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## Quasi-monoenergetic electron beams produced by colliding cross-polarized laser pulses in underdense plasmas

C Rechatin<sup>1</sup>, J Faure<sup>1</sup>, A Lifschitz<sup>1,2</sup>, X Davoine<sup>3</sup>, E Lefebvre<sup>3</sup> and V Malka<sup>1,4</sup>

<sup>1</sup> Laboratoire d'Optique Appliquée, ENSTA, CNRS, Ecole Polytechnique, UMR 7639, 91761 Palaiseau, France

<sup>2</sup> Laboratoire de Physique des Gaz et des Plasmas, CNRS, UMR 8578, Université Paris XI, Bâtiment 210, 91405 Orsay cedex, France

<sup>3</sup> Département de Physique Théorique et Appliquée, CEA, DAM Ile-de-France, BP 12, 91680 Bruyères-le-Châtel, France

<sup>4</sup> Author to whom any correspondence should be addressed.

E-mail: [victor.malka@ensta.fr](mailto:victor.malka@ensta.fr)

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**Abstract.** The interaction of two laser pulses in an underdense plasma has been proven to be able to inject electrons into plasma waves, thus providing a stable and tunable source of electrons. Whereas previous works focused on the 'beatwave' injection scheme in which two lasers with the same polarization collide in a plasma, this present paper studies the effect of polarization and more specifically the interaction of two colliding cross-polarized laser pulses. It is shown both theoretically and experimentally that electrons can also be preaccelerated and injected by the stochastic heating occurring at the collision of two cross-polarized lasers and thus, a new regime of optical injection is demonstrated. It is found that injection with cross-polarized lasers occurs at higher laser intensities.

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### 1. Introduction

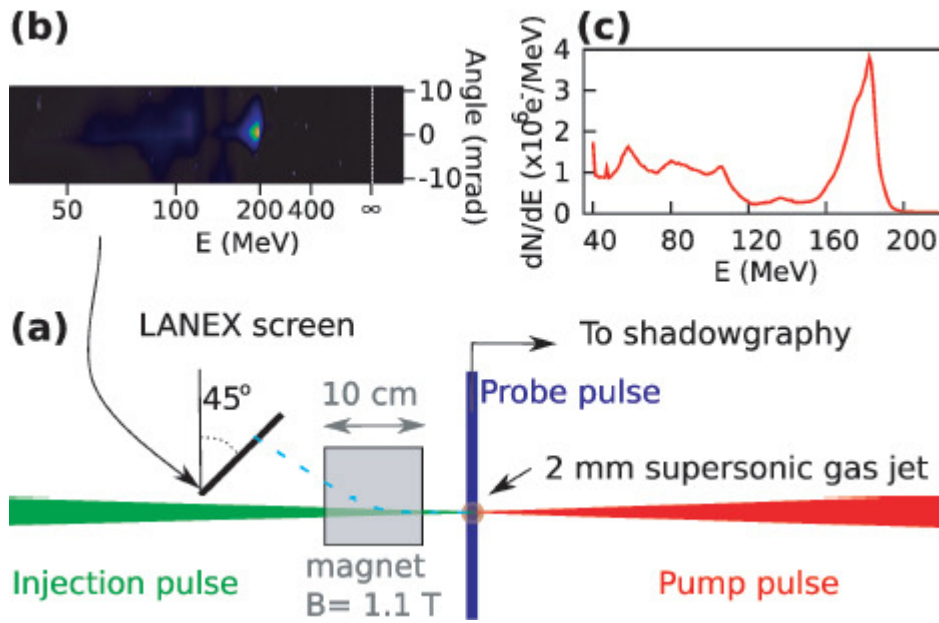
Plasma-based accelerators can sustain high electric fields in excess of  $100 \text{ GV m}^{-1}$ , which is approximately 1000 times beyond what can be achieved in conventional accelerators. In the plasma medium, an intense laser pulse can drive a longitudinal wave, called a wakefield, travelling with a phase velocity  $v_p = v_g$ , where  $v_g$  is the group velocity of the laser, and can be close to the speed of light  $c$ . This high phase velocity enables ultra relativistic acceleration [1], but also requires that the initial speed of the particles is high enough to allow trapping in the plasma wave. Whereas in a linear

