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Optimization of proton beams created by laser-plasma interaction for various applications

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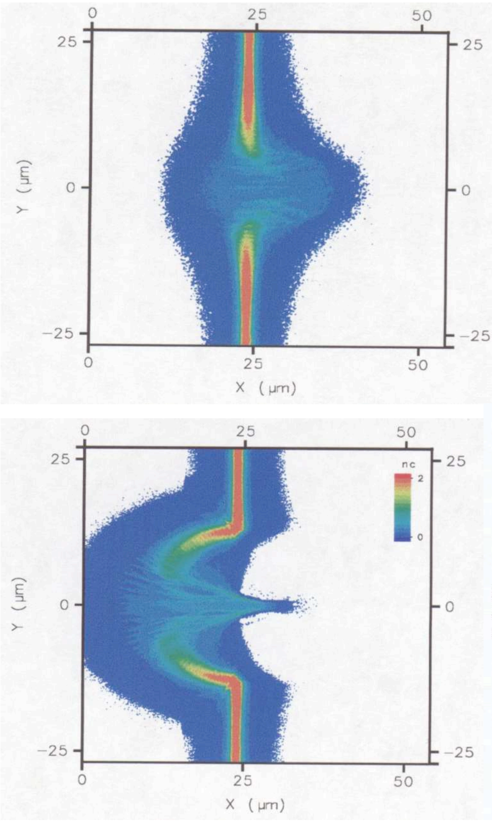
Proton beams accelerated during laser-plasma interaction are very promising for applications in inertial confinement fusion, plasma diagnostics, isochoric heating of matter or medical applications. When a high intensity laser hits a very thin overdense target, the target is quickly heated and expands. The density of the plasma decreases and induced transparency becomes possible. Part of the laser pulse is transmitted and the bulk of the target is efficiently heated. Proton acceleration is optimized in this regime but the divergence of the beam is affected [1]. For very high intensities (10^{20}-10^{21} W/cm^2), shock acceleration from the front or the core of the target is increased and the most energetic protons can first be accelerated by this mechanism. In this case, the number of protons accelerated to the highest energies is smaller than when the most energetic protons are accelerated from the back surface. These shock-accelerated beams are therefore less interesting for most applications than proton beams coming directly from the back of the target. The present study reviews different applications of laser-based proton acceleration and for each one of them, look at the most interesting parameters.

Isochoric heating consists in heating matter while keeping a constant volume. Protons beams produced by laser-plasma interaction are promising for this application because they have a very short duration which permits to heat matter before it has time to expand. The PIC code Calder [2] was used to simulate the production of a proton beam by laser-plasma interaction and Calder MC [2], a 3D Monte Carlo code, was used to simulate its propagation through a solid to obtain the heating. Calder MC uses the Bethe formula [3] for the stopping power of protons in cold matter and the Melhorn formula [4] for the stopping power in plasmas. The temperature is calculated using the amount of energy deposited by the protons with the help of tabulated data, and ionization is described using the model of More [5]. Numerical and experimental works have been carried out recently [6] on optimizing isochoric heating. Spherical targets are adapted for this application, as they tend to focalize the protons leaving the target. The combination of Calder and Calder MC was used to look for optimum parameters; the results are plotted on Figure 1 and Figure 2. For the flat target, the secondary target is heated to a maximum of 12 eV with a FWHM of 160 μm. For the curved target, the secondary target is heated to a maximum of 33 eV with a FWHM of 20 μm. As it is the case for protontherapy, the energy spread has to be as small as possible to ensure that the heating is limited to a small volume.



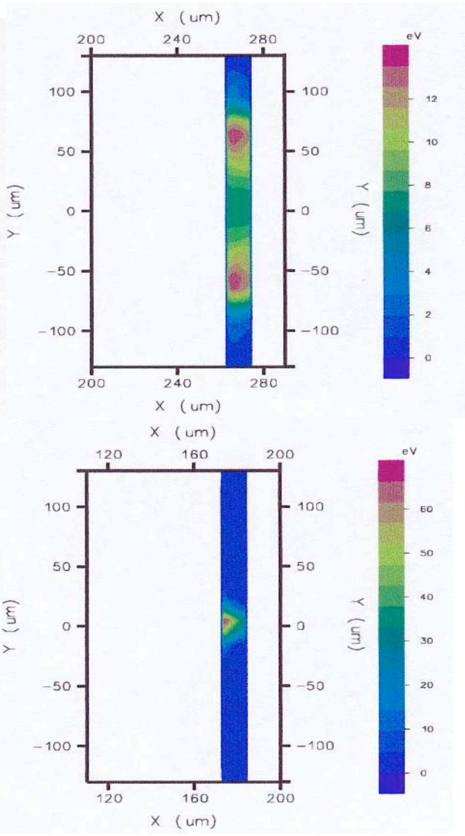


Figure 1 (left): density map for a flat target (top) and a curved target (bottom) hit by a high intensity laser.

