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PROBING MULTIPERIOD PLASMA RESPONSE REGIMES USING SINGLE SHOT WAKEFIELD MEASUREMENTS

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Abstract

Systematic differences between the linear and nonlinear regimes of plasma wakefield acceleration from electron beams are manifested in the plasma response. Typically, the ratio of peak beam density to nominal plasma density determines operation in the linear or nonlinear regime. Previous reports have shown that a the cross-over into the nonlinear regime is associated with an increase in the wakefield amplitude, as well as sawtooth-like shape. In this paper, we present preliminary measurements of quasi-nonlinear wakefields driven by a linearly ramped beam, with a maximum charge close to the unperturbed plasma density. We also demonstrate nonlinear wakefield behavior in a probe bunch using a single shot, multi-period wakefield measurement and its dependency on plasma density.

INTRODUCTION

Development of strongly nonlinear plasma wakefield acceleration (PWFA) in the blowout regime is a major focus of the advanced accelerator field. Accelerating gradients up to tens of GeV/m have been have been observed using tightly focused ($k_p\sigma_r \ll 1$), ultra-short ($k_p\sigma_z < 2$) electron bunches to excite highly nonlinear wakefields in plasmas [1]. This gradient is far higher than any conventional accelerating structures and has the potential to shrink accelerator sizes many-fold. Furthermore, the plasma blowout regime has attractive properties due to the complete rarefaction of plasma electrons in the accelerating region.

However, the efficiency of energy exchange in these schemes is often limited by the drive bunch used to excite the plasma wakefield. In order to reach the blowout regime, the drive bunch needs to be more dense then the unperturbed plasma. For the highest reported accelerating gradients, plasma densities on the order of 10^{17} cm^{-3} are used [2]. For an electron beam to reach this density, it must be longitudinally compressed multiple times using magnetic chicanes [2]. Coherent synchrotron radiation in these chicanes leads to unwanted transverse emittance growth that can prevent proper matching into the plasma [3]. This limits the amount of charge in the drive, which in turn limits the non-linearity of the plasma interaction.

A longitudinally ramped beam can be used to excite a similar non-linear wakefield response by slowly building up the longitudinal slice beam charge over several plasma wavelengths and then abruptly cutting off. The plasma electrons will slowly be displaced from the beam region until a rarefied region develops. When the beam current drops off sharply, the electrons will fall back onto the axis in a similar manner to the blowout collapse seen from short beams[4], creating the similarly extreme accelerating gradients as those previously observed. Beam shaping, already experimentally demonstrated using various methods [5–7], would relax the need for strong longitudinal compression.

EXPERIMENTS AT THE ARGONNE WAKEFIELD ACCELERATOR

The Argonne Wakefield Accelerator (AWA) facility provides an ideal environement to investigate key facets of PWFA driven by shaped beams. The AWA incorporates a cesium telluride photocathode based gun to produce electron bunches with a charge of 12 nC and pulse length of 6 ps. These bunches are accelerated to 40 MeV using normal conducting L-band (1.3 GHz) accelerating structures. The beam is then injected into the AWA emittance exchange beamline (EEX). This beamline consists of two dogleg sections, separated by a transverse deflecting cavity oriented such that the time dependent transverse kick is directed along the horizontal (bend) plane. The EEX beamline exchanges the horizontal and longitudinal phase spaces [7], allowing flexible longitudinal bunch shaping through the use of a transverse mask prior to the first EEX dogleg. For this experiment, the mask was shaped such that it produced a linear ramp in current density over roughly 20 ps and a similar length, low charge, witness beam to sample the resulting wakefield. This shaping technique was used previously to measure high transformer ratio wakefields from slab dielectric structures [8].

