AIP Applied Physics Letters

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Citation: Appl. Phys. Lett. **100**, 014104 (2012); doi: 10.1063/1.3673911
View online: http://dx.doi.org/10.1063/1.3673911
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v100/i1
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Electron acceleration via high contrast laser interacting with submicron clusters

Lu Zhang,[1] Li-Ming Chen,[1,a)] Wei-Ming Wang,[1] Wen-Chao Yan,[1] Da-Wei Yuan,[1] Jing-Yi Mao,[1] Zhao-Hua Wang,[1] Cheng Liu,[1] Zhong-Wei Shen,[1] Anatoly Faenov,[2,3] Tatiana Pikuz,[2,3] Da-Zhang Li,[1,4] Yu-Tong Li,[1] Quan-Li Dong,[1] Xin Lu,[1] Jing-Long Ma,[1] Zhi-Yi Wei,[1] Zheng-Ming Sheng,[5] and Jie Zhang[1,5]

[1]*Beijing National Laboratory of Condensed Matter Physics, Institute of Physics, CAS, Beijing 100080, China*
[2]*Joint Institute for High Temperature of the Russian Academy of Sciences, Izhorskaya 13/19, Moscow 127412, Russia*
[3]*Quantum Beams Science Directorate, JAEA, Kizugawa, Kyoto, Japan*
[4]*Institute of High Energy Physics, CAS, Beijing 100049, China*
[5]*Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China*

(Received 27 October 2011; accepted 12 December 2011; published online 4 January 2012)

We experimentally investigated electron acceleration from submicron size argon clusters-gas target irradiated by a 100 fs, 10 TW laser pulses having a high-contrast. Electron beams are observed in the longitudinal and transverse directions to the laser propagation. The measured energy of the longitudinal electron reaches 600 MeV and the charge of the electron beam in the transverse direction is more than 3 nC. A two-dimensional particle-in-cell simulation of the interaction has been performed and it shows an enhancement of electron charge by using the cluster-gas target. [doi:10.1063/1.3673911]

With the development of terawatt ultrashort lasers using the chirped pulse amplification technique, the focused laser intensity could easily reach 10^{18} W/cm^2 and higher. Such pulses can drive various types of plasmas to accelerate beams of relativistic electrons[1–7] and MeV protons, produce hard x-rays[8–10] and other exotic particles. In electron acceleration, the laser's ponderomotive force creates laser wake field acceleration[2] structure which traps and accelerates electrons to a very high energy within a very short distance. In recent years, significant progress[11–13] has been made in enhancing the energy and quality of electron beams. Monoenergetic electron bunches with energies up to 1 GeV can be generated[6,7] by the interaction of tens terawatt laser pulses with underdense plasmas. But in these results, the charge of the electrons was limited to 10s pC or less limiting the applications those electron beams. In order to get a higher electron charge, several injection mechanisms have been proposed; however, these are experimentally hard to implement.

Clusters have recently received attention as a unique laser-plasma media. Compared with gaseous and solid targets, a cluster target formed by high-pressure gas nozzle has very important properties, such as local solid electron density, but low density on average. The laser transmission distance in the clusters is longer than the distance in gas target and also the laser energy absorption in the cluster higher than the solid target. Clustering gas has been demonstrated as an efficient medium for self-guided propagation of laser pulses in previous experiments.[14–16] And, a directional hot electron beam with energy about 100 keV was generated along the laser propagation direction from Ar clusters using non-relativistic laser pulses.[17]

In the experiments reported here, we study the effect of high contrast laser pulses interacting with a cluster-gas target containing argon clusters. We observed high-energy electron beam with energy up to 600 MeV along the laser propagation direction and another electron beam having even higher charge of about 3 nC in the direction perpendicular to the laser propagation. Simulation shows that the electron charge in the transverse direction is greatly enhanced by using the gas-cluster mixture compared with atomic gas.

