Modeling the interaction of an ultra-high intensity laser pulse with nano-layered flat-top cone targets for ion acceleration

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1. Introduction

At Extreme Light Infrastructure Nuclear Physics (ELI-NP) experiments are envisioned employing the two ten Petawatts power lasers for laser-ion acceleration with applications in medicine such as hadron therapy [1, 2]. In the last two decades, a lot of target geometries were proposed in order to obtain very energetic protons which can be used to treat cancer [3–8]. Some works showed that the interaction of the ultra-high intensity laser pulse with a micro-cone target can generate protons accelerated at energies of tens of MeV with low angular divergence and high laser absorption [9–12] in the Target Normal Sheath Acceleration and Direct laser-light-pressure regimes. Other papers were devoted to different kinds of cone targets suitable for proton acceleration at energies up to few tens of MeV [13–18]. A new experiment at Vulcan facility shows that the interaction of the ultra-high intensity laser pulse with a ultra-thin foil can generate protons accelerated at energies exceeding 94 MeV [19].

We propose two new types of nanotargets for laser-ion acceleration. The first type is a flat-top cone target [9, 12] with a nano-layer foil in the tip of the cone named as 'flat-top cone' through all the text. The second type is a flat-top cone target with a flat-top foil consisting of two nano-layers. We call this target as ‘cone with nanospheres’ in our paper. The first nano-layer is composed by nanospheres with the same diameter and tangential to each other and the second one is a nano-layer foil. We perform two-dimensional (2D) particle-in-cell (PIC) simulations for the interaction of an ultra-high intensity laser pulse with the plastic targets

Abstract

We study the interaction of an ultra-high intensity laser pulse with plastic nano-layered flat-top cone targets by performing particle-in-cell simulations. Also, we analyze the spatio-temporal dynamics of the electromagnetic field based on the finite-difference time-domain method in order to isolate the geometric effects which affect the incoming laser-plasma interaction. We consider an ultra-high intensity laser pulse with linear and circular polarization. We have determined the optimum diameter of the nanospheres for a given nano-layer foil thickness for which it can be obtained beams of very energetic protons with low angular divergence. We point out that the protons are accelerated by a hybrid mechanism composed of target normal sheath acceleration and radiation pressure acceleration. This numerical study will allow to prepare and optimize first laser ion acceleration experiments on Extreme Light Infrastructure-Nuclear Physics and other PW laser facilities.

Keywords: laser-ion acceleration, ultra-high intensity laser pulse, nano-layered flat-top cone target, radiation pressure acceleration, target normal sheath acceleration, plasma

(Some figures may appear in colour only in the online journal)
described above in order to find the optimum nanosphere diameter for which an ion beam with the highest ion energy and the smallest angular divergence is obtained. The linearly polarized (LP) laser pulse used in this approach has the similar parameters with the pulse that will be delivered by the two high-power lasers from ELI-NP [20]. The circularly polarized (CP) laser pulse has the intensity twice of the intensity of the LP laser pulse. Also, a spatio-temporal analysis of the electromagnetic field distribution during the interaction of the ultra-high intensity laser pulse with the nano-layered flat-top cone targets has been performed using a commercial software (RSoft, by Synopsys Optical Solution Group). This method aims to provide a complementary approach to the PIC simulations in order to isolate the geometric effects which affect the incoming laser-plasma interaction.

In the section 2 of the paper, we describe the laser-pulse and the target characteristics. The parameters of the PIC simulations and the numerical results are presented in section 3. We analyze the proton and carbon ion acceleration in sections 3.1 and 3.2, respectively. In the section 3.3 we explain the proton acceleration by a hybrid acceleration mechanism composed of TNSA and radiation pressure acceleration (RPA). The numerical simulations based on FDTD method and the results are derived in section 4. We conclude our work with some remarks in the section 5.

