ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR67

ION-ION COLLISIONS IN PLASMA WAKEFIELD ACCELERATORS

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Abstract

The plasma wakefield accelerator, with acceleration gradients ranging from GeV/m to TeV/m, holds promise for propelling particles to high energies in linear colliders. This results in exceptionally bright beams characterized by intense ion-derived focusing, leading to the collapse of plasma ions. Our study extends prior research focused on electron acceleration by investigating ion-ion collisions, studying different collision models and emphasizing the near-equilibrium state post-ion collapse using the OSIRIS Particle -in-cell (PIC) code. Notably, our findings reveal that parametric excitations arising from plasma non-uniformity have an insignificant impact on phase space diffusion, a crucial insight for optimizing linear colliders.

INTRODUCTION

Plasma wakefield acceleration (PWFA) employs waves in a plasma medium chosen to naturally avoid breakdown issues. These waves are excited by an intense drive beam to accelerate a trailing beam. PWFAs have already demonstrated acceleration gradients exceeding 50 GeV/m. To explore the suitability of the PWFA for linear collider applications, proposals [1, 2] have been put forward that analyze the use of an afterburner at the end of a conventional linear collider injector, with the goal of doubling the beam energy [3].

Current experimental and theoretical research on PWFAs has focused on the nonlinear blowout regime due to its favorable properties for acceleration and focusing. In the blowout regime, the electron beam density is much greater than the ambient plasma electron density, and the collective fields of the beam eject the plasma electrons from the region near the beam axis. This creates a bubble of negligible electron density [4].

Furthermore, in this scenario, an electromagnetic wave is trapped inside of this bubble that provides acceleration in uniform phase fronts, as in standard relativistic electron accelerators. Further, in this scenario the plasma ions left behind, if undisturbed, provide a uniformly charged column that yields strong, linear (emittance-preserving) focusing. In this way, one may achieve high quality, low energy spread acceleration without emittance growth due to geometric aberrations. However, the stationary ion assumption does not hold in the proposed PWFA afterburner case [5]. In this case the plasma ions fall toward the center of the beam. The degree of ion motion can be quantified by a dimensionless parameter known as the phase advance

$$\Delta\phi = 2\pi\sigma_z\sqrt{\frac{r_e Z_i n_{b,0} m_e}{m_i}} \tag{1}$$

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where r_e is the classical electron radius, Z_i is the ion charge state, m_i is the ion mass, $n_{b,0}$ is the number density of electrons at the center of the beam, and σ_z is the rms length of the beam. Ion-ion collisions can be treated as similar to the electron-ion collisions, but their thermal motion is different. The goal is to study the change in PWFA due to ion-ion collisions using PIC code OSIRIS simulations [6]. In the strong blowout regime, a very different evolution of the subsequent plasma motion was obtained, and the potential role of ion-ion collisions in the approach to equilibrium deduced.

PARTICLE-IN-CELL SIMULATIONS

Table 1: Parameters of the PIC Simulation

Parameter	Value	Unit
Plasma		
n_0	10^{18}	cm^{-3}
l_{plasma}	10	cm
Beam		
E	10	GeV
Q	3	nC
ϵ_n	2	μm
$\sigma_{x,y}$	328	nm
n_e/n_0	267	

We simulated extreme ion motion using the PIC code OSIRIS. The parameters of this simulation, shown in Table 1, are based on what is likely achievable in the future experiments at FACET-II in Fig. 1. A long, dense beam was chosen to give ample interaction time for the quasi-equilibrium to develop.

When ion motion is significant, Coulomb attraction causes plasma ions to fall into the beam forming an ion column. The ion column focuses the beam, which, in turn, focuses the ions even more tightly. We notice that the ion-ion repulsion and ion thermal pressure balance out the beam-ion attraction, and the system reaches an equilibrium. Strong permanent magnet quadrupoles will be used to focus the beam down to spot sizes on the order of hundreds of nanometers.

