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Fast ion generation by a picosecond high-power laser

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Recent progress in ultrashort-pulse high-power laser technology has resulted in the production of extremely high light intensities approaching 10^{20} W/cm^2. The great non-linear forces generated by the laser pulse during its interaction with plasma can be used to accelerate electrons and ions to energies from hundreds of keV to hundreds of MeV over distances of only microns. This creates the prospect of construction of compact laser-based particle accelerators and their application in material science, medicine, nuclear physics, and inertial confinement fusion. In this paper, the results of our recent studies on fast ion generation in plasma produced by an intense 1-ps laser pulse, performed using the terawatt Nd:glass laser at Institute of Plasma Physics and Laser Microfusion (IPPLM) in Warsaw, are briefly reviewed. The properties of fast proton beams generated from thin foil targets of various structures as well as the heavy ion fluxes emitted from massive high-*Z* targets are discussed. The possibility of producing picosecond ion beams of ultrahigh ion current densities (> 10^{10} A/cm^2 close to the target) is considered. The most important features of fast ion generation in the plasmas produced by ultrashort (1 ps) and long (0.5 ns) laser pulses are also compared.

Keywords: fast ion, plasma, picosecond laser.

1. Introduction

The generation of fast particles using lasers was first observed in the sixties when the first experiments with a *Q*-switched laser irradiating a solid target were performed [1, 2]. Those experiments showed that plasma created on the target surface is a source of ions of energies (up to several keV) considerably higher than the mean energy of ions in the plasma. Along with the development of pulsed lasers with ever increasing power, higher and higher ion energies have been achieved; in particular, anomalously fast ions in the MeV energy range have been recorded [3]. However, for many years, fast particles emitted from plasma were studied mainly from the point of view of their importance for laser-driven inertial confinement fusion, where they play a “negative” role as a source of significant energy loss and the cause of preheat of the fusion target.

More recently, however, some useful aspects of fast ion emission from laser-produced plasma have been emphasized. In particular, the application of laser-driven ion sources in accelerator technology [4, 5] and in ion implantation for modifying material properties [6] has been suggested and investigated using ns and sub-ns laser pulses [7–13].

A real breakthrough in the investigation of laser acceleration of charged particles was the use of high power lasers generating ultrashort pulses ($\tau_L \leq 1$ ps). These lasers can produce radiation of much higher intensity (currently up to ~10^{21} W/cm^2 [14]), are smaller, and can work at pulse repetition rate orders of magnitude higher than ns or sub-ns lasers with similar peak powers [15], which is of vital importance for practical applications. Moreover, ultrashort-pulse lasers (USP-lasers) are capable of producing a short-lived hot plasma, which can emit intense beams of high-energy particles in extremely short bursts of sub-ns or ps duration [16–18]. The above features create prospects for applications of USP-laser-produced ion beams in medicine [19, 20], materials science [6, 13], inertial fusion [21], and nuclear physics on a tabletop [22, 23].

In this paper, our recent studies of fast ion generation in the plasma produced by an intense 1-ps laser pulse, carried out using the terawatt Nd:glass laser at the Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, are briefly reviewed. In Section 2, the essential differences in the properties of fast ion fluxes emitted from the plasmas produced by ultrashort (1 ps) and long (0.5 ns) laser pulses are presented and discussed. In Sections 3 and 4, some results of studies on laser generation of protons (Sec. 3) and heavy ions (Sec. 4) in ps-pulse-produced plasma are presented. The possibility of production of picosecond ion beams with ultrahigh ion current densities (>10^{10} A/cm^2 close to the target) using picosecond lasers is considered in Sec. 5. The last section briefly summarizes the main results of the paper.

2. Comparison of the properties of fast ion fluxes produced by ultrashort and long laser pulses

In recent years both long (> 0.1 ns) and ultrashort (≤ 1 ps) laser pulses have been used to produce intense ion fluxes with ion energies from hundreds of keV up to tens and hundreds of MeV (see Secs. 3 and 4). However, the characteristics of ion fluxes emitted from plasma depend on many other factors than just laser pulse duration and intensity (*e.g.*, laser focusing conditions, laser prepulse parameters, target features). So, a detailed quantitative comparison of the ion characteristics from previous long-pulse and ultrashort-pulse experiments, where different experimental arrangements have been used, can be difficult or impossible. As a result, the potential advantages (or disadvantages) of the ion fluxes produced using USP-lasers over those generated by long-pulse lasers have not been fully and unambiguously determined.

In experiments at IPPLM, the properties of fast ion fluxes emitted from the plasma created by interaction of a 1-ps laser pulse with a massive Au target were compared

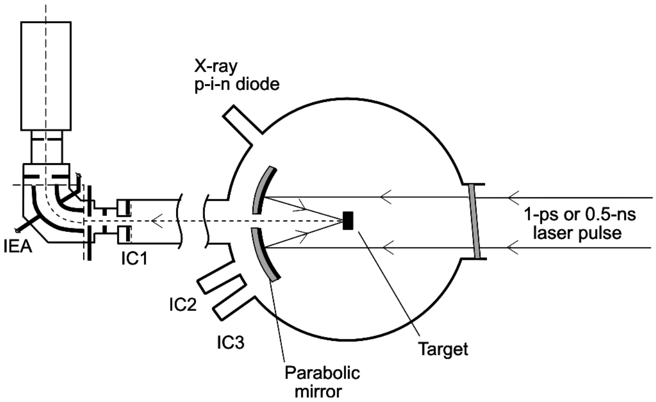

Fig. 1. Schematic diagram of experiment (IEA – electrostatic ion-energy analyzer; IC1, IC2, IC3 – ion collectors).

to the properties of the fluxes produced by a 0.5-ns laser pulse under the same conditions. The comparison was carried out using 1-ps and 0.5-ns laser pulses produced by the same chirped-pulse-amplification (CPA) Nd:glass laser system [24, 25]. Excluding the pulse duration and intensity (up to 10^{17} W/cm^2 for 1-ps and up to 2×10^{14} W/cm^2 for 0.5-ns pulses), other parameters of the laser beam (energy, wavelength, focal spot diameter, *etc*.) were roughly identical for both pulses. The measurements were performed using the experimental set-up presented in Fig. 1 [26]. Ion flux parameters were measured using ion collectors (ICs) and an electrostatic ion-energy analyzer (IEA) [25, 27]. The IEA and the ring ion collector (IC1) recorded the backward-emitted ion beam passing through the hole in the parabolic mirror along the target normal and the laser beam axis. To enable a rough estimate of the angular distribution of ion emission, two additional ion collectors, viewing the target at angles Θ of 26° and 34° with respect to the target normal, were used.

Figure 2 presents typical IC1 collector signals illustrating the time dependence of backward ion emission (against the laser beam) from the Au target for the cases of 1-ps and 0.5-ns laser pulses. The rough angular distributions of fast ion emission for the ps and sub-ns pulses are presented in Fig. 3. These figures demonstrate the principal differences between the properties of fast ion fluxes emitted from plasmas produced by ultrashort and long laser pulses. In the long-pulse case, several groups of fast ions (subscript *f* in Fig. 2) are generated, the maximum of the fast ion current density does not coincide with the target normal ($\Theta = 0°$), and the angular divergence of the fast ion expansion is high.

In the ultrashort-pulse case, only a single fast ion group is generated and this group is well separated in time from the thermal ion group. The fast ions expand with small angular divergence and with a pronounced maximum along the target normal (at $\Theta \geq 26°$ the ion current density was more than 100 times less than that recorded at $\Theta = 0°$). The above features were observed independent of laser energy and laser focus position with respect to the target surface (within ±0.8 mm).

