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Laser-Triggered Quasi-Monoenergetic Ion Beams at a Moderate Intensity and Pulse Duration

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Abstract—Plasma produced by short laser pulses from thin homogeneous foils with light and heavy ions is capable of generating quasi-monoenergetic light ions. This happens for the tail of light ions near the front of heavy ions. It was found that this effect is well pronounced for a moderate laser intensity (~10^{18} W/cm^2) and pulse duration (~1 ps) by using a 2D particle-in-cell simulation of the laser interaction with thin CD_2 foils. Quasi-monoenergetic deuterons form a jet from the rear side of the foil with the energy ~1 MeV. The conversion efficiency to these quasi-monoenergetic ions is 10^{-3}.

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1. INTRODUCTION

The interaction of intense laser pulses with thin foils is accompanied by the acceleration of ions to energies of tens of megaelectronvolts [1–4]. The production of high-quality beams of ions has received considerable attention throughout the last few years because of their potential for applications in science, technology, and medicine. Electrons accelerated at the front side of the foil leave the target at the rear surface and build up a quasi-static electric field which accelerates ions in the forward direction (that is, in the direction of the propagation of laser irradiation). Typically ion beams show an energy spectrum exhibiting a quasi-exponential shape with a distinct energy cutoff. However, recently, in a number of experiments [5–7], a group of quasi-monoenergetic ions have been detected. Such quasi-monoenergetic ions may enable significant advances in the development of high-energy ion accelerators. Hence, a fundamental understanding of the quasi-monoenergetic ion generation process is important in order to pursue further research in this area and for the development of reliable laser-driven ion accelerators in the future.

In order to generate high-quality ion beams with monoenergetic spectra, a bilayered target consisting of a thin high-Z foil and an ultrathin coating with light atoms on the back surface has been proposed [8]. This scheme served as the basis for the experiments on a light ion acceleration from the foil structures [5, 6]. Note that the bilayered target naturally takes place due to the water contamination of its rear side and is the reason for the band structure of the proton spectrum [9]. However, quasi-monoenergetic ions were observed as well from the initially homogeneous heavy water microdroplets [7]. We believe that such ions with monoenergetic features are the result of light ion acceleration at the heavy ion front clearly demonstrated in a semi-analytical Boltzmann–Vlasov–Poisson (BVP) model for expanding multispecies plasmas [10], which that was pointed out in [7]. The effect of light ion acceleration at the heavy ion front was also derived in the analytical approach of the adiabatic expansion of a quasi-neutral plasma bunch, where the spectrum of light ions is dominated by a narrow band structure around the energy corresponding to the heavy ion spectrum cutoff [9, 11]. Vlasov simulations of the adiabatic expansion of a plasma slab (CH) with a charge separation field also demonstrated that the electrostatic shock at the heavy ion front gives rise to a peak in the proton energy spectrum for a low relative proton density [12]. The spectral modulations in the ion energy due to the simultaneous acceleration of several ion components were also observed in the particle-in-cell (PIC) simulations [13]. Following this understanding of the mechanism of the laser acceleration of light ions, we performed PIC simulations as described in this paper. The mechanism of ion acceleration at the heavy ion front differs fundamentally from our prior work on the energetic ion production from bilayered targets [5, 6, 8]. This motivates the search for a certain regime of the laser-target interaction where this mechanism could be most effective. One could expect that the attainable ion energy might be selectable by an appropriate target composition and the choice of laser parameters.

