INVESTIGATION OF A GAS JET-PRODUCED HOLLOW PLASMA WAKEFIELD ACCELERATOR*

N. Kirby, I. Blumenfeld, M. J. Hogan, R. H. Siemann, D. R. Walz, SLAC, Menlo Park, CA 94025
A. W. Davidson, C. Huang, UCLA, Los Angeles, CA 90095

Abstract

The effect of ion motion and the need for practical positron propagation in a plasma wakefield accelerator (PWFA) have incited interest in hollow plasma channels. These channels are typically assumed to be cylindrically symmetric; however, a different geometry might be easier to achieve. The introduction of an obstruction into the outlet of a high Mach number gas jet can produce two parallel slabs of gas separated by a density depression. Here, there is a detailed simulation study of the density depression created in such a system. This investigation reveals that the density depression is insufficient at the desired plasma density. However, insights from the simulations suggest another avenue for the creation of the hollow slab geometry.

INTRODUCTION

Plasma-based particle accelerators have shown immense potential for future high energy colliders [1] [2]; however, there are several remaining issues. Two of the biggest obstacles for the PWFA are ion motion [3] and the need for positron propagation [4]. A hollow channel plasma does not have ions on the axis of bunch propagation. The absence of on-axis ions removes the possibility for ion motion and eliminates the intrinsic defocusing they create for positrons. Thus, the creation of a hollow channel plasma would be a tremendous asset for the PWFA.

While a hollow channel plasma offers solutions to PWFA problems, there is not yet a proven method for generating one. A current idea for the production of a hollow channel is to use a cylindrically-symmetric acoustic standing wave to create a density depression on the axis of bunch propagation; this is similar to methods used for the purpose of laser guiding [5]. Another idea utilizes a high-order Bessel laser beam with an intensity profile that peaks off-axis. When applied to a gas of uniform density, this laser could create a hollow channel of plasma centered about the axis [6]. These ideas focus on the production of cylindrically-symmetric hollow channels. Consider instead a different geometry, one with an evacuation of gas atoms from a small region in the Cartesian y-coordinate. This geometry consists of two parallel slabs of gas, between which a drive bunch could create a plasma wake.

This paper investigates one idea for a method to produce such a hollow channel plasma. The basic concept is to insert an obstruction into a high Mach number gas jet. In the absence of interatomic collisions, the atoms that contact the obstruction scatter, producing a perfect hollow channel behind the obstruction (illustrated in Fig. 1). A computational technique is developed here to study the effect of the atom-atom collisions on the density depression.

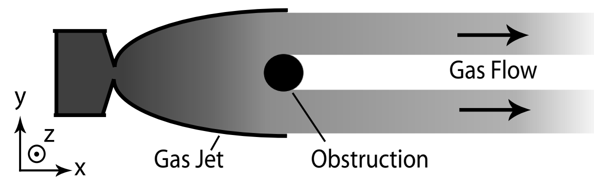

Figure 1: An illustration of a gas jet-produced hollow channel. A drive bunch would travel in the z-direction, between the two slabs of flowing gas.

Before progressing into the computational techniques, it is important to quantify how deep the density depression must be for the PWFA application. This allows for the interpretation of results. Consider this question from the perspective of ion motion. Rosenzweig et al. [3] examined the motion of ions induced by the intense transverse electric field of a matched drive bunch. They found that these intense fields could cause ions to move significantly before the bunch passes, which creates nonlinear focusing forces and transverse emittance growth. At the core of the drive bunch, the transverse electric field is linear as a function of separation from the bunch axis, so the ion motion is modeled as a harmonic oscillator. The amount of ion motion is judged by the phase advance in this harmonic oscillator, where 2π represents a full cycle. A phase advance of $\pi/2$ is catastrophic, causing the ions to collapse from their initial radii to a radius of zero. For phase advances less than this value, the ions have transverse positions that are proportional to their initial positions. Thus, the ion density would still be uniform at the core of the bunch, but at an increased magnitude. For simplicity, let $\pi/4$ set the scale for an endurable amount of phase advance.

Current concepts for a plasma-based linear collider utilize a bunch with 10^{10} electrons, energy of 500 GeV, longitudinal bunch length equal to 10 μm, and normalized transverse emittances, $\epsilon_{N,x}$ and $\epsilon_{N,y}$, equal to 2 and 0.05 μm, respectively [7]. As is discussed later, simulations here are performed for helium, which has an atomic number of 2 and a mass number of 4. For these parameters, the plasma density must be reduced to $1.5 \cdot 10^{19}$ m^{-3} before the phase advance equals $\pi/4$ (from Eq. 10 of [3]). This is almost four orders of magnitude below the density used in current concepts for a PWFA-based collider, 10^{23} m^{-3}. Thus, extremely deep density depressions are required for this application of the PWFA.

* This work was supported by Department of Energy Contracts No. DE-AC02-76SF00515, DE-FG03-92ER40727, DE-FG52-06NA26195, DE-FC02-07ER41500, and DE-FG02-03ER54721.