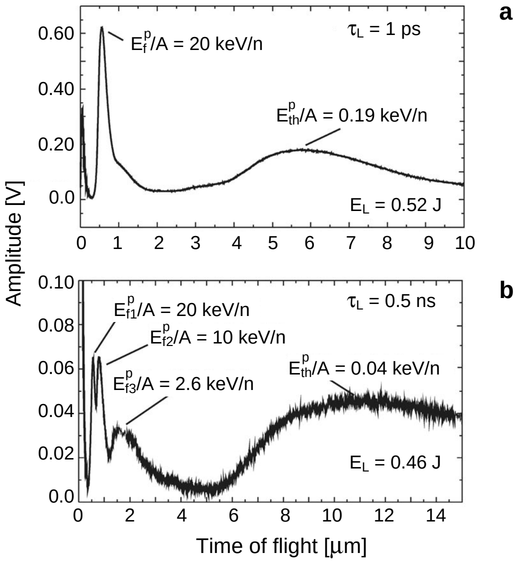

Fig. 2. IC1 collector signals for an Au target irradiated by 1-ps (**a**) and 0.5-ns (**b**) laser pulses. The ion energies per nucleon at the amplitude peaks are indicated (E^p).

Our IEA measurements showed that, for both the ultrashort-pulse and long-pulse cases, the fast ion groups contain highly charged ($z \sim 20$–30) Au ions as well as contaminant ions (H, C and O). The maximum charge states and energies of the H, C, O and Au ions, measured using the IEA, were comparable for both cases.

Significant differences between the properties of the ion fluxes produced by ps and sub-ns laser pulses can also be observed, when the dependence on laser intensity of the maximum ion energy and the ion energy at the amplitude peak (≈ mean energy),

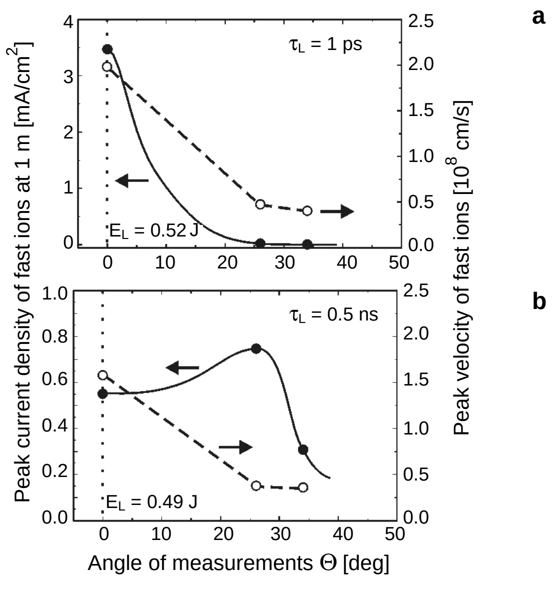

Fig. 3. Rough angular distributions of the ion current densities and velocities at the peak of the backward-emitted fast ion pulses driven by 1-ps (**a**) and 0.5-ns (**b**) laser pulses.

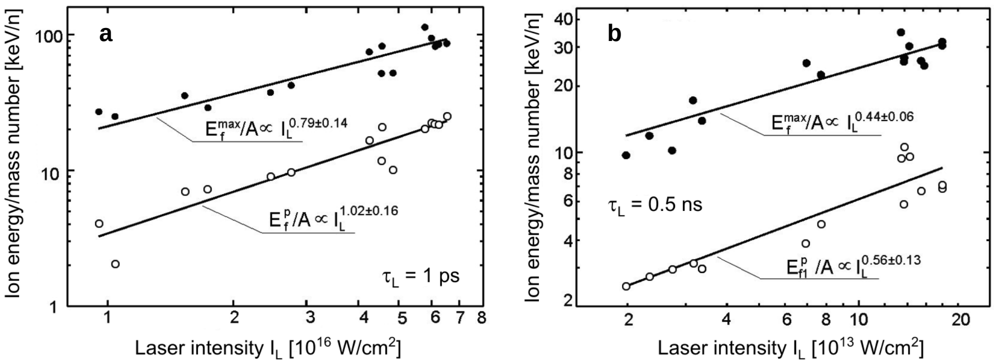

Fig. 4. Maximum ion energy and ion energy at the amplitude peak, measured normal to the Au target, as a function of laser intensity for 1-ps (**a**) and 0.5-ns (**b**) laser pulses.

measured by IC1, are taken into account (Fig. 4). For sub-ns pulses, ion energies are dependent on approximately the square root of the intensity, which is consistent with the $I\lambda^2$ hot electron temperature dependence obtained by GITOMER *et al.* [3], by means of compiling data from various laboratories. However, for ps pulses, ion energies increase approximately linearly with laser intensity.

Contrary to the long-pulse case, where self-focusing of the laser beam in the plasma and various plasma instabilities may contribute to the production of hot electrons and fast ion generation [3, 5], our ps laser pulse results can be qualitatively explained by a less complex physical picture. It assumes that the main role in the ion acceleration process is played by non-linear ponderomotive forces produced by a skin layer interaction of the pulse with a thin (several λ) pre-plasma layer in front of the target [28, 29]. In such a case, the ps laser beam interacts most intensely with the plasma in the skin layer near the critical electron density surface, $n_{ec} = m_e\omega^2/4\pi e^2$ where ω is the laser frequency, and the geometry of the interaction is almost planar because $L_{pre} \ll d_{foc}$, where L_{pre} is the pre-plasma thickness and d_{foc} is the focal spot diameter. The high plasma density gradient in the interaction region produces a non-linear ponderomotive force acting nearly parallel to the target normal – if the laser beam is perpendicular to the target surface. For such geometry, the force density f_{NL} can be expressed approximately as the one-dimensional negative gradient of the electromagnetic energy density of the laser field given by its (dielectric modified) electric and magnetic vectors **E** and **H** [28]: $f_{NL} = -(\partial/\partial x)(\mathbf{E}^2 + \mathbf{H}^2)/8\pi$, where the x-direction is normal to the target. When the electron density $n_e(x)$ of the plasma increases monotonically in the direction of laser pulse propagation, the energy density $(\mathbf{E}^2 + \mathbf{H}^2)/8\pi$ increases up to a maximum shortly before the density reaches n_{ec} and then drops exponentially to zero in the overdense plasma ($n_e > n_{ec}$) within the skin depth. The gradients of the energy density result in two opposite non-linear forces: one, in the underdense plasma, acting in the backward direction, and the other, in the overdense plasma, acting in the forward direction. These forces break the plasma near the critical surface and drive the two plasma blocks (electron clouds with attached ions) towards the vacuum and towards the plasma interior, respectively. Due to the almost one-dimensional geometry of plasma acceleration, the fast ion beam emitted has a small angular divergence, in agreement with observations (Fig. 3**a**).

