Numerical Investigation of optical acceleration of protons and perspectives for hadrotherapy

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Abstract

Dramatic progress has been made with optical acceleration during the last decade opening a serious perspective for its application to cancer therapy with proton beams. The highest energies presently reached fall below the therapeutic threshold near 60 MeV, but the use of new targets and/or post acceleration devices might allow us to overcome this limit. Simulations with PIC codes to solve the Maxwell-Vlasov equations are used to explore new promising scenarios considering presently available laser power (100-TW class) and new targets’ designs. One of them is based on targets of quasi-critical density which allow reaching energies of therapeutic relevance, the second one is obtained using a solid foil, as in TNSA, with an attached low density layer (foam) \( n_{ef} \approx n_c \) with a thickness in the micron range. After a brief survey of the present state-of-the-art proton acceleration, we report the results recently obtained with our PIC code AlaDyn running in a fully 3D configuration considering the near critical density target. These simulations confirm the potential of this regime in the sense that energy and angular spreads of the proton bunches are more favorable for a post-acceleration manipulation by conventional acceleration devices, even if this topic is still challenging. As a second set of simulation we present here also a 2D detailed investigation of TNSA regime obtained from multi-layered target using low density foam attached. Even if a fully 3D campaign is still in progress we present preliminary 3D results which allow to interpret the 2D findings with some confidence.

1 Introduction

The idea of using protons or neutrons for cancer therapy was born shortly after the invention of cyclotrons. Clinical experiments were developed mainly using the spallation neutrons until it was recognized that no particular advantage relative to X ray treatment was really obtained. Subsequently the proton beams were considered and some laboratories were equipped with a
treatment room dedicated to oncological therapy. At the end of last century the first medical centres for proton therapy were built.

More recently the use of synchrotrons made carbon ion beams available in addition to proton beams, widening the range of treatment to tumours resistant to the conventional therapy [1]. The progress of the beam deposition techniques using pencil beams has improved the effectiveness of treatments so that the main problem to face is the limited number of patients which can be treated due to the size and cost of these centres. For this reason new compact devices such as superconducting cyclotrons, dielectric wall accelerators and high field linacs are presently investigated.

The optical acceleration of protons is a promising research line, which might lead within a decade to a compact low cost device [3, 2]. For this reason research programs devoted to the laser acceleration of proton beams for therapy were developed in several laboratories. Some of these programs, such as PMRC Center in Nara have conducted radiobiological studies to determine the relative biological effectiveness (RBE) of laser-accelerated proton bunches, that are typically of much shorter (\( \sim \) picosecond) duration, for cancer therapy [4].

Two possible strategies have been explored:

- the all-optical acceleration of protons up to energies of clinical interest, requiring high power where RPA (Radiation Pressure Acceleration) regime is dominant and a monochromatic bunch generation is effective.

- the acceleration at lower energies where classical TNSA (Target Norma Sheat Acceleration) regime is dominant and the proton bunch characterized by a wide exponential energy spectrum would require the injection into a linac for further manipulation (hybrid strategy).

Both strategies are challenging with respect to the present state of the art, because of the intensity required, the beam quality and its shot-to-shot stability. Most of the experiments performed up to now restricted to the range of low-medium laser intensities, show an exponential spectrum with an average energy in the few MeV range. As a consequence selecting a considerably higher energy with a small spread can reduce the number of protons below the threshold required by any treatment. Efficient post acceleration requires the use of compact high field and high frequency linacs, whose injection energy is normally above 30 MeV. To assure optical acceleration with a sufficient number of protons with energy above 30 MeV it is necessary to envisage acceleration mechanisms with optimized target configurations.

The targets at near critical electron densities \( n \approx n_c \approx 1.1 \cdot 10^{21} e/cm^3 \) through which the laser can propagate by drilling a channel, seem to be promising since proton bunch with higher energies and lower angular spread with respect to the classical thin solid targets are produced. The preliminary experiments and the 2D simulation seem to confirm this trend. We shall present here the results obtained by 3D simulations with the code ALaDyn [5].

