Determination of hybrid and direct laser acceleration dominated regimes in a 55fs laser driven plasma accelerator with ionization induced injection

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Abstract:

An experimental study on 55fs (intensity ~5×10¹⁸ W/cm²) laser driven plasma accelerator using mixed gas-jet target (He+few%N₂) with varying plasma density (~2-7.1×10¹⁹ cm⁻³) is used to identify applicable acceleration mechanisms, viz. hybrid: Direct Laser Acceleration (DLA) + Wakefield (WF), and DLA. Towards lower density of ~2×10¹⁹ cm⁻³, electron acceleration could be attributed mainly to DLA with ionization induced injection (III). With increase in density, increasing role of WF was observed leading to hybrid regime, and at densities higher than self-injection (SI) threshold (≥5.8×10¹⁹ cm⁻³, observed experimentally for He target) contribution of DLA and WF was found to be comparable. Dominant DLA mechanism was also observed in case of pure N₂ target with III at a density of ~2×10¹⁹ cm⁻³. 2D PIC simulations performed using the EPOCH code corroborate the above scenario, and also showed generation of surface waves, considered as a potential mechanism of pre-acceleration to DLA.
Keywords: Laser Plasma Acceleration, Laser Wakefield Acceleration, Direct Laser Acceleration, Self-Injection, Ionization Induced Injection.

Several electron acceleration mechanisms e.g. Laser wakefield acceleration (LWFA), and Direct Laser Acceleration (DLA) etc. are applicable in high intensity laser plasma interaction. Through LWFA [1], subsequent to generation of high quality quasi-monoenergetic (QM) electron beams [2-4], acceleration of electrons to GeV class energies has been demonstrated [5-11] in the bubble or blowout regime [12,13], where an intense short laser pulse such that \( L < \lambda_p \), (where \( L \) is the laser pulse length and \( \lambda_p \) is the plasma wavelength) is used satisfying a matching condition between laser focal spot (\( \omega_0 \)), normalized laser intensity (\( a_0 \)) and bubble radius (\( R \)) such that \( k_p R \sim k_p \omega_0 \approx 2 \sqrt{a_0} \), where \( k_p = 2\pi/\lambda_p \). Another wakefield mechanism termed as self-modulated laser wakefield acceleration (SMLWFA) is applicable for cases \( L > \lambda_p \), achieved at comparatively higher plasma density and longer laser pulse duration. This regime has been studied using several hundreds of fs [14-16] as well as few tens of fs long laser pulses [17-21], and generation of electron beams with broad spectrum and QM spectrum were reported respectively. Generation of QM beams was explained considering long laser pulses are modulated at the order of \( \lambda_p \) leading to formation of multiple short laser pulse lets which are intense enough to create bubble regime conditions [17].

In the regime of \( L \gg \lambda_p \), another possible mechanism of DLA was also proposed and observed experimentally [22-26], in which case electrons mostly interact with the transverse field of laser. Even in the case of laser pulse duration of few tens of fs (\( L \geq \lambda_p \)) contribution of DLA along with wakefield (WF) have also been considered [27, 28] using pure He target where self-injection (SI) of electrons was applicable. Recently, DLA contribution in laser wakefield
accelerator with $L > \lambda_p$ has been established experimentally by Shaw et al. [29] using ionization induced injection (III) [30,31] in mixed gas-jet target (He+N$_2$). Further, through detailed PIC simulations it was found that DLA can double the energy of accelerating electrons in a LWFA [32-35]. Importance of DLA in laser plasma acceleration is due to the fact that it can lead to an increase in betatron oscillation of the trapped electrons and thereby very high energy photons through betatron radiation could be generated [36,37]. It may be pointed out here that there are very few experimental reports on pure DLA regime [23,25,26] using long (several hundreds of fs) laser pulses, whereas no reports in the few tens of fs regime, and hence further investigations would be of interest.

