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HIGH BRIGHTNESS ELECTRON BEAMS FROM DRAGON TAIL INJECTION AND THE E-312 EXPERIMENT AT FACET-II

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Abstract

The advent of optically triggered injection in multi component plasma wakefield accelerators has been shown to enable a substantial increase in witness electron beam quality. Here we present a novel way of using the overlap of laser and beam radial fields to locally liberate electrons from the tunneling ionization of the non-ionized gas species. These liberated ultracold electrons gain sufficient energy to be trapped in the accelerating phase at the back of the plasma blowout. This method of controlled injection has advantages in precision timing since injection is locked to peak beam current and has the potential of generating beams with very low emittance and energy spread. This method has been investigated using particle-in-cell (PIC) simulations. This scenario corresponds to a planned experiment, E-312, at SLAC's FACET-II facility.

INTRODUCTION

Plasma wakefield acceleration can support high accelerating and focusing gradients which can reduce the footprint of particle accelerators. However, plasma wakefield accelerators require two beams: a drive beam to create the plasma structures which create the accelerating and focusing wakes and a secondary beam, called the witness beam, which is accelerated. This creates an impediment as insertion into the plasma accelerator stage can compromise the beam quality of the witness beam. To mitigate this, a hybrid scheme of combining the electron source with the acceleration section was proposed [1] which uses a laser to trigger ionization within the plasma blowout cavity [2, 3], thereby creating witness beam electrons that are ultracold. In this method of injection, the target is composed of both a high ionization threshold (HIT) gas as well as a low ionization threshold (LIT) gas. The LIT gas is preionized and the drive beam creates a strong plasma wave blowout. A laser is used to locally ionize the high ionization threshold (HIT) gas within the blowout and the created electrons are captured and accelerated to relativistic energies by the strong electric fields associated with the plasma wake. The electric fields at the hot spots (wake vertex and drive beam) should be less than the ionization threshold of the HIT medium to ensure that there is no uncontrolled injection which can degrade the beam quality and the plasma wake [4].

The injection process can produce witness beams with low energy spread and mm-mrad emittance with high tunability. However, these attributes depend on the spatiotemporal precision of the injection laser which poses significant challenges as the injection process is not locked to the beam current. In this paper, we propose a method which would ensure alignment and, at the same time, allow for the advantages associated with optically triggered ionization.

The proposed scheme, dubbed *dragon tail injection*, uses a laser pulse overlapped with the peak beam current. The superposition of the beam and laser fields during the overlap enable tunnel ionization of the HIT medium in a manner temporally locked locked to the beam current, enhancing the injection phase stability by considerably reducing the timing jitter. The injection region is small which could lead to the creation of very low emittance beams and also require a laser system with modest energy output. Ramped driver beams can be employed to ensure that the injection occurs at the tail of the beam and that the acceleration would have a high transformer ratio. This experimental scheme has been formally approved for FACET-II with E-312 as the assigned experimental number.

The simulations in this article were performed using the 3D, fully relativistic PIC code, OSIRIS [5] characterize this proposed scheme.

CONDITION FOR LOCAL IONIZATION

The electrostatic oscillations in a plasma for a small perturbation occur at the cold plasma frequency ω_p. For a high current, tightly focused ($k_p\sigma_r \leqslant 1$), axisymmetric beam, the maximum radial fields $E_r^{b,\max}$ are given by [6]:

$$\frac{E_r^{b,\max}(\zeta)}{E_{\mathrm{WB}}} \approx -0.45\frac{\Lambda_b(\zeta)}{k_p\sigma_r}, \tag{1}$$

where $\zeta = ct - z$, $E_{\mathrm{WB}} = mck_p^2/e$ is the wave-breaking field, $\Lambda_b(\zeta) = k_p^2\int_0^\infty (n_b(\zeta)/n_0) r dr$ is the normalized charge per unit length of the beam, and k_p is the plasma wave number. The maximum radial fields are obtained at r $\approx 1.585\ \sigma_r$ and at the location corresponding to the peak current. Since the magnitude of the radial fields are dependent on the structure of the beam, it is highly sensitive to betatron oscillations and current fluctuations. Injection using only the drive beam radial fields would therefore not be easily controlled.

