head erosion.

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For field-ionized plasma, erosion rate is predicted from theoretical calculations and simulations [2] for a matched beam to be:

$$V[\mu\text{m/m}] = (3.6617\times10^4)\varepsilon_i^{1.73}[\text{eV}]\frac{\varepsilon_N[\text{mm}\cdot\text{mRad}]}{\gamma}\frac{1}{I^{3/2}[\text{kA}]}, \quad (1)$$

where ionization energy ε_i is 5.39 eV for lithium (Li) as the vapor source, ε_N is the normalized bunch emittance, γ is the bunch relativistic factor, and I is the bunch current. It measures the amount of beam coordinate distance the ionization front slips back over the propagation distance. Equation 1 explicitly indicates that the scale of the rate at which the beam head erodes is driven by three controllable parameters: the bunch normalized emittance, energy and current. In practice, varying the energy or current requires great care to make sure that the beam trajectory, emittance and shape remain the same, and that the feedback systems are stable. For example, a change in beam current results in change of emittance due to wakefield effects in the linac, and thus makes the parameters more difficult to control. In our experiments the simplest way to vary emittance without change of beam conditions is to insert a retractable emittance spoiler. Therefore, we choose to study the dependency of head erosion on emittance growth in field-ionized plasma at FACET.

EXPERIMENTAL APPARATUS

The PWFA experiments [3] were performed at FACET – the Facility for Advanced aCcelerator Experimental Tests at SLAC National Accelerator Laboratory. A 20.3 GeV bunch with 1.8×10^{10} electrons is longitudinally compressed to 35 μm and focused to 30 μm × 30 μm transverse size at an interaction point (IP). The achieved beam parameters and corresponding plasma parameters at the IP in single bunch operation are shown in Table 1, as of June 9th, 2012.

TABLE (1). FACET beam parameters and corresponding plasma parameters at the interaction point for PWFA experiments in single bunch operation.

Parameter	Achieved Value
Particle Type	Electrons
Beam Energy	20.3 GeV
Energy Spread (r.m.s)	~1%
Dispersion (η)	≥0.014 m
Bunch Length (σ_z)	~35 μm
Transverse Size (σ_x, σ_y)	21 μm, > 25 μm
Peak Current	20 kA
Repetition Rate	1-10 Hz
Plasma Type	Lithium
Vapor Density (cm^{-3})	$(0.5–2.5)\times10^{17}$
Plasma Length	Variable, 20-40 cm

The experimental setup (Figure 2) for the PWFA experiments is located on the IP optical table in Sector 20 of the SLAC linac. The ultra-short electron bunches pass through a one-micron thick titanium foil oriented at 45° (relative to the beam axis) that reflects optical transition radiation (OTR) that is captured by a CCD camera to determine the bunch transverse size and shape. A wire scanner provides an independent measurement of the beam size. To parameterize head erosion with beam emittance, a target foil can be inserted in the beamline upstream of the IP before interacting with the plasma source in order to increase emittance through multiple scattering. The incoming electron bunch interacts with the neutral lithium vapor produced in a heat-pipe oven [4] that is mounted on a movable table. With a high peak current and a small transverse size, the electron bunch ionizes the vapor and drives large amplitude wakefields in the plasma to provide high gradient acceleration. When the oven is bypassed, an OTR foil at the IP (IPOTR) provides a measurement of the beam size at the plasma entrance. Another OTR foil at the DSOTR location provides a measurement of the beam size after the beam exits the oven. An imaging magnetic spectrometer further downstream disperses the electrons vertically according to their energy. Any energy changes resulting from the beam-plasma interaction are observed in a Cherenkov light based energy spectrometer [5] after the vertical bend magnet and before the beam dump, not shown in Figure 2. More details of beam diagnostics are discussed elsewhere [6].

