# Optical injection into the laser wakefield accelerator by co-propagating weaker pulse

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The considerable progress in the investigation of electron acceleration in laser plasmas was achieved within the last several decades. The main advantage of this concept in comparison with standard radiofrequency accelerators is in the plasma ability to sustain large accelerating gradients in order of hundreds of GV/m [1]. Currently, the most promising approach to the electron acceleration in underdense laser plasma is cavitated wakefield regime, when electrons are accelerated by the nonlinear plasma wave dragged by the ultrashort (tens of fs), ultraintense ($I > 10^{19}$ W/cm$^2$) laser pulse propagating through the gaseous target.

However, the most simple and spontaneous mechanism to inject the electrons into the acceleration phase called self-injection has significant drawback; it is very difficult to control parameters of produced electron bunches due to its unstable, nonlinear nature. Therefore, various alternative mechanisms such as an injection by a density ramp, ionisation injection using a mixture of lighter and heavier gases or optical injection employing additional laser pulse(s) were proposed.

This paper proposes new optical injection scheme by a weaker injection pulse preceding the plasma wave driving pulse. The considered experimental configuration is depicted in Fig. 1. The main advantage in comparison with earlier introduced optical schemes like injection by perpendicular pulse [2] or counter-propagating pulse [3] is in its simplicity. The incident laser pulse is divided into two parts by combination of pellicle beamsplitter and standard flat mirror. The delay between preceding injection pulse and following drive pulse is easily controllable by the distance between these mirrors. The ratio of the intensities of both laser pulses is determined by a pellicle splitting ratio. This simple configuration avoids the issues with temporal and spatial synchronization which are characteristic for other optical injection schemes. Contrary to previous proposals of

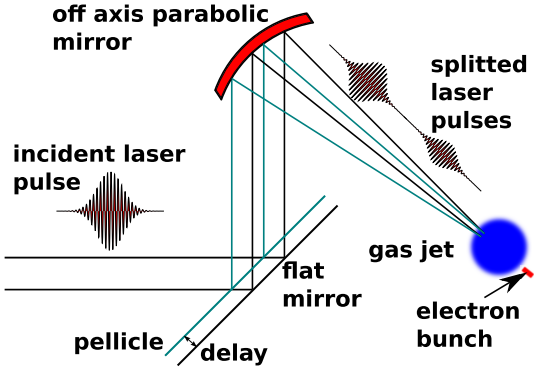


Figure 1: *Scheme of suggested configuration, in which the injection pulse is splitted from the main pulse by thin beamsplitter prior the main focusing optics.*

