Electron acceleration in perpendicularly crossed laser beams with following injection in the laser wakefield accelerator

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Introduction

Electrons are accelerated by the plasma wave dragged by a short, intense laser pulse propagating in plasma [1]. The advantage of plasmas is in their ability to sustain an accelerating gradient much larger than in a conventional radiofrequency accelerator. Currently, the most efficient mechanism to accelerate electrons in a plasma by a laser pulse is the cavitated wakefield regime (bubble regime), i.e. electron acceleration in an ion cavity propagating behind the laser pulse in plasmas. Electrons can be trapped at the back of the ion cavity (the bubble) and they form a bunch which is accelerated by the high electric field of the plasma wave (the space-charge force). The electron bunch can be either formed from plasma by the self-injection, or by other mechanisms, e.g. by optical injection [1, 2, 3] during a collision with another additional (injection) laser pulse. In this proceeding, electron acceleration in a main laser beam (MB) colliding in plasma with an additional laser beam (ALB) which propagates perpendicularly to the MB [2] is explored by numerical modelling. In contrast to the cases of counter-propagating beams and other schemes with perpendicularly crossed beams [2], the scheme where low intensity ALB is polarized perpendicularly to the MB polarization is proposed. MB intensity in terms of normalized vector potential $a_{0,MB}$ may be even greater than 2 in this configuration opposed to standard self-injection avoiding schemes. All the numerical simulations were performed by EPOCH 2D PIC code [4].

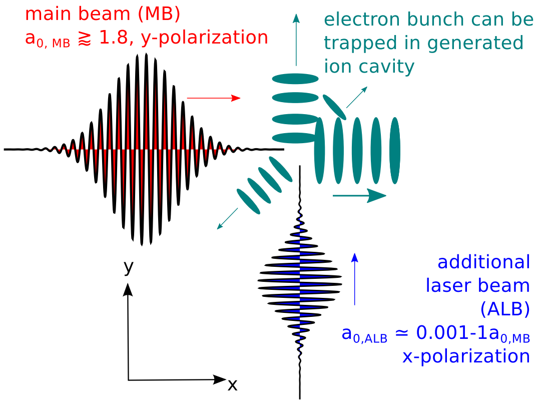

Figure 1: *Scheme of proposed configuration.*

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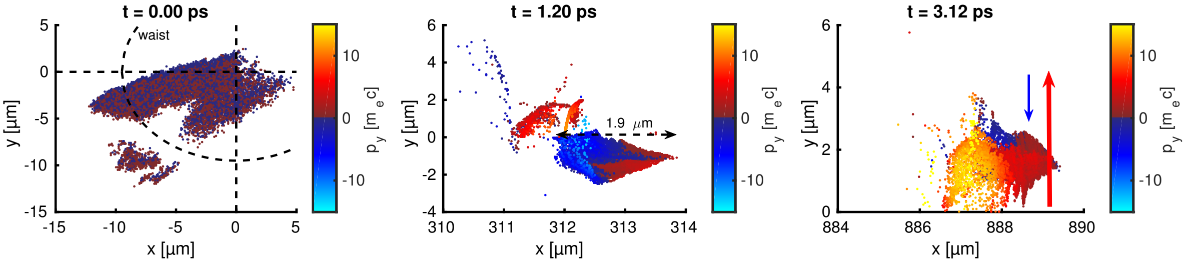
Presented injection scheme MB comes from the left, ALB from bottom, foci in [0,0].



Injection by counter-propagating beams MB from the left, ALB from the right, foci in [0,0].

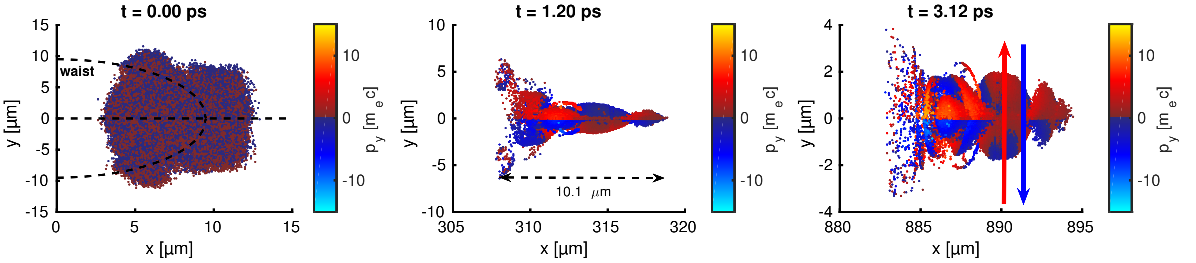


Figure 2: *Positions of trapped electrons in time. Colours represents the transverse momentum.*