In this letter, we present an experimental investigation on electron acceleration using Ti:Sapphire laser pulses of ~55fs duration (peak power~18TW, intensity~5×10$^{18}$W/cm$^2$) interacting with three different gas targets of He, mixed gas (He+few%N$_2$) and N$_2$. Three distinct regimes of electron acceleration along with the role of DLA have been identified. In case of He, associated with bubble formation and subsequent SI of electrons, at a threshold density of ~5.8×10$^{19}$cm$^{-3}$ QM electron beam generation was observed, where both WF and DLA (Hybrid+SI: Regime-1) was found to contribute to the total energy gain of electrons. In case of mixed gas target assisted by III, electron acceleration was observed at a much lower threshold density of ~2.1×10$^{19}$cm$^{-3}$. Due to expected weakening of WF this could lead to a pure DLA dominated regime (DLA+III: Regime-2). With increase in density to ~4.1×10$^{19}$cm$^{-3}$, in case of mixed gas target, the role of WF increases and the accelerator enters into the hybrid regime, as in case of pure He, but with III (Hybrid+III: Regime-3). 2D PIC simulations using the EPOCH code [38] was performed which showed clear and distinct features of these three different
acceleration regimes, along with generation of surface waves as potential pre-acceleration mechanism for DLA. Further, effect of three different regimes on the electron beam properties viz. spectrum, beam profile, charge, and pointing stability is also discussed. Such a comparative study in a single experimental set up using three different gas targets (hence applicable different injection mechanisms), thereby identifying the thresholds required for separating the different regimes of acceleration, i.e. pure DLA from hybrid regime, has not been reported earlier, particularly observation of dominated DLA regime with laser pulse duration in the range of several tens of fs.

Ti:Sapphire laser pulses of ~55fs were focused to a spot of ~25×12.5µm (radius at 1/e²) using f/5 optics along 1.2mm length of three different gas targets of He, mixed gas (He+few%N₂) and N₂ (plasma density ~2-7.1×10¹⁹cm⁻³) [21,26]. Considering 50% of total energy inside focal spot, the laser pulse provides a total power (P) of ~18TW and intensity of ~5×10¹⁸W/cm² at focus which corresponds to a₀=1.5. Electron densities in case of He and N₂ gas-jets were calculated using the corresponding atomic gas densities for a given pressure and 2⁺ and 5⁺ ionization states respectively. Electron beam spectrum was recorded using a magnetic spectrograph, with a resolution of ~34% at 30MeV and 67% at 60MeV (for 10mrad beam). A circular aperture of 10mm placed in front of the magnet providing an acceptance angle of ~36mrad.

The experimental study was performed using a fixed laser pulse duration of ~55fs, with plasma density in the range of ~2–7.1×10¹⁹cm⁻³ (L/λₚ~2.2-4.1, the/λₚ~1.7-3.16, P/Pₖ~12-43, where Pₖ is the critical power for self-focusing=17.4×nₑ/nₑ (GW) [39], nₑ is critical density and nₑ is electron density). The above parameters conform to the SMLWFA regime [17-21], where self-
modulation of the laser pulse drives strong WF leading to SI and acceleration of electrons to relativistic energies. At first electron acceleration was studied using pure He gas, where generation of QM electron beams (Fig.1a & b, beam profile shown in the inset) were observed at a threshold density of $\sim 5.8 \times 10^{19} \text{cm}^{-3}$, which is SI threshold for present experimental conditions. This is consistent with several other reports on QM electron beam generation via wakefield acceleration using similar parameters [17-21]. However, as considered in few earlier [27,28] and also recent reports [29], for the condition of $L > \lambda_p$, one would expect an overlap and interaction of laser field with the injected electrons in the bubble leading to gain in energy from DLA also. Earlier, we had estimated maximum electron energy for DLA regime of acceleration [24,26], using which in the present case we estimate a maximum energy gain of $\sim 25 \text{MeV}$, less than the observed maximum energy of $\sim 48 \text{MeV}$, which suggests hybrid regime of electron acceleration i.e. WF and DLA with almost equal contributions (for details see supplementary, Fig.S1). We define this hybrid regime of acceleration with SI as ‘Regime-1’. Also for the conditions of Shaw et al [29], where DLA was considered with WF in the blowout regime (i.e. hybrid regime), our theoretical formulation predicts comparable energy gain from DLA (66 MeV) and WF (66 MeV) (Total $\sim 132 \text{MeV}$, observed experimental value of $>120 \text{MeV}$), similar to that reported by the authors.

Next, it would be interesting to study the behavior of the accelerator in a regime below the SI threshold with the same laser parameters, where reduction in role of WF is expected. For that, a mixed gas target was used ($\sim 2.5-7.5\% \text{N}_2 \text{ in He}$) which allowed the accelerator to operate at lower threshold density of $\sim 2.1 \times 10^{19} \text{cm}^{-3}$ ($\sim 7.5\% \text{ N}_2$) due to III mechanism. By gradually increasing the backing pressure of He, keeping \text{N}_2 pressure fixed, plasma density could be varied up to $\sim 7.1 \times 10^{19} \text{cm}^{-3}$ ($\sim 2.5\% \text{ N}_2$), thereby achieving density both below and above the SI
threshold of $\sim 5.8 \times 10^{19}$ cm$^{-3}$ observed with He. A series of energy dispersed electron beams and corresponding spectra (with mostly quasi-thermal feature) for different plasma densities are shown in Fig.1c & d respectively. For a plasma density of $\sim 2.1 \times 10^{19}$ cm$^{-3}$, a maximum energy gain from DLA is estimated to be $\sim 61$ MeV, which is comparable to the observed maximum electron energy of $\sim 63$ MeV (Fig.1c i & ii), which suggests dominant DLA regime of acceleration with III (Regime-2). It is consistent with the fact that at much lower density (compared to the SI threshold), increase in $\lambda_p$ would lead to increase in bubble radius violating the matching condition for the same laser parameters, hence would not support bubble formation and strong WF [13].

