Positron acceleration in non-linear plasma wakefields driven by tightly focused particle bunches

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Abstract

In this work we propose a novel positron driven plasma wakefield acceleration configuration in the non linear regime, using tightly focused positron drive be ams that can accelerate witness positron bunches. Unlike in the blowout regime, the ion motion is not negligible, and we find that the focusing wakes also focus the witness bunches throughout the acceleration. The proposed scheme was demonstrated and studied resorting to multidimensional PIC simulations using the numerical code OSIRIS. A simplified model of the ion motion on beam axis was presented.

Plasma wakefield accelerators are capable of sustaining acceleration gradients that exceed the 100GV/m [1], which is more than three orders of magnitude higher than for the conventional linear accelerators. Plasma based accelerators typically use an intense and short electron or laser driver propagating in a plasma and exciting relativistic plasma wakefields in the nonlinear blowout regime [2]. In the blowout the plasma electrons are expelled radially from the beam axis while the remaining background plasma ions form a positively charged bubble that attracts the electrons back to beam axis. Although well suited for electron acceleration, the transverse electromagnetic fields associated with the blowout regime defocus trailing positron (witness) bunches before they can be significantly accelerated.

Due to the relevance of positron acceleration for future linear colliders, several plasma wakefield acceleration techniques were proposed [3]-[6]. Namely, the use of hollow channels for positron acceleration in linear regimes [4] has been studied. The use of positron drive beams in the so-called suck-in regime has also been proposed for the acceleration of witness positron bunches [5]. More recently, it has been shown that positron acceleration could occur in non-linear regimes using Laguerre-Gaussian laser pulse drivers [6]. Nevertheless, it is still interesting and relevant to explore new techniques to accelerate positrons in the non-linear plasma wakefield acceleration regimes.

In this work we propose a novel positron driven plasma wakefield configuration for positron acceleration in the non linear regime. In our configuration the density of the beam that drives the wakefields is much higher than the background plasma density, inducing ion motion and leading to the formation of a hollow channel suitable for positron acceleration. We present numerical results from simulations performed with the particle-in-code OSIRIS [7]. The condition for the formation of the self-driven hollow channel and the onset of positron focusing and accelerating fields in non-linear regimes is discussed.

In previous works the effects of ion motion posed challenges for wakefield acceleration in future experiments [8]. In our work we explore how to take advantage of the ion motion in positron driven wakefields non linear regimes with high acceleration gradients for positron acceleration.

We illustrate our scheme with a 3D OSIRIS simulation. The simulation was performed in 3D cartesian coordinates (x_1,x_2,x_3) with a moving window traveling at the speed of light c (acompagining the drive beam propagation) in the x_1 direction. We use normalized units where the densities are normalized to the uniform background plasma density n_0, the lengths are normalized to $c/\omega_p = c\, m_e/4\pi e^2 n_0$, where e and m_e are the electron charge and mass, respectively, and the electromagnetic fields are normalized to the cold wave breaking field, $E_0 = m_e c \omega_p/e$. The computational box is 20x15x15 c^3/ω_p^3 divided into 650 x 487 x 487 cells with 1x1x1 plasma and bunches particles per cell.

The setup simulated to investigate the proposed acceleration regime follows Fig.1, where a positron drive beam (red) generates a hollow channel (white) with no background plasma ions (grey). The resulting wakefield structure is used to accelerate a test-particle positron witness bunch (blue). The profiles of the positron drive beam and witness bunch are given by:

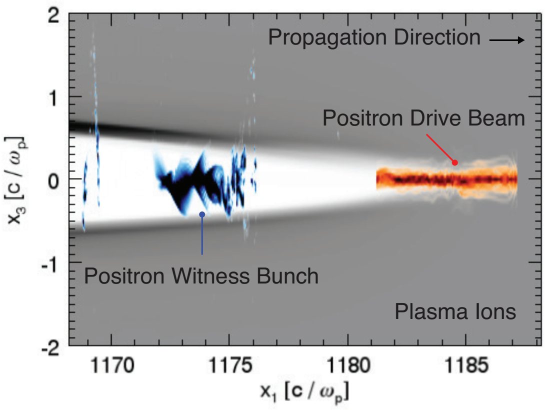

Figure 1: *Scheme of the simulation setup showing the positron drive beam and witness bunch, in grey the ions and in white the hollow channel.*