The energy of ions accelerated by the ponderomotive force can be estimated from [28, 29] as

$$E_i \approx \frac{s}{2} z m_e^o c^2 \left[\left(1 + \frac{3I}{I_{\mathrm{rel}}} \right)^{1/2} - 1 \right] \tag{1}$$

where $s = S - 1$ ($S = 1/|n|$ is the dielectric swelling factor, n is the plasma refractive index), m_e^o is the electron rest mass, z is the ion charge state and $I_{\mathrm{rel}} \approx 4.1 \times 10^{18}/\lambda^2$ [W/cm^{-2}, μm^2] is the relativistic intensity. At subrelativistic laser intensities ($I << I_{\mathrm{rel}}$), we have

$$E_i \approx \frac{3}{4} s z m_e^o c^2 \frac{I}{I_{\mathrm{rel}}} \tag{2}$$

in agreement with the nearly linear dependence $E_i(I)$ shown in Fig. 4**a**.

Summing up, our experiment has shown that the properties and plausible mechanisms of fast ion generation are essentially different for plasmas produced by ultrashort (≤ 1 ps) and long (> 0.1 ns) laser pulses. In the long-pulse case, several groups of fast ions are emitted into a wide solid angle and self-focusing of the laser beam in plasma and various plasma instabilities seem to determine the ion flux properties. In the ultrashort-pulse case, only a single fast ion group with a small angular divergence is generated and ions are likely to be accelerated by an axial ponderomotive force produced by the skin layer interaction of the pulse with a pre-plasma layer in front of the target. For a majority of applications of laser-driven ion fluxes, the ultrashort-pulse laser-plasma interaction would be more favorable, due to better temporal and spatial characteristics of the ion flux and a higher fast ion current.

3. Fast proton generation in picosecond laser-produced plasma

The possibility of generating high-energy (0.1–1 MeV) proton fluxes from laser plasma was discovered in the eighties in experiments with ns and sub-ns lasers [3]. In the past, however, high-energy ($E_L \sim 10^2$–10^3 J) laser pulses were required, which could only be generated in large laser installations designed for research on laser -driven inertial fusion. Low proton generation efficiency, high angular divergence and inhomogeneity of the proton beam, and, most of all, the impossibility of such big lasers operating at sufficiently high pulse repetition rates did not create an encouraging prospect for practical application of laser-generated protons. The situation changed radically when lasers producing ps and sub-ps pulses began to be used to generate proton beams [16, 18, 22, 30–39]. Although the experiments were generally carried out at lower pulse energies than with ns lasers (but with higher intensities), the

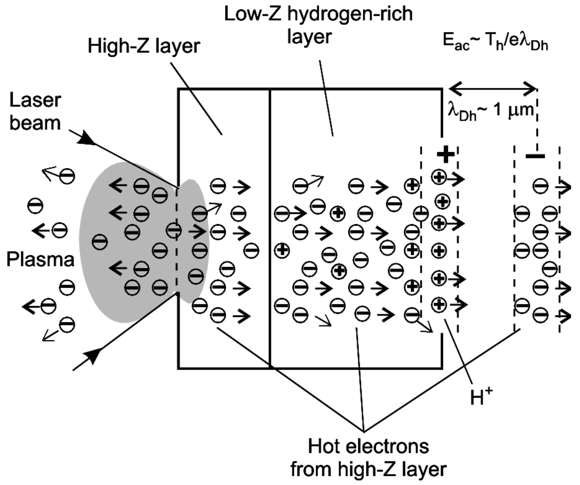

Fig. 5. Double-layer system for laser generation of fast protons.

proton energies E_p obtained were considerably higher (E_p ~ 0.1–1 MeV, even with E_L < 1 J [22, 32, 36]) and the beam was more homogeneous and had smaller angular divergence.

As a rule, in proton generation experiments with ultrashort laser pulses, thin plastic (mylar, polystyrene) or metal foils are used. The target thickness d_T should suit both the energy and the intensity of the pulse so that, generally, d_T ~ 1–100 µm. In the case of plastic targets, the main source of protons is hydrogen from the chemical constituents of the target. In the case of metal targets, protons come from hydrogen adsorbed on the target surface (from contaminants always found on the target unless it is specially processed). Protons can be generated both towards the laser (backwards; from the surface hit by the laser beam) and in direction of laser beam propagation (forwards; from the back of the target). More favorable energetic and spatial proton beam characteristics are obtained for the case of a forward generated beam and this will be considered as the basic variation.

At IPPLM, a double-layer system for fast proton generation has been proposed [36]. The concept is presented in Fig. 5. An ultrashort laser pulse directly interacts with a high atomic number (Z) layer, creating a plasma at its surface. Ponderomotive forces generated by the laser pulse and other mechanisms accelerate some of the electrons to high velocities. These “hot” electrons have temperatures T_h of ~ 10^4–10^6 eV (at I ~ 10^{17}–10^{20} W/cm^2). Hot electrons are emitted both backwards (towards the laser) and forwards (towards the target back surface) in the form of a short duration pulse $\tau_e \approx \tau_L$. Electrons propagating forwards partly ionize the low-Z hydrogen containing target layer and, in particular, the hydrogen on the back surface of this layer. The cloud of hot electrons, flying out of the rear side of the target, creates a so-called Debye sheath at a distance λ_{Dh} from the back surface of the target. The sheath is negatively charged and functions as a virtual cathode. It produces a strong electric field, which additionally ionizes the hydrogen on the target back surface and accelerates the protons formed at this surface. If the density gradient scale-length L_i at this surface is smaller than λ_{Dh} (the surface is smooth and undisturbed), the field strength is

$$\varepsilon_{\mathrm{ac}} \approx \frac{T_h}{e\lambda_{\mathrm{Dh}}} \sim 10^4\text{–}10^8\ [\mathrm{V}/\mu\mathrm{m}]\ =\ 10^8\text{–}10^{10}\ [\mathrm{V/cm}] \tag{3}$$

assuming a typical value for λ_{Dh} of ~ 1 μm and the values for T_h of ~ 10^4–10^6 eV given earlier. Proton acceleration takes place during the time t_{ac} ~ 1 ps over a distance L_{ac} ~ 10 μm [16, 40]. As a result, the protons acquire the energy

$$E_p \sim e\varepsilon_{\mathrm{ac}}L_{\mathrm{ac}} \sim 0.1\text{–}10\ [\mathrm{MeV}] \tag{4}$$

and are mainly generated perpendicular to the back target surface.

As research at IPPLM has shown [36, 38], double-layer systems make it possible to obtain higher proton energies and current densities than with single-layer systems. The investigations used a set-up similar to that in Fig. 1, with the parabolic focusing mirror replaced by an aspheric lens. The characteristics of forward emitted ion fluxes from various kinds of single-layer and double-layer targets at $I \leq 2\times10^{17}$ W/cm^2 were measured using ion collectors and an electrostatic ion-energy analyzer. Additionally, the amplitude of the hard (4–30 keV) X-rays emitted from the target was measured using semiconductor detectors.

In Figure 6, both the mean and maximum proton energies as well as the proton current density at 1 m from the target are shown as a function of the amplitude of the hard X-ray signal [36]. Measurements were performed for targets of various thickness,

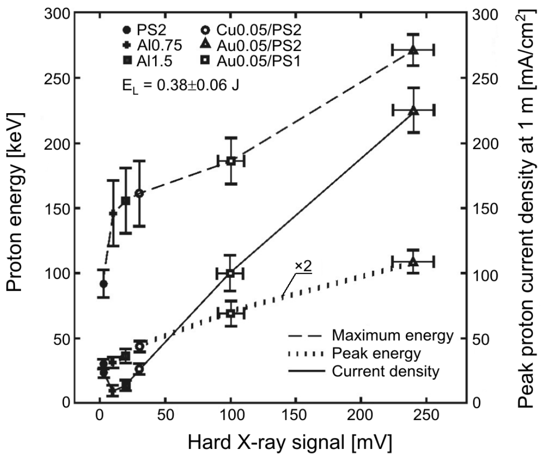

Fig. 6. Mean and maximum laser-generated proton energies and proton current density at 1 m from the target as a function of hard X-ray signal amplitude.

