Laser-driven ion acceleration: methods, challenges and prospects

J Badziak
Institute of Plasma Physics and Laser Microfusion, 01-497 Warsaw, Poland
E-mail: jan.badziak@ifpilm.pl

Abstract. The recent development of laser technology has resulted in the construction of short-pulse lasers capable of generating fs light pulses with PW powers and intensities exceeding $10^{21}$ W/cm$^2$, and has laid the basis for the multi-PW lasers, just being built in Europe, that will produce fs pulses of ultra-relativistic intensities $\sim 10^{23} – 10^{24}$ W/cm$^2$. The interaction of such an intense laser pulse with a dense target can result in the generation of collimated beams of ions of multi-MeV to GeV energies of sub-ps time durations and of extremely high beam intensities and ion fluencies, barely attainable with conventional RF-driven accelerators. Ion beams with such unique features have the potential for application in various fields of scientific research as well as in medical and technological developments. This paper provides a brief review of state-of-the-art in laser-driven ion acceleration, with a focus on basic ion acceleration mechanisms and the production of ultra-intense ion beams. The challenges facing laser-driven ion acceleration studies, in particular those connected with potential applications of laser-accelerated ion beams, are also discussed.

1. Introduction
High-energy particle accelerators driven by a radio-frequency (RF) electromagnetic field are among the largest and most complex facilities built on Earth. Currently, the largest RF-driven accelerator is the Large Hadron Collider (LHC) at CERN, which accelerates protons to multi-TeV energies (1 TeV = $10^{12}$ eV) in a 27-km high-vacuum ring. One of the main reasons for the enormous size of the accelerator is a limit on the acceleration field strength, which is about 1 MV/cm. Due to this limit, to accelerate ions/protons to multi-GeV or TeV energies, the acceleration path has to be very long, meaning that the accelerator has to be very large. This lead to the question as to whether RF-driven ion accelerators are the only possible ones that enable us to accelerate ions to very high velocities close to the speed of light c. One potential alternative, or at least an important supplement to the RF-driven ion accelerators, seems to be ion accelerators driven by an intense laser beam.

A simple scheme of a laser-driven ion accelerator is shown in Figure 1. The accelerator consists of a short-pulse high-intensity laser and a target, e.g. thin foil, placed in a vacuum chamber. The laser beam interacting with the target produces plasma, in which electrons are partly separated from ions by the action of the laser field. Between the layer of electrons and the ions, a very strong electric field is produced. This field pulls the ions, which follow the moving electron layer. The field strength can reach extremely high values (up to tens or even hundreds GeV/cm) and, as a result, the ions can be accelerated to high energies over sub-mm distances, by many orders of magnitude shorter than required in conventional RF-driven accelerators. In this way, the laser-driven accelerator can potentially be much smaller and less complex than conventional ones. Furthermore, since the laser-accelerated ion bunch is very dense and compact, the ion beam intensities/powers can be very high,
and the time duration of the ion pulse can be very short. Such ion beams have the potential to be used in various branches of science, technology and medicine, and can significantly extend the current scope of ion beam applications.

![Figure 1. A simple scheme of the laser-driven ion accelerator.](image)

Studies into the generation of energetic ions from laser-produced plasma have a long history and begin in the nineteen sixties [1,2]. However, a real breakthrough in these studies came at the turn of the millennium, when collimated forward-emitted beams of MeV protons generated from thin foil targets irradiated by a short (≤ 1 ps) high-power laser pulse were demonstrated [3-5]. Following these pioneering experiments, the research on laser-driven ion acceleration has developed rapidly and this research field is currently one of the most intensely studied areas of plasma physics.

This paper is a brief review of recent research on laser-driven ion acceleration based on a talk presented at the International Conference on Research and Application of Plasmas, held in Warsaw, in September, 2017. Interested readers can find an extended review of this topic in [6,7]. In section 2 of this paper, the forces and mechanisms of ion acceleration in laser-produced plasma are presented. In sections 3 and 4, the basic features of the most studied mechanisms of ion acceleration, namely the target normal sheath acceleration (sec. 3) and the radiation pressure acceleration (sec. 4) are described. Section 5 presents examples of numerical studies on the acceleration of protons and super-heavy ions at ultra-relativistic laser intensities performed by the IPPLM team. Section 6 discusses the main challenges faced by research on laser-driven ion acceleration, and section 7 summarises the main conclusions from the paper.

2. Basic forces and mechanisms accelerating ions in plasma

The main forces induced by a laser beam in plasma, which are capable of accelerating ions to high velocities over very short distances, can be roughly divided into the electromagnetic (EM) forces and the hydrodynamic forces. The EM forces clearly dominate in the case of high (> 10^{15} W/cm^2) and very high (> 10^{18} W/cm^2) intensities of the laser beam interacting with the plasma (the latter are often called the relativistic intensities, since at such intensities an electron placed in the laser field can reach velocities close to the speed of light c). The field strengths of the laser-induced EM forces can reach extremely high values (up to > 100 GV/cm) and, as a result, these forces can accelerate ions to high velocities \( v_i \), including relativistic ones (\( v_i \approx c \)), over sub-mm distances. The laser-driven ion accelerators, in which EM forces are the main forces accelerating ions, can be referred to as laser-driven electromagnetic accelerators.