$$n_b = n_{b0} \exp\left(\frac{-r^2}{2\sigma_r^2}\right), x_1 \in \left[x_{1_0}, x_{1_f}\right] \quad (1)$$

where $n_{b0} = 200\ n_0$ (highly non-linear regime), $x_{1_f} = 19\ c/\omega_p$, $x_{1_0} = 13\ c/\omega_p$ (i.e. the bunch length is $\sigma_z = 6\ c/\omega_p$) for the drive beam and where $n_{b0} = 10^{-4}\ n_0$, $x_{1_f} = 1\ c/\omega_p$, $x_{1_0} = 12\ c/\omega_p$ for the witness bunch. In addition, $r = \sqrt{x_2^2 + x_3^2}$ and $\sigma_r = 0.12\ c/\omega_p$ for both driver and witness.

Simulations show that plasma electrons are strongly focused towards the positron drive beam. Due to the very high beam density and currents, the background plasma ions are strongly repelled from the beam region. Since ions are much heavier than electrons, they continue to drift radially away from the axis at the back of the beam. Consequently, a self-driven hollow plasma channel is generated (in white in Fig. 1).

Figure 2 shows the accelerating longitudinal (a) and the focusing transverse (b) wakefields associated with the hollow channel of Fig. 1. The maximum accelerating wakefield in the witness bunch region is $\sim 0.6\, E_0$. The lineout in Fig. 2 (a) shows the on-axis accelerating field. The characteristic saw-tooth profile clearly indicates that non-linear wakefields are present. Inside the hollow channel the transverse field is mainly focusing for positrons, as can be seen in Fig. 2 (b), i.e. for $x_3 > 0$ ($x_3 < 0$) the field is negative (positive) thereby focusing the positrons towards the axis. The typical focusing fields are much lower than those of the non-linear blowout regime. Within the channel they do not vanish because some plasma electrons can still propagate.

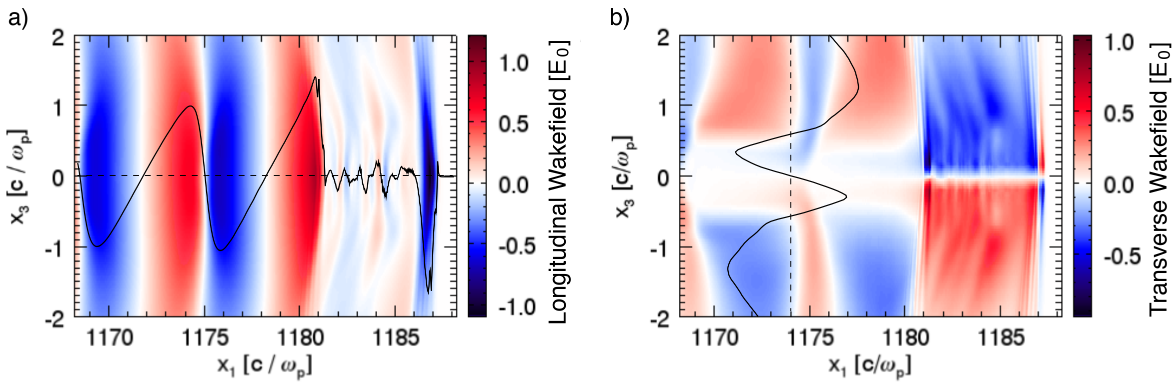

Figure 2: *2D projection for $x_2 = 0$ of the accelerating longitudinal and the focusing transverse wakefields for $t = 1168\ /\omega_p$. Red (blue) colors represent accelerating (decelerating) regions for plot (a). For $x_3 > 0$, red (blue) colors are focusing (defocusing) regions for plot (b), otherwise they are the opposite. Lineouts for (a) at $x_3 = 0$ and for (b) at $x_1 = 1174\ c/\omega_p$ are also shown.*

The initial and final (at $t = 1168\ /\omega_p$) energy distributions along the longitudinal direction for the positron drive beam and the witness positron bunch are shown in Fig. 3 (a) and (b), respectively. Figure 3 (a) shows energy loss by the front of the drive beam to the generation of plasma waves. The total acceleration distance corresponding to the time of Fig. 3 is $L_{acc} \sim 900\ c/\omega_p$. Since the maximum amplitude of the accelerating wakefield in the witness bunch region is $E_{acc} \sim 0.6 E_0$ the expected energy gain is $\Delta E = e\ E_{accel}\ L_{accel} \sim 540 m_e c^2$, which is close to the result shown in Fig. 3 (b).