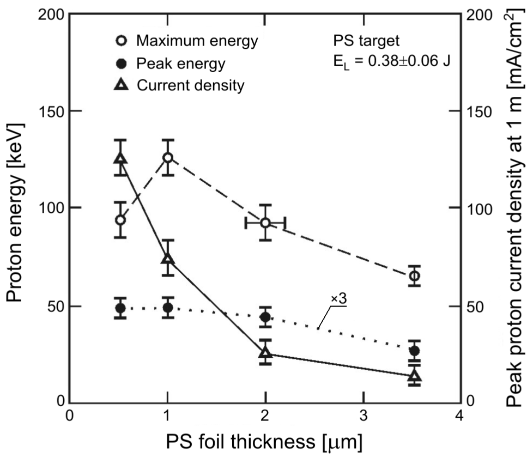

Fig. 7. Maximum and mean laser-generated proton energies and proton current density at 1 m from the polystyrene target as a function of target thickness.

atomic number *Z*, and structure. Layer composition and thickness are denoted as m_1t_1/m_2t_2, where m_1 and t_1 are the composition and thickness (in μm), respectively, of the first, or only, target layer and m_2 and t_2 those of the second layer of double-layer targets. Thus, Au0.05/PS2 designates a double-layer target with a 0.05-μm gold front layer and a 2-μm polystyrene back layer. As can be seen, the best proton beam parameters are obtained for the case of double-layer targets with a high-*Z* front layer (Au). In paper [36] it was proved that this is mainly caused by an increase in hot electron generation efficiency with increasing target atomic number. Moreover, it has been found that the proton beam parameters substantially depend on the total thickness of the target [37, 38] (Fig. 7) and – in the case of double-layer targets – on

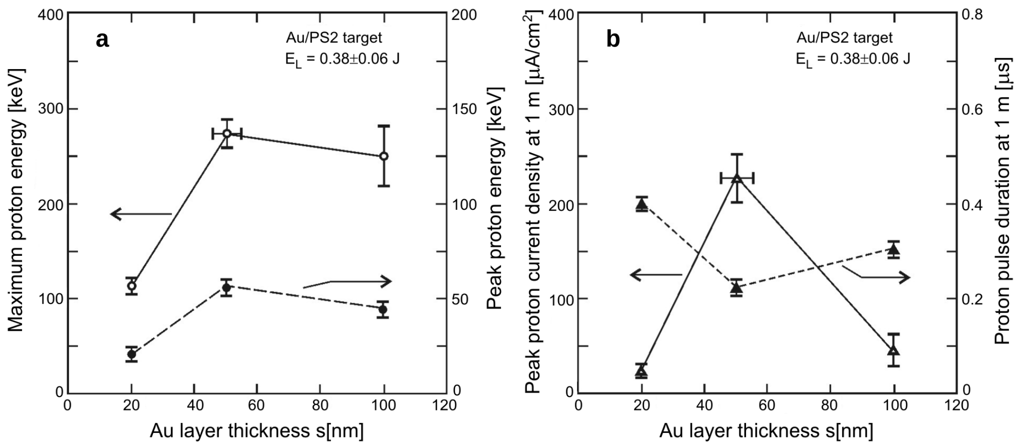

Fig. 8. Characteristics of proton beams emitted from Au/PS2 targets as a function of Au layer thickness.

the thickness of the high-Z layer [38] (Fig. 8). With appropriate choice of target parameters, the proton beam has low angular divergence (> 10^9 protons with energy > 0.1 MeV were recorded within a 3° angle [36]), which makes it possible to achieve relatively high proton current densities at a large distance from the target (Fig. 6). On the other hand, at a very small distance from the target (< 1 mm), proton current density may attain very high values, even at low laser pulse energies (E_L < 1 J), and can significantly exceed the current densities achieved in conventional proton accelerators (see Sec. 5).

4. Heavy ion generation in picosecond laser-produced plasma

In the case of laser generation of heavy ions, *i.e.*, ions of high atomic number (*e.g.*, Z > 50), we must deal with two problems: achieving high ion energies E_i and obtaining high charge states z. Depending on the potential application, the importance of each of these problems could be different. For instance, for ion implantation ion energy matters most whereas the charge state is of minor importance. Conversely, when a beam of laser-generated heavy ions is used as an ion source for traditional accelerators, the issue of ion charge is essential.

The investigation of ion generation in laser-produced plasma, including heavy ion generation, is inseparably linked to the investigation of laser-produced plasma in general and laser-driven inertial fusion in particular, which is why it has been carried out for over 30 years. Lasers generating ns and sub-ns pulses have usually been used in these investigations, *e.g.*, [3, 7–11, 41–46]. But, recently, ultrashort pulses have also been used [25, 47–53]. For high-energy pulses, thick solid targets have been generally used. As a result, only fluxes of backward-emitted (towards the laser) ions have been measured. For ns or sub-ns laser pulses with energies of ~10–10^3 J and intensities of ~10^{15}–10^{16} W/cm^2, maximum heavy ion (*e.g.*, Ta, Au, Pb) energies are tens of MeV while maximum ion charge states in the far expansion zone (a large distance from the target) are ~50 [3, 8–11, 42–46]. For sub-ns laser pulses, the team of IPPLM and the Institute of Physics, A.S.C.R. (Prague), among others, has obtained remarkable results. Experiments on this subject have been carried out in Prague, initially using the PERUN iodine laser (50 J/400 ps) [8–11, 41] and more recently with the kilojoule PALS iodine laser (1.2 kJ/400 ps) [42–46].

As mentioned earlier, from the point of view of some future applications of laser -generated ion beams, lasers generating ultrashort pulses (≤ 1 ps) seem to be more desirable than ns or sub-ns lasers. However, due to the short duration of the ultrashort pulse’s interaction with the target as well as rapid adiabatic cooling of the plasma, favoring the fast recombination of ions, achieving highly charged ion fluxes in the far expansion zone with ultrashort pulses is harder than with long pulses.

The first experiment that demonstrated the possibility of producing a beam of high-energy highly charged heavy ions using an ultrashort laser pulse of relativistic intensity was performed at the Rutheford Appleton Laboratory in England [49]. In this

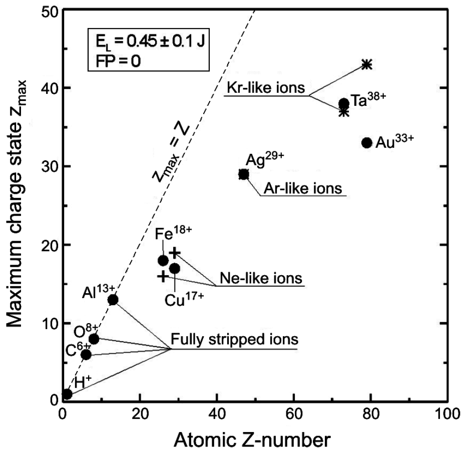

Fig. 9. Maximum charge state of ions measured using the IEA (•) as a function of target *Z* number.

experiment, at $I \approx 5\times10^{19}$ W/cm^2, a flux of Pb ions with maximum charge state $z_{\max} = +46$ and maximum energy $E_i^{\max} \approx 430$ MeV was obtained. This is the highest ion energy achieved so far using a laser.