The basic source of the EM forces accelerating ions in plasma at high and very high laser intensities is the Lorentz force \( \mathbf{F} = q \mathbf{E} + q (\mathbf{v} \times \mathbf{B}) \), where \( q \) is the particle charge, \( \mathbf{v} \) is the particle velocity and \( \mathbf{E} \) and \( \mathbf{B} \) are the electric and the magnetic part of the laser field in the plasma. This force interacts with both plasma electrons and plasma ions, though in practice (at laser intensities < 10^{24} W/cm^2) the movement of ions due to the direct action of this force can be neglected (due to a large ion
mass) and only electrons are set in motion by the force. The electrons are pushed away from the ions (from the equilibrium position) by the force, which results in creating a huge electric field between the moving electron cloud and the ions. This electric field accelerates ions, which are usually moving together with the electron cloud. Since the electric field strength is extremely high, the ions can reach high velocities in very short distances and during very short time periods. A detailed mechanism of ion acceleration depends on both the laser pulse and the target parameters, and the acceleration mechanisms can be different for different laser-target interaction conditions. Presently, several ion acceleration mechanisms are known and have been extensively studied. They include: the target normal sheath acceleration (TNSA) [6,7,8-15], the skin-layer ponderomotive acceleration (SLPA) [16-20], the radiation pressure acceleration (RPA) [6,7,21-26], the laser break-out afterburner (BOA) [6,7,27,28], the collisionless electrostatic shock acceleration (CESA) [6,29,30], the ion solitary wave acceleration (ISWA) [31,32] and the Coulomb explosion acceleration (CEA) [33,34]. In a real experiment, two or even more acceleration mechanisms indicated above can contribute to the ion acceleration process.

At low laser intensities (~ $10^{10} - 10^{15}$ W/cm$^2$) and long laser pulses (from tens of ps to tens of ns), a significant or even dominant role in the process of accelerating plasma ions can be played by hydrodynamic forces (hydrodynamic or thermal pressure) induced by the laser pulse. In a real situation, these forces are usually a complex function of density $n$ and temperature $T$ of the plasma electrons, $F_h = f(n,T)$, and their absolute values are higher for higher values of $n$ and $T$. The velocities of ions driven by the hydrodynamic forces are relatively small ($v_i < 0.01 c$), but the number and density of the accelerated ions can be very high. As a result, the total mass and kinetic energy of the accelerated ion (plasma) bunch can be high, even higher than in the case of EM ion acceleration driven by a short (sub-ps) laser pulse (attainable energies of long-pulse laser drivers are much higher than those of short-pulse laser drivers). The laser-driven ion accelerators, in which hydrodynamic forces play a dominant role in ion acceleration, can be referred to as laser-driven hydrodynamic accelerators. Examples of this kind of accelerator are the ablative acceleration systems [35-38] (used, among other things, for the acceleration and compression of DT fuel in fusion targets) or accelerators using the laser-induced cavity pressure acceleration (LICPA) mechanism [39-41].

It should be underlined that also in the low-intensity case dominated by the hydrodynamic acceleration, strong electric fields can exist in plasma (e.g.[42]), which are a result of the inhomogeneous distribution of density and velocity of plasma electrons. These fields can produce supra-thermal (fast) ions of multi-MeV energies [43], though the total energy and number of these ions is usually much lower than those of ions driven by hydrodynamic (thermal) pressure.

This paper is focused on laser-driven ion acceleration at high and very high laser intensities when ions are accelerated by EM forces. In the next two sections, the most studied mechanisms of laser-driven EM ion acceleration – namely TNSA and RPA – will be described.

3. Ion acceleration by the TNSA mechanism

A simplified scheme of ion acceleration by the TNSA mechanism [6,7,15] is shown in Figure 2. In this method, a short laser pulse interacting with the target front surface produces plasma and hot electrons with a temperature of $T_e \approx 0.1 - 10$ MeV. The electrons penetrate through the target and on the target rear surface they form a Debye sheath playing the role of a virtual cathode. The electric field induced by the cathode: $E_{ac} \approx T_e/e\lambda_{Dh} \approx 1 - 100$ GeV/cm ionises atoms at the rear surface and accelerates the produced ions over the distance $L_{ac} \approx 10 - 50 \mu$m to the energies $E_i \approx z\lambda_{Dh}E_{ac} \approx 1 - 100$ MeV ($\lambda_{Dh}$ is the Debye length and $z$ is the ion charge state). The ions are accelerated mostly along the rear surface normal and, as a result, the angular divergence of the ion beam is relatively small.