regime, an electron with no initial velocity is not trapped, in a more nonlinear regime, transverse wave breaking effects [2, 3] can result in the self-trapping of electrons in the so-called 'bubble regime' [4]. In this case, the injection of electrons occurs in a short space-time volume and leads to the production of narrow energy spread electron beams as observed in [5]–[7]. Nevertheless, in this scheme, self-injection and acceleration depend on the precise evolution of the laser pulse. Therefore, fine control over the output electron beam is hard to achieve. The precise control of electron injection can be achieved by an all-optical external injection scheme. This idea, first proposed by Umstadter *et al* [8], relies on an additional laser pulse for injecting electrons. In [8], the ponderomotive force of a second laser pulse ensures the injection of electrons in the wakefield, making this mechanism insensitive to laser polarization. An alternative scheme with three laser pulses was then proposed by Esarey *et al* [9, 10]. In this so-called beatwave scheme, two counterpropagating lasers with the same polarization are used to inject electrons in the wakefield created by a third more intense laser pulse with crossed polarization. The beatwave potential created at the collision of the pulses is indeed an efficient preacceleration stage for the electrons. In its simplest form, this scheme uses only two lasers, the pump pulse drives the wakefield and collides with the injection pulse [11, 12]. Previous publications [13, 14] have shown experimentally that this last injection scheme with only two linearly polarized lasers allows a fine control over the injection and therefore brings tremendous flexibility to laser–plasma accelerators. In particular, it makes it possible to tune the energy of the electron beam in a stable way.

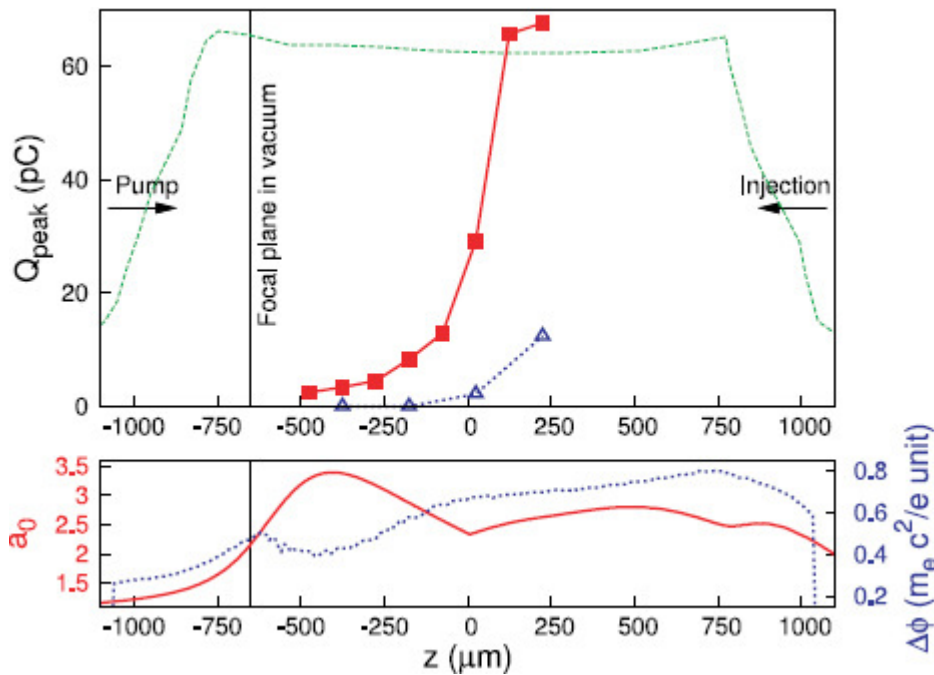
The slow ponderomotive beatwave potential  $\phi_b$  is proportional to  $\langle \mathbf{a}_0 \cdot \mathbf{a}_1 \rangle$  where  $\mathbf{a}_0$  and  $\mathbf{a}_1$  are respectively, the normalized vector potentials of the pump and injection pulses. For the circular polarization case the motion of electrons is integrable and if both lasers have the same frequency  $\omega_0$ , the maximum energy gain is  $2\sqrt{a_0 a_1}$ . This preacceleration then allows the electrons to be trapped in the main plasma wave and to be further accelerated. The ponderomotive beatwave acceleration can be conversely seen as a heating process. The motion of electrons in two parallel polarized laser fields is not analytically tractable since there is not only the slow ponderomotive beatwave but also a fast varying component at  $2\omega_0$ . For a colliding (head-on) geometry and above a certain threshold, the motion becomes stochastic [15]–[17]. In this case, the collision of the laser pulses leads to an even more efficient heating of the electrons. In the case of cross-polarized lasers  $\mathbf{a}_0 \cdot \mathbf{a}_1 = 0$  and there is no ponderomotive beatwave, thus no beatwave injection. However, we will show experimental and numerical evidence that, under some conditions, injection of high quality electron beams is still possible with cross-polarized laser pulses and that their features are comparable with the beatwave-injected beams.