The first experiment of this kind at non-relativistic intensities ($\leq 5\times10^{16}$ W/cm^2), which produced Ta^{+38} and Au^{+33}, was carried out at IPPLM [50]. This experiment was performed using an arrangement similar to that in Fig. 1 [50]. The source of the ultrashort pulse ($\tau_L \approx 1$ ps) was a terawatt picosecond laser and the ion flux parameters were measured using ion collectors and an electrostatic ion-energy analyser (IEA). The parameters of the ions produced from massive metal targets of medium (Al, Fe, Cu, Ag) and high (Ta, Au) atomic numbers were studied.

A diagram showing the maximum charge state of the ions produced as a function of the *Z* number of the target, measured using the IEA (full circles), is presented in Fig. 9 [50]. Fully stripped ions up to $Z = 13$ and highly charged ions of heavier elements are visible. The measured charge states in the low-*Z* range of the diagram ($Z \leq 13$) are considerably higher than those observed earlier [47] for high-contrast 170-fs laser pulses of 3×10^{17} W/cm^2 intensity (thus of energy fluence on target close to that in our experiment). Besides longer pulse duration, which is usually advantageous for obtaining a higher degree of target ionization (both collisional and optical field ionization rates are finite), the probable reason for this difference is the pre-plasma formed by a prepulse on the target surface under the conditions of our experiment. This pre-plasma, whose thickness is estimated to be a few μm, can positively influence the possibility of attaining high ion charge states in the far expansion zone, both for low-*Z* and high-*Z* targets, for at least two reasons. First, it significantly increases the absorption of light by the target [25, 54]. Second, it diminishes the cooling rate of the plasma [55], which, in turn, decreases the effectiveness of electron-ion recombination.

Figure 10 presents the maximum ion energy measured using the IEA, $E_{\max}$, as a function of the *Z* number of the target [50]. $E_{\max}$ is not a smooth function of *Z* and a local maximum occurs at low *Z*. The reason why low-*Z* ions from contaminants reach

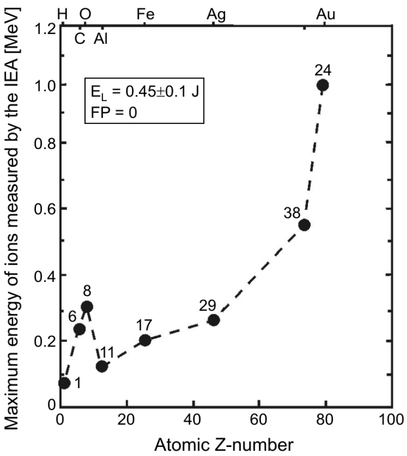

Fig. 10. Maximum ion energy, measured using the IEA, as a function of the Z number of a target. Numbers near the points indicate the ion charge states for which maximum energies were recorded.

higher velocities than heavier ions could be the higher z/A ratio of these ions (A is ion mass number).

We observed a tendency of the heavy ion current density to decrease with Z number, probably resulting from the increasing ion energy and the increasing ionization losses with increasing Z-number. However, for both medium- and high-Z targets, quite high ion current densities ≥ 1 mA/cm^2 at 1 m from the target were recorded [50].

The most important reason for the high ion current density in the far expansion zone, in spite of the relatively low energy of the laser pulse, was the small angular divergence of the ion beam. For all Z numbers, most of the high-energy ions, both thermal and fast, were confined within a cone angle less than 30^o with the maximum of the emission normal to the target surface [50].

5. Production of ultrahigh current density ion beams

The important consequence of the fact that an ultrashort laser pulse interacting with a thin preplasma layer accelerates plasma with a density comparable to the critical density n_{ec} (see Sec. 2), is the potential to produce very high fast ion current densities near the target surface (in the laser focus) [56]. For a rough estimate of these current densities we can neglect the fact that, close to the critical surface, the ion density n_i is somewhat higher in the overdense plasma region than in the underdense region and assume $n_i \approx n_{ic} = n_{ec}/z$. Taking $j = zen_i \upsilon_i$, where υ_i is the ion velocity, we obtain the fast ion current density close to the ion source

$$j_s \approx en_{ec} \upsilon_i = e(2/m_p)^{1/2} n_{ec}(E_i/A)^{1/2} \quad (5)$$

where m_p is the proton mass, E_i is the ion energy and A is the atomic mass number. For subrelativistic laser intensities ($I \ll I_{rel}$), from (2) and (5) we obtain

$$j_s \approx 74(sz/A)^{1/2}\lambda^{-1}I^{1/2} \text{ [A/cm}^2\text{, µm, W/cm}^2\text{].} \qquad (6)$$

For instance, at $sz/A = 1$, $\lambda = 1$ µm, and $I = 10^{17}$ W/cm^2, we get $j_s \approx 2.3\times10^{10}$ A/cm^2.

To compare the absolute value of the fast ion current density at the ion source obtained from the theoretical formula (5), j_s^{th} with the value deduced from the experiment $j_s^{\exp}$ we substitute $E_i/A = 20$ keV/nucl (Fig. 2**a**) in the formula, which gives $j_s^{\mathrm{th}} \approx 3.1\times10^{10}$ A/cm^2 at $\lambda = 1.05$ µm. To roughly estimate $j_s^{\exp}$ on the basis of our time-of-flight measurements, we use

$$j_s^{\exp} \approx Q_i / \tau_{is}S_s \qquad (7)$$

where Q_i is the total fast ion charge measured in the far expansion zone ($Q_i \le Q_{is}$, due to possible recombination, where Q_{is} is the fast ion charge exiting the ion source); τ_{is} is the duration of fast ion generation (roughly equal to the laser pulse duration $\tau_{is} \approx \tau_L$ [16], [18], [40]), and S_s is the area of the fast ion source. Since $j(\Theta)$ was determined with a large error (Fig. 3**a**), we have calculated the fast ion charge passing through the IC1 collector aperture Q_i^{IC1} instead of Q_i ($Q_i^{\mathrm{IC1}} < Q_i$ because the fast ions are emitted within an angle wider than the 3° seen by IC1) and we have taken $S_s = S_f$, where S_f is the area of the laser focal spot. Formula (7) then effectively becomes a formula for the lower limit of the current density

$$j_{s,\,\min}^{\exp} \approx Q_i^{\mathrm{IC1}} / \tau_L S_f. \qquad (8)$$

For ions emitted from the Au target, the lower limit of the current density in the focus is $j_{s,\,\min}^{\exp} \approx 0.8\times10^{10}$ A/cm^2. So, the real value of $j_s^{\exp}$ for backward-emitted ions should be > 10^{10} A/cm^2, which agrees with our theoretical predictions. A comparable value is expected for the current density of ions emitted forward (towards the target interior), as the lower velocity of these ions is compensated in part by their higher density.

Using the formula for $j_s^{\exp}$, we also calculated the fast ion current density at the laser focus for the sub-joule 0.5-ns laser pulse and for high-energy (0.5 kJ) high-intensity (10^{16} W/cm^2) 0.4-ns laser pulses from the PALS iodine laser system [46]. The 0.5-ns laser produces current densities $j_s^{\exp}$ 3 orders of magnitude lower and the PALS laser at least one order of magnitude lower than the 1-ps pulse. The lower value of $j_s^{\exp}$ for a 0.4-ns pulse of a thousand times higher energy, compared to the energy of the 1-ps pulse, can be understood if we realize that – apart from an over 100 times longer ion generation time – in the sub-ns case the ions are pulled by hot electrons from a plasma corona [3, 5] of relatively large thickness and low average ion density $\bar{n}_i \ll n_{ic}$. A situation similar to that for the long-pulse case will occur for ultrashort laser pulses with intense prepulses.