In the proposed scheme, ionization only occurs if the superposition of the beam and laser fields, E_l, is higher than the ionization potential of the HIT species, E_{HIT}. The condition of local ionization is therefore:

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$$|E_z^w|, |E_r^{\max}|, |E_l| < E_{\mathrm{HIT}} < \left|\vec{E}_r^{b,\max} + \vec{E}_l\right| \qquad (2)$$

where $|E_z^w|$ is the maximum longitudinal fields expected at the end of the bubble near the plasma electron density spike and $E_r^{\max}$ is the maximum radial field of the beam-plasma system.

SIMULATION RESULTS

There are several modes of witness injection that are possible in such a system including cases where the laser propagates along the mid-plane or with the laser propagating off mid-plane. The ionization area and concomitantly the properties of the witness beam are dependent on the injection mode. In the first mode, the laser can interact on both sides of the mid-plane provided that the beam spot size is large enough while in the second mode, the laser can be made to interact with only one side of the beam which can allow for the possibility of an off axis injection of the witness beam. We have presented here the case where the laser propagates along the mid-plane (at x = 0). The slice of the beam and plasma densities along the mid-plane are shown in Fig. 1.

Table 1: Simulation Parameters

Parameter	Value	Unit
Medium		
Plasma/LIT species	H^+	-
HIT species	He	-
Gas density, $n_{\mathrm{LIT}} = n_{\mathrm{HIT}}$	1.789×10^{16}	cm^{-3}
Plasma wavelength, λ_p	250	µm
Beam		
Charge, Q_b	1.46	nC
Energy, E	10	GeV
Peak density, n_b/n_0	43	-
Total length	187.5	µm
$\sigma_\perp$	4.4	µm
$\epsilon_{n,\perp}$	50	µm-rad
rms energy spread	5	%
Laser		
λ_l	800	nm
a_0	0.011	-
Pulse waist, w_0	19.9	µm
Pulse duration	15	µm
Simulation		
Moving window (x,y,z)	(6, 6, 10)	k_p^{-1}
Grid	(60, 3000, 100)	-
Timestep	0.001	ω_p^{-1}
Particles per cell (Beam)	(1, 1, 1)	-
Particles per cell (LIT)	(1, 1, 1)	-
Particles per cell (HIT : After ionization)	(50, 1, 50)	-

The associated longitudinal and transverse fields of the wake are shown in Fig. 2.

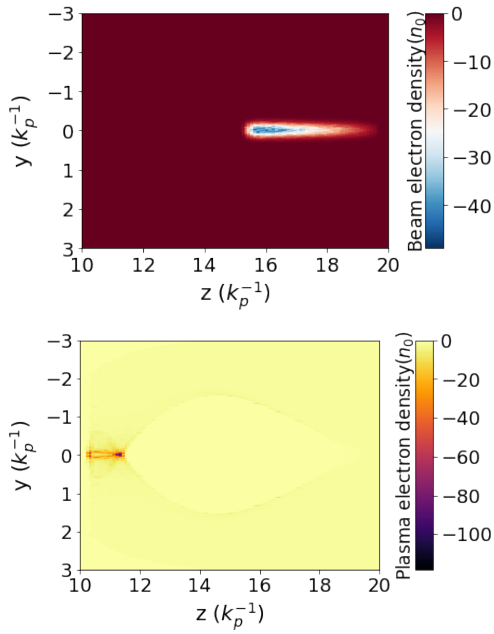

Figure 1: Beam charge (a) and plasma charge densities (b) on the mid-plane y-z.

