

FIRST RESULTS FROM THE ELECTRON HOSE INSTABILITY STUDIES IN FACET*

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Abstract

We present the status of transverse instability studies in the plasma-wakefield acceleration experiments at FACET. PIC simulations indicate that a head-tail tilt on the electron beam as it enters to the plasma may lead not only to hosing but also a coherent transverse motion of the system beam and plasma bubble. The FACET dump line is equipped with a Cherenkov light based spectrometer which can resolve transverse motion as function of beam energy. We discuss new simulation results and the current status of the experiment.

INTRODUCTION

Beam driven plasma wakefield acceleration (PWFA) holds promise for accelerating fields of orders magnitudes larger than conventional rf acceleration. Accelerating fields of the order of 10 of GV/m have already been demonstrated experimentally at a number of experiments [1]. At the Facility for Advanced Accelerator Experimental Tests at SLAC (FACET) we aim to further investigate the feasibility of PWFA as a very-high gradient particle accelerator [2]. In this paper we focus on transverse instabilities in the single-bubble regime. We study the well-known electron-hose instability for which plans for experiments at FACET are discussed in [3]. During this work we have observed a coherent transverse motion that to our knowledge is not described by earlier PWFA theory. We present here new simulation results and experimental considerations for studying both transverse effects at FACET. We also present the status of the transverse dynamics experiments at FACET.

ELECTRON HOSE INSTABILITY

The electron hose instability is the result of interaction between the electron beam and the plasma sheath-electrons, resulting in an amplification of an initial oscillation at the tail of the electron beam [4]. Substantial simulation work and theoretical developments have been done to understand and quantify this instability [5]. At FACET we aim to perform experimental verification and benchmarking of hosing [3], by a careful choice of beam and plasma parameters and by controlling the incoming beam head-tail tilt as described in the following.

PARAMETER CHOICES

In the FACET 2012 run a Lithium oven without pre-ionization is used for the PWFA experiment. The FACET

beam must thus have a charge density high enough to field-ionize the Lithium gas. On the other hand, we desire a bunch sufficiently long to sample the accelerating phase of the plasma wakefield, since the spectrometer will then distribute the tail electrons, which will undergo the strongest hosing, at different angles than the decelerated and eroded part of the bunch. We suggest to work with a Lithium gas density of $n_0 = 3.6 \times 10^{17}/\text{cm}^3$ and a flat top gas length of 30 cm; both parameters in the upper range of what the installed heat-pipe oven can produce [6]. The corresponding plasma wavelength is $\lambda_p = 56 \mu\text{m}$.

The FACET chicane can be set to either full beam compression or over/under compression as illustrated in Figure 1. We suggest to work with an $R_{56} = 7 \text{ mm}$ yielding a bunch length of $\sigma_z = 30 \mu\text{m}$. This ensures that a good fraction of the bunch will sample the accelerating field. For the nominal FACET linac charge of 3.2 nC the resulting peak current of 13kA is sufficient for field-ionization. We assume transverse spot sizes $\sigma_r \leq 20 \mu\text{m}$ in vacuum, a performance target for the FACET commissioning [7]. We further assume a beam energy of 20 GeV and normalized emittances of $\epsilon_{N,\{x,y\}} = \{550,55\} \mu\text{m}$. Taking into account the additional focusing by the gradual plasma ramp, we obtain a transverse spot size at the entrance of the plasma density flat top of about $\sigma_r = 6 \mu\text{m}$. We have assumed a full plasma-ramp focus effect giving a factor ~ 10 decrease in beta function. The resulting initial beam to plasma density ratio is about 4, yielding a complete blow-out of plasma electrons resulting in an ion-channel surrounding the electron beam. Figure 2 illustrated the initial plasma bubble formation calculated with QuickPIC [8] for these beam and plasma parameters.

Because the FACET beam is over-compressed at the proposed chicane setting the beam will have a remaining chirp (z-p correlation) after compression. This gives the possibility to induce a transverse head-tail tilt (z-x correlation) at the plasma by changing the dispersion. We control the dispersion by moving the two chicane sextupoles; moving the sextupoles in opposite horizontal directions changes the horizontal dispersion while other beam parameters are constant to first order. Elegant [9] simulations show that a horizontal dispersion of 1 mm gives a maximum beam z-x correlation of about 5% at the IP.

COHERENT TRANSVERSE MOTION

When modeling and simulating PWFA scenarios for FACET we have observed that QuickPIC simulations of beams with a large tilt ($> \sim 1/100$ rad) propagating in field-ionized plasmas show a net transverse beam drift.