A hollow cathode arc plasma source [9] was used to produce a plasma column for the experiment. The source contains a set of three concentric tantalum tubes as a cathode and a ring anode. Argon gas flows between the two innermost tubes, which are restively heated to 2000 K and is then ionized by a 150 V, 200 µs capacitive arc discharge. This produces a stable plasma column approximately 8 mm in diameter and 6 cm in length. The plasma density was determined through the use of a triple Langmuir probe [10] and optical imaging of the plasma afterglow. The plasma density is tunable via changing the strength of an external solenoid field used for plasma confinement [9] as well as varying heating power delivered to the cathode tubes. The measured plasma density profiles due to these variations are shown in Fig. 1.

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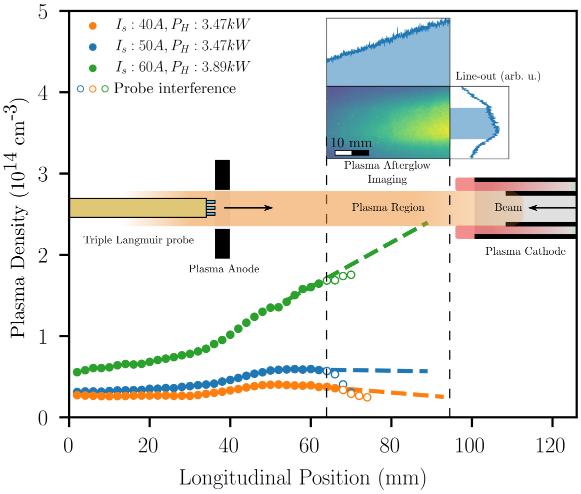

Figure 1: Longitudinal plasma density profile characterization as a function of solenoid current I_s and heating power delivered to cathode tubes P_H with a cartoon of source geometry and diagnostics properly scaled in the longitudinal direction. The unaffected profile is extrapolated (dashed lines) using a linear relation, inferred from a measurement of the corresponding plasma afterglow brightness (inset). Imaging also shows a root-mean-squared plasma column width of 8 mm.

Emittance gains in the EEX beamline and in vacuum windows causes significant loss in beam charge at the plasma source. Due to the 20° bends in the EEX beamline, the transverse beam emittance increases greatly as a result of coherent synchrotron radiation [11]. Further increases in transverse emittance are due to 125 µm thick beryllium vacuum windows, used to isolate the plasma chamber from the rest of the accelerator, due to multiple scattering [12]. As a result, the remaining beam charge after transport into the plasma interaction region is approximately 1.8 nC due to beam scraping in the final focusing optics, as measured using Faraday cups downstream of the interaction region.

To measure the wakefields from the beam-plasma interaction, a single-shot longitudinal phase space (LPS) diagnostic is used. This diagnostic is comprised of a transverse deflecting cavity which maps the longitudinal beam current onto the vertical axis and a dipole spectrometer to map the energy domain onto the horizontal axis. Due to the long nature of the witness beam, the multi-period wakefield can be sampled in a single shot [13]. To isolate the plasma wakefield contribution to the beam energy, the background time dependent energy centroid was measured over a number of accelerator shots with the plasma source turned off. This not only captures the systematic time dependent energy characteristics of the plasma off beam, but it also characterizes the accelerator jitter. The plasma wakefield response was calculated by subtracting this background from the plasma on measured energy centroid as seen in Fig. 2.

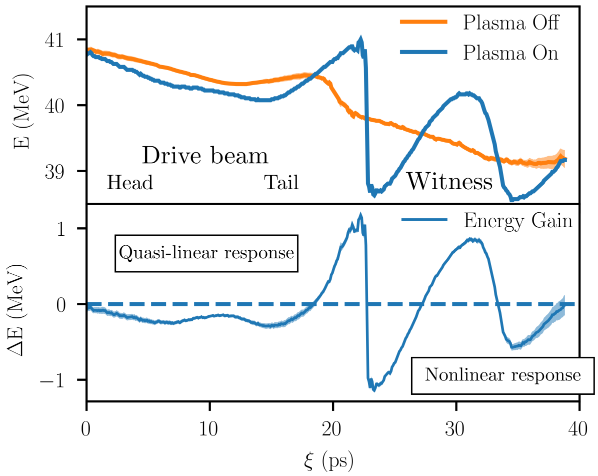

Figure 2: Single shot wakefield measurement. Top: Time dependent energy centroid of plasma on and plasma off shots measured using the longitudinal phase space diagnostic. Bottom: Subtracted energy difference between plasma on and plasma off energy centroids showing averaged plasma wakefield energy perturbation.

