Effects of the dopant concentration in laser wakefield and direct laser acceleration of electrons

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Abstract
In this work, we experimentally study the effects of the nitrogen concentration in laser wakefield acceleration of electrons in a gas mixture of hydrogen and nitrogen. A 15 TW peak power laser pulse is focused to ionize the gas, excite a plasma wave and accelerate electrons up to 230 MeV. We find that at dopant concentrations above 2% the total divergence of the electrons is increased and the high energy electrons are emitted preferentially with an angle of ±6 mrad, leading to a forked spatio-spectral distribution associated to direct laser acceleration (DLA). However, electrons can gain more energy and have a divergence lower than 4 mrad for concentrations below 0.5% and the same laser and plasma conditions. Particle-in-cell simulations show that for dopant concentrations above 2%, the amount of trapped charge is large enough to significantly perturb the plasma wave, reducing the amplitude of the longitudinal wakefield and suppressing other trapping mechanisms. At high concentrations the number of trapped electrons overlapping with the laser fields is increased, which rises the amount of charge affected by DLA. We conclude that the dopant concentration affects the quantity of electrons that experience significant DLA and the beam loading of the plasma wave driven by the laser pulse. These two mechanisms influence the electrons final energy, and thus the dopant concentration should be considered as a factor for the optimization of the electron beam parameters.

1. Introduction
Laser wakefield acceleration (LWFA) stands out as a promising mechanism to complement other kind of electron accelerators, providing a new and more compact source of relativistic electrons [1]. In this acceleration scheme [2], an ultra-short laser pulse is focused to a peak intensity above $10^{19}$ W cm$^{-2}$ in a gas, which becomes ionized at the front of the pulse. As a result, the remainder of the laser pulse, including the peak, interacts with an under-dense plasma. The ponderomotive force exerted by the large intensity gradients perturbs the electron density and creates a relativistic plasma wave. The electron density perturbation results in strong longitudinal fields up to hundreds of GV m$^{-1}$. If the laser pulse is intense enough and matches with the plasma parameters, the electrons are completely blown out from the path of the laser pulse, forming a bubble in the so called blowout regime [3]. An electron located in this region with sufficient velocity is trapped in the wave and accelerated to relativistic energies of few hundreds of MeVs in only a few hundreds of micrometers.

In the presence of a strong quasistatic electric and/or magnetic field, as the generated in the plasma bubble, energetic electrons undergo transverse oscillations. These are known as betatron oscillations [4] and generate x-ray pulses with a synchrotron-like spectral distribution and photon energies in the keV range [5]. If the betatron transverse motion of the electrons is in resonance with an overlapping laser field, the electrons can gain a significant transverse momentum from the electric field in the laser polarization direction. This gain in
transverse momentum is then transferred into longitudinal momentum via the magnetic part of the Lorentz force, which can accelerate the electrons in the longitudinal direction. This mechanism is known as direct laser acceleration (DLA) [6, 7]. A laser wakefield accelerator creates a scenario in which, provided that there is an overlap between the laser pulse and the trapped electrons, DLA can coexist and contribute directly to the total energy gained by the electron in the plasma wave [8–11].

DLA was first experimentally studied in such schemes where the laser pulse duration extended to several plasma wavelengths [12–14]. However, DLA in the LWFA quasi-blowout regime was initially investigated only numerically by particle-in-cell (PIC) simulations [8, 9, 11]. Recently, experimental work has finally identified in this regime an imprint of DLA in the accelerated electrons [15]. The dispersion of the electrons through a magnet in the direction perpendicular to the laser polarization showed a forked structure in the electron spatio-spectral distribution, with two symmetrical peaks along the divergence of the high energy electrons. The origin of this structure will be discussed in more detail later in this paper.