The experiment was performed using the Extreme Light-III laser facility at the Institute of Physics, Chinese Academy of Sciences. A sketch of the experimental setup is shown in Fig. 1. We focused an ultrashort 100 fs laser pulses at a wavelength of 800 nm with an f/3 off-axis parabola onto a supersonic argon gas-jet. The energy of the laser is about 1 J, 30% of the energy was contained in a diameter of 6 μm at full width half maximum (FWHM) of the focus spot. With the help of the optical parametric chirped pulse amplification technique, the laser contrast (picosecond pre-pulse) of the laser has been optimized to 10^{-10} (Ref. 18). The cluster-gas target is produced by the expansion of high pressure Ar gas

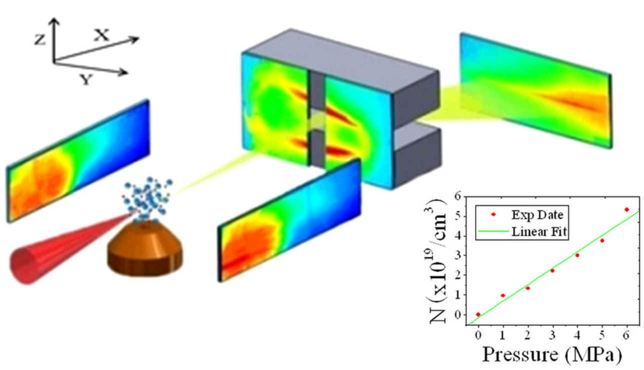

FIG. 1. (Color online) Schematic diagram for the experiment. The inset shows gas jet density at Z=1mm, the points are the density measured in the experiment and the line is the fitting curve.

a)Electronic mail: lmchen@aphy.iphy.ac.cn.

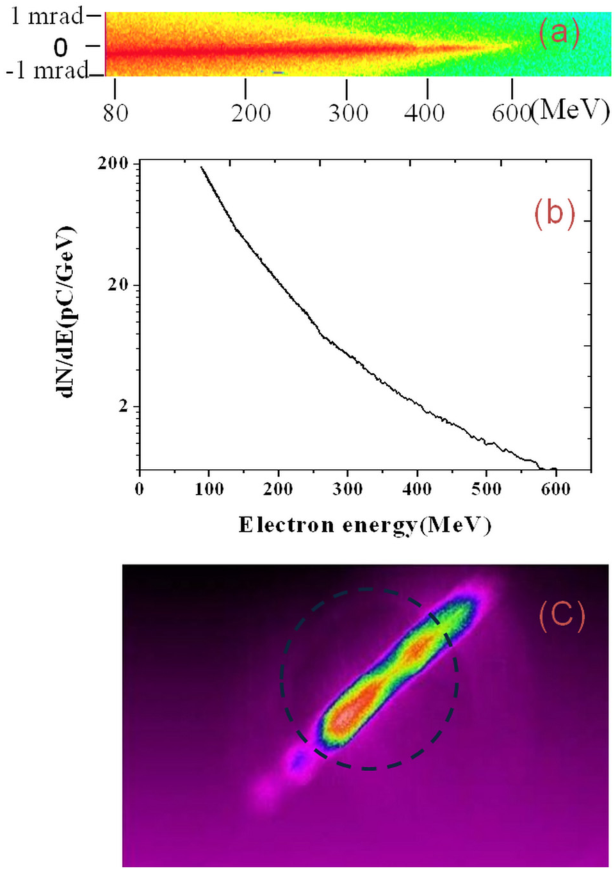

FIG. 2. (Color online) (a) Image of electron signal obtained on the IP after dispersive magnet. (b) Experimental electron spectra after calculated. (c) Thomson scattering imaging on topview CCD, dashed line is the position of 2 mm nozzle.

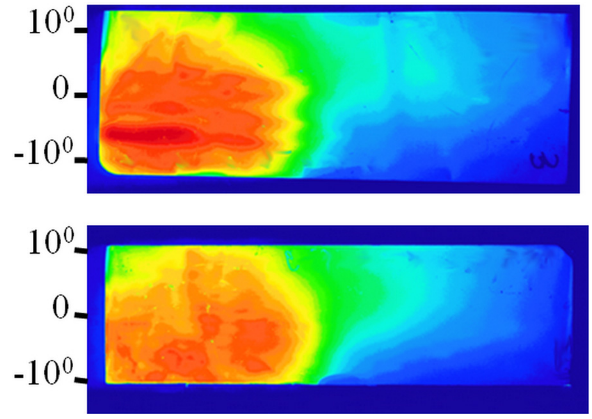

FIG. 3. (Color online) Image of transverse electron spatial distribution.

