QUASI NONLINEAR PLASMA WAKEFIELD ACCELERATION EXPERIMENTS

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Abstract

It is generally agreed that the best way forward for beam driven plasma wakefield acceleration (PWFA) is in the nonlinear or blowout regime. In this regime the expulsion of the plasma electrons from the beam occupied region produces a linear transverse focusing effect and position independent longitudinal accelerating fields, which can, in principle, produce high quality beams accelerated over many meters. However, certain aspects of a linear plasma response can be advantageous, such as the possibility for resonant excitation of wakefields through the use of pulse trains. Exploiting advantages of both linear and nonlinear PWFA may be achievable through the use of low emittance and tightly focused beams with relatively small charge. In this case the beam density can be greater than that of the ambient plasma while simultaneously having a smaller total charge than the plasma electrons contained in a cubic plasma skin depth allowing for blowout in the region of the beam while simultaneously maintaining a quasi linear response in the bulk plasma. Recent experiments at the Accelerator Test Facility at Brookhaven National Lab have been aimed at probing various salient aspects of this regime and are presented here.

INTRODUCTION

Plasma based acceleration schemes promise to revolutionize the field of accelerator physics in a way that would permit a continued push into the high energy frontier as a well as provide a path to the development novel radiation sources such as a compact XFELs. With a wide variety of technical and physical challenges, there is much theoretical and experimental work devoted to optimizing such schemes. Generally speaking, the focus is on operations in the nonlinear regime, which provides a conceptually neat way of accelerating beams at high gradients while preserving high quality phase spaces. There are, however, certain aspects of the linear regime that would prove useful in many instances; namely, the ability to resonantly excite the wakefields.

The quasi nonlinear regime [1] provides a delicate compromise between the two regimes, allowing for blowout and accompanying ideal accelerating and focusing fields without the expense of a plasma response which can be driven resonantly. In this regime, the beam density exceeds that of the ambient plasma leading to blowout. At the same time, the normalized charge, defined as $\tilde{Q} \equiv N_b k_p{}^3 / n_0$ (where N_b is the total number of beam electrons, k_p is the plasma wavenumber and n_0 is the plasma density) is kept below one. A low $\tilde{Q}$ mitigates strong nonlinear effects such as wavebreaking and amplitude dependent periodicity of the wake. While simulations have demonstrated the feasibility of operating in this regime, there is to date little experimental evidence.

Recently, an experimental program at the Accelerator Test Facility at Brookhaven National Lab (ATF BNL) has begun[2]. The aim of these experiments is to verify certain aspects of the quasi nonlinear regime. In particular, the goals of these experiments are twofold: using electron pulse trains observe resonant wakefield excitation and observe strong focusing/guiding of a matched pulse train through the plasma. The latter will be the focus of the present paper.

EXPERIMENTAL RESULTS

The ATF at BNL is well suited for this experiment as a number of beam-plasma interaction experiments have already been performed there [3-5]. Furthermore, they have demonstrated a masking technique to generate electron pulse trains with adjustable separations [6]. These experiments, however, have been always been performed with $n_b << n_0$. In order to perform experiments in the QNL regime the focusing capabilities at ATF need to be augmented to get transverse beam sizes on the order of a few microns instead of ~100 microns, increasing the beam density by a factor of ~400.

Accordingly, a permanent magnet quadrupole triplet was installed [7]. With an effective focal length of ~8 cm at 60 MeV and assuming a typical normalized emittance for ATF of 2 mm-mrad, it is reasonable to anticipate RMS transverse spot sizes of ~5 microns. Combined with a peak current of ~100 A, these beams will have densities with $n_b \geq 2\times10^{16}$ cm^{-3}. Beyond simply making small spot sizes at the interaction point, it is desirable to match the beam to the plasma, which for a 10^{16} cm^{-3} requires a beta function of ~1 mm.

In order to measure these electron beam parameters, a high-resolution optical transition radiation (OTR) imaging system is used. This system includes a 10 micron Ti foil placed in the focal plane of a Schwarschild objective. The collected light is directed out of vacuum to a CCD with an imaging lens providing 2 micron resolution. The objective and foil are mounted to a longitudinal stage making it possible to image the transverse spot size over a range of 50 mm along the beam path, more than sufficient to extract twiss parameter information for beams with such short beta functions. At each position of the motor, several OTR images are saved and the average RMS value in both the horizontal (x-direction) and vertical (y-direction) is calculated. From these values, a three parameter fit is used to determine the waist position, beta function and emittance. Typical measurements, with fits, are shown in Fig. 1 and a summary of the measured parameters are given in Table 1.

