Inhibition of self-injection by ionisation injection

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Introduction

The field of plasma based accelerators is taking great strides towards producing applications where conventional radio frequency particle accelerators dominate. The laser-wakefield acceleration scheme, proposed by Tajima and Dawson [1], evolved from first laser based experiments producing thermal electrons [2] into accelerators producing high charge, quasi-monoenergetic, collimated relativistic electron beams [3]. These well collimated relativistic electron beams are produced when the pulse length τ of the high intensity laser pulse is of optimal length, namely $c\tau \approx \lambda_p$, where $\lambda_p = 2\pi c/\omega_p$ and $\omega_p = (n_e e^2/m\varepsilon_0)^{1/2}$ is the plasma frequency. The ponderomotive force of the laser sets up a relativistic plasma wave in its wake, which, if driven to very high amplitudes, breaks with some electrons becoming dephased from the plasma wave. This is called self-injection and all the first quasi-monoenergetic electron beams were obtained using this technique. Despite its simplicity the self-injection technique suffers due to the nonlinear nature of the process. Self-injected electron beams typically have large transverse momentum, yielding beams with unacceptably large emittances for many accelerator applications. Hence much of the ongoing research focuses on finding alternatives to self-injection to enable controllable injection into the wakefields. Some of these methods include ionization injection [4], colliding pulse injection [5] and density gradient injection [6]. All of these methods require the plasma accelerator to be in a regime where self-injection does not occur. However, apart from experimental simplicity, one of the great advantages of the highly nonlinear self-injection regime over the quasi-linear regime is the presence of emittance conserving linear focusing fields in the former [7]. Here, we report on the experimental observation of suppression of self-injection when an alternative injection technique is used, implying the injected charge in the bubble is inhibiting further injection via the self-injection mechanism.

Experimental setup

The experiment was performed using the Astra laser in Target Area 2 at the Central Laser Facility. The experimental setup is depicted in Figure 1. Pulses of 600 mJ energy with temporal full-width-half-maximum duration of 37 fs were focused using a *f*/18 parabolic mirror to a spot with waist of 19 μm. This yields a peak focused intensity of $2.7 \times 10^{18}\,\mathrm{Wcm^{-2}}$ or a peak normalized vector potential of $a_0 = 1.1$. For these laser parameters the empirical self-injection threshold [8] is calculated to be 9×10^{18} cm^{-3}.

The laser was focused 1 mm above a 3 mm diameter supersonic gas jet. The plasma density profile was characterized with transverse interferometry and consisted of a 2.0 mm plateau with 0.5 mm linear ramps on either side. The maximum plasma density investigated was 4×10^{19} cm^{-3} with either a jet of pure helium or helium with 5% CO_2 impurity.

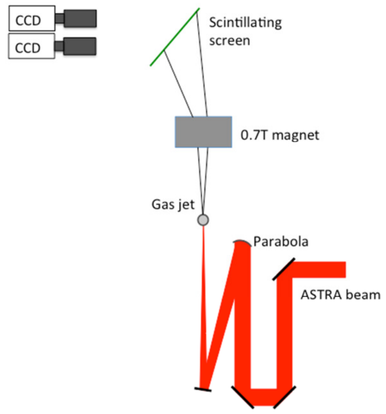

Figure 1: The schematic layout of the experiment.

The impurity species for ionisation injection was chosen to ensure that there existed electrons in energy levels that only became ionised near the peak of the laser pulse. Carbon dioxide was chosen as the outer 4 electrons of a carbon atom are fully ionised at an intensity $4.3 \times 10^{15}\,\mathrm{Wcm^{-2}}$, whereas the two inner shell electrons are only ionised once the laser intensity reaches $3.8 \times 10^{18}\,\mathrm{Wcm^{-2}}$ and $6.4 \times 10^{18}\,\mathrm{Wcm^{-2}}$. All outer shell electrons from oxygen are ionised at an intensity of $4 \times 10^{16}\,\mathrm{Wcm^{-2}}$ while the inner shell electrons are only ionised at $2.4 \times 10^{19}\,\mathrm{Wcm^{-2}}$. Hence the oxygen atoms contribute to the uniform density background but not to the ionisation injection.

The electron beams were diagnosed using an electron spectrometer comprising of a 70 mm long 0.7 T permanent dipole magnet and a scintillating screen (Lanex). The screen was imaged with two 14 bit CCD cameras with bandpass filters to avoid all other light except that from the scintillation screen.

Experimental results

Figure 2 depicts experimentally measured electron spectra. The geometrical factor due to imaging at 45 degrees to the scintillator surface has been corrected for using an affine transformation. The nonlinear dispersion due to the magnet spectrometer has also been accounted for. Panels (a)-(f) in Figure 2 were obtained using pure helium whereas spectra in panels (g)-(l) was measured using helium with 5% CO_2 impurity. The background plasma density is the same for electron spectra in the same column. The laser pulse length and energy were within their shot-to-shot variation for each of these shots.

