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Authors
Yadav, M
Hansel, C
Rosenzweig, J
et al.

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ION MOTION IN FLAT BEAM PLASMA ACCELERATORS

M. Yadav[1,2*], C. Hansel[†], J. Rosenzweig
University of California, California, USA
[1]O. Apsimon, [1]C. P. Welsch
University of Liverpool, Liverpool, UK
[1]also at Cockcroft Institute, Warrington, UK
[2]also at University of Liverpool, Liverpool, UK

Abstract

Intense beams, such as those in proposed plasma based linear colliders, can not only blow out electrons to form a bubble but can also attract ions towards the beam. This violates the assumption that the ions are stationary on the timescale of the beam, which is a common assumption for shorter and less intense beams. While some research has been done on understanding the physics of ion motion in blowout plasma wakefield accelerators (PWFAs), this research has almost exclusively focused on cylindrically symmetric beams rather than flat asymmetric emittance beams. This contribution presents results of particle-in-cell (PIC) simulations which demonstrate the formation of a beam electron-plasma ion quasi-equilibrium. We discuss the physics of the beam-ion interaction and the relevance to future linear colliders.

INTRODUCTION

Plasma based linear colliders promise to achieve higher beam energies while simultaneously having a smaller physical footprint. Proposed colliders typically operate in the blowout regime [1] where a dense drive beam blows out electrons forming a trailing bubble rarefied of plasma electrons. Due to their much larger mass, the plasma ions inside this bubble are typically assumed to be stationary and thus generate linear focusing fields which are desirable for preserving beam emittance. However, in some proposals such as the "plasma afterburner" [2, 3], an energy doubling plasma accelerator at the end of a traditional linear collider, the long, high density beams cause this assumption to be violated [4].

While there have been a number of studies devoted to the topic of ion motion, previous research has almost exclusively focused on cylindrically symmetric beams rather than flat, asymmetric emittance beams which are often used in order to minimize beamstrahlung at the final focus [5].

ION MOTION CONDITION

In this section we derive a dimensionless parameter that allows us to quantify the degree of ion motion in a flat beam PWFA. This is done in a similar way to the round beam case [4]. Consider a trigaussian flat beam where $\sigma_x \gg \sigma_y$. Close to the core of the beam, the force on a plasma ion due to the beam is

$$\vec{F} = -\frac{Z_i e^2 n_{b,0}}{\epsilon_0}\vec{y}, \tag{1}$$

where Z_i is the ion charge state and $n_{b,0}$ is the peak beam density. The position of an ion near the core of the beam as a function of time is thus $y(\xi) = y_0 \cos(k_i \xi)$ where $\xi = ct - z$ and $k_i^2 = 4\pi r_e Z_i n_{b,0} m_e / m_i$ where r_e is the classical radius of the electron. As in [4], we account for longitudinal variation in the beam density by taking the beam's effective length to be $\Delta\xi = \sqrt{2\pi}\sigma_z$. Thus the phase advance of the ion at the end of the beam is

$$\Delta\phi = k_i \Delta\xi = 2\pi\sigma_z\sqrt{\frac{2 r_e Z_i n_{b,0} m_e}{m_i}}, \tag{2}$$

which is used to quantify ion motion. Note that this is $\sqrt{2}$ times the expression for the phase advance in the cylindrical symmetric case. For $\Delta\phi \ll 1$, the change in the position of an ion is negligible. For $\Delta\phi \lesssim \pi/2$, the ions move but their motion is still laminar and wavebreaking does not occur. In this case there is a nonlinear perturbation to the fields which focus the beam. For $\Delta\phi > \pi/2$, the ions cross the $y = 0$ plane where there is a density spike. In this case the

Table 1: PIC Simulation Parameters

Parameter	Value	Unit
Plasma		
n_0	1.5×10^{17}	cm^{-3}
L_p	54.3	cm
Species	H^+	-
Beam		
Peak density	4000	n_0
E	10	GeV
σ_x	5.89	µm
σ_y	0.12	µm
σ_z	20.03	µm
$\epsilon_{n,x}$	250	µm
$\epsilon_{n,y}$	0.1	µm
$\Delta\phi$	5.40	µm
Simulation		
Transv. Cell Size	54	nm
Long. Cell Size	268	nm