Together with the spatial overlap with the laser fields, electrons must be trapped in the plasma wave with significant transverse momentum in order to experience noticeable DLA [9, 16]. Electrons can be self-trapped if the plasma wave becomes highly nonlinear and eventually breaks, but other trapping mechanisms have been developed [17–21]. In particular, the mixture of gases can lead to ionization-induced trapping by combining a low percentage of a high-\(Z\) gas dopant, such as nitrogen, with a low-\(Z\) gas, such as hydrogen [22, 23]. While the plasma wave is formed by the background electrons of hydrogen and the outer electrons of nitrogen, the two electrons from the \(K\) shell of nitrogen are released only around the peak intensity of the laser pulse, due to over-the-barrier ionization. These electrons also get, during the nitrogen ionization process, a certain momentum in the laser polarization direction, and are more easily trapped in the wake potential at the back of the first plasma wave period or bubble, closer to the laser pulse in comparison to self-injected electrons. Ionization-induced trapping is then a very convenient mechanism to explore DLA [8, 11]. In addition, the dopant concentration in the gas mixture allows to change the number of electrons trapped in the plasma bubble without modifying neither the background electron number density \(n_e\) nor the parameters of the incoming laser pulse.

Here we present a parametric experimental study of ionization-induced trapping of electrons for different concentrations of hydrogen and nitrogen in the gas mixture. Our work shows that the number of electrons accelerated to high energy and large transverse momentum along the laser polarization increases with the nitrogen concentration and the electron density in the target. Quasi-cylindrical PIC simulations with CALDER-Circ support that the amount of ionization-induced trapped electrons increases for higher nitrogen concentration, and thereby also increases the number of accelerated electrons in the bubble that overlap with the laser electromagnetic fields. The transverse fields of the laser influence the acceleration of electrons, showing both, experimentally and in the simulations, the mentioned forked structure. This effect of DLA is experimentally enhanced when reducing the size of the plasma bubble, by increasing the background electron density. The control of the nitrogen concentration and the electron number density can affect the DLA contribution to the LWFA accelerated electrons and decrease or increase the electrons transverse momentum in the laser polarization direction.

2. Experimental method

The experimental data was acquired at the Lund Laser Centre in Sweden, using the multi-terawatt laser system. Pulses of 585 mJ at 800 nm central wavelength were delivered on target, with a pulse duration of \(\tau_L = 37\) fs full width at half maximum (FWHM). The laser was linearly polarized. A 775 mm focal length off-axis parabolic mirror (OAP) focused the beam to a FWHM spot size of 17 \(\mu\)m after wavefront optimization with a deformable mirror. The image of the spatial intensity distribution in the focal plane together with the measured pulse energy and duration gave an estimated peak intensity in vacuum of \(3.0 \times 10^{18}\) W cm\(^{-2}\), corresponding to a peak normalized vector potential \(a_0 = 1.2\). The peak power \(P_L \approx 15\) TW of the laser pulse was higher than the critical power for relativistic self-focusing \(P_{crit} = (8\pi\varepsilon_0 m_e c^3)/(\varepsilon_0^2) \times (n_e/n_i) = 3.2\) TW where \(n_e = (\omega_0^2 \varepsilon_0 m_e)/(\varepsilon_0^2) \approx 1.75 \times 10^{21}\) cm\(^{-3}\) is the critical density of the plasma. Nonlinear effects are then expected to happen during the propagation of the laser beam in the plasma, including self-focusing and self-compression of the laser pulse, that can locally increase the normalized vector potential. In order to improve the beam pointing stability of the system, the transverse position of the focal spot was actively corrected with the image of a focused leak of the last mirror before the OAP. The position of the centre of the spot was used to control the response of a piezo-actuated mirror just after the compressor. The correction was made between the full power shots using a train of pulses with MHz repetition rate and a few \(\mu\)J per pulse that propagated collinearly with the high energy pulse.

