PROTON-DRIVEN ELECTRON ACCELERATION IN HOLLOW PLASMA

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Abstract

Proton driven plasma wakefield acceleration has been proposed to accelerate electrons to TeV-scale in a single hundreds of meters plasma section. However, it is difficult to conserve beam quality due to the positively charged driven scheme. In this paper, we demonstrate via simulation that hollow plasma is favourable to maintain the long and stable acceleration and simultaneously be able to achieve low normalized emittance and energy spread of the witness electrons. Moreover, it has much higher beam loading tolerance compared to the uniform case. This will potentially facilitates the acceleration of a large number of particles with high beam quality.

INTRODUCTION

The two most commonly adopted plasma wakefield acceleration schemes (i.e., laser driven and electron driven) have advanced significantly in recent years and can experimentally generate electrons of several to dozens of GeV [1][2]. However, for the laser driven case the ultimate energy gain is subject to the acceleration distance, which is limited by natural diffraction and depletion of the laser pulse and the dephasing between accelerated particles and the laser. As to the electron driven case, the transformer ratio determines the obtainable witness energy gain cannot be much higher than the energy of the realistic driving beam [3]. Multi-stage acceleration has been proposed to accelerate particles to energy frontier (~TeV) but this has been proved to be challenging technically in experiment [4].

Due to the availability of TeV-scale proton beams, Caldwell et al. proposed a new scheme of proton driven plasma wakefield acceleration (PDPWFA) [5] and numerically proved that electrons can be accelerated over a single hundreds of meters long plasma channel to TeV-level. A drawback of such positively charged particle driven plasma wakefield acceleration is the so-called "phase mixing" effect. It results from the "suck in" of plasma electrons from different radii. Then the plasma electrons reach the axis at different times, and apparently leave the axis due to inertia force differently, causing different phases of plasma oscillation. Moreover, unlike the electron driver, the positively charged driver sucks in plasma electrons rather than fully expel them and form an electron-free bubble, which is not favourable for conserving high beam quality. Also, as plasma electrons do not return to the propagation axis as an ensemble, the excited wakefield gradient is less than the electron driven case under the same conditions [6][7].

Fortunately, some numerical work [6-9] indicates that a hollow plasma can alleviate the aforementioned issues. More specifically, the hollow channel helps generate an ion-free and nearly electron-free region which resembles the advantageous bubble structure in laser/electron driven cases. In this paper, we propose and investigate the electron acceleration driven by high energy protons in a hollow plasma and further demonstrate the advantages of the hollow plasma on positively charged particle driven acceleration over a uniform plasma.

SIMULATION RESULTS

The 2D quasi-static code LCODE [10][11] based on the axisymmetric geometry was chosen to conduct the simulations owing to its high computational efficiency. Table 1 gives the set of beam and plasma parameters. Here the proton beam parameters are the same as in Ref. [5] except for the proton population of 1.7×10^{11}. This was chosen as in preliminary simulations we found that the beam density of 3.6×10^{14} cm^{-3} corresponding to the nominal 1.0×10^{11} protons is too small to excite strong wakefield in hollow plasma. This is probably because there are initially no plasma electrons in the hollow channel which are actually more easily drawn by protons compared to that in the plasma wall. More importantly, the proton driver diverges quickly due to weak transverse focusing, leading to significant degradation of the excited wakefield. Ref. [12] describes that the ultimate performance of the upgraded LHC will be 1.7×10^{11} protons per bunch at the same emittance. Considering the feasibility of this proton population, we adopt it in our simulations. The optimal results are shown in Fig. 1a-h. For comparison, we give the corresponding simulation results under uniform plasma with the same beam and plasma densities in Fig. 2. Since other parameters remain unchanged, the simulation is probably not optimal but can be compared with the hollow case.

The maximum longitudinal electric field along the witness bunch (WB) in the uniform plasma is 1.66 GV/m (Fig. 2a), which is as expected, larger than the 1.16 GV/m for the hollow case (Fig. 1a). However, due to nearly equal peak accelerating field of the WB and the peak decelerating field of the driving bunch (DB), the hollow case is superior in terms of the transformer ratio which is only 0.23 for the uniform case. It indicates that the hollow plasma case has a higher acceleration efficiency. Moreover, its larger plasma wavelength is beneficial to relax the requirement on synchronization of WB.