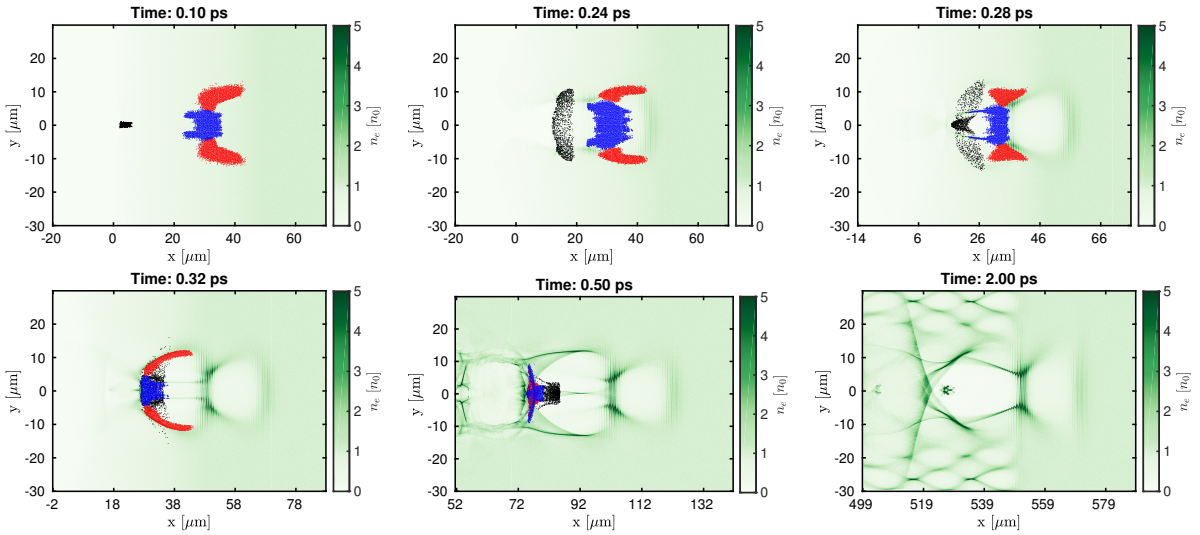


Figure 2: *Evolution of electron density with marked position of macroparticles injected by various injection mechanisms. Red: transverse injection, blue: longitudinal injection, black: additional injection.*

injection by two co-propagating pulses which were based on optically induced ionization by delayed more intense injection pulse [4], or on different focusing of both pulses [5], our approach is easier to implement, and the injection pulse is weaker than drive pulse.

The injection process was studied by means of 2D and 3D particle-in-cell (PIC) simulations. The following parameters were chosen for the demonstration of this scheme: laser wavelength $\lambda = 0.8$ μm, waist size $w_0 = 9.5$ μm, pulse duration $\tau = 25$ fs, drive and injection pulses laser strength parameter $a_{0,DP} = 4$ and $a_{0,IP} = 2.5$. The mutual delay between pulses was 65 fs, both are linearly polarized. Plasma was represented as homogeneous electron gas with density $3 \times 10^{18}$ cm$^{-3}$ and immobile ions assumed (they were not simulated). The initial 50 μm long linear density ramp was chosen. Simulation box dimensions were 90 μm×60 μm (85 μm×36 μm×36 μm) with 34×12 (25×4×4) cells per wavelength and 3 (2) particles per cell in 2D case (3D case).

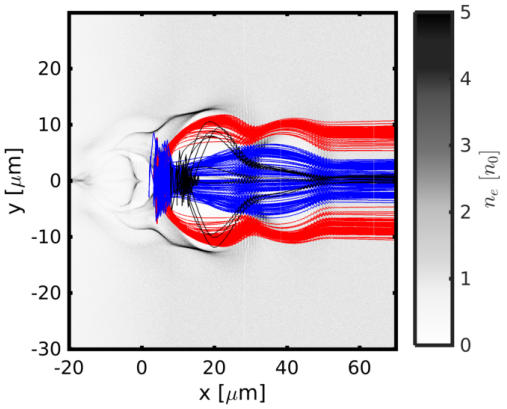


Figure 3: *Trajectories of electrons trapped by various injection mechanisms.*

Multiple numerical simulations with varied physical parameters indicate that the injection occurs at the beginning of the plasma layer or in the density ramp. The parameters of the density ramp do not have significant influence on the properties of produced electron bunch. Three injection mechanisms can be distinguished.

*Transverse injection*: This was the original idea of presented scheme, i.e. to increase the

electron density in the electron collection region of the standard transverse self-injection [6] by the ponderomotive force of the injection pulse. Numerical simulations indicate that it is the dominant injection mechanism with $\approx 60\%$ proportion between all the trapped electrons. It is represented by red color in Figs. 2 and 3.

*Longitudinal injection*: Significant number of trapped electrons ($\approx 40\%$) are initially located around the central axis in the region $|r_0| < w_0/2$. Due to the prolonged period of time spent in the region with the longitudinal electric field pushing them in the laser pulses propagation direction they gain enough forward momentum to be sustained in the accelerating plasma wave. They are represented by blue color in Figs. 2 and 3.

*Additional injection*: It is not an interesting effect similar to longitudinal injection. Less than 1 % of the trapped electrons originate from this mechanism. They are marked in black.

