Generating High-Energy Highly Charged Ion Beams from Petawatt-Class Laser Interactions with Compound Targets

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A new method of generation of high-energy highly charged ion beams is proposed. The method is based on the interaction of petawatt circularly polarized laser pulses with high-Z compound targets consisting of two species of different charge-to-mass ratio. It is shown that highly charged ions produced by field ionization can be accelerated up to tens of MeV/u with ion (actually with $Z \leq 25$) beam parameters like density and total charge inaccessible in conventional accelerators. A possibility of further ionization of the accelerated ion bunches in foil is also discussed.

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Introduction.—During the past decade, the generation of energetic ion beams from ultrahigh intensity lasers has become an area of active research (see, e.g., Ref. [1] for reviews, and references therein). Such great interest is motivated by their important applications to fast ignition of inertial confinement fusion [2], proton imaging [3], particle accelerators [4], and medicine [5]. Several methods for laser-based ion acceleration are proposed, including target normal sheath acceleration [6], shock acceleration at the front of the foil [7], breakout afterburner acceleration [8,9], and others. For ultraintense lasers the most relevant method seems to be radiation-pressure acceleration that allows reaching the highest energies [10–12]. All of the above methods are based on proton or light ion acceleration, highly charged ion acceleration is not considered. Meanwhile, it is of great interest for nuclear physics, particularly for the FAIR project aimed at developing a heavy-ion accelerator [13]. The heaviest ion discussed is C^{6+}, for which the charge-to-mass ratio is only 2 times less as compared to proton [9,12,14].

In this Letter, we would like to draw the reader's attention to the possibility of producing and accelerating highly charged ions from compound targets irradiated by petawatt laser pulses. We show that multicharged ion beams with parameters like ionic density and total ion bunch charge inaccessible by conventional techniques can be produced effectively. The method is based on the use of multilayer foils in which the process of producing highly charged ion beams comprises three consecutive stages. At the first stage, the short-pulse laser with intensity 10^{22} W/cm^2 produces through field ionization multicharged ions with very high Z depending on ion species (in our model, for example, we use Fe ions providing $Z = 24$). The second stage, where ions are actually accelerated, takes place in the first part of the compound target represented as a mixture of thin layers: a narrow lighter ion layer (Fe) and a heavy-ion foil (Au) irradiated by circularly polarized (CP) laser pulses. The advantage of using circular polarization is that the ponderomotive force pushes electrons steadily forward, thus inducing a charge separation field which can accelerate preferably ions with lower charge-to-mass ratio. Heavy ions are mainly used as a heavy background for producing the space-charge field. The accelerated ion beam then, at the third stage, passes an additional foil with energy sufficient to be further stripped by the background electrons. We have verified our model with 2D particle-in-cell (PIC) simulation and show that fully ionized quasimonoenergetic Fe-ion bunches with energies of 20–30 MeV/u and nC levels are produced. It is interesting to note here the early result of Ref. [15] showing Xe ion generation with kinetic energy up to 1 MeV and a charge state as high as 40^{+} during high-energy ion explosion of atomic clusters, in which, of course, ions move in all directions.

We propose to use microstructured metallic foils from which hydrogen contaminants can be effectively removed by resistive heating. A schematic of the compound target is shown in Fig. 1(a). A thin layer of comparatively light ions (Fe) is placed inside a heavy ion substrate (Au) near the front side [12]. The additional layer used as a stripper can be attached directly to the heavy ion substrate (even some part of the heavy ion substrate can be used as a stripper) or placed behind the latter.