## 2. Experimental results

The experiment was performed on the 'Salle Jaune' laser system at LOA. It delivers 720 mJ (pump pulse) and 250 mJ (injection pulse) at  $\lambda_0 = 0.8 \mu\text{m}$  on target with full width half maximum (FWHM) duration 30 fs. The setup is the same as the one used in [13, 14]. The pump pulse is focused by a 1 m focal length spherical mirror to an intensity of  $I_0 = 3.4 \times 10^{18} \text{ W cm}^{-2}$  thus giving a normalized strength parameter  $a_0 = 1.3$ . The injection pulse is focused by a 1 m focal length off axis parabola to an intensity of  $I_1 = 4 \times 10^{17} \text{ W cm}^{-2}$ , corresponding to  $a_1 = 0.4$ . The two collinear and counter-propagating lasers are focused on the edge of a 2 mm supersonic helium gas jet (figure 1(a)). Its density profile, independently measured by interferometry, is represented by the green dotted line on the top frame of figure 2. The profile has sharp edges and an electronic density plateau at  $n_e = 7.5 \times 10^{18} \text{ cm}^{-3}$ . A third low-intensity laser pulse was used for synchronizing and overlapping the two main pulses by means of side-view imaging and shadowgraphy. The accelerated electrons are deviated by a permanent magnet with  $B_{\text{eff}} = 1.1 \text{ T}$  over 10 cm. The light emitted when they hit the LANEX screen is then recorded (figure 1(b)). After proper deconvolution, it is then possible to retrieve the electron spectrum between 40 and 400 MeV (figure 1(c)). This spectrometer also gives access to the charge and divergence of the electron beam [18].



**Figure 1.** Overview of the experimental setup. (a) Diagram of the experiment. (b) A typical raw image obtained on the LANEX screen of the electron spectrometer. (c) Corresponding deconvoluted spectrum.



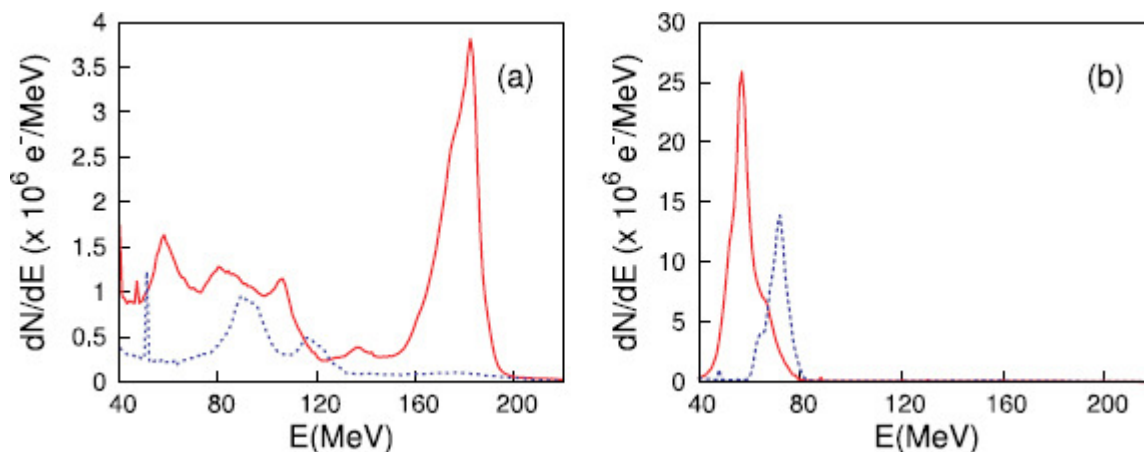
**Figure 2.** Top: experimental evolution of charge in the monoenergetic peak with collision position, for parallel (red solid squares line) and crossed (blue dotted triangles line) polarizations. The measured electron density profile is also represented (green slash dotted line). Bottom: simulated evolution along the gas jet of  $a_0$  (red solid line) and  $\Delta\phi$ , average depth of the plasma wave potential in the accelerating and focusing regions (blue dotted line).