The electrons were accelerated by focusing the laser pulse to the entrance of a gas cell, filled by a mixture of hydrogen and a chosen concentration \(\chi\) of nitrogen. The gas mixture was enclosed in a cylindrical cell with a...
fixed inner length of 800 μm. Two 500 μm thick sapphire plates with 200 μm diameter holes were placed at the entrance and output of the cell, through which the laser pulse and the accelerated electrons propagated. The gas was stored in a reservoir connected to the cell by an electrovalve. The valve was opened 40 ms before each laser pulse arrived in order to reach a stationary gas density distribution. Inside the cell, the gas density is essentially constant. However, due to the aperture of the sapphire plates, a density gradient was formed at the entrance and the output of the gas cell. The density gradient length was calculated using computational fluid dynamics simulations (COMSOL CFD) to be around 0.6 mm. Different percentages $\chi$ of nitrogen were added to the hydrogen for the gas mixture: 0.1%, 0.5%, 2.0% and 5.0%. Note that the parameter $\chi$ accounts for the percentage of nitrogen molecules in the gas mixture, and not for the percentage of the output of the gas cell. Inside the cell, the gas density is essentially stored in a reservoir connected to the cell by an electrovalve. The valve was opened 40 ms before each laser entrance and output of the cell, through which the laser pulse and the accelerated electrons propagated. The gas concentration for nitrogen of 0.0% to the background electrons in the later formed plasma. Comparison of the accelerated electron beam parameters for nitrogen concentration of 0.0% (pure hydrogen) and 1.0% can be found in a previously published work [21].

The spectrum and charge of the accelerated electrons were calculated from the dispersion of the electrons through a 100 mm long permanent magnet with a peak magnetic field strength of 0.7 T on a Kodak Lanex Regular scintillation screen. The magnet was placed so that the electrons were dispersed in the direction perpendicular to the polarization plane of the laser pulses. The full acceptance angle of the electron spectrometer was approximately 60 mrad. The divergence of the electrons introduces an uncertainty in the electron energy calculated from the screen signal. 150 MeV electrons with an angle of ±3 mrad are estimated to introduce an uncertainty of ±8.4 MeV, corresponding to ±5.6%. Due to the geometry of the diagnostics only electrons with an energy above approximately 45 MeV were detected. The scintillation emission was recorded by a 16 bit CCD camera, from which the charge is calculated by using published calibration factors of the screen [24]. An aluminium plate covering the front part of the screen blocked any light reaching the detector.

The molecular density in the gas cell used in the experiment was previously characterized by interferometry for both gases in the mixture independently, at backing pressures ranging from 200 mbar to 1 bar. The background electron density is calculated for each gas mixture by considering that all hydrogen is fully ionized and nitrogen releases five electrons per atom, up to the fifth ionization state, by the leading edge of the laser pulse. The intensity required to ionize $N^{4+}$ corresponds to a normalized vector potential $a_0^{N^{4+}} = 0.08$, more than one order of magnitude lower than the peak normalized vector potential of the laser in vacuum.

3. Experimental results

The features of the accelerated electrons, such as collected charge, energy spectrum and divergence were explored by scanning the gas cell backing pressure for different nitrogen concentrations in the gas mixture. The results are sorted into values of electron number density within ±1%, ranging from $8.1 \times 10^{18}$ to $9.5 \times 10^{18}$ cm$^{-3}$. No data was collected at $8.1 \times 10^{18}$ and $8.6 \times 10^{18}$ cm$^{-3}$ at a nitrogen concentration of 5% as the minimum backing pressure explored produced an electron number density already above these values. Though the data with 0.1% at $8.1 \times 10^{18}$ cm$^{-3}$ was collected, it is not included as its finite energy spread indicates that the charge was not continuously trapped by the ionization of the $K$ shell electrons. As such, it should not be compared to data where that was the case.