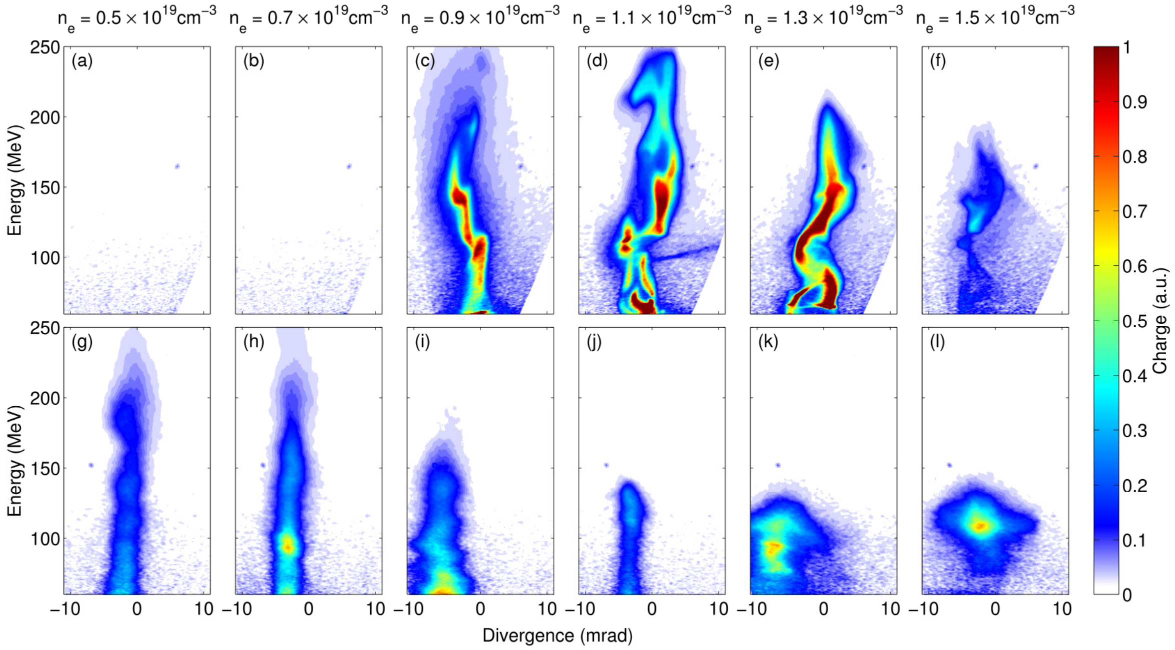

Figure 2: Measured electron spectra for pure helium (top row) and helium with carbon dioxide impurity (bottom row). The plasma density for each column is indicated above the top row.

The self-injection threshold is experimentally seen at $\sim 8.5 \times 10^{18}$ cm^{-3}, which agrees well with the calculation above. The beams measured with plasma densities above this threshold have large transverse momentum, which is uncorrelated with longitudinal momentum, resulting in messy and wiggly beams. These are common features of self-injected beams. The ionisation-injected beams are much more narrow, with a much smaller spread in transverse momentum. The distinctly different beam characteristics at the same plasma densities imply that for shots with ionisation impurities the self-injection process has been suppressed. This hypothesis is further supported by the fact that the total accelerated charge is of the same order for self-injected and ionisation injected cases. This means the difference in the beams is not due to a larger amount of charge overwhelming the transverse features of the self-injected beams.

The qualitative differences between the two injection methods can be put on a more quantitative footing by analysing the spread of the transverse momentum of the measured spectra. The standard deviation of the transverse peak location for each energy slice is calculated for each electron spectra and plotted as a function of electron density in Figure 3. This is effectively a measure of the 'wiggliness' of the electron beam, where beams with little transverse features yield a smaller value. The difference between self-injected and ionisation injected beams is clear. The ionisation injected electron beams have better beam quality for all densities at which self-injection is also observed, showing there is a clear difference between beams from different injection techniques.

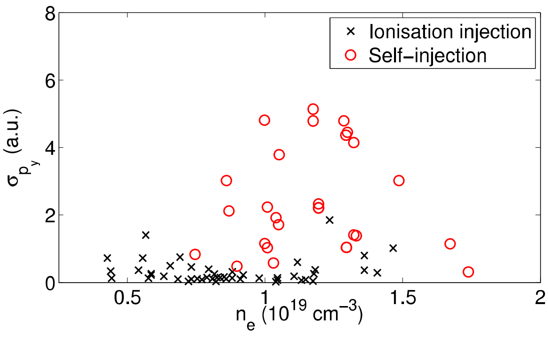

Figure 3: The standard deviation of slice peak brightness location as a function of plasma density for electron spectra obtained with self inejction and ionisaiton injection.

The disparity in final energies of accelerated electrons seen in Figure 2 is due to the electrons having started to dephase in the ionisation injection shots. Typically, self-injection requires the laser intensity to reach $a_0 \approx 4$ via self-focusing [9]. On the other hand, ionisation induced trapping is shown to require $a_0 > 1.7$ [10]. This suggests that injection happens much earlier in the interactions as compared to self-injection as the amount of self-focusing required for electron trapping is reduced considerably. The dephasing lengths for plasma densities of 0.5×10^{19} cm^{-3} and 1.5×10^{19}cm^{-3} are 1.2 mm and 220 µm, respectively. Hence, for ionisation injection, which happens much earlier in the gas jet, electrons will have caught up with the laser beam and started to lose energy for higher plasma densities as the dephasing length is much shorter than the plasma interaction length. However, the lack of features at higher energies other than those from dephased electrons from ionisation injection again suggests that no self-injection has happened. Evidently the charge due to ionisation injection has inhibited further self-injection from occurring.

Conclusions

Electron beams with distinctly different features have been observed under the same laser conditions but with different gas targets. Electron beams generated by self-injection in pure helium have been seen to be very different to those obtained using ionisation injection in helium with impurity under the same plasma densities. This suggests the self-injection process has been suppressed by the charge injected from ionisation induced trapping. Although simulations are required to fully understand the physics of this suppression mechanism, this result does suggest that laser plasma accelerators can be operated in the fully nonlinear bubble regime, even with controlled injection mechanisms such as ionisation injection and not necessarily in the quasi-linear regime, as suggested by previous work. This means that the linear focusing forces present in the fully nonlinear bubble regime can be exploited to further improve the emittance of electron beams generated using injection techniques other than self-injection.

Acknowledgements

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