Finally, a half-wave plate makes it possible to rotate the polarization of the pump pulse during the experiment, thus allowing to study and compare the parallel and crossed polarizations cases. The collision point of the two lasers could be tuned simply by changing the time delay between the two pulses. This is an important feature of the experiment since

nonlinear evolution of the laser in the plasma—due to self-focusing [19, 20] and self-compression [21, 22]—changes the laser intensity along the position in the gas jet. We used the particle code WAKE [23] to simulate the nonlinear evolution of the laser pulse and the corresponding wakefield in cylindrical geometry. The results of this simulation are shown in the bottom frame of figure 2: the red solid line represents the evolution of  $a_0$  and the blue dotted line represents the average depth of the plasma wave potential in the accelerating and focusing regions  $\Delta\phi$ . The average is made over a diameter of 18  $\mu\text{m}$ , i.e. the focal spot FWHM to take into account the transverse profile of the wakefield. This parameter characterizes the ability of the wakefield to trap preaccelerated electrons since it is directly related to the minimum momentum that an electron needs to be trapped, in normalized units:  $u_{z,\text{min}} = \beta_p \gamma_p (1 + \gamma_p \Delta\phi) - \gamma_p \sqrt{(1 + \gamma_p \Delta\phi)^2 - 1}$ , where  $u_z = p_z/m_e c$ ,  $\beta_p = v_p/c$  and  $\gamma_p = (1 - \beta_p^2)^{-1/2}$ . The nonlinear evolution of the pulse allows us to indirectly obtain data over a broad range of laser amplitudes  $a_0$  at the collision of the two lasers and thus to change the heating conditions. Simultaneously, the wakefield becomes more suitable for trapping as the pump pulse self-compresses and distorts spatially.

The experimental results are summarized in the top frame of figure 2. The graph represents the charge of the monoenergetic component of the spectrum for different collision positions for the cases of parallel and crossed polarizations. The figure shows that in the case of parallel polarizations, injection of a monoenergetic beam starts for  $z_{\text{inj}} > -500 \mu\text{m}$ . This corresponds to positions where the laser pulse has self-focused (figure 2, bottom). From that point, the charge increases as injection occurs further inside the gas jet. The increase of the charge can be explained by the evolution of the wakefield: as the laser propagates in the gas jet,  $\Delta\phi$  increases, making the wakefield more suitable for trapping a large amount of electrons (see also [24] for more detailed simulations). For the case of crossed polarizations, the behavior is different: there is a threshold behavior and monoenergetic electron beams are injected only for  $z_{\text{inj}} > 25 \mu\text{m}$ . The charge also increases with  $z$ , as in the parallel polarizations case, but it is lower by a factor of 5–6.

Figure 3 shows typical electron spectra obtained with parallel (red solid line) and crossed (blue dotted line) polarizations, at two injection positions ((a):  $z_{\text{inj}} = -175 \mu\text{m}$  and (b):  $z_{\text{inj}} = 225 \mu\text{m}$ ). At  $z_{\text{inj}} = -175 \mu\text{m}$ , we have observed a stable monoenergetic beam at 170 MeV with low charge ( $\approx 10 \text{ pC}$ ) in the parallel polarizations case. When the polarizations are crossed, the high energy monoenergetic component of the spectrum vanishes and a broad component at lower energy remains. This case corresponds to the results already published in [13, 14].