out of a conical nozzle with a 3 mm diameter orifice and 1 mm diameter throat. Clusters with size of 0.14 μm can be produced when the argon gas pressure is 7 MPa. We have characterized the atomic density profile of the gas jet with a Mach-Zehnder Interferometer. The inset of Fig. 1 shows the cluster densities versus the stagnation pressure of the argon gas. The energy spectrum of the forward electron beam was detected by using a magnetic spectrometer which is composed of the following components: dipole magnet (0.9 T), high resolution image plate (IP of Fuji BAS-SR), and 200 μm thick Cu foils wrapped IP to block the laser light or interference-ray. The magnet and IP were located at distances of 16 cm and 47 cm from the nozzle center. A 1 mm thick lead slit was placed in front of the magnet and two IPs with 37.5 μm thick Al filter were put on the slit. Another two IPs were installed at 90° to the laser axis to detect transversely emitted electrons, the distance between the IPs and the nozzle was 7 cm. These two IPs are all covered by the 400 μm Cu foils.

We know the prepulse of low contrast laser can ionize clusters, and clusters will be shrinked in size or destroyed before interacting with the main laser pulse.[19] By using high contrast laser, the damage of clusters can be avoided. In order to get an optimized electron beam signal, the Ar gas stagnation pressure and the position of the nozzle with respect to the laser focus were optimized. The best interaction point was about vertically 1 mm above the gas jet and 0.5 mm longitudinally away from the nozzle center. The size of clusters is very important for the level of cluster ionization.[20,21] There was no electron beam along the laser propagation direction when the Ar gas pressure was in the range 1–6 MPa. The accelerated electron beam was observed at 7 MPa pressure. This proved, in the case of large clusters, the colliding ionization will be enhanced which lead to strengthen the effective injection for the longitudinal acceleration and the transverse acceleration mentioned after. Under these experimental conditions, the average density of the cluster-gas target was about $5.5 \times 10^{19}\,\mathrm{cm}^{-3}$. Fig. 2(a) shows the image of the longitudinal electron beam on the IP after magnet. Limited by the size of the IP, we detect a continuous energy spectrum, covering from 80 MeV to 600 MeV. The electron beam had a minimum angle of divergence less than 1.4 mrad as determined from vertical axis. Fig. 2(b) shows the electron spectrum calculated from the image. The photostimulated luminescence (PSL) number of the IP can be used to estimate the electron beam charge,[22] the total charge of the electron with energy larger than 80 MeV is estimated to be about 50 pC. The spectra assume to have a Maxwellian distribution. A top-view CCD can record the Thomson scattering in Fig. 2(c) by which we know the transmission length of the laser beam inside the cluster target media. It is about 3 mm in this case.

The spatial distribution of electrons along laser polarization direction is presented in Fig. 3. The 400 μm Cu filters in front of the IP can block x-rays and electrons having energies up to 1 MeV. The stopping energies are calculated with the Casino V2.42 Code.[23] The divergence angle of the electron beam in x-z plane is about 11° in FWHM. From the images, the transverse electrons seem to be conical acceleration. From the PSL number of one IP, the electric charge of accelerated electrons with energy larger than 1 MeV is about 1.5 nC, and the total charge of the transverse beams are estimated to be 3 nC per shot. This high charge electrons' emission indicate that clusters as a medium can interact strongly with intense laser pulses.[24] And the accelerated hot electrons can emission from the narrow interaction channel easily because of the small focal spot.

2D particle-in-cell simulation code is used to further study the laser-cluster interactions. The laser parameters in the simulations are same to those used in the experiment. Plasma densities are chosen between $1 \times 10^{19}\,\mathrm{cm}^{-3}$ and

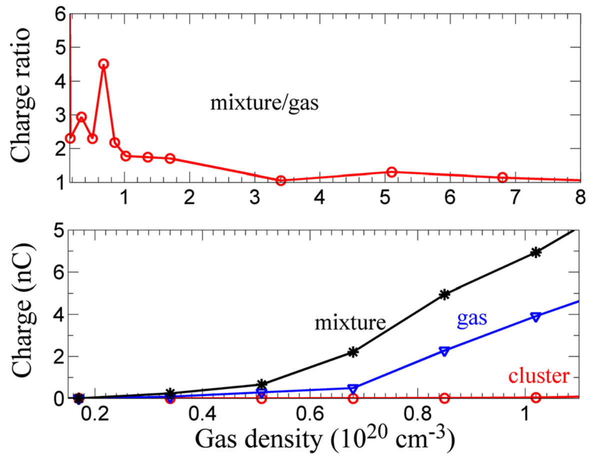

FIG. 4. (Color online) Particle-in-cell code simulation results of electron charge.

