Acceleration of carbon ions to high energies by a multi-PW laser

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Abstract. Extreme Light Infrastructure (ELI) is a large-scale European project, still in the development stage, offering parameters of laser drivers required for multiple applications (femtosecond pulse duration, ultra-relativistic laser intensities ~ $10^{22} - 10^{23}$ W/cm$^2$), however, studies of ion acceleration in the given intensity regime are still in the very early stages and require a deeper understanding of the processes occurring during laser-matter interactions to maximize the efficiency of ion acceleration. The purpose of this work is a numerical examination of the properties of carbon ion beams produced during the interaction of an ultra-intense laser beams (of intensities ~ $10^{21} - 10^{23}$ W/cm$^2$ and pulse duration order of femtoseconds, predicted to be available at ELI-NP, Romania) with C$^{12}$ target. The dependence of ion beam parameters, such as intensity, energy spectrum, maximum and average ion energy and spatial distribution of ion charge density, on laser pulse parameters (mainly intensity) and the target thickness is investigated. The possibility of generation of high intensity, GeV energy ion beams in the foregoing conditions is demonstrated. The obtained results can be useful for research in high energy-density physics, nuclear physics or medical applications of ion beams.

1. Introduction
The invention of the chirped pulse amplification method, used in modern laser facilities, granted rapid evolution to laser-plasma physics and increased interest in the field of laser-driven ion acceleration. Since the 1960’s, several mechanisms of laser-driven ion acceleration were proposed and have been confirmed to exist experimentally and through numerical simulations: the Target Normal Sheath Acceleration (TNSA) [1]-[2], the Break-out Afterburner (BOA) [2]-[3], the Radiation Pressure Acceleration (RPA) [2]-[4], the Collisionless Electrostatic Shock Acceleration (CESA) [5] or the Laser Induced Cavity Pressure Acceleration (LICPA) [6]. So far, experimental conditions to enter the regime in which RPA dominates as an acceleration mechanism are impossible to achieve, but it has been numerically proven to be the dominating mechanism for laser intensities exceeding $10^{22}$ W/cm$^2$ [2].

Extreme Light Infrastructure (ELI) is a large-scale European project [7]-[8]-[9], split into three divisions: ELI-Beamlines in Czech Republic, ELI-Nuclear Physics in Romania and ELI-ALPS in Hungary. The main goal of this infrastructure is to build and apply multi-petawatt (multi-PW) lasers of femtosecond pulse duration and ultra-relativistic intensities from the range $10^{22} - 10^{23}$ W/cm$^2$. These values of laser intensity may permit production of ion beams with sub-GeV or GeV ion energies,
which could be employed in various fields of science (e.g. nuclear or high energy-density physics), medicine (e.g. hadron cancer therapy) or technology (e.g. ion implantation useful in research for the new materials).

In this work, we numerically examined the interactions of ultra-intense femtosecond laser pulses of circular polarization with pure $^12$C targets of different thicknesses for laser parameters predicted to be available at the ELI-NP facility (laser power 10 PW). During PIC simulations, performed using the 2D3V code developed at Institute of Plasma Physics and Laser Microfusion [10], properties of the system such as intensities of electric $E_x, E_y, E_z$ and magnetic $B_x, B_y, B_z$ fields, charge density distribution $\rho_i$ of ions and $\rho_e$ of electrons, velocities $v_x, v_y, v_z$ of the particles and their energies were calculated. The laser pulse intensity shape was described by a super-Gaussian function with 6 as the power index [11], the laser focal spot (full width at half maximum) varied from 3 $\mu$m to 20 $\mu$m with the laser intensity scaled to $I_L = 1.4 \times 10^{23}$ W cm$^{-2}$ for the smallest focal spot, the laser pulse duration $\tau_L = 30$ fs and wavelength $\lambda_L = 800$ nm, the target thickness ranged from 20 nm – 200 nm and it’s molecular density corresponded to the density of CVD-produced (CVD - chemical vapor deposition) diamond equal to $1.76 \times 10^{29}$ molecules cm$^{-3}$. The pre-plasma was 20 nm thick ($L_{pre} = 20$ nm) and it’s density shape was given by an exponential function $n(x) \propto \exp[-\frac{x}{L_{pre}}]$.