As discussed above also, another possible acceleration mechanism in laser channels for $L > \lambda_p$ could be SMLWFA. However, in several earlier simulations [22] and also in recent reports [26,29,33] it has been found that in similar conditions DLA could be dominant above a threshold value of $P/P_c (>6)$, as complete cavitation at the front of the laser pulse opposes regular WF formation in the remaining trailing part of the pulse. In the present case also, high value of $P/P_c$ ($\sim 12$) supports DLA at a density of $\sim 2.1 \times 10^{19}$ cm$^{-3}$ due to weakening of WF. Similar to other reports [23,25], recently, we also reported experimental observation of DLA using longer laser pulses of 200fs ($P=7.5$ TW, $P/P_c\sim 9$-$28$) in He plasma, at a threshold density of $\sim 4 \times 10^{19}$ cm$^{-3}$, with observed maximum energy of $\sim 30$ MeV [26]. Comparatively, in the present case, use of higher laser power (18 TW) allowed to achieve pure DLA regime at lower density, with assistance of III, and hence leading to higher energy of $\sim 63$ MeV. Here role of III may be emphasized which allowed to achieve acceleration at lower density through DLA using such a short laser pulse which otherwise could not be effective. Recent simulation study has also shown favorable role of III for DLA [35].
Further, with mixed gas target, role of WF could be enhanced with increase in plasma density. At a higher density of \(3.7-4.1\times10^{19}\text{ cm}^{-3}\) (Fig.1c iii-v), we observed increase in the maximum energy to \(100\text{ MeV}\), having almost equal contributions from DLA and WF. Since this density is below SI threshold, injection takes place by III, and we define this regime as ‘Regime-3’. As stated above also, similar scenario of hybrid acceleration with III having equal contributions from DLA and WF has also been observed in a recent experiment reported by Shaw et al. [29] and through simulations [32]. Here, we further explore this acceleration regime by enhancing the WF strength by increasing the density up to \(7.1\times10^{19}\text{ cm}^{-3}\) i.e. above SI threshold. The contribution of DLA and WF was almost found to be equal in the higher density cases also, however maximum energy of electrons reduced as shown in Fig.1c (ix-xii).

In summary, using high \(P/P_c\) and mixed gas target, we could observe electron acceleration through DLA with III \((2.1\times10^{19}\text{ cm}^{-3})\), which with increase in density transformed to hybrid regime with III \((4\times10^{19}\text{ cm}^{-3})\). Hybrid regime of acceleration with SI was observed in case of pure He \((5.8\times10^{19}\text{ cm}^{-3})\). In Fig.1g we plot theoretically estimated maximum energies via DLA and WF for the range of plasma density used along with the observed experimental values, showing above discussed three distinct regimes of acceleration.

To further confirm the role of III in DLA, experiment was also performed using N\(_2\) gas target. Similar to mixed gas target, in this case also electron acceleration was observed at a threshold density of \(2\times10^{19}\text{ cm}^{-3}\) (Fig.1e & f). Generation of quasi-thermal electron beams with average maximum energy of \(50^{+10.5}_{-13.4}\text{ MeV}\) (at 10% of peak), comparable to mixed gas target (Fig.1c i-ii) was observed with higher energy spread and shot to shot energy fluctuation. The errors represent rms deviation from average value. Considering the operation at same lowest density of \(2\times10^{19}\text{ cm}^{-3}\) the electron acceleration and observed maximum energy could be
attributed to DLA (Regime-2) as in the case of mixed target discussed above. There are several reports on electron acceleration in N$_2$, both for L<\lambda_p$ [40,41] and L>\lambda_p$ [42,43] with a comparatively lower P/P_c ~2-4 showing WF as the dominant acceleration mechanism. However, Adachi et al [44] with higher P/P_c ~13.6 considered role of DLA and reported a cascade acceleration of SMLWFA and DLA.