2. Laser pulse and target description

In all simulations from this work the ultra-high intensity laser pulse has a Gaussian profile with a central wavelength $\lambda_0 = 800$ nm, period $\tau_0 = 2.7$ fs, pulse duration $\tau = 25$ fs, a laser focal spot FWHM $d = 5.6 \mu$m and a normalized laser pulse amplitude $a_0 = 100$ for both linear and circular polarization of the laser pulse. By using the formula for the intensity of a LP laser pulse $I = a_0^2/(0.85\lambda_0(\mu m))^2$ [21] we obtain the intensity peak equal to $2.16 \times 10^{22}$ W cm$^{-2}$. The power is related with the intensity by the expression $P = \pi d^2 I$ which gives the value of 21.3 PW at peak intensity. The laser pulse energy is $E = P/\tau = 532$ J. These parameters are close to the parameters of the two lasers of 10 PW from the ELI-NP [20]. The laser pulse with circular polarization has the intensity $I = 4.32 \times 10^{22}$ W cm$^{-2}$, in accordance with the relation between the intensity and the amplitude of the electric field, $I = 2a_0^2/(0.85\lambda_0(\mu m))^2$ [21]. Therefore, the ultra-high intensity laser pulse energy and power have the values of 1 kJ and 42.6 PW, respectively. We notice that the CP laser pulse has the intensity two times higher than the intensity of the LP laser pulse. The ultra-high intensity laser pulse propagates along the symmetry axis of the nano-layered flat-top cone target as it can be seen in figures 1(a) and (b). Hence, the incidence angle of the laser beam on the foil from the tip of the nano-layered flat-top cone target is zero degree. The $x$-axis is chosen parallel with the symmetry axis of the nano-layered flat-top cone target. In our studies, we consider both linearly $p$-polarized ($E_z = 0$ and $E_y = 0$) and CP ($E_z = E_y = 0$) laser pulse, where $E_z$ and $E_y$ are the $z$-component and $y$-component, respectively of the electric field. The laser pulse always comes from the left.

We performed the conceptual design of the laser beam interaction with the targets which consist in a plastic flat-top cone (see figure 1(a)) and a cone with nanospheres (figure 1(b)). All nanospheres have the same diameter and they are tangent to each other. From our PIC simulations of the interaction of the ultra-high intensity CP laser pulse with a plastic (CH) foil target we get the highest proton energy in the case of using a foil which has the thickness of 80 nm. Hence, we decided to use in our study halved of the thickness of the flat-foil from the tip of the cone target and to vary only the nanosphere diameter. We performed PIC simulations for flat-top cones with the flat-top foil thickness equal to the sum of the nanosphere diameter and the flat-top foil thickness of the cones with the nanospheres.

The cone height is 20 $\mu$m, the base diameter is 25 $\mu$m, the cone neck diameter is 5 $\mu$m, the walls thickness is 4 $\mu$m and the width of the flat-top foil is 15 $\mu$m. Nowadays, these types of cone targets can be printed with commercial printers by two-photon polymerization process on nano-films and nano-structured foils.

3. PIC simulations

We intend to obtain the optimum nanosphere diameter in order to have protons and carbon $C^{6+}$ ions accelerated at hundreds of MeV and few GeV, respectively, in beams with very low angular divergence. For this propose we used 2D version of the 3D relativistic PIC code PICLS [22]. The PIC simulations have been performed on the cluster from the High Performance Computing Center, Faculty for Automatic Control and Computers, University POLITEHNICA of Bucharest, Romania [23].

We use a simulation box with the dimensions of $60 \mu$m $\times$ $75 \mu$m (6000 cells $\times$ 7500 cells). The total time of a simulation is 230 fs. The grid step-size of the simulations is 10 nm and the time step is 0.033 fs. The plasma has the density $n_e = 320 n_c$, where the critical plasma density is $n_c = 1.72 \times 10^{21}$ cm$^{-3}$. In our PIC simulations we include the entire cone target. A preplasma of 0.5 $\mu$m scale length with exponential decay function is considered on the cone walls. The simulated plasma and preplasma are totally ionized, i.e. with carbon ions $C^{6+}$ due to the ultra-high intensity of the laser pulse. We put in each grid cell 21 electrons, 3 protons and 3 $C^{6+}$ ions.