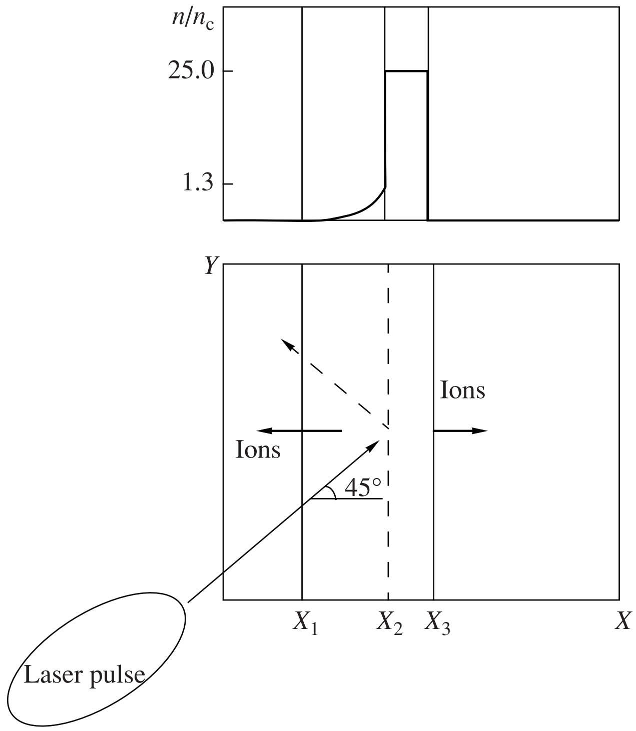

Fig. 1. Schematic drawing of the laser–target interaction geometry for PIC simulations.

In this paper, we present a numerical study of one regime of the laser–target interaction providing strongly pronounced light ion acceleration at the heavy ion front. This regime corresponds to quite a moderate laser intensity (~10^{18} W/cm^2) and a rather long pulse duration (~1 ps), which is relevant for the parameters of a Sokol-P laser [14]. We study the dynamics of the energy spectrum for deuterons accelerated in the forward direction from a CD_2 foil and demonstrate how a quasi-monoenergetic ion beam is formed in time.

2. THE LASER–TARGET INTERACTION PIC MODEL

We performed a 2D PIC simulation of the ion generation from an overdense plasma foil illuminated by a laser pulse with the intensity $I = 1.4 \times 10^{18}$ W/cm^2, wavelength $\lambda = 1$ ∝m, and FWHM (full width at half maximum) duration $\tau = 0.6$ ps. Correspondingly, the normalized amplitude of the laser vector potential is $a = 1$. The computer simulation is carried out by using the latest version of the UMKA2D3V code [17], which allows us to study the interaction of the laser radiation with microstructured multispecies plasma targets for different types of boundary conditions for the electromagnetic fields and particles (reflection, absorption, periodic conditions). Simulations were performed on the multiprocessor complexes MBC-1000M and MBC-15000BM (Russia). For 100–150 processors of a complex MCS-15000, a simulation of up to 400 laser periods (1.3 ps) required 3000–5000 h of combined processor time. The total number of particles and the number of particles per cell are 3×10^8 and 38, respectively.

We consider a Gaussian p-polarized laser pulse, which is incident at a 45 angle on the slab of an ideal collisionless plasma having an inhomogeneous underdense preplasma in front of it. We include such preplasma because, in the experiments, laser pulses have low-intensity parts, such as a prepulse and amplified spontaneous emission (ASE), which can change the structure of the solid target before the main laser pulse arrives. Such underdense plasma in front of the target with the size of a few laser wavelengths is crucial for the high-energy electron generation and correspondingly to the ion acceleration. The laser pulse is defined with a Gaussian distribution in its spacial cross direction. Schematically, the geometry for the irradiation of the plasma by the laser pulse and the initial configuration of the plasma density are shown in Fig. 1.

The target is a thin dense-plasma slab with front and back sides positioned at $x = X_2$ and X_3, respectively. The plasma consists of electrons, carbon, and deuterium ions that corresponds to a CD_2 foil of thickness 5λ. The electron density of the foil, n, is 25 times higher than the critical density n_c. A preplasma, which models a target blow-off due to the laser prepulse, occupies the domain, $X_1 < x < X_2$. The density in preplasma grows exponentially with x from $n = 0$ to $1.3n_c$ over a distance of $X_2 - X_1 = 10\lambda$, $n(x) = 1.3n_c[\exp(x/L) - \exp(X_1/L)]/[\exp(X_2/L) - \exp(X_1/L)]$, where $L = 5\lambda$. The longitudinal and transverse dimensions of the pulse are equal to 180λ and 6λ FWHM, respectively. The entire simulation box is a rectangle $0 < x < 80\lambda$ and $0 < y < 150\lambda$. In the discussion below, the coordinates x and y, time t, electron (ion) momenta $p_{e(i)}$, and electron and ion energies $\epsilon_{e(i)}$ are given in λ, λ/c, $m_{e(i)}c$, and $m_{e(i)}c^2$ units, respectively, where $m_{e(i)}$ is the electron (ion) mass and c is the speed of light.

