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Plasma wakefield acceleration at CLARA facility in Daresbury Laboratory

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ABSTRACT

A plasma accelerator research station (PARS) has been proposed to study the key issues in electron driven plasma wakefield acceleration at CLARA facility in Daresbury Laboratory. In this paper, the quasi-nonlinear regime of beam driven plasma wakefield acceleration is analysed. The wakefield excited by various CLARA beam settings are simulated by using a 2D particle-in-cell (PIC) code. For a single drive beam, an accelerating gradient up to 3 GV/m can be achieved. For a two bunch acceleration scenario, simulation shows that a witness bunch can achieve a significant energy gain in a 10–50 cm long plasma cell.

1. Introduction

Plasma wakefield acceleration is one of the most promising technologies to miniaturize the scale of next generation particle accelerators due to its capability to sustain very large electric field. From the initial idea proposed to nowadays, plasma based accelerators have achieved tremendous breakthroughs in the last three decades [1,2]. Plasma accelerators driven by high power and short pulse lasers, so-called laser wakefield acceleration (LWFA) could achieve hundreds MeV to several GeV electron beam in a single stage acceleration. The resultant mono-energetic beams have the energy spread of only a few percent [3–5]. The recent highlight from LBNL has successfully demonstrated a 4.25 GeV electron beam acceleration from a 9 cm long capillary discharge plasma source [6]. This electron beam energy is already well comparable to most of today's third generation light sources and the resulting beam can be used to drive free electron laser as well [7]. On the other hand, the plasma accelerators driven by electron beam, so-called beam driven plasma wakefield acceleration (or PWFA) has doubled the energy of the electron beam from the Stanford Linear Collider (SLC) within an 85 cm plasma cell [8]. The FACET facility has recently also achieved the high efficient acceleration for a separate witness electron bunch [9]. The latest results showed that positron beam can also excite significant wakefield and accelerate the positrons at the rear part of the bunch in a self-loaded mode [10]. All these breakthroughs have shown great promise to build tabletop and efficient energy use of plasma accelerators as alternatives to conventional accelerators. This is mainly due to plasma based accelerators can provide an accelerating gradient of 1–100 GeV/m, which are usually over two to three orders of magnitude higher than the field in conventional RF-based accelerating structures (in general equal or less than 100 MeV/m) [11].

Compared to laser driven wakefield accelerators, the advantages of a relativistic beam driven plasma wakefield acceleration lie in that the beam can propagate in plasma for much longer distances than that of the laser beam in plasma, as the laser beam is subject to the 3D effect, i.e. diffraction, depletion and dephasing in the plasma. Therefore the energy gain for a one-stage acceleration is significant for PWFA. Secondly, the conventional RF-based accelerator can obtain the relativistic electron beam with relatively high efficiency (usually more than 10%). Using this relativistic beam as drive beam for plasma wakefield excitation is more efficient than using the laser beam for beam acceleration (if compared to low wall-plug efficiency for producing laser beam). Currently, there are a number of dedicated facilities to demonstrate the great potential of the beam driven plasma wakefield acceleration method, e.g. FACET and FACET II facility at SLAC [12], the FLASHForward at DESY [13], the SPARC LAB facility of INFN [14] and the AWAKE experiment driven by the 400 GeV proton beam from the SPS at CERN [15–18].

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We have proposed a high gradient plasma wakefield acceleration experiment based at CLARA (Compact Linear Accelerator for Research and Applications) facility in the Daresbury Laboratory [19–21]. The idea is to investigate the critical issues for the next generation plasma accelerators, e.g. test of the PWFA theory, high acceleration gradient (1–10 GeV/m), two-bunch acceleration, high transformer ratio, plasma focusing effect (plasma lens), and related advanced beam dynamics concepts. Since the CLARA beam is designed for Free Electron Laser (FEL) research, which makes the beam ideal for plasma wakefield acceleration experiments. Firstly, the beam is relativistic so it can propagate in plasma for a long distance, i.e. tens of centimetres. Therefore the energy gain from a one-stage acceleration will be significant. Secondly, the bunch length can be tuned from a few pico-second down to tens of femtosecond, which enables us to study the scaling laws for PWFA and reach high accelerating gradient in an ultrashort bunch operation case. Thirdly, the well-developed beam diagnostics at CLARA can be easily employed to characterise beam precisely, and knowing the beam parameters are crucial for PWFA experiments.

In this paper, the theory of quasi-nonlinear PWFA regime (QNL) is introduced and analysed in Section 2. The particle-in-cell (PIC) code VSIM [22] is employed to model the electron-plasma interactions for a single drive beam and two bunch acceleration case respectively based on the CLARA beam parameters. The detailed simulation results are presented in Section 3.

2. PWFA in quasi-nonlinear regime

In the blowout regime of PWFA, the driving bunch has much higher electron density n_b than the background plasma density n_p, i.e. $n_b \gg n_p$, and thus excites an ion filled bubble behind it. The radial focusing field is linear along the bubble radius and the longitudinal accelerating field is constant in radius. However, the nonlinear plasma oscillation occurs simultaneously, which limits the beam quality of the witness bunches. Therefore, a new regime called weak blowout has been proposed and investigated recently [23–25]. It operates in the quasi-nonlinear regime (QNL), where the total charge of the driving bunch is relatively low to maintain the resonant plasma response, especially a constant wakefield frequency, while the density of the driving bunch is still larger than that of the plasma to form the bubble. Such a driving bunch can be achieved by using a cigar shape, where the transverse size of the bunch σ_r is much smaller than the bunch length σ_z, i.e. $\sigma_r \ll \sigma_z$. The QNL-PWFA is very promising to provide high-quality and high-energy bunches under ultra-high accelerating gradient. Meanwhile, the transformer ratio is also an important figure of merit, which is defined as the ratio of the maximum accelerating wakefield behind the driving bunch and the maximum decelerating wakefield within it, i.e. $R = W_{acc}/W_{dec}$. R is usually less than two for a single symmetric driving bunch in the linear regime. Fortunately, there are a few ways to overcome this limit, for instance, using an asymmetric driving bunch [26,27], a ramped bunch train [28,29] and the nonlinear plasma dynamics [27,30] as in the case of single bunch driven QNL-PWFA.