3.1. Proton acceleration

First, we perform 2D PIC simulations to study the proton acceleration as a result of the interaction of the ultra-high intensity laser pulse with a flat-top cone. The thickness of the nano-layer flat-top foil varies in the range of 60 and 120 nm with 20 nm step. We choose the thickness of the nano-layer flat-top foil (nano-film) to be comparable with the thickness of the two nano-layers flat-top foil from the cone with nanospheres.
The maximum proton energy versus the nano-layer foil thickness is represented by black and red dots in the figure 2(a) for linear and circular laser pulse polarization, respectively. The highest value of 988 MeV of the maximum proton energy is obtained in the case of the CP ultra-high intensity laser pulse which interacts with a flat-top cone with the nano-layer flat-top foil having the thickness equal to 80 nm. In the case of the LP ultra-high intensity laser pulse which interacts with a flat-top cone with the nano-layer flat-top foil having the thickness equal to 120 nm we obtained the highest maximum energy of the protons equal to 739 MeV. In the case of cone with nanospheres we varied the nanospheres diameter while we kept constant the thickness of the nano-layer foil to 40 nm. In figure 2(b) we plot the dependence of the maximum proton kinetic energy on the nanospheres diameter for both LP and CP ultra-high intensity laser pulse. The diameter of the nanospheres is 20, 40, 60 and 80 nm. The maximum proton kinetic energy is obtained for both laser pulse polarizations for a nanospheres diameter of 80 nm. The interaction of the ultra-high intensity laser pulse with nanospheres creates a preplasma with a number of the hot electrons which is directly proportional with the diameter of the nanospheres. These hot electrons amplify the electric field created in the nano-foil by the other hot electrons, electric field which accelerates the protons to higher energies. From the figure 2(a) we note that the proton energy scales with $\sim I^{1/2}$ for a flat-top cone which is a feature of the TNSA. We must remark from the figure 2(b) that for a cone with nanospheres the proton energy scales with $\sim I$ like in the RPA regime.

Figure 3 illustrates the distributions of the longitudinal electric field component $E_x$ at the simulation time $t = 168$ fs in the case of the interaction of a LP ultra-high intensity laser pulse with a cone with nanospheres for which we vary the nanosphere diameter in the range of 20−80 nm with 20 nm step.

One can see from figures 3(a)–(d) that the maximum value of the longitudinal component of the electric field, $E_x$, which accelerates the protons, increases directly proportional with the
nanosphere diameter. The same behavior of the longitudinal component of the electric field, \( E_x \), is observed in the case of a CP laser pulse. The protons are accelerated by the electric field and therefore their energy varies in the same manner as the electric field does with the nanosphere diameter.

Figure 3. The distribution of the longitudinal component of the electric field, \( E_x \), at the simulation time \( t = 168 \text{ fs} \) for a nanosphere diameter of (a) 20, (b) 40, (c) 60 and (d) 80 nm. The laser pulse is linearly polarized.

Figure 4. Proton energy spectra for a plastic flat-top cone and a (a) circularly and (b) linearly polarized ultra-high intensity laser pulse at the simulation time \( t = 240 \text{ fs} \) for \( x \geq 30 \mu m \).

The energy spectra of the protons from the rear side of the flat-top foil of the cone target at the simulation time \( t = 240 \text{ fs} \) for all the investigated targets are shown in figure 4.

In figure 4(a) it can be observed that the highest number of the accelerated protons at energies higher than 1 GeV is
obtained for the interaction of a CP laser pulse with a cone with nanospheres which have the diameter equal to 80 nm. But for a LP laser pulse from figure 4(b) we can see that the very energetic protons, with the energy higher than 600 MeV, are obtained for a flat-top cone with a flat-top foil which has the thickness equal to 120 nm.

We calculated the ratio between the number of the protons accelerated under the angle \( \theta \), \( N_{\text{prot}} \) and the total number of the accelerated protons \( N_{\text{tot}} \) to describe the divergence of the proton beam. The divergence angle is defined \( \theta = |\arctan(p_x/p_y)| \), where \( p_x \) and \( p_y \) are the components of the proton momentum on the x and y-axis, respectively. In figure 5 is represented the normalized number of protons, \( N_{\text{prot}}/N_{\text{tot}} \) versus proton divergence angle, \( \theta \), for all investigated targets. We considered only the protons with energies higher than 600 MeV for a CP laser pulse and higher than 300 MeV for a LP laser pulse.