Electron heating in crossed beams and following injection

A typical case of the bubble regime achievable with standard ∼ 100 TW laser systems was chosen for a demonstration of the injection mechanism: the plasma density $n_e = 5\times10^{18}$ cm^{-3}, the laser wavelength 0.8 µm, waist size $w_0 = 9.5$ µm, a pulse duration of 25 fs, and the MB intensity $a_{0,MB} = 4$ ($I_{MB} = 3.42\times10^{19}$ W/cm^2). The presence of the ALB enhances the electron heating in the crossing region of the beams [5]. It perturbs electron motion on the eight-like trajectory in its phase space. Single particle simulations of the electron motion in the presence of fields of both laser beams indicate that a part of the electrons from the crossing region gains energy and is thrown off the crossing region by the ponderomotive force, mainly in the direction of the MB propagation. Simultaneously, a wake wave is arising behind the main pulse and expelled electrons are carried away in this wave, trapped and further accelerated. By particle tracing, the initial positions of electrons in the bunch were determined, cf. Figure 2 ($I_{ALB} = 0.01 I_{MB}$).

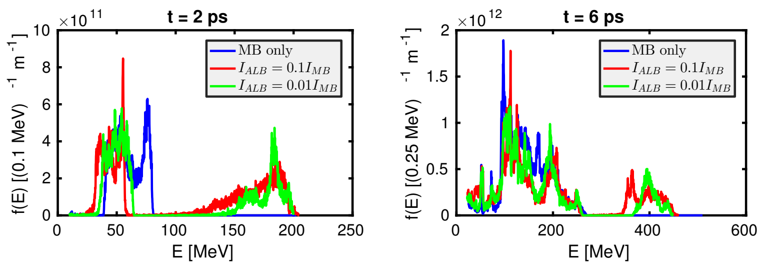


Figure 3: *As the spectrum is divided into two parts, low energy part can be easily filtered and thus* ***narrow spectrum*** *obtained.*
t =2 ps: $\overline{E_{el}} = 184$ MeV, $\sigma_{E_{el}} = 4$ MeV
t =6 ps: $\overline{E_{el}} = 394$ MeV, $\sigma_{E_{el}} = 10$ MeV

Figure 4 shows the plasma density profile in the moving bubble at several simulation times for the case of zero ALB intensity (upper row), and for the proposed configuration (bottom row). The bunch injected by the ALB is denoted

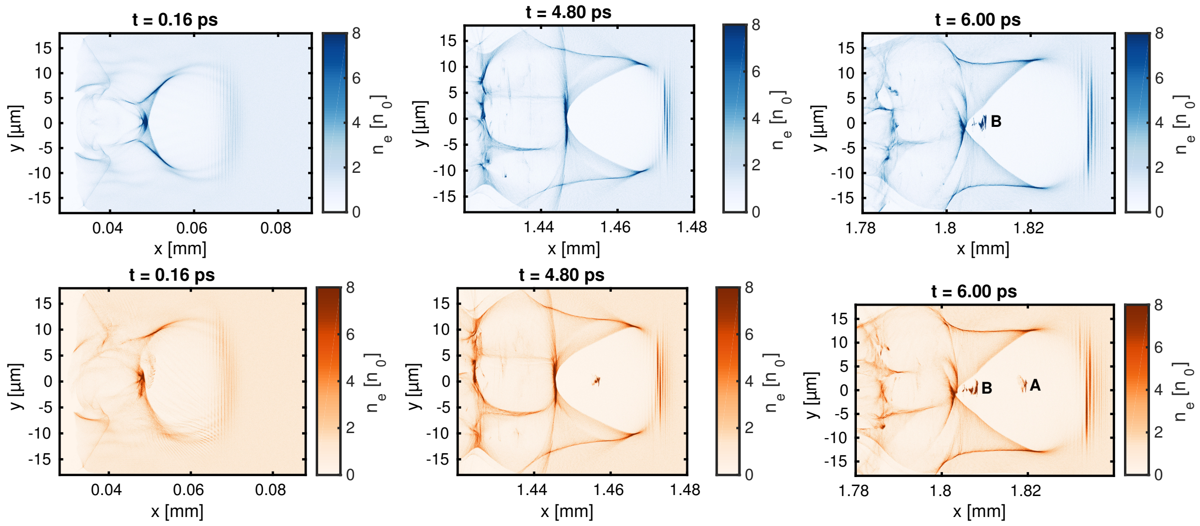


Figure 4: *Evolution of the electron density for the case with the main beam only (blue) and the case when $I_{ALB} = 0.01 I_{MB}$ (orange). **A** - electron bunch injected by presented injection scheme. **B** - self-injected electron bunch. Injection pulse does not disturb bubble dynamics and self-injection when it is very weak in comparison with main beam.*