Ion charge composition in strong fields.—When an ultraintense laser interacts with a substance comprising heavy ions, one of the important questions is ion charge distribution in ionized plasma. We pay particular attention to an intensity of about 10^{22} W/cm^2 that can be delivered by PW-class lasers. Highly charged ions can be generated effectively at such intensities [16]. To make quantitative estimates of the actual ion charges produced, we integrate the balance equations for each ion charge Z with the corresponding tunnel ionization rate given by [17]

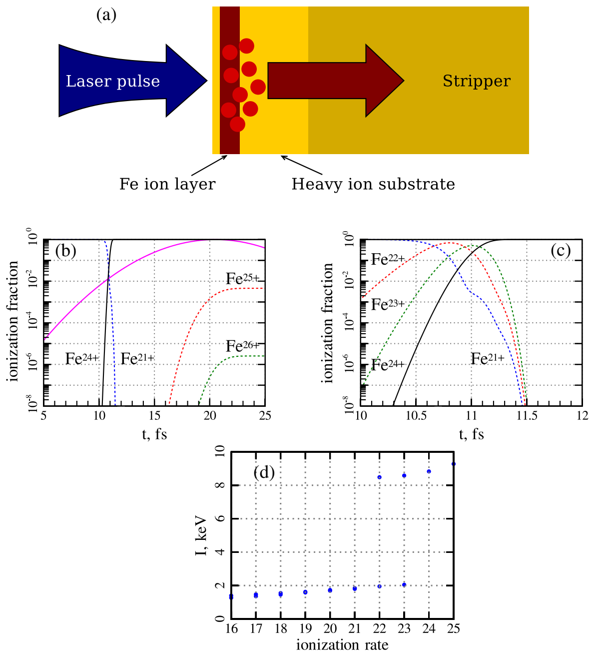

FIG. 1 (color online). (a) Schematic of the compound target consisting of a narrow Fe ion layer (red) inside a μm-size heavy ion substrate (light brown), and a stripper (dark brown) needed to completely strip the accelerated ions. (b),(c) Ion charge composition versus time for a 10 fs pulse with intensity 10^{22} W/cm^2. The laser intensity is depicted by magenta dotted line. (d) Ion (Fe^{+Z}) ionization potential versus Z.

$$w_Z(|\mathbf{E}|) = \omega_a \kappa^2 \frac{(2l+1)(l+m)!}{2^m m!(l-m)!} C_{\kappa l}^2 2^{2n^*-m} F^{m+1-2n^*} \times \exp\left(-\frac{2}{3F}\right), \quad (1)$$

where $C_{\kappa l}^2 = \frac{2^{2n^*-2}}{n^*(n^*+l)!(n^*-l-1)!}$, $\mathbf{E}$ is the laser field, $F = |\mathbf{E}|/\kappa^3 E_a$, $\kappa = \sqrt{I_Z/I_H}$, I_Z is the ionization potential of the Z ion, I_H is the ionization potential of hydrogen, $n^* = Z/\kappa$ is the effective principal quantum number, l and m are the angular momentum and its projection along the field, and $\omega_a = me^2/h^3 = 4.13 \times 10^{16}\ \mathrm{s}^{-1}$ and $E_a = m^2 e^5/h^4 = 5.1 \times 10^9$ V/cm are the atomic frequency and field, correspondingly. Estimates for a 10 fs pulse with the intensity of 10^{22} W/cm^2 ($|\mathbf{E}| \sim 2$ TV/cm) readily show that ions with $Z \leq 21$ are fully ionized. In Figs. 1(b) and 1(c) we present the ion charge composition for higher Z. As is clearly seen, quite narrow charge distribution is realized almost instantaneously on a femtosecond time scale, and the target is actually a Fe^{24+} ion layer. Such charge distribution holds for a wide range of laser intensities (roughly from 10^{20} to 10^{22} W/cm^2). This occurs because there is a big gap in the ionization potentials (from a $2s$ orbital to $1s$) [see Fig. 1(d)]. A similar calculation for gold ions gives that only Au^{69+} ions are produced at such intensities.

Ion acceleration.—The idea of ion acceleration we use was proposed in Ref. [12] and shown by PIC modeling to be efficient for protons and light ions, e.g., C^{6+} for GeV energies. Like the widely discussed radiation-pressure acceleration scheme [10,11], it is based on the charge separation fields due to electron shifts forward by the ponderomotive force of the CP laser. However, it is important to have a heavy ion substrate for keeping these fields throughout the acceleration stage. Next we show that this method can be applied to mid-Z ions as well, if the target comprises two species with different charge-to-mass ratios. Moreover, since there is no essential difference in charge-to-mass ratio, allowance for heavier ion motion can help to obtain in energy space a narrower light ion beam, even quasimonoenergetic with energy spread less than 2%.

