Positron plasma wakefield acceleration in a self-driven hollow channel

Lígia D. Amorim' , Jorge Vieira' , Ricardo A. Fonseca' , and Luís O. Silva'

Citation: **1777**, 070001 (2016); doi: 10.1063/1.4965644
View online: http://dx.doi.org/10.1063/1.4965644
View Table of Contents: http://aip.scitation.org/toc/apc/1777/1
Published by the American Institute of Physics

Positron Plasma Wakefield Acceleration in a Self-Driven Hollow Channel

Lígia D. Amorim[1, a)], Jorge Vieira[1, b)], Ricardo A. Fonseca[1,2, c)] and Luís O. Silva[1, d)]

[1]GoLP/Instituto de Plasmas e Fusão Nuclear –Laboratório Associado, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal.

[2]*Departamento Ciências e Tecnologias da Informação, ISCTE – Instituto Universitário de Lisboa, 1649-026 Lisboa, Portugal.*

[a)] ligia.diana.amorim@ist.utl.pt
[b)]Jorge.vieira@ist.utl.pt
[c)]ricardo.fonseca@iscte.pt
[d)]luis.silva@ist.utl.pt

Abstract. In this work we propose a novel positron driven plasma wakefield acceleration configuration in the non linear regime using tightly focused positron drive beams to create a hollow plasma channel with no background plasma ions, where positrons can accelerate to high energy. A simplified model for the background plasma ion motion in this scenario was analyzed. The proposed scheme was explored numerically resorting to multi-dimensional PIC simulations using the numerical code OSIRS.

MOTIVATION

Progress on the fundamental physics knowledge requires the study of the interactions of particles in the energy frontier, i.e. TeV. Nowadays, conventional high-energy accelerators are associated with acceleration gradients on the order of 10 MeV/m. Thus, the acceleration of leptons (such as electrons or positrons) to the TeV regime could require more than 100 Km long linear accelerators. Since plasma based accelerators have produced higher acceleration gradients (more than three orders of magnitude larger) than conventional accelerators in proof of principle experiments, they are promising candidates for future more compact particle accelerators. In particular, gradients that exceed the 100 GeV/m have been reached recently with the plasma wakefield accelerator at the Stanford Linear Accelerator Center (SLAC) allowing for the energy doubling of 42 GeV electrons in a 85 cm long plasma [1].

The typical configuration for plasma wakefield acceleration (PWFA) consists of an intense and short electron drive beam that is propagating in an uniform plasma exciting relativistic plasma wakefields in the non-linear blowout regime [2]. In the blowout regime plasma electrons are expelled radially from the drive beam axis. Although the acceleration in the blowout regime has the potential to enable high energy gain for electrons, the transverse electromagnetic fields would defocus a trailing positron bunch and hence are not well suited for positron acceleration.

Several techniques have been proposed [3-6] for positron acceleration in plasmas. Positrons can be accelerated in linear wakefield excitation regimes at the expense of lower accelerating fields. In addition, the use of hollow channels for positron acceleration in linear regimes has also been studied [4]. The use of positron beams as drivers of the plasma wakefields in the so-called suck-in (blowout equivalent) regime has also been investigated [5]. Recently, it has been shown that positron acceleration could occur in non-linear regimes of PWFA when Laguerre-Gaussian laser pulses are used as the drivers of the wakefield [6]. Nevertheless, it is relevant and timely to search for new processes to accelerate positrons in the non-linear PWFA regimes.

Advanced Accelerator Concepts 2014
AIP Conf. Proc. 1777, 070001-1–070001-5; doi: 10.1063/1.4965644
Published by AIP Publishing. 978-0-7354-1439-6/$30.00

In this work we propose a novel positron driven plasma wakefield configuration for positron acceleration in the non-linear PWFA regime. In our configuration the density of the beam that drives the wakefields is much higher than the background plasma density inducing significant ion motion and leading to the repulsion of the plasma ions from the drive beam axis generating a hollow plasma channel. We find that the non-linear wakefields excited in the hollow channel are suitable for positron acceleration. Here we include a simple analytical model describing the ion motion in the hollow channel. We present the numerical results from a 3D simulation performed with the particle-in cell code OSIRIS [7]. To conclude the onset of positron focusing and accelerating fields in the non-linear regime is discussed. Note that ion motion in plasma based accelerators has been considered before [8] but in the electron driven blowout regime and in the self-modulation regime where it poses a challenge for optimal wakefield acceleration.