The very high ion current density and ps duration of the fast ion pulse produced by the optimized skin layer interaction opens the prospect for fundamentally new experiments in nuclear physics and inertial confinement fusion. In particular, a block of DT plasma accelerated by a ps laser pulse towards the DT plasma interior seems to be ideal for generation of a laser fusion ignition front. The plasma block acts like a (space charge neutral) DT ion beam for which the ignition condition in solid density (frozen) DT fuel of $>10^{10}$ A/cm^2 current density [57] for optimum ion energy (80 keV) can be easily achieved by ps laser pulses of $I < I_{rel}$. For example, a ps laser pulse of $I \sim 0.3I_{rel}$ can produce an ~ 80-keV DT ion flux with a current density of $j_s \sim 5.5\times10^{10}$ A/cm^2 at $\lambda = 1.05$ μm or $j_s \sim 5\times10^{11}$ A/cm^2 at $\lambda = 0.35$ μm. We see that such extremely high ion current densities are attainable even at low energies (≤ 1 J) and subrelativistic laser pulse intensities, which can be easily generated at high repetition rate. In particular, it opens a prospect for highly efficient DD or DT fusion in small-scale devices for, *e.g.*, fast neutron production. Achievement of high ($\gg$1) fusion gain through use of an optimized DT ion beam from the ps skin layer interaction in large-scale experiments can also be imagined, but it needs to be confirmed by further detailed studies.

6. Summary

In this paper, the main achievements of our recent studies of fast ion generation in plasma produced by picosecond laser pulses of subrelativistic intensity have been briefly reviewed. In particular, we have:

– shown that essential differences exist between the properties and acceleration mechanisms of ion fluxes in plasmas produced by ultrashort (≤ 1 ps) and by long (> 0.1 ns) laser pulses,

– presented a novel, efficient method for USP-laser-driven fast proton generation utilizing double-layer targets,

– demonstrated the generation of intense fluxes of highly charged high-energy heavy ions, and

– demonstrated the production of ultrahigh ion current densities (> 10^{10} A/cm^2) using low energy (< 1 J) ps laser pulses of subrelativistic intensity.

The results presented should be useful for development of highly efficient laser -driven ion sources for applications in accelerator technology, material science, medicine, inertial fusion science, and nuclear physics on a tabletop.

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References

[1] LICHTMAN D., READY J.F., *Laser beam induced electron emission*, Physical Review Letters **10**, 1963, pp. 342–5.

[2] LINLOR W.I., Applied Physics Letters **3**, 1963, p. 210.

[3] GITOMER S.J., JONES R.D., BEGAY F., EHLER A.W., KEPHART J.F., KRISTAL R., *Fast ions and hot electrons in the laser-plasma interaction*, Physics of Fluids **29**(8), 1986, pp.2679–88, and references therein.

[4] HASEROTH H., HILL C.E., *Multicharged ion sources for pulsed accelerators*, Review of Scientific Instruments **67**(3), 1996, pp. 945–9.

[5] HASEROTH H., HORA H.. *Physical mechanisms leading to high currents of highly charged ions in laser-driven ion sources*, Laser and Particle Beams **14**(3), 1996, pp. 393–438.

[6] BOODY F.P., HOPFL R., HORA H., KELLY J.C., *Laser-driven ion source for reduced-cost implantation of metal ions for strong reduction of dry friction and increased durability*, Laser and Particle Beams **14**(3), 1996, pp.443–8.

[7] COLLIER J., HALL G., HASEROTH H., KUGLER H., KUTTENBERGER A., LANGBEIN K., SCRIVENS R., SHERWOOD T., TAMBINI J., SHARKOV B., SHUMSHUROV A., MASEK K., *The CERN laser-ion source*, Laser and Particle Beams **14**(3), 1996, pp. 283–92.

[8] WORYNA E., PARYS P., WOŁOWSKI J., LASKA L., KRASA J., MASEK K., PFEIFER M., KRALIKOVA B., SKALA J., STRAKA P., ROHLENA K., *Au^{49+}, Pb^{50+}, and Ta^{48+} ions from laser-produced plasmas*, Applied Physics Letters **69**(11), 1996, pp. 1547–9.

[9] MRÓZ W., PARYS P., WOŁOWSKI J., WORYNA E., LASKA L., MASEK K., ROHLENA K., COLLIER J., HASEROTH H., KUGLER H., LANGBEIN K.L., SHAMAEV O.B., SHARKOV B.YU., SHUMSHUROV A.V., *Experimental investigations of multicharged ion fluxes from laser-produced plasmas*, Fusion Engineering and Design **32-33**, 1996, pp. 425–33.

[10] LÁSKA L., KRÁSA J., MAŠEK K., PFEIFER M., ROHLENA K., KRÁLIKOVÁ B., SKALA J., STRAKA P., WORYNA E., PARYS P., WOŁOWSKI J., MRÓZ W., HASEROTH H., GOLUBEV A., SHARKOV B., KORSCHINEK G., *Multiply charged ions of heavy elements produced by an iodine laser with subnanosecond pulses*, Review of Scientific Instruments **69**(2), 1998, pp. 1072–4.

[11] LÁSKA L., KRÁSA J., MAŠEK K., PFEIFER M., KRÁLIKOVÁ B., SKALA J., STRAKA P., ROHLENA K., MRÓZ W., WORYNA E., PARYS P., WOŁOWSKI J., HASEROTH H., GOLUBEV A.A., SHARKOV B.YU., *Multiply charged ions from iodine laser-produced plasma of medium- and high-Z targets*, Laser and Particle Beams **16**(1), 1998, pp. 5–12.

[12] WORYNA E., WOŁOWSKI J., KRÁLIKOVÁ B., KRÁSA J., LÁSKA L., PFEIFER M., ROHLENA K., SKALA J., PERINA V., BOODY F.P., HOPFL R., HORA H., *Laser produced Ag ions for direct implantation*, Review of Scientific Instruments **71**(2), pp. 949–51.

[13] TORRISI L., GAMMINO S., MEZZASALMA A.M., BADZIAK J., PARYS P., WOŁOWSKI J., WORYNA E., KRÁSA J., LÁSKA L., PFEIFER M., ROHLENA K., BOODY F.B., *Implantation of ions produced by the use of high power iodine laser*, Applied Surface Science **217**(1-4), 2003, pp. 319–31.

[14] UMSTADTER D., *Review of physics and applications of relativistic plasmas driven by ultra-intense lasers*, Physics of Plasmas **8**(5), 2001, pp. 1774–85, and references therein.

[15] PITTMAN M., FERRE S., ROUSSEAU J.P., NOTEBAERT L., CHAMBARET J.P., CHERIAUX G., *Design and characterization of a near-diffraction-limited femtosecond 100-TW 10-Hz high-intensity laser system* Applied Physics B: Lasers and Optics **B74**(6), 2002, pp. 529–35.