To assess the potential of the proposed method, we first assume the heavier ions to be immobile. At the quasistationary stage when the electrons are steadily shifted under the action of ponderomotive force, as follows from the analytical theory [12], the energy acquired by the light ions with charge Z is

$$\varepsilon_i = Z \frac{2a_0^2}{n_0} mc^2, \quad (2)$$

where $n_0 = N_{e0}/N_c$, N_{e0} is the electron density of the unperturbed plasma, $N_c = m\omega^2/4\pi e^2$, ω is the laser frequency, $a_0 = eE_0/mc\omega$ is the laser field amplitude normalized to the relativistic value, and c is speed of light. As seen from Eq. (2), the energy is inversely proportional to plasma density; thus, by choosing a lower density plasma, which can be achieved by using porous low-density or nanocompound materials (see, e.g., Ref. [18] and references therein), we can attain higher energy. However, there is a density limit due to the relativistic self-induced transparency effect, which can break the quasistationary stage. In the ultrarelativistic limit the threshold of the self-induced transparency is taken to be [19]

$$a_{\mathrm{th}} = 27n_0^2/64. \quad (3)$$

Thus, in the optimal mode $a_0 = a_{\mathrm{th}}$, i.e., in a plasma with density $n_0 \simeq (2.37a_0)^{1/2}$, the highest energy is

$$\varepsilon_{\max} \simeq 1.3Za_0^{3/2} mc^2. \quad (4)$$

A simple estimate for $a_0 = 50$ ($I = 10^{22}$ W/cm^2 at $\lambda = 800$ nm) and Fe_{56}^{24+} gives energies of about 110 MeV/u.

To get an insight into a real situation, we have performed numerical simulation in 1D and 2D geometries.

In the 1D case it was done within the framework of the Vlasov-Maxwell equations. The Vlasov equation was solved by the positive flux conservative method [20], and the Maxwell equations by the standard finite-difference-time-domain method [21]. The target was a layer of gold ions Au_{197}^{69+} with a thickness of 800 nm for a Ti:sapphire wavelength ($0 \leq x \leq 1\lambda$), inside of which gold ions in the interval $0.05\lambda < x < 0.1\lambda$ were displaced by lighter Fe_{56}^{24+} ions of 40 nm width. The electron density in the Au layer was $n_{01} = 30\,(5.2 \times 10^{22}\ \mathrm{cm}^{-3})$, and in the Fe layer $n_{02} = 60\ (1.04 \times 10^{23}\ \mathrm{cm}^{-3})$. The simulation areas in momentum space were 3×10^4 pixels for electrons in the interval $(-150mc, 150mc)$, and 2×10^3 pixels for gold and iron ions in the intervals $(-M_{\mathrm{Au}}c, M_{\mathrm{Au}}c)$ and $(-M_{\mathrm{Fe}}c, M_{\mathrm{Fe}}c)$, respectively ($M_{\mathrm{Au}}$ and M_{Fe} are the mass of gold and iron ions). The initial temperature of the electrons was 1 keV, and of the ions 10 keV. The incident laser pulse had a Gaussian envelope with maximal intensity $I = 10^{22}\ \mathrm{W/cm^2}$; the pulse duration was varied to achieve a most optimal interaction mode. As was noted in Ref. [12], there exists an optimal laser pulse duration at which maximum energy of accelerated ions is attained. A shorter laser pulse terminates before the acceleration process, but for a longer pulse the accelerated ions may overtake the shifted electrons and escape from the accelerating field. In Fig. 2 we present results of simulation with optimal parameters. The energy of Fe ions reached its maximum of 27 MeV/u at the pulse duration at full width half maximum $\tau_{\mathrm{FWHM}} = 12\pi\omega^{-1} = 16$ fs. It is important to note that the ion bunch is sufficiently well spaced and energy localized (the energy spread does not exceed 10%), but the maximum energy attained is close to but less than the theoretical prediction of 36.5 MeV/u given by Eq. (4), as was to be expected. And also, a typical feature of the 1D case is that ion bunches leaving the target are quasineutral.