Besides the near-critical density regime we also consider a multi-layered target in which a low density layer (foam), \( l_{\text{foam}} 1 - 10 \mu m \) \( n_{e,\text{foam}} \sim n_c \), is attached to a solid thin foil. This configuration is expected to increase the protons acceleration efficiency by enhancing the energy coupling from laser to plasma [11]. This enhancement in 2D simulations can be estimated to be within a factor of 2-3 with respect to a bare solid target. These findings allow to reduce the difference of the foam-solid target configuration with respect to the near-critical
density regime at least concerning the protons maximum energy [17]. An important advantage of this design is the easier production and handling of the real target in an experiment. In particular we detail the investigation of this regime by considering a parametric numerical study in 2D, changing the target configuration and the laser power. To confirm the trends shown in the 2D simulations we planned to extend this analysis to 3D configurations. Running 3D simulations using solid densities is, as widely known, very demanding in terms of memory and CPU resources. Here we are able only to present some preliminary results.

2 Near Critical Target

2.1 Physical background

The acceleration of protons arising from the interaction of the laser pulse of wavelength $\lambda$ with a near critical density target with thickness $L_{ch} \gg \lambda$, was proposed and explored numerically some years ago [12, 13, 14, 15]. Under these conditions, a relativistic laser pulse $a \gg 1$, where

$$a = \frac{eA}{m_e c^2}, \quad A = |A_\perp|$$

(1)

propagates through the plasma even for overcritical electron density, up to $n < an_c$, where $n_c \simeq 1.1 \times 10^{21}/\lambda^2[cm^{-3}]$. For $n \simeq n_c$, a self-focused channel forms, acting as a wave-guide for laser propagation. The basic physical mechanism controlling the proton acceleration is provided by the formation of a slowly evolving magnetic dipole (a toroidal configuration in 3D geometry) behind the leading laser pulse. This coherent electromagnetic structure is generated by the return axial current due to the accelerated electron beam and contains a large fraction $\simeq 80 - 85\%$, of the whole pulse energy, the remaining part being depleted by particles acceleration inside the channel. This magnetic vortex, when exiting on a low density (or a vacuum) region, expands symmetrically thus creating a strong induction axial electric field. At higher electron density $n \simeq 1 - 3n_c$ this mechanism is the most effective in the acceleration process. At lower density $n < n_c$, a significant contribution comes also from the electrostatic field due to charge separation at the channel rear side, much alike the TNSA regime.

For medium power laser pulse, the near-critical regime are expected to present several advantages over a standard TNSA configuration with thin solid targets, as documented also by recent experiments: [18, 19]

- The larger volume where interaction takes place allows a higher absorption of the laser energy and finally to a more efficient proton acceleration;
- The final energy proton spectrum shows a lower decay (i.e. a higher mean energy);
- The exiting proton bunch has better averaged collimation properties, the highest energy protons being the best collimated $\theta \simeq 0$ along the propagation axis;
- The absence of debris is convenient for most applications and the prepulse is less detrimental because at low intensities the plasma is already transparent.
Theoretical modeling of a self-focusing channel is difficult because of the strong non-linearity. As a consequence, estimates of the acceleration efficiency and of the maximum proton energy are still based on phenomenological arguments.

From the balance between the laser and particles energy, it is possible to derive a scaling law among the relevant parameters only on the assumption that the length of the plasma channel is much larger than the pulse length $L_{\text{ch}} >> L_p$, to insure that the depletion of the laser energy is complete. In this case, one has:

$$a_L = k \frac{n}{n_c} \frac{L_{\text{ch}}}{L_p}$$

(2)

where $a_L$ is the value of the adimensional vector potential $a$ inside the self-focusing channel and $k \approx 13.5$ is a geometric factor obtained from wave-guide theory. For a given vector potential $a = a_0$ for the laser pulse in free space, 2D simulations give $a_L \approx 2.5a_0$, whereas in the present 3D simulations we find $a_L \approx 2a_0$.

For typical values $a_L \approx 60-100$ and $n = 1-3n_c$, this relation predicts large $L_{\text{ch}} > 2L_p$, whereas numerical experience shows that for large distances the filamentation instability becomes relevant and large scale hosing instability leads to a loss of axial symmetry, both phenomena being strongly detrimental for the acceleration efficiency.