In the QNL-PWFA regime, several case studies have been performed by using 2D particle-in-cell simulations. The idea is to find out the optimal plasma density for certain driving beam parameters. In order to enhance the transformer ratio, one can manipulate the driving bunch shape, namely the ratio of σ_r to σ_z. The test bunches to be used are typically achievable at a few existing and oncoming facilities at the energy level of hundreds of MeV, e.g. at CLARA facility. The driving bunches have the azimuthally symmetric bi-Gaussian shape as follows:

$$n_b(r,z) = n_b e^{-r^2/2\sigma_r^2} e^{-z^2/2\sigma_z^2}, \tag{1}$$

here n_b is the driving beam density which is given by

$$n_b = N_b/((2\pi)^{3/2}\sigma_r^2\sigma_z). \tag{2}$$

The normalized charge that is used to evaluate the nonlinearity in the PWFA is defined as the total electron numbers in the driving bunch N_b normalized to the numbers of the plasma electrons inside a cubic plasma skin depth k_p^{-3} as follows [23]:

$$Q_n = N_b k_p^3/n_p = n_b/n_p(2\pi)^{3/2} k_p\sigma_z(k_p\sigma_r)^2, \tag{3}$$

where $k_p = 2\pi/\lambda_p = \sqrt{e^2 n_p/m_e\epsilon_0}/c$ is the plasma wave number with λ_p the plasma wavelength. In linear theory, the number of the plasma electrons that response to the driving beam is approximately limited to $n_p k_p^{-3}$. It can be seen that Q_n should be smaller than 1 to have linear plasma response. On the other hand, n_b should be higher than (or comparable to) n_p to excite bubbles in plasma. $Q_n < 1$ and $n_b > n_p$ are the two conditions to achieve the QNL-PWFA. It has been demonstrated that the prediction from the linear theory that the maximum accelerating gradient appears at $k_p\sigma_z = \sqrt{2}$ still holds even though the nonlinear blowout regime is reached, i.e. when $n_b \gg n_p$, as long as the normalised charge per unit length of the driving beam $\Lambda = (n_b/n_p)(k_p^2\sigma_r^2) \ll 1$ [31]. Therefore, the bunch with a cigar shape ($\sigma_r \ll \sigma_z$) is the best candidate to drive a PWFA in the QNL regime.

For the QNL-PWFA, the maximum accelerating wakefield may be estimated by the following equation of the linear theory:

$$E_{z,max} \approx 236\ \mathrm{MV/m}\left(\frac{N_b}{4\times10^{10}}\right)\left(\frac{600}{\sigma_z\ (\mu\mathrm{m})}\right)^2 \ln\left(\sqrt{\frac{10^{16}}{n_p\ (\mathrm{cm}^{-3})}}\frac{50}{\sigma_r\ (\mu\mathrm{m})}\right), \tag{4}$$

which shows that $E_{z,max}$ depends not only on the driving bunch charge and length, but also on the optimum plasma density and the bunch spot size σ_r. According to the linear theory, the optimal plasma density occurs at $k_p\sigma_z = \sqrt{2}$. However, beyond this limit $\sigma_r \ll \sigma_z$ when σ_r approaching σ_z, the optimal plasma density n_p will be lower and $k_p\sigma_z < \sqrt{2}$ [32], since in this case the driving bunch density n_b will be likely decreases along with the increasing of the spot size. In addition, $E_{z,max}$ can also be predicted by the following expression if $n_b/n_p \le 10$ [32]:

$$E_{z,max}/E_{0,max} \approx 1.3(n_b/n_p)(k_p\sigma_r)^2 \ln(1/k_p\sigma_r), \tag{5}$$

for the narrow driving bunch, i.e. $k_p\sigma_r < 0.3$ and in the weakly nonlinear limit $\Lambda < 1$, where the wave breaking wakefield $E_{0,max} = mc\omega_p/e \sim 100\sqrt{n_p\ (\mathrm{cm}^{-3})}\ \mathrm{V/m}$.

The maximum energy that can be given to the witness bunch is limited by the transformer ratio R. For the single symmetric driving bunch, the limit of $R < 2$ can be overcome by operating the PWFA in the QNL regime, where nonlinear blowout occurs. It is meaningful to study the dependence of R on the plasma density for given driving bunch parameters. Due to the incomplete nonlinear theories, numerical simulations must be employed to study the detailed wakefield structures in the QNL regime.

3. Simulation study of beam-plasma interactions

3.1. Electron beam from CLARA facility

CLARA is a normal conducting linear electron accelerator. It can generate ultrashort and bright electron bunches and use these bunches in the experimental production of stable, synchronised, ultrashort photon pulses of coherent light from a single pass free electron laser (FEL) with techniques directly applicable to the future generation of light source facilities [19]. The CLARA facility comprises of a photo-injector electron gun, S-band normal conducting accelerating cavities, magnetic bunch compressor, fourth