The TNSA mechanism is effective in accelerating light ions, primarily protons [3-15]. Such ions can be produced from both insulator (e.g. plastic) and metal targets, typically ~ 2 - 20 $\mu$m thick; however, the metal target is usually more efficient, both in terms of the maximum ion energy and the ion beam quality (due to more efficient electron transport in metal). When a metal target is used, a
source of light ions constitute hydrocarbon contaminants (H, C) almost always existing on the target (sometimes, to increase the number of accelerated ions, the target rear surface is covered with a thin plastic layer [44]). Independent of the target composition and structure, only ions from a very thin (~2 – 10 nm) layer on the target rear surface are accelerated by the TNSA mechanism. As a result, the areal ion density of the ion source is relatively small, \( \sigma_i < 10^{13} \text{ cm}^{-2} \), and the ion density at the source is moderate, \( n_i \leq 10^{19} \text{ cm}^{-3} \). Thus, attaining high ion beam intensities \( I_B = n_i \sigma_i \) (around \( I_B > 10^{18} \text{ W/cm}^2 \)) and/or energy fluencies \( \Phi_B = \sigma_i \Phi_i \) (around \( \Phi_B > 1 \text{ MJ/cm}^2 \)) is possible only at very high ion energies (~100 MeV or higher). On the other hand, the total number of accelerated ions can be fairly high (up to \( \sim 10^{12} – 10^{13} \) [5-7]) since, due to the transverse transport of fast electrons in the target, the ions are extracted from an area much larger than the area of the laser beam on the target \( S_L \) (the ion source area \( S_o >> S_L \)).

The TNSA mechanism of ion/proton acceleration is fairly efficient, provided that the target rear surface is of high quality and that it is not disturbed significantly during laser-target interaction by the shock wave generated in the target by the laser pulse leading edge, or the laser pre-pulse [8,14,15]. The last requirement imposes constraints on the laser pulse duration and its contrast ratio. For relativistic laser intensities and very thin targets (the target thickness \( L_T < 1 \mu\text{m} \)), the pulse duration should be in the sub-ps range, and the contrast ratio must be high (the intensity contrast ratio \( > 10^9 – 10^{10} \)). For a thicker target, of tens of \( \mu\text{m} \) thick, picosecond (~1 – 10 ps) laser pulses are also acceptable and the contrast ratio can be much lower. It is suggested that for non-relativistic laser intensities of \( I_L < 10^{18} \text{ W/cm}^2 \), the TNSA mechanism works efficiently also for much longer, sub-ns laser pulses [45] but this conjecture has not been sufficiently proved yet.

The TNSA method of ion acceleration has several advantages, confirmed experimentally, in particular: (1) an excellent quality of the transverse intensity distribution of the ion (proton) beam; (2) very low transverse emittance of the beam; (3) moderate requirements for the laser beam quality (both for the transverse distribution and the contrast ratio of the beam) and intensity (both relativistic and sub-relativistic laser intensities are applicable); as a result, proton beams with energies of tens of MeV (up to 90 MeV in [46]) can be produced with currently attainable laser intensities (<10^{15} \text{ W/cm}^2).

The main drawbacks of the TNSA scheme are: (1) a broad (quasi-Maxwellian) ion energy spectrum; (2) unfavorable scaling of the maximum ion energy \( E_{\text{max}} \) with laser intensity: \( E_{\text{max}} \sim (I_L)^{0.5} \) [6,7] (as a result, \( E_{\text{max}} \) is limited in practice to several hundred MeV, since \( I_L \) cannot surpass \( 10^{22} – 10^{23} \text{ W/cm}^2 \) in this method); (3) relatively small areal ion density at the source \( \sigma_i < 10^{17} \text{ cm}^{-2} \) (which results in relatively low ion beam intensity at a source that is below \( 10^{17} \text{ W/cm}^2 \) for presently achievable laser intensities); (4) relatively low laser-to-ions energy conversion efficiency \( \eta \) (typically below a few per cent, though using the double-pulse technique \( \eta \approx 15\% \) was achieved [47]); (5) high sensitivity of the ion beam parameters and \( \eta \) on the target rear surface quality. In spite of these drawbacks, TNSA is still the most successful and recognized method of ion (proton) acceleration, having the potential to produce ion beams of parameters desirable for numerous applications. The
main achievements in the generation of ion beams using this method, and their possible applications, are described in other review papers (e.g. [6,7]).

4. Ion acceleration by the RPA mechanism

The radiation pressure acceleration (RPA) [6,7,21-26] can be considered as a special, high-intensity case of what is known as the skin-layer ponderomotive acceleration (SLPA) mechanism [16-20] of laser-driven ion acceleration. This mechanism uses strong ponderomotive forces induced at the interaction of a short laser pulse with a thin and dense preplasma layer created by the laser pulse leading edge in front of a target (Figure 3). The main part of the pulse interacts with the preplasma near the critical plasma surface, producing two opposite ponderomotive forces (see, for example, [48]). Each of these forces acts on the plasma electrons placed near the critical surface, and the electrons are pushed along the force direction and locally separated from the plasma ions. The system of the electron layer and the ion layer forms a so-called double layer (e.g. [48,49]), which is a region of non-neutral plasma where a large potential drop produces a very strong electric field (the charge-separation field) that accelerates ions. Since, in general, there are induced two opposite ponderomotive forces that push electrons near the critical surface, these forces drive (through the double-layer mechanism) two ion bunches moving in a forwards and backwards direction. At high laser intensity (> 10^{20} – 10^{21} W/cm²) and high plasma density gradient, the forward-directed ponderomotive force (the ponderomotive or radiation pressure) clearly prevails over the backward-directed one and only a high-density forward-accelerated (along the laser beam axis) ion bunch is actually produced. This high-intensity case of SLPA is usually referred to as RPA.