Figure 2 (right): temperature map for secondary targets hit by the proton beams produced by the interaction of Figure 1.

The production of short-lived isotopes such as ^{11}C or ^{18}F is important in medicine for Positron Emission Tomography (PET), since they undergo β^+ decays. These radio-pharmaceuticals are generated using proton beams produced by cyclotrons or Van de Graaf accelerators, which induce (p,n) reactions with ^{11}B and ^{18}O nuclei inside a target. Due to the size, cost and shielding required for such installations, PET is limited to only a few facilities. A typical patient activation for PET is 200 MBq and it is necessary to go up to 800 MBq so that fast chemistry can be performed. With a smaller accelerating system, protons accelerated by laser-plasma interaction could be interesting to produce these radio-isotopes [7].

Using both Calder and Calder MC, a ^{11}C activation of 143.3 kBq is obtained when shooting 30 minutes at 10 Hz with a 3×10^{19} W/cm^2 laser at 36 fs with a 6 micron carbon and hydrogen target. Using a 0.5 micron hydrogen target at 10 n_c with a 10^{20} W/cm^2 and 36 fs laser shooting at 10 Hz during 30 minutes gives an activation of 2.76 GBq, showing that the required activation can theoretically be reached with nowadays lasers. Other simulations were performed to compare the influence of the maximum proton energy and the number of accelerated protons. Maxwellian distributions were used to reproduce the proton energy spectrum. The two parameters are the ion temperature and the total number of particles.

Parameters of the distribution	T_i=0.5 MeV 5.16×10^{11} protons	T_i=1 MeV 2.58×10^{11} protons	T_i=2 MeV 1.29×10^{11} protons	T_i=4 MeV 6.4×10^{10} protons
Number of ^{11}C produced	1.06×10^4	7.03×10^5	7.5×10^6	2.87×10^7

Table 1: number of ^{11}C produced for different sets of distribution parameters.

This study shows that having a higher temperature, therefore a higher maximum proton energy, is more efficient than having a higher total number of protons (Table 1). To be able to find the best laser parameters to produce radioisotopes, another step is needed. When high energy protons create (p,n) reactions on a target, they also have a chance to create (p, 2n) or (p,3n) reactions depending on their energy. These other reactions produce elements that are difficult to extract and that increase the cost of the process. A complete calculation taking into account the production of these poisons is therefore needed to determine at which laser intensity, they become too important.

To treat a brain tumor or an eye tumor, protons used for protontherapy, i.e. the treatment of cancerous tumors by energetic protons, have to go a few cm deep. The protons have to be very energetic, between 60 and 300 MeV. For reasons of size and cost, powerful lasers could replace conventional accelerators in hospitals [8]. To produce such beams with very high intensity lasers, the intensity has to be greater than 10^{21} W/cm^2 for a pulse lasting a few tens of fs. The target has to be very thin and composed of a layer of heavy ions and one very thin layer of protons. Enhancement by a gas jet in front of the target if made possible in experiments would be very useful to reduce the constraints on laser energy. The protons energy spread strongly depends on the proton layer thickness. The protons closest to the surface are accelerated first and screen the field for the protons deeper in the target. The thinner the proton layer, the narrower the energy spread, but the energy conversion efficiency is strongly reduced [9].

Using numerical simulations, new regimes of proton acceleration with high intensity lasers have been explored. These regimes have to be tested experimentally but they could help on many applications envisioned for such beams. We have used the combination of a PIC code and a Monte Carlo code to progress in the search of the best parameters for three applications: isochoric heating, radio-isotope production and protontherapy. The needs for each application differ completely but the availability of next generation lasers will help fulfill most of them.

References

[1] E. d'Humières et al., Phys. Plasmas **12**, 062704 (2005).

[2] E. Lefebvreet al., Nucl. Fusion **43**, 629 (2003).

[3] H. A. Bethe et al., Phys. Rev. A, **79**, 413 (1950).

[4] T. A Melhorn, J. Appl. Phys. **52**, 11 (1981).

[5] R. M. More, J. Quant. Spectrosc. Radiat. Transfer, **27**, 345 (1982).

[6] P. K. Patel et al., Phys. Rev. Lett. **91**, 125004 (2003).

[7] I. Spencer et al., Nucl. Instrum. Methods Phys. Res. B **183**, 449 (2001); S. Fritzler, et al., Appl. Phys. Lett. **83**, 3039 (2003).

[8] C.-M. Ma et al., Med. Phys. **28**, 1236 (2001); E. Fourkal et al., Med. Phys. **30**, 1660 (2003); V. Malka, et al., Med. Phys. **31**, 1587 (2004).

[9] T. Zh. Esirkepov et al., Phys. Rev. Lett. **89**, 175003 (2002).