In order to model analytically the setup in the described regime we studied the ion motion inside the hollow channel. The momentum equation of the non-relativistic background plasma ions can be computed from the *Lorentz* force, neglecting the $\mathbf{v} \times \mathbf{B}$ term due to their low velocities, and is given by:

$$\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} = \frac{+e\mathbf{E}}{m_{ion}} \Rightarrow c^2 \frac{\partial^2 \mathbf{r}}{\partial \xi^2} = c^2 \frac{2\pi e^2 n_b}{m_{ion}} \mathbf{r} \equiv c^2 k_{ion}^2 \mathbf{r} \tag{2}$$

where m_{ion}, $\mathbf{r}$ are the ion mass and position vector. The field vector $\mathbf{E}$ can be determined applying the *Gauss* law assuming that the beam is well described as an infinitely long positively

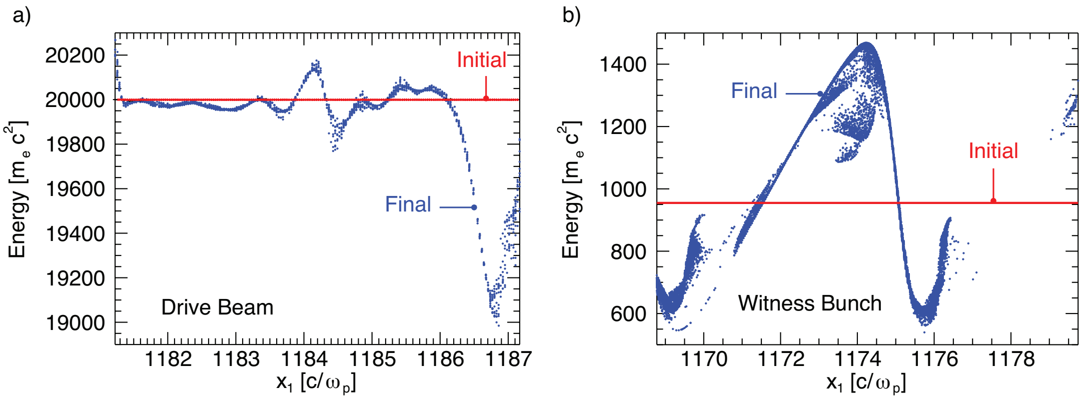

Figure 3: *Energy distribution as a function of position x_1 at $t = 0$ (red) and at $t = 1168\ /\omega_p$ (blue) for the positron drive beam (a) and witness bunch (b).*

charged cylinder. The transformation to the boosted frame $\xi = x_1 - c\,t$ was performed. According to Eq. (2) the typical distance is given by $1/k_{ion} = \sqrt{2\ (m_{ion}/m_e)\ (n_0/n_{b0})}\ c/\omega_p$. Therefore, the onset of the ion motion occurs when $1/k_{ion} > \sigma_z$ or $n_{b0}/n_0 > 2\,(c/\omega_p)^2\,/\sigma_z^2\,(m_{ion}/m_e)$. This condition can be strongly relaxed for longer drive beams. For the parameters of our simulation, where $\sigma_z = 6\ c/\omega_p$ and $m_{ion}/m_e = 1836$ then $n_b/n_0 > 101$, which is in agreement with our findings.

We have shown that self-driven hollow channel formation can occur in the plasma wakefield acceleration driven by tightly focused positron beams as long as the beam density is much higher than the background plasma. The numerical results showed the acceleration and focusing of a test-particle positron bunch in the hollow channel.

Acknowledgments

This work was partially supported by FCT grant SFRH / BD / 84851 / 2012. We acknowledge PRACE for access to resources on SuperMUC (Leibniz Research Center).

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