3. QUASI-MONOENERGETIC LIGHT ION BEAMS FROM THE REAR SIDE OF THE FOIL

In this section, for definitiveness, we take $Z_C = 4$ for the carbon charge. The simulation shows that the accelerated electrons from the target described in Section 2 possess a quasi-thermal energy distribution both in the forward (with momentum $p_{ex} > 0$) and backward ($p_{ex} < 0$) directions. The characteristic energies (temperatures) T_h for the electron distributions in the forward and backward directions are close to each other and evolve in a similar fashion to the laser intensity. The value T_h for the forward direction is slightly higher than for the backward direction. On the time scale of the laser pulse duration, the electron temperature reaches a value of ≈0.4 MeV. The similarity of the electron energies for the forward and backward directions is due to a relatively modest laser intensity that differs from the ultrarelativistic case, $a > 1$, where the production of hot electrons in the forward direction dominates.

Ions are accelerated following the initial electron acceleration. On the time scale of the laser pulse duration, their energy distributions are quasi-thermal with a sharp energy cutoff. However, some time later, $t > 350$ ($t > 1.2$ ps), the spectrum of the light ions (D) in the forward direction is dominated by a narrow band structure around the energy $E_D = 0.85$ MeV with a FWHM $\simeq$ 0.15 MeV or 18%. This is not the case for the backward-generated deuterons whose distribution stays quasi-thermal. The spectra of the carbon ions also do not demonstrate a band structure either in the forward or backward directions. The spectra of the forward-generated deuterons (dN_D/dE_D) and carbon ions (dN_C/dE_C) are shown in Figs. 2 (D) and 3 (C). Figure 2a corresponds to the time moment just before the formation of the quasi-monoenergetic deuteron bunch. Figure 2b shows a well-pronounced band structure in the D spectrum at a later time, which indicates the formation of quasi-monoenergetic ions accelerated from the rear side of the target. The conversion efficiency of the laser energy to fast deuterons within the energy range 0.85 ± 0.15 MeV is $\approx 10^{-3}$. Although the simulation shows a small group of fast electrons generated at the initial stage of the laser-plasma interaction in the direction close to the direction of the reflected laser light, they do not considerably affect backward-accelerated ions.

The formation of the group of quasi-monoenergetic light ions was predicted by the analytical theory of quasi-neutral adiabatic expansion of a two-species plasma foil [9, 11], the hybrid BVP approach [10, 16], and an analytical approximation to the hybrid BVP model [15]. This group of light ions is associated with the electrostatic shock due to the separation of light and heavy ions. In accordance with [10, 15], the light ions gain energy on a steep density profile created by the heavy ions due to the enhanced electric field. Hence, one may expect a quasi-monoenergetic light ion bunch formation in the forward direction rather than in the backward direction where preplasma inhibits this effect.

The formation of the group of quasi-monoenergetic ions due to a potential jump created as a result of the spatial separation of light and heavy ions should manifest itself in a plateau-like domain in the velocity–coordinate phase plot showing the particle expansion with the same velocity. In Fig. 4, such a phase plot is shown for the time moment ($t = 400$) when the quasi-monoenergetic ion bunch is already formed. The plateau-like domain appears clearly, although it is absent at earlier times at $t \lesssim 350$. In accordance with [15], an estimation of the characteristic energy of the quasi-monoenergetic light ions is given by

$$\epsilon_i \simeq Z_2 T_h \ln\left[2.1\frac{n_1}{n_2}\sqrt{\frac{A_1 Z_1}{A_2 Z_2}}\right], \qquad (1)$$

