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# Emission of a hot electron jet from intense femtosecond-laser–cluster interactions

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A directional hot electron jet with energy higher than 100 keV was generated along the laser propagation direction from Ar clusters irradiated with a laser pulse of duration 28 fs and intensity $1\times10^{17}$ W/cm$^2$. The hot electron jet was detected only with linearly polarized laser pulses, not with circularly polarized pulses. Channel betatron resonance is believed to be the main accelerating mechanism for this directional hot electron jet.

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Hot electrons generated by intense laser pulses incident on rare gas targets have attracted much attention because of their relevance to advanced concept accelerators and radiation sources [1]. Recent development of ultrashort high-power lasers using the chirped pulse amplification technique has achieved laser intensity well above $10^{18}$ W/cm$^2$, intense enough to drive ionized electrons to relativistic velocity. The ponderomotive force of intense laser field can result in relativistic self-focusing of the propagating laser beam and directional electron acceleration [1,2]. A high-energy electron beam can be generated mainly through two mechanisms. One is the laser wake-field acceleration (LWFA) [2], in which the ponderomotive force of a driving laser drives plasma waves quasiresonantly. This mechanism is considered dominant at low gas density and high laser intensity. The second acceleration mechanism is a direct laser acceleration (DLA) at the channel betatron resonance (CBR) [3], observed when transverse oscillation of electrons at betatron frequency matches the laser frequency. The DLA can be stimulated at comparatively lower intensity than LWFA, but at relatively high gas density [4].

The interaction of intense ultrashort laser pulses with van der Waals–bonded atomic clusters creates unique conditions for laser-matter interactions. The high local density within a cluster, coupled with low average-density gas, provides an effective coupling of the intense laser pulse with the interacting medium. It has been observed that cluster targets could absorb incident laser energy efficiently [5]. Efficient coupling of intense ultrashort laser pulses with cluster targets can generate high-temperature plasma with highly charged ions, and local electron density during the laser-pulse duration can be quite high since the plasma expansion is minimal. These interaction conditions can provide quite different environments, compared to those of gas targets, producing strong extreme ultraviolet (XUV) emission [6], along with high-energy electrons [7] and ions [8], or fusion neutrons [9]. In this Rapid Communication, we report on the observation of a hot electron jet emitted from atomic clusters irradiated with a femtosecond laser pulse at modest intensity ($1\times10^{17}$ W/cm$^2$). The polarization dependence of the hot electron jet emission indicates that the hot electron jet is generated through the DLA at CBR.

The experiments on the generation of hot electron jet were carried out with a chirped pulse amplification Ti:Sapphire laser operating at 820 nm at a repetition rate of 10 Hz. The laser delivered 28-fs, 30-mJ pulses. The Ti:Sapphire oscillator was operated in a long cavity mode (45 MHz) to minimize any leakage femtosecond prepulses. The linearly polarized laser beam was focused with a spherical mirror of 45-cm focal length, yielding a peak intensity of about $1\times10^{17}$ W/cm$^2$. A quarter-wave plate was used when a circularly polarized light was needed. Atomic Ar clusters were produced with a pulsed gas jet with a nozzle diameter of 0.2 mm. With sufficiently high backing pressure, clusters are formed in the gas jet flow due to the adiabatic cooling of a gas expanding into vacuum [10]. The jet was operated at a backing pressure up to 22 bars, and the gas jet could be cooled by passing the gas line through a liquid nitrogen reservoir that also cooled the nozzle tip [6].