To support the above described three regimes of acceleration we performed 2D PIC simulations using EPOCH code [38]. The simulation was performed in a moving window frame with box size of 60×80µm in longitudinal and transverse directions respectively. Laser pulse of 55fs (L=16.5µm) duration, wavelength (\lambda) 800nm, and intensity of 5×10^{18}W/cm$^2$, propagating along X with polarization along Y direction, enters the simulation box from left and interacts with the plasma. The plasma length within the simulation box was modeled with an initial linear density ramp of 100µm followed by 500µm of uniform density. A resolution of \lambda/30 was used in both directions. In case of He, at a density of 5.8×10^{19} cm$^{-3}$, clear bubble formation (Fig.2a) was observed after 1040fs of laser propagation inside plasma, associated with laser pulse modulation leading to pulse compression up to L~8µm and strong WF amplitude >1 (Fig.2b) i.e. above wave breaking limit leading to SI of electrons. In the case of mixed gas, at a lower density of 4×10^{19} cm$^{-3}$, initially at 1320fs, a channel like structure tending towards bubble formation is seen in Fig.2c, and with negligible laser pulse modulation (Fig.2d) is observed. However, with further propagation upto 1740fs, laser pulse modulation was observed (Fig.2f) leading to initiation of bubble formation (Fig.2e). This also leads to strengthening of WF (Fig.2d & f) however amplitude is still <1. Hence, injection could be only due to III mechanism. At still lower density of 2×10^{19} cm$^{-3}$, in case of N$_2$, an elongated laser channel formation (with almost negligible signature of bubble) was observed after 1040fs of laser propagation (Fig.2g). In this case laser
pulse modulation was also absent and hence very weak WF amplitude $\ll 1$ (Fig. 2h) was observed, so electron injection could be only due to III. In all the above cases, injected electrons have an overlap with the laser electric field and hence betatron oscillation was clearly observed (Fig. 2a,c,e,g), suggesting role of DLA. The gradual decrease in WF amplitude with decrease in density leads to transformation from a hybrid regime to DLA dominated regime, as discussed above in the context of experimental observations. It may be noted that, hybrid regime of acceleration observed here with betatron oscillations inside bubble is similar to that also reported by Shaw et al (c/f from Fig. 9 in Ref. 29).

Next, to quantify separate energy contributions of WF and DLA, maximum transverse $(\gamma_y)$ and longitudinal $(\gamma_x)$ energy gain $(\gamma_y = -\int_0^t \frac{2ep_y E_y}{(mc)^2} \, dt, \gamma_x = -\int_0^t \frac{2ep_x E_x}{(mc)^2} \, dt)$ to the total energy gain $\gamma^2 = 1 + \gamma_x + \gamma_y$ were studied for the three cases, as shown in Fig. 3(i,ii,iii). In case of He, both WF and DLA has equal contributions of $\sim 60\%$ and $\sim 40\%$ respectively with SI (Regime-1). In case of mixed gas target, at comparatively lower density, WF contribution reduces to $\sim 20\%-25\%$, in a hybrid regime but with III (Regime-3). In case of $N_2$ at further lower density, WF contribution is very negligible, $\sim 5\%-10\%$ only, and therefore describes a pure DLA in channel with III (Regime-2). The above observations suggest onset of WF at a threshold density of $\sim 4\times 10^{19} \text{cm}^{-3}$, thereby transforming from Regime-2 at lower density to Regime-1&3 at higher density. This is consistent with our experimental observations supported by theoretical estimations (Fig. 1g).

Further, an interesting observation of electron density modulations (surface waves: SW) at the channel boundaries with periodicity of $\sim 1 \mu\text{m}$ was observed in case of mixed and $N_2$ gas
targets at lower densities (Fig.4b & c). Observed electron densities approaching >0.1n_c at channel boundaries gives a SW wavelength (\(\omega_{pe}^2/c\omega_0\)) of ~2-3\(\mu\)m. Generation of SW have also been observed in earlier reported PIC simulations mostly using longer laser pulses of few hundreds of fs [45-47], however, here we observe for first time using shorter laser pulse duration of ~55fs in a gas jet target. Presence of such SW in case of mixed and N_2 targets supports the role of DLA [47] as it has been suggested that electrons trapped in SW are pre-accelerated to relativistic energies and further accelerated by DLA [45,46]. It may be noted that, in case of He (Fig.4a), operating at higher densities, no SW modulations were observed due to clear bubble formation.

