SIMULATIONS OF POSITRON CAPTURE AND ACCELERATION IN THE LINEAR WAKEFIELD OF PLASMA

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Abstract

We present the study of positrons capturing dynamics in the wakefield of plasma generated either by a laser or electron beam. Only simplified linear wakefield models were used as first order approximation. By analysing the phase space and beam dynamics, we show that the phase space for capturing is rather small, only high brightness beam with very short pulse length can be captured with a reasonable rate for wakefields of 1 – 10 GeV/m and wavelength of 100 μm.

INTRODUCTION

Plasma based accelerators are attracting for its high gradient (multi-GV/m) and potential small sizes for its wide applications, including a potential candidate for a e+e- linear collider [1]. One of the challenge is to accumulate positrons in the wakefields generated either with electron or laser beams. A scheme is proposed by LBNL [2], which is to use an electron beam (~ 10 GeV) from a laser wakefield accelerator to strike a thin tungsten target, then the positrons from the target will be captured by the wakefields, as shown in Fig. 1.

For the purpose of understanding the problem, we employ a simplified linear wakefield for this study, the input beam from target were assumed ranging from very high brightness to more practical particle distributions. Our goal is to identify a trend for the positron capturing parameters, thus provide some understanding how the scheme works.

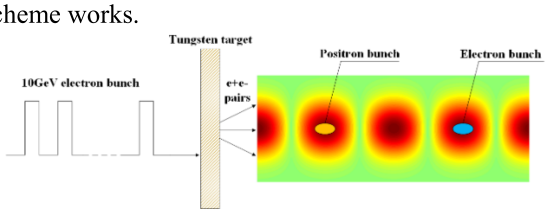

Figure 1: Layout of the scheme proposed by LBNL.

WAKEFIELD OF PLASMA

As lowest order approximation, if the plasma wakefield were linear, plasma wakefields either generated by a laser or electron beam can be described in same format, and we have the longitudinal laser wakefield in plasma [3]:

$$W_{\parallel} = -\frac{\pi}{4} a_0^2 E_0 e^{-2r^2/r_s^2} cos(k_p \zeta) \quad (1)$$

In which a_0 is a normalized driver laser strength parameter, E_0 is the wavebreaking field, r is the transverse off-set of positron bunch from the centre axis, r_s is the laser spot size, k_p is the wave number of plasma frequency, and $\zeta = z - ct$ is the longitudinal space from the driver laser or beam to the positron bunch.

Equation (1) can be simplified as below:

$$W_{\parallel} = -E_z e^{-2r^2/r_s^2} cos(\varphi) \quad (2)$$

The E_z is a reflection of the parameters of both electron bunch and plasma.

Panofsky-Wenzel theorem gives the relation between longitudinal and transverse wakefields [3]

$$\frac{\partial W_{\parallel}}{\partial r} = \frac{\partial (E_r - B_\theta)}{\partial \zeta} \quad (3)$$

We can easily have the transverse wakefield

$$W_{\perp} = E_r - B_\theta = \frac{4r}{k_p r_s^2} E_z e^{-2r^2/r_s^2} sin(\varphi) \quad (4)$$

Given the longitudinal and transverse wakefields in equations (2) and (4), the beam dynamics of the positron could be accurately simulated, which are introduced in next section.

BEAM DYNAMICS STUDY OF THE POSITRON INJECTION

Firstly, we assume that the accelerating gradient of the wakefield is 10 GV/m and r_s is 500 μm. The generated positron bunch has a population of one million, normalized emittance of 1 mm•mrad, beam spot size of 100 μm. The initial energy of the positron bunch is 100 MeV with no energy spread. The bunch length is 100 μm longitudinal size, which occupies the full wavelength of the plasma wakefield. It is obvious that half of the positrons will be decelerated and lost.

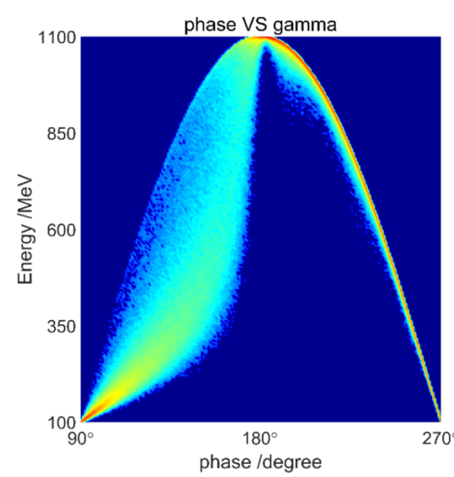

Figure 2: Energy distribution of position versus the wakefield phase at z=10 cm while injecting with full wavelength.