![Figure 3. Simplified physical picture of ion acceleration by the RPA mechanism.](image)

In the RPA regime of ion acceleration, two stages of acceleration can be distinguished [6,7,25,26]: the hole-boring (HB) stage and the light-sail (LS) stage (Figure 3). In the HB stage, the ions from the target front surface are accelerated towards the target interior by the moving forward charge-separation field driven by the ponderomotive (radiation) pressure. An increase in ion energies is accompanied by an increase in the number of accelerated ions and the ion bunch density since the moving double layer (in fact, its positively charged ion layer) acts as a piston on ions stored in a non-perturbed part of the target. The HB stage terminates when the accelerated ions (potentially, all ions stored in the target) reach the target rear surface. Then the LS stage begins. In this stage, the overdense plasma bunch, containing electrons and ions that cross the initial position of the target rear surface, are accelerated by the radiation pressure in free space like a sail pushed by the wind (for a more detailed
description of the HB and LS stages of RPA [6,7,25,26]). Depending on the target thickness and the laser pulse duration $t_L$ and fluence $F_L$, HB RPA or LS RPA dominates the acceleration process. When the target is sufficiently thick (or $F_L$ is not sufficiently high) the whole laser energy is exploited for the acceleration of the ion bunch inside the target and the HB stage dominates. In turn, when the target is sufficiently thin (or $F_L$ is sufficiently high) only a small part of laser energy is used for the formation and acceleration of the bunch inside the target (for the HB stage), and most of the laser energy is used for the acceleration of the bunch (the whole target, in practice) in the free space behind the initial target position. Thus, the LS stage dominates the acceleration process.

As mentioned in section 2, in a real ion acceleration process, two or even more acceleration mechanisms can contribute to this process, and very often the RPA mechanism competes with the TNSA mechanism in ion acceleration (sometimes RPA and TNSA produce clearly different groups of ions [19]). Since the forward-directed ponderomotive force (the radiation pressure) increases proportionally to the laser intensity, the contribution of RPA to the acceleration process grows with an increase in the laser intensity, and at very high laser intensities (well above $10^{21}$ W/cm$^2$) RPA can dominate over TNSA. This contribution also depends on the irradiated target properties as well as on the laser pulse contrast ratio (a high contrast ratio is preferred [50]) and the laser beam polarisation [6,7,22] and wavelength [51,52] (the TNSA contribution to ion acceleration can be reduced by using circular light polarisation [6,7,22] or/and a short-wavelength laser beam [51,52]).

RPA has several advantages over TNSA. The most important of them, demonstrated by numerical simulations and theory, are the following (e.g. [6,7,19,20]): (1) very high (up to tens of %) laser-to-ions energy conversion efficiency; (2) favourable scaling of ion energy with laser intensity/fluence (E$_i \sim (I_{l0})^\alpha$, $\alpha \approx 2$ for $v_i \ll c$ and $\alpha \approx 1$ for the LS mode, or $\alpha \approx 1/3$ for the HB mode at $v_i \approx c$); (3) very high ion energies are possible (up to hundreds of GeV, limited by the laser pulse group velocity and the relativistic target transparency); (4) high areal ion density at the source, up to $\sigma \geq 10^{20}$ cm$^{-2}$ (an ion beam of very high intensity/power/energy fluence can be produced even at moderate ion energies); (5) quasi-monoenergetic ion energy spectrum; (6) very short (down to fs) ion pulses can be produced; (7) both light and heavy ions can be efficiently accelerated.

RPA also has some drawbacks. The most significant are the following [6,7]: (1) very high laser intensities ($> 10^{21}$ W/cm$^2$) are required for efficient acceleration (circularly polarised or short-wavelength laser beams are preferred); (2) the transverse homogeneity of the laser beam must be high; (3) Rayleigh-Taylor-like (and other) instabilities can occur and destroy the ion beam; (4) most RPA properties have not yet been confirmed experimentally.

RPA has been much less studied experimentally than TNSA, with investigations only performed for relatively low laser intensities from the range $10^{19}$ – $10^{21}$W/cm$^2$ [6,7,19,50,53] in which ion acceleration is significantly influenced by other acceleration mechanisms (mostly TNSA). The main achievements of these studies include the measurements of ion (proton) energies of 93 MeV [50] and proton beam current densities and intensities at the source ~ $10^{12}$ A/cm$^2$ and ~ $10^{18}$ W/cm$^2$ respectively [19], as well as a rough confirmation of the quadratic scaling of the ion energy with laser intensity [50,53]. For higher laser intensities, where RPA can dominate the ion acceleration process, this mechanism has been investigated only numerically, using particle-in-cell (PIC) codes (e.g. [6,7,21-26,51,52]). Detailed experimental studies of RPA require next-generation short-pulse lasers with laser powers and intensities much higher than those of the lasers used currently.

5. Ion acceleration at ultra-relativistic laser intensities

Laser-driven ion beams have the potential to be used in many branches of science, as well as in technology and medicine. In particular, they can be applied in:

- nuclear and particle physics,
- high energy-density physics (e.g. in research on the extreme state of matter),
- inertial confinement fusion (e.g. for proton/ion fast ignition of DT fuel),
- materials science (e.g. for ion implantation),
- nuclear medicine (in hadron cancer therapy or for the production of radio-isotopes),
- radiography (e.g. for ultra-fast proton radiography).