In the 2D case we obtained an unexpectedly better acceleration mode. The modeling was carried out with a parallel PIC code ELMIS [22]. Its characteristic feature is the use of the fast Fourier transform for computation of electromagnetic fields. The simulation box (x, y) is $9.6\ \mu\mathrm{m} \times 9.6\ \mu\mathrm{m}$ for $\lambda = 800$ nm (i.e., $12\lambda \times 12\lambda$) and contains 1024×512 cells. Each cell is filled with 2000 quasiparticles. We take, as in the 1D case, the same target but with the initial temperature of 16 keV for all particles. The plasma was irradiated by a laser pulse with a Gaussian envelope in the longitudinal direction and a fourth-order super-Gaussian profile in the transverse direction. The

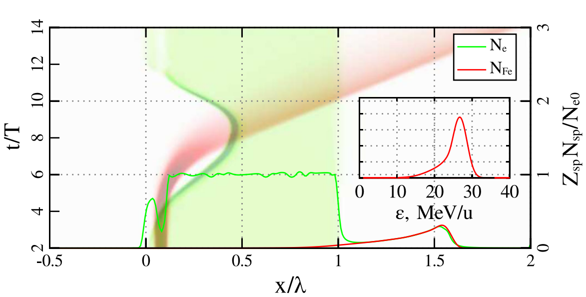

FIG. 2 (color online). Time-space diagram of 1D simulation for electrons (green curve) and Fe_{56}^{24+} ions (red curve) with the distribution of electron and iron densities at $t = 12$ T. Inset: Energy distribution function of the output ion beam.

beam width was 6.4 μm (8λ) and the duration was varied as well, aiming at finding an optimal interaction regime. Note that, in the 2D case, unlike 1D, the choice of optimal pulse duration is also affected by development of transverse instabilities [11,23] which disturb the acceleration process primarily for sufficiently long pulses.

The simulation results are shown in Fig. 3. In the optimal mode at pulse duration $\tau_{\mathrm{FWHM}} = 6\pi\omega^{-1} = 8$ fs [Figs. 3(a) and 3(d)], the Fe_{56}^{24+} ions acquire the energy up to 36 MeV/u, very close to the theoretical value. But what is more important is that the energy distribution has a narrow peak at about 28.2 ± 0.4 MeV/u. The much narrower energetic peak compared to the 1D case is due to the role of directed Coulomb explosion, which follows the process of the acceleration by ponderomotively shifted electrons (similar to what has been explored in Ref. [24]). Despite the occurrence of instabilities, in the optimal mode they do not appreciably affect acceleration of the leading ion bunch, which is actually of interest. Indeed, if for a longer pulse the accelerated ion beam distribution is instability modulated as shown in Fig. 3(b), the output beam at optimal duration has a clear central clump, which is well localized in space [see Fig. 3(a)]. A similar effect was observed earlier in Ref. [25], where a self-organization regime of proton acceleration was identified at a laser intensity of $7 \times 10^{21}\ \mathrm{W/cm^2}$ producing a nanocoulomb, well collimated proton beam. However, the distinguishing feature in our case is that the propagation length when such a one-hump beam is formed is only a few microns, thus providing good energy uncertainty of about 2%, whereas for protons it is tens of microns. The total number of accelerated Fe_{56}^{24+} ions (assuming the transverse sizes were the same) is 1.8×10^9 particles, or 7 nC. It is worth noting that a better energy uncertainty of about 1% was discussed recently in Ref. [26] but with less intense beams of 10^7 particles per bunch. The beam duration is about 5 fs, so the produced ion current is 1.4 MA. The total energy deposited into ions is about 0.5 J, that is 0.2% of the initial laser pulse energy. Thus, a very important parameter such as the ion beam power is about 80 TW, which is almost 2 orders more powerful than the one designed under FAIR [13]. Although specific FAIR's beam parameters, such as the intensity of 10^{12} ions per bunch, the particle energies of 400 MeV/u–2.7 GeV/u determined by the bunch length in the 20–100 ns range, and very high-Z ions like uranium, are inaccessible using the proposed scheme, it can be of interest as a seed ion source for FAIR accelerators. Another important feature is that the ion bunch leaving the target is not quasineutral, which is evidently a consequence of Coulomb force decay with distance in the multidimensional case. The presence of the total charge in the output bunch may be used for its further acceleration by a conventional accelerator.