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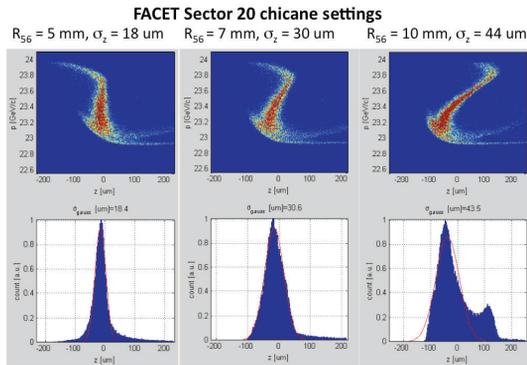


Figure 1: The electron bunch z - p correlation (top) and charge distribution (bottom) at the plasma interaction point for three different chicane settings, as simulated by Elegant. a) $R_{56} = 5$ mm: maximum compression, the shortest bunch length, and no remaining z - p correlation. b) $R_{56} = 7$ mm: significant z - p correlation, relatively short bunch and near Gaussian distribution. c) $R_{56} = 10$ mm: strong z - p correlation, two-bunch charge distribution. We suggest $R_{56} = 7$ mm as a working point for the transverse studies.

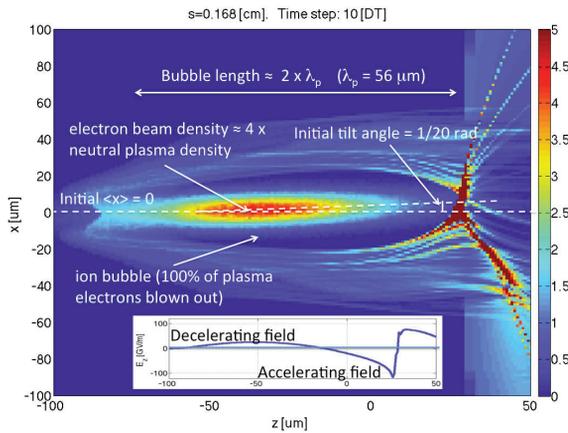


Figure 2: Beam density and plasma electron density just after the beam has entered the flat-top portion of the Lithium column with a density of $n_0 = 3.6 \times 10^{17}/\text{cm}^3$. Beam traveling towards the left. The Gaussian beam enters with a head-tail tilt of $1/20$ rad. The beam space charge field is high enough to fully ionize the Lithium vapour. The beam density is four times higher than the plasma density after ionization, sufficient to create an ion bubble where 100% of the plasma electrons are blown out. The bubble length is about $100 \mu\text{m}$, two times the plasma wavelength. The rms bunch length is $\sigma_z = 30 \mu\text{m}$ and a significant fraction of the beam electrons sample the accelerating part of the wake field, present in the right third of the bubble.

In a moving window following the electron beam as it travels through the gas, both the beam centroid and the plasma bubble electrons undergo a coherent transverse motion (CTM), increasing in speed as the beam propagates through the plasma. For the parameter choices discussed above, after traveling through $s = 30$ cm of Lithium gas, the slice transverse offset and angle induced by CTM on the tail part of the beam is $\Delta \langle x \rangle_{\text{CTM}}|_{s=30\text{cm}} \approx 50 \mu\text{m}$ and $\langle x' \rangle|_{s=30\text{cm}} \approx 250 \mu\text{rad}$ respectively. In com-

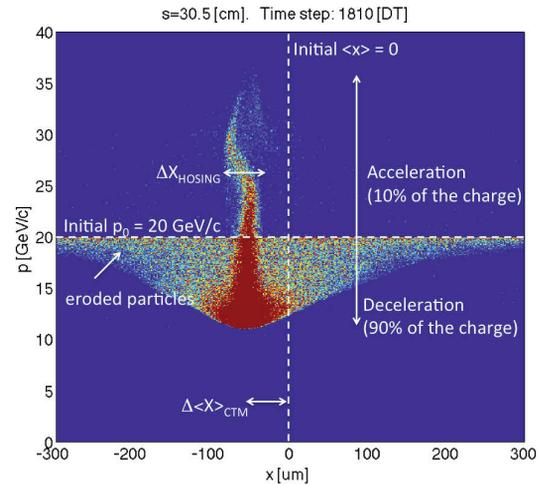


Figure 3: Beam density in the x - p space after the beam has propagated through 30 cm of plasma. Ten percent of the beam has been accelerated. The accelerated electrons are in the tail part of the bunch and the tail centroid oscillations due to the initial head-tail tilt have been amplified by about a factor 10 due to the electron hose instability [3], yielding a peak-to-peak amplitude of the oscillations of about $50 \mu\text{m}$. In addition, the electron bunch has drifted horizontally by $50 \mu\text{m}$ with respect to the initial axis. This drift is not present for head particles that have already eroded away; see Figure 4.

parison, the peak-to-peak tail oscillation after hosing is $\Delta x_{\text{HOSING}} \approx 50 \mu\text{m}$. Figure 3 illustrates both hosing and the CTM after propagating the beam through 30 cm of Lithium gas with an initial tilt angle of $1/20$ rad. Figure 4 shows the magnitude of the CTM at a tail slice located σ_z behind the beam center, for three different head-tail tilt angles, normalized to the initial tilt angle. The graphs show that the CTM is proportional to the tilt angle. The magnitude depends strongly on the beam parameters like emittance and charge profile. For low emittance beams we observe small or no CTM. The CTM is reproduced by the momentum-conserving 3D PIC code Osiris [10].