However, the vast majority of these applications require next-generation laser drivers with a laser power or intensity higher than achievable presently. The Extreme Light Infrastructure (ELI) [54] currently being built in Europe is just a laser infrastructure where the feasibility of various potential applications of laser-driven ion beams can be tested.

5.1. Extreme Light Infrastructure
ELI will be the first laser infrastructure in the world enabling the investigation of light-matter interaction in the ultra-relativistic intensity regime (at \( I_L \geq 10^{23} \) W/cm\(^2\), where not only electrons but also protons can be accelerated to relativistic velocities) and will be a platform for both pioneering fundamental research and applications in various branches of science, technology and medicine. The primary mission of ELI consists of producing a new generation of laser-driven sources of electromagnetic radiation from the THz range to gamma-rays and bunches of electrons, protons and ions that will be used as research tools in many scientific disciplines and in the development of new technologies. ELI comprises three pillars located in three European countries, in particular: ELI-Beamlines (in the Czech Republic), ELI-Nuclear Physics (in Romania) and ELI-ALPS (in Hungary). All of them will be equipped with multi-PW femtosecond lasers. The 10 PW lasers at ELI-Beamlines (ELI-BL) and ELI-Nuclear Physics (ELI-NP) will be able to produce fs laser pulses of ultra-relativistic intensities (up to \( \sim 10^{23} - 10^{24} \) W/cm\(^2\)) and are planned to be used, among other things, in research on the laser-driven acceleration of ions and their various applications in plasma physics, high energy-density physics, nuclear astrophysics and in biomedical and material sciences [54]. However, studies on ion acceleration in the ultra-relativistic intensity regime (in which the generated ion beams can make many of these applications feasible) are at a very initial stage [21,55-58] and need to be intensely developed. Below, some example results of numerical investigations on the acceleration of protons (from a CH target) and super-heavy ions (from a thorium target) driven by an fs laser pulse of ultra-relativistic intensity are presented. The investigations were performed by the IPPLM team using a fully electromagnetic, relativistic 2D3V particle-in-cell (PIC) code.

5.2. Acceleration of protons at ultra-relativistic laser intensities
The studies of proton acceleration by an fs laser pulse of ultra-relativistic intensity were carried out for the laser pulse parameters predicted for the ELI-BL 10 PW laser. The numerical PIC simulations were performed for the CH target with a thickness \( L_T \) ranging from 0.1 \( \mu \)m to 1 \( \mu \)m and a transverse dimension equal to 12 \( \mu \)m. The molecular density of the target corresponded to solid-state density and was equal to 4.86*10\(^{22} \) molecules/cm\(^3\), and the target components (C, H) were fully ionised. A pre-plasma layer with a thickness of 0.25 \( \mu \)m and the density shape described by an exponential function was placed in front of the target. The laser pulse shape in time and space (along the y-axis) was described by a super-Gaussian function with a power index equal to 6. The laser beam of linear or circular polarisation had a width (FWHM) of 8 \( \mu \)m and the laser pulse length (FWHM) and wavelength were equal to 130 fs and 800 nm respectively. The simulations were carried out in the s, y space of dimensions 160*32 \( \mu \)m\(^2\), and the number of macro-particles was assumed to be 5*10\(^6\) for the thinner targets (\( L_T \leq 0.3 \) um) and 9*10\(^6\) for the thicker targets (\( L_T > 0.3 \) um). Example results of the simulations are presented in Figures 4, 5 and 6.

Figure 4 presents a 2D spatial distribution of charge density of protons (a, c) and carbon ions (b, d) generated from the CH target with a thickness of 0.1 um for the final stage of ion acceleration (the simulation time \( t = 0.4 \) ps). The target was irradiated by a linearly-LP (a, b) or circularly-CP (c,d) polarised laser pulse with an intensity equal to \( 10^{23} \) W/cm\(^2\) for CP and \( 2*10^{23} \) W/cm\(^2\) for LP (the laser energy fluencies were approximately the same for both types of polarisation). It can be seen that for both polarisations protons are accelerated to relativistic velocities in the form of a compact, high-density proton (plasma) block, which is typical for the acceleration process dominated by RPA in the LS mode (sec. 4). For both polarisations, the proton energy spectrum is quasi-monoenergetic (slightly broader for LP), and the mean proton energy is approximately the same – about 1.8 GeV (Fig.5). In
**Figure 4.** 2D spatial distributions of charge density of protons (a, c) and carbon ions (b, d) generated from the 0.1-µm CH target. The laser pulse intensity is equal to $10^{23}$ W/cm$^2$ for CP and $2 \times 10^{23}$ W/cm$^2$ for LP.

**Figure 5.** The energy spectra of protons generated from the 0.1-µm CH target. The laser pulse intensity is equal to $10^{23}$ W/cm$^2$ for CP and $2 \times 10^{23}$ W/cm$^2$ for LP.

turn, C ions are broadly dispersed in space for both polarisations and, as a result, the carbon ion energy spectra are broad. However, the mean and maximum energies of C ions are similar for LP and CP, equal to 5.0 GeV and 19.8 GeV for LP, and 5.8 GeV and 21.0 GeV for CP respectively. A more detailed analysis shows that an important role in the broadening of the energy spectrum of carbon ions is played by the relativistic transparency of the target plasma. In the case of protons, this effect had a small influence on the properties of the accelerated proton beam, since the high-density electron-proton double layer formed in the initial stage of laser-target interaction and pushed forward by the laser field was opaque for the laser beam during the whole acceleration process.