The diagnostic used for the measurement of hot electron spectra was a 45° focusing magnetic spectrometer, placed in a permanent magnetic field of $B=650$ G. An array of LiF thermoluminescent dosimeter (TLD) pieces (model GR-200F) was used as detectors. Recent development of ultrasensitive LiF TLD provided thin TLD for hot electron detection [11]. The energy range of this instrument is from 7 keV to 1 MeV. Its energy resolution was better than 5%. The background of these TLDs that were heat-treated at 240 °C was less than 10 $\mu$Gy (1 Gy = the radiation dose of one joule of energy absorbed per kilogram of matter). For the measurement of the forward direction, we also piled up a stack of TLD pieces wrapped with 18-$\mu$m Al foil to detect hot electrons, which provided an electron spectrum after deconvolution. With an array of TLDs attached inside a hemisphere, the angular distribution of hot electron emission was measured. The electron energy reaching the TLDs was controlled by the thickness of Al foil wrapped around the TLD film. Soft x-ray emission was measured using a space-resolving, flat field XUV spectrometer [12]. We also used a calorimeter to measure a laser absorption rate in laser-cluster interactions and a visible charge coupled device to measure a plasma length.

Hot electron spectra were measured in the transverse and forward directions at a laser intensity of $1\times10^{17}$ W/cm$^2$ and Ar backing pressure of 20 bars. The gas jet was cooled down to a temperature of −70 °C using a cooling reservoir [6]. Figure 1 shows that the hot electron energy in the transverse

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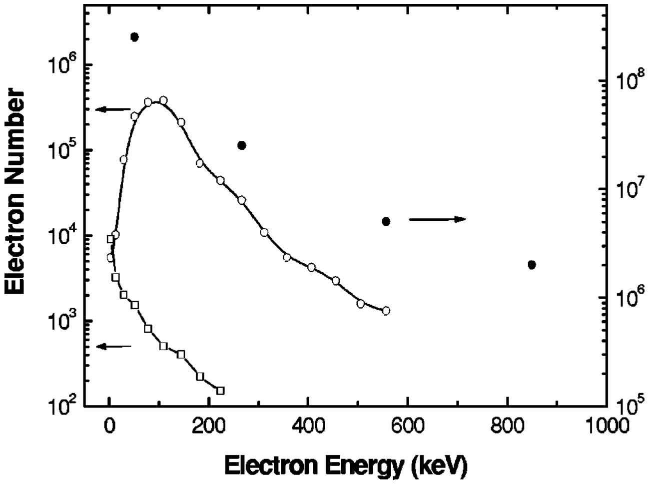
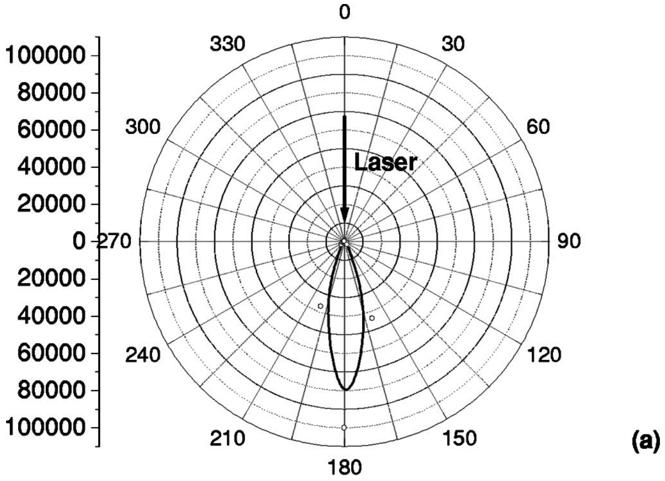


FIG. 1. Hot electron spectra, measured along the transverse direction (open circle) and longitudinal direction (solid circle), from Ar clusters irradiated with a laser pulse of duration 28 fs and intensity $1\times10^{17}$ W/cm$^2$. The electron spectrum (open square) taken with a femtosecond prepulse at 80 ps before the main pulse is also shown.

direction reached over 500 keV and that in the forward direction it extended much further. The number of electrons in the forward direction was larger by three orders of magnitude than that in the transverse direction when compared at the same solid angle of $4\times10^{-4}$ sr. Another important feature was a large difference in electron temperature. In the forward direction, hot electron temperature, fitted with a Maxwellian distribution, was as high as 250 keV; however, in the transverse direction, it was only 60 keV. Consequently, it clearly shows that electrons were strongly accelerated along the laser propagation direction.