Figure 1(a) shows the collected charge of the dispersed electrons. The charge increases with the density, as the laser group velocity becomes slower which lowers the trapping threshold. The addition of nitrogen in the gas mixture increases the accelerated charge up to a maximum before decreasing for higher nitrogen concentrations. This maximum is reached for lower nitrogen percentage as the electron number density increases. Thus the maximum collected charge depends on both, the electron number density and the nitrogen concentration. For the explored parameters, the charge is maximum with 26 pC at a nitrogen concentration of 0.5% and an electron number density of $9.5 \times 10^{18}$ cm$^{-3}$.

The experimental results also show that electrons experience lower acceleration with higher concentration of nitrogen in the gas, see figure 1(b). The maximum energy is obtained creating a $dQ_{\text{max}}/dE$ vector from the reconstructed spatio-spectral charge distribution, finding the maximum value of charge at each energy level. From this vector, the maximum energy is defined for when the signal is at least five times the minimum signal above the noise level. Figure 1(b) shows that the maximum energy varies around similar values independently of the electron number density, but decreases when the nitrogen concentration $\chi$ increases to 5%. In fact, the error bars for the different electron number densities overlap in more or less degree, and the maximum energy decreases from around 250 MeV at $\chi = 0.1\%$ to around 188 MeV at $\chi = 5\%$.

The electron spectra obtained for a fixed electron density $n_e = 9.5 \times 10^{18}$ cm$^{-3}$ as a function of the nitrogen concentration are shown in figure 2(a). Each plot is an average of the reconstructed spectrum after five consecutive acquisitions. In order to make the charge distribution of high energy electrons visible, the colour-scale for $\chi = 0.1\%$ and $\chi = 0.5\%$ are saturated. An example of the stability of the electron beams can be found
in figure 2(b) with five consecutive measurements obtained for $\chi = 2\%$ and averaged in figure 2(a). The general distribution of charge along the energy and angular dispersion axes is consistent in all shots. This stability of the beams is similar in all the studied cases. However the averaging in electron spectra in figure 2(a) smears out some details of the transverse distribution of the accelerated charge.

The divergence of the electron beams is calculated as FWHM of the integrated charge along the energy dispersion. Figure 2(c) shows the divergence as a function of the gas mixture for the same electron densities as in figure 1. The total divergence of the electron beam along the laser polarization plane increases with the concentration of nitrogen. This is observed directly from the spectra in figure 2(a), which also shows that the growth in divergence occurs for the whole electron energy range. Back to figure 2(c), the electron number density has a smaller impact on the divergence of the electron beam. The presence of more nitrogen in the gas mixture seems to increase the transverse momentum of the electron beam. In terms of shot-to-shot stability, the...
measurements of charge, maximum energy, and divergence vary within a maximum of 20%, 7% and 13% respectively, although their reproducibility also depends on the concentration and electron number density as shown in each case by the error bars.

The transverse spectral distribution is noticeably different for the different nitrogen percentages. In particular, at high concentrations of nitrogen the distribution of charge for high electron energies becomes preferentially off-axis and accumulates at non-zero divergence. The high energy electrons are then preferentially emitted at an angle. This forked structure is akin to the one associated to DLA \[15\]. To emphasize it, the inset in figure 2(a) shows the electron charge integrated between energies from 140 to 250 MeV, which values are represented by the dashed lines. Although for $\chi = 0.1\%$ and $\chi = 0.5\%$ the angular distribution of the charge gathers in the electron beam axis, at higher concentrations of nitrogen the off-axis charge grows around $\pm 6\text{ mrad}$ while the on-axis charge gradually decreases. It is found that there is always a non-zero charge at $\pm 6\text{ mrad}$ at energies above 140 MeV for any nitrogen concentration, including 0.1% and 0.5%. Even so, this is not the case when replacing the gas mixture by pure hydrogen. It therefore seems that the increase in transverse momentum associated with DLA affects more electrons when increasing the nitrogen concentration.

