DYNAMICS OF SELF-INJECTED BUNCHES IN CYLINDRICAL AND CONICAL PLASMA CHANNELS IN LASER-PLASMA ACCELERATION

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Relativistic self-injected electron bunch is formed in wakefield acceleration in plasma by a laser pulse (LPA) with acceleration rates up to 0.3 TV/m. However, self-injection necessitates indirect control by varying laser pulse and plasma parameters, for example by using inhomogeneous plasma and plasma channel. In this study wakefield excitation in plasma channel of complex shape, consisting of a cylindrical section, a conical segment, and a narrow cylindrical channel was investigated. It was also shown that compared to the cylindrical channel, the conical channel enhances the energy of the self-injected bunch.

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INTRODUCTION

Laser wakefield acceleration (LPA) has emerged as an innovative approach for generating high-energy electron beams in compact setups, overcoming the limitations imposed by conventional accelerators [1, 2]. However, the nonlinear dynamics of self-injection provides self-injected bunches parameters highly sensitive to variations in laser pulse intensity, duration, and plasma density [3, 5, 6]. The efficiency of accelerating electrons to high energies (1 GeV) in a capillary waveguide using LPA was shown in [4]. Investigations [5, 6] shown that inhomogeneous plasma profile is crucial for controlling self-injection and optimizing acceleration. Paper [7] demonstrates that incorporating a hollow plasma channel in a dielectric waveguide significantly enhance radial focusing and improving electron beam quality. The study [8] shown high-quality bunches obtaining in inhomogeneous plasma under laser wakefield acceleration.

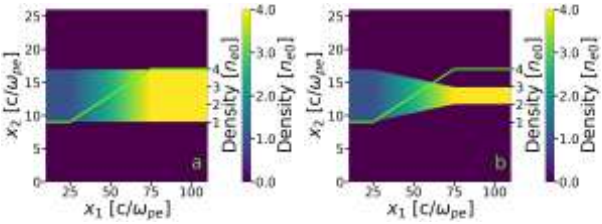
Thus, the study of LPA in a plasma channel with longitudinally inhomogeneous plasma is a promising method for improving the parameters of self-injected bunches. The OSIRIS PIC code was used [9].

STATEMENT OF THE PROBLEM

Wakefield acceleration in a plasma channel is considered. The walls of the channel are represented by a layer of denser plasma (critical density plasma).

The study was devoted to comparing the dynamics and parameters of self-injected bunches and the dynamics of a laser pulse in the case of cylindrical (Fig. 1,a) and conical (with complex shape, Fig. 1,b) plasma channels with an inhomogeneous longitudinal density distribution. Plasma density outside channel is critical $n_e=n_{cr}=1.74\cdot10^{21}$ cm^{-3}. The densities on figures are normalized to $n_{e0}=1.74\cdot10^{19}$ cm^{-3}.

The laser pulse parameters: $a_0=eE_0(m_e\omega c)^{-1}=3.5$, radius $r_{laser}=4.29$ μm, length L_{laser}(fwhm)=1.84 μm, $\lambda_{laser}=800$ nm. The longitudinal and transverse profile of the laser was chosen to be Gaussian. All lengths are normalized to $c/\omega_{pe}=1.27$ μm. Times are normalized to $\omega_{pe}^{-1}=4.25$ fs. The length of the plasma region in the simulation along x_1 was 100 c/ω_{pe}. The width of the window along x_2 was 26 c/ω_{pe} (axis $x_2=13$ c/ω_{pe}).



a *b*

Fig. 1. Plasma electron density longitudinal profile $n_e(x_1, x_2)$. Cylindrical channel (a); Conical channel (b). The density outside the channels is 100 n_{e0}

RESULTS OF SIMULATION

Figs. 2, 3 shows the density graph and the self-injected bunch in the maximum phase of wakefield acceleration. Figs. 4, 5 shows the last moment of time when the self-injected bunch is in the acceleration phase in the conical channel and simultaneously already in the deceleration phase in the cylindrical channel, all other parameters being equal. This clearly indicates the advantage of the conical channel in bunch acceleration.

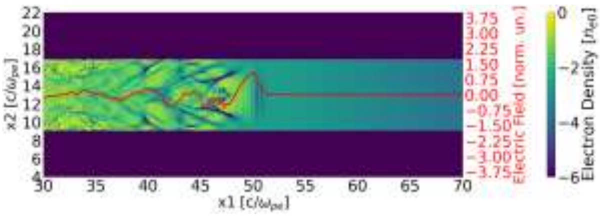


Fig. 2. Density graph $n_e(x_1, x_2)$, acceleration field $E_x(x_1)$. Cylindrical channel. t=214.2 fs