**Figure 3.** Experimental spectra for  $z_{\text{coll}} = -175 \mu\text{m}$  (a),  $z_{\text{coll}} = 225 \mu\text{m}$  (b): red solid line: parallel polarizations, blue dotted line: crossed polarizations.

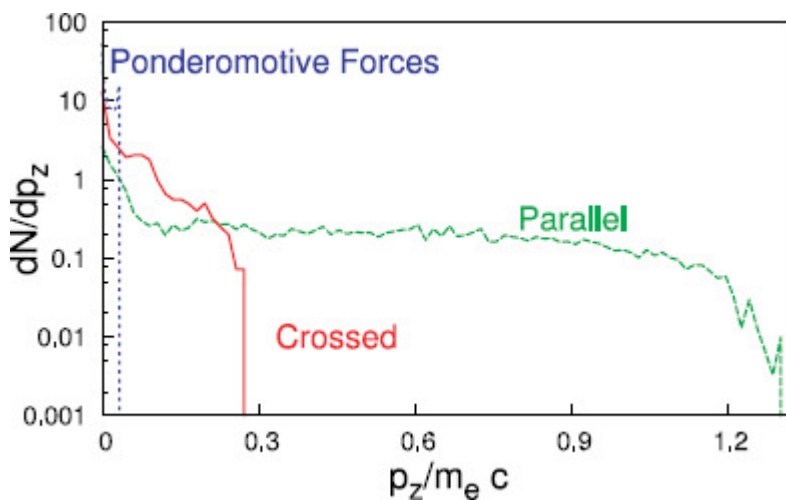
When the collision takes place further inside the gas jet, e.g. at  $z_{\text{inj}} = 225 \mu\text{m}$ , trapping becomes easier. Thus, for the parallel polarizations case, a 50 MeV beam with 68 pC is injected. The decrease of energy from position (a) (170 MeV) to (b) (50 MeV) can easily be explained by the decrease of the remaining acceleration length after the injection [13]. In the crossed polarizations case, the striking result is the production of a stable quasi-monoenergetic electron beam (see figure 3(b)). The beam is stable in energy  $E = 72 \pm 6 \text{ MeV}$ , in energy spread  $\delta E/E = 14 \pm 2\%$  (FWHM), divergence  $5 \pm 2 \text{ mrad}$  and charge  $Q = 11 \pm 3 \text{ pC}$ . The injection of such a beam cannot be explained by the beatwave scheme since the residual parallel polarization component due to the possible half-wave plate misalignment is well below the threshold for

beatwave injection. Other heating mechanisms that are not polarization dependent such as ponderomotive heating by the colliding envelopes of the lasers [11], phase-kick injection where a colliding laser stimulates the wavebreaking of a nonlinear wake [25], or even wake collision [26, 27] could be possible explanations. Here, we will show that the features of this injection of electrons in a cross-polarized scheme can be explained by the concurrence of two physical phenomena: the heating of electrons during the laser collision and the plasma wake inhibition.

### 3. Theory and simulations

First, we will show that heating of electrons occurs even with cross-polarized laser pulses. Here, we use a simple one-dimensional (1D) model in order to obtain an estimate of the stochastic heating for two lasers with arbitrary linear polarizations: we neglect collective plasma effects and follow test electrons in the laser fields. We use Gaussian laser pulses at 800 nm with duration  $\tau = 30$  fs at FWHM with normalized strength  $a_0 = 2$  for the pump pulse and  $a_1 = 0.4$  for the injection pulse, which are close to the parameters of the experiment (after some self-focusing has occurred). Electrons are initially randomly distributed in the interval  $z \in [-2\tau c, 2\tau c]$ ,  $z = 0$  corresponding to the position where the two pulse maxima collide. Outside this region, electrons interact with the laser pulses successively and we have checked that they are not significantly heated.

Figure 4 shows the electron spectra after the collision: the green dashed line represents the heating when the polarizations of the two pulses are parallel, the red solid line corresponds to the crossed polarizations case and the blue dotted line corresponds to the case where electrons experience only the ponderomotive forces  $\propto (\langle \mathbf{a}_0^2 \rangle + \langle \mathbf{a}_1^2 \rangle)$ . The latter case, where high frequencies are averaged, corresponds to the reference case for which there is no stochastic or beatwave heating.