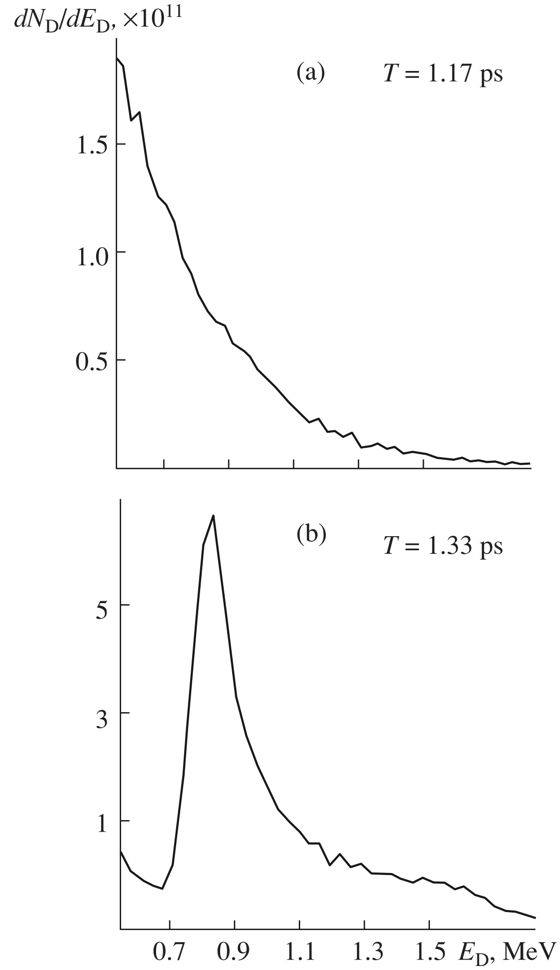

Fig. 2. Deuteron energy spectra for two time moments.

where $Z_{1(2)}$, $A_{1(2)}$, and $n_{1(2)}$ are the charge, atomic number, and density of heavy (light) ions, respectively. For CD_2 plasma, where $Z_1 = Z_C = 4$, $Z_2 = 1$, $A_1 = 6A_2$, and $n_2 = 2n_1$, Eq. (1) gives

$$\epsilon_i \simeq 1.64 T_h \simeq 660 \text{ keV}. \qquad (2)$$

Despite the fact that theoretical estimation (2) somewhat underestimates the simulation result, it be should recognized as quite a good scaling for the ion energy particularly because the applicability conditions $Z_1 n_1/Z_2 n_2 \gg A_1 Z_2/A_2 Z_1 \gg 1$ for the theory are not well met. Thus, this comparison demonstrates that, although Eq. (1) has been derived for $Z_1 n_1/Z_2 n_2 \gg A_1 Z_2/A_2 Z_1 \gg 1$, the estimation of the light ion energy is still valid when these inequalities merely $\gtrsim 1$, i.e., the simulation shows that the mechanism of the quasi-monoenergetic ion generation takes place also beyond the formal applicability conditions of the theoretical model.

One additional important conclusion is that the above mechanism of the light ion acceleration is quite robust. Indeed, recently it was identified for very different laser parameters, with a significantly shorter pulse