All the protons with energies higher than 600 MeV are accelerated by a CP laser pulse under an angle \( \theta \) lower than 5° as can be seen in figure 5(a). From our calculations we notice that the total number of the accelerated protons from the previously mentioned spatial region and under an angle lower than 5° is directly proportional with the nanosphere diameter for the LP and CP laser pulse (see figures 5(a) and (b), top panel). The highest number of the accelerated protons is obtained for the nanosphere diameter of 80 nm. Comparing the total number of the accelerated protons for the cone with nanospheres and a flat-top cone which has the flat-foil thickness same as the sum of the nanosphere diameter and the nano-foil thickness (e.g. the cone with nanospheres which has the nanosphere diameter of 80 nm and the nano-foil thickness of 40 nm compared with the flat-top cone which has the thickness of the flat-foil equal to 120 nm) we can see that one obtain more accelerated protons for the cone with nanospheres for both polarizations of the laser pulse. Also, the protons with energies higher than 300 MeV are accelerated by a LP laser pulse under an angle lower than 5° as it is shown in figure 5(b). The number of the accelerated protons by a LP laser pulse increases with the increase of the flat-foil thickness (see figure 5(b), bottom panel). For a CP laser pulse which interacts with a flat-top cone the highest number of the accelerated protons is obtained for the flat-top foil thickness of 80 nm.

Therefore, we obtained low divergent beams of very energetic protons.

3.2. Carbon ion acceleration

The carbon \( \text{C}^{6+} \) ions acceleration in Break-Out Afterburner regime at energies of 700 MeV (60 MeV/amu) [24] and 1 GeV (83 MeV/amu) [25] was experimentally obtained for nm-scale targets and a relativistic intensity laser pulse of \( 5 \times 10^{20} \text{ W cm}^{-2} \). Our simulated plasma contains carbon \( \text{C}^{6+} \) ions, too. Therefore, we study the acceleration of the carbon \( \text{C}^{6+} \) ions. For this purpose, we calculate the maximum \( \text{C}^{6+} \) ion kinetic energy and we plot it as a function of the nano-layer foil thickness and the nanospheres diameter in figures 6(a) and (b), respectively. The ultra-high intensity laser pulse has linear and circular polarization.

Figure 6(a) shows that the maximum carbon ion \( \text{C}^{6+} \) energy is inversely proportional to the flat-top foil thickness of the flat-top cone target. The maximum carbon ion \( \text{C}^{6+} \) energy is directly proportional to the nanosphere diameter in the case of the cone with nanospheres target as can be seen in figure 6(b) for both laser pulse polarizations. In the figure 6 we note that the carbon ion energy scales with \( \sim I \). This is a feature of the RPA.
Figures 7(a) and (b) illustrate the carbon C$_{6}^{+}$ ion energy spectra for CP and LP ultra-high intensity laser pulse, respectively. We considered only the carbon C$_{6}^{+}$ ions from the rear side of the flat-foil from the tip of the nano-layered cone target at the simulation time $t = 240$ fs.

All the carbon C$_{6}^{+}$ ion energy spectra from the figures 7 show an exponential decay for lower carbon ion energies which is specific to TNSA. For higher carbon ion energies the carbon ion energy spectra is broad and modulated. In figure 7(a) we can see that the highest number of the accelerated carbon ions at energies greater than 7 GeV is obtained for the interaction of a CP laser pulse with a cone with nanospheres which have the diameter equal to 80 nm. Also, for a LP laser pulse, the figure 4(b) illustrates that the very energetic protons, with the energy higher than 2.5 GeV, are obtained for a cone with with nanospheres which have the diameter equal to 80 nm. We can conclude that the cone with nanospheres which have the diameter equal to 80 nm and the flat-top foil thickness equal to 40 nm is the optimum target from those studied be us which can be used to obtain very energetic ions with low angular divergence.