The increase in nitrogen is not the only factor inducing a larger transverse momentum of the electron beam. Figure 3 shows the averaged electron spectra obtained as a function of the electron number density $n_e$ for nitrogen concentrations of (a) 2% and (b) 5%. Note that the colour-scale is the same as in figures 2(a), (b). The presence of high energy electrons with the forked structure becomes more prominent when increasing the electron density $n_e$, while the on-axis high energy charge decreases. Again, charge integrated between 140 and 250 MeV is shown in the inset above the electron spectra. The high energy electrons clearly peak at $\pm 6\text{ mrad}$ for high electron densities, being dominant over the on-axis charge for electron number density above $10.1 \times 10^{18} \text{ cm}^{-3}$ for $\chi = 2\%$, but already from $n_e = 9.1 \times 10^{18} \text{ cm}^{-3}$ for $\chi = 5\%$. The main part of the high energy charge is there distributed off-axis, with certain angular dispersion. We observe then a growth in the electrons transverse momentum in the direction of the laser polarization, that is only visible with gas mixtures and that is enhanced for a higher electron number density, i.e. for smaller plasma wavelength $\lambda_p$ as $\lambda_p \approx 2\pi \times c/\omega_p \propto \sqrt{1/n_e}$.

4. CALDER-Circ simulations

We compare the experimental data with PIC simulations performed with CALDER-Circ to get a better understanding of the electron acceleration dynamics. The code CALDER-Circ uses cylindrical coordinates, but decomposes the fields into azimuthal Fourier modes. Only a small number of modes are required in order to correctly describe the non-cylindrical features of LWFA such as a linearly polarized laser pulse. The Fourier expansion can thus be truncated which significantly reduces the computational load of the simulations. In
comparison with full 3D codes CALDER-Circ has shown a solid reproduction of the laser–plasma interaction [25], including nonlinear effects occurring to the laser pulse during its propagation in the plasma.

In our simulations, the laser pulse is represented by a linearly polarized Gaussian beam with a spot size of 18 \( \mu \text{m FWHM} \). Its normalized vector potential \( a_0 \) and temporal duration \( \tau_L \) varies for different simulations and it is described for each case below. The gas density profile reproduces the estimated density gradient described in section 2, with density ramps 650 \( \mu \text{m} \) long and a density plateau of 500 \( \mu \text{m} \). The laser pulse is focused at the beginning of the plateau of the gas cell. The background electron number density in the plateau corresponds to \( 10^{19} \text{ cm}^{-3} \), created by a preformed plasma with both, hydrogen and nitrogen \( L \) shell electrons. In the following, the axis will be appointed as \( x \) for the longitudinal direction (laser propagation), \( y \) for the transverse direction parallel to the polarization of the laser electric field, and \( z \) for the transverse direction perpendicular to the polarization. The plane \( x = 0 \) corresponds to the beginning of the density up-ramp. The code considers the background hydrogen ions immobile and the nitrogen ions mobile, and includes Ammosov–Delone–Krainov-based strong-field ionization modules [26] to compute the ionization that release the \( K \) shell electrons of the nitrogen. Simulations are performed applying the scheme proposed by Lehe et al [27] to avoid numerically overestimation of the betatron oscillations due to spurious Cherenkov radiation. The spatial cells are set to be 16 nm long in the direction of the laser propagation, and 127 nm long in the transverse radial direction, with 32 macro-particles per cell representing background electrons and two macro-particles per cell representing \( \text{N}^{5+} \) ions. The time step corresponds to 52 as, and three Fourier modes are used for the fields in the azimuthal direction. Furthermore it has been shown that the interpolation of the magnetic field in the PIC lattice can induce a spurious force that increases the transverse momentum of the accelerated particles that propagate inside the plasma wave [28]. To avoid these non-physical forces, the second-order time-interpolation method used by Lehe et al [28] is applied here.