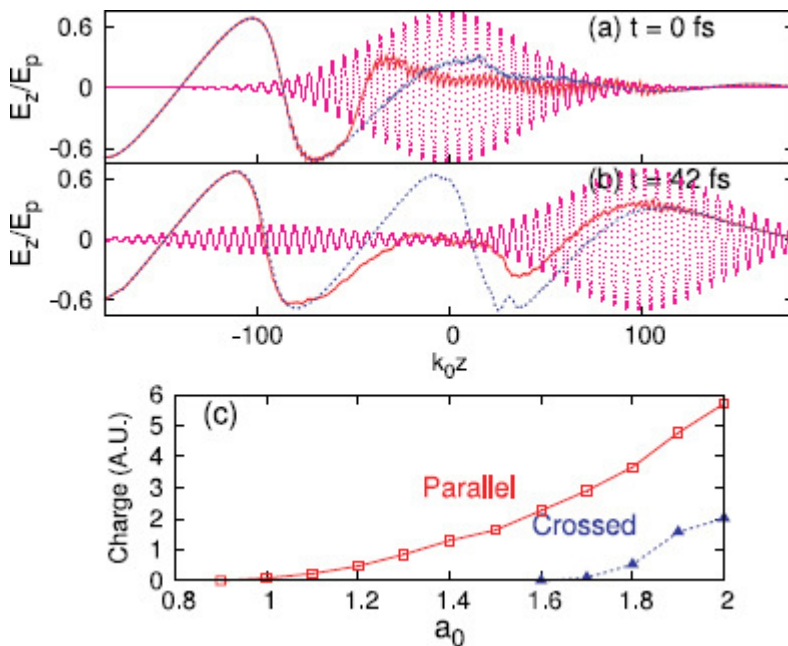
**Figure 4.** Normalized relativistic longitudinal momentum ( $p_z/m_e c$ ) distribution after the interaction of two Gaussian pulses with duration  $\tau = 30$  fs,  $a_0 = 2$  and  $a_1 = 0.4$ . The figure shows how electrons are heated for different polarization cases. Green dashed line: parallel polarizations, red solid line: crossed polarizations, blue dotted line: ponderomotive forces only.

The first remarkable feature is that electrons are more heated by two cross-polarized pulses (red solid line) than by the sum of the two ponderomotive forces (blue dotted line). This can be explained by the fact that for high laser intensities, the electron motion becomes relativistic ( $a_0 > 1$ ) which introduces a longitudinal component  $p_z$  through the  $\mathbf{v} \times \mathbf{B}$  force. Thus, the two perpendicular laser fields couple through the relativistic longitudinal motion of electrons. This relativistic coupling makes it possible to heat electrons stochastically [17].

This simple model also shows that the heating is much more efficient when the polarizations of the two pulses are parallel (dashed line), the maximal momentum obtained being four to five times higher than in the crossed polarizations case. This is why the injection is strongly correlated with the polarization of the two pulses as we have seen in the experimental results.

If the electron injection were only dependent on the preacceleration spectrum of the electrons, the crossed polarizations case should always result in a decrease of the trapped charge by several orders of magnitude compared to the parallel polarizations case. This corresponds to the discussion on polarization influence on the trapped charge made in [11]. However, in [11] the electromagnetic fields do not depend self-consistently on the motion of electrons, and therefore the model does not take into account an important physical phenomenon: the wakefield inhibition [28] at the collision of the laser pulses. To exhibit the influence of this phenomenon, we have performed self-consistent 1D particle-in-cell (PIC) simulations. We have used the code CALDER [29] with the same laser parameters as above and an electronic density of  $n_e = 7 \times 10^{18} \text{ cm}^{-3}$ . The simulation box consists of 13 600 cells measuring each  $0.1/k_0 \approx 0.013 \mu\text{m}$  and containing 20 pseudo-particles each. The time step of the computation lasts  $0.05/(ck_0) = 2.1 \times 10^{-2} \text{ fs}$ .