ANALYTICAL MODEL

We propose to use a tightly focused positron bunch to create a hollow channel emptied of background plasma ions. In order to study the background plasma ion dynamics we consider a simplified model in which an uniform cylindrical positron bunch with density n_b propagates in an uniform plasma with density n_0 consisting of electrons and single charged ions with masses m_e, m_i, respectively. The density of the plasma ions inside the hollow channel (radially close to the beam axis) can be computed from their equation of motion [9], yielding:

$$\frac{n_i}{n_0} = \sec h\left(\xi k_i\right)^2, \tag{1}$$

where the transformation to the co-moving frame $\xi = z - ct$ (z is the propagation distance) was performed and where k_i represents the ion skin depth associated with the positron drive beam density, given by:

$$k_i = \sqrt{\frac{1}{2}\frac{m_e}{m_i}\frac{n_b}{n_0}}\frac{\omega_p}{c}. \tag{2}$$

The skin depth is given in units of the plasma wavenumber $k_p = c/\omega_p$. The hollow channel formation is dependent on the typical ion motion length, $1/k_i$, that decreases for lighter plasma background ions and for denser drive bunches. We note that even for low n_b/n_0 a quasi hollow channel can still be produced. According to Eq. (2), state-of-the-art conventional accelerators can deliver positron bunches capable of driving hollow (or quasi hollow) channels.

3D OSIRIS SIMULATIONS

In order to confirm the generation of the hollow channel, we performed 3D simulations with OSIRIS from which we present here one to illustrate the proposed scheme. The 3D (x_1,x_2,x_3) simulations were done with a moving window traveling at the speed of light, c in the direction of the propagation of the positron drive beam, x_1. The computational box used was 20x15x15 $(c/\omega_p)^3$ divided in 650x487x487 cells in 1x1x1 plasma and bunches particles per cell. We used normalized units in which the densities are normalized to n_0, the lengths to $c/\omega_p = c\, m_e / 4\, \pi\, e^2\, n_0$ and the electromagnetic fields are normalized to the cold wave breaking field, $E_0 = c\, \omega_p\, m_e / e$.

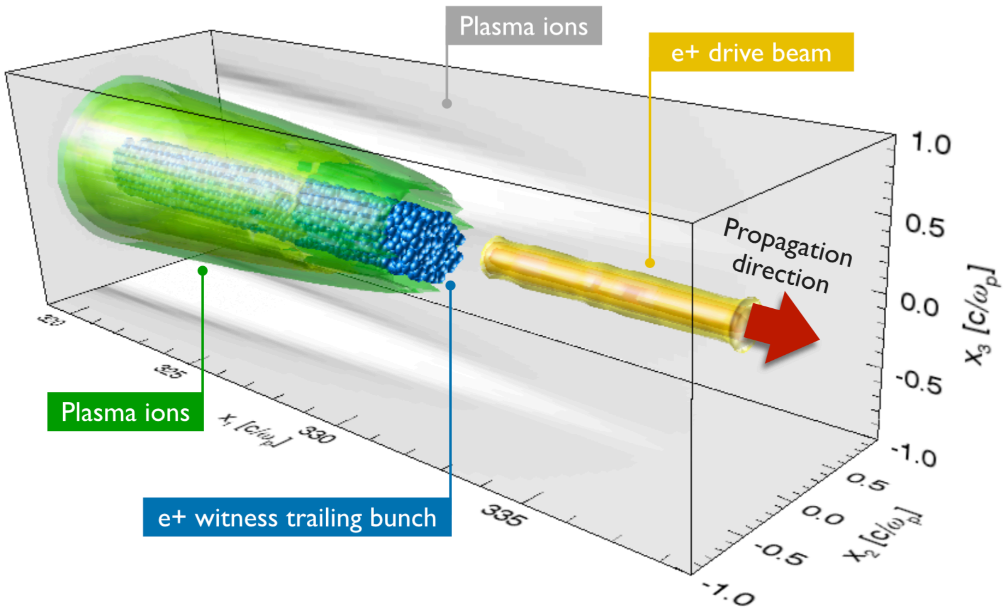

FIGURE 1. Simulation setup showing the drive positron beam, the trailing positron beam, the plasma ions at the borders of the hollow channel and the projections of the plasma ion density.

