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EXCITATION OF VERY HIGH GRADIENT PLASMA WAKEFIELDS FROM NANOMETER SCALE BEAMS

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Abstract

The plasma based terawatt attosecond project at SLAC, termed PAX, offers near mega-Ampere beams that could be used to demonstrate plasma wakefield acceleration at very high gradients (TV/m). The beam has a large aspect ratio which allows it to be used at high densities since the longitudinal beam size is lower than the plasma skin depth. This beam can be focused using a permanent magnitude quadrupole (PMQ) triplet to further reduce its transverse size. Since the beam is extremely short compared to the plasma skin depth, it behaves like a delta-function perturbation to the plasma. This reduces the expected focusing effect of the ion column and simulations show that only the tail of the beam is notably focused and decelerated. This scenario is investigated with attendant experimental considerations discussed. The creation of the witness beam by the deceleration of the tail of the beam is also discussed.

INTRODUCTION

Plasma accelerators can create beams that have ultra high brightness in a relatively small physical footprint due to the achievable high gradients. The plasma based terawatt attosecond x-ray source project, termed PAX [1], proposes to use this promising technique to generate near mega-Ampere beams with attosecond duration which can, in turn, be used to generate few-cycle, coherent, tunable soft x-ray pulses with terawatt peak power. The beam is created using density downramp injection [2, 3] in a plasma wakefield accelerator (PWFA). These PWFA accelerated beams will be cable of driving x-ray free electron laser (XFEL) pulses which are an order of magnitude more powerful and with shorter temporal duration than current, state of the art XFELs. Additionaly, this mega-Ampere beam with its attendant bunch length, on the order of nanometers, can be used to drive wakefields in high density plasmas as the longitudinal size of the beam is very small compared to the plasma skin depth ($\sigma_z \ll k_p^{-1}$), where $k_p = \omega_p/c = \sqrt{e^2 n_0/m\epsilon_0}$. The beam has a high aspect ratio and is significantly larger in the transverse direction, which can subject it to the current filamentation instability (CFI) [4]. We describe a focusing lattice, downstream of the first plasma stage, using a defocusing triplet and a high gradient quadrupole triplet based on permanent magnet quadrupoles (PMQ) [5]. Subsequently, we used the longitudinal and transverse dimensions of the density spike associated with the focused PAX beam to simulate the beam plasma interaction of the beam with a plasma with a

Table 1: Table of Beam Parameters after the Chicane

Parameter	Value	Unit
Beam charge, Q	81.1	pC
Energy, E_b	3.3	GeV
σ_z	0.0135	μm
σ_x, σ_y	12.7, 4.8	μm
$\epsilon_{n,x}$, $\epsilon_{n,y}$	2.48, 0.22	μm-rad
β_x, β_y	0.41, 0.67	m
Energy spread	1.5	%

Table 2: Table of Parameters for the Simulation shown in Fig. 3

Parameter	Value	Unit
Beam		
Norm. beam density, n_b/n_0	10.3	-
Energy, E_b	3.3	GeV
σ_z	0.0135	μm
σ_x, σ_y	1.95, 1.19	μm
$\epsilon_{n,x}$, $\epsilon_{n,y}$	2.48, 0.22	μm-rad
β_x, β_y	8.51, 27.4	mm
Energy spread	1.5	%
Plasma		
Species	H^+	-
Density, n_0	1.0×10^{20}	cm^{-3}
Simulation		
Simulation window (x,y,z)	(12, 12, 3.5)	k_p^{-1}
Grid cells	$(512)^3$	-
Particles per cell	4	-
Timestep	2.5	ω_p^{-1}
Beam macroparticles	1.68×10^7	-

very high density of 10^{20} cm^{-3} having a skin depth (k_p^{-1}) of 0.53 μm. A schematic of the proposed layout is shown in Figure 1. The focusing of the PMQ triplet is simulated using Elegant [6]. The simulations of the second plasma stage were performed using QuickPIC [7], a three-dimensional quasi-static particle-in-cell (PIC) code.

FOCUSING SYSTEM

A witness beam is created in the first plasma stage via density downramp injection and accelerated to an energy of 3.3 GeV with a large, approximately constant, linear chirp. After the first plasma stage, the diverging, chirped witness beam is focused using a quadrupole triplet and compressed using a four dipole chicane (R_{56} = 27 μm). This compressed beam has a current spike of 0.64 MA with a length of 23 nm

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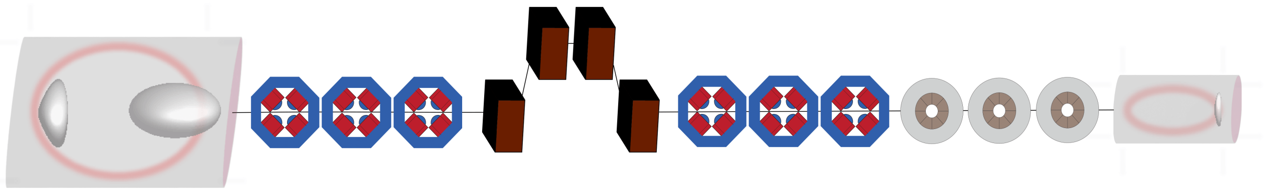

Figure 1: Schematic overview of the proposed experiment. A witness beam is created in first PWFA stage using density ramp injection. This beam would then have to be defocused to increase the beta functions and subsequently focused by the PMQ triplet before going into the second PWFA stage.

