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POSITRON ACCELERATION IN LINEAR, MODERATELY NON-LINEAR AND NON-LINEAR PLASMA WAKEFIELDS

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Abstract

Accelerating particles to high energies with high efficiency and beam quality is crucial in developing accelerator technologies. The plasma acceleration technique, providing unprecedented high gradients, is considered as a promising future technology. While important progress has been made in plasma-based electron acceleration in recent years, identifying a reliable acceleration technique for the positron counterpart would pave the way to a linear e^+e^- collider for high-energy physics applications. In this work, we show further studies of positron beam quality in moderately non-linear (MNL) plasma wakefields. With a positron bunch of initial energy 1 GeV, emittance preservation can be achieved in optimized scenarios at 2.38 mm·mrad. In parallel, asymmetric beam collisions at the interaction point (IP) are studied to evaluate the current luminosity reach and provide insight to improvements required for positron acceleration in plasma. It is necessary to scale down the emittance of the positron bunch. In the MNL regime, a positron beam with 238 µm·mrad level emittance implies compromise in charge or necessity for ultra-short bunches.

INTRODUCTION

Several proposals have been made for future colliders as we enter a new era of discovery and precision measurements, including circular lepton and hadron colliders [1-3], linear $\gamma\gamma$ colliders [4, 5] and circular $\mu^+\mu^-$ colliders [6, 7]. A linear electron-positron collider is one of the leading options for its non-convoluted nature during the collision [8-13]. In order to make any linear collider economical in both funding and space, high-gradient acceleration is highly desired. Plasma accelerators have been shown to provide multi-GeV gradient in experiments for electron acceleration [14, 15]. Electrons can be accelerated with high efficiency and quality in a full blow-out regime, where focusing is provided by plasma ions and acceleration is achieved at a certain phase of the wakefields created by a particle or laser driver [16-19]. Positrons, on the other hand, cannot be accelerated in the same regime due to the defocusing nature of the positively charged ions, which is detrimental to the positron beam quality.

In a recent study [20], positron acceleration is optimized in the linear regime using a gaussian electron driver and in the non-linear regime using a donut-shaped electron driver, in the context of drive-to-main energy transfer efficiency and uncorrelated energy spread. The uncorrelated energy spread is introduced as an important limit that cannot be compensated easily, unlike the correlated energy spread where several techniques have been proposed and tested to minimize or compensate for the chirp [21-23]. The result of the optimizations and comparison in different regimes, presented in Fig. 8 of Ref. [20], is that the MNL regime can achieve simultaneously high efficiency (>30%) and low uncorrelated energy spread (<1%). At the time of publication, other important beam qualities, such as emittance and emittance preservation, had not been studied in detail in this regime. In this proceeding, we first introduce the moderately non-linear (MNL) regime, followed by emittance studies in the regime towards collider requirements, and conclude with implications in working towards collider parameters for positron acceleration in plasma. In the study, we use an electron drive beam to be consistent with the previous publication.

THE MODERATELY NON-LINEAR REGIME

Traditionally, a linear plasma wakefield is created by a drive beam with $n_b/n_o << 1$. All fields are sinusoidal; weak loading and discrete positioning of the positron trailing bunch inside the linear part of the transverse fields ensure emittance preservation. However, only low-charge, low-gradient acceleration is obtainable in this regime. On the other hand, with a drive beam density $n_b/n_o >> 1$, non-linear wakefields are created. Such a regime sustains much higher acceleration gradients but suffers from poor efficiency due to high drive-beam charge and poor beam quality due to plasma electron motion inside the positron bunch. The MNL regime takes the middle-ground between the two traditionally known regimes, where the drive beam has a density $n_b/n_o \cong 1$.

Using 3D quasistatic simulation code QuickPIC [24-26], an example of the fields and plasma response produced by such a driver is shown in Fig. 1. The bubble-like cavity is only a partial blow-out where the plasma electron density is greater than 0 inside. In this regime, an elongated positron focusing and acceleration region, provided by plasma electrons returning to axis in a similar way as in the non-linear blowout regime, can be found between two partial blow-outs. In this case, the drive electron beam has a tri-gaussian profile with parameters $\sigma_{x,y} = 8.6$ µm, $n_b = n_o = 5\cdot10^{16}$ cm^{-3}, $\sigma_z = 16.7$ µm. The tri-gaussian positron beam parameters are given in row 1 of Table 1. The average accelerating field sampled by the positron bunch is 4.2 GeV/m, the energy efficiency 15% and total

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Table 1: Positron Beam Parameters in the MNL Regime

ε_N [mm·mrad]	k_b[1]σ_z	σ_z [µm]	Q [pC]
2.38	0.78	5.2	7.9
0.238	0.78	5.2	0.79
0.238	0.35	0.24	8.5

energy spread of 8.1% with an uncorrelated energy spread of 1.1%. The beam is quasi-matched to the transverse fields with an emittance growth of 5%. The MNL regime can therefore accelerate positron beams with moderate emittance and charge at good efficiency and quality.