by A. There is also a bunch, denoted by B, arising by the self-injection at the simulation time about 5 ps. Electrons in this second bunch at 6 ps gain much less energy than the optically injected bunch.

Figure 3 shows the energy spectra of accelerated electrons. For crossing beams with the perpendicular polarization, the mean value of electron energy in the injected bunch A is about 400 MeV at 6 ps. The energy spread is lower than in the case of the parallel polarization or when the bunch is injected by a counter-propagating pulse for the same parameters of laser pulses.

Betatron radiation of accelerated bunch

Since the trapped electron bunches observed in the all the simulations mentioned above exhibit strong transverse oscillations in addition to their motion in the direction of the MB propagation, they can be used for the generation of short X-ray pulses called betatron radiation [6]. In Figure 5, the radiation spectrograms are presented for the three cases (i) the bunch injected by transverse ALB with perpendicular polarization, (ii) the case of the parallel polarization and (iii) the case of the bunch injected by a counter-propagating beam.

The time interval of the radiation pulse is the shortest for the proposed perpendicular polarisation configuration. Whereas the case of the parallel polarization exhibits a longer X-ray pulse, the largest time interval is observed by the case of the counter-propagating beam injection.

Discussion and Conclusion

Within this study, two set of parameters were tested: (a) ALB intensity in range of (0.001–1)I_{MB} and (b) the time of the ALB arrival occurring within ± 10 fs. The simulations show that the

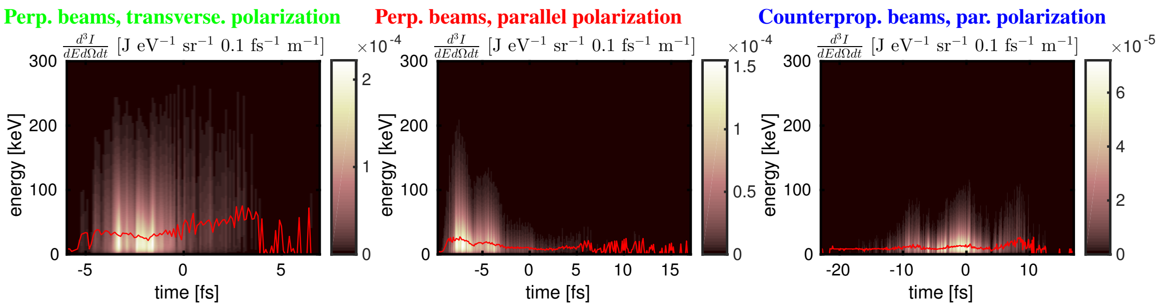


Figure 5: *Betatron radiation spectrograms and time evolution of critical energy (red solid).*

maximum energy peak E_{peak} of produced electron bunches is almost independent of the ALB arrival. However, the maximum charge is generated when the low intensity ALB arrives "in time", i.e. when both beam centres overlap. Moreover, the simulations reveal that the ALB should be focused to the similar size as MB. The increase in the ratio I_{ALB}/I_{MB} then results in a larger energy spread, the decrease in maximum energy and a small enhancement of the bunch charge.

In the presented contribution, the configuration of the optimum injection by a perpendicularly propagating and transverse polarised low intensity laser beam, which does not significantly disturb a bubble dynamics, was suggested. Compared to earlier proposed schemes, perpendicular propagation and parallel polarisation and counter-propagating 2-pulse scheme, the beams in the scheme presented here provide a higher bunch energy, the lower energy spread, and the injected charge is of the same order of magnitude.

As the simulation show, X-ray range betatron radiation is produced due to transverse electron oscillations in the ion cavity. All numerical simulations taking into account generated bunch properties indicate that the X-ray pulse has appropriate features, i.e. it is shorter and it has a higher critical energy.

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