A set of four simulations are performed to compare the laser–plasma interaction for different nitrogen concentrations. The simulations consider a mixture of hydrogen and 0.1%, 0.5%, 2% and 5% of nitrogen in the gas forming the plasma, similar to the gas mixtures studied experimentally. The electrons contributing to the background plasma density are differentiated to the ones released from the \( K \) shell of the nitrogen around the peak intensity of the laser pulse. The laser beam has a peak normalized vector potential of \( a_0 = 1.08 \) and the FWHM laser pulse duration is 37 fs. The simulations show that for all concentrations, \( a_0 \) evolves due to self-compression and self-focusing of the laser beam and exceeds the peak normalized potential corresponding to the ionization intensity required to release the innermost \( K \) shell electron \( a_0^{\text{N}^{5+}} = 2.75 \) just at the beginning of the density plateau, remaining mainly above this value until 200 \( \mu \text{m} \) after the beginning of the density down-ramp. The evolution is similar at all concentrations and achieves a maximum peak normalized vector potential \( a_0 = 3.4 \).

Figures 4(a)–(d) show the electron density distribution and laser field in a snapshot of the simulations in the density plateau of the gas cell \( x = 970 \mu \text{m} \) for (a) 0.1%, (b) 0.5%, (c) 2% and (d) 5% of nitrogen in the gas mixture. The longitudinal field originated in the plasma wave is plotted on the electron density distribution in violet. Simulations show that with \( \chi = 2\% \) and \( \chi = 5\% \), there is so much ionization-induced trapped charge already before the beginning of the density plateau that beam loading strongly influences the formation of the plasma wave. In this case, as electrons are trapped in the density up-ramp, the charge clusters at the rear part of the bubble before the density plateau. This charge drives its own wake and expels the background electrons in the back of the first plasma period. It also flattens and reduces the amplitude of the longitudinal field in the rear part of the bubble. However, the simulations performed for lower nitrogen concentrations (0.1% and 0.5%) agree with our previous study [21]. Along the plateau of the electron density distribution most of the accelerated charge comes from ionization-induced trapped electrons in the first plasma period. During the density down-ramp at the exit of the gas cell, both electrons from the background and electrons from the \( K \) shell of the nitrogen become trapped in the rear part of the plasma bubble, behind the charge accelerated in the plateau. Thence the maximum energy at which electrons are accelerated decreases as the beam loading increases with the dopant concentration, as shown in figure 4(e) by the purple diamonds, in agreement with the tendency observed during the experiment in figure 1(b).

For this reason, despite a larger amount of \( K \) shell electrons available for ionization-induced trapping, at higher nitrogen concentrations the LWFA is not always able to efficiently accelerate the charge to energies above 45 MeV. The bar graph in figure 4(e) compares the total charge accelerated at the end of the simulations (left bars, light colours) and the fraction of this total charge above 45 MeV (right bars, dark colours) as a function of \( \chi \). In each bar, the blue colour represents accelerated background electrons while the nitrogen \( K \) shell electrons are represented in green. Although the total charge increases with the nitrogen concentration, the charge above 45 MeV is maximum for 2% of nitrogen in the gas mixture and then decreases for 5%. This represents the same trend as observed in the experimental results for an electron number density \( n_e = 9.1 \times 10^{18} \text{ cm}^{-3} \) in figure 1(a). In addition, the acceleration of background electrons in the laser–plasma interaction quickly
the density down-ramp \( x = 1.44 \) mm. The macro-particles are coloured according to their longitudinal momentum \( p_x \). In the laser polarization transverse phase space, figure 5(a), the electrons distribution forms a ring. It can be seen that the electrons with higher longitudinal momentum are also the ones in the outer part of the ring. Nevertheless these particles have a very different distribution in the transverse phase space perpendicular to the laser polarization, figure 5(b). There, most of the electrons have an almost null transverse momentum, and are localized close to the axis independently on their longitudinal momentum. The rest of tracked particles with \( p_x < 145 \, m_e c \) and not shown in the figure, are however distributed homogeneously along a larger transverse position \( \pm 6 \, \mu m \), and a narrower transverse momentum \( \pm 5 \, m_e c \) for both axis \( y \) and \( z \).