However, it should be emphasized that the proposed acceleration method works best for very short laser pulses,

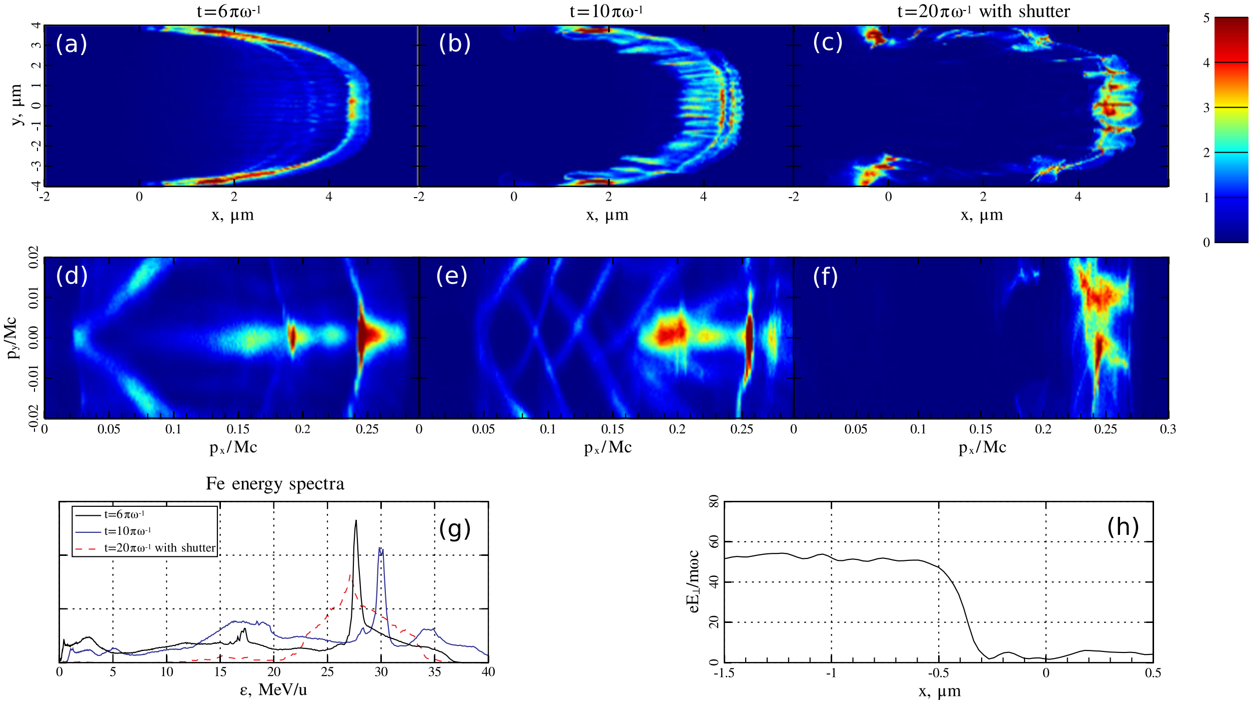

FIG. 3 (color online). Snapshots of Fe_{56}^{24+} ion density in configuration (a)–(c) and momentum space (d)–(f) for three cases [optimal pump pulse duration (a),(d), 15 fs pulse (b),(e), and 30 fs pulse with shutter (c),(f)]. (g) Output energy spectra of the accelerated ions for optimal (black solid curve), 15 fs (blue dot-dashed curve), and 30 fs with shutter (red dashed curve) cases. (h) Profile of the front of the laser pulse transmitted through the shutter in the third case.

