

STUDY OF SELF-INJECTION OF AN ELECTRON BEAM IN A LASER-DRIVEN PLASMA CAVITY

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Abstract

Over the last few years, remarkable advances in laser wakefield acceleration of electrons have been achieved, including quasi-monoenergetic beams and GeV energy in a few centimeters. However, it is necessary to achieve good beam quality (large current, low energy-spread and low emittance) for applications such as free-electron lasers. We study self-injection in two regimes of the laser-plasma interaction: the moderate intensity, self-guiding regime, and the low intensity, near-injection-threshold regime, both in a homogeneous plasma that completely fills the simulation volume. We find good beam quality with injection of on-axis electrons, especially at lower intensity. We also study the case when the laser has to travel through vacuum before entering the plasma. We find that injection here is completely different, from off-axis electrons, and the beam quality is poorer.

INTRODUCTION

Acceleration of charged particles [1,2] by means of laser-plasma interaction has become an interesting area of research. In laser wakefield acceleration (LWFA), a short intense laser pulse interacting with plasma, generates a wakefield behind the laser pulse. The phase velocity of this wakefield is nearly equal to the group velocity of the laser pulse. A particle injected in this wakefield can gain energy up to several GeV. It has been observed in three dimensional simulation that for higher intensity ($a_0 > 2$) instead of a periodic plasma wave, a cavitating region (bubble) either nearly free of (for high intensity, $a_0 > 8$) [3], or with very few (for low intensity, $a_0 = 2-4$) [4,5,6], plasma electrons, is created. Background plasma electrons can be (self-)injected into the cavity and accelerated to high energy.

THREE-DIMENSIONAL SIMULATIONS

Three-dimensional simulations were performed using the code VORPAL [7]. We considered a linearly polarized laser pulse, of wavelength $0.8 \mu\text{m}$, having Gaussian spatial and temporal profiles, propagating in a low-density homogeneous plasma of wavelength $22 \mu\text{m}$ (density $2 \times 10^{18} \text{cm}^{-3}$). The laser pulse propagated in the x -direction and was polarized in the y -direction. The simulation volume was completely filled with plasma, and at the start of the simulation the pulse was just

entering the plasma. The laser wavelength (λ) was resolved over twenty cells in the propagation direction and the resolution in both the transverse directions was equal to the laser wavelength. There were two particles per cell, and the grid extent was $(80, 40, 40) \mu\text{m}$ in (x, y, z) . The time step (0.13fs) was chosen according to the Courant condition.

Low Intensity

These simulations were performed with a laser intensity of $a_0=2.2$, pulse-length of 10fs , and spot-size of $20 \mu\text{m}$. We found cavitation ('bubble' formation) and self-injection, and subsequent acceleration of electrons to 550MeV over 6.8mm . These electrons formed a well-defined beam, with an rms energy-spread of 1% , normalized rms emittance of $10\pi \text{mm-mrad}$, and charge of 20pC (the latter corresponding to around $5,000$ simulation particles). These high-energy particles were tagged in the simulation, and using these tags, we traced back the locations of these particles at time $t=0$; i.e. we looked at where these particles originated. We found that, without exception, all the $5,000$ particles originated from near the origin, i.e. within $5 \mu\text{m}$ of the origin in x , and within $\pm 5 \mu\text{m}$ in y and z .

In order to better understand the actual injection process, i.e. how the plasma electrons behave as the laser makes its way through the plasma, we generated, at time-step zero, tags for electrons lying in the volume $0 < x < 80 \mu\text{m}$, $-8 < y < 8 \mu\text{m}$, $-8 < z < 8 \mu\text{m}$. To reduce somewhat the number of particles tracked, and hence the time taken for tracking, in x alone we chose only every 20^{th} particle. Since the resolution in x is $\lambda/20$, we get one particle every $0.8 \mu\text{m}$, and therefore total of 100 particles in x . In y and z , since the resolution is λ , we have taken every particle, and there are 10 particles in each dimension. The total number of particles to be tracked is $100 \times 20 \times 20 = 40,000$. Simulations were run without a moving window, for $2,000$ time-steps.