A second phenomenological argument is presented in [17] where a scaling relation for the maximum proton energy as a function of the incident laser power $P_L$ of the form $E_p = k_1 \sqrt{P_L}$ is proposed, the $k_1$ constant value being essentially determined from numerical simulations. For the 2D case and a self-focusing channel ending in a lower density plasma, the $k_1 = 16.7$ value is obtained.

In the 3D case selecting a set of optimal parameters $(n/n_c, L_{\text{ch}}, P_L)$ to derive robust scaling laws is more challenging, and quite different results are also obtained depending on the channel ending in empty space or in a lower density plasma.

For that reason, in the following we report a preliminary 3D investigation, by concentrating on near critical density values $n \approx 1 - 2$ for plasma channels ending in free space with length $L_{\text{ch}} \leq 2L_p$ and moderate laser powers $P_L \approx 100 - 300 \text{TW}$.

### 2.2 3D PIC numerical simulations

We have considered a laser pulse having a fixed length $L_p = 20.6 \mu m$ corresponding to a FWHM time length $\tau = 25 fs$ and a focused radial profile of the standard form $\approx e^{-r^2/r_0^2}$, with a fixed waist $r_0 = [2.5-3] \mu m$. To limit filamentation instability even smaller focal spots should be selected. The chosen values are easily experimentally accessible and we find that the control of instability is still insured. In all models we choose circular polarization, since in 3D linear polarized pulses, as expected, lead to a channel deformation along the polarization axis and then to strongly reduced efficiencies.

The channel structure is illustrated here only for the model where $P_L = 200 \text{TW}$, $L_{\text{ch}} = 30 \mu m$, $a_0 = 32$ and $n/n_c = 1$. In the first set of figures we show the electrons and protons density projected in the $(x, y)$ plane, where $x$ denotes the pulse propagation axis at different times. Plots on the $(x, z)$ plane are similar, confirming a well shaped circular structure. Here the position of channel rear side is $x_{\text{end}} = 52 \mu m$. 

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Figure 1: The electron density (left frame) and proton density (right frame) at time $T = 40\mu/c$.

Figure 2: The electron density (left frame) and proton density (right frame) at time $T = 60\mu/c$.

In the Figures 3 and 4 we show the formation of the magnetic vortex and its expansion into the vacuum region. For computed $(B_y, B_z)$ cartesian components on the plane orthogonal to the laser propagation axis, the magnetic vortex is well described by the azimuthal component $B_\phi = B_z \cos \phi - B_y \sin \phi$ arising from the $J_x$ axial current density. As shown, typical field values $B \simeq 400 - 500MG$ over the channel scale $R_{ch} \simeq 4\mu m$ are obtained.

In the Figure 5, the induction electric $E_x$ field arising from the $B_\phi$ expansion and the residual laser $E_z$ exiting the channel end side, are shown. It is evident that for $L_{ch} = 30\mu m$, $n = n_c$, self-focusing still insure a stable electrons and protons beaming, but the laser energy depletion is not complete.
Figure 3: The $B_z$ field on the $z = 0$ $(x, y)$ plane, at time $T = 40\mu/c$ (left) and at the time $T = 60\mu/c$ (right).

Figure 4: The $B_\phi$ field on the $(y, z)$ plane at $x = 46\mu m$, before the channel end (left), and at $x = 56\mu m$ after the channel end (right).

2.3 The accelerated proton bunches

In a phenomenological approach, the growth of the normalized vector potential due to self-focusing, before the laser depletion takes place, represents a first model parameter having relevance for the proton acceleration. The Figure 6 documents a growth of the field by a factor of 2 in all the cases: $a_L \simeq 2a_0$, to be compared with a factor of 2.5 obtained in 2D configurations.

On the other hand, the evolution of the maximum proton energy exhibits a marked difference among the three cases reported in the right panel of the same figure, the best result being obtained for the case of the shortest channel length. In the figures 7, 8 the collimation properties of the proton bunches exiting the self-focusing channel are documented for models $(a)$ and $(c)$ of the Figure 6, respectively. In the same figures the corresponding proton spectra are plotted and show an exponential decay. The number of high energy protons is still
Figure 5: The $E_x$ component (left) and the $E_z$ component (right) at the channel end side at $T = 60\mu m$.

