PLASMA DARK CURRENT IN SELF-IONIZED PLASMA WAKE FIELD ACCELERATORS*

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Abstract

Evidence of particle trapping has been observed in a beam driven Plasma Wake Field Accelerator (PWFA) experiment, E164X, conducted at the Stanford Linear Accelerator Center by a collaboration which includes USC, UCLA and SLAC. Such trapping produces plasma dark current when the wakefield amplitude is above a threshold value and may place a limit on the maximum acceleration gradient in a PWFA. Trapping and dark current are enhanced when in an ionizing plasma, that is self-ionized by the beam. Here we present experimental results.

INTRODUCTION

Dark current is one of the fundamental limits to achieving high acceleration gradients in conventional metallic particle accelerators; it results from trapping of electrons ionized at the metal surfaces. This has led to active research on plasma accelerating structures that are already ionized and therefore potentially not damaged by the large accelerating fields that they can support. Recent plasma wakefield accelerator experiments driven by lasers or particle beams have successfully accelerated particles at rates of 10-100 GeV/m, several orders of magnitude above the limits set by breakdown in metals. It is natural then to consider what are the fundamental physics limits to accelerating gradients in plasmas. Ultimately, wave fields become so large that they begin to trap electrons from the plasma itself. This is associated with wave breaking and has been described theoretically by several authors[1]. Experimentally, it has been observed in many laser wakefield experiments in the self-modulated regime in which the plasma wave grows via an instability until wave breaking and particle trapping occur. In these experiments, the trapping is not deleterious, rather it acts as the injector for the accelerator[2]. However, largely because the wave amplitude is growing from an instability and hence not well determined, it is not possible in those experiments to study the onset of trapping in a very controlled way. In this Letter we explore the onset of plasma dark current (trapping) in a beam-driven plasma wakefield in which the wake amplitude can be controlled by the extent of compression of the drive bunch. We show that in the experiment there is a well-defined threshold for the onset of dark current.

EXPERIMENT AND DIAGNOSTICS
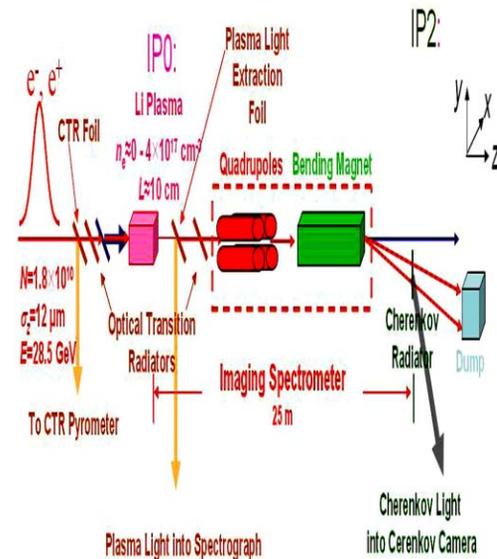
Figure 1:

The experiment uses the ultra-relativistic (28.5 GeV) ultra-short (< 100 fs) electron bunches available at the Stanford Linear Accelerator Center (SLAC). The electron beam is focused near the entrance of a lithium vapor of density n_0 contained in a heat-pipe oven [3]. The plasma is created through tunnel ionization of the low ionization potential (4.55 eV) lithium vapor by the large radial space charge field of the bunch. The plasma density is therefore equal to the neutral gas density. The gas density is varied in the $0.5-3.5\times10^{17}$ cm^{-3} range by changing the heating power delivered to the heat-pipe oven. The lithium column length, and therefore plasma length, is about 10 cm. The lithium is confined to the oven hot region by a helium buffer gas at room temperature and the pressure is constant along the heat pipe oven. The individual bunch charge is measured before and after the plasma using fast current transformers and beam position monitors. The beam size and shape are monitored using the visible optical transition radiation (OTR) emitted by the beam when traversing 1 μm thick titanium foils located $\approx$1 m upstream and downstream from

the plasma. A magnetic spectrometer images and disperses the beam to yield single-bunch energy spectra from which we can infer wakefield amplitudes. As the electron bunch enters the plasma, its space charge field first ionizes the lithium vapor and then expels the plasma electrons out of the bunch volume. As a result the excess plasma ion charge left behind the head of the bunch focuses the beam. In expelling the plasma electrons, the head and core bunch particles also lose energy to the plasma. The plasma electrons rush back to the beam axis, approximately one half plasma period after being expelled. This creates an on axis negative charge spike that can accelerate the electrons in the back of the bunch or trap the electrons from the plasma. An energy gain of about 4 GeV, the largest to date in any plasma accelerator, has been observed at a plasma density of $3 \times 10^{17} \ cm^{-3}$ [4] using this plasma wake excitation scheme.