2. Results and discussion

Figure 1 presents a two-dimensional spatial distribution of electric field component $E_y$ perpendicular to laser beam propagation (a, b), charge density of carbon ions (c, d), charge density of electrons (e, f) and electric field component $E_x$ parallel to laser beam propagation (g, h) in the early stage of the acceleration process, corresponding to 45 femtoseconds after the start of simulation (a, c, e, g), and 100 fs after the laser-target interaction (b, d, f, h) for laser intensity $I_L = 1.4 \times 10^{23}$ W cm$^{-2}$ and laser beam width $d_L = 3$ $\mu$m and a 100 nm thick carbon target. Due to relativistic effects, the target was nearly transparent for the laser, as evidenced by the absence of a reflected electric field in front of the target (a) and intense field formation behind the rear surface of the target (seen on the $E_y$ distribution (b)), with fringes of widths equal to ~800 nm (which corresponds to the wavelength of the laser used in simulation). Comparing spatial distributions of charge density of ions (c, d) and electrons (f), it can be seen that carbon particles accelerated to the highest velocities form a high-density ion block, typical for the RPA ion acceleration mechanism, that propagates along the path of the laser beam. However, the accompanying broad dispersion in space of carbon ions accelerated to moderate and low energies indicates the presence of strong radial ponderomotive forces induced by high gradients of electromagnetic fields on the edges of the super-Gaussian beam profile, which results in a broad, quasi-Maxwellian energy spectrum, which can be seen in Figure 3.

In the same manner as previously, Figure 2 presents characteristic distributions of laser-driven ion acceleration for laser intensity $I_L = 3.15 \times 10^{21}$ W cm$^{-2}$, laser beam width $d_L = 20$ $\mu$m and carbon-made target of thickness $L_T = 100$ nm in early (corresponding to 45 fs of simulation (a, c, e, g)) and latter (corresponding to 200 fs of simulation (b, d, f, h)) stages of the acceleration process. In this case, the shape of the generated ion beam is affected by the target being more opaque for the laser and low radial ponderomotive forces, resulting in a flat, rectangular density profile.

The energy spectra for the two previously described cases are shown in Figure 3. In both instances, the energy spectrum has a broad, quasi-Maxwellian shape and no evidence of quasi-monoenergetic peaks is observed. The maximum ion energy for $I_L = 1.4 \times 10^{23}$ W cm$^{-2}$ is approximately $E_{i,max} = 18.76$ GeV while the average ion energy $E_{i,avg} = 466$ MeV. For $I_L = 3.15 \times 10^{21}$ W cm$^{-2}$, the maximum and average ion energies are about two orders of magnitude lower and equal $E_{i, max} = 187$ MeV and $E_{i, avg} = 11$ MeV.
Figure 1: Spatial distributions of $E_y$ (a, b), $\rho_i$ (c, d), $\rho_e$ (e, f) and $E_x$ (g, h) in 45 fs (a, c, e, g) and 100 fs (b, d, f, h) after the start of the simulation. Target thickness $L_T = 100$ nm, laser intensity $I_L = 1.4 \times 10^{23} \, \text{W/cm}^2$. 
Figure 2 Spatial distributions of $E_y$ (a,b), $\rho_i$ (c,d), $\rho_e$ (e,f) and $E_x$ (g,h) in 45fs (a,c,e,g) and 200 fs (b,d,f,h) after the start of the simulation. Target thickness $L_T = 100$ nm, laser intensity $I_L = 3.15 \times 10^{21}$ W cm$^{-2}$. 
Figure 3 Energy spectrum for target thickness $d_L = 100\ nm$ and laser beam intensity $I_L = 1.4 \times 10^{23}\ \text{W/cm}^2$ (upper) and $I_L = 3.15 \times 10^{21}\ \text{W/cm}^2$ (lower).

Figure 4 and Figure 5 present the differences in spatial distributions of the previously considered characteristics of the produced ion beams for different target thicknesses. For $I_L = 1.4 \times 10^{23}\ \text{W/cm}^2$ and the target thickness $L_T = 50\ nm$ (Fig. 4, (a, c, e, g)) the compact, high-density bunch of carbon ions is visible in front of the generated ion beam (Fig. 4, (c)). Considering the laser-like pattern visible on the y-component of the electric field distribution $E_y$ (Fig. 4 (a)), the light sail (LS) regime of RPA is the dominant regime of ion acceleration in this case. In contrast, for the same value of $I_L$ and $L_T = 200\ nm$, more laser energy is lost in the hole boring stage of RPA and as a result, the acceleration of the high-density ion bunch in the LS stage is less efficient (Fig. 4 (b,d)).

For $I_L = 3.15 \times 10^{21}\ \text{W/cm}^2$ two target thicknesses were compared – 20 nm (Fig. 5, (a, c, e, g)) and 200 nm (Fig. 5, (b, d, f, h)). It can be seen that for the 20 nm thick target, the RPA mechanism dominated in the early stage of the acceleration process ($t \sim r_L$), which resulted in displacement of the central part of the target towards the laser propagation path, although the biggest contribution to the achieved energy values came from the TNSA acceleration scheme. For the 200 nm thick target, the dominating acceleration mechanism is TNSA for entire duration of the simulation.