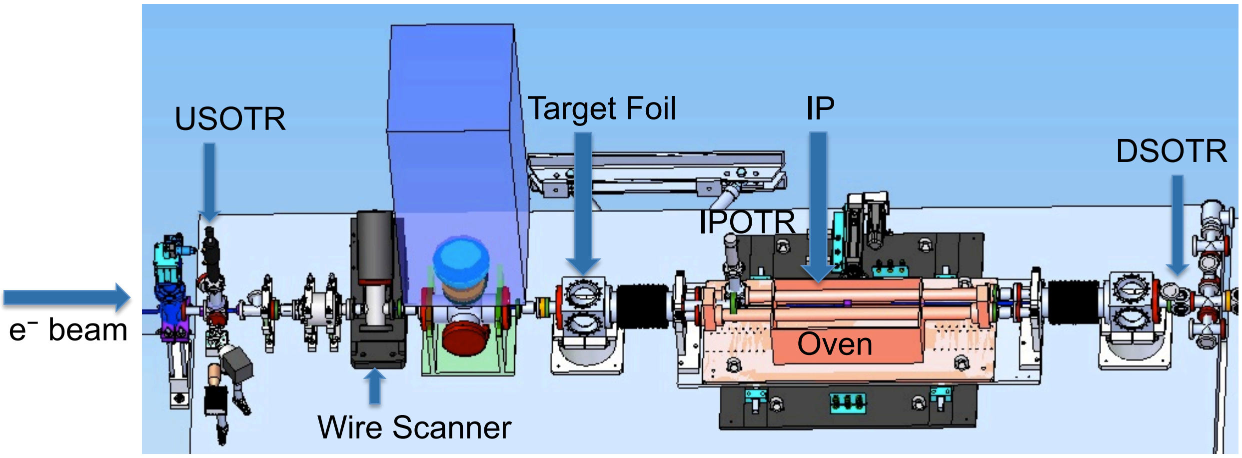

FIGURE 2. The experimental setup and beam diagnostics near the IP.

SIMULATION RESULTS

To study the beam head erosion resulting from nonzero beam emittance, we need a beam that is dense enough to ionize the lithium vapor and to drive plasma wakes but large enough in emittance to limit the energy gain. The amount of emittance growth depends on the type and thickness of the material to be used as the target foil. Therefore, the target foil for emittance spoiling should be chosen accordingly. The effect of various materials on the beam size and emittance was studied with the FACET design beam parameters in ELEGANT simulations [7]. Simulation results for the normalized emittance ε_N and bunch size σ_r at IP as a function of effective radiation length χ_{eff} are shown as data points in Figure 3, where χ_{eff} is defined as thickness divided by the material's radiation length. A linear fit to the emittance as a function of effective radiation length gives

$$\varepsilon_N[\mu m] = 12110\chi_{eff} + 260. \qquad (2)$$

A second order polynomial fit to the transverse beam size at IP as a function of effective radiation length gives

$$\sigma_r[\mu m] = -45680\chi_{eff}^2 + 2440\chi_{eff} + 20. \qquad (3)$$

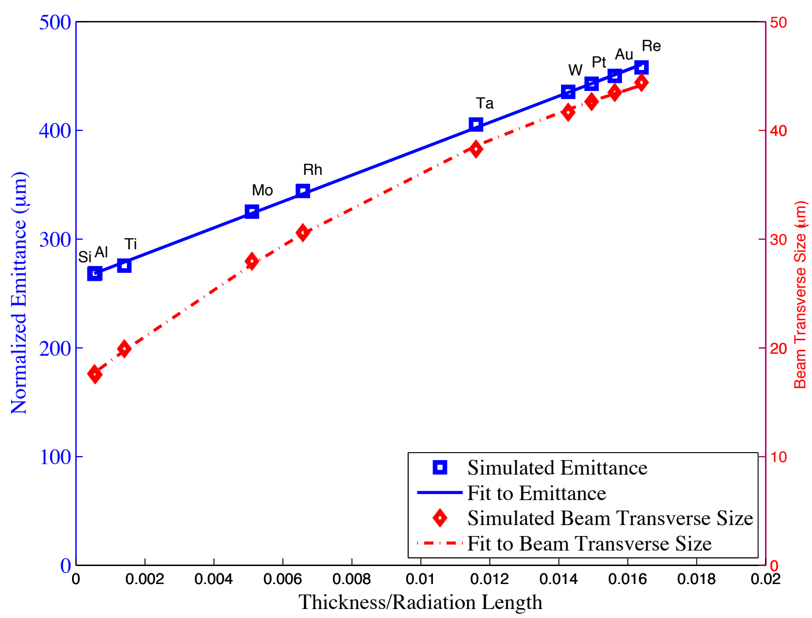

FIGURE 3. Simulated emittance (in blue) and beam transverse size (in red) at IP vs the effective radiation length for various materials. The blue solid line and red dashed line are first and second order polynomial fits to the emittance and transverse size, respectively.