As the beam is focused by the plasma to a size smaller than that at the plasma entrance, its space charge field can be large enough to ionize the helium buffer gas (24.6 eV ionization potential), or even the second lithium atom electron (75.6 eV ionization potential) along the plasma itself. These newly ionized plasma electrons are born inside the plasma wake and can therefore be trapped and accelerated by the wake. The trapped plasma electrons exit the plasma with the electron bunch and are detected after the plasma in the form of excess charge on the current monitor and excess light on the spectrograph.

TRAPPING THRESHOLD

In order to be able to observe a trapping threshold the wake field amplitude needs to be varied. In this experiment this is done by varying the bunch length. The magnitude of the plasma wake is inversely related to the bunch length, and the bunch length can be adjusted by changing the energy chirp of the beam that is compressed by a combination of bends and a chicane in the linac.The bunch compression is achieved by accelerating the beam at zero degrees phase of the RF for part of the linac to give it a correlated energy chirp. The magnetic chicane causes particles with higher energy to take a shorter path, allowing particles in the tail of the beam to catch up to the head. The incoming bunch energy spectrum and the total coherent transition radiation (CTR) energy emitted by the bunch when traversing a foil located upstream from the plasma (see fig. 1) are monitored on a bunch-to-bunch basis. The CTR energy is expected to be inversely proportional to the bunch length and is used as a relative bunch length monitor.Since average energy loss is directly related to the wake amplitude we determine the magnitude of the plasma wake by measuring the energy change of the beam after the plasma. This is done with an imaging magnetic spectrometer that measures the beam energy spectrum after it interacts with the plasma with an accuracy of the order of 40 MeV.

Experimentally there is a threshold in wakefield amplitude above which we observe a sudden increase in the
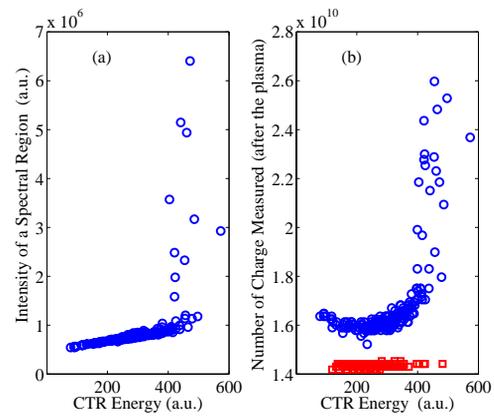
Figure 3: a)Relative amount of light recorded over a spectral region with no atomic lines as seen on Fig. 2. (b) Charge measured by a fast current monitor located after the plasma versus CTR energy,

amount of OTR light detected as shown in Fig. 2. The event of Fig. 2 b corresponds to a low CTR energy value, and therefore to a relatively long bunch length. In contrast, Fig. 2 c shows the plasma light image and spectrum obtained with a shorter bunch, as indicated by the corresponding higher CTR energy. We can also infer the difference in wakefield amplitude corresponding to these images which has the same color map by just looking at the intensity of the individual neutral lithium lines, since the amount of spectral energy released by the plasma as visible light is proportional to the amount of energy loss of the beam [6]. A quantitative estimate for the wakefield amplitude is obtained from the cerenkov diagnostic. Fig. 2 a shows the intensity of one of the strongest LiI lines, at 670.8 nm, as a function of the mean beam energy as measured by cerenkov diagnostic. This linear relationship between these two quantities is used to find the wakefield amplitude corresponding to these images which are marked on fig. 2 a. A continuous component to the spectrum is visible on Fig. 2. Appearance of this excess of light emission coincides with the abrupt increase in current detected downstream of the plasma by the toroidal current monitors (Fig. 3). Figure 3 a shows the relative amount of light recorded in a spectral region as indicated in Fig. 2 c. as a function of the CTR energy. Figure 3 a shows a clear threshold at a relative CTR energy of 450. Above this value the amount of light becomes much larger, and has rather large amplitude variations. A charge monitor (toroid) located immediately after the plasma light extraction foil also indicates an excess of charge above the relative CTR energy value of 450 (Fig. 3b).We interpret these results to be due to the onset of the trapped particles -i.e.,plasma dark current. The total charge in dark current in Fig. 3 is on the order of that in the beam (10^{10} electrons). At higher plasma densities, the trapped charge is larger and has been observed as high as 9×10^{10} electrons at $n_0 = 2.6 \times 10^{17} cm^{-3}$.