Fig. 1b illustrates that in the hollow plasma the transverse field along the WB is almost zero, which implies that the WB is free from transverse modulation. Fig. 1c confirms this and shows that the witness electrons maintain low transverse momentum, which along with small

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Table 1: Beam and Plasma Parameters for Simulation

Parameters	Values	Units
Initial driving proton beam (DB):		
proton population	1.7×10^{11}	
initial energy	1	TeV
energy spread	10%	
longitudinal beam length	100	μm
beam radius	430	μm
angular spread	3×10^{-5}	
Initial witness electron beam (WB):		
total charge of the electron bunch	1.6	nC
initial energy	1	GeV
energy spread	10%	
Unperturbed hollow plasma:		
plasma density	5×10^{14}	cm^{-3}
hollow radius	0.6	mm

beam radius makes normalized emittance less than 5 mm mrad within 3 times initial beam radius (noted as $3\sigma_r$) (Fig. 1d). Some normalized emittance values deviate due to large transverse momenta of a small fraction of not well-focused particles (refer to Fig. 1c), which can be ignored. As the transverse field becomes negative after the radius exceeds the hollow channel boundary, electrons travelling near the boundary will easily escape, leading to a downward trend of the survival particles within $3\sigma_r$ (Fig. 1e). However, the simulation shows that more than 87% of electrons survive after a 200 m acceleration. In fact, the WB can be placed closer to the DB to get focusing force outside the channel, but the accelerating field seen will decrease accordingly. So a trade-off between energy gain and the survival rate of the accelerated electrons exists.

Compared to the hollow plasma, the radial field in the uniform plasma is quite different. The witness electrons first see a defocusing force but then are focused by a strong positive radial field (Fig. 2b). As a result, over 95% of witness electrons (within $3\sigma_r$) survive after acceleration (Fig. 2e). The increasing survival rate with propagation distance can be explained by previously scattered witness electrons being reflected back to the $3\sigma_r$ region. However, despite the witness beam being focused within a quite small radius, it is strongly modulated by the defocusing and focusing fields, which makes the transverse momentum and then normalized emittance of particles within $3\sigma_r$ significantly large, as shown in Fig. 2c-d. Such bad beam quality makes it unsuitable to practical applications.

Another advantage of hollow plasma over the uniform one is that it maintains stable wakefield acceleration. The evolution of the longitudinal on-axis electric field in the hollow plasma (Fig. 1f) demonstrates that the accelerating fields seen by every part of the WB keep almost uniform along the 200 m propagation distance. It means that the WB sees an average constant accelerating field so that the beam energy is linearly increasing with the acceleration distance (Fig. 1g). The energy spread (Fig. 1h) decreases gradually because when the relativistic factor of the accelerated beam exceeds that of the initial proton beam, it slips and witnesses an increasing accelerating field from the front to the end. For the uniform plasma case, however, the longitudinal electric field not only decreases with the propagation distance, but also changes along the witness beam (Fig. 2f). The degradation is especially notable after 150 m when the accelerating field decreases greatly and the increase of the bunch energy slows down (Fig. 2g). The degradation also causes the growth of beam energy spread (Fig. 2h). Ref. [13] proves that the longitudinal variation of plasma density helps keep the WB in an almost constant field. Nevertheless, this approach could be tricky in practice.

In accelerating bunches with higher total charge, we find that the hollow plasma case has much higher beam loading tolerance. It is shown in Fig. 3a that when loading

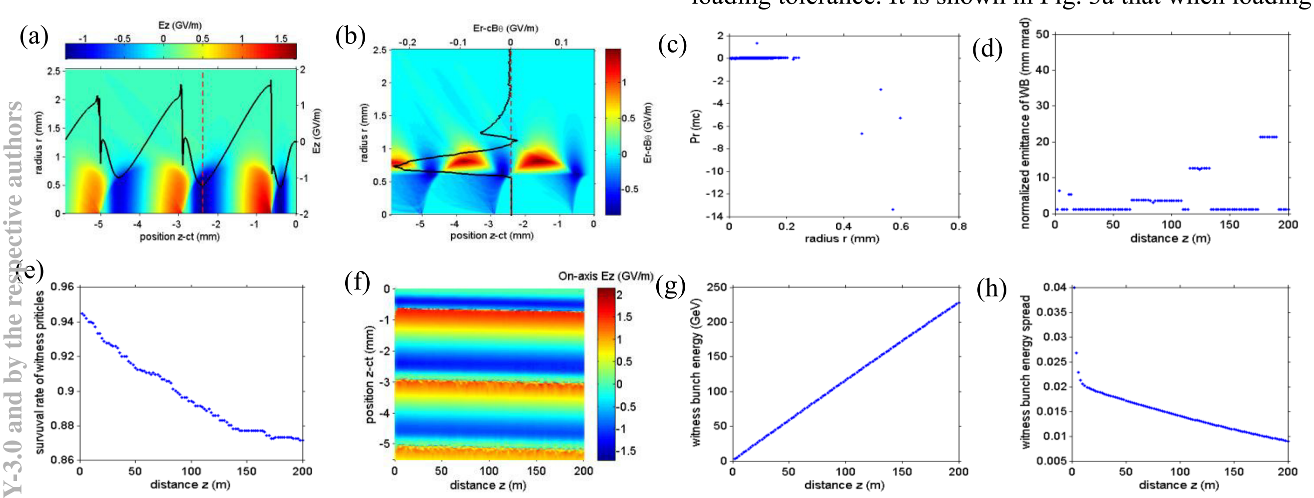

Figure 1: Hollow plasma case: two-dimensional distribution of the longitudinal electric field (a) and the transverse field (b), transverse phase space of the WB at z=100 m (c), evolution of the normalized emittance (d) and survival rate (e) of witness electrons within 3σr, and evolution of the longitudinal on-axis electric field (f), witness bunch energy (g) and energy spread (h). The longitudinal midpoint of the WB is marked by the blue lines in (a) and (b). The on-axis electric field is described by the red line in (a) and the radial field at the longitudinal midpoint of the witness beam is illustrated by the red line in (b).