Figure 2 shows the longitudinal phase space of those positrons in the given parameters. The upper envelope of the phase space is the cosine curve of $W_{\parallel}$. $W_{\perp}$ is a sine

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function of the phase and will defocus the positron bunch when it has a positive value. For the fact that the longitudinal field damping exponentially with the transverse offset, it is easy to explain that the energy spread of where phase is less than 180° is much bigger than those on the right side. The capture condition requires the energy spread lower than 10% and transverse distance smaller than r_s. In such a case, the capture rate is 0.1.

We simulated a shorter bunch length of 10 μm at the injection phase of 180°~216°, the accelerating and focusing phase, for both accelerating and focusing. Figure 3 shows the statistical histogram of the energy and transverse position of the bunch at the end of the plasma cell. Most positron's energy is ranged from about 730 MeV to 1.1 GeV and their transverse position are all within the range of r_s. Comparing with the capture condition, we conclude that the loss of positron in the proceeding of accelerating is mainly because of the energy spread. With the zero initial energy spread, we can say that the difference of transverse off-set and phase is the only reason causing the energy spread at z=10 cm.

Figure 4 shows how the transverse phase space changed at different longitudinal positions and the normalized emittance trend with a unit of mm•mrad. From Fig. 4, it is seen that the beam spot is getting smaller as positrons move forward before z=4 cm, and then grows bigger after. We can find that the phase space rotates more and more slowly as energy increasing.

However, a non-linear force exists in the plasma wakefield for large offset particles from axis according to Eq (4). This non-linear force is significant if the beam has large transverse offset, which will dilute the phase space. On the other hand, the large transverse offset results in a lower accelerating gradient as expressed in Eq (2), thus increase the energy spread. This causes emittance grows faster after z=5 cm. The capture rate at the end of plasma cell is 0.72 with 10% energy spread and spot radius not more than r_s.

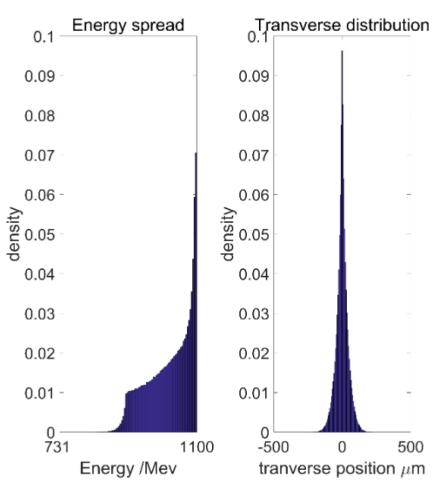

Figure 3: Statistics of positron's energy and transverse distribution at Z=10 cm while injecting with 180°~216°.

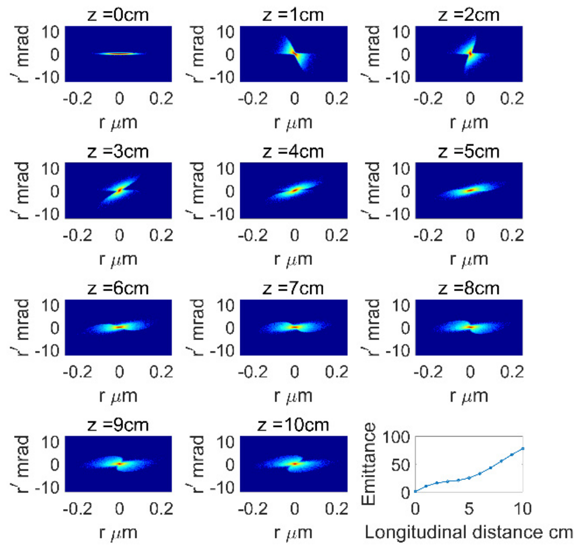

Figure 4: Transverse phase space and normalized emittance at different position.

PARAMETERS SCANNING

In this section, we study the dependency of the capture rate for ranges of the initial parameters (i.e. emittance, accelerating gradient and the bunch length) of the positron beam. Starting parameters are given as r_s=500 μm, initial energy = 100MeV, plasma wakefield wavelength = 100 μm, and normalized emittance, accelerating gradient, bunch length are kept at 1 mm•mrad, 10 GV/m and 10 μm, and the we only scan a single parameters, for example, emittance from 1 -100 mm·mrad as in Fig. 5.

Figure 5 shows a dependency of the capture rate as the initial emittance of positron bunch varies.