Figure 1 shows the initial positions (in x & y) of the tracked particles, with particles at different positions identified by different colours. Figure 2 then shows the positions of these particles after $2,000$ time-steps. It can be seen that only particles located near the origin within $5 \mu\text{m}$ of the origin in x , and within $\pm 5 \mu\text{m}$ in y and z , are injected and accelerated. Recall, from the discussion

above, that all the high-energy electrons are exclusively from this region. Looking at the intermediate steps we observed that these electrons are not expelled transversely; it is the electrons around them that are transversely expelled. Once they are expelled, a cavity is formed around the on-axis electrons, which then see a linear electric field and are accelerated straight forward.

case too, electrons that are injected not expelled significantly. However, unlike the low intensity case, some off-axis electrons are also injected. Also, here, because of the higher laser intensity, the expulsion is more. However, we did not find any evidence of electrons being expelled transversely, sliding down the sheath to the rear of the bubble, and then getting injected.

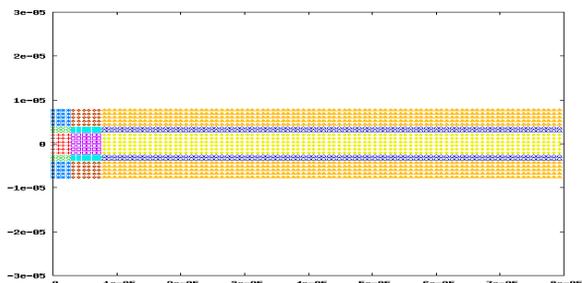


Figure 1: Initial distribution of electrons.

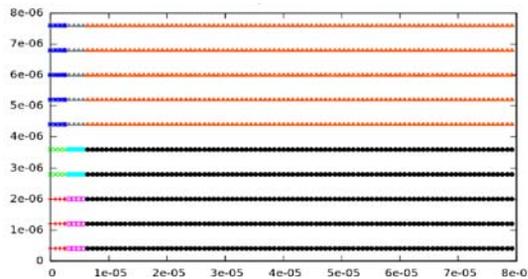


Figure 3: Initial distribution of electrons.

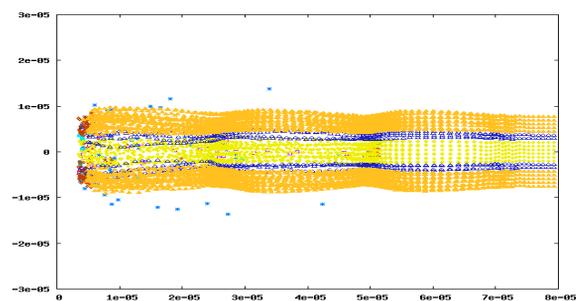


Figure 2: Distribution of electrons after 2,000 time steps.

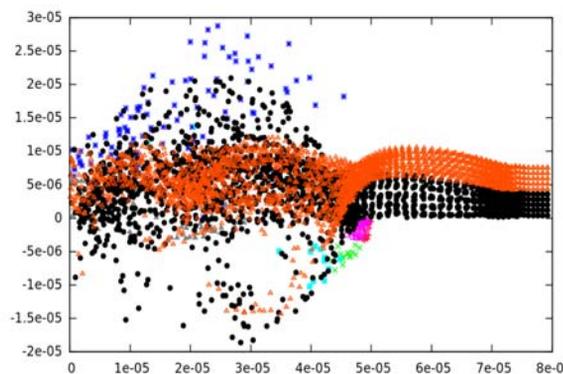


Figure 4: Distribution of electron after 2,000 time steps.

Moderate Intensity

Simulations were done at the same plasma wavelength of 22 μm , with a laser intensity $a_0=3.8$, pulse-length of 10 fs, and spot-size of 14 μm . In this case an accelerated beam was found of energy 660 MeV (after 6.8 mm), rms energy-spread 4.8%, rms normalized emittance of 36(y) & 33(z) π mm-mrad, and charge of 95 pC (corresponding to around 11,000 simulation particles). We tagged the electrons that reached this high energy, and used these tags to look at the initial positions of these particles. We found that out of these 11,000, nearly 10,000 are electrons which are located 0-10 μm in x and $\pm 7 \mu\text{m}$ in y and z. This gives us a clue that all injected and accelerated electrons lie near the origin, as in the low intensity case.

