DESIGNING LWFA IN THE BLOWOUT REGIME*

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Abstract

In recent experiments of Laser Wakefield Acceleration (LWFA), ultra-short (sub 50fs) monoenergetic (energy spread of a few percent to twenty percent) electron bunches of high charge (10s of pC to a few hundreds of pC) with energy range from 100MeV to 1GeV have been observed. In most of these experiments the laser drivers undergo significant longitudinal and transverse evolution during the acceleration process. How to extend the results from these experiments towards a more stable regime conducive to making an accelerator is of fundamental importance. In a recent work, a phenomenological theoretical framework of the blowout regime was developed to address this quest. In this paper, a design table based on this theoretical framework will be provided to illustrate possible parameters for reaching GeV to TeV energies.

INTRODUCTION

Recently, plasma based acceleration has experienced great progress. For electron beam driven Plasma Wakefield Accelerator (PWFA), energy doubling of an incoming 42GeV electron beam has been achieved in a meter long plasma[1]. For Laser Wakefield Acceleration (LWFA), ultra-short (sub 50fs) monoenergetic (energy spread of a few percent to twenty percent) electron bunches of reasonable charge (10s of pC to a few hundreds of pC) with energies ranging from 100MeV to 1GeV have been observed[2, 3, 4, 5]. In either case, the laser/ beam plasma interaction occur in a 3D highly nonlinear regime (the so called blowout/bubble regime), in which the plasma electrons are expelled by the radiation pressure of a short pulse laser or the Coulomb force of an electron bunch, leading to nearly complete blowout.

In principle, the blowout regime is an excellent accelerating structure for accelerating high quality electron beams. It has uniform accelerating field in the transverse dimension, which can help to maintain small energy spread if combined with longitudinal field shaping by beam loading. it can be used to accelerate large amounts of charge (∼nC), which is necessary for many applications ranging from coherent light sources to high energy physics. it also has ideal linear focusing force, which can conserve the beam transverse emittance during the acceleration process, thereby maintaining the brightness of an injected high quality electron beam.

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However, in many of the recent LWFA experiments, the laser drivers undergo significant longitudinal and transverse evolution, leading to significant energy fluctuation and pointing jitter for the self-injected electron beams. Therefore, determining how to extend the results from these experiments towards a more stable regime conducive to making an accelerator is of fundamental importance.

Recently, a phenomenological theoretical framework for the blowout regime was developed to address this quest[6]. This theory includes the concepts of nonlinear multi-dimensional wake excitation, local pump depletion, dephasing, laser guiding, and beam loading. It provides a recipe for designing a LWFA for given laser and plasma parameters and estimates the number and the energy of the accelerated electrons whether self-injected or externally injected. Furthermore, these formulas apply for self-guided as well as externally guided pulses (e.g. by plasma channels).

FORMULAS AND DESIGN TABLE

The key formulas from this theory are listed here, including the matching condition for stable laser propagation, the dephasing and pump depletion distance, the energy gain and the total charge that can be accelerated, and the self-guiding threshold condition. a_0 is the peak normalized vector potential at focus for a linear polarized laser pulse, W_0 is the matched laser spot size and R is the matched blowout radius, P_c is the critical power for relativistic self-focusing in underdense plasma ($P_c \approx 17\frac{n_c}{n_p}[GW]$), k_p is the plasma wavenumber, and τ_{FWHM} is laser pulse duration.

Matching Condition

$$a_0 \simeq 2(P/P_c)^{1/3} \tag{1}$$

$$k_pR \simeq k_pw_0 = 2\sqrt{a_0} \tag{2}$$

$$k_pc\tau_{FWHM} \leq 2\sqrt{a_0} \tag{3}$$

Dephasing and Pump Depletion Distances

$$L_{dp} \simeq \frac{4}{3}\frac{\omega_0^2}{\omega_p^2}\sqrt{a_0}k_p^{-1} \tag{4}$$

$$L_{pd} \simeq \frac{\omega_p^2}{\omega_0^2}c\tau_{FWHM} \tag{5}$$

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Energy Gain

$$\Delta E[GeV] \simeq 1.7\left(\frac{P[TW]}{100}\right)^{1/3}\left(\frac{10^{18}}{n_p[cm^{-3}]}\right)^{2/3} \times\left(\frac{0.8}{\lambda_0[\mu m]}\right)^{4/3} \quad (6)$$

Total Charge

$$N \simeq 2.5\cdot 10^9 \frac{\lambda_0[\mu m]}{0.8}\sqrt{\frac{P[TW]}{100}} \quad (7)$$

Self Guiding Threshold

$$a_{0c} \simeq (n_c/n_p)^{1/5} \quad (8)$$

Based on these formulas, we present a parameter table, which describes how to choose parameters to reach GeV to TeV energy level by a single stage LWFA.

There are two possible scenarios depending on if external guiding is used. For designs using preformed plasma density channels with a parabolic profile (marked by $\Delta n_c/n_p > 0$), relatively low laser power ($P \sim P_c$) is needed to reach electron blowout and stable propagation. In this table, $P/P_c = 0.67$ is used, which is on the margin of electron blowout. For designs using self-guiding, P/P_c are chosen to satisfy the condition of self-guiding.

For both cases, externally injected high quality electron beams are preferred. For the self-guided cases, self-injection can occur, however, the self-injected beams have large emittance, which may not be sufficient for many applications.

DISCUSSION

The first row in table 1 shows that what might be possible for a 30fs 20TW laser and a matched plasma channel with minimum density $1 \times 10^{18} cm^{-3}$ on axis and of a length of $1.6cm$. The scaling laws predict such condition could lead to 30fs 180pC high quality electron beam with an energy around 1GeV. To realize such a compact high quality GeV electron accelerator, synchronized full optical injection with fs timing jitter is highly preferred. Whether all optical injection can produce 180pC is still an open question. The second row shows that electron beam with more than twice the charge (400pC) and roughly the same energy (1GeV) can be achieved using a 30fs 100TW laser interacting with a 9mm uniform plasma of a density $2 \times 10^{18} cm^{-3}$. The injection for this case can be either external or self injection. The test of these two designs in near future may become an important milestone to establish LWFA as a practical accelerator technology. For energy beyond GeV, higher power lasers that are coming on line as well as newer plasma source are needed. It can be clearly seen from Table 1. Very high laser power (PW) and long plasma sources with good uniformity (meter scale plasma channel or uniform plasma) are needed to reach 10GeV and beyond.

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Table 1: Parameter Designs for GeV and Beyond

$P(PW)$	$\tau(fs)$	$n_p(cm^{-3})$	$W_0(\mu m)$	$L(m)$	a_0	$\Delta n_c/n_p$	$Q(nC)$	$E(GeV)$
0.02	30	1×10^{18}	14	0.016	1.76	60%	0.18	0.99
0.10	30	2×10^{18}	15	0.009	3.78	0%	0.40	1.06
0.20	100	1×10^{17}	45	0.52	1.76	60%	0.57	9.9
2.0	100	3×10^{17}	47	0.18	5.45	0%	1.8	10.2
2.0	310	1×10^{16}	140	16.3	1.76	60%	1.8	99
40	330	4×10^{16}	146	4.2	7.6	0%	8	106
20	1000	1×10^{15}	450	500	1.76	60%	5.7	999
1000	1000	6.5×10^{15}	460	82	12.1	0%	40	1040