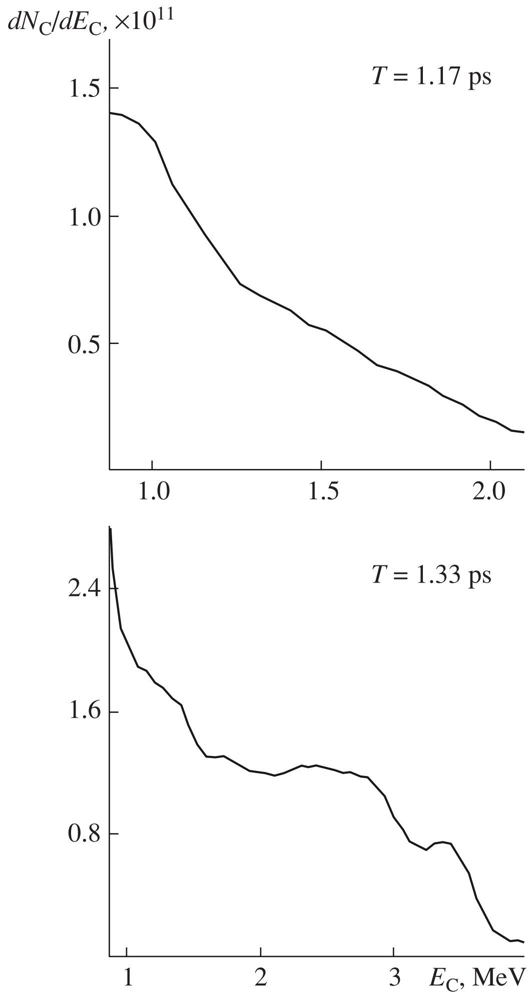

Fig. 3. Carbon energy spectra for two time moments.

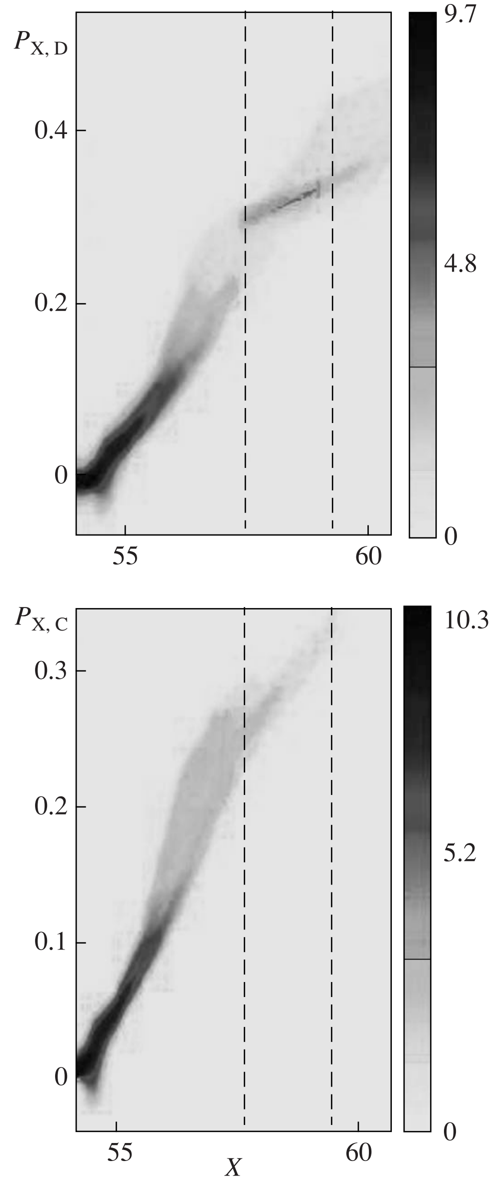

Fig. 4. Phase plot (x, p_{ix}) for deuterons and carbon ions at t = 400. The parallel vertical lines mark the spatial domain, where the quasi-monoenergetic deuterons are formed.

duration (40 fs) and a much higher laser intensity (10^{19} W/cm^2) [7]. In that study [7], a similar peak in the deuteron spectra with an energy spread of about 20% was formed when heavy water microdroplets were irradiated with ultrashort laser pulses. The corresponding deuteron acceleration time is comparable to the laser pulse duration, while in our simulation, it is shorter than the latter and the formation of quasi-monoenergetic deuterons occurs on a time scale comparable to the pulse duration. However, for a laser pulse duration less than the characteristic time of the ion acceleration, one should expect a less effective quasi-monoenergetic ion production. This conclusion follows from a comparison with the result of the Vlasov simulations of the adiabatic plasma expansion [12], which formally corresponds to zero laser pulse duration and do not predict a well-pronounced peak in the ion spectrum in the case where the light ion density is comparable to the heavy ion density. It is also important that the presence of the preplasma is essential for the appearance of the acceleration mechanism. We performed a similar PIC simulation for the no preplasma case and detected no effect for the quasi-monoenergetic ion generation. This fact is in agreement with the result of PIC simulations showing an absence of a monoenergetic ion peak for the case of a sharp vacuum–plasma interface [13].

