Original Article

# Quasi-Mono-Energetic Electron Beams From An Argon Clustered Gas Target Driven By A Laser For Radiation Therapy

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## Abstract

**Purpose:** To suggest that electron beams with almost the same amount of energy could be used instead of traditional accelerators for high-energy electron radiation therapy. **Methods:** Electron beams with energy up to hundred MeV, 1.8% energy spread, 125 pC charges and a few mDivergences have been made with a clustered gas plasma that is 3 mm long and It operates on a laser pulse with a peak power of up to 100 TW. High-quality electron beams and dependable laser propagation are produced by optimizing experimental factors including laser contrast and the time of the laser-plasma interaction. **Results:** In addition to the self-focusing effect, clustered gas has two other crucial properties: a strong local electron density and effective ultra-short laser pulse absorption. Therefore, high electron densities and ionization levels might produce intense electron beams with a high charge. Our test has shown that the gas jet clusters affect the Wakefield evolution and laser propagation, resulting in steady laser guiding and high-quality electron beams. **Conclusion:** These findings demonstrate that a beam clustered gas target offers a novel method of injecting electrons and has a lot of potential for making collimated electron beams with a high beam charge from a single source of energy. For medical applications like radiation therapy, you need stable, repeatable, and strong enough single-energy electron beams Laser-sped electron beams could be a good way to do radiation therapy in the future. But there are some technical problems that need to be solved before they can be used in real life.

**Keywords:** radiation treatment, gas clusters, and laser-plasma accelerators

## Introduction

Right now, people are thinking a lot about the cluster that Walls' van der-soldiers built [1-4]. In a low-density gas backdrop, a multi-cluster structure develops as supersonic gas expands into vacuum. At the nanoscale level, clusters are a different kind of matter than gases or solids. The interaction of powerful, very brief laser pulses with atomic & molecular clusters has greatly advanced due to the chirped pulse amplification method (CPA) [4] is a current field of study. It has a number of intriguing uses, such table-top plasma Waveguides [5-7] accelerators for relativistic particles [8-12] and sources of X-rays [13,14]. In addition to the characteristics of both solid targets (high density locally and effective energy absorption) & gas targets (prolonged laser–plasma contact), clustered gas targets also possess their own unique optical characteristic [15,16]. A cluster begins to break down after being exposed to a high-power laser pulse thanks to optical field ionization (OFI). Under the circumstances of local solid density, the first creation of free electrons created by OFI effectively generates collision ionization. The clusters now provide a concave refractive index profile over the laser beams cross section. Because of this, the laser beam will automatically concentrate on its target. Some people think that atomic clusters could be used to assist self-guided laser pulses move well. This would join relativistic self-focusing as well as ready-made plasma waveguides as ways to help laser pulses travel well.

(LWFA) Laser Wakefield Acceleration [17] is anticipated to be an effective strategy for the next generation of compact electron accelerators. more than 100 GeV/m acceleration gradients, these portable accelerators have a good chance of taking the place of high-energy accelerators that are used now. Experimental LWFA research has significantly improved the electron beam's purity, stability, controllability, as well as maximum electron energy during the last ten years [18-22]. Electrons can get out of the focused laser volume completely, but they can also get stuck in the accelerating forces of the plasma wave if the laser intensity is more than 1018 W/cm2 [23].

Transverse wave-breaking self-injection, on the other hand, is not the best way to make high-quality electron beams. It needs a strong laser beam a0~4 where a0 aoeAaser / mc2 ) and high plasma density (ne~1018 cm-3), which stops the electron from getting more energy.

$E_{gain}$ (GeV =$(1.7P/100TW)^{1/3}$ $(ne/1018\ cm-3)^{-2/3}$. Very recent

According to the research, 0.3PW may generate electron beams as high as 4.2 GeV. laser pulses driving a9-cm-longcapillarydischarge waveguide at a density of less than 1018 cm-3 [24]. Ionization-induced electron injection is another method [25-28], created electron bunches in pure nitrogen and mixed gases with maximal acceleration lengths near to the dephasing length. Taking advantage of the large gap between the ionization potentials of successive atomic ionization states, this novel method, has the potential to inject electrons into Wakefield, which is powered by low-density lasers. But for a terawatt (TW) femtosecond (fs) laser to have an effective plasma channel for LWFA, the density of the plasma should be above 1018 cm-3. The length of an electron's wave at this density $L_d = L_p^3 3 / L_0^2$ ($L_p$ is the plasma wavelength and $L_0$ is the laser wavelength) is around 1 cm, and inside a 1-cm-long plasma channel, electrons might reach a maximum energy of roughly 1 GeV [20]. To what extent the plasma channel has been planned The acceleration length may be increased to the dephasing length Ld, which would be the distance at which the accelerated electrons first begin to slow down after crossing the plasma wave, if the laser pulse is sufficiently focused.