COMPUTATIONAL TECHNIQUES

A particle tracking method is used to simulate the flow of atoms around the obstruction. The number of particles in the physical system is too large for the simulation of individual atoms, so a macro-particle represents the movement of a collection of atoms. To properly represent the interatomic collisions, the mean free path of the macro-particles must be equal to that in the physical system, $\lambda = (4\pi r_v^2 n)^{-1}$, where n is the gas density and r_v is the van der Waals radius. Since the macro-particle density, n_s, is less than n, the macro-particle hard sphere radius, r_s, must increase to maintain λ: $r_s = r_v\sqrt{n/n_s}$.

Proper boundary conditions are also required to accurately simulate the flow of atoms. A discussion of the simulation boundaries, as illustrated in Fig. 2, follows. Let dt denote the simulation time step. At each time step, macro-particles with a velocity of $v\hat{x}$ are initialized at side 1 with a density of n_s and in a space of size $v \cdot dt$, D_y, and D_z in x, y, and z, respectively. Then, the coordinates for all of the macro-particles are propagated, based on the particle velocity, to the next time step. Upon contacting sides 5 or 6, a particle is re-emitted from the opposing side with its same momentum and x and y position. Contact to sides 1, 2, 3, or 4 results in deletion of the particle. The obstruction surface is coarse compared to r_v, so the scatter from it must be diffuse. A macro-particle is elastically scattered from the obstruction with a randomly distributed direction into the half-space facing away from the obstruction.

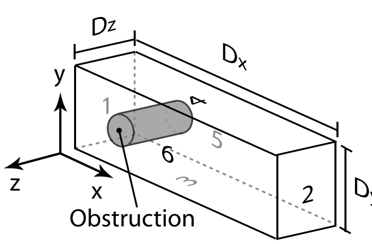

Figure 2: The simulation boundaries.

Next, the simulation compares macro-particle positions. The particles with a separation smaller than $2r_s$ are propagated back to the time they first collided and scattered elastically as hard spheres. Let N_s denote the number of simulation particles. The computational time required for the interatomic collisions is proportional to N_s^2. To minimize calculation time, the simulation box is divided into grids in the $x - y$ plane, where macro-particle positions are only compared within the same grid. The computational time is still proportional to N_s^2, but is decreased roughly by a factor of the number of grids.

A discussion of the computational techniques is not complete without addressing the resolution issues. These issues involve r_s, dt, v, n_s, the obstruction position, and the grid size. As was just introduced, the simulation space is divided into grids in the $x - y$ plane. The size of these grids in x, y, and z must be significantly larger than r_s. This ensures that the errors introduced at the boundaries of the grids do not affect the results. Another resolution issue is that dt must be considerably smaller than r_s/v. Otherwise, macro-particles could pass through each other without interacting. An additional critical resolution issue is that $2r_s$ must be much smaller than the average interatomic separation, $n_s^{-1/3}$. If not, the particles would function as an incompressible fluid. Also, sides 1, 2, 3, and 4 must be sufficiently separated from the obstruction.

RESULTS

A discussion of the specific simulation parameters follows. Current PWFA experiments utilize a plasma with a density near 10^{23} m^{-3}, so the gas jet simulations are performed for this density. Although specifics of the gas jet are ignored here, monatomic gases are easier to scale to high Mach numbers, so the simulations are of a monatomic gas, helium. Helium has a van der Waals radius of $1.4 \cdot 10^{-10}$ m [8]. The van der Waals radius for other monatomic gases is of the same order as helium, so the results here are also representative of other gas species.

Another parameter of importance is the width of the obstruction. This width governs the separation of the gas slabs and the coupling between the drive bunch and the plasma. For a non-hollow PWFA in the nonlinear bubble regime, the density of the drive bunch exceeds that of the plasma, so the bunch expels all the plasma electrons from the region around it. This produces a bubble containing a region of uniformly charged ions that are surrounded by a sheath of plasma electrons, which is characteristic of the bubble regime. The maximum radius of this bubble, R_m, is representative of the coupling between the bunch and the plasma. This maximum radius can be connected to the drive bunch peak current, I_d, as $R_m\omega_p/(2c) \approx \sqrt{2I_d/I_A}$ [9], where $I_A \approx 17$ kA is the Alfven current, $\omega_p = \sqrt{n_p e^2/(m\epsilon_0)}$, and n_p is the plasma density. To produce accelerating wakes in a hollow plasma that are comparable to those in a uniform plasma, the separation between the drive bunch and the gas must not greatly exceed R_m. For $I_d = I_A$, $R_m = 2^{3/2}c/\omega_p$, which is 48 μm for a density of 10^{23} m^{-3}. For this reason, the simulations are of cylinder obstructions with a radius at and below 50 μm.

The density depression is deepest directly behind the obstruction, so the closer a drive bunch can come to the obstruction the better. However, if the bunch comes too close it can cause breakdown of the obstruction surface. Consequently, the separation between the drive bunch and the obstruction is another critical parameter. The results of Thompson et al. [10] are useful for choosing an appropriate separation. They showed that 3 nC electron bunches with a 10 kA peak current, which are similar to drive bunches in recent PWFA experiments, created breakdown when coming within 50 μm of a dielectric fiber. To account for the use of bunches with peak current at or slightly above I_A and to add an additional safety buffer, the simulations presented here are specifically dealing with a separation of 200 μm.