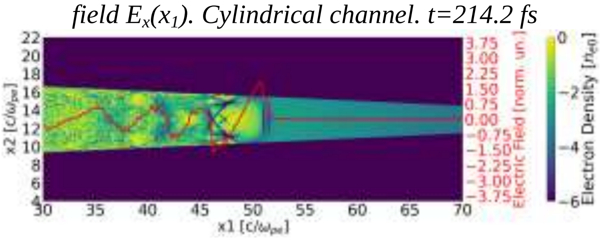


Fig. 3. Density graph $n_e(x_1, x_2)$, acceleration field $E_x(x_1)$. Conical channel. t=214.2 fs

At 214.2 fs, in the case of cylindrical channel a bunch with length of 2.413 μm, diameter of 2.286 μm and a charge of 160 pC was observed. Bunch average longitudinal momentum measured 17.67 m_ec (calculated from the distribution on Fig. 6), reaching a peak energy of 14.34 MeV. In the case of conical channel at 214.2 fs shorter bunch length of 1.905 μm and the diameter of 2.54 μm and a charge of 160 pC are observed. However, average momentum reached 29.60 m_ec, resulting in a higher peak energy of 19.97 MeV. At 297.5 fs, further evolution is observed. The bunch length in the case of cylindrical channel increased to 2.286 μm and its diameter expanded to 3.302 μm, with the charge rising to 330 pC. Its average momentum increased to 24.95 m_ec, corresponding to a peak energy of 19.8 MeV – an energy gain of 5.46 MeV (38.08% increase from 214.2 to 297.5 fs). In the case of conical channel, a bunch length of 2.032 μm and a lower diameter of 1.27 μm, with a charge of 290 pC. Its average momentum surged to 48.70 m_ec, resulting in a peak energy of 27.39 MeV, an energy gain of 7.42 MeV (37.2% increase from 214.2 to 297.5 fs). As a result, an increase in the longitudinal momentum by 1.88 times and energy by 1.41 times is observed in the case of a conical channel. At the moment 297.5 fs in the conical channel the self-injected bunch is in an accelerating field of 0.3 TV/m.

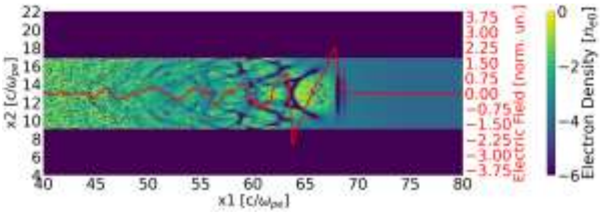


Fig. 4. Density graph $n_e(x_1, x_2)$, acceleration field $E_x(x_1)$. Cylindrical channel. t= 297.5 fs

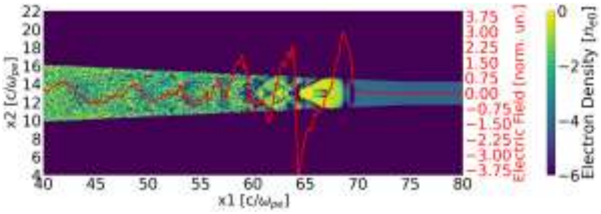


Fig. 5. Density graph $n_e(x_1, x_2)$, acceleration field $E_x(x_1)$. Conical channel. t= 297.5 fs

On Fig. 6 distribution of the longitudinal momentum of the bunch particles (the number of macroparticles along the ordinate axis) is shown. The distribution is well interpolated by the Gaussian distribution.

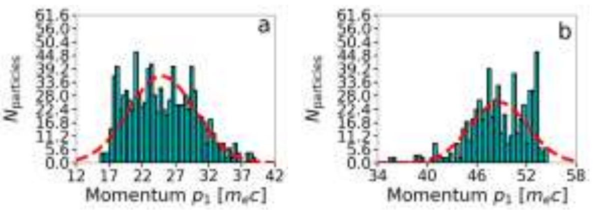


Fig. 6. Distribution of the longitudinal momentum of the bunch particles. (a) Cylindrical channel; (b) Conical channel. t= 297.5 fs

Additional laser-plasma interaction data further highlight the conical channel benefits. An inhomogeneous longitudinal density facilitates moving of the self-injected bunch within the acceleration phase. Using the conical channel reduces the transverse size of the laser pulse from 10.04 to 4.93 μm at 297.5 fs, while the laser continues to propagate along the channel.

At 297.5 fs, the average energy density in the cylindrical configuration reaches 0.342 $m_ec^{-1}\omega_{pe}^3$ compared to 0.8234 $m_ec^{-1}\omega_{pe}^3$ in the conical case (2.41 times increasing). A stable wake bubble shape in the conical channel is observed, as its walls support the bubble structure and prevent disruption. In the case of a conical channel, the wake bubble exists up to 416.5 fs and tends to continue after that. In the case of a cylinder, at 380.8 fs, a significant filling of the bubble with electrons is observed.

CONCLUSIONS

Study demonstrates that using complex-shaped plasma channels in LPA improving the performance of self-injected electron bunches. The conical channel using provides increasing in both the longitudinal momentum and energy of the self-injected bunch. The time of the wake bubble moving through the plasma also increases. Thus, the advantages of using conical plasma channels to improve the parameters of self-injected bunches in LPA were demonstrated.

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