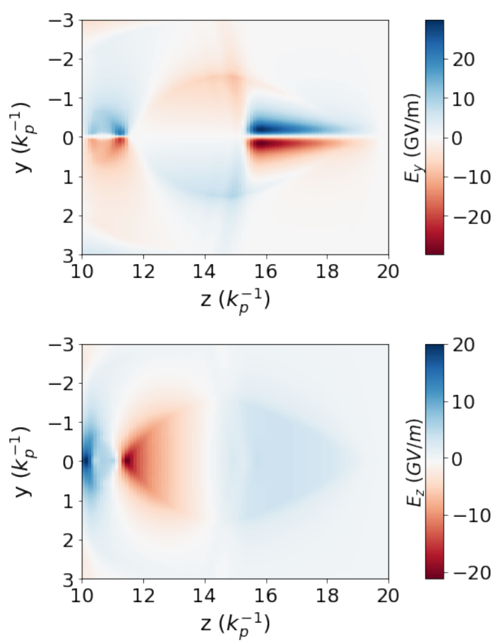

Figure 2: Transverse (a) and longitudinal fields (b) on the mid-plane y-z.

The laser is injected perpendicular to the propagation direction of the beam as was done in the E-210 Trojan Horse experiment [7]. The superposition of the laser fields with the radial fields of the beams causes the electric field to be greater than the ionization potential of the high ionization threshold species and locally ionizes it. The cold, liber-

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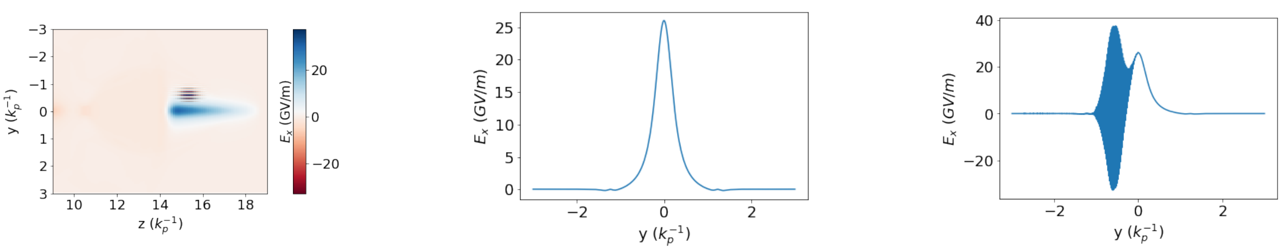

(a) (b) (c)

Figure 3: The laser pulse interacts with the beam radial fields on both sides of the mid-plane. The fields on one side of the mid-plane are shown here. The radial field of the beam without the laser is shown in (b) while the superposition of the laser field and beam radial field is shown in (a) and as a lineout in (c) at position x = -7.96 µm.

ated electrons interact with the beam fields and are initially defocused. However, since the wake is propagating, these electrons fall backwards with respect to the beam and are then focused by the ion column. These electrons reach the accelerating phase of the wake and are captured, stably accelerating to relativistic energies. Increasing the laser intensity leads to the formation of a sliver of charge analogous to the plasma torch injection experiment [8] before the spatial overlap with the beam. It significantly increases the witness beam charge as the probability of tunneling ionization also increases at the laser-beam overlap region.

The system described above was simulated (see simulation parameters in Table 1) for a distance of 80 k_p^{-1}, about 3.18 mm, after injection and the ions were considered to be immobile. The superposition of the beam radial and laser fields is shown in Fig. 3. The simulations are computationally intensive as the laser wavelength must be resolved which imposes restrictions on the number of grids in the other directions. Due to the low resolution imposed by the asymmetry in the grids, the initial ionized charge was observed to be quite granular. The final charge that was accelerated and captured by the plasma wake was 23.6 fC, about 40% of the initially ionized charge of 61.2 fC. The final emittance in the x direction ϵ_x and y direction ϵ_y was 4.77 µm-rad and 2.53 µm-rad respectively. The final beam spot size in the x direction σ_x and y direction σ_y was 5.41 µm and 3.98 µm and the final bunch length σ_z was 0.56 µm. The final witness beam phase space is shown in Fig. 4.