Figure 6: Evolution of the maximum value of the normalized vector potential $a$ for: case(a): $P = 155TW$, $n = n_c$, $L_{ch} = 40\mu m$; case(b): $P = 330TW$, $n = 2n_c$, $L_{ch} = 40\mu m$; case(c): $P = 200TW$, $n = n_c$, $L_{ch} = 30\mu m$.

Appreciable over 40 MeV proving to be interesting for biomedical application.
3 Foam Attached Solid Target

The majority of the experimental campaigns on proton acceleration are conducted using thin targets \((l_t = 1 \div 10 \mu m)\), mostly metallic. The contaminants, normally present in the vacuum chamber deposit themselves onto the surfaces and their proton component produces the bunches accelerated in the TNSA regimes. This experimental configuration can be sketched as a high density plasma slab coming from the ionization of the solid foil, plus an hydrogen rich thin layer on the surfaces, typically with a thickness in the 10 nm range.

A systematic experimental investigation with short pulses (30 fs) of 100 TW of variable intensity was carried out in Dresden [8] and the fit to the spectrum is exponential. In general
let the spectrum be defined by
\[ \rho(E) = \frac{dN}{dE} = \frac{N_0}{E_0} e^{-E/E_0} \vartheta(E_{\max} - E) \] (3)

where \( E_{\max} \) denotes the highest energy. The total number of particles and the total energy, supposing \( E_{\max} \gg E_0 \), are given by
\[ N_{\text{tot}} = \int \frac{dN}{dE} dE = N_0 \quad E_{\text{tot}} = \int \frac{dN}{dE} E dE = N_0 E_0 \] (4)

As a consequence the average energy is
\[ \langle E \rangle = \frac{E_{\text{tot}}}{N_{\text{tot}}} = E_0 \] (5)

If we select a bunch of energy \( E \) and spread \( \Delta E \) then the total number of particles is given by
\[ n([E, E + \Delta E]) = N_0 \Delta E/E_0 \exp(-E/E_0) \] (6)

In order to have a significant number of protons in the selected bunch, the energy \( E \) must be chosen close to average energy \( E_0 \) rather than to the cutoff energy \( E_{\max} \). For instance the Dresden experiments were performed on Al targets 5 \( \mu \)m thick with a laser beam focused on 10 \( \mu \)m\(^2\) spot, where the intensity is \( I = 10^{21} \) W/cm\(^2\), and the energy spectrum can be fitted by
\[ \frac{dN}{(dE d\Omega)} = 3 \cdot 10^{11} \exp(-E/E_0) \quad E_0 = 1.7 \text{MeV} \] (7)

with a cutoff maximum energy of 12 MeV. In this case if we select a bunch with \( E = 10 \) MeV and \( \Delta E = 0.1 \) MeV we obtain \( dN/d\Omega = 5 \times 10^7 \).

The experiments show that the maximum proton energy is a decreasing function of the target thickness.

We have carried out a systematic campaign of simulations with the PIC code ALaDyn to explore the dependence of the protons energy spectra on various parameters such as the target thickness, and intensity whereas the energy and pulse duration are kept constant. Our findings are in agreement with the experimental results within the tolerances coming from a reduced dimensionality and the use of lower density targets, namely \( n = 80n_c \) rather than several hundreds \( n_c \).

### 3.1 Three layer target

We now present the result obtained considering a more complex target configuration in which a low density, foam, layer is attached to a solid main layer. A scheme of the target is presented in figure 9.

The target considered in the simulation has the central metal layer with a thickness \( l_m = 0.5\mu \) whose front side is at \( x = 0 \) where \( x \) is the propagation axis. The foam layer, is placed on the illuminated side (front) and has a thickness ranging from 1 to 8 \( \mu \)m and electron density \( n_{e,f} = 1 \div 4n_c \). The contaminants layer, has been arbitrarily chosen to be pure hydrogen with a thickness of 50nm and density \( n_{e,c} = 10n_c \).