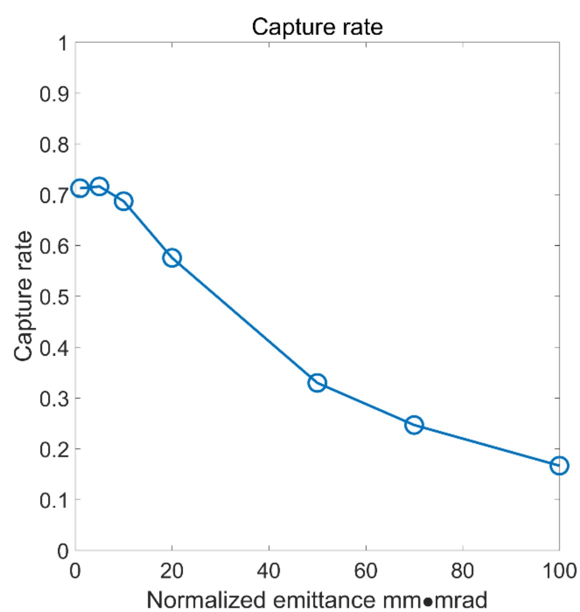

Figure 5: Capture rate versus normalized emittance.

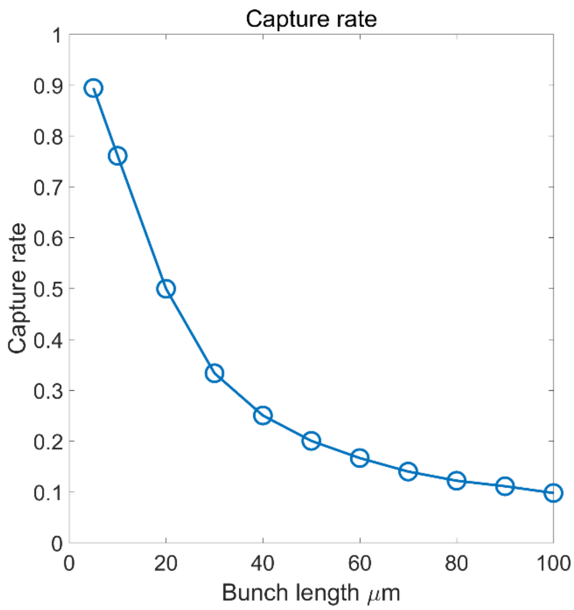

Figure 6: Capture rate vs. the bunch length.

Figure 6 shows that the longer bunch length will result in a lower capture rate.

Figure 7 shows the scan of the gradient from 1 - 10 GV/m, 100 MeV initial energy and injection phase ranges from 180°~216°, which means a 10 µm length bunch, the maximum of the bunch energy at z=10 cm is 1100 MeV. Lower capturing rate for higher gradient is due to the large focusing force for the off-axis particles.

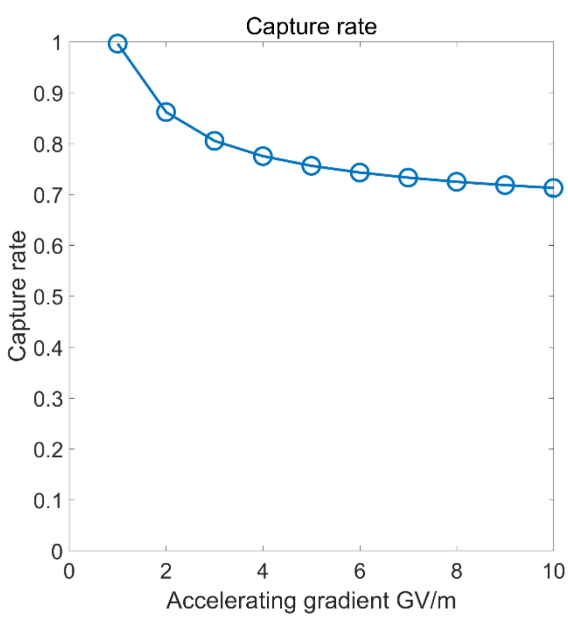

Figure 7: Gradient scanning.

CONCLUSION

We have attempted to gain understanding of a positron capture process using a simplified model. While it seems it is very difficult just to use a parameter set for common laser plasma wakefield accelerator, other parameters space might help. Also, different positron production process may also help. In addition, truly non-linear wakefield in blow out regime is yet to be explored; we will investigate this in the future.

We acknowledge the useful discussion with Wim Leemans on this topic and the previous works in Ref [2].

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