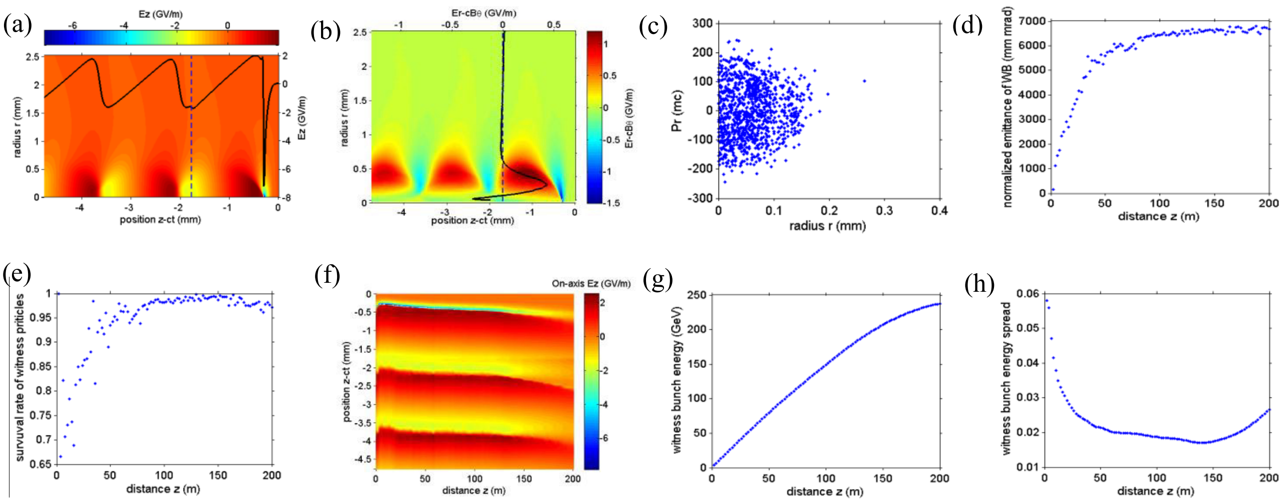

Figure 2: Uniform plasma case: two-dimensional distribution of the longitudinal electric field (a) and the transverse field (b), transverse phase space of the WB at z=100 m (c), evolution of the normalized emittance (d) and survival rate (e) of witness electrons within 3σr, and evolution of the longitudinal on-axis electric field (f), witness bunch energy (g) and energy spread (h). The longitudinal midpoint of the WB is marked by the blue lines in (a) and (b). The on-axis electric field is described by the black line in (a) and the radial field at the longitudinal midpoint of the witness beam is illustrated by the black line in (b).

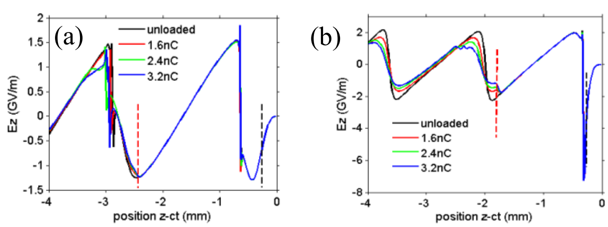

Figure 3: The on-axis accelerating field for the unloaded and different particle population loaded cases in hollow plasma (a) and uniform plasma (b). The black and red dashed lines mark the longitudinal midpoints of the DB and the WB respectively.

up to 2.0×10^{10} (3.2 nC) witness electrons, the maximum on-axis accelerating field seen by the WB still does not change and only the accelerating crest deforms a little. While for the uniform case, the maximum field decreases significantly from 2.22 GV/m (unloaded) to 1.66 GV/m when loading only 1.0×10^{10} witness electrons.

In summary, although the driving proton beam can excite a larger accelerating field in the uniform plasma than the hollow one, the "suck-in" effect makes the wake structure in uniform plasma undesirable for long and stable acceleration and conserving high beam quality. The hollow plasma, however, can mitigate this effect and helps create an accelerating and focusing region which resembles the bubble in the laser or electron driven cases. Despite the energy gain being slightly lower, it is favourable to accelerate more witness particles and conserve low normalized emittance and energy spread.

CONCLUSION

In this paper, we prove that the proton driven plasma wakefield acceleration of electrons in a hollow plasma is advantageous in maintaining the long and stable acceleration and promoting beam quality compared to the uniform plasma case. Over 87% of electrons within $3\sigma_r$ can be accelerated to 228 GeV over 200 m long hollow plasma with normalized emittance lower than 5 mm mrad and energy spread of 1%. Moreover, the beam loading effect has less effect on the wave in the hollow plasma, which makes acceleration of 2.0×10^{10} particles or more possible.

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