Gas targets have been used in the majority of laser plasma electron accelerators, as is common knowledge. In addition to the previously described self-focusing action, clustered gas has two other key characteristics: Local solid electron density and efficient ultrashort laser pulse absorption [28]. Therefore, large electron densities and high 2 ionization levels might produce intense electron beams with high charge.

Clusters also change how the Wakefield changes and serves as a source of injected electrons because the laser field ionizes them, and electrons collide with them. According to reports, high-charge relativistic electron beams were created when direct laser acceleration was used to inject and speed up the ejected electrons from the clusters (DLA) [9,14,29].

Radiation treatment has employed electron beams extensively for more than 50 years [30]. To treat skin and superficial illnesses, conventional radiation uses S-band linear accelerators to produce mono-energetic beams with energies between 5 and 20 MeV [31]. These low-energy electrons are unsuitable for cancers of the deep tissue. however, Numerous studies have shown the significant potential of laser-driven electron accelerators for direct electron and X-ray therapy [32,33]. Future medical applications will need mono-energetic electron beams that are stable, repeatable, and have sufficient electron intensities.

Here, we provide the first demonstration of the generation of collimated quasi-mono-energetic ( ~7 mrad) electron beams coming from a target of clustered gas. In our experiment, an Ar supersonic cluster-gas nozzle was targeted by a 100 TW laser pulse to produce electron beams up to 210 MeV. Additionally, we showed how clustered gas exhibits the self-focusing phenomenon, which results in intense laser interactions.

## Methods

Figure 1 depicts our conceptual experimental setup.

The Ti: Sapphire laser system was employed in this experiment. The investigation for this topic was completed at Shanghai Jiao Tong University's Key Laboratory of Laser Plasmas. The current laser setup can generate laser pulses that have a peak power of 100 TW as well as a pulse width of 30 fs. An off-axis parabolic mirror (OAP) with a focal ratio of F/20 was utilised to concentrate the laser beam onto a pinpoint in the sky. The laser's focus point was just 30 m wide at its widest point (FWHM). The maximal laser intensity and related normalized vector potential are determined by these circumstances.

$a_0 = \sqrt{L^2(\mu M) I_o (10^{18} wcm^{-2})}$

where 7.0 × 1018 W/cm-18 and 1.9, respectively. Above the middle of a cylindrical gas jet nozzle, the focus point was positioned [34] 3 mm in diameter. The nozzle makes an Argon gas flow that is 99.99 % pure and goes at 4.8 Mach. Adjusting the gas-jet stalling pressure from 0 to 5 MPa alters the gas density. Hagena's scaling rule states that [1] our experiment was carried out at a significantly lower degree of clustering, with tiny cluster sizes and low distribution densities. When quasi-monoenergetic electron beams were identified, for example, at 3 MPa backing pressure, the predicted average cluster-gas jet density is 3×1019 cm-3 [1,11,34]. By utilizing a band-pass filter to picture the dispersed laser light from above, the laser-plasma interaction was investigated. Using Fuji BAS-SR image plates, DRZ (Mitsubishi Chemical), With a 0.98 T, 16 cm long dipole moments magnet, the accelerated electron beam's spatial profile was assessed (Gd2O2S: Tb) [20].

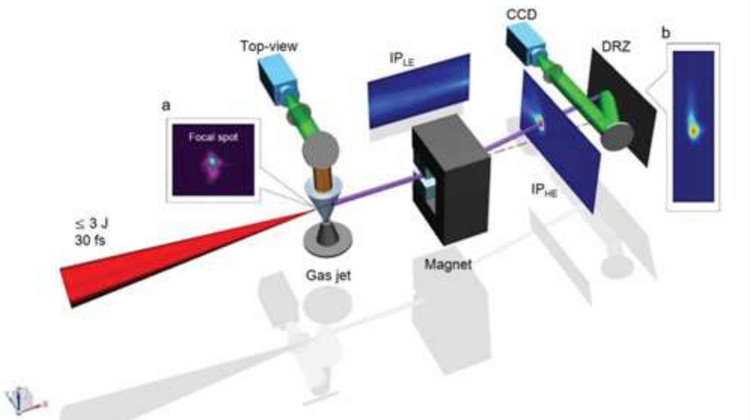


**Figure 1** The experimental setup is shown schematically here. Pictured inset (a) demonstrates the ideal vacuum focus location. Inset displays raw data of electron beam energy spectrum (b).

energy spectrum. In this case, the laser's polarization is vertical, and the magnet field scatters the electrons horizontally. Two 15-m-thick Al foil image plates were set up at right angles and diagonally opposite the direction of laser light, respectively, at the dipole magnet's exits. IPLE collected electrons with energies below 100 MeV, while betatron X-rays and energy-dispersed electrons with energies more than 100 MeV were distinguished by IPHE. The beam dump was hit by deflected electrons with kinetic energies less than 50 MeV. An improved charge-coupled device (ICCD) camera was used to study the spectral energy distribution of electron beams at the DRZ.