$8 \times 10^{20}\,\mathrm{cm}^{-3}$, and the plasma are gas, cluster, or a mixture of cluster-gas individual. As seen in Fig. 4, simulation shows that in pure clusters a transverse electron beam is not generated. And we found that the highest electron charge ratio of about 5 between mixture gas-clusters and pure gas can be achieved when the density is $7 \times 10^{19}\,\mathrm{cm}^{-3}$ in case cluster size reaches to the maximum in experiment.

In Fig. 1, two IPs in front of the magnet shows a strong signal of one shot. The emission angle of this signal is about 15° to the x-axis. The 37.5 μm thick Al filter before the IP can almost block the K-shell x-ray (2.96 keV) of Ar cluster; however, we found that the center of the signal is already saturated. The nature of this signal could possibly be electrons as observed by other group.[25] However, the electron charge in our case is higher than 4 nC, which is much larger than their measurement. The other possibility is that this signal is hard x-ray when accelerated electrons are wiggling in the wakefield cavity.[26]

In conclusion, electrons with energy up to 0.6 GeV in forward direction are generated by the interaction of a 10 TW laser pulse with a gaseous argon cluster target; it provides an alternative to enhancing electron energy by using laser with medium size. And the high energy electrons also mean the effective coupling between laser and plasmas. It may result in stronger target normal sheath acceleration for the ions.[15] The charge with the energy higher than 80 MeV is about 50 pC. We also observed a transversally emitted ultra-relativistic electron beam with charge larger than 3 nC due to laser-cluster interaction in the transverse direction. There can be many attractive applications of those electrons if their energy is relativistic, such a high charge of the transversally generated electrons having a certain initial velocity could be useful for injection into laser driven wake field accelerator or conventional accelerators, as well as the generation of strong THz radiation. Applications of those electrons beams are planned in future experiments.

We thank N. M. Hafz of SJTU for fruitful discussions. This work was supported by the NSFC (GrantsNo. 60878014, No. 10974249, No. 10735050, No. 10925421, No. 11105217, and No. 10734130) and partly by the Russian Foundation for Basic Research (Projects 10-02-91174-GFEN_a and 10-02-00345-a)

[1] T. Tajima and J. Dawson, Phys. Rev. Lett. **43**, 267 (1979).

[2] V. Malka, S. Fritzler, E. Lefebvre, M.-M. Aleonard, F. Burgy, J.-P. Chambaret, J.-F. Chemin, K. Krushelnick, G. Malka, S. P. D. Mangles *et al.*, Science **298**, 1596 (2002).

[3] S. P. D. Mangles, C. D. Murphy, Z. Najmudin, A. G. R. Thomas, J. L. Collier, A. E. Dangor, E. J. Divall, P. S. Foster, J. G. Gallacher, C. J. Hooker *et al.*, Nature **431**(7008), 535 (2004).

[4] C. G. R. Geddes, C. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, Nature **431**(7008), 538 (2004).

[5] J. Faure, Y. Glinec, A. Pukhov, S. Kiselev, S. Gordienko, E. Lefebvre, J. P. Rousseau, F. Burgy, and V. Malka, Nature **431**(7008), 541 (2004).

[6] W. P. Leemans, B. Nagler, A. J. Gonsalves, C. Toth, K. Nakamura, C. G. R. Geddes, E. Esarey, C. B. Schroeder, and S. M. Hooker, Nat. Phys. **2**(10), 696 (2006).

[7] N. A. M. Hafz, T. M. Jeong, I. W. Choi, S. K. Lee, K. H. Pae, V. V. Kulagin, J. H. Sung, T. J. Yu, K.-H. Hong, T. Hosokai, J. R. Cary, D.-K. Ko, and J. Lee, Nature Photon. **2**(9), 571 (2008).

[8] M. Yoshida, Y. Fujimoto, Y. Hironaka, K. G. Nakamura, K. Kondo, M. Ohtani, and H. Tsuneme, Appl. Phys. Lett. **73**, 2393 (1998).