4. THE ROLE OF THE EFFECTIVE Z/M RATIO

Direct proof that quasi-monoenergetic deuterons appear because of a potential jump created due to the spatial separation of the deuterons and the carbon ions would be to carry out a test run for the same Z/A ratio for light and heavy ions. In such a case, both species of ions are accelerated at the same rate and the mechanism for the light ion acceleration at the heavy ion front disappears. We performed such a run. The spectrum of forward-accelerated deuterons for the same CD_2 target and the geometry of the laser–target interaction, but with $Z_C = 6$ for carbon ions (when $Z_1/A_1 = Z_2/A_2$) is shown in Fig. 5. In contrast to the case $Z_C = 4$ (Fig. 2), the spectrum of the D ions is monotonously decreasing and identical to the carbon spectrum.

We also performed a simulation for $Z_C = 5$ and 3. For $Z_C = 5$, the deuteron spectrum is similar to that for $Z_C = 4$; however, bunch appears some time earlier and has a maximum at an energy slightly (several percents) higher compared to Fig. 2. In the case $Z_C = 3$, quasi-monoenergetic deuterons appear some time later (at the breaking point of our computational resources) and have an energy slightly less than in the case $Z_C = 4$. This is in qualitative agreement with theoretical estimation Eq. (1) and also proves the mechanism of the light ion acceleration discussed.

A comparison of the number of monoenergetic D ions (Fig. 2b) with the number of D ions around the region of 0.8 MeV from the thermal-like spectrum for a pure D foil or $C^{+6}D_2$ foil (Fig. 5) shows that the acceleration mechanism studied here does not give an advantage in terms of a noticeably larger number of accelerated ions than the mere energy selection after the conventional ion acceleration. However, the ion spectrum presented in Fig. 2 may be considered more advantageous for some applications in comparison to the one presented in Fig. 5, even though the numbers of ions are about the same for both figures for an energy near 0.8 MeV. It is obvious that the quality of the spectrum presented in Fig. 2, which can be characterized by the ratio of the number of particles within a small energy interval to the total number of particles, is much higher than the quality of the spectrum in Fig. 5. Among the applications which require a higher spectrum quality is the time-resolved proton radiography of electric or magnetic fields of a secondary plasma. The difference in proton energy corresponds to a different arrival time at the plane of the studied plasma. Protons which arrive earlier or later in time will contribute to the degradation in the temporal as well as in the spatial resolution of the image of the expanding plasma under study. By using a system of dipole and quadrupole magnets, it is possible, in principle, to select a narrow region of the ion spectrum and to refocus the beam of protons. However, these elements are typically bulky and require a precise alignment, and so the main advantages of the compactness and the simplicity of the experiment will be lost. Moreover, our choice for the $C^{+4}D_2$ composition is motivated by the availability of well-engineered plastic targets as a source of high-energy D ions, where C^{+4} ions are expected to be the most highly ionized species. Pure D foils are practically unrealistic and, for typical conditions, carbon ions with $Z \geq 5$ in graphite targets hardly appear (e.g., [18]).

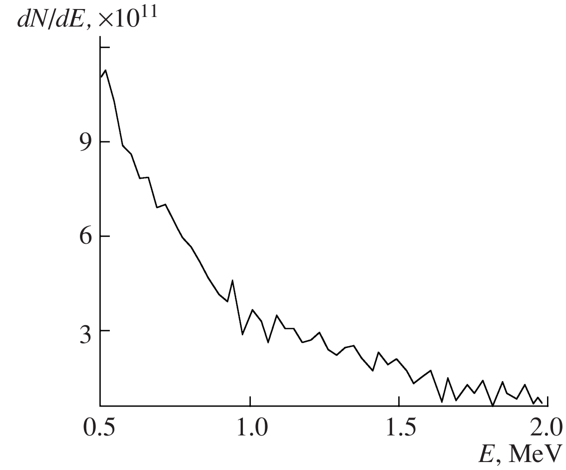

Fig. 5. Ion (both D and C) energy spectra for $Z_C = 6$ at $t = 400$.