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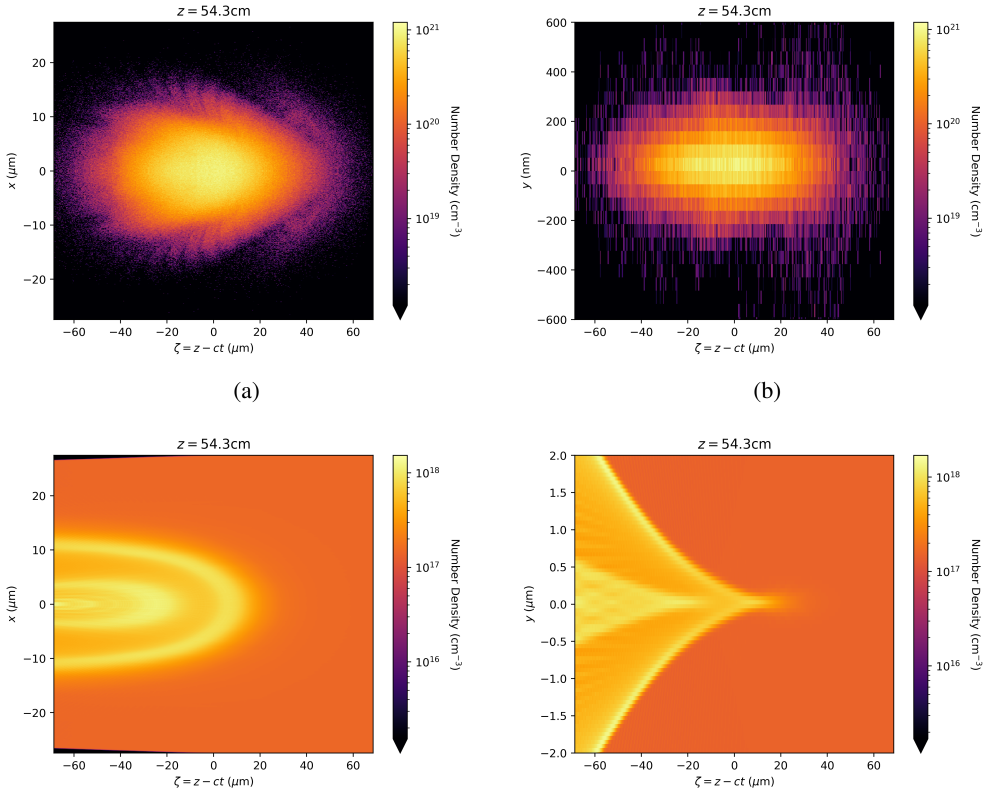
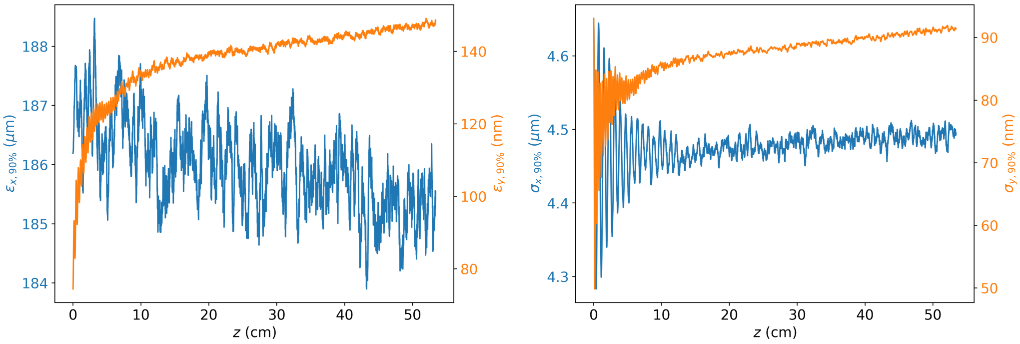
[*] monika.yadav@liverpool.ac.uk
[†] clairehansel3@gmail.com



(a) (b)

(c) (d)

Figure 1: Top: Beam electron number density x-z (a) and y-z (b) slices at $z = 54.3$ cm. Bottom: Ion number density x-z (c) and y-z (d) slices at $z = 54.3$ cm.



(a) (b)

Figure 2: Evolution of beam 90% emittance (a) and 90% spot size (b) over the length of the plasma.

ion motion is non-laminar and the fields focusing the beam become highly nonlinear.

FLAT BEAM EQUILIBRIA

In the cylindrically symmetric case, extreme ($\Delta\phi \gg \pi/2$) ion motion causes the formation of a beam-ion equilibrium [6]. In this section we investigate the formation of an asymmetric beam-ion equilibrium. To do this, we simulated a single flat beam travelling through a uniform ion background using the quasi-static PIC code `QuickPIC` [7,8]. `QuickPIC` was modified to allow the simulation of non-neutral plasmas so that the plasma electron blowout could be ignored. This was discussed further in [6]. The parameters of the simulation are shown in Table 1.

This simulation demonstrated the formation of an asymmetric beam-ion equilibrium. 2D slices of the number density distribution at the end of the plasma for both the beam electrons and plasma ions are shown in Fig. 1. From this figure, we can see that the beam becomes a complex, non-gaussian distribution as a result of phase space mixing due to the nonlinear fields which are a consequence of ion motion. The $x = 0$ 2D ion number density slice clearly shows extreme ion motion. Shocks can be seen emanating from the density spikes that occur when $k_i\xi = \pi(2n+1)/2$ where $n \in \mathbb{Z}, n \geq 0$. The $y = 0$ 2D ion number density slice shows a series of rings of increased density. The outermost ring corresponds to the $k_i\xi = \pi/2$ density spike, the next ring corresponds to the $k_i\xi = 3\pi/2$ spike and so on. The number of spikes decreases for increasing values of $|x|$ as the beam density shrinks causing less extreme ion motion.

The collisionless relaxation to equilibrium can be seen in the evolution of the beam spot size and emittance, which are shown in Fig. 2. 90% emittance and 90% spot size were used due to the large number of large amplitude particles especially near the end of the plasma. This is possibly a result of chaotic diffusion, and requires further study. The emittance plots show that emittance is conserved in the large transverse dimension x. There is fast, nontrivial emittance growth in the small transverse dimension y as the collisionless relaxation takes place over the first few centimeters. However, unlike in the cylindrically symmetric case, the y spot size and emittance continue to grow, albeit at a slower rate, after the collapse to equilibrium.

CONCLUSION

In this paper we have discussed the physics of ion motion in flat beam plasma wakefield accelerators. We have shown that an asymmetric beam-ion quasi-equilibrium is formed in the flat beam case. Unlike the cylindrically symmetric case [6], there are no plans to perform a flat beam ion motion experiment at FACET-II due to the difficulty in accessing the required parameter space. Before a plasma based flat beam linear collider can be built, additional work must be done to better understand the relativistic beam-ion interaction. In particular emittance growth mitigation through beam matching must be studied in a way analagous to [9]. The beam-ion equilibrium should be studied further and modeled analytically. Scattering and chaotic diffusion should be investigated as possible sources of emittance growth.

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