Plasma bubble evolution related electron beam parameter estimation in laser wakefield acceleration

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ABSTRACT

Laser-wakefield acceleration provides a compact electron acceleration scheme for producing a multi-GeV electron beam, utilizing the high longitudinal electric field gradient generated by high intensity, ultrashort laser pulse. The blow-out regime of the laser wakefield acceleration (LWFA) is one of the most recent and reassuring mechanisms for generating quasi-mono-energetic electron beams. In this work, we propose simulation-based studies for plasma bubble evolution and corresponding electron beam quality parameters. The primary focus of this work is to find out the dependency of the electron beam energy and beam-quality on the shape and size of the bubble. The evolution of bubble with time and correlation of bubble length (longitudinal and transverse radius) with the intensity of laser pulse has been revealed in this study. The results show that the longitudinal bubble length grows with time. It has also been confirmed that the shape of the bubble cannot be predicted using fixed shape models as spherical or elliptical. Moreover, the simulation-based findings predict that as the bubble traverses in plasmas, it evolves from spherical shape to the highly elliptical shape. Moreover, as it approaches the dephasing length, the eccentricity decreases further.

INTRODUCTION

Laser Wakefield Acceleration has been widely used as a potential acceleration mechanism due to its ability to yield superior quality mono-energetic electron beams in GeV energy range. The progress in laser technology all over the world has led to the development in the area of LWFA. The Chirped Pulse Amplification (CPA) technique has made Petawatt lasers possible. The PW laser systems can generate very high-intensity lasers (10^{20} to 10^{22} W/cm^2), which further ease the realization of the highly non-linear regime- bubble regime. In this non-linear regime, when a laser pulse is transmitted in the under dense plasma, the electrons in plasma are completely evacuated due to the ponderomotive force exerted by the laser pulse, creating an electron free region behind it, called blow out or bubble regime[1-3]. The electrons in the background plasma may get trapped at the back of the bubble and get accelerated to high energies due to longitudinal space charge field in the bubble. So, self-injection phenomenon is very advantageous in order to avoid various experimental challenges faced in inducing a charge in the bubble using various techniques.It has already been reported by various researchers that various non-linear processes such as pulse-compression and self-focusing is accountable for the amplification of the laser pulse intensity. The intensity amplification further leads to the lengthening of the bubble, which is responsible for the injection of electrons at the back of the bubble. Hence, understanding the bubble lengthening process is highly desirable to enhance the understanding and control of the self-injection process [4]. It is crucial to control the self-injection process to enhance the electron energy and beam quality in LWFA. The theory for electromagnetic fields in the bubble and its geometry was proposed earlier by few researchers [5]. The bubble is assumed to be spherical. Sadighi-Bonabi *et al.* [6] assumed the bubble shape to be elliptical and found the elliptical cavity model more consistent in explaining the monoenergetic electron trajectory. Benedetti *et al.* [7] proposed a study of the self-injection process, relating the self-injection mechanism and wake properties like wake velocity, wake amplitude, etc. In 2015, Li *et al.* presented the solution for the electromagnetic fields in the non-linear bubble wake and bubble shape, assuming the bubble shape to be elliptical. The effect of residual electrons on the shape of the bubble is also presented in the paper.

SIMULATION RESULTS

In this section,we discuss the evolution of the bubble wake structure while it propagates in plasmas. In order to observe the shape and size of the bubble, 2D-PIC simulations have been performed on plasma simulation VORPAL code. A laser pulse of pulse duration τ = 20 fs, laser spot size r_0 = 12 µm, laser wavelength λ = 1 µm, and power in Petawatt regime is considered. The simulation length of 1.2 mm has been considered. The plasma density considered in the simulations is 10^{19} cm^{-3}. A window of size 100 × 65 μm, moving with the velocity of light has been considered.