To describe the beam-plasma interaction, QuickPIC simulations [8] were performed with the FACET design beam parameters (shown in Table 2) and with beam parameters corresponding to the projected emittance growth due to a 50-micron thick gold foil. Both cases are simulated for a uniform Li vapor density of 1×10^{17} cm^{-3} interacting with a 23 GeV beam with 2×10^{10} electrons. The bunch electron density is much greater than the plasma electron density and the beam-rise length $k_p\sigma_z$ is 1.19, where k_p is plasma wavenumber. This bunch drives a large amplitude wake in the nonlinear blowout regime. The value of $k_p\sigma_r$ is 0.96 without the target foil and $k_p\sigma_r = 2.65$ with the 50-micron thick gold foil. After propagating through 39 cm of Li vapor, the electron profiles along the propagation direction z are shown in Figure 4 (a) and (c) and their corresponding longitudinal wakefield in Figure 4 (b) and (d). The plasma electrons are expelled away from x=0 (beam axis) while the drive bunch electrons are concentrated in the center of the bubble. The electron bunch density is about a factor of 4 smaller for the case with the spoiled emittance which results in a larger erosion rate, as well as a smaller maximum longitudinal accelerating field.

TABLE (2). Input beam parameters for QuickPIC simulations.

	σ_x (μm)	σ_y (μm)	σ_z (μm)	ε_{Nx} (μm)	ε_{Ny} (μm)
Without Target Foil (Design Beam)	15	6	20	260	16
With a 50-μm Thick Gold Foil	33	30	20	450	70

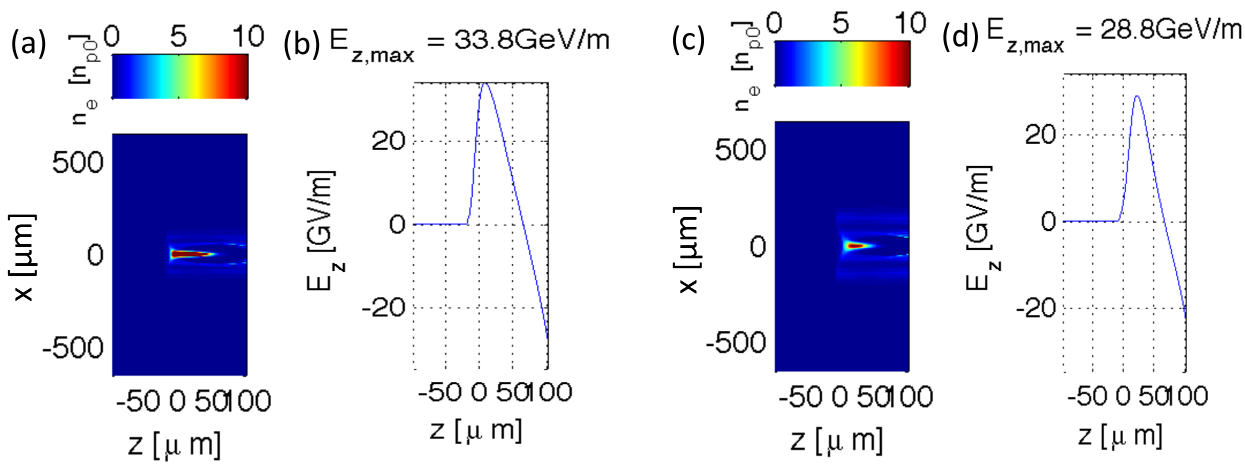

FIGURE 4. QuickPIC simulations. (a). Plasma and beam electron density for design beam parameters. (b). Longitudinal wakefield with design beam parameters. (c). Plasma and beam electron density for the case of a larger beam emittance. (d). Longitudinal wakefield for the case of a larger beam emittance.

Based on the above simulation results, a 50-micron thick gold foil increases the emittance by a factor of 1.7 in x and 4.4 in y and more importantly still allows ionization for PWFA, assuming design beam parameters were achieved. This gold foil is the choice of target foil for the first experiments.

EXPERIMENTAL RESULTS

During the FACET users run in May 2012, data were taken with single bunches of 20.3 GeV electrons. A set of sample data taken at a rate of 1 Hz on May 28, 2012 is represented in Figure 5. When the oven was bypassed (no plasma), no change in energy was observed as shown in Figure 5 (a). Both energy loss and energy gain were observed in Figure 5 (b) after the beam passed through a Li vapor length of 39 cm with density of 2.5×10^{17} cm^{-3}. Figure 5 (b) suggests that the head of the bunch drove large amplitude wakefields in the Li plasma to accelerate the tail of the bunch. However, no significant deceleration and acceleration were observed in Figure 5 (c) when the 50-μm thick gold foil was inserted into the beam path to spoil the emittance. We postulate that this is due to the fact that the beam was not dense enough to ionize the lithium vapor after the emittance spoiling. It is also possible that the beam had totally eroded due to the large emittance.