Table 1: Measured Beam Parameters at Interaction Point

Parameter	Value
ε_{nx}, ε_{ny}	2.5, 0.8 mm-mrad
β_x, β_y	0.9, 4.0 mm
σ_x, σ_y	4.5, 5.2 µm

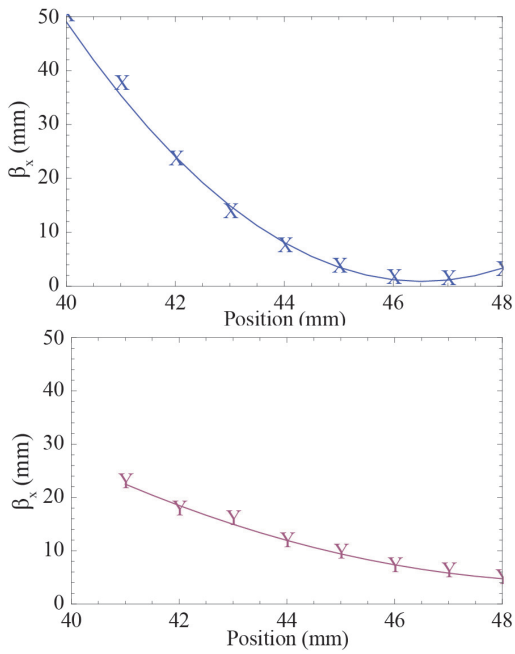

Figure 1: Electron beam transverse size measurements in the horizontal (top, blue x's) and vertical (bottom, red y's) directions. Solid lines indicate best fits.

The plasma source is a hydrogen-puffed discharge capillary. A 100 Torr hydrogen reservoir is opened to a 1 mm diameter, 2 cm long capillary for 50 ms and arced with 15 kV. This produces a plasma with peak density ~2×10^{17} cm^{-3} which decays exponentially with a characteristic decay time of ~450 ns. The plasma density experienced by the passing electron beam is selected by adjusting the arrival time of the beam relative to the discharge time and is tuneable in the range ~$10^{15\text{-}17}$ cm^{-3}, which corresponds to plasma wavelengths in the range of ~700-100 microns.

One of the primary interests of these experiments is in the transverse focusing of the electron beam by the plasma. In the case of blowout, the bulk of the beam feels a uniform linear restoring force. When the beam is matched, it will propagate through the plasma without an increase in transverse size or emittance, thus eliminating any phase advance the beam would experience in an otherwise plasma free drift. In an experimental sense, we can learn something of the dynamics of this process by passing an electron beam through plasmas of varying densities and monitoring the transverse size of the beam just downstream. In the context of this experiment we are interested in the comparison of two types of electron beam distributions: a "long" beam with RMS length of 350 µm and a pulse train of three equally spaced short beamlets generated by chopping the long beam.

At the higher plasma densities, the plasma wavelength is shorter than the length of the long beam. Consequently, the focusing force, which is periodic at the plasma period, reverses sign along the bunch strongly defocusing portions of the beam. In this case, the beam will undergo a number of instabilities including hosing and transverse self-modulation, leading to break up of the beam. As the plasma density decreases, the plasma wavelength will eventually be long enough to encompass the full length of the beam and thus the whole beam is focused. A further decrease in the plasma density will reduce the focusing strength, as the linear restoring force is proportional to plasma density.

On the other hand, with a train of short pulses, the relation between the beam spacing and plasma wavelength can be tuned such that the charge is loaded only into the focusing regions of the wake. This occurs when the spacing of the bunches is equal to $(n+\frac{1}{2})\lambda_p$ where $n=1,2,3...$ and λ_p is the plasma wavelength. Thus, even at the higher plasma densities, the pulse train can experience net focusing rather than breakup like with the long beam. This effect, of course, hinges critically on a linear, periodic response of the plasma.

With the OTR diagnostic placed a few mm downstream of the plasma (30 mm from the waist) we directly observe these effects. Figure 2 shows OTR images of the long beam (total charge 300 pC) after passing through two different density plasmas, as well as a reference image when there is no plasma present. When the plasma wavelength is shorter (Fig. 2b) the beam clearly breaks up, but when the bulk of the beam fits within a single plasma period (Fig. 2c) the beam is strongly focused and is actually 5 times smaller at the exit than in the no plasma case (Fig. 2a).

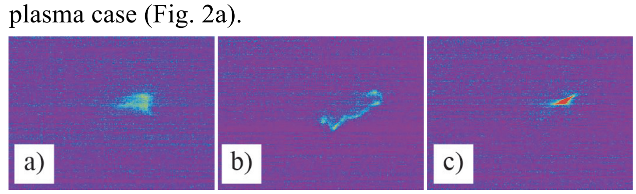

Figure 2: OTR images of electron beam. Reference image when plasma is turned off (a), and after interaction with plasma density with wavelengths 120 and 650 µm (b) and (c), respectively. Note, that the same color scale is used for all three and so (c) is heavily saturated.