PIC simulations were conducted to confirm that an approximate equilibrium is achieved, in which the transverse densities of the beam electrons and plasma ions are characterized by a Bennett-type profile after ion collapse, as shown in Fig. 2 [7–9]. Since the collapse to near-equilibrium occurs much faster than the overall time scale of the PWFA interaction, we use the PIC simulations only to examine few 10's of femtosecond transient period. Following the approach of [10], the ion channel is established before the arrival of the beam involved in the collapse dynamics. We compared two cases for ions, one with ion-ion collisions and another with

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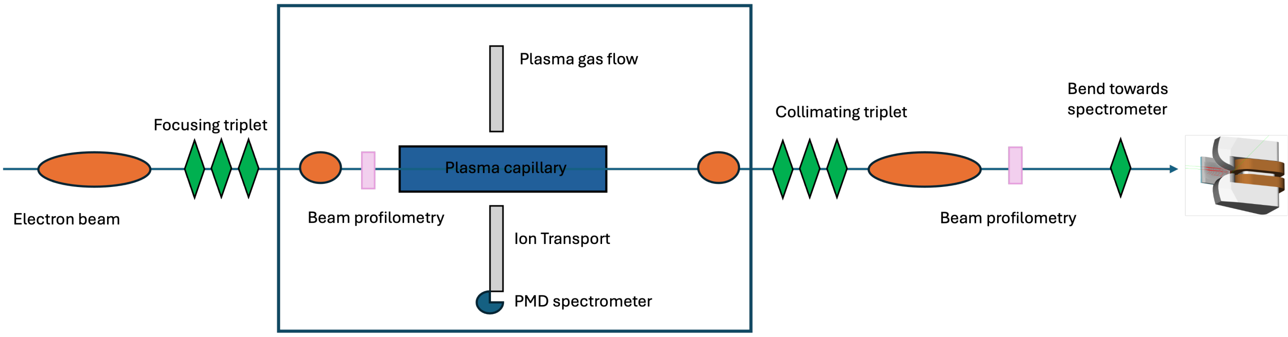

Figure 1: Possible PWFA experiment to understand ion motion in plasmas.

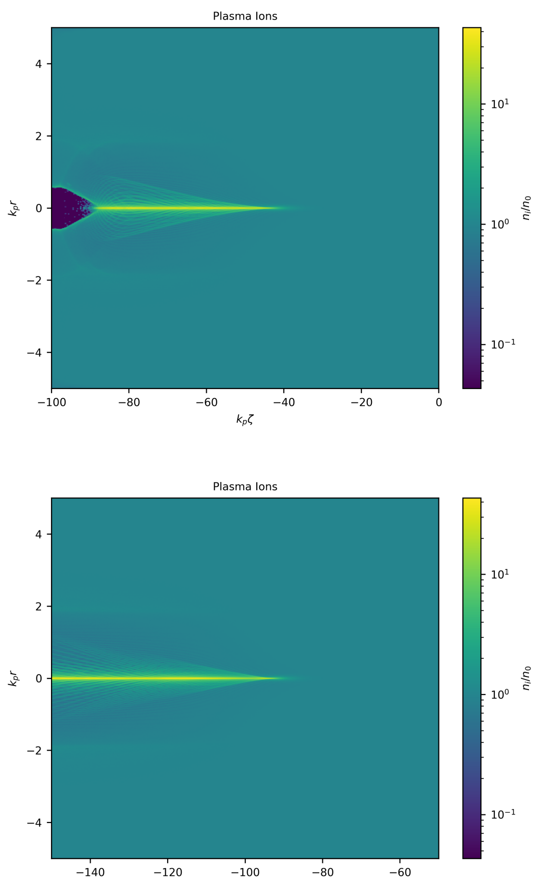

Figure 2: Densities of plasma ions in the 2D slice y = 0 at the end of the ion collapse simulation. Simulation performed using OSIRIS code with the parameters shown in Table 1.

no ion-ion collisions. In the case of the ion-ion collisions we notice a perturbation between the ions far from the head of the beam.