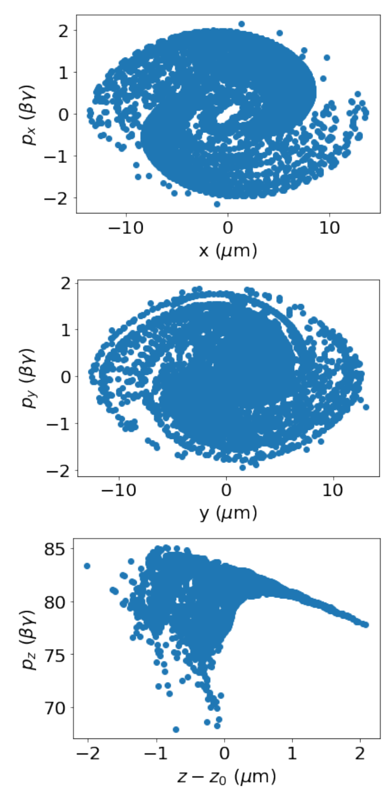

Figure 4: Final witness beam phase space with z_0 representing the witness beam location.

CONCLUSION

This experiment will extend the progress in plasma photocathode injection schemes along with the planned co-linear Trojan Horse experiment at FACET-II [9]. The experiment can also operate in different modes of injection as has been specified and provides a solution for locking the injection to the beam current. The area of ionization can be further increased by changing the angle of the laser, which would increase the spatial overlap of the beam with the laser and lead to an enhancement of the witness charge. Further exploration and optimization of the parameter space would require more intensive simulations with much higher resolution and the numerical effects introduced by the asymmetrical nature of the grids need to be further characterized.

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REFERENCES

[1] B. Hidding, G. Pretzler, J. B. Rosenzweig, T. Königstein, D. Schiller, and D. L. Bruhwiler, "Ultracold electron bunch generation via plasma photocathode emission and acceleration in a beam-driven plasma blowout", *Phys. Rev. Lett.*, vol. 108, p. 035001, 2012. doi:10.1103/physrevlett.108.035001

[2] N Barov, J. B. Rosenzweig, M. Conde, W. Gai, and J. Power, "Observation of plasma wakefield acceleration in the underdense regime", *Physical Review Special Topics - Accelerators and Beams*, vol. 3, p. 011301, 2000. doi:10.1103/PhysRevSTAB.3.011301

[3] W. Lu, C. Huang, M. Zhou, W. B. Mori, and T. Katsouleas, "Nonlinear theory for relativistic plasma wakefields in the blowout regime", *Phys. Rev. Lett.*, vol. 96, p. 165002, 2006. doi:10.1103/PhysRevLett.96.165002

[4] G. G. Manahan *et al.*, "Hot spots and dark current in advanced plasma wakefield accelerators", *Phys. Rev. Accel. Beams*, vol. 19, p. 011303, 2016. doi:10.1103/PhysRevAccelBeams.19.011303

[5] R. Fonseca *et al.*, "Osiris: A three-dimensional, fully relativistic particle", in *Cell Code for Modeling Plasma Based Accelerators*, NY, USA: Springer, 2002, pp. 342–351.

[6] A. Martinez de la Ossa, T. J. Mehrling, L. Schaper, M. J. V. Streeter, and J. Osterhoff, "Wakefield-induced ionization injection in beam-driven plasma accelerators", *Physics of Plasmas*, vol. 22, no. 9, p. 093107, 2015. doi:10.1063/1.4929921.

[7] A. Deng *et al.*, "Generation and acceleration of electron bunches from a plasma photocathode", *Nature Physics*, vol. 15, no. 11, pp. 1156–1160, 2019. doi:10.1038/s41567-019-0610-9

[8] G. Wittig *et al.*, "Optical plasma torch electron bunch generation in plasma wakefield accelerators", *Physical Review Special Topics - Accelerators and Beams*, vol. 18, p. 08, 2015. doi:10.1103/PhysRevSTAB.18.081304

[9] C. Joshi *et al.*, "Plasma wakefield acceleration experiments at FACET II", *Plasma Physics and Controlled Fusion*, vol. 60, no. 3, p. 034001, 2018. doi:10.1088/1361-6587/aaa2e3