STATUS OF PLASMA ELECTRON HOSE INSTABILITY STUDIES IN FACET*

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Abstract

In the FACET plasma-wakefield acceleration experiment a dense 23 GeV electron beam will interact with lithium and cesium plasmas, leading to plasma ion-channel formation. The interaction between the electron beam and the plasma sheath-electrons may lead to a fast growing electron hose instability. By using optics dispersion knobs to induce a controlled z-x tilt along the beam entering the plasma, we investigate the transverse behavior of the beam in the plasma as function of the tilt. We seek to quantify limits on the instability in order to further explore potential limitations on future plasma wakefield accelerators due to the electron hose instability.

INTRODUCTION

The FACET plasma-wakefield experiment at SLAC [1] will study beam driven plasma wakefield acceleration. A dense 23 GeV electron beam will interact with lithium or cesium plasma, leading to plasma ion-channel formation. The interaction between the electron beam and the plasma sheath-electrons drives the electron hose instability, as first studied by Whittum [2]. While Ref. [2] indicates the possibility of a large instability growth rate for typical beam and plasma parameters, other studies including [3, 4] have shown that several physical effects may mitigate the hosing growth rate substantially. So far there has been no quantitative benchmarking of experimentally observed hosing in previous experiments [1]. At FACET we aim to perform such benchmarking by for example inducing a controlled $z-x$ tilt along the beam entering the plasma, and observing the transverse behavior of the beam in the plasma as function. The long-term objective of these studies is to quantify potential limitations on future plasma wakefield accelerators due to the electron hose instability.

THEORY

Ref. [2] describes how coupled motion between an electron beam off center in a pre-formed ion-channel and the surrounding plasma sheath electron may lead to an amplification of an initial transverse offset x_0 by a factor

$$x(s,\xi)/x_0(\xi) \sim 0.34 e^{A(s,\xi)}$$

where the growth factor, A, depends on both the distance traversed in the plasma, s, and the relative position along bunch in a co-moving frame, $\xi = ct - z$, as

$$A(s,\xi) = 1.3[(k_\beta s)(\omega_0 \xi)^2]^{1/3} \qquad (1)$$

For typical FACET parameters, a Lorentz factor of $\gamma = 45,600$ and a plasma wavenumber $k_p = 36 \times 10^3 \mathrm{mrad/m}$, $k_\beta = k_p/\sqrt{2\gamma} = 120$ mrad/m and $\omega_0 = k_p/\sqrt{2} = 26$ mrad/m. FACET will study interactions in plasmas of length from about 20 cm to 100 cm, with bunch lengths σ_z from about 20 μm to a few 100 μm. According to Eq. (1) a 20 μm bunch penetrating 100 cm into the plasma would have the initial offset of a tail slice located at $\xi = 2\sigma_z$, x_{t0}, amplified by a factor

$$x_t/x_{t0} = 0.34 \times e^{A(100\mathrm{cm}, 40\mu\mathrm{m})} \sim 230$$

However, such large magnitudes of hosing growth have not been reported in earlier experiments. More recent work [3, 4] have studied mitigation factors for the hosing growth. In [4] two factors that reduce hosing growth for intense beam-plasma interactions has been quantified analytically, both which can be written as growth rate reduction expressed as

$$A(s,\xi) = 1.3[c_r c_\psi (k_\beta s)(\omega_0 \xi)^2]^{1/3}$$

where c_r is a reduction factor for the case of where ion-channel formation is non-adiabatic, varying along the beam, and c_ψ is a reduction factor for the case when the plasma electron velocity is large and their magnetic field becomes significant. Using expressions in [4] an analytical estimate for typical FACET parameters, assuming a single bunch forming its own plasma channel, yields $c_r c_\psi \sim O(0.1)$. This would imply a relatively small amplification of beam offsets in FACET, of order $x_t/x_{t0} \sim 10$. The exact amplification will depend on the experimental scenario, including the shaping of the FACET electron beams.

ELECTRON BEAM SHAPING

The optics of the FACET Sector 20 experimental area [5] is designed as allow tuning of relevant optics parameters, including the longitudinal dispersion controlling the bunch length; R_{56}; and the transverse dispersion at the plasma interaction point (IP); D_x. A set of optics knobs where one can either tune the R_{56} while keeping $D_x = 0$ or, tune D_x while keeping R_{56} constant have been developed and are further described in [6].