EMITTANCE AND COLLIDER PARAMETER STUDIES FOR POSITRONS IN THE MNL REGIME

Emittance Growth and Quasi-Matching

The optimal point in Fig. 8 of Ref. [20] has an energy efficiency of close to 40% while keeping the uncorrelated energy spread around 1%. However, the point is not practical as continuous emittance growth is observed due to the high density of mobile plasma electrons when the positron beam is placed close to the back of the first partial blow-out or defocusing from the second partial blow-out when the positron beam is placed back in ξ. In the prior case, the problem originates from the plasma electrons crossing the axis and getting drawn back towards the positron bunch, thereafter, oscillating inside the positron beam. With an intense, longitudinally gaussian positron beam, the plasma electron motion is innately non-uniform and a detriment to the emittance evolution of the positrons. This effect can be mitigated by opting to a less dense drive beam, leading to an extended favorable region for positrons, resembling more the linear regime, with slightly lower charge and efficiency, but preserved emittance and moderate energy spread (as given in the previous section).

Quasi-matching is achieved using an estimate of a linear unloaded focusing field (e.g. the red curve in the inset of Fig. 1). For a given x where the beam centroid is located, the quasi-matched β is given by:

$$k_p\beta = \frac{1}{\sqrt{A/\gamma}},$$

where A is the linear fit parameter given by $F_r = e\cdot(E_r - cB_\theta)/E_o = -A\cdot k_p r$, and γ is the Lorenz factor of the beam. The beam β is then slightly adjusted around the quasi-matched value calculated above for a given beam emittance to minimize emittance growth.

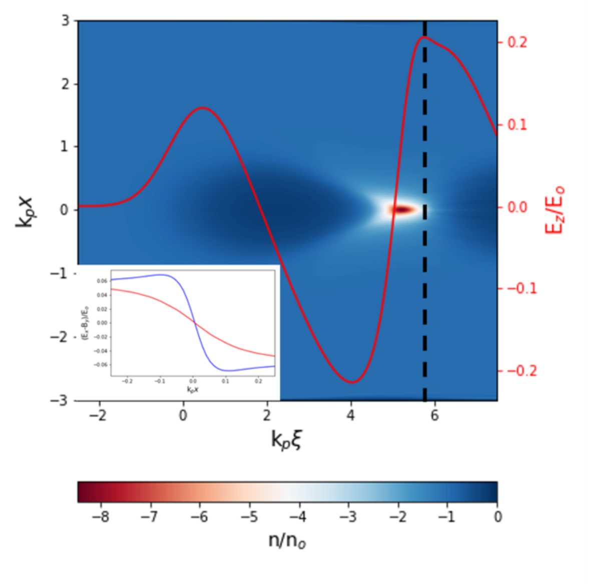

Figure 1: Plasma electron density for a drive beam in the MNL regime and a trailing positron beam, on-axis E_z (red) and $(E_x - cB_y)/E_o$ (inset) at the central beam slice, unloaded (red) and loaded (blue), plotted across $5\sigma_x$ of the positron bunch. The dashed black line indicates the longitudinal positron beam centroid.

Collider Requirements and Implications on Emittance

It is important to keep in mind the luminosity requirement of 10^{34} $cm^{-2}s^{-1}$ in a future high-energy collider. Simulations using GUINEA-PIG [27, 28] are performed to evaluate the luminosity achievable with feasible positron parameters in the MNL regime. The electron counterpart can be accelerated in the non-linear blow-out regime, rendering the two colliding bunches asymmetric. Nevertheless, the goal is to take the bottom-up approach and attempt to reach the target luminosity working from presently feasible acceleration regimes. Simulation results for beam collisions at IP with a chosen set of electron parameters [29] and various positron parameters are shown in Table 2. It becomes evident that it is necessary to reduce the normalized emittance of the positron bunch to get closer to the target luminosity, in addition to eventually increasing the beam charge. Case 3 has the most demanding requirements on positrons compared to what is achievable in the MNL regime at present, with increased charge and reduced emittance and bunch length. However, it is more relaxed than the requirements for symmetric collisions [30, 31]. In addition to the total luminosity, the luminosity of collisions by particles with energies greater than 90% of the center-of-mass energy √s is shown in the table, depicted as $L_{0.1}$. This parameter is arguably considered as the minimum requirement in luminosity for physics output at a high-energy collider [32].