Figure 5(c) shows the \( p_y / p_y \) histogram of the accelerated electrons at the end of the simulation, after exiting the density down-ramp \( x = 1.8 \) mm. The distribution with maximum longitudinal momenta \( p_y \) is less dense around \( p_y = 0 \), and clusters at the sides of the axis, forming the forked structure. Charge along the transverse momentum \( p_y \) is integrated in figure 5(d) in analogy to the inset of figures 2(a) and 3. The charge is maximum for \( p_y = \pm 5.5 \, m_e c \), and drops in the centre of the transverse axis. The shape is alike to the experimentally observed integrated charge of the high energy electrons for similar nitrogen concentration and electron number density in figure 3(b). The phase space trajectories of four of these macro-particles accelerated to high final energies are shown in figure 5(e). The particles are chosen in the leading part of the accelerating electrons, closer to the laser pulse, with final longitudinal and transverse momenta over 250 \( m_e c \) and 6 \( m_e c \) respectively. The particles start being tracked at around 4 MeV but soon increase their longitudinal momentum. This can be seen looking at the distance between the equally spaced time-steps represented by the points and defining the trajectories. The
longitudinal momentum gain is more significant where the absolute value of transverse momentum is large, while it can slightly decreases while the transverse momentum changes sign. The transverse momentum $p_y$ changes sign periodically during the trajectory indicating betatron oscillations of the electrons, and increases gradually the maximum absolute value in each period. The particle spends more time in the regions where the transverse momentum is non-zero, as can be seen from the larger distance between time-steps around the $p_y$ axis. Our interpretation is that regardless the transverse position of the electrons, it is more probable that the electrons close to the laser pulse have a non-zero transverse momentum when leaving the plasma wake, originating the forked shape.

5. Discussion

The fact that ionization-induced trapped electrons show a larger divergence along the laser polarization axis has been observed since the first experimental studies of ionization-induced trapping [22]. Momentum conservation imposes that the electrons released by ionization within the laser field are emitted with a certain momentum in the laser polarization direction. Although this entails an intrinsic asymmetrical divergence in beams generated by ionization-induced trapping, this effect does not depend on the nitrogen concentration $\chi$.

The observed electron divergence dependence on $\chi$ in the laser polarization axis, and shown in figure 2(c), is reproduced also in the simulations presented in figure 4. The increase in divergence is only visible in the direction of the laser polarization and grows with the trapped charge, which suggests that it is related to the laser fields and to the beam loading occurring in the bubble when more electrons are trapped, but not necessarily by DLA. However, as explained below, the preferential angle the high energy electrons are emitted with can only be attributed to DLA.

Simulations of different nitrogen concentrations in figures 4(a)–(d) show that at 2% and 5% of nitrogen in the gas mixture, there is a significant amount of charge trapped by ionization of the N$^{5+}$ and N$^{6+}$ ions already at the beginning of the density plateau. This charge is trapped in the first plasma bubble. As the amount of trapped charge increases, the number of electrons in the leading part of the electron beam also increases. Thus there are more electrons overlapping with the laser fields than in the case of 0.1% or 0.5% percentages of nitrogen, where the ionized K shell electrons get trapped in a slower ratio. The increase of trapped charge induces also an increase in the beam loading of the wakefield. Due to beam loading, the most accelerated electrons are closer to the laser pulse and are subjected to DLA, while the heavy perturbation of the already trapped electrons suppresses electron trapping in the density down-ramp. In contrast, at 0.1% and 0.5%, even though existent, the charge subjected to DLA is much lower than for higher concentrations. As mentioned in section 3, at these dopant concentrations we experimentally find a non-zero charge distributed as a forked structure, but the charge in this region is much lower than on-axis. Besides, as beam loading is weaker for these cases, the wake can accelerate the...
charge to higher energies and there is the chance of trapping electrons in the density down-ramp, reducing the relative contribution of DLA.