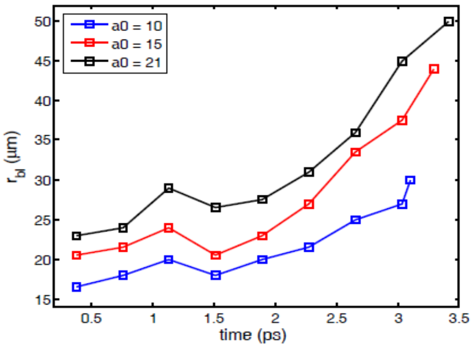

FIG. 1. Variation of longitudinal bubble radius (r_{bl} in micron) with time (in picosecond) for different values of normalized laser strength parameter a_0=10, 15, 21. Other laser-plasma parameters considered are: laser pulse duration τ = 20 fs, laser spot size r_0 = 12 μm, laser wavelengthλ= 1 μm, and plasma density of 10^{19} cm^{-3}.

As the process of self-injection of electrons in bubble wake is closely related to the evolution of bubble. Thus it is crucial to understand the dynamic process of bubble lengthening. Bubble shape is basically characterized by longitudinal bubble radius (r_{bl}). The bubble evolution has been studied for three different values of a_0 (i.e., a_0=10, 15, 21 for the corresponding laser intensities 1.37 $\times10^{20}$, 3.1$\times10^{20}$, 6.4 $\times10^{20}$ W/cm^2, respectively). Initially, the longitudinal bubble radius increases with time and starts to fall (as shown in Fig.1). The lengthening of bubble is due to the intensity amplification of the pulse in plasmas. To explore the bubble shape during propagation, both longitudinal and transverse radii have been considered. Initially spherical bubble shape has been found to transform in to longitudinally elliptical shape. The eccentricity of the elliptical bubble is found to be varying with time. This is due to the change in residual electrons in bubble depending on laser intensity variation in plasma.

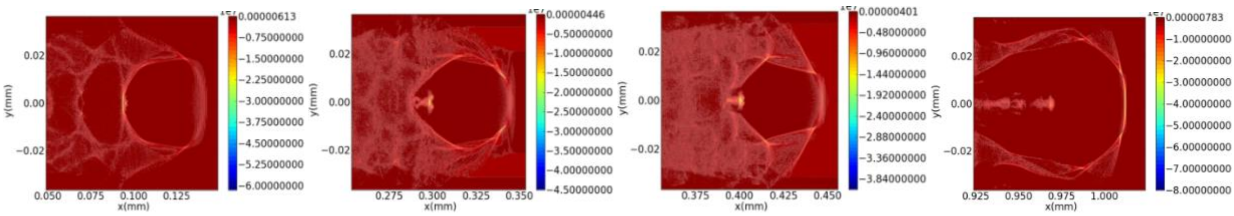

FIG 2: Electron density distribution plots extracted from PIC simulation at different simulation time (i) t= 0.5 ps, (ii) t = 1.2 ps, (iii) t = 1.5 ps, and (iv) t = 3.4 ps. Other parameters are the same as taking in Fig.1.

The density plots shown in Fig. 2 shows that the self-injection of electrons at the bubble back is primarily affected by the bubble evolution. It can be observed from Figs. 1 and 2 that no substantial injection is visible initially. This is because the bubble has not started to expand yet. The injection becomes noticeable as the longitudinal radius starts to grow. At t = 1.5 ps, the longitudinal bubble radius falls and the corresponding injected charge also gets reduced. This is due to the de-trapping of electrons from the bubble. A significant amount of charge is injected into the wake only after the bubble radius has started to increase significantly (for example, after the propagation time 1.5

ps). The simulation results also show that the self-injection of electrons is accompanied by bubble expansion. The beam quality depends on self-injection process, which further depends on bubble evolution. So controlling the bubble shape and its evolution can be of great importance to control the beam quality and energy. Hence simulations have been performed to control the beam quality by reducing energy spread using plasma density parameter, which will be presented in our future work.

CONCLUSION

In this paper, PIC simulations have been performed to analyse the bubble evolution process in laser wakefield acceleration. Previous assumptions of spherical and ellipsoidal geometry of the bubble throughout the propagation length is found deficient to explain various non-linear phenomena such as self-injection. Hence this concept of constant bubble shape has been re-analyzed. The quantitative analysis of the change in bubble shape during its propagation in plasma has also been provided. It has been shown that the evolution of bubble is majorly determined by laser evolution. The self-injection dynamics and its relation with the bubble evolution have been discussed. It has been shown that bubble expansion facilitates electron injection and contraction suppresses it. The beam energy and the beam quality is shown to be dependent on electron injection, hence, it is necessary to understand the mechanism of bubble evolution.

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