Since the thickness $l_p$ of the proton bunch generated from the CH target is small ($l_p < 5 \mu$m, Fig. 4) and its velocity is very high ($v_p \approx c$), the time duration of the proton pulse $\tau_p$ (which is equivalent to the time of interaction between the bunch and a plane surface of any target perpendicular to the bunch
propagation axis $t_{\text{int}} \sim l_{p}/v_{p}$ is very short (in the multi-fs range). In turn, the high density of the bunch, coupled with its high velocity, results in an extremely high intensity of the bunch. Figure 6 presents a temporal shape of the proton pulse generated from the 0.1-µm CH target irradiated by an LP or CP laser beam, and recorded 40 µm behind the target. It can be seen that the shapes, durations and peak intensities $I_{p}$ of the proton pulse are almost identical for both polarisations and $\tau_{p} \approx 11$ fs, $I_{p} \approx 8 \times 10^{21}$ W/cm$^2$.

![Figure 6. The temporal distribution of intensity of the proton beam generated from the 0.1-µm CH target. The laser pulse intensity is equal to $10^{23}$ W/cm$^2$ for CP and $2 \times 10^{23}$ W/cm$^2$ for LP.](image)

The main conclusions from the performed studies are as follows:

(1) At ultra-relativistic intensities ($\sim 10^{23}$ W/cm$^2$) predicted for ELI lasers, RPA is the dominant mechanism for the acceleration of protons from a sub-µm plastic target, and the effect of laser polarisation on the parameters of the generated proton beam is relatively weak; for both polarisations, quasi-monoenergetic proton beams with a mean proton energy $\sim 2$ GeV are generated from the 0.1-µm CH target.

(2) At short distances from the irradiated target (< 50 µm), the proton pulse is very short (< 20 fs), and the proton beam intensities reach extremely high values $> 10^{21}$ W/cm$^2$, which are much higher than those attainable in conventional RF-driven accelerators.

(3) Such proton beams can open the door to new areas of research in high energy-density physics and nuclear physics, and can also be useful for other applications, e.g. in materials research as a tool for high-resolution proton radiography.

5.3. Acceleration of super-heavy ions at ultra-relativistic intensities

Heavy and super-heavy (A > 200) ion beams are especially important for research in nuclear and particle physics, but also find applications in other domains (e.g. in high energy-density physics). Although the possibility of a laser-driven generation of fast ions of this kind was demonstrated in experiments, both with long-pulse lasers (e.g. [59,60] and references therein) and short-pulse ones [60-65], the parameters of the produced ion beams, in particular the ion energies, were far from what was required for the above-mentioned applications. The number of numerical studies of laser-driven acceleration of ions of this kind is also very limited [66,67], and in the case of super-heavy ions numerical simulations were performed for relativistic but rather moderate laser intensities ($\sim 10^{20} – 10^{22}$ W/cm$^2$) [67]. In fact, it is only at ultra-relativistic intensities that the energies of super-heavy ions can reach values in the GeV or multi-GeV range required in the majority of applications. Laser-driven generation of heavy and super-heavy ions of such energies, and using them for research in nuclear physics, and particularly in nuclear astrophysics, is one of the main goals of the ELI-NP infrastructure.

One of the key research topics of the ELI-NP scientific programme is to study the production of extremely neutron-rich nuclei by a new reaction mechanism called fission-fusion, using laser-accelerated thorium ($^{232}$Th) ions [68]. This research is of crucial importance for understanding the nature of the creation of heavy elements in the universe; however, the proposed fission-fusion mechanism requires Th ion beams with very high ion fluencies $F_{i}$ and beam intensities $I_{i}$ that are
unattainable in conventional RF-driven accelerators. In particular, for the ion energy per nucleon of 7 MeV/amu, the beam parameters should be as follows: $F_i \sim 10^{18}$ cm$^{-2}$, $I_i \sim 10^{20}$ W/cm$^2$ and the total number of Th ions $N_i \sim 10^{11}$ [68]. We carried out numerical simulations using our 2D3V PIC code to investigate the possibility of producing Th ion beams with the required parameters by an fs laser pulse of ultra-relativistic intensity to be generated by the ELI-NP 10 PW laser.

The results of the numerical simulations presented below were obtained for a flat thorium target with a thickness of 0.4 um and a transverse dimension equal to 12 μm. The molecular density of the target corresponded to the solid-state density and was equal to 3.04x10$^{22}$ molecules/cm$^3$, where the ionization level of Th was assumed to be 30. A pre-plasma layer of 0.25 μm thickness and a density shape described by an exponential function was placed in front of the target. The target was irradiated by a circularly polarised 20 fs laser pulse with an intensity of 10$^{23}$ W/cm$^2$, the beam width was 3 μm (FWHM) (the laser energy of 150 J) and the laser wavelength was 0.8 μm. The laser beam shape in time and space (along the y-axis) was described by a super-Gaussian function with a power index equal to 6.