From the measurement, we observe that the wakefield shows two distinct functional forms. In the ramped drive beam, we see periodic, sinusoidal, undulations of the wakefield similar to what is predicted by single mode convolutions of an ideal liner ramp [14]. However, the wakefield inside the drive beam tail shows a distinct deviation from single mode sinusoidal behavior. The observed accelerating spike is consistent with a nonlinear blowout type response. We can explain this change of behavior by considering the plasma interaction to be in the quasi-nonlinear blowout regime. Due to strong transverse focusing, peak beam density of the drive is on the same order of magnitude as the unperturbed plasma density. As such, we expect the blowout to be non-relativistic and the maximum blowout radius to be $r_m < k_p^{-1}$. In this case, the on-axis wakefield inside the drive is dominated by the laminar plasma response outside the rarefaction region, which approximates a linear response [15, 16]. However, after the drive beam current drops to zero, plasma electrons fall back on-axis due to the ion column created by the blowout, which creates a large plasma density spike on axis, thus creating the accelerating field spike observed. Furthermore, the multi-period wakefield shows a similar "sawtooth" like response, indicative of periodic nonlinear oscillations. The observed decrease in amplitude of the wakefield oscillations in the witness can be explained by beam loading, as the witness has up to an estimated 450 pC of charge.

To probe the multi-period nonlinear response we can scan the plasma density while keeping beam profile constant. The resulting average wakefield from a collection of measurements in each case is plotted in Fig. 3. The nonlinearity of the response can be characterized by n_b/n_p where $n_b/n_p > 1$ results in a strongly nonlinear response. As we

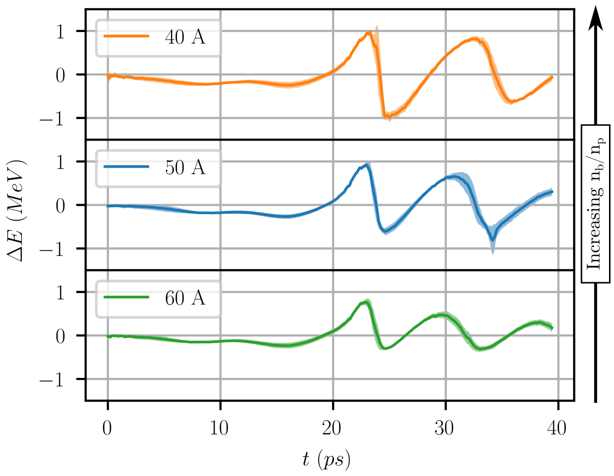

Figure 3: Average energy gain measurements for three different plasma densities while keeping beam current constant.

increase the confinement solenoid current the plasma density increases (as seen in Fig. 1), decreasing n_b/n_p. We observe three effects from changing the plasma density in our wakefield measurement. First, we observe that the wakefield amplitude increases with increasing n_b/n_p. Second, the "sawtooth" structure becomes more sinusoidal as we decrease n_b/n_p. Finally, we see that the wakefield oscillation wavelength decreases with increasing plasma density. The dependence of the first two observations is consistent with predicted scaling of n_b/n_p [15]. The change is wakefield oscillation wavelength can be attributed to the change in plasma wavelength, which scales as $\lambda_p \propto n_p^{-1/2}$.

CONCLUSION

Our paper demonstrates single shot plasma wakefield measurements that shows quasi-nonlinear wakefields within ramped drive beams, and nonlinear wakefields trailing the drive. This provides a potential path forward for achieving nonlinear accelerating wakefields without the need for strong longitudinal compression of the drive beam.

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