optimally 8 fs. Also, as can be seen in Fig. 3(b), good results have been obtained for a 15 fs pulse, the petawatt level of which may be reached with state-of-the-art technologies, whereas the working duration of available petawatt lasers is about 30 fs. Unfortunately, even for such pulses the arising instabilities can prevent quality beam acceleration. However, the important point is that the acceleration mechanism depends rather on leading pulse steepening than on duration itself. As has been shown recently, it can be made much sharper by the so-called relativistic shutter—a very thin (several nanometers thick) foil [27]. When a relativistically strong laser pulse impinges on a foil, its leading front is reflected, but when the intensity exceeds some threshold value, the plasma layer becomes transparent due to the relativistic effects (its reflectivity is limited by a maximum current in the foil which is determined by a total areal density of electrons in the foil and speed of light) [28]. So, the leading front in the transmitted pulse becomes much sharper than in the incident one. We apply this idea for a 30 fs pulse by placing a shutter (a gold foil with 8×10^{22} cm^{-3} density and 270 nm thick—the density has been chosen so as to make simulations easier and the thickness has been chosen so as to make the foil transparent in the maximum of the incident pulse) 1 μm before the main target. The result of the simulations can be seen in Figs. 3(c) and 3(f). As is clear from Fig. 3(h), the leading front of the pulse transmitted through the shutter is extremely sharp, and the ion bunch energy, as is seen in Fig. 3(g), is as high as in the case of the optimal conditions. Based on simulations, we also note that a 20–30% change of duration from the optimal one only slightly affects the energy of the accelerated ions, but makes them less monoenergetic as a result of instabilities in the case of longer pulses and nonoptimal acceleration for shorter pulses. In the latter case, the difference in the energies accumulated by the ions is attributed to the fact that the ions that are closer to the irradiated side are accelerated for a longer time; hence, they do not have enough time to acquire the same energy as the deeper ions.

High-energy fully stripped ions.—The ions partially ionized by laser radiation and accelerated to several tens of MeV/u may further be fully ionized when they pass through a foil (stripper). To assess the foil thickness we make use of the above simulation results showing 28 MeV/u Fe_{56}^{24+} ions and let them propagate through a gold foil. In the frame of reference moving with iron ions the energy of the flying electrons is estimated to be $E_e \approx$ 8170 eV. Comparison of this magnitude with the magnitude of the ionization potential in a gold atom shows that 67 electrons from each atom of gold are free in the chosen frame of reference. Thus, their density in the flow is $N_e \approx 4 \times 10^{24}$ cm^{-3}.

The electron impact ionization cross sections for the iron ions can be assessed by the phenomenologic parametric formula proposed by Younger [29] and adapted by Pindzola *et al.* [30]:

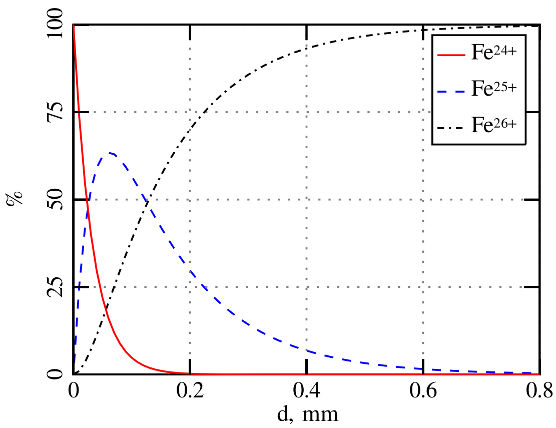

FIG. 4 (color online). Fraction of Fe ions with multiplicity $Z = 24$, 25, and 26 vs propagation length in gold foil.

$$\sigma(E_e) = \sum_j \frac{1}{u_j I_j^2}\left[A_j\left(1-\frac{1}{u_j}\right) + B_j\left(1-\frac{1}{u_j}\right)^2 + C_j Ln(u_j) + D_j \frac{Ln(u_j)}{u_j}\right], \quad (5)$$

where $u_j = E_e/I_j$, I_j stands for ionization potential, and the summation is made over all electron orbitals from which the ion may be ionized. The coefficients A_j, B_j, C_j, and D_j are found empirically. We assessed them using the values presented in Ref. [31]. Next we solved the system of standard balance equations for the corresponding ion charges