The experiment's electron beam quality was enhanced by adjusting variables such as the gas jet nozzle, laser pulse delay time, and gas background pressure. When heated by a laser pre-pulse, clusters created by the condensation of atoms in vacuum would gradually expand and unite to create spatially homogeneous plasma in 10-100 ps [5]. Because of this, the gas jet nozzle must be activated just before the contact; otherwise, the clusters would be destroyed or unformed when the laser pulse arrived, resulting in inadequate plasma channels and ineffective signals from the electron beams. This experimental finding shows that clusters are where the majority of the injected electrons come from. Figure 2 shows that when the background pressure was set to 3 megapascals and 7.8 milliseconds before to the arrival of the laser pulse, the gas jet nozzle was turned on, the best guiding efficiency was achieved. This was the case when the background pressure was also 3 megapascals.

In almost all pictures, collimated electron beams can be seen alongside the laser pulse, as seen in Figure 2a. This is made possible by the laser pulse's self-guiding.Along its journey, we also saw the laser pulse periodically concentrating and blurring as it moved. The physical characteristics of a collimated, optimally-parameterized electron beam is shown in Figure 2b.The 6.4 m rad and 9.1 mrad (FWHM) horizontal and vertical divergences, respectively.

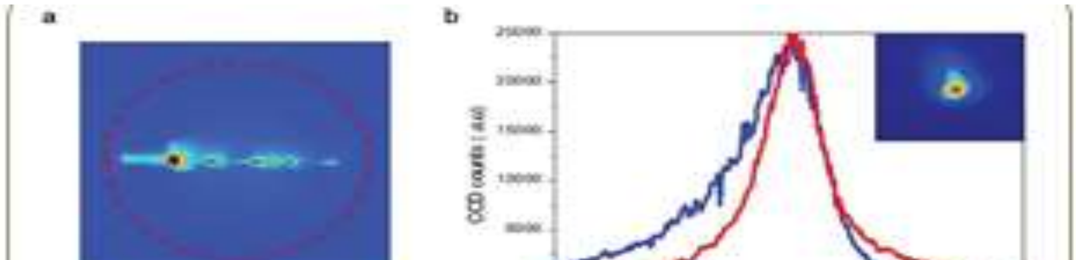
Long interaction channels or filaments channels stretching to multiple Rayleigh lengths (where $\omega_0$ is the laser frequency and p is the plasma frequency) arise often in LWFA if the power of the laser is great enough, it will self-focus in a relativistic sense. In contrast, a pure helium target under the same circumstances showed no evidence of a plasma channel (0.5 mm in width) or an electron beam, demonstrating the absence of self-guided laser propagation or self-injection. These results give a novel approach for accelerating electrons and show that clusters induce strong laser pulse self-focus.

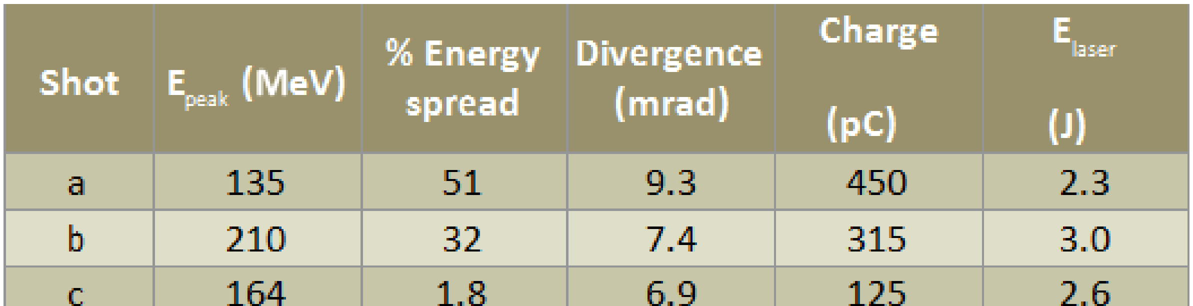
## Results

In Figure 3, we see the resultant electron energy spectra from three separate shots made at different laser intensities. IPLE (100 MeV), IPHE (>100 MeV), and the original energy spectra around the high energy peak are given in three columns, left to right. Table 1 provides useful data for these photos. And the appropriate laser contrast is rising from 10-6 to 10-8 in turn. Cluster damage may be reduced or even eliminated by employing high contrast laser. The wide energy spectrum seen in Figure 3a has a peak energy of around ~135 MeV and a total charge of about ~450 pC. Low laser contrast is often used to produce poor-quality beam energy spread. And as the laser contrast grows, so does the beam quality. The increase in beam quality is shown in Figure 3b, which results in a quasi-monoenergetic e-beam with an energy peak of ~210 MeV, an energy spread of 32 percent, and a total charge of ~315 pC. Meanwhile, electrons with energies over 300 MeV may be seen near the high-energy front. The beam quality will significantly increase with further laser contrast optimization. A quasi-monoenergetic electron beam with an energy spread of ~1.8%, a peak electron energy of 164 MeV, and a total charge of ~125 pC is shown in Figure 3c. When the peak width contribution from the horizontal by assuming that the electrons' energy dispersion plane divergence is identical to the e-vertical beam's divergence, In Table 1, we see the computed absolute energy spread.