### 3.3. TNSA combined with RPA

From the introduction of the RPA regime of the ion acceleration by an ultraintense laser pulse at the interaction with a foil target [26, 27] a lot of papers were devoted to the study of this laser-ion acceleration regime [21, 28–35]. A hybrid regime including TNSA and RPA has been introduced and used in order to explain the ion acceleration in quasimonenergetic beams by an ultra-high intensity LP laser pulse interacting with a foil target [36–38].

In this section we show that the protons are accelerated by a hybrid acceleration mechanism including TNSA and RPA for a LP and CP ultra-high intensity laser pulse which interacts with a cone with nanospheres. We will present only the results for a cone with nanospheres with the diameter of 80 nm and the flat-top foil with the thickness of 40 nm. The spatial proton density evolution when a CP laser pulse interacts with the cone with nanospheres target is depicted in figures 8(a) and (c). The spatial carbon C$_{6}^{+}$ ion density evolution when a CP laser pulse interacts with the cone with nanospheres target are plotted in figures 8(b) and (d). The spatial proton and carbon ion density evolution show us that
the protons are pushed forward by the carbon density. However, the fastest carbon ions can not penetrate the proton bunch, which makes the proton bunch stable in time [32]. In the figure 8(e) it can be seen for LP and CP laser pulses that at the beginning of the expansion of the proton shell bunch the proton phase space experiences a distinct head where the most of the protons are concentrated [32], a typical RPA curl. At the same relativistic proton momentums on the same positions on x-axis there is a rarefied distribution of accelerated protons same as in TNSA regime [37]. The maximum proton energy variation in time for linear and circular polarizations of the laser pulse is plotted in figure 8(f).

The maximum proton energy scales with $t^{1/3}$ at a later time both for the LP and CP ultra-high intensity laser pulse which is also a feature of the RPA [28, 39]. The proton energy spectra from the figure 4 have a ‘bump’ at low proton energies which implies a quasimonoenergetic proton beam what is characteristic of RPA. At higher energies the proton energy spectra show a broad and modulated profile. The modulation is related to the Rayleigh–Taylor instability [38, 40]. Therefore, we can conclude that the protons are accelerated in the hybrid TNSA and RPA regime of acceleration.

The study of the electromagnetic field distribution is based on the finite-difference time-domain (FDTD) method for solving Maxwell equations and it was used to determine the electromagnetic field in the vicinity of the femtosecond pulses-nano-layered flat-top cone target interaction point for different nano-layer foils and nanospheres dimensions. A lot of FDTD studies have been elaborated in order to determine the optimum conditions for extreme electromagnetic field generation [41–43]. We must emphasize that in these simulations it is considered only the propagation of the electromagnetic field through the target without any other processes such as ionization. In this kind of simulations the target is not transformed into a plasma. This FDTD method is used in order to

**4. Electromagnetic field distribution by FDTD**

Figure 8. The plastic cone with nanospheres target for which the nanospheres have the diameter equal to 80 nm and the nano-layer flat-top foil has the thickness equal to 40 nm. The distribution of the proton density at the simulation time (a) $t = 178$ fs and (c) $t = 208$ fs, the distribution of the carbon ion $C^{6+}$ density at the simulation time (b) $t = 178$ fs and (d) $t = 208$ fs, when a CP laser pulse with the intensity of $4.32 \times 10^{22}$ W cm$^{-2}$ interacts with the cone with nanospheres target; (e) proton phase space ($x, (\beta \gamma)$) and (f) maximum proton energy evolution in time for both LP and CP laser pulse.

Figure 9. Sketch of the ultra-high intensity laser pulse flat-top cone target interaction geometry in FDTD simulations.
isolate the geometric effects which affect the incoming laser-plasma interaction.

Numerical analysis of the electric field distribution during the interaction of femtosecond laser pulses with nanolayered flat-top cone targets has been performed using a commercial software (RSoft, by Synopsys Optical Solution Group). The numerical model was used to determine the field amplitude in the vicinity of the femtosecond pulses-cone targets interaction point for different nano-layer foil and nanospheres dimensions.