Hot electrons would not be observed if clusters were disassembled before the arrival of a laser pulse. For verifying the hot electron generation through the interaction of intense laser pulse with clusters, a prepulse was introduced before the main pulse. A part (7%) of the laser pulse was split as the prepulse and injected 80 ps before the main pulse. This prepulse was still strong ($>10^{15}$ W/cm$^2$) enough to heat and expand the clusters. Most clusters should be completely disassembled when the main pulse arrived 80 ps after the prepulse, according to the expansion time scale for clusters [13], especially at the central part of the focal spot. With the prepulse, the observed electron energy spectrum was quite different from the prepulse-free case. As shown in Fig. 1, the number of hot electrons and also the hot electron energy decreased dramatically. Thus, the observed hot electrons in the prepulse-free case were generated from irradiated clusters.

Using hemispherically installed detectors, the angular distribution of hot electron generation was measured to identify the directionality of hot electron generation. An array of TLD detectors wrapped with 18-$\mu$m-thick Al foil was placed on the inner side of a hemisphere. This Al foil could block energetic ions, scattered laser light, the majority of soft x rays, and electrons with energy below 50 keV. Thus, this system was suitable for the angular detection of energetic electrons.



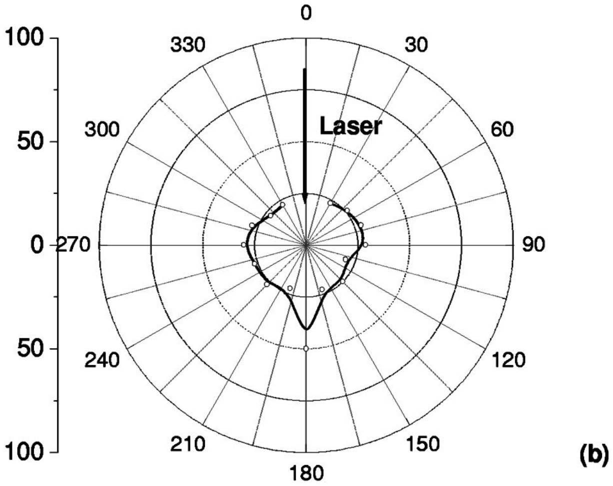


FIG. 2. Angular distribution of hot electrons at the horizontal plane with energy over 50 keV. (a) Linearly polarized laser pulse with a duration of 28 fs and an intensity of $1\times10^{17}$ W/cm$^2$ was interacting with Ar clusters and (b) circularly polarized laser pulse with the same duration and intensity was incident on clusters.

Hot electron angular distribution, shown in Fig. 2(a), was obtained with the same experimental conditions as in Fig. 1. At this temperature and Ar backing pressure, an average cluster radius of about 40 Å was estimated from a Rayleigh scattering measurement [14]. The angular detection of hot electrons showed a sharply directional hot electron jet emission along the laser propagation direction. The angular divergence of the hot electron jet was less than 30° at FWHM for electrons with energy above 50 keV. The highest TLD dose was nearly several tens of mGy, which is about 1000 times higher than that in the transverse emission. When a circularly polarized laser pulse was incident on the cluster, noticeable hot electron jet emission was not detected on TLDs placed inside the hemisphere, as shown in Fig. 2(b), and also in the electron spectrometer, which means that the hot electron jet emission occurred only from the interaction of a linearly polarized laser pulse with atomic clusters.