Next, we compare the effect of three distinct regimes (Regime:1, 2, 3) on electron beam properties viz. spectrum, charge, beam profile and pointing stability. In case of Regime-1, observed in He target, generation of QM electron beams with average peak energy ~30\(\pm\)4.8 MeV and mean energy spread of ~40\%\(\pm\)26.5\% (Fig.1a & b) is typical for bubble regime of acceleration as reported by various groups [17-20] and also observed in our earlier report [21]. Whereas, for Regime-2&3, observed with mixed (Fig.1c&d) and N_2 (Fig.1 e & f) gas target, the spectra are quasi-thermal with almost 100% energy spread. In case of mixed gas, maximum energy of ~120MeV was observed at \(~4\times10^{19}\)cm\(^{-3}\) (Fig.1c, v-vi) and for higher density close to SI threshold (Fig.1c, ix-x) maximum electron energy was similar to He, however QM feature was absent suggesting role of III in Regime-3 compared to only SI in Regime-1. Another manifestation of III over SI is the observed increase in the beam charge above 7MeV from ~5pC in case of He to ~22pC in case of mixed gas and N_2 target [30,31]. Electron beam profile recorded (inset Fig.1b & f), showed ellipticity of 1.3\(\pm\)0.3 in case of He, and a comparatively
larger divergence and ellipticity in case of N\textsubscript{2} (1.5\textsuperscript{+0.37}_{-0.41}) with beam profile elongation along laser polarization direction due to interaction of electrons with the laser field [48], suggesting its more pronounced effect in case of DLA (Regime-2) compared to hybrid (Regime-1). Finally, it was also found that DLA with III in case of N\textsubscript{2} (Regime-2), leads to better pointing stability of electron beams (~3×4 mrad) compared to the hybrid with SI (Regime-1) in case of He (~24×9 mrad) (inset Fig.1b & f). This could be attributed to the fact that uncontrolled injection in a larger bubble volume in case of SI (He) with further interaction with laser field will lead to larger pointing variation, compared to III (N\textsubscript{2} target) where injection primarily occurs along the laser axis.

In conclusion, an experimental investigation on electron acceleration using 55fs laser pulses interacting with three different gas targets of He, mixed gas (He+few\% N\textsubscript{2}) and N\textsubscript{2}, in the density range of 2-7.1×10\textsuperscript{19} cm\textsuperscript{-3}, in a single experimental set up, is presented. Role of DLA and WF mechanisms are investigated and hence three different regimes of acceleration are identified: hybrid+SI (Regime-1) in case of He, DLA+III (Regime-2) in case of mixed and N\textsubscript{2} at lower density, and hybrid+III (Regime-3) at comparatively higher density. Applicability of different acceleration regimes was supported by 2D PIC simulations which also showed SW generation in case of mixed and N\textsubscript{2} gas targets, which could be a pre-acceleration mechanism to DLA. Observation of pure DLA with III using short laser pulse of few tens of fs duration in mixed and N\textsubscript{2} gas targets have not been reported till date. Role of higher laser power along with high value of P/P\textsubscript{c} is suggested as the main factor to establish such a regime.
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FIG. 1 (Color online): (a) Raw images of typical dispersed electron beams and corresponding spectra (a)-(b) for He at density of ~5.8×10^{19} cm^{-3}; (c)-(d) for mixed (He+N\textsubscript{2}) gas target at various densities ~2.1-7.1×10^{19} cm^{-3}; (e)-(f) for N\textsubscript{2} at density of ~2×10^{19} cm^{-3}. Insets in (b) and (f) show pointing stability and typical electron beam profiles (white curves show lineouts). (g) Identification of different acceleration regime by theoretically estimating energy contributions from DLA (blue) and WF (red) at various densities. Experimentally observed maximum electron energies are also shown (green) and compared to DLA+WF (magenta).
FIG.2. (Color online). Simulation results: Electron density profiles and corresponding lineouts of normalized laser field $E_y$ (blue dot) and wakefield $E_x$ (red solid). (a)-(b) for He at 1040fs, (c)-(d) for mixed (He+N$_2$) target at 1320fs and (e)-(f) at 1740fs and (g)-(h) for N$_2$ at 1040fs.
FIG. 3. (Color online): Estimation of energy contributions from DLA and WF derived from simulations, (i) He, (ii) mixed (He+N\textsubscript{2}) and (iii) N\textsubscript{2}.
FIG.4. (colour online): Expanded view of electron density profiles simulated at 1040fs (a) He, (b) mixed (He+N\textsubscript{2}) and (c) N\textsubscript{2} targets, showing electron density modulation (SW generation) at channel boundaries in case of mixed and N\textsubscript{2}.