5. CONCLUSIONS

In conclusion, the effect of the light ion acceleration at the heavy ion front for a moderate laser intensity and pulse duration has been diagnosed via direct PIC simulations. This direct modeling is in good agreement with the previous theoretical predictions of a new mechanism of quasi-monoenergetic ion generation and the results indicate that the mechanism extends even beyond the applicability conditions for the theoretical models.

Finally, we emphasize that the analysis presented demonstrates the possibility of the quasi-monoenergetic ion beam production by an laser pulse interacting with a homogeneous two-species target that is different from the commonly discussed case of a microstructured target [5, 6, 8]. This is an interesting aspect, which should be taken into account for practical applications. In our simulation with a relatively low laser intensity, the characteristic ion energy is about 1 MeV. Assuming that the typical fast electron energy can be estimated from the square-root dependence on the laser intensity [12, 16, 17], our simulation shows that a wide range of energy selections $\epsilon \propto I^{1/2}$ can be achieved, depending on the laser intensity, which predicts, for example, the monoenergetic ion production with an energy about 10 MeV for $I \simeq 10^{20}$ W/cm^2.

After the submission of this paper, we became aware of the work by Brantov et al. [19] with a simulation of the deuteron acceleration from a heavy water target for a different ultrashort high-intensity regime of the laser–target acceleration ($I = 10^{19}$ W/cm^2 and $\tau = 40$ fs), where the effect of the quasi-monoenergetic ion bunch formation was also observed.

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REFERENCES

1. A. Maksimchuk, S. Gu, K. Flippo, et al., Phys. Rev. Lett. **84**, 4108 (2000).
2. E. Clark, K. Kruchelnick, J. Davies, et al., Phys. Rev. Lett. **84**, 670 (2000).
3. S. P. Hatchett, C. G. Brown, T. E. Cowan, et al., Phys. Plasmas **7**, 2076 (2000).
4. R. A. Snavely, M. H. Key, S. P. Hatchett, et al., Phys. Rev. Lett. **85**, 2945 (2000).
5. B. M. Hegelich, B. J. Albright, J. Cobble, et al., Nature **439**, 441 (2006).
6. H. Schwoerer, S. Pfotenhauer, O. Jäckel, et al., Nature, **439**, 445 (2006).
7. S. Ter-Avetisyan, M. Schnürer, P. V. Nickles, et al., Phys. Rev. Lett. **96**, 145006 (2006).
8. T. Zh. Esirkepov, S. V. Bulanov, K. Nishihara, et al., Phys. Rev. Lett. **89**, 175003 (2002).
9. A. Maksimchuk, K. Flippo, H. Krause, et al., Plasma Phys. Rep. **30**, 473 (2004).
10. V. Yu. Bychenkov, V. N. Novikov, D. Batani, et al., Phys. Plasmas **11**, 3242 (2004).
11. V. F. Kovalev, V. Yu. Bychenkov, and V. T. Tikhonchuk, JETP **95**, 226 (2002).
12. A. P. L. Robinson, A. R. Bell, and R. J. Kingham, Phys. Rev. Lett. **96**, 035005 (2006).
13. A. J. Kemp and H. Ruhl, Phys. Plasmas **12**, 033105 (2005).
14. A. V. Andriyash, D. A. Vikhlyaev, D. A. Dmitrov, et al., Plasma Phys. Rep. **32**, 135 (2006).
15. V. T. Tikhonchuk, A. A. Andreev, S. G. Bochkarev, and V. Yu. Bychenkov, Plasma Phys. Control. Fusion **47**, B869 (2005).
16. S. G. Bochkarev, V. Yu. Bychenkov, and V. T. Tikhonchuk, Plasma Phys. Rep. **32**, 205 (2006).
17. T. V. Liseykina, V. Yu. Bychenkov, G. I. Dudnikova, and F. Pegoraro, Appl. Phys. B **81**, 537 (2005).
18. M. Hegelich, S. Karsch, G. Pretzler, et al., Phys. Rev. Lett. **89**, 085002, (2002).
19. A. V. Brantov, V. T. Tikhonchuk, O. Klimo, et al., Phys. Plasmas **13**, 122705 (2006).