Transverse dispersion will introduce a correlation in the beam energy and transverse position x. Because of the

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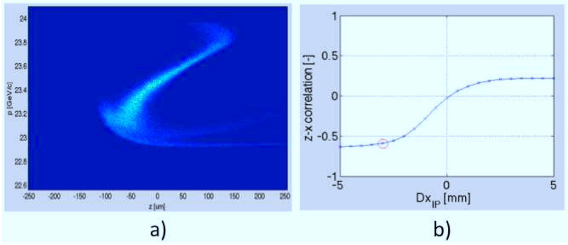

Figure 1: a) Longitudinal phase space of the FACET beam with the chicane set up $R_{56} = -10$ mm. Because of the strong correlation between z and p, a $z - x$ tilt can be induced by imposing horizontal dispersion at the IP. b) Correlation in the z-x beam coordinates at the entrance of the plasma, as function of horizontal dispersion. Maximum correlation is reached for negative dispersion, and starts to saturate below $D_x = -3$.

strong correlation between the beam energy and longitudinal position z for an $R_{56} = -10$ mm, illustrated in Figure 1a), the dispersion introduces a tilt in the beam $z - x$ plane. The beam head has the largest fraction of the charge and will create the ion-channel. The trailing part will thus travel offset to the center of the ion-column, and may experience hosing effects. By Elegant [7] simulations we have scanned the linear dispersion at the IP for $R_{56} = -10$ mm in order to identify working points with large the $z - x$ correlation while keeping the magnitude of the dispersion small. Figure 1b) shows that a negative dispersion of about $D_x = -3$ mm gives a correlation factor of about 0.6, close to the maximum correlation value achievable. For these studies we choose working points of $R_{56} = -10\text{mm},\ D_x = \{0, -3\}\text{mm}$.

PLASMA PIC SIMULATIONS

While theory may give order of magnitude estimates for hosing effects, PIC simulations are needed for a more precise calculations; we use the code QuickPIC [8]. Currently an arbitrary 6D phase-space cannot be input to QuickPIC. However QuickPIC allows an arbitrary initial longitudinal charge profile and an arbitrary correlation between the x and y coordinate and z. The initial transverse phase space is Gaussian with user defined rms values. We create a best fit QuickPIC distribution from the elegant output by extracting the charge profile, the beam tilt in x and fitting Gaussian rms values for the transverse parameters.

We have performed PIC simulations of FACET scenarios with $R_{56} = -10$ mm, for $D_x = 0$ mm and $D_x = -3$ mm. We studied cases where the beam is matched to the plasma and, for comparison, unmatched beams. In the latter case the beam breathing will affect the observability of the hosing. For $D_x = 0$, for the unmatched case it is not clear that significant hosing is present. The matched case, however, shows a visible growth of oscillations at the tail end of the bunch by a factor or 3-4, resulting in serpentine transverse offsets on the order to 10 μm. The tail position is very close to the plasma electrons, which perturbs the tail electrons further. Figure 2 summarizes the simulation results. For $D_x = -3$ mm scenario no clear amplification of transverse offsets were observed for the unmatched case. For the matched case the simulation results were marred by a coherent transverse deflection of the whole bunch inside the simulation box, which puts the validity of that simulation in doubt. This point is under further investigation.

EXPERIMENTAL SETUP

Amplification of transverse offsets due to hosing will lead to emittance growth which could in principle be detected on detector screens downstream the plasma. However, as indicated in Figure 2e) the contribution of hosing to the total emittance growth may be drowned in emittance growth due to head erosion. For the scenarios investigated above, the bunch emittance growth due to hosing is negligible to the emittance growth due to head erosion. Depending on the pulse to pulse stability of the beam entering the plasma, one may attempt to separate hosing contributions by comparing the emittance of a shot with no tilt applied to a shot with a dispersion induced tilt applied, however, the current stability of the FACET linac indicates that this method may be challenging.

A possibly more straight-forward observation of hosing may be to take advantage of the fact that hosing occurs more strongly towards the end of the bunch, which for many of the FACET scenarios will be accelerated with respect to the incoming energy. The FACET imaging spectrometer downstream of the plasma is based on Cherenkov light emission, and is similar to the spectrometer for the FFTB PWFA experiment [10]. A vertical bend magnet disperses the electron beam before it exits into an air gap, generating Cherenkov radiation. The radiation is reflected by a silicon wafer and imaged onto a CCD. Two quadrupoles downstream the plasma image the beam out of the plasma onto the plane of the reflection. The spectrometer will provide an $x - p$ distribution of the charge out of the plasma, as simulated in Figure 2f) for the $Dx = 0$ scenario. In this case about 20% of the charge is in the high energy tail, while the hosing has lead to transverse beam offsets of the order of 10 μm. The sensitivity of the FACET screens is reported from earlier experiment to be within 1% level. The resolution is 70 μm/pixel at the downstream image point, while the geometry of the imaging yields a demagnification of about 5 in the horizontal and $1/2$ in the vertical (uniquely set by the position of the two imaging quadrupoles) . The effective resolution is thus of $\sim 70/5 = 14$ μm at the plasma exist. The horizontal resolution may be improved by zooming in the camera field of view and/or temporarily increasing the demagnification in x at the cost of loosening the imaging condition for y.