While a complete physical understanding of the CTM is still under development, we believe the transverse motion might be linked to the fact that while the head of the beam erodes, the new head of the beam picks up a transverse momentum from betatron motion. Earlier hosing theory [5] was developed neglecting channel deformation. The simulation results indicate that for large tilts this assumption may not be valid.

DIAGNOSTICS

The main diagnostics for the transverse instability studies at FACET is a Cherenkov light based spectrometer [11]. After interacting with the plasma the electron beam exits into air. The beam emits Cherenkov radiation at a rate of about 30 photons per electron per meter. Digital cameras captures the light emitted between pairs of Si wafers, where the first wafers blocks radiation generated up to that point

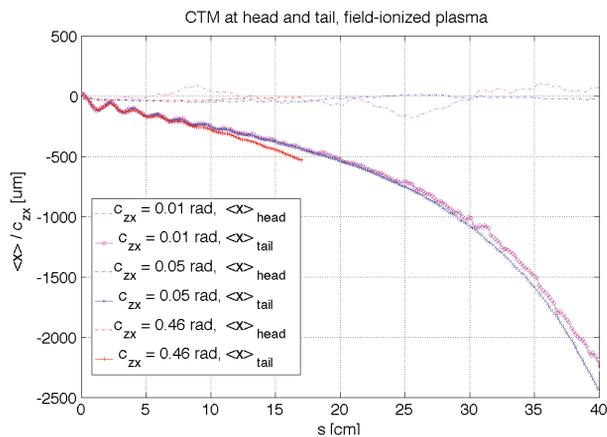


Figure 4: Coherent transverse motion observed in PIC simulations where an electron beam enters neutral Lithium vapour with a large initial head-tail tilt, c_{zx} . The graphs show the horizontal centroid motion of a slice located a distance σ_z behind the beam center for three different tilt angles, 0.01 rad, 0.05 rad and 0.46 rad, normalized to the initial angle. The 0.46 rad line is cut where the beam approaches the simulation box edge. We observe that the motion is building up coherently in the opposite direction of the initial tilt, and picks up speed as the beam propagates through the plasma. The centroid slice at the head of the beam, which quickly erodes away, does not observe the coherent motion and the head slice centroid remains at zero.

and the second wafer reflects the radiation generated between the wafers into an optical line. Two independent optical lines/cameras are installed; one with high resolution and small field of view, and one with large field of view but lower resolution. The electron beam is imaged onto the air-gap of the Cherenkov emitters using two quadrupoles, resulting in a magnification of spot sizes from plasma exit to the air-gap of a factor 5.5 in x and a factor 0.7 in y . A spectrometer bend induces a vertical dispersion of $D_y = 8$ cm at the air-gap. The high resolution camera gives a horizontal resolution of less than $10 \mu\text{m}$. The large field of view line covers an energy range from 13 GeV to 28 GeV. The two systems are designed to together have both the resolution and the range needed to investigate the transverse effects discussed in this paper.

EXPERIMENTAL STATUS

At the time of writing, the FACET plasma-wakefield acceleration experiment is being commissioned [7]. The FACET beam transverse spot-sizes and bunch compression are currently small enough to achieve a small level of Lithium gas ionization and beam-plasma interaction, as illustrated in Figure 5. To study experimentally the transverse instabilities discussed in this paper, a significantly higher level of ionization is needed, in particular to achieve sufficient acceleration to observe electrons having undergone hosing in the high-energy part of the spectrum.

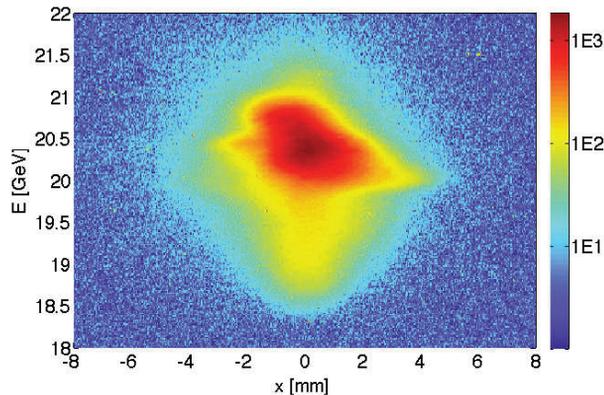


Figure 5: Experimental status : an electron pulse is imaged onto the Cherenkov spectrometer after traversing through a 24 cm long Lithium gas with density of $n_0 = 2.4 \times 10^{17}/\text{cm}^3$. A small deceleration tail of about 1 GeV deceleration is shown. No significant acceleration is observed. This pulse was typical of the ionization level during the first experiments to study transverse PWEA effects in FACET, since the FACET machine is still being commissioned. This figure should be compared with Figure 3.

CONCLUSIONS AND OUTLOOK

We plan to continue the experimental studies of both hosing and the CTM. The studies will also be performed for two-bunch acceleration experiments. An experimental benchmarking of these effect will be sought and resulting tolerances for PWEA for use in linear colliders and other applications will be developed. In parallel we work at developing a solid physical understanding for the coherent transverse gas motion reported in this paper.

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