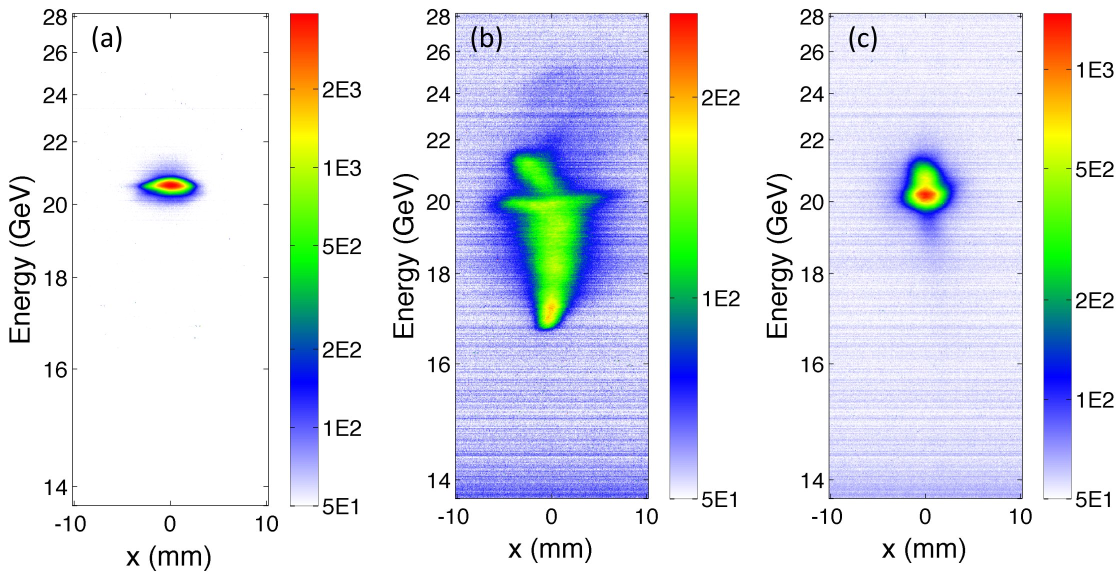

FIGURE 5. Energy spectrum of the beam. (a). No Li plasma interaction when the oven is bypassed. (b). Beam interacts with the Li plasma; evidence of acceleration and deceleration. (c). A 50-μm thick gold foil spoils the emittance before the Li plasma interaction; no appreciable acceleration and deceleration.

SUMMARY AND PLANS

The PWFA experiments at FACET have demonstrated accelerating gradients greater than 10 GeV/m [9] provided by single electron bunches with high density, field-ionized lithium plasma. We also showed that vapor field-ionization and plasma wakefields excitation can be suppressed by increasing the incoming bunch emittance. Some improvements in the next experiments are required to quantify head erosion. We will run the PWFA experiments with a rubidium source whose ionization threshold is lower than lithium and is thus easier to ionize. This will decrease the rate of head erosion. Moreover, we will try thinner target foils and materials with lower atomic number to reduce emittance growth in order to ensure ionization can occur and a plasma wake can be generated for head erosion studies. In addition, a new design of the emittance spoiling foil holder will be in place for the next experiments to provide more data points than in May 2012. One of the prototypes for the emittance spoiler is shown in Figure 6 where three different foils are mounted in one holder, actuated by an inline stepper motor to vary the resulting emittance. Future results will be reported in later publications.

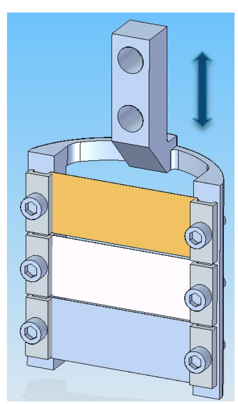

FIGURE 6. A prototype of emittance spoiler for the next experiments. This holder can mount three foils with different effective radiation lengths, represented by the gold, white, and blue color. It can be inserted vertically in and out of the beam path.

ACKNOWLEDGMENTS

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