The average sensitivity of the IP horizontal dispersion to variation of the Sector 20 quadrupoles is $\frac{dD_x[mm]}{dk_{\text{quad}}/k_{\text{quad}}} \approx 0.5$ mm per %. This level of optics precision control will only be achieved at a certain stage in the commissioning; before one can except dispersion on the mm level to leak into the

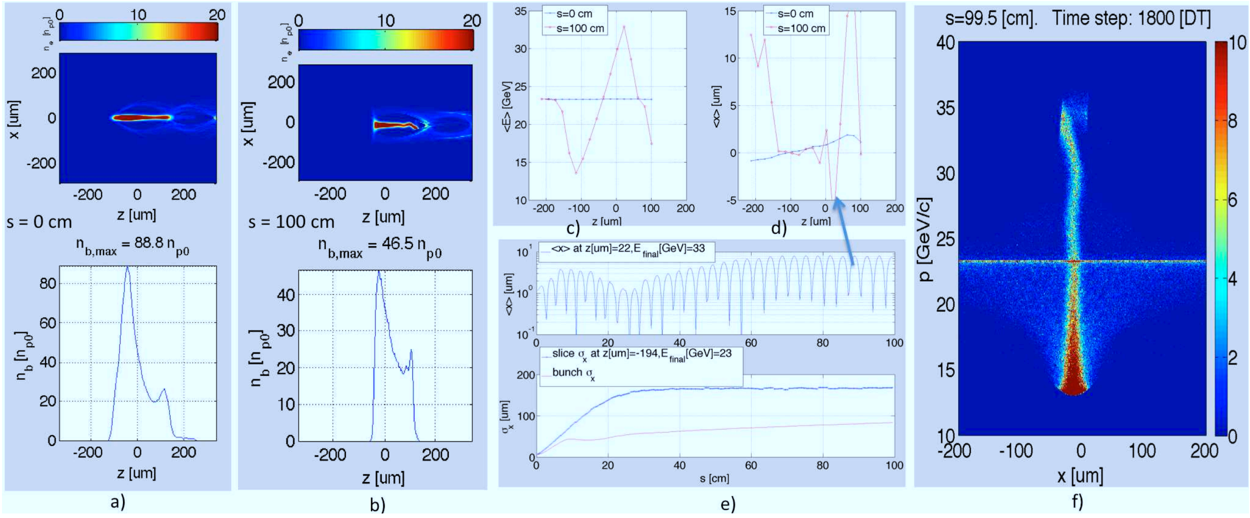

Figure 2: QuickPIC simulation for a bunch generated with FACET chicane settings at $R_{56} = -10$ mm, $D_x = 0$, traversing 100 cm of Lithium plasma with density n_0 = 3.7×10^{16} cm^{-3}. The transverse dimension are matched to the plasma. a) Initial charge distribution. The bunch density is much larger than the plasma density ensuring full blow-out. b) Final charge distribution. The bunch density is reduced due to head erosion. c) Initial and final energy profile. Peak energy gain and energy loss is about 10 GeV. d) Initial and final transverse profile. Initial transverse offsets of a few μm have have been amplified by a factor of 3-4. e) The magnitude of transverse oscillation for a slice towards the accelerated tail of the bunch. The oscillations are amplified as the bunch traversed the plasma. f) Charge in the $x - p$ plane, as potentially measured by an imaging spectrometer. The accelerated tail contains about 20% of the charge, and hosing effects in the tail, here in the order of 10 μm, should be visible on the spectrometer. The broad transverse distribution in the low energy part of the beam is due to head erosion.

IP. In hosing experiments a scan in dispersion knobs with a range ensuring to encompass the real $D_x = 0$ point should be performed. Depending on the stage of the commissioning ranges of several cm of dispersion should be scanned.

According to Eq. (1) hosing amplification increases with bunch length. The maximum bunch density for ionization puts a limit on the maximum bunch length for hosing experiments until the facility is upgraded with a laser for plasma pre-ionization (planned for late 2012). Assuming a Gaussian charge distribution with an rms length of σ_z, the nominal FACET parameters $\sigma_x = \sigma_y \approx 10$ μm and $Q = 3$ nC, the maximum bunch length for ionization can be estimated [9] to $\sigma_z \lesssim 200$ μm.

CONCLUSIONS AND FUTURE WORK

For the FACET scenarios investigated here (one bunch, $\sigma_z \sim \lambda_p$) the amplification of transverse offset is small, and hosing effects are limited to order of ~ 10 μm; the order consistent with theoretical estimates. PIC simulations showed that hosing was more predominant in matched beams than in unmatched beams. Using dispersion to introduce a strong $z - x$ correlation in the beam did not result in a significantly more visible hosing effect, possibly due to the less dense charge distribution of the bunch due to the dispersion.

Hosing effects may result in serpentine transverse tails in the beam, which for the scenarios discussed occur in the accelerated part of the beam, and hosing may therefore be observed directly on the Cherenkov imaging spectrometer. The current resolution of the spectrometer ($\sim$10 μm) might be a limiting factor.

Future work is planned to study stronger hosing effects by investigating longer beams ($\sigma_z \gg \lambda_p$), two-bunch scenarios where a transverse cavity is used to offset the witness bunch with respect to the ion-channel formed by the drive bunch [11], and sending offset beams into a ion channel pre-formed using a laser. We plan to improve the accuracy of simulations by inputing the full 6D phase space of the elegant simulation into QuickPIC, including a realistic model of the plasma edge lensing. The SLAC linac successfully started commissioning summer 2011, and we expect to perform the first hosing experiments during the FACET runs scheduled for 2012.

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