We then tracked electrons that started out between 0-80 micron in x, and 0- 8 μm in y and z; we ignored particles with negative y & z to save computational time, and assuming symmetry. In x we again considered every 20th particle. We ran this simulation for 2,000 steps without a moving window. Figures 3 and 4 show the distribution of electrons at the initial and the 2000th time-steps, with particles at different positions identified by different colours. Figure 4 shows clearly that the electrons at larger transverse distances form the sheath, while the electrons closer to the axis (pink in the figure) are self-injected. Note, from the discussion above, that these are precisely the electrons that are accelerated to high energy. In this

SIMULATION WITH VACUUM, DENSITY RAMP AND PLASMA

We also performed simulations in which the plasma did not completely fill the simulation volume. Rather, there was an initial segment, 6.5 μm in length, of vacuum, followed by a 6.5 μm segment in which the plasma density is ramped up, and then a homogenous plasma of density $5.2 \times 10^{18} \text{cm}^{-3}$. These simulations were *two-dimensional*, with a laser intensity $a_0=4.0$, FWHM pulse-length of 27 fs, and spot-size of 16 μm . The laser still enters the simulation box from the left, so that it propagates through vacuum and the density ramp before entering the homogeneous plasma. Note that the distance travelled by the laser before it hits the homogeneous plasma (13 μm) is much less than its Rayleigh range (1 mm), so we do not expect the laser spot-size to have changed much.

Compared to the results obtained when the plasma completely fills the simulation volume, in this case we find that injection starts after the laser has propagated a distance 0.44 mm. More interestingly, in the present case the injected electrons are not the on-axis electrons, but are

located off-axis, between 6-22 μm (in y). Figures 5 and 6 show the initial distribution of electrons, and the distribution after 1.58 mm, respectively, with particles at different positions identified by different colours. It can be seen clearly from Fig. 6 that the injected and accelerated electrons come from off the axis. We have confirmed that the results are the same even if there is no density ramp, and the laser only traverses vacuum before entering the plasma.

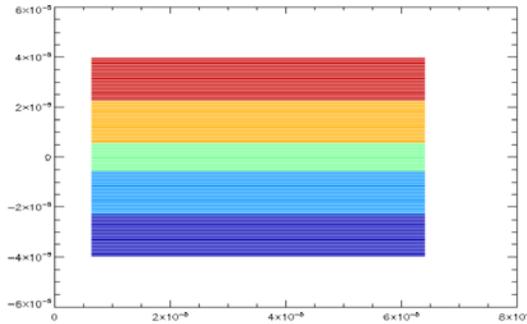


Figure 5: Initial distribution of electrons.

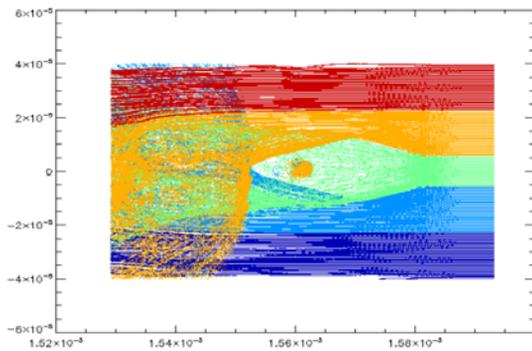


Figure 6: Distribution of electrons after 1.58 mm.

CONCLUSION

In summary, our simulations in low intensity regime show that electrons close to the origin are the only electrons that are accelerated to high energy. These electrons are not expelled transversely. Rather it is the electrons around them that are transversely expelled. Once they are expelled, a cavity is formed around the on-axis electrons, which then see a linear electric field and

are accelerated straight forward. Meanwhile the outer electrons fall back toward the centre to form the bubble, but by the time the bubble forms, the injected electrons have moved forward, and there is no further injection of electrons. In the moderate intensity case, the same mechanism largely holds. However, there is somewhat greater transverse expulsion of even the injected electrons, and this explains why the beam quality is better for the low-intensity case.

However, these results seem to depend whether or not the laser directly enters the homogeneous plasma. If the laser traverses vacuum (and a density ramp) first, then the injection mechanism changes drastically. None of the on-axis electrons are injected; all the injected and accelerated electrons come from off-axis, between 6-22 μm .

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