[16] HATCHETT S.P., BROWN C.G., COWAN T.E., HENRY E.A., JOHNSON J.S., KEY M.H., KOCH J.A., LANGDON A.B., LASINSKI B.F., LEE R.W., MACKINNON A.J., PENNINGTON D.M., PERRY M.D., PHILLIPS T.W., ROTH M., SANGSTER T.C., SINGH M.S., SNAVELY R.A., STOYER M.A., WILKS S.C., YASUIKE K., *Electron, photon, and ion beams from the relativistic interaction of Petawatt laser pulses with solid targets* Physics of Plasmas **7**(5), 2000, pp. 2076–82.

[17] ZWEIBACK J., COWAN T.E., SMITH R.A., HARTLEY J.H., HOWELL R., STEINKE C.A., HAYS G., WHARTON K.B., CRANE J.K., DITMIRE T., *Characterization of fusion burn time in exploding deuterium cluster plasmas*, Physical Review Letters **85**(17), 2000, pp. 3640–3.

[18] PATEL P.K., MACKINNON A.J., KEY M.H., COWAN T.E., FOORD M.E., ALLEN M., PRICE D.F., RUHL H., SPRINGER P.T., STEPHENS R., *Isochoric heating of solid-density matter with an ultrafast proton beam*, Physical Review Letters **91**(12), 2003, pp. 125004/1-4.

[19] SANTALA M.I.K., ZEPF M., BEG F.N., CLARK E.L., DANGOR A.E., KRUSHELNICK K., TATARAKIS M., WATTS I., LEDINGHAM K.W.D., MCCANNY T., SPENCER I., MACHACEK A.C., ALLOTT R., CLARKE R.J., NORREYS P.A., *Production of radioactive nuclides by energetic protons generated from intense laser -plasma interactions*, Applied Physics Letters **78**(1), 2001, pp. 19–21.

[20] BULANOV S.V., ESIRKEPOV T.ZH., KHOROSHKOV V.S., KUZNETSOV A., PEGORARO F., *Oncological hadrontherapy with laser ion accelerators*, Physics Letters A **299**(2-3), 2002, pp. 240–7.

[21] ROTH M., COWAN T.E., KEY M.H., HATCHETT S.P., BROWN C., FOUNTAIN W., JOHNSON J., PENNINGTON D.M., SNAVELY R.A., WILKS S.C., YASUIKE K., RUHL H., PEGORARO E., BULANOV S.V., CAMPBELL E.M., PERRY M.D., POWELL H., *Fast ignition by intense laser-accelerated proton beams*, Physical Review Letters **86**(3), 2001, pp. 436–9.

[22] NEMOTO K., MAKSIMCHUK A., BANERJEE S., FLIPPO K., MOUROU G., UMSTADTER D., BYCHENKOV V.YU. *Laser-triggered ion acceleration and table top isotope production*, Applied Physics Letters **78**(5), 2001, pp. 595–7.

[23] MCKENNA P., LEDINGHAM K.W.D., MCCANNY T., SINGHAL R.P., SPENCER I., CLARK E.L., BEG F.N., KRUSHELNICK K., WEI M.S., GALY J., MAGILL J., CLARKE R.J., LANCASTER K.L., NORREYS P.A., SPOHR K., CHAPMAN R., *Effect of target heating on ion-induced reactions in high-intensity laser-plasma interactions*, Applied Physics Letters **83**(14), 2003, pp. 2763–5.

[24] BADZIAK J., CHIZHOV S.A., KOZLOV A.A., MAKOWSKI J., PADUCH M., TOMASZEWSKI K., VANKOV A.B., YASHIN V.E., *Picosecond, terawatt, all-Nd:glass CPA laser system*, Optics Communications **134**(1-6), 1997, pp. 495–502.

[25] BADZIAK J., MAKOWSKI J., PARYS P., RYC L., WOLOWSKI J., WORYNA E., VANKOV A.B., *Intensity-dependent characteristics of a picosecond laser-produced Cu plasma*, Journal of Physics D: Applied Physics 34(12), 2001, pp. 1885–91.

[26] BADZIAK J., HORA H., WORYNA E., JABLONSKI S., LASKA L., PARYS P., ROHLENA K., WOLOWSKI J., *Experimental evidence of differences in properties of fast ion fluxes from short-pulse and long-pulse laser-plasma interactions*, Physics Letters A **315**(6), 2003, pp. 452–7.

[27] WORYNA E., PARYS P., WOLOWSKI J., MROZ W., *Corpuscular diagnostics and processing methods applied in investigations of laser-produced plasma as a source of highly ionized ions*, Laser and Particle Beams **14**(3), 1996, pp. 293–321.

[28] HORA H., *Skin-depth theory explaining anomalous picosecond-terawatt laser plasma interaction II*, Czechoslovak Journal of Physics **53**(3), 2003, pp. 199–217.

[29] HORA H., BADZIAK J., BOODY F.P., HOPFL R., JUNGWIRTH K., KRALIKOVA B., KRASA J., LASKA L., PARYS P., PERINA V., PFEIFER M., ROHLENA K., SKALA J., ULLSCHMIED J., WOLOWSKI J., WORYNA E., *Effects of ps and ns laser pulses for giant ion source*, Optics Communications **207**(1-6), 2002, pp. 333–8.

[30] FEWS A.P., NORREYS P.A., BEG F.N., BELL A.R., DANGOR A.E., DANSON C.N., LEE P., ROSE S.J., *Plasma ion emission from high intensity picosecond laser pulse interactions with solid targets*, Physical Review Letters **73**(13), 1994, pp. 1801–4.

[31] CLARK E.L., KRUSHELNICK K., DAVIES J.R., ZEPF M., TATARAKIS M., BEG F.N., MACHACEK A., NORREYS P.A., SANATALA M.I.K., WATTS I., DANGOR A.E., *Measurements of energetic proton transport through magnetized plasma from intense laser interactions with solids*, Physical Review Letters **84**(4), 2000, pp. 670–3.

[32] MAKSIMCHUK A., GU S., FLIPPO K., UMSTADTER D., BYCHENKOV V.YU., *Forward ion acceleration in thin films driven by a high-intensity laser*, Physical Review Letters **84**(18), 2000, pp. 4108–11.

[33] SNAVELY R.A., KEY M.H., HATCHETT S.P., COWAN T.E., ROTH M., PHILLIPS T.W., STOYER M.A., HENRY E.A., SANGSTER T.C., SINGH M.S., WILKS S.C., MACKINNON A., OFFENBERGER A., PENNINGTON D.M., YASUIKE K., LANGDON A.B., LASINSKI B.F., JOHNSON J., PERRY M.D., CAMPBELL E.M., *Intense high-energy proton beams from petawatt-laser irradiation of solids*, Physical Review Letters **85**(14), 2000, pp. 2945–8.

[34] MACKINNON A.J., BORGHESI M., HATCHETT S., KEY M.H., PATEL P.K., CAMPBELL H., SCHIAVI A., SNAVELY R., WILKS S.C., WILLI O., *Effect of plasma scale length on multi-MeV proton production by intense laser pulses*, Physical Review Letters **86**(9), 2001, pp. 1769–72.

[35] MURAKAMI Y., KITAGAWA Y., SENTOKU Y., MORI M., KODAMA R., TANAKA K.A., MIMA K., YAMANAKA T., *Observation of proton rear emission and possible gigagauss scale magnetic fields from ultra-intense laser illuminated plastic target*, Physics of Plasmas **8**(9), 2001, pp. 4138–43.

[36] BADZIAK J., WORYNA E., PARYS P., PLATONOV K.Y., JABLONSKI S., VANKOV A.B., WOLOWSKI J., *Fast proton generation from ultrashort laser pulse interaction with double-layer foil targets,* Physical Review Letters **87**(21), 2001, pp. 215001/1–4.