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[1] $k_b = \sqrt{(n_b e^2/(m_e\varepsilon_0))}\,/c$

Table 2: Expected Luminosities From e^+e^- Collisions for Various e^+ Parameters in the MNL Regime and a Particular Set of e^- Parameters at $\sqrt{s} = 3$ TeV

	PWFA e^-	**e^+ case 1**	**e^+ case 2**	**e^+ case 3**
Q [pC]	800	8	8	25
σ_z [μm]	5	5	5	0.5
σ_x,σ_y [μm]	39, 0.2	64, 2	20, 0.6	6, 0.2
$\varepsilon_{Nx},\varepsilon_{Ny}$, [mm·mrad]	0.887, 0.02	2.38, 2.38	0.238, 0.238	0.024, 0.024
L_{total} [$cm^{-2}s^{-1}$]		$2.84\cdot10^{32}$	$1.65\cdot10^{33}$	$1.31\cdot10^{34}$
$L_{0.1}$ [$cm^{-2}s^{-1}$]		$1.92\cdot10^{32}$	$1.17\cdot10^{33}$	$1.02\cdot10^{34}$

From the feedback of the results on the collision luminosity, a study is performed using QuickPIC where the emittance of the positron beam is reduced by one order of magnitude, and the beam is rematched to the plasma wakefields in the MNL regime. The beam density is also scanned to vary and optimize the beam charge. The beam is propagated over a certain distance until emittance equilibrium is observed. The results demonstrated in Fig. 2 show catastrophic emittance growth when $k_b\sigma_z > 1$, a limitation similar to the one in the linear regime [20]. In addition, stringent matching conditions are necessary to keep the emittance growth within 10% (the dark blue region in Fig. 2).

Restraining the conditions of accelerating positrons with lower emittance in the MNL regime to $k_b\sigma_z < 1$, two potential solutions are proposed in Table 1: Accelerating at a lower charge and efficiency or at sub-micron bunch lengths. In the simulations, the positron bunch has an initial energy of 1 GeV. The limitation becomes more demanding at higher energies as $\gamma \sim 1/\sigma_r^2 \sim n_b \sim k_b^2$.

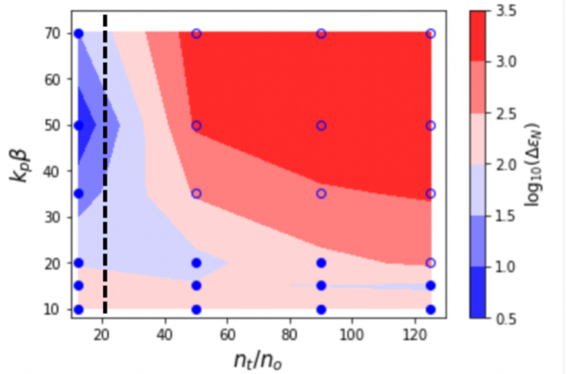

Figure 2: Emittance evolution scan for a positron beam with $\varepsilon_N = 0.238$ mm·mrad. The solid dots indicate that the beam reaches emittance equilibrium at some point, and hollow dots indicate beams with continuous emittance growth. The dashed black line shows where $k_b\sigma_z = 1$, increasing towards higher positron beam density.

CONCLUSION

A comprehensive numerical study for positron acceleration in the MNL regime of plasma wakefields shows the feasibility of accelerating positrons with good efficiency and beam quality in this regime at the emittance level of a few mm·mrad. With these positron parameters, and assuming the electron parameters given in Table 2, the attainable total luminosity in an electron-positron collider with a center-of-mass energy of 3 TeV is $2.84\cdot10^{32}$ $cm^{-2}s^{-1}$, and the peak 10% luminosity $1.92\cdot10^{32}$ $cm^{-2}s^{-1}$. In order to approach the required luminosity of 10^{34} $cm^{-2}s^{-1}$ in a linear e^+e^- collider application, the emittance of the positron bunch needs to be reduced. In the MNL regime, this implies either a compromise in charge or the necessity for ultra-short bunches. A compromise in charge would further reduce the luminosity, leaving the option to producing ultra-short positron bunches. Other mitigation techniques are needed in this regime to avoid overloading (and emittance growth as a result) as increasing the positron charge and energy becomes prominent in reaching the target luminosity. We have shown that it is not necessary to accelerate symmetrically the electrons and positrons, loosening the requirements for positron acceleration in plasma. Further studies of positron acceleration with low emittance in plasma are required to evaluate the feasibility and capability of a high-energy collider that accelerates asymmetrically electrons and positrons.

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