The simulated setup for the proposed scheme, see Fig. 1, consisted of a 10GeV positron drive beam that generated a hollow channel in the plasma ions. The resulting wakefield structure was used to accelerate a test particle positron bunch. The initial drive and witness bunches profiles were respectively given by:

$$n_{b1} = 200 n_0 \exp\left(\frac{-r^2}{2\times\left(0.12c/\omega_p\right)^2}\right), \quad x_1 \in [13,19]\ c/\omega_p;$$
$$n_{b2} = 10^{-4} n_0 \exp\left(\frac{-r^2}{2\times\left(0.12c/\omega_p\right)^2}\right), \quad x_1 \in [1,\ 12]\ c/\omega_p. \tag{3}$$

Simulations show strong focusing of the plasma electrons towards the drive beam. However, the beam space charge is not fully compensated by those electrons and it remains capable of expelling the plasma ions from the beam region. Thus a hollow channel is generated in the back of the drive positron beam.

The longitudinal wakefield profile associated with the hollow channel is shown in Fig. 2 a). We note that the characteristic saw-tooth shape of the on-axis lineout shown in Fig. 2 a) (solid line) evidences the presence of non-linear wakefields. The value of the maximum accelerating wakefield in the region of the witness bunch was of about 0.6 E_0. Figure 2 b) shows that inside the hollow channel, the transverse focusing wakefield is much lower than the typical values associated with a pure ion column in the non-linear blowout regime thereby enabling a more stable transverse positron bunch dynamics throughout the acceleration distance.

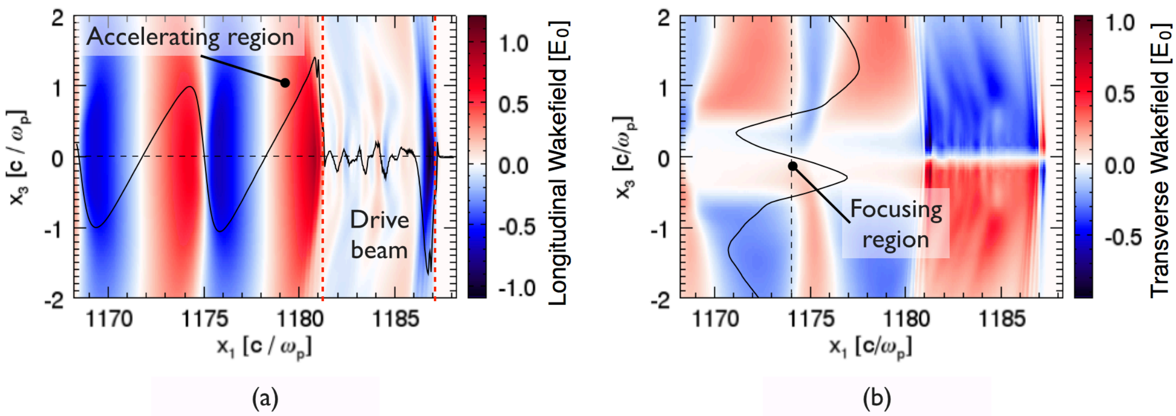

FIGURE 2. Slice of the longitudinal accelerating (a) and transverse focusing (b) wakefields for t = 1168 1/ωp taken at the middle of the simulation box. The solid lines represent the lineout for a) x3 = 0 and b) x1 = 1174 c/ω_p.