[37] BADZIAK J., WORYNA E., PARYS P., WOLOWSKI J., PLATONOV K.YU., VANKOV A.B., *Effect of foil target thickness on fast proton generation driven by ultrashort-pulse laser,* Journal of Applied Physics, **91**(8), 2002, pp. 5504–6.

[38] BADZIAK J., WORYNA E., PARYS P., PLATONOV K.YU., JABLONSKI S., RYC L., VANKOV A.B., WOLOWSKI J., *Generation of energetic protons from thin foil targets irradiated by a high-intensity ultrashort laser pulse,* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **498**(1-3), pp. 503–516.

[39] ZEPF M., CLARK E.L., BEG F.N., CLARKE R.J., DANGOR A.E., GOPAL A., KRUSHELNICK K., NORREYS P.A., TATARAKIS M., WAGNER U., WEI M.S., *Proton acceleration from high-intensity laser interactions with thin foil targets*, Physical Review Letters **90**(6), 2003, pp. 064801/1–4.

[40] WILKS S.C., LANGDON A.B., COWAN T.E., ROTH M., SINGH M., HATCHETT S., KEY M.H., PENNINGTON D., MACKINNON A., SNAVELY R.A., *Energetic proton generation in ultra-intense laser-solid interactions*, Physics of Plasmas **8**(2), 2001, pp. 542–9.

[41] KRASA J., LASKA L., ROHLENA K., PFEIFER M., SKALA J., KRALIKOVA B., STRAKA P., WORYNA E., WOLOWSKI J., *The effect of laser-produced plasma expansion on the ion population*, Applied Physics Letters **75**(17), 1999, pp. 2539–41.

[42] WOLOWSKI J., BADZIAK J., BOODY F.P., HORA H., HNATOWICZ V., JUNGWIRTH K., KRASA J., LASKA L., PARYS P., PERINA V., PFEIFER M., ROHLENA K., RYC L., ULLSCHMIED J., WORYNA E., *Fast ion emission from the plasma produced by the PALS laser system*, Plasma Physics and Controlled Fusion **44**(7), 2002, pp. 1277–83.

[43] SZYDLOWSKI A., BADZIAK J., PARYS P., WOLOWSKI J., WORYNA E., JUNGWIRTH K., KRALIKOVA B., KRASA J., LASKA L., PFEIFER M., ROHLENA K., SKALA J., ULLSCHMIED J., BOODY F.D., GAMMINO S., TORRISI L., *Solid state track detectors applied in measurements of ion streams produced by the high energy laser pulses*, Czechoslovak Journal of Physics **52**, suppl. D (CD-ROM), 2002, pp. D299–304.

[44] WOLOWSKI J., BADZIAK J., BOODY F.P., GAMMINO S., HORA H., JUNGWIRTH K., KRASA J., LASKA L., PARYS P., PFEIFER M., ROHLENA K., SZYDLOWSKI A., TORRISI L., ULLSCHMIED J., WORYNA E., *Characteristics of ion emission from plasma produced by high-energy short-wavelength (438 nm) laser radiation*, Plasma Physics and Controlled Fusion **45**(7), 2003, pp. 1087–93.

[45] SZYDLOWSKI A., BADZIAK J., PARYS P., WOLOWSKI J., WORYNA E., JUNGWIRTH K., KRALIKOVA B., KRASA J., LASKA L., PFEIFER M., ROHLENA K., SKALA J., ULLSCHMIED J., BOODY F.D., GAMMINO S., TORRISI L., *Measurements of energetic ions emitted from laser produced plasma by means of solid state nuclear track detectors of the PM-355 type*, Plasma Physics and Controlled Fusion **45**(8), 2003, pp. 1417–22.

[46] LASKA L., JUNGWIRTH K., KRALIKOVA B., KRASA J., PFEIFER M., ROHLENA K., SKALA J., ULLSCHMIED J., BADZIAK J., PARYS P., WOLOWSKI J., WORYNA E., GAMMINO S., TORRISI L., BOODY F.P., HORA H., *Generation of multiply charged ions at low and high laser-power densities*, Plasma Physics and Controlled Fusion **45**(5), 2003, pp. 585–99.

[47] GUETHLEIN G., FOORD M.E., PRICE D., *Electron temperature measurements of solid density plasmas produced by intense ultrashort laser pulses*, Physical Review Letters **77**(6), 1996, pp. 1055–8.

[48] BADZIAK J., KOZLOV A.A., MAKOWSKI J., PARYS P., RYC L., WOLOWSKI J., WORYNA E., VANKOV A.B., *Investigations of ion streams emitted from plasma produced with a high-power picosecond laser*, Laser and Particle Beams **17**(2), 1999, pp. 323–9.

[49] CLARK E.L., KRUSHELNICK K., ZEPF M., BEG F.N., TATARAKIS M., MACHACEK A., SANTALA M.I.K., WATTS I., NORREYS P.A., DANGOR A.E., *Energetic heavy-ion and proton generation from ultraintense laser-plasma interactions with solids*, Physical Review Letters **85**(8), 2000, pp. 1654–7.

[50] BADZIAK J., PARYS P., VANKOV A.B., WOLOWSKI J., WORYNA E., *Generation of fluxes of highly charged heavy ions from a picosecond laser-produced plasma*, Applied Physics Letters **79**(1), 2001, pp. 21–3.

[51] BADZIAK J., MAKOWSKI J., PARYS P., WOLOWSKI J., WORYNA E., VANKOV A.B., *Generation of streams of highly charged Ag ions by picosecond laser*, Applied Physics Letters **78**(13), 2001, pp. 1823–5.

[52] HEGELICH M., KARSCH S., PRETZLER G., HABS D., WITTE K., GUENTHER W., ALLEN M., BLAZEVIC A., FUCHS J., GAUTHIER J.C., GEISSEL M., AUDEBERT P., COWAN T., ROTH M., *MeV ion jets from short-pulse-laser interaction with thin foils*, Physical Review Letters **89**(8), 2002, pp. 085002-1-4.

[53] WOLOWSKI J., BADZIAK J., KRASA J., LASKA L., PARYS P., ROHLENA K., WORYNA E., *Investigations of ion emission from plasma produced by a high-power 1 ps laser pulse*, Plasma Sources Science and Technology **11**(3A), 2002, pp. A173–7.

[54] BADZIAK J., JABLONSKI S., PARYS P., RYC L., WOLOWSKI J., WORYNA E., KRASA J., LASKA L., PFEIFER M., ROHLENA K., *High-intensity interactions of 1-ps and 0.5-ns laser pulses with a high-Z target – a comparison*, Czechoslovak Journal of Physics **52**, suppl. D (CD-ROM), 2002, pp. D318–23.

[55] MURNANE M.M., KAPTEYN H.C., GORDON S.P., FALCONE R.W., *Ultrashort X-ray pulses*, Applied Physics B: Lasers and Optics **B58**(3), 1994, pp. 261–6.

[56] BADZIAK J., GLOWACZ S., JABLONSKI S., PARYS P., WOLOWSKI J., HORA H., *Production of ultrahigh -current-density ion beams by short-pulse skin-layer laser-plasma interaction*, Applied Physics Letters **85**(15), 2004, pp. 3041–3.

[57] HORA H., *Interpenetration burn for controlled inertial confinement fusion driven by nonlinear laser forces*, Atomkernenergie Kerntechnik **42**(1), 1983, pp. 7–10.

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