[9] L. M. Chen, M. Kando, J. Ma, H. Kotaki, Y. Fukuda, Y. Hayashi, I. Daito, T. Homma, K. Ogura, and M. Mori, Appl. Phys. Lett. **90**, 211501 (2007).

[10] L. M. Chen, M. Kando, M. H. Xu, Y. T. Li, J. Koga, M. Chen, H. Xu, X. H. Yuan, Q. L. Dong, Z. M. Sheng, S. V. Bulanov, Y. Kato, J. Zhang, and T. Tajima, Phys. Rev. Lett. **100**, 045004 (2008).

[11] S. P. D. Mangles, A. G. R. Thomas, M. C. Kaluza, O. Lundh, F. Lindau, A. Persson, F. S. Tsung, Z. Najmudin, W. B. Mori, and C.-G. Wahlström *et al.*, Phys. Rev. Lett. **96**, 215001 (2006).

[12] W. M. Wang, Z. M. Sheng, and J. Zhang, Appl. Phys. Lett. **93**, 201502 (2008).

[13] W. Lu, C. Huang, M. Zhou, W. B. Mori, and T. Katsouleas, Phys. Rev. Lett. **96**, 165002 (2006).

[14] L. M. Chen, H. Kotaki, K. Nakajima, J. Koga, S. V. Bulanov, T. Tajima, Y. Q. Gu, H. S. Peng, X. X. Wang, T. S. Wen *et al.*, Phys. Plasmas **14**, 040703 (2007).

[15] Y. Fukuda, A. Ya. Faenov, M. Tampo, T. A. Pikuz, T. Nakamura, M. Kando, Y. Hayashi, A. Yogo, H. Sakaki, T. Kameshima *et al.*, Phys. Rev. Lett. **103**, 165002 (2009).

[16] Y. Fukuda, A. Ya. Faenov, T. Pikuz, M. Kando, H. Kotaki, I. Daito, J. Ma, L. M. Chen, T. Homma, K. Kawase *et al.*, Appl. Phys. Lett. **92**, 121110 (2008).

[17] L. M. Chen, J. J. Park, K. H. Hong, J. L. Kim, J. Zhang, and C. H. Nam, Phys. Rev. E **66**, 025402 (2002).

[18] C. Liu, Z. H. Wang, W. C. Li, Q. Zhang, H. N. Han, H. Teng, and Z. Y. Wei, Opt. Lett. **35**, 3096 (2010).

[19] T. Auguste, P. D'Oliveira, S. Hulin, P. Monot, J. Abdallah, A. Ya. Faenov, I. Yu. Skobelev, A. I. Magunov, and T. A. Pikuz, JETP Lett. **72**, 38 (2000).

[20] J. Abdallah, Jr., G. Csanak, Y. Fukuda, Y. Akahane, M. Aoyama, N. Inoue, H. Ueda, K. Yamakawa, A. Ya. Faenov, A. I. Magunov *et al.*, Phys. Rev. A. **68**, 063201 (2003).

[21] M. E. Sherrill, J. Abdallah, Jr., G. Csanak, E. S. Dodd, Y. Fukuda, Y. Akahane, M. Aoyama, N. Inoue, H. Ueda, K. Yamakawa *et al.*, Phys. Rev. E **73**, 066404 (2006).

[22] K. A. Tanaka, T. Yabuuchi, T. Sato, R. Kodama, Y. Kitagawa, T. Takahashi, T. Ikeda, Y. Honda, and S. Okuda, Rev. Sci. Instrum. **76**(1), 013507 (2005).

[23] P. Hovington, D. Drouin, and R. Gauvin, Scanning **19**, 1 (1997).

[24] Y. Kishimoto, L. Hillman, and T. Tajima, *High Field Science*, (Kluwer-Plenum, New York, 2000), p. 85.

[25] D. Kaganovich, D. F. Gordon, and A. Ting, Phys. Rev. Lett. **100**, 215002 (2008).

[26] K. T. Phuoc, S. Corde, R. Shah, F. Albert, R. Fitour, J.-P. Rousseau, F. Burgy, B. Mercier, and A. Rousse, Phys. Rev. Lett. **97**, 225002 (2006).