The radial force on an ion is due to the nonlinear electric field generated by the Gaussian beam and the linear electric field produced by the other uniformly distributed ions. This force is

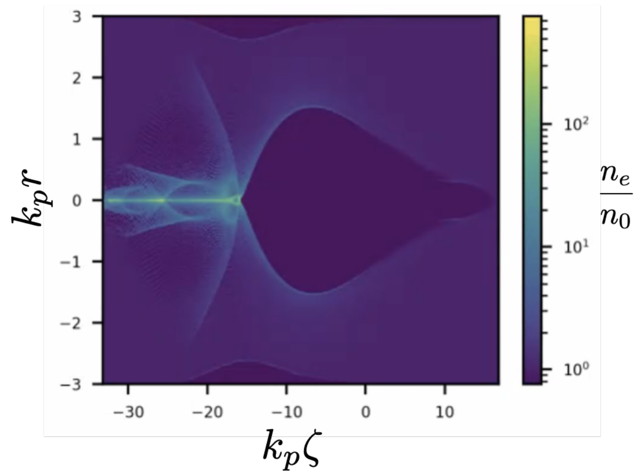

Figure 3: Densities of plasma electrons in the 2D slice. Pure electron filament is achieved behind the blowout bubble. Which could be useful for positron acceleration.

$$F_{i,r} = -\frac{Z_i e^2 n_{b,0} \sigma_i^2}{\epsilon_0 r}\left(1 - e^{-\frac{r^2}{2\sigma_i^2}}\right) + \frac{Z_i^2 e^2 n_0 r}{2\epsilon_0} \quad (2)$$

where Z_i is the ion charge state, $n_{b,0}$ is the peak density of the beam, and σ_i is the transverse beam spot size.
The potential is

$$V(r) = -\lim_{\epsilon \to 0} \int_{\epsilon}^{r} F_{i,r}(r) dr \quad (3)$$

equilibrium transverse ion distribution is given by

$$n_i(r) = \frac{\kappa}{r}. \quad (4)$$

Figure 3 shows the densities of plasma electrons in the 2D slice. Pure electron filament is achieved behind the blowout bubble, which could be useful for positron acceleration. In Fig. 4 density lineout plot of plasma ions for y = 0 and at the end of the ion collapse simulation. Shown are the PIC simulation data (black dots) Bennett profile. In Fig. 5 we discuss the density lineout plot of plasma ions for y = 0 and at the end of the ion collapse simulation.

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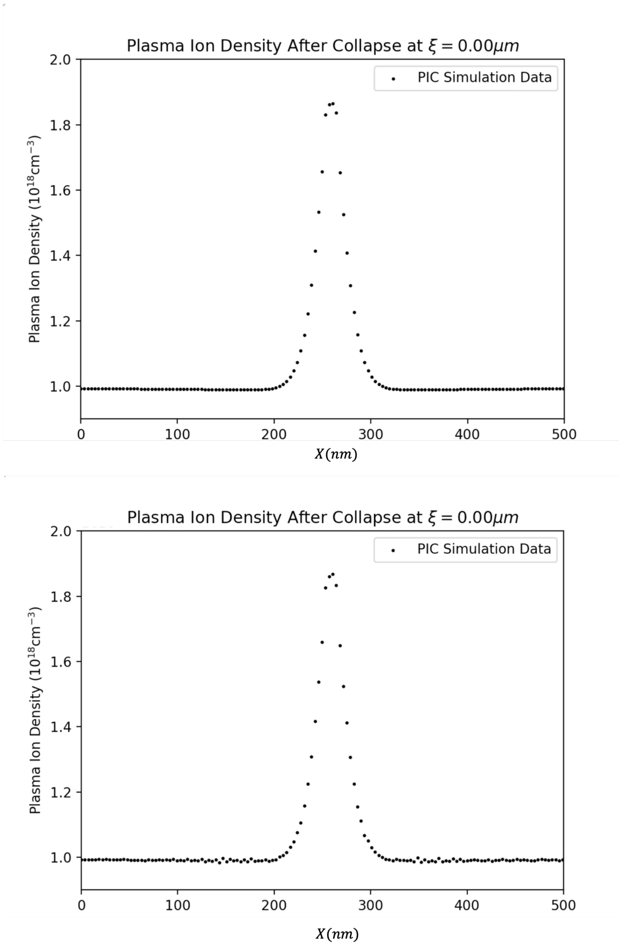

Figure 4: Density lineout plot of plasma ions for y = 0 and at the end of the ion collapse simulation. Shown are the PIC simulation data (black dots) Bennett profile.