Figures 5(a) and (b) show snapshots of the longitudinal electric field, during and after collision. The time  $t = 0$  corresponds to the collision of the laser pulse maxima. The red solid line corresponds to the case of parallel polarizations, whereas the blue dotted line corresponds to the case of crossed polarizations. The laser fields are also represented by the thin dotted line.



**Figure 5.** (a) and (b): 1D PIC simulation snapshots of the longitudinal electric field during the collision at different times for  $a_0 = 2$ . Red solid line: parallel polarizations. Blue dotted line: crossed polarizations. Thin dotted line: laser fields. (c) Trapped charge versus  $a_0$  (all other parameters being the same) in 1D PIC simulations. Red solid square line: parallel polarizations. Blue dotted triangle line: crossed polarizations.

When the pulses have the same polarization, electrons are trapped spatially in the beatwave and cannot sustain the collective plasma oscillation. Therefore the plasma wave is strongly distorted during and after the collision (see figures 5(a) and (b)). It has been shown in [28] that this process has a dramatic influence on the injected charge: in an inhibited plasma wave, it is harder to trap electrons and the charge is reduced by approximately one order of magnitude compared with trapping in an unaffected plasma wave.

When the polarizations are crossed, the motion of electrons is only perturbatively disturbed compared with the motion under only one laser, and the plasma wave is almost unaffected during the collision, see figures 5(a) and (b). This tends to facilitate trapping.

In order to scan different injection conditions we have performed a numerical scan on  $a_0$ , all other parameters of the 1D PIC simulations being the same. Figure 5(c) represents the trapped charge: it shows that the threshold for injection is higher when polarizations are crossed. This is consistent with the fact that electron heating is less efficient with cross-

polarized lasers. It also shows that above this threshold, there is only approximately three times less charge injected with cross-polarized pulses than in the parallel polarizations case: the charge difference due to the heating efficiency is balanced by the charge reduction due to wake inhibition occurring only in the parallel polarizations case.

In these simulations, we have also checked that all trapped electrons witness the overlapping of the two lasers, i.e. electrons located outside the collision region are not trapped. This rules out the wake-wake and wake-laser collisions [25]–[27] as main injection processes. This has also been confirmed in 2D PIC simulations.

Simulations can also give a partial understanding of the spectra experimentally observed with the cross-polarized pulses. In figure 3(a), in the crossed polarizations case, the spectrum exhibits a broad component at lower energy, even though the threshold for the crossed polarizations injection is not reached. This could be explained by a staged acceleration mechanism: the electrons are first heated under the collision of the two lasers but as they have not gained enough momentum to be trapped, they slip back in the following buckets of the wakefield. They are then further accelerated in the collision of the two wakefields until they become trapped in the accelerating structure. In that case, injection is not localized as it occurs in multiple buckets, and it leads to the observed broad spectrum at low energy. On the other hand, when operating above the threshold, the volume where the electrons reach the required energy for trapping is very localized. Therefore injection results in a narrow energy distribution beam accelerated in the first plasma wave bucket. Due to the higher threshold, this injection volume is even smaller in the crossed polarizations case than in the parallel polarizations case. Therefore, for a given collision position, injection with crossed polarizations results in a lower charge and a smaller energy spread electron beam (see figure 3(b)). Finally, the energy difference (10 MeV) observed between the two cases (see figure 3(b)) could be explained by beamloading. The wakefield is less distorted by the lower charge injected in the crossed polarizations case and in consequence, electrons are accelerated to higher energies.

#### 4. Conclusion

We have demonstrated both experimentally and theoretically a new regime of optical injection using the stochastic heating at the collision of two cross-polarized laser beams. This scheme can provide stable monoenergetic electron beams. The injection threshold for crossed polarizations is higher and in our experiment, we found that the beams produced in this case had lower charge and smaller energy spread than those injected by the beatwave scheme. Injection with crossed polarizations is also safer for the laser system when operating in a collinear colliding geometry: two polarizers are sufficient to protect the system from laser feedback. This would be particularly interesting for experiments using waveguides [30], for which the collinearity of the laser beams is mandatory.




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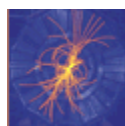
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