The considered laser pulses propagate along the \( x \) axis towards the positive values, is linearly P polarized and has time duration Full Width Half Maximum \( \tau = 25 \) fs, waist \( w_0 = 3\mu \)m, wavelength \( \lambda_0 = 0.8\mu \)m, adimensional vector potential \( a_0 = 10 \div 32 \).
Figure 9: Scheme of the foam-attached target. A low density foam layer (blue), a solid density layer main layer (red) and a thin hydrogen rich contaminant layer (green). Values of the densities and thickness are close to the ones used in the simulations.

<table>
<thead>
<tr>
<th>layer</th>
<th>thickness</th>
<th>$n_e$ density</th>
<th>ions $Z/A$</th>
<th>longitudinal domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foam</td>
<td>$l_f = 0.5 \div 8,\mu\text{m}$</td>
<td>$n_{e,f} = 1 \div 4n_c$</td>
<td>1/2</td>
<td>$[l_f; 0]$</td>
</tr>
<tr>
<td>Metal</td>
<td>$l_m = 0.5,\mu\text{m}$</td>
<td>$n_{e,m} = 40 - 80n_c$</td>
<td>1/3</td>
<td>$[0; l_t]$</td>
</tr>
<tr>
<td>Contaminants</td>
<td>$l_c = 0.05,\mu\text{m}$</td>
<td>$n_{e,c} = 9n_c$</td>
<td>1</td>
<td>$[l_f; l_f + l_c]$</td>
</tr>
</tbody>
</table>

Table 1: Target Layers

The proton spectra obtained using the foam layer show a significant increase of the cutoff energy with respect to the bare target. This increment correspond to a factor of 2 to 3. In fig. 10 we show the protons spectra obtained using a rather low intensity $a_0 = 10$ laser onto foam attached targets compared to the case of the pure metallic layer with contaminants. Figure 11 shows the electron density for the case with a foam of $8\,\mu\text{m}$ $n_{e,f} = n_c$, irradiated by a laser with $a_0 = 10$. The figure shows how the electrons of the foam are strongly accelerated by the laser and, expanding on the backside of the foil, generate a strong longitudinal electric field see fig. 12. The accelerating field in the case of a foam target is increased by a factor of 3, so the protons present on the backside, contaminants, reach much higher energies.

In the TNSA regime the highest proton maximum energy can obtained by optimizing the electron areal density with respect to the laser characteristics; for a target of thickness $l$

$$\sigma = \pi \frac{n l}{n_c \lambda}.$$  

(8)

Esirkepov et. al. [26] using a parametric 2D numerical study, show how optimum target density can be defined for each laser intensity: $\sigma_{opt} \sim 3 + 0.4a_0$. For values $\sigma < \sigma_{opt}$, the transmitted part of the laser increases and dominates over the absorbed part. On the other hand, for values $\sigma > \sigma_{opt}$ the reflected fraction of the laser energy becomes dominant.

When considering a real target, its mechanical robustness with respect to the laser pre-pulse has to be taken into account. An optimum areal density, as pointed out in [26], is feasible
in an idealized configuration, like the numerical simulation, or for a very high contrast laser pulses. Most of the time, to achieve a higher laser contrast, a relevant part of the laser pulse energy is lost through the laser cleaning, i.e. use of plasma mirror. To exploit the laser system maximum achievable power without loosing a too big fraction of the initial energy a compromise has to met between the optimum target thickness and its resistance to the prepulse.

A configuration that exploits a solid foil with a foam attached, seems to partially overcome some of these constraints; the fraction of laser energy absorbed by the target is strongly increased while a reasonably target robustness is maintained. The foam layer plays the role of an absorbing layer, whose electron population gets heated by the laser and is mostly responsible for the creation of the accelerating field, whereas the solid layer reflects the laser and represents a sort of mechanical support. The accelerated proton bunch comes from the contaminants as in the TNSA regime, and maintains very similar characteristics, spectrum shape and angular distribution.