(FWHM) [1]. The resultant beam carries features of the shape of the blowout cavity, and is wide and inhomogeneous in the transverse planes. The inhomogeneities in the beam do not contribute to further plasma wakefield interaction, so the relevant components in the second plasma stage are isolated by windowing only the core of the beam, i.e. the part around the density spike. The beam density core is approximated to a Gaussian beam and the relevant beam parameters of this approximation are presented in Table 1.

The beam cannot directly be focused using the PMQ triplet because the beta functions at this point are too small. A defocusing triplet is needed to increase the beta functions to tens of meters. It should be noted that an alternative method is also possible, by using the earlier set of quadrupoles to produce a wider beam with larger beta functions prior to compression. Once the beam has the appropriately large beta functions, it can then be focused by the PMQ triplet. In the current design, the quadrupoles have a field gradient of 650 T/m, readily achievable with current technology. The transport of the beam through the triplet is shown in Fig. 2. The resulting beam parameters, used for the second PWFA stage simulation, are shown in Table 2.

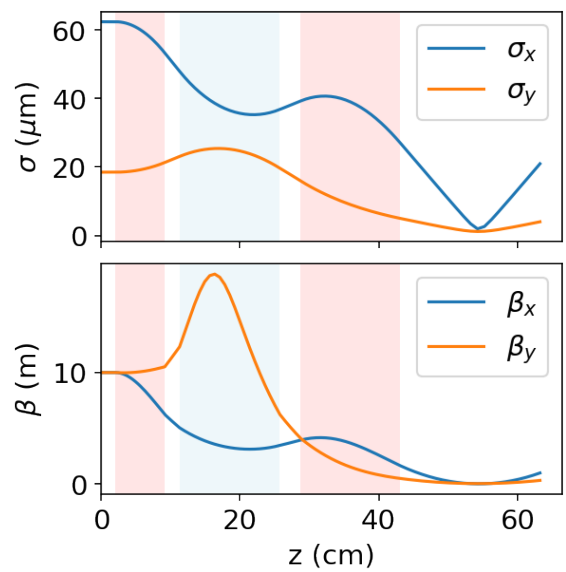

Figure 2: Elegant simulation of the PAX beam transported through the PMQ final focus. The plot shows the rms spot sizes (top) and the beta functions of the beam (bottom). The shaded area corresponds to the PMQ length and polarity. Horizontal focusing is shown in red and vertical focusing is shown in blue.

SECOND PLASMA STAGE

After the beam is focused using the PMQ triplet, it is used to drive very high gradient wakefields in a high density plasma. The beam is further focused by a density ramp in the plasma which has a final uniform density (n_0) of 10^{20} cm^{-3}. At this density, the transverse size of the beam is larger than the plasma skin depth ($k_p\sigma_x = 3.67$, $k_p\sigma_y = 2.23$) while the longitudinal size of the beam is very small ($k_p\sigma_z = 0.025$). The beam dynamics and plasma profile are shown in Fig. 3. A separate simulation with a longer window and same grid spacing was done to study the characterisitics of the blowout. Although the beam is wider than the plasma skin depth in the uniform plasma section, the beam has a high normalized charge density, $\tilde{Q}$ [8] of 33.6 and this is sufficient to create a strong blowout, and the interaction achieves a longitudinal field of 3 TV/m. This is illustrated in the snapshot of the beam-plasma interaction after 3 mm, shown in Fig. 4. The beam behaves like a delta function perturbation to the plasma and is very small compared to the longitudinal size of the blowout cavity.

Only parts of the beam that are inside the blowout cavity are affected by the plasma wakefields. The tail of the beam that is inside the cavity is strongly decelerated and focused by the wakefield. Some of the particles at the tail of the beam quickly lose all of their energy. Within a few millimeters, some of the electrons that are lost from the driver are later recaptured and accelerated by the plasma wakefield. Ultimately, the beam diverges and the nonlinear characteristics of the blowout regime are lost. This is because of several reasons that include: the short beta functions; the bulk of the beam being insusceptible to the focusing forces of the blowout cavity; and the deceleration of the beam. Decreasing the plasma density can increase the interaction length and ensure that the beam is smaller than the plasma skin depth but concomitantly amplify the delta function like behavior of the interaction.