![Figure 7](image1.png)

**Figure 7.** 2D spatial distribution of the electric field component $E_y$ (perpendicular to the laser beam axis) at $t = 30$ fs when the interaction of the laser pulse with the thorium target is being terminating.

![Figure 8](image2.png)

**Figure 8.** 2D spatial distributions of charge density of thorium ions (left) and electrons (right) for a late stage of ion acceleration ($t = 100$ fs).

Figure 7 presents the 2D spatial distribution of the laser electric field $E_y$ (perpendicular to the laser beam axis) at $t = 30$ fs when the direct interaction of the beam with the thorium target is being terminating. The laser beam penetrates through the target, pushing forward a dense plasma bunch and at the presented stage ($t = 30$ fs) the laser beam reaches the target rear surface while the plasma bunch is pushed out behind this surface and starts to move into free space (not shown in the figure). This is a typical picture for HB RPA accompanied with an onset of the LS stage of acceleration (section 4). However, the LS stage of the plasma bunch acceleration cannot develop further, since the laser pulse has terminated and the ponderomotive (radiation) pressure is equal to 0. In spite of this, the ions are
still accelerated during a time period much longer than the laser pulse duration. This can be seen in Figure 8, where 2D spatial distributions of the charge density of Th ions (left) and electrons (right) are shown for a late stage of acceleration (at t = 100 fs, when the acceleration time is longer than the laser pulse duration by a factor of 5). At this stage, a significant part of the plasma electrons move together with the ions and a highly collimated and relatively dense plasma (ion) beam is formed in the central part of the target. For a better understanding of the acceleration mechanism at this stage, a spatial distribution of the electric field in the plasma along the laser beam axis $E_s$ (the field directly accelerating ions) is shown in Figure 9. It can be seen that, even at a long distance from the target initial position, the $E_s$ field is very strong with the maxima $\sim 100$ GeV/cm both in front of the central ion beam and on the side parts of the target not irradiated by the laser beam. A source of this field is hot electrons (produced at the RPA stage) with energy sufficiently high to escape from the ions and to create a negative sheath (virtual cathode) able to accelerate them. This field effectively accelerates ions in the late (post-RPA) stage of the acceleration process. However, the ions from the central part of the target are much faster than those from the side parts, in spite of the fact that the accelerating fields $E_s$ are similar for all these parts. It can be supposed that the main reason for the much higher velocities of the ions from the central part is the ballistic movement of these ions initiated in the RPA stage. Due to very high mass of the Th ions, the ballistic movement has a significant influence on the ion acceleration process in the late stage and, in particular, is a probable cause of the observed collimation of the ion beam.

![Figure 9](image1.png)

**Figure 9.** 2D spatial distribution of the electric field component $E_s$ (parallel to the laser beam axis) for a late stage of ion acceleration ($t = 100$ fs).

Contrary to the case of proton acceleration considered in the previous sub-section (5.2), the accelerated ions are rather broadly dispersed along the main ion propagation direction and, as a result,
the ion energy spectrum is wide — Figure 10. The main reason for this is the spatial inhomogeneity of the accelerating field at the sheath acceleration stage. In spite of the broad energy spectrum, the parameters of the produced ion beam are fairly high. For the central part of the target, with a diameter of 6 μm (where the main ion beam is generated — Figure 8), these parameters are as follows: the mean ion energy \( E_i \approx 0.9 \text{ GeV} \) (3.9 MeV/amu), the maximum ion energy \( E_{im} \approx 6.6 \text{ GeV} \) (27.6 MeV/amu), the ion fluence \( F_i \approx 0.9 \times 10^{18} \text{ cm}^{-2} \), the peak ion beam intensity (2 μm behind the target) \( I_i \approx 1.4 \times 10^{22} \text{ W/cm}^2 \), and the total ion number \( N_i \approx 3.4 \times 10^{11} \).

The main conclusions from these preliminary investigations are as follows:

1. The acceleration process of super-heavy ions at ultra-relativistic laser intensities seems to be more complex than in the case of light ions or protons; in this process, the RPA stage is followed by the sheath acceleration stage and a significant role in the second stage is played by the ballistic movement of ions accelerated at the RPA stage; this fairly complex acceleration mechanism leads to the production of a collimated high-energy ion beam of broad energy spectrum;

2. The 20-fs laser pulse with an intensity of \( \approx 10^{22} \text{ W/cm}^2 \) and an energy of 150 J is capable of producing, from the 0.4-μm Th target, a thorium ion beam with more than \( 10^{11} \) ions of GeV energies (with the maximum ion energy \( > 6 \text{ GeV} \)), the ion beam intensity \( > 10^{21} \text{ W/cm}^2 \) and the ion fluence \( \approx 10^{18} \text{ ions/cm}^2 \). The last two values are much higher than attainable in conventional accelerators, and are fairly promising for the planned ELI-NP experiments.

3. One of the challenges that must be overcome is finding a way to narrow the energy spectrum of the accelerated ions without a dramatic reduction in other ion beam parameters, particularly in the ion beam intensity and fluence.