Since the low values of electron density are chosen, the self-injection does not occur during the 7 ps of simulation corresponding to plasma layer 2.1 mm thick. Within this time, the electron bunch gains the energy up to ≈400 MeV. The electron spectrum from 3D simulation is plotted in Fig. 4. Total injected charge is 54 pC and transverse emittance is 5.2 $\pi$·mm·mrad. This high value of emittance is caused by the fact that multiple injection mechanism are present. On the other hand, the accelerated electron bunch is well separated from the dark current and the length of the electron bunch is as short as 6 μm. Additionally, we believe that the electron bunch properties can be considerably improved by further research.

During the acceleration process, electron bunch undergoes transverse betatron oscillations. The corresponding radiation spectrogram was calculated employing the recent method [7]. The critical energy of the betatron radiation is 11.6 keV and the time duration (FWHM) is 4.8 fs.

There is a inherit drawback of the scheme emerging from its nature. When the delay between injection and the drive pulse is too high, trapped electron bunch may be dispersed by an electron stream generated due to the contact between the most rear part of the injection pulse bubble and

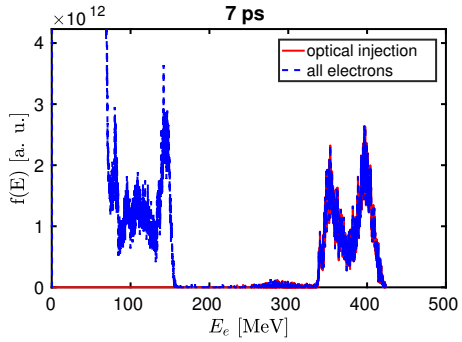


Figure 4: *Electron spectrum after 7 ps of acceleration from 3D simulation.*

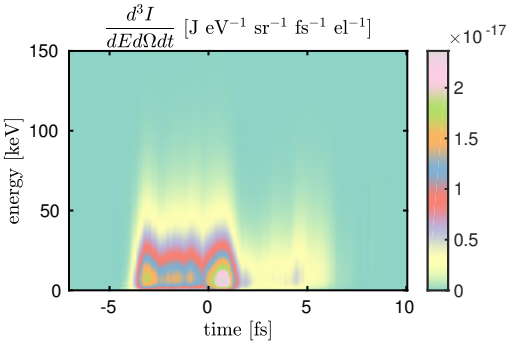


Figure 5: *Corresponding spectrogram of X-ray betatron radiation.*

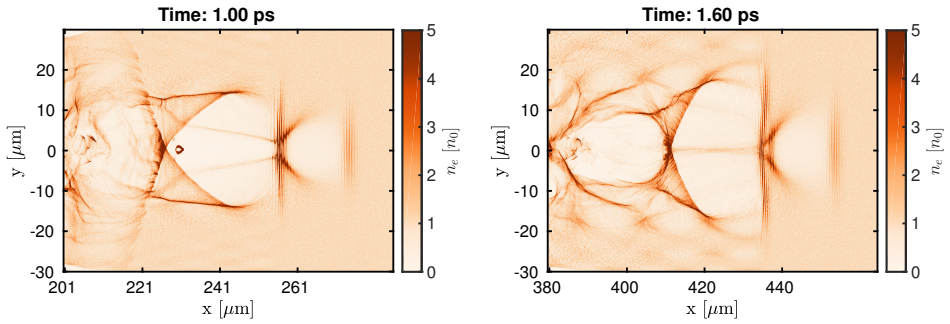


Figure 6: *Disruption of the trapped electron bunch by the electron stream caused by the contact of the rear part of the first bubble and the drive pulse.*

the drive pulse. Such phenomenon is displayed in Fig. 6, time delay was 72.5 fs.

Presented scheme is very sensitive to time delay between pulses. Sustainable acceleration process is achieved when $1.75 < c\tau/w_0 < 2.25$. Injection pulse intensity must be sufficiently high to generate own wake, but too strong injection pulse may destroy wakefield driven by drive pulse, i.e. $a_{0,IP} > 1.8$ and $(a_{0,IP}/a_{0,DP})^2 < 0.6$. In conclusion, we believe that our scheme represents reasonable alternative to currently considered schemes of optical injection thanks to its main advantage of simplicity.

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