$$\frac{dN_i}{dt} = N_e v_e(\sigma_{i-1}N_{i-1} + \sigma_i N_i), \quad (6)$$

where v_e is the electron velocity, i corresponds to the ion multiplicity, and σ_i is the corresponding ionization cross section calculated by Eq. (5). For the reasons considered above, monocharged distribution with $Z = 24$ is taken to be initial. The results for a monoenergetic 28 MeV/u ion bunch are presented in Fig. 4, where ion fractions are plotted along the propagation length. The iron ions are seen to be almost fully ionized in the gold layer after propagating the thickness of about 400–500 μm. With the energy spread as in Fig. 3(g) (black curve), the ion bunch will diffuse insignificantly over such small distances, thus retaining the same space and energy localization.

Conclusions.—A new method of highly charged ion acceleration from compound foils by CP laser pulses is proposed. It has been shown that heavy ions with $Z \sim$ 20–30 may be produced and accelerated up to energies of tens of MeV/u with current femtosecond laser systems providing the intensity of the order of 10^{22} W/cm^2. The accelerated ions may be fully ionized during further propagation in the foil. For example, for iron ions to be fully stripped. an Au foil 400–500 μm thick is required. The output ion beams may have energy spread as low as 2% and be well spatially localized providing ion currents of hundreds of kA. Such heavy ion bunches may be of interest by themselves for experimental nuclear physics as an alternative to low-current bunches of high energies from conventional accelerators.

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[1] K. W. D. Ledingham and W. Galster, New J. Phys. **12**, 045005 (2010); A. V. Korzhimanov, A. A. Gonoskov, E. A. Khazanov, and A. M. Sergeev, Phys. Usp. **54**, 9 (2011).

[2] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S. C. Wilks, J. Woodworth, E. M. Campbell, M. D. Perry, and R. J. Mason, Phys. Plasmas **1**, 1626 (1994).

[3] M. Borghesi, A. Schiavi, D. H. Campbell, M. G. Haines, O. Willi, A. J. MacKinnon, L. A. Gizzi, M. Galimberti, R. J. Clarke, and H. Ruhl, Plasma Phys. Controlled Fusion **43**, A267 (2001).

[4] T. Cowan *et al.*, Phys. Rev. Lett. **92**, 204801 (2004); L. Robson *et al.*, Nat. Phys. **3**, 58 (2007).

[5] S. V. Bulanov, T. Z. Esirkepov, V. S. Khoroshkov, A. V. Kuznetsov, and F. Pegoraro, Phys. Lett. A **299**, 240 (2002); E. Fourkal, B. Shahine, M. Ding, J. S. Li, T. Tajima, and C.-M. Ma, Med. Phys. **29**, 2788 (2002).

[6] B. M. Hegelich, B. J. Albright, J. Cobble, K. Flippo, S. Letzring, M. Paffett, H. Ruhl, J. Schreiber, R. K. Schulze, and J. C. Fernández, Nature (London) **439**, 441 (2006); H. Schwoerer, S. Pfotenhauer, O. Jäckel, K.-U. Amthor, B. Liesfeld, W. Ziegler, R. Sauerbrey, K. W. D. Ledingham, and T. Esirkepov, Nature (London) **439**, 445 (2006).

[7] L. O. Silva, M. Marti, J. R. Davies, and R. A. Fonseca, Phys. Rev. Lett. **92**, 015002 (2004).

[8] L. Yin, B. J. Albright, B. M. Hegelich, K. J. Bowers, K. A. Flippo, T. J. T. Kwan, and J. C. Fernández, Phys. Plasmas **14**, 056706 (2007).

[9] A. Henig *et al.*, Phys. Rev. Lett. **103**, 045002 (2009).

[10] T. Esirkepov, M. Borghesi, S. Bulanov, G. Mourou, and T. Tajima, Phys. Rev. Lett. **92**, 175003 (2004); A. Macchi, F. Cattani, T. Liseykina, and F. Cornolti, *ibid.***94**, 165003 (2005); H. B. Zhuo, Z. Chen, W. Yu, Z. Sheng, M. Yu, Z. Jin, and R. Kodama, *ibid.***105**, 065003 (2010).