The geometry of the problem is depicted in figure 9. The FDTD numerical study presented here implies a Gaussian laser source with the same wavelength, pulse duration and focal spot FWHM as used in the PIC simulations which propagates along the x-axis, to the fs pulse-target interaction point. The intensity of the LP and CP laser pulse is $I = 2.16 \times 10^{22}$ W cm$^{-2}$. The 5.6 μm source diameter is specified at a distance of 20 μm from the interaction point, along the propagation x-axis, where the field is generated as initial condition. The material considered for the cones, foils and the nanospheres is plastic. The resulting electric field data in a certain observation point are plotted in figures 10(a) and (b). The x-component of the electric field, $E_x$, is calculated in a specific observation plane which corresponds to the ultra-high intensity laser pulse-target interaction point. Initially, the study has been elaborated using a flat-top cone target with the nanolayer foil thickness in the range mentioned in section 3.1. The on-axis electromagnetic field was computed by the specific time monitor for both linear and circular laser pulse polarization, at a given moment of time, when the maximum value of the electric field is reached.

As depicted in figures 10(a) and (b), the x-component of the electric field measured in the laser pulse-flat-top cone target interaction point reaches the highest value when the foil thickness is equal to 80 nm. The same qualitative results was obtained within PIC simulations in the case of an ultra-high intensity CP laser pulse (see figure 2(a), red points). This moment of time is noted with $t_0$. At the moment $t_1$, which occurs 27 fs after the moment $t_0$, the same temporal monitor indicates another maximum in the slope of the x-component of the electric field, with a different distribution of its highest registered values. At this moment of time, the highest value of the electric field corresponds to the flat-top foil thickness equal to 120 nm (figure 10(b)). In accordance with the PIC simulations we achieved the highest value of the maximum proton energy in the case of the LP laser pulse for the the flat-top foil thickness equal to 120 nm (see figure 2(a), black points).

Comparing the case of the flat-top cone target (figure 10) with the case of the cone target with nanospheres (figure 11) for each nanospheres and nano-layer foil dimensions previously mentioned, we observe a similar electromagnetic field behavior in terms of the maximum values obtained in the laser-matter interaction point. The highest registered value of the electric field at the moment $t_0$ corresponds to the nanosphere diameter equal to 40 nm while at the moment $t_1$, the electric field reaches the maximum value in the case of the nanospheres having the diameter equal to 80 nm. The same qualitatively result was obtained by PIC simulations (see figure 2(b)), where the highest proton energy is obtained for the nanosphere diameter equal with 80 nm for both LP and CP laser pulses.

5. Conclusions

In summary, we studied via PIC simulations and simulations based on FDTD method, two new types of plastic nanotargets which can be used for laser-ion acceleration. First target was a plastic flat-top cone target with a nano-layer foil on the tip having the thickness of tens of nanometers. The second target was a plastic flat-top cone target with a foil on the tip composed by two nano-layers. One of the nano-layer consists of nanospheres with the same diameter of tens of nanometers. The other one is a nano-layer foil with a thickness of tens of nanometers, too. A LP ultra-high intensity laser pulse with the intensity of $2.16 \times 10^{22}$ W cm$^{-2}$ and a CP ultra-high intensity laser pulse with the intensity of $4.32 \times 10^{22}$ W cm$^{-2}$ interacts with these targets. In the case of the interaction of a CP ultra-high intensity laser pulse with the two investigated
types of the nano-layered flat-top cone targets we obtained more energetic protons and carbon C\(^{6+}\) ions for the cone with nanospheres. The optimum nanosphere diameter from the range of the investigated values is 80 nm. In the other case of nanospheres. The optimum nanosphere diameter from the

In near future, we plan to extend the work by consider 3D PIC simulations in order to be able to obtain quantitatively appropriate energies of the accelerated protons and carbon ions.

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Figure 11. The behavior of the electric field measured in the ultra-high intensity laser pulse-cone with nanospheres target interaction point at (a) the moment \( t_0 \) and (b) the moment \( t_1 = t_0 + 27 \text{ fs} \).
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