ionization-induced injection and beam loading might explain our experimental findings [35]. Ar+ has an ionization potential of 144 eV, needing IL 4 1016 W/cm-2, whereas Ar9+ and Ar10+ require 425 and 481 eV, respectively, and 1018 W/cm-2 of IL. The leading front of the laser pulse pre-ionizes the Ar M-shell electrons, forming the Wakefield bubble's electron sheath. The laser pulse peak and optical-field ionization of the gas atom cause the inner shell electrons in Ar clusters to be collision ally ionized out. The laser-driven charge separation creates a field and an electrostatic field, where clusters of electrons flit about [8,13]. Due to laser absorption, energetic electrons exit clusters [28] The longitudinal electric field will trap and accelerate them if they have sufficient energy to move at the phase velocity of the wake.

As the Wakefield's longitudinal accelerating field is depleted by the injection of ionized electrons from clusters, the injection ceases because the electrons no longer acquire sufficient energy to be imprisoned. Beam loading [36], Our experiment's energy dispersion can be controlled by limiting the charge of the electron bunch. Loaded charge Q (nC) > (where is the plasma surface thickness (in kp-1), is the wake blowout radius, and Rb is the electric field due to the injected electrons) [35].





| Shot | $E_{peak}$ (MeV) | % Energy spread | Divergence (mrad) | Charge (pC) | $E_{laser}$ (J) |
|---|---|---|---|---|---|
| a | 135 | 51 | 9.3 | 450 | 2.3 |
| b | 210 | 32 | 7.4 | 315 | 3.0 |
| c | 164 | 1.8 | 6.9 | 125 | 2.6 |

Table Figure 3's laser settings and e-beam characteristics. In the energy spectrum, E peak is the energy peak. The final energy distribution after unfolding is shown in the third column. In the fourth column, we see how far the electron beams are splayed out vertically. The fifth column displays the total charge (more than 50 MeV). From a to c, the laser contrast rises progressively.

Considering matching condition, estimate total loaded charge [37]. The laser & plasma properties are incompatible; hence the formula did not perform well in our case. The clusters are protected from the pre-pulse and guaranteed fast engagement with the main laser pulse when the laser contrast is strong. The laser-cluster interaction produces a significant number of injected electrons at practically solid density. Thus, a huge number of electrons will be ionized from the clusters as well as pumped into the Wakefield by means of a strong laser pulse [8,13]. Compared to a nitrogen gas laser-driven target, this scenario's high ionization levels and high electron densities result in a much speedier injection procedure (typical ionization-induced electron injection regime). As the injected electrons counteract the longitudinal accelerating force, the electron beam loads the wake instantly, stopping the injection.

The quasi-monoenergetic electron beam can only have an energy dispersion of 1.8 percent due to the beam loading effect, hence it must be produced using an incredibly rapid injection method. The image of this electron beam shown in Figure 3c. The reduced laser contrast, which has an impact on the effectiveness of directing laser pulses, is the primary cause of the apparent insufficiency of the plasma channels. A pre-pulse ionized the clusters and raised the plasma density before the major laser pulse arrived. It has been demonstrated that the relationship between the total loaded charge Q and the plasma density [37,38]. As can be seen in Figures 3a and 3b, this prolonged injection technique produces e-beams with a large charge and a wide range of energies. Figure 3a shows a broad energy spectrum, but the maximum cumulative charge is 450 pC. (Despite being above 50 MeV).

## Conclusion

According to the results of the studies, quasi-monoenergetic electron beams with just an energy dispersion of 1.8% and peak energies of ~164 MeV, and high beam charges of ~125 pC (> 50 MeV) can be made with the help of 100 TW lasers and a cluster of Argon gas jets. High-quality electron beams and steady laser propagation are produced by optimizing experimental variables including laser contrast and gas jet nozzle timing. We discovered that clusters in the gas jet had an impact on the Wakefield evolution and laser propagation, resulting in steady laser guiding and high-quality electron beams. Based on our findings, laser-driven clustered gas targets provide a fresh approach to electron injection and hold great promise for producing monoenergetic electron beams with high beam charge. With sufficient electron intensities, mono-energetic e-beams with stable and repeatable characteristics are produced, offering a potential plan for future radiation therapy.

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