[11] O. Klimo, J. Psikal, J. Limpouch, and V. Tikhonchuk, Phys. Rev. ST Accel. Beams **11**, 031301 (2008); A. P. L. Robinson, M. Zepf, S. Kar, R. G. Evans, and C. Bellei, New J. Phys. **10**, 013021 (2008); X. Q. Yan, C. Lin, Z. Sheng, Z. Guo, B. Liu, Y. Lu, J. Fang, and J. Chen, Phys. Rev. Lett. **100**, 135003 (2008); T. V. Liseykina, M. Borghesi, A. Macchi, and S. Tuveri, Plasma Phys. Controlled Fusion **50**, 124033 (2008).

[12] A. V. Korzhimanov, A. A. Gonoskov, A. V. Kim, and A. M. Sergeev, JETP Lett. **86**, 577 (2008); A. A. Gonoskov, A. Korzhimanov, V. Eremin, A. Kim, and A. Sergeev, Phys. Rev. Lett. **102**, 184801 (2009).

[13] N. A. Tahir *et al.*, Phys. Rev. Lett. **95**, 035001 (2005).

[14] L. Ji, B. Shen, X. Zhang, F. Wang, Z. Jin, X. Li, M. Wen, and J. R. Cary, Phys. Rev. Lett. **101**, 164802 (2008).
[15] T. Ditmire, J. Tisch, E. Springate, M. Mason, N. Hay, J. Marangos, and M. Hutchinson, Phys. Rev. Lett. **78**, 2732 (1997).
[16] N. Milosevic, V. P. Krainov, and T. Brabec, Phys. Rev. Lett. **89**, 193001 (2002); H. G. Hetzheim and C. H. Keitel, *ibid.* **102**, 083003 (2009).
[17] V. S. Popov, Phys. Usp. **47**, 855 (2004).
[18] S. Okihara *et al.*, Phys. Rev. E **69**, 026401 (2004).
[19] F. Cattani, A. Kim, D. Anderson, and M. Lisak, Phys. Rev. E **62**, 1234 (2000).
[20] F. Filbet, E. Sonnendrocker, and P. Bertrand, J. Comput. Phys. **172**, 166 (2001).
[21] K. Yee, IEEE Trans. Antennas Propag. **14**, 302 (1966).
[22] M. Burza, A. Gonoskov, G. Genoud, A. Persson, K. Svensson, M. Quinn, P. McKenna, M. Marklund, and C.-G. Wahlström, New J. Phys. **13**, 013030 (2011); A. V. Korzhimanov and A. A. Gonoskov, in *Proceedings of the 22nd International Conference on Numerical Simulations of Plasma, 2011* (Princeton Plasma Physics Laboratory, Princeton, 2011), http://www.ipfran.ru/english/structure/lab334/simlight.html.
[23] M. Chen, A. Pukhov, Z. M. Sheng, and X. Q. Yan, Phys. Plasmas **15**, 113103 (2008).
[24] S. S. Bulanov *et al.*, Phys. Rev. E **78**, 026412 (2008).
[25] X. Q. Yan, H. Wu, Z. Sheng, J. Chen, and J. Meyer-ter-Vehn, Phys. Rev. Lett. **103**, 135001 (2009).
[26] B. Galow, Y. Salamin, T. Liseykina, Z. Harman, and C. Keitel, Phys. Rev. Lett. **107**, 185002 (2011).
[27] I. Nam, V. Kulagin, M. Hur, I. Lee, and H. Suk, Phys. Rev. E **85**, 026405 (2012).
[28] V. A. Vshivkov, N. M. Naumova, F. Pegoraro, and S. V. Bulanov, Phys. Plasmas **5**, 2727 (1998).
[29] S. M. Younger, Phys. Rev. A **24**, 1272 (1981).
[30] M. Pindzola, D. C. Griffin, C. Bottcher, S. M. Younger, and H. T. Hunter, Nucl. Fusion **27**, 21 (1987).
[31] M. Arnaud and J. Raymond, Astrophys. J. **398**, 394 (1992).