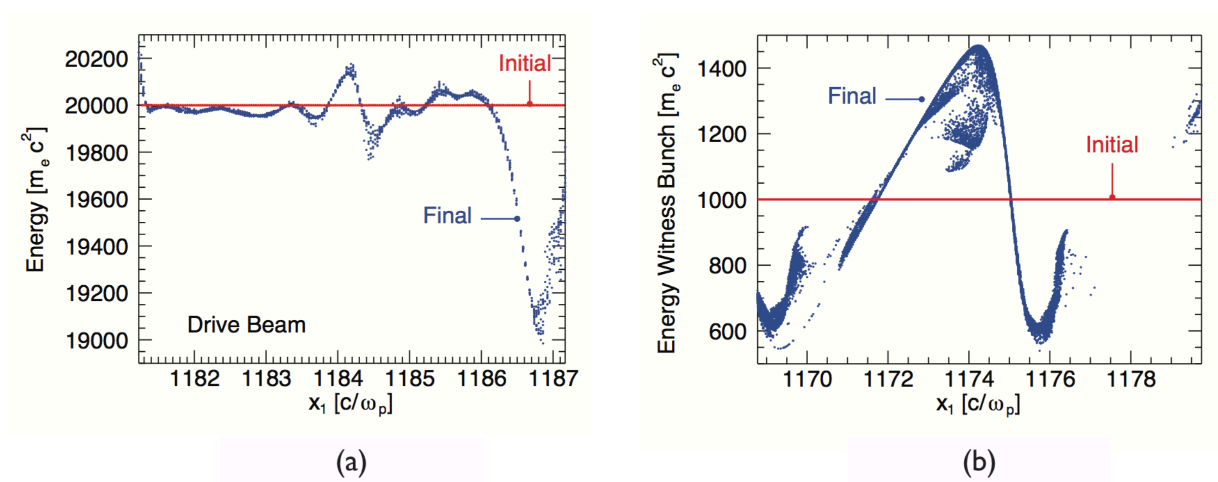

FIGURE 3. Energy distribution at the beginning of the simulation and after t = 1168 1/ωp for the positron drive and witness beams, (a) and (b), respectively.

The energy of both driver and trailing positron bunch at t=0 and at t = 1168 $/\omega_p$ are shown in Fig. 3 a) and b), respectively. The final time step corresponds to the propagation of the beams in an acceleration distance of 800 c/ω_p, at which point the front of the drive beam lost some of its energy to generate the hollow channel and drive the wakefields. The energy gain by the trailing positron bunch is roughly 480 m_ec^2 which is in good agreement with the accelerating gradients associated with the result shown in Fig. 2 b).

CONCLUSIONS

We have shown that tightly focused positron beams can drive hollow plasma channels, exciting plasma wakefields in the non-linear regime. This configuration is thus promising for positron acceleration and may allow for positron acceleration with little emitttance growth due to positron-ion collisions. We derived a threshold for the onset of the self-driven hollow channel formation. This threshold shows that relaxed conditions for hollow channel formation can be achieved for longer positron drivers. Inside the hollow channel the accelerating wakefield reaches very high accelerating gradients whereas the transverse field is mainly focusing for positrons. In the simulation used to illustrate the proposed scheme a test-particle positron bunch was accelerated by about 450 $m_e c^2$ in 800 c/ω_p with maximum accelerating wakefields of about 0.6 E_0, where E0 is the cold wavebreaking electric field

ACKNOWLEDGMENTS

This work was partially supported by Fundação para a Ciência e a Tecnologia (FCT, Portugal) through grants SFRH / BD / 84851 / 2012 and EXPL/FIS-PLA/0834/2012. We acknowledge PRACE for access to resources on SuperMUC (Leibniz Research Center).

REFERENCES

1. I. Blumenfeld et al., Nat. **445**, 741 (2007).
2. W. Lu et al., Phys. Rev. Lett. **96**, 165002 (2006).
3. X. Wang et al., Phys. Rev. Lett. **101**, 12 (2008).
4. T.C. Chiu et al., Phys. of Plasmas **2**, 310 (1995); W.D. Kimura et al., Phys. Rev STAB **14**, 041301 (2011); C.B. Schroeder et al., Phys. of Plasmas **20**, 080701 (2013).
5. S. Lee et al., Phys. Rev. E **64**, 045501 (2001).
6. J. Vieira and J.T. Mendonça, Phys. Rev. Lett. **112**, 215001 (2014); J. Vieira, J.T Mendonça and L.O. Silva, these proceedings.
7. R.A. Fonseca et al., Lect. Notes Comput. Sci. **2331**, 342 (2002).
8. J. Vieira et al, Phys. Rev. Lett. 109 145005 (2012); J. Vieira et al, Phys. Plasmas **21**, 056705 (2014); J.B. Rosenzweig et al., Phys. Rev Lett. **95**, 195002 (2005).
9. L.D. Amorim, J.Vieira, R.A. Fonseca and L.O. Silva, in preparation (2014).