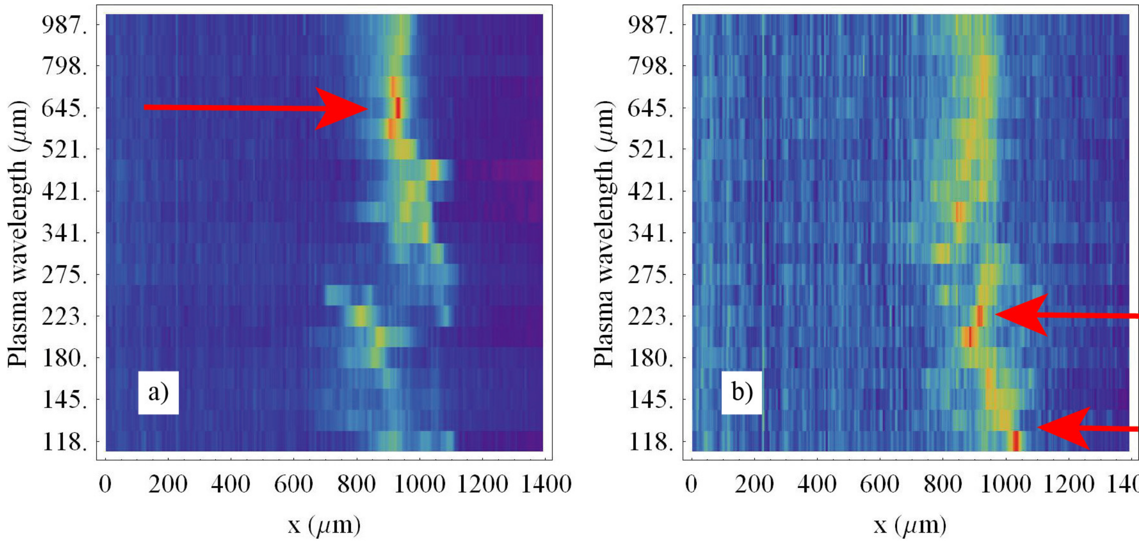

Figure 3: Plasma density is scanned over a range of densities while OTR images are captured. Each line in is the integrated lineout of the OTR image in the horizontal direction for the long beam case (a) and for a three pulse train with 300 µm spacing (b). Best focus points are indicated by red arrows.

The transition from beam breakup to strong focusing was investigated in detail by scanning the plasma density over a large range. The results are compiled in Fig. 3a in which each line represents the horizontal lineout of the OTR image. Clearly, the beam achieves a best focus (indicated by the red arrow) after the plasma interaction around $\lambda_p = 650$ µm.

The tests with the long (350 µm RMS) provide a nice result and an important benchmark for tests with pulse trains. As mentioned previously, a train of equally spaced beamlets can be generated by inserting a comb shaped emittance spoiling mask at a point of high dispersion. The spacing between the beams is tuned through control of the correlated energy spread of the beam. Separation of distances of the beams is confirmed via autocorrelation of the coherent transition radiation generated after the pulse train passes through a thin foil. It was found that the original 350 µm RMS beam can be chopped to generated three beamlets with bunch separations in the range of 300-500 µm. Each beamlet has roughly 30 pC of charge and an RMS length of 45 µm.

The same plasma density scan was performed with a three pulse train of 300 µm spacing, Fig. 3b. In contrast to the long beam case, the best focuses (red arrows) occur at higher densities $\lambda_p = 120\,\mu\text{m}$ and $\lambda_p = 200\,\mu\text{m}$. These values correspond nicely the predicted values based the bunch separation, which definitively demonstrates that the interaction is satisfying a resonant condition. In other words, a pulse train with $n_b \approx n_0$ was successfully matched and guided through a high density plasma with a plasma wavelength on the order of the bunch spacing.

CONCLUSION

An important step was made in the experimental verification of the quasi nonlinear regime of PWFA. By comparing the transverse dynamics of a long beam and a pulse train interacting with plasmas of different densities, it was possible to identify a resonant condition. That is, when the spacing between the bunches in a pulse train is appropriately tuned relative to the plasma wavelength, the charge will be loaded only in the focusing phases of the wake, thus experiencing a net focusing force, making it feasible for pulse trains to propagate long distances in the plasma. This is a critical step in confirming the viability of using pulse trains for PWFA purposes.

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