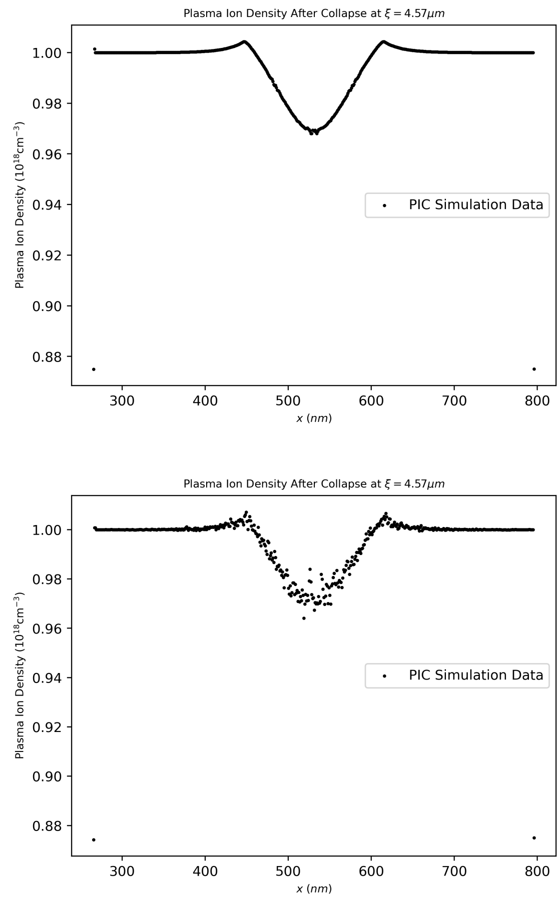

Figure 5: Density lineout plot of plasma ions for y = 0 and at the end of the ion collapse simulation.

To observe the differences between the scenarios with and without collisions, the "if-collide" parameter for the ion species must be set to "true." For intra-species collisions (collisions between particles of the same species), the "if-like-collide" parameter should also be set to "true." We employed the non-relativistic "Takizuka" model. The aim is to understand the dual Bennett-type equilibrium in this system. Achieving the final matching of the beam to the extremely strong ion focusing after collapse is experimentally very challenging in the FACET-II context due to limitations in the final focus.

DISCUSSION AND CONCLUSION

In this paper, we improved our analytical understanding of nonlinear equilibria in PWFAs with ion-ion collisions. By extending previous research through theoretical and computational methods, we confirmed that these equilibria follow Bennett-type profiles. We discussed a scenario to be explored at FACET-II by the E-314 experimental collaboration. Using cutting-edge methods in photoinjector electron sources, beam preparation, and high-gradient final focusing permanent magnet quadrupoles, we aim to achieve a collapsed-ion equilibrium at the FACET-II interaction point [11]. The collisionless relaxation of plasma ions occurs along the beam's length, while the beam electrons relax along the accelerator, excluding the very head of the beam where ion motion is negligible. Ion-ion collisions play a pivotal role in shaping the dynamics of PWFA. This understanding is crucial for advancing PWFA technology and achieving the high-energy acceleration goals of future linear colliders. In the future plan is to predict the final emittance from the initial conditions, and optimize the initial conditions to minimize it.

ACKNOWLEDGEMENT

This work was performed with the support of the US Department of Energy, Division of High Energy Physics, under Contract No. DE-SC0009914, DE-SC0017648, NSF PHY-1549132 Center from Bright Beams, DARPA under Contract N.HR001120C007.

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