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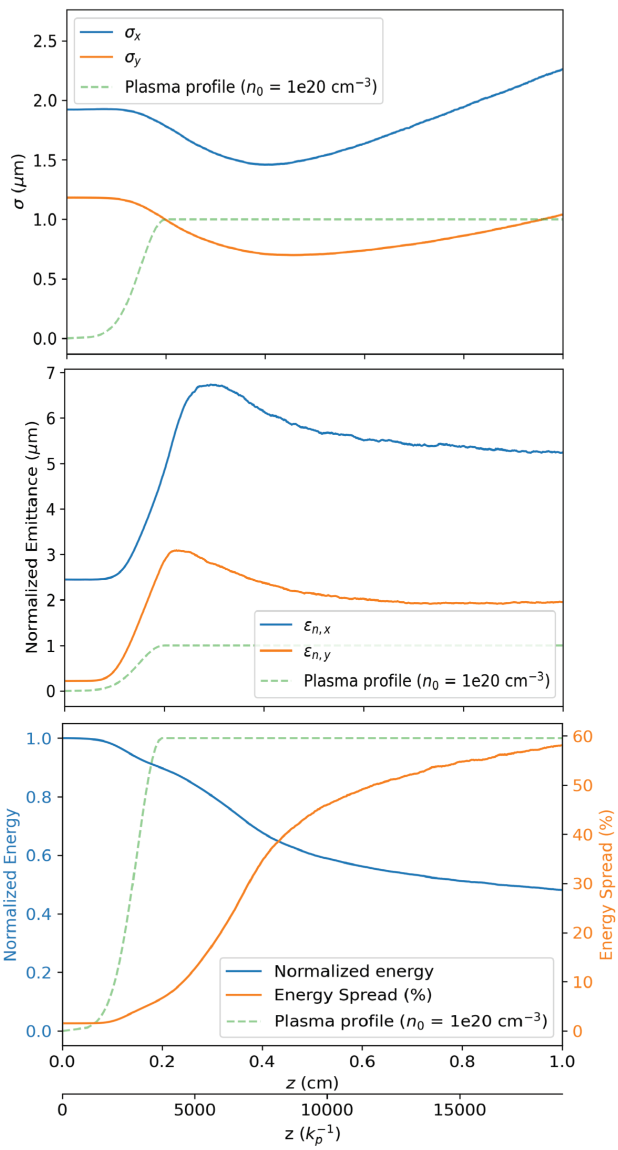

Figure 3: Evolution of the beam transverse spot sizes (top), emittances (middle), and energy (bottom) with the plasma profile in the second plasma stage. The beam is focused due to the ramp but is strongly decelerated and quickly diverges because of the short beta functions.

CONCLUSION AND FUTURE WORK

We have presented a path to achieve very high gradient wakefields by employing two PWFA stages having different plasma densities. The first PWFA stage can create a beam with a linear chirp that, after compression, can have enormous currents and, after focusing, can be used to drive plasma wakefields in a the second PWFA stage. However, operating at these high currents and plasma densities can impose certain restrictions on the beam quality and focusing systems. The delta function behavior of the beam plasma interaction further curtails the possibilities of using plasma based lenses and matching sections. Longitudinal space charge effects of the nanometer scale beam in the beam

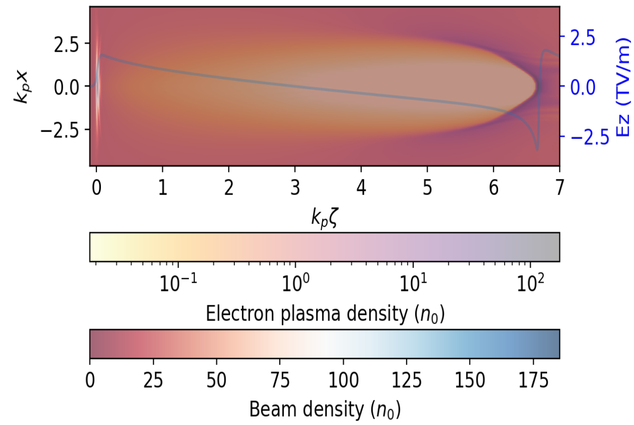

Figure 4: PIC simulation snapshot showing the interaction of the focused beam with the plasma at 3 mm. The accelerating field reaches 3 TV/m gradients.

transport will need to be investigated and simulations using a full PIC code will need to be carried out to fully understand the effects of plasma instabilities on the beam. The path presented in this paper promises to be a robust alternative for accessing TV/m fields [9, 10] with minor modifications to the PAX program.

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