It is of great importance to determine the emission mechanism of the hot electron jet at our experimental conditions. Inverse bremsstrahlung cannot generate high-energy electrons at this modest laser intensity [15]. The result obtained with circularly polarized laser pulses also verifies this assertion. It is not possible for these electrons to come from photoelectrons generated through high-order above-threshold ionization (ATI) process because the ponderomotive energy (average kinetic energy of sinusoidally oscillating free electrons) is less than 6 keV at this intensity [16]. These photoelectrons cannot pass through the 18-$\mu$m Al foil and also the direction of the electron emission from ATI is along the laser polarization [17]. Only two kinds of mechanisms can produce hot electrons along the laser propagation direction—LWFA and CBR. With laser intensities well above $10^{18}$ W/cm$^2$, LWFA can produce energetic electrons along the laser propagation direction [1,2]. With ion inertia providing an electrostatic restoring force, an intense laser field can drive a large amplitude electron plasma wave, converting the laser energy into a longitudinal electrostatic laser wake field. Propagating at nearly the speed of light, the electron plasma wave can accelerate electrons along the laser propagation direction. The laser intensity to stimulate the LWFA is much higher than the laser intensity used in our experiments. The observation that the emission of a hot electron jet was absent in the cases of the prepulse and of the circularly polarized pulse rules out the possibility of LWFA because the hot electron emission cannot be greatly affected by a prepulse or by laser polarization in the case of LWFA [2]. In addition, strong electron plasma waves for LWFA can be achieved when the laser-pulse duration is of the order of $1/\omega_p$, where $\omega_p$ is the plasma frequency. In particular, the electron density required for the quasiresonant condition to be established is given by $3\times10^{-9}\tau^{-2}$ [1], where the pulse duration $\tau$ is given in seconds and the density in cm$^{-3}$. For a 30-fs laser pulse, the optimum density will be $3\times10^{18}$ cm$^{-3}$ (similar to the case with prepulse), which is much less than the experimental conditions without prepulse ($\sim5\times10^{19}$ cm$^{-3}$). This means that LWFA should be weak in this high-density domain. On the other hand, even if LWFA is weakly stimulated, the overoptimum density will generate a backward electric field and accelerate electrons backward, as shown in Ref. [4]. Therefore, LWFA cannot be the mechanism to generate the hot electron jet at our experimental conditions, i.e., linearly polarized laser-cluster interactions.

CBR, on the other hand, may occur in the interaction of high-local-density cluster with a laser at modest intensity. Relativistic self-channeling can occur when a laser power significantly exceeds the critical power for self-focusing, $P_{th}\approx17(n_e/n_c)$GW [18], where $n_c$ and $n_e$ are the critical density ($=1.7\times10^{21}$ cm$^{-3}$ at 820 nm) and electron density, respectively. Pukhov *et al.* [3] showed in their simulation results that strong self-generated electric and magnetic fields could confine energetic electrons in the relativistic channel. Energetic electrons in the fields can make oscillations at the betatron frequency $\omega_\beta\approx\omega_p/(2\gamma)^{1/2}$ while drifting along the channel, in which $\gamma$ is the relativistic factor. When $\omega_\beta$ coincides with the laser frequency seen by relativistically moving electrons, CBR occurs and results in energy transfer from laser light to electrons. The energy gain in the transverse motion is then converted into an energy gain in the longitudinal direction via the $v\times B$ drift by a self-generated azimuthal magnetic field, which was generated by the current of accelerated electrons via ponderomotive expulsion of background plasma electrons from the channel [3].

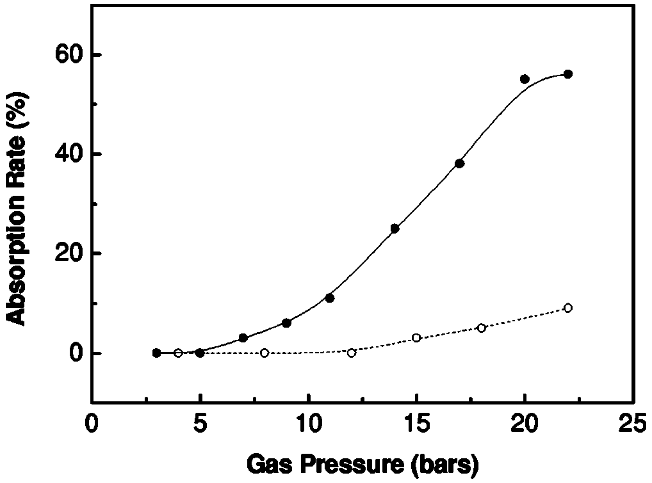


FIG. 3. Laser absorption as a function of the backing pressure of Ar in the case of a laser pulse without a prepulse (solid circle) and with a prepulse of 80 ps in advance (open circle). The laser intensity was $1\times10^{17}$ W/cm$^2$.