6. The main challenges faced by research on laser-driven ion acceleration

In spite of the considerable progress in research on laser-driven ion acceleration during the last two decades, the achieved parameters of laser-driven ion beams are still far from what is required in most of the applications mentioned in section 5. To reach these requirements, various parameters of the ion beams should be improved, and the set of parameters that would need to be upgraded depends on the type of application envisaged.

For the application of laser-driven ion beams in nuclear and particle physics, the ion energies should be considerably increased and the ion energy spectrum width would have to be decreased. A significant narrowing of this spectrum (down to 1-2 %) is also a key challenge for medical applications such as the hadron cancer therapy. Both for applications in nuclear/particle physics and medicine, the ion beams should be generated with a high repetition rate (~ 10 Hz or higher). Furthermore, since in these applications the ion beam must usually be transported over a relatively long distance (from tens of cm to tens of m), the angular divergence of the beam would have to be minimised. A promising ion acceleration mechanism with the potential to increase ion energies up to tens or even hundreds GeV is RPA working in the LS mode. However, obtaining very narrow ion energy spectrum (with a width comparable to that of conventional accelerators) with RPA seems to be an extremely difficult task. For producing such narrow spectra, it is possible that the emerging ion acceleration mechanisms like ISWA [31,32] will be more effective.

Applications of ion beams in high energy-density physics or inertial confinement fusion do not require very high ion energies (multi-GeV or higher) or a very narrow ion energy spectrum and moderate values of ion energy (from the 1 MeV – 1 GeV range) and spectrum width (~ tens %) are usually sufficient. However, the values of ion beam power/intensity or ion current/current density, as well as the ion fluences required for these applications are very high, sometimes much higher [28,69] than those attainable in RF-driven accelerators operating currently. The ion beams of such extreme parameters can also be useful in nuclear-physics experiments for studies of nuclear reactions of very low cross sections (such as that mentioned in sec. 5). Due to the ability to produce very dense and compact ion beams (both from very thin – tens of nm and “thick” – up to tens of μm), RPA is the most promising mechanism capable of producing ion beams of the parameters required in these applications. RPA-driven intense ion/proton beams can also be useful for applications in materials...
science, since the very short proton pulses produced by RPA can probe and diagnose material properties with unprecedented temporal and spatial resolution.

The vast majority of applications of ion beams require rather compact and economical devices that are flexible enough to be used in a variety of conditions. In the case of laser-driven accelerators, the largest and most costly element is the laser driver. Since the size, cost and complexity of the driver grows with the increase in energy of the laser pulse generated by the driver, minimising this energy without a remarkable reduction in the ion beam parameters is necessary in order to build a laser-driven accelerator useful for applications. From this point of view, the main challenge is to increase the laser-to-ions energy conversion efficiency to a level ensuring a compactness and cost of the accelerator enabling its practical usefulness. Also in this aspect, RPA seems to be the most promising method of ion acceleration, especially at ultra-relativistic laser intensities when the conversion efficiency can reach even tens of per cent.

The practical usefulness of laser-driven accelerators depends essentially on whether they can be competitive with conventional RF-driven accelerators, and whether at least some parameters of laser-driven ion beams can be comparable to or higher than those achieved in conventional accelerators. Based on the current knowledge, it is reasonable to suppose that, in the foreseeable future (say two next decades), energies of ions produced by laser-driven accelerators will still be much lower than the energies achieved currently in the largest RF-driven accelerators. Obtaining very narrow ion energy spectra and high average ion beam powers in laser-driven accelerators comparable to those attained in the conventional accelerators is also questionable. On the other hand, achieving peak ion beam powers/intensities, peak ion current/current densities or ion fluencies higher than attainable presently in the RF-driven accelerators seems to be feasible within the next decade. However, to reach this goal, next generation multi-PW laser drivers have to be used, and the ion acceleration mechanism must be better understood and controlled.

7. Summary
Laser-driven ion acceleration is a new, rapidly growing field of research, and one of the most important applications of high-peak-power lasers and laser-produced plasma.

The very high strength of laser-induced electromagnetic fields in the plasma allows the acceleration of ions up to relativistic velocities over sub-mm distances; this opens the prospect of constructing a substantially new generation of ion accelerators – more compact, less complex, and much cheaper than conventional accelerators currently operating.

Among the several laser-based methods of ion acceleration proposed so far, the methods using the TNSA mechanism and the RPA mechanism are currently most developed.

Due to its ability to accelerate ions to relativistic velocities and very high energetic efficiency, RPA seems to be the most promising ion acceleration mechanism for the use in future laser-driven accelerators; detailed experimental studies of RPA still require, however, higher laser powers and intensities than attainable currently.

Extreme Light Infrastructure will be the first laser infrastructure enabling the production of fs laser pulses of ultra-relativistic intensities and an investigation of the RPA properties, as well as testing the feasibility of various potential applications of laser-accelerated ions.

Very high intensities, powers and fluencies, and very short durations (down to tens of fs) of laser-driven ion beams generated at ultra-relativistic laser intensities provide the prospect of a variety of innovative applications of these beams in scientific research (nuclear physics, high energy-density physics, inertial fusion), as well as in technology (material engineering) and medicine (hadron cancer therapy, production of isotopes for PET). To achieve this prospect, further development of laser drivers is necessary, along with a better understanding and control of ion acceleration mechanisms.

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