There is good agreement between the toroid charge mon-
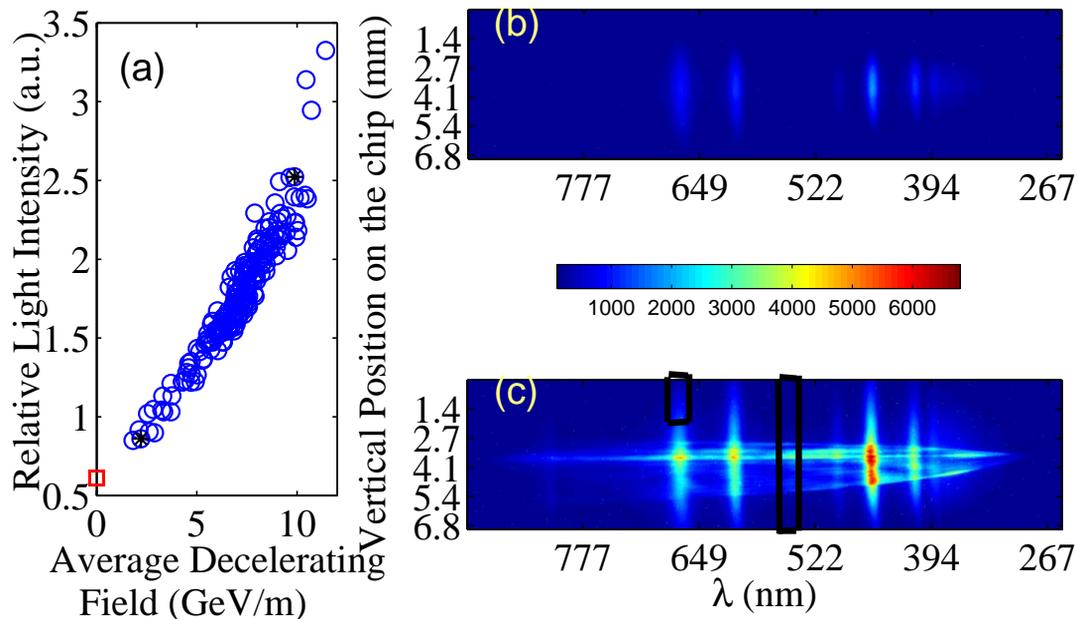
Figure 2: a) Intensity of the lithium atomic line at 670.8 nm, which is obtained from the sum of intensity counts inside the little box on trapped particle light free region on c, as a function of the average energy loss. The plasma density is constant at $1.6 \times 10^{17} cm^{-3}$ (blue circles), the red square corresponds to plasma off events, and the energy loss varies because the bunch length varies from bunch to bunch. The line intensity is proportional to the mean beam energy, i.e., to the beam energy lost to the plasma wake. Lower marked circle indicate the event of b and upper marked circle indicate the event of c. b) Spectrograph image when there is no trapping corresponding to a relatively weak wakefield amplitude; c) image with trapping for a high wakefield amplitude. Light is a combination of discrete neutral line emission from the plasma, and continuum light from Cherenkov radiation in the gases and continuous OTR radiation at the mirror by relativistic beam and trapped particles (Note that the OTR light by the beam particles only is too weak to be visible on Fig. 2b)

itor and optical diagnostics as to the value of the threshold for trapping. However, the OTR light emitted increases much more than the increase in charge. This may be due to additional coherent mechanisms for light emission by the trapped electrons.

Density gradients can also cause particle trapping. This effect was investigated by Suk et al. [5] as a way of injecting particles in a PWFA. It only occurs in the case of very sharp decreasing gradients where the density scale length is smaller than the skin depth k_p^{-1} (i.e., $\frac{n_0}{dn_0/dz} \times c/w_p < 1$). In our experiment this condition is not satisfied.

CONCLUSION

In summary, we have seen a clear experimental threshold for particle trapping and production of dark current in a PWFA. Future work for finding an analytic model of particle trapping threshold incorporating detailed analysis using simulations of the experiment is in progress.

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