The hot electron spectrum in the transverse direction in Fig. 1 shows that electrons with energy above 100 keV were generated. These energetic electrons could come from resonance absorption at the critical density layer [19,20], resulting from resonantly driven electrons in expanding clusters by the incident laser pulse. The electron spectrum in the case with a prepulse (7% splitting of the main femtosecond pulse) in Fig. 1 shows that hot electron number was dramatically reduced and electron energy dropped monotonically. Since the prepulse destroyed clusters, electron density could not reach the critical density needed for resonance absorption. These results indicate that the hot electrons in the case without prepulse were generated in the laser-cluster interaction through the resonance absorption process. This was also supported by an energy absorption measurement. Figure 3 shows the laser absorption by Ar targets with respect to different backing pressure. The absorption of laser light was more than 50% at a backing pressure of 20 bars. But in the case with prepulse, the interaction became much weaker and the absorption was less than 10%. Thus, the experimental results show that the efficient coupling of laser and cluster generates energetic electrons through resonance absorption. The energy of the electrons can be enhanced further through CBR under appropriate conditions.

For the stimulation of CBR the laser power must exceed the critical power for laser self-channeling, which depends on electron density. The gas density at our experiment was $6\times10^{18}$ cm$^{-3}$. At the applied laser intensity of $1\times10^{17}$ W/cm$^2$, strong emission from Ar$^{8+}$ ions were observed [14], providing an average electron density close to $5\times10^{19}$ cm$^{-3}$. With this electron density, the laser power used, 1.1 TW, exceeds the self-focusing threshold of $P_{th}\approx0.6$ TW. Because the local electron density in a cluster during the laser pulse can be much higher, a small-scale density modulation along the direction of the laser electric field can serve as an initial perturbation for the growth of ponderomotive filaments [21]. In this way, laser self-focusing can be enhanced much more efficiently. However, detailed theoretical investigations on this kind of conditions have not been performed until now; it will be a challenging task that is required to develop for clear understanding of intense femtosecond laser interaction with clusters. On the other hand, in the case with a prepulse most clusters are destroyed before the arrival of the main pulse; so, the electron density cannot be as high as that without prepulse. The threshold laser power for self-channeling will increase in this case. Thus in the case with prepulse CBR could not occur, consistent with the observation of no jet emission.

One method to verify the CBR stimulation may be to detect the formation of a plasma channeling [4]. We obtained visible images of plasma to show the formation of a plasma channel. The visible images of plasmas generated by laser pulses with and without prepulse are shown in Figs. 4(a) and 4(b), respectively. The gas temperature was cooled up to $-70\,^{\circ}\mathrm{C}$. The plasma length obtained with a prepulse was about 500 $\mu$m [Fig. 4(a)], and this length did not change significantly at different gas temperatures. In the case without prepulse, the plasma length increased by more than a factor of 2, reaching 1400 $\mu$m [Fig. 4(b)], and the plasma volume and brightness were increased with cooling. Because the self-channeling critical power dropped to below the applied laser power, the plasma channel was formed and much more laser energy is trapped in the channel. This will contribute to higher energy absorption. The electrons trapped in the channel start to continuously gain energy by catching the laser pulse at the right phase and form a directional electron jet along the laser propagation direction.

FIG. 4. Visible images of plasma observed when Ar clusters were irradiated with (a) a laser pulse with a prepulse at 80 ps in advance, and (b) without prepulse. The experimental conditions were the same as in Fig. 2.

In conclusion, we observed the emission of a directional hot electron jet when intense femtosecond laser pulses with duration of 28 fs and intensity of $1\times10^{17}$ W/cm$^2$ interacted with Ar clusters. Experimental results from the polarization dependence, prepulse effect, and channel formation indicate that the hot electron jet emission came from CBR when the intense femtosecond laser pulse efficiently coupled with clusters. There can be attractive applications using this result. The laser intensity for an electron accelerator can be decreased through *clustering* of a high-pressure gas. This will result in a new method to generate an electron beam at moderate laser intensity, especially when a high atomic number medium, such as argon, is used.

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