As already referred, higher dopant concentration leads to more ionization-induced trapping, which also implies a larger beam loading effect. Both simulations and experimental results display a net reduction in the maximum energy at which the electrons are accelerated as the nitrogen percentage is increased to 5%. It is also seen that the electron charge accelerated above 45 MeV, which is the lower limit defined by the geometry of the electron spectrometer, decreases at higher nitrogen concentrations despite more charge is trapped in the plasma wave. At 2% and 5% of nitrogen the electron beam is strong enough to drive its own wake in the plasma wave, reducing the longitudinal wakefield and hence the energy to which the electrons are accelerated.

As a result, the forked structure found in the spatio-spectral charge distribution and originated by the preferential angular emission of the high energy electrons subject to DLA, is more visible at high concentrations of nitrogen, when the number of electrons affected by DLA is larger and the electrons accelerated by the wakefield and emitted on-axis achieve lower energies.

The simulation summarized in figure 5 shows the effect of the laser pulse fields on the electron momenta. Electrons with the highest longitudinal momentum appear to be entangled in a driven harmonic oscillator potential in the laser polarization axis phase space, forming a ring along $y/p_y$. Those with a higher longitudinal momentum are besides located in the outer part of the ring, thus achieving the largest transverse momentum, as observed in figure 5(c). In addition, the ring shape of the $y/p_y$ phase space implies that the majority of the high energy particles have a non-zero transverse momentum, as exhibit in figure 5(d). The high energy electrons, despite located around the optical axis within a narrow space, are emitted preferentially with an angle. The angular emission forms the fork structure and corresponds qualitatively to the experimental observations. The fact that this angular distribution is visible at high nitrogen concentrations, when more charge is trapped at the beginning of the density plateau, and at high electron densities, when the decrease of the plasma wavelength enhances the overlap between the laser fields and the trapped electrons, reinforces that the effect is produced by DLA, and agrees with a previous experimental study [15].

Other studies on DLA have modified either the plasma wave structure or the laser pulse temporal shape to change the DLA contribution to the electron acceleration [8, 9, 11, 13–16]. In those cases a dopant was added only when ionization-induced trapping was required, but not as a variable that affects DLA. However, in this work the dopant concentration allows to influence the DLA contribution to the electrons energy while keeping the same plasma wave and laser pulse parameters. There are several properties of DLA that could be explored by modifying the dopant concentration. Since the first experimental studies, the enhancement of the betatron oscillations attributed to the overlap of electrons and laser pulse in DLA has brought interest for the amplification of the betatron x-ray yield, as the total number of x-ray photons scales with the betatron oscillation amplitude [14]. The dopant concentration might increase the total number of x-ray photons by increasing both, the number of accelerated electrons and their betatron oscillation amplitude.

6. Conclusions

We have shown that the dopant concentration in the gas target for LWFA alters the ratio of ionization-induced trapping of electrons which significantly affects the acceleration mechanism and electron parameters. PIC simulations support that by increasing the amount of nitrogen in the gas mixture, the charge is trapped earlier in the plasma wave and can experience DLA by the overlap with the laser fields, while beam loading decreases the maximum energy of the accelerated electrons and cancels other trapping mechanisms. Our experimental results show that for a given electron number density and laser parameters, electrons emitted from a higher doped gas show a larger total divergence in the direction of the laser polarization and, at concentrations above 2%, the high energy electrons $>145$ MeV are emitted with a preferential angle $\pm6$ mrad, producing a forked structure in the charge’s spatio-spectral distribution which is an indication of DLA. This is the first time to our knowledge that the dopant concentration is contemplated as a factor that influences contribution of DLA in a LWFA. Our results open the possibility of using the dopant concentration to control or study other effects of DLA, as the increase in amplitude of the electron betatron oscillations, as well as its influence on the x-ray betatron emission.

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