Figures 3a and b show the resulting density in the $x-y$ plane for cylinders of radius 50 and 10 μm, respectively, in the path of a helium gas jet of density 10^{23} m^{-3}. The density as a function of y at a 200μm x-separation from the obstruction are shown in Figs. 4a and b. These results fall far short of the density depressions required for the PWFA.

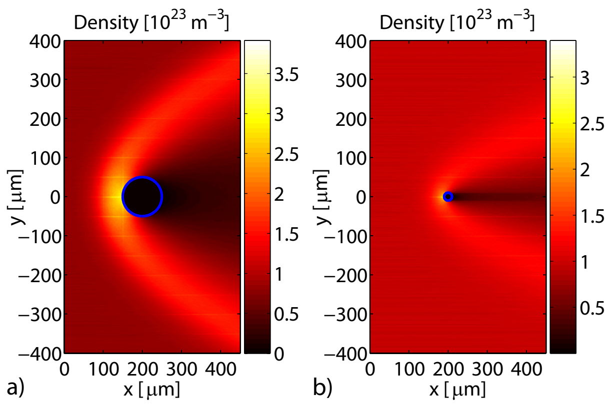

Figure 3: The density in the $x-y$ plane for a helium gas jet of density 10^{23} m^{-3} flowing around cylinders of radius 50 (a) and 10 μm (b).

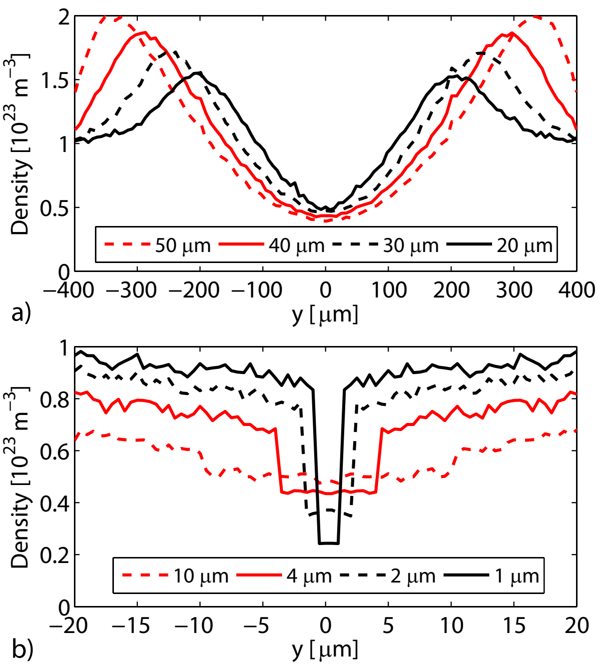

Figure 4: Density versus y at a 200μm x-separation from cylinders of various radii in a helium gas jet of density 10^{23} m^{-3}; a) For cylinders of radius 50, 40, 30, and 20 μm; b) For cylinders of radius 10, 4, 2, and 1 μm.

As the cylinder radius decreases in Fig. 4b, the density depression deepens. The mean free path for helium at a density of 10^{23} m^{-3} is 41 μm, which is significantly larger than the cylinder radii of Fig. 4b. For these small cylinder radii, the obstruction acts as a point source of scattered atoms. Some of these atoms are then re-scattered to behind the obstruction. Smaller cylinder radii scatter fewer atoms, so they naturally create deeper density depressions. Note, however, the simulations here do not include the thermal spread of the gas jet atoms. The inclusion of a realistic thermal spread would fill in the density depressions for these smaller radii. For this reason, the cylinder radius can not be reduced to arbitrarily low values to obtain deeper density depressions.

CONCLUSION

The gas jet and obstruction parameters, simulated here, fail to produce a sufficient density depression for the PWFA application. However, the basic concept of the gas jet produced hollow channel does become more effective when the mean free path greatly exceeds the cylinder radius. As discussed above, the cylinder radius can not be scaled to arbitrarily small values. Thus, methods to increase λ must be explored. A significant reduction in the gas density would lengthen λ, but would decrease the accelerating gradient. The collisional cross section for plasma particles can be significantly below that of neutral atoms. Thus, the flow of plasma around an obstruction is an alternative avenue to explore for the production of a hollow channel.

REFERENCES

[1] I. Blumenfeld et al., Nature (London) 445 (2007) 741.

[2] W. P. Leemans et al., Nature Physics 2, (2006) 696.

[3] J. B. Rosenzweig et al., Phys. Rev. Lett. 95 (2005) 195002.

[4] B. E. Blue et al., Phys. Rev. Lett. 90 (2003) 214801.

[5] C. M. Fauser et al., Appl. Phys. Lett. 73 (1998) 2902.

[6] W. Kimura, Private Communication (2008).

[7] T. Raubenheimer, Private Communication (2008).

[8] A. Bondi, J. Phys. Chem. 68 (1964) 441.

[9] W. Lu et al., Phys. Plasmas 13 (2006) 056709.

[10] M. C. Thompson et al., Phys. Rev. Lett. 100 (2008) 214801.