Figure 6 shows both maximum and average ion energies as a function of target thickness. For the highest laser intensity, correlated with focal spot $d_L = 3\ \mu m$, the optimal target thickness can be determined for either $E_{i,\text{max}}$ (50 nm) or $E_{i,\text{avg}}$ (100 nm) (Fig. 6, (a)). In contrast, for the lowest considered laser intensity ($d_L = 20\ \mu m$) such an effect is nonexistent in the given range of $L_T$ (20-200 nm) (Fig. 6, (b)).

For the thinnest target ($L_T = 20\ nm$) irradiated by the laser beam of intensity $I_L = 1.4 \times 10^{23}\ \text{W/cm}^2$ only a very small number of ions were accelerated along the direction of laser beam propagation, as shown in Figure 7. In this case, the target became extremely transparent to the laser beam due to relativistic induced transparency effect, which resulted in drastically reduced effectiveness of ion acceleration process.

For $I_L = 1.4 \times 10^{23}\ \text{W/cm}^2$ and target thickness $L_T = 100\ nm$, which transpired as the optimal set of parameters for achieving the highest value of the average energy of carbon ions, the intensity of the ion beam as a function of time was calculated and presented in Figure 8.
Figure 4 Comparison of $E_y$ (a, b), $\rho_i$ (c, d), $\rho_e$ (e, f) and $E_x$ (g, h) spatial distributions for 50 nm (a, c, e, g) and 200 nm (b, d, f, h) target thickness and $I_L = 1.4 \times 10^{23} \frac{W}{cm^2}$. Both sets of images picture the same time of simulation $t = 80 \, fs$. 
Figure 5 Comparison of $E_y$ (a,b), $\rho_l$ (c,d), $\rho_e$ (e,f) and $E_x$ (g,h) spatial distributions for 20 nm (a,c,e,g) and 200 nm (b,d,f,h) target thickness and $I_L = 3.15 \times 10^{21} \frac{W}{cm^2}$. Both sets of images picture the same time of simulation $t = 120 fs$. 
Figure 6 Ion energy dependence on target thickness $L_T$ for $I_L = 1.4 \times 10^{23} \frac{W}{cm^2}$ (a) and $I_L = 3.15 \times 10^{21} \frac{W}{cm^2}$ (b).

Figure 7 Extremely strong evidence of Relativistic Induced Transparency (RIT) effect which occurred for target thickness $L_T = 20 \text{ nm}$ and laser intensity $I_L = 1.4 \times 10^{23} \frac{W}{cm^2}$.

Taking into account the FWHM of the temporal intensity distribution, the duration of the produced ion pulse and the peak intensity can be estimated as $\tau_{ion_1} \approx 15 \text{ fs}$, $I_{ion_1} = 5.23 \times 10^{22} \frac{W}{cm^2}$. The duration and the peak intensity of the ion beam for the case of lower ($3.15 \times 10^{21} \frac{W}{cm^2}$) laser intensity and the thinnest (20 nm) target approach values $\tau_{ion_2} \approx 50 \text{ fs}$ and $I_{ion_2} = 1.4 \times 10^{21} \frac{W}{cm^2}$. 
Figure 8 Time dependence of ion beam intensity 10 μm behind the target for laser intensity $I_1 = 1.4 \times 10^{23} \frac{W}{cm^2}$ and target thickness $L_{T_1} = 100\,nm$ and laser intensity $I_2 = 3.15 \times 10^{21} \frac{W}{cm^2}$ and target thickness $L_{T_2} = 20\,nm$. The intensity for second case (blue line) was multiplied by the factor 10 to fit the scale of intensity related to the most efficient parameters of laser-matter action (red line).

3. Conclusions

It has been shown that the ion acceleration process using ultra-thin homogenous $C^{12}$ targets strongly depends on both target thickness and laser beam intensity. For laser intensities predicted to be available at the ELI research centers ($\sim 10^{23} \frac{W}{cm^2}$), it is possible to achieve carbon ion beams of energies approaching 19 GeV and 450 MeV for maximum and average ion energies respectively, extremely high intensities above $10^{21} \frac{W}{cm^2}$ and ultra-short duration (< 20 fs). Due to relativistic effects occurring during laser-matter interactions at such ultra-intense laser fields, optimal target thickness exist for both average and maximum ion energy. Such ion beams can be used for new areas of research in high-energy-density physics and nuclear physics [12] in addition to being useful for some medical applications of ion beams [13].

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