Figure 13 shows how the maximum proton energy evolves with respect to time for different laser intensities $a_0 = 10$, $a_0 = 20$, $a_0 = 32$ using two different metal foil electron densities $n = 40n_c$ and $n = 80n_c$ (with and without foam layer). From this plots we can conclude how for low intensity laser $a_0 = 10$ the difference in terms of maximum proton energy achieved for different metal target is not very relevant whereas for raising values of the laser power the difference increases in favour of lower density target or lower aerial density targets. We interpret this as the consequence of the absorption of the laser energy by the foam, which in the low intensity case is already very high leaving a low fraction of the laser to interact with the metal foil, hence reducing the importance of its electron density. For increasing laser intensity the foam is able to absorbs only a small part of the pulse, and partially focalize the rest. The pulse that reaches the solid foil leads to a TNSA-like interaction and, because of its still high intensity, the target thickness and density become important. In such case the foam aerial density should be increased to enhance the absorption, hence obtaining a more efficient
Figure 11: Electron density (foam + main target) obtained from the interaction of the laser $a_0 = 10$ on a target with a foam layer $n_{fe} = 1n_c$ $l_f = 8\mu$m. The figure shows the channel drilled in the foam by the laser and the expansion of the electron cloud on the backside of the foil.

acceleration. It is interesting to note, also, that the optimization of the foam layer allows for the solid density to be much less relevant for the final protons’ spectrum. The use of a lower electron density, is a very positive aspect from the point of view of the PIC simulations, because it allows to save an important amount of load on both memory an computational time, making a 3D simulation less demanding while maintaining a reasonably trustworthy results. For that reasons we started a fully 3D campaign to investigate the lower $n = 40n_c$ configurations. A first result is documented in the Figure 13.

We have shown a possible alternative target design which allows to increase the amount of laser energy absorbed by the target and the resulting accelerating electric fields experienced by the protons present on the back surface. This target design seems experimentally much more feasible, because it basically exploits a metal foil with an attached low density layer which can be a foam, as suggested previously and in [11].
4 Conclusions

In the framework of the feasibility study of the PROMETHEUS project, we have performed a systematic numerical investigation of laser-plasma proton acceleration considering two different types of target: near critical and overcritical with a low density foam layer attached. We have analyzed the results obtained from simulations performed with the PIC code ALaDyn developed by our research group. We have considered laser pulses in the $100 \div 200$ TW range and with a pulse duration of 25 fs. These lasers of moderate size are now commercially available and highly reliable.

The nearly-critical target regime allows to reach protons energy in the range of $40 \div 80$ MeV with a low slope exponential spectrum and a good collimation of the most energetic particles. The number of high energy protons is above $10^8$ opening a perspective for preclinical studies either using directly the beam, or after a post acceleration stage.

The solid thin foil with a low density foam layer attached on the front side, showed a substantial improvement of the protons energy spectra compared to the bare metallic target as usually considered for TNSA acceleration. The simulations confirm an increased absorption of the laser energy by the electron population which reaches a higher temperature and drives the protons to higher energy values.

The quality of the proton bunches immediately after the optical acceleration are quite favorable but are subject to rapid degradation due to the angular spread. In this respect, in the near critical targets case significant improvements can be obtained by creating a low density plasma right after the exit from the channel ([17]). Very preliminary simulations of the beam transport have been carried out. Using a collimator and a solenoid to focalize the beam,
Figure 13: Maximum proton energy evolution with respect to time, for 4 different targets in 2D configurations: with a foam attached (solid line) or without foam (dashed line), with a solid layer density of $n_{e,m} = 80n_c$ (blue) or $n_{e,m} = 40n_c$ (red). Three laser intensity has been used: $a_0 = 10$ (top-left) $a_0 = 20$ (top-right) $a_0 = 32$ (bottom-left). The comparison between the 2D and 3D evolution on a shorter time scale for $a_0 = 20$ with foam (bottom-right)

the growth of emittance and beam size of can be controlled as also shown experimentally, but we are still far from the values required for the injection in a post-acceleration device. As a consequence, the improvement of the beam quality of the optically accelerated bunch appears to be a crucial issue for any further application which in any case requires the transport over macroscopic distances.

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The simulation work has been done on the SP6 machine of CINECA (Bologna) under the
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