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New micro-cones targets can efficiently produce higher energy and lower divergence particle beams

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Abstract

Small conical targets have been used in high intensity laser target interaction mostly in the context of fast ignition. We demonstrate that when cone targets are shaped appropriately and used with specific interaction conditions, they can produce particle beams of higher maximum energy and number in a lower angular divergence than flat targets. This is relevant to fast ignition, small compact particle beams, medical applications, focused ion and/or electron beam microscopes. This fact carries the potential to produce particle beams that are no longer limited by the characteristics of the laser. Note that for fast ignition, reducing the divergence of the beam lowers the energy requirement and enhances the energy deposition into the compressed fuel.

Keywords: Cone targets; High-intensity laser interaction; Laser-produced particle beams

1. INTRODUCTION

Cone targets appeared in laser target interaction after a series of key steps in the pursuit of fusion. In 1963, applications of fusion were just starting to be studied (Basov & Krokhin, 1963). Nuckols *et al.* (1972) conceived the laser implosion concept to produce fusion and inertial confinement fusion research was born. Concepts of fusion through ion beams (Winterberg, 1974) or laser generated ion beams and target design for ions were developed (Kindel & Lindman, 1979, and references therein). Some decades later, Tabak *et al.* (1994) introduced the concept of fast ignition and Kodama *et al.* (2001) introduced the idea of a cone target for fast ignition to allow the laser beam to get far enough into the compressed plasma to produce the fast electron beam that would deliver the ignition spark to the right place. Based on experimental results and simulations, Roth *et al.* (2001) expanded this concept by adding a curved proton-producing interface that the laser hits first for the proton fast ignition concept. New target concepts along with new ideas to achieve ignition of fusion targets with laser and particle beams are presently of high interest and have a wide range of applications in the field of high energy density physics (Bieniosek *et al.*, 2010; Holmlid *et al.*, 2009; Johzaki *et al.*, 2007; Koresheva *et al.*, 2009; Nakamura *et al.*, 2008, 2006*a*, 2006*b*; Sakagami *et al.*, 2006; Tahir *et al.*, 2008; Wu *et al.*, 2009; Winterberg, 2004). We present here studies of the cone target along with other shapes that have paved the way to enable a better understanding of the cone physics, along with its relevance for an array of applications.

2. EFFICIENT USE OF CONES

For such a target to give its full potential, because of the physics occurring in a cone, some criteria need to be met. The cone target needs to be precisely aligned (Nakamura *et al.*, 2009, 2010; Lasinski *et al.*, 2009; Yu, 2010). The laser enters the cone and starts hitting the faces when its diameter is about 3 to 4 times the inside tip size (Sentoku *et al.*, 2004; Nakamura *et al.*, 2007, 2008; Renard-Le Galloudec *et al.*, 2008). Under low pre-plasma conditions, so as to not destroy the conical shape the laser interacts with the cone micro-focuses the laser light into the tip (Sentoku *et al.*, 2004; Renard-Le Galloudec *et al.*, 2008). At the same time, the laser interacts with the faces of the cone, creates electrons, and guides them along the faces to the tip where the electron beam exits (Renard-Le Galloudec *et al.*, 2008, 2009). This increases dramatically the electron density in the tip, enables a higher conversion efficiency of laser light into very energetic or hot electrons (Nakamura *et al.*, 2004, 2006, 2007, 2009; Sentoku *et al.*, 2004; Nakatsutsumi *et al.*, 2007) and

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thus enhances both electrons and protons characteristics (Chen *et al.*, 2005). Note here that the cone, not the laser, defines the beam diameter (Renard-Le Galloudec *et al.*, 2009). A smaller cone angle produces more energetic electrons compared to a more open cone (Noda *et al.*, 2002; Chen *et al.*, 2005; Nakamura *et al.*, 2007). In addition, cones show an increased absorption of the laser light compared to flat targets (Nakamura *et al.*, 2007; Lasinski *et al.*, 2009), which makes them more efficient. More complex cone-based geometries have also been studied (Flippo *et al.*, 2008) and also show an increased efficiency compared to flat targets. A similar increased efficiency and higher energy protons have been reported in simulations with a concave target (Bin *et al.*, 2009). In our case, both the inside and outside tip of the cone are slightly curved (Fig. 1). Figure 1a shows the concept of such a target shape and Figure 1b, the simulated target. Shaping the back of flat targets has been demonstrated to focus protons beams (Wilks *et al.*, 2001; Ruhl *et al.*, 2001; Roth *et al.*, 2002*a*, 2002*b*; Patel *et al.*, 2003; Snavely *et al.*, 2007), it is however the first time that this concept is adapted to a cone geometry in order to use cones as an essential element of the particle beam production and reap the benefits of the increased efficiency of its shape. It does more than a standard flat or curved target. It adds three essential aspects. The first aspect is that making use of the cone faces by allowing the laser to spread on them greatly reduces the amount of pre-plasma filling the cone, thus enabling an efficient use of the cone shape (Renard-Le Galloudec *et al.*, 2008, 2009). It also uses the faces to create the electrons and guide them to the tip. Several articles have showed the imprint of the laser pattern on flat targets into the particle beam (Roth *et al.*, 2002*a*; Fuchs *et al.*, 2003). As the laser bounces several times on the faces on its way to the tip, its imprint disappears. It creates, at the tip, a laser imprint free area of high energy density, enabling more uniform beams. Also, its best focus is positioned toward the entrance of the cone, then all of the laser light available gets in regardless of the *f*-number of the focusing optic compared to the cone angle. The second aspect is the fact that the cone, then, not the laser, defines the particle beam (Renard-Le Galloudec *et al.*, 2008). The particle beam diameter has the potential to be smaller or bigger than the laser best focus by defining the size of the inside tip of the cone (Renard-Le Galloudec *et al.*, 2009). The laser is clearly not directly driving the characteristics of the beam produced. The third aspect is the ability to control the divergence of the output beam. The tip of the cone is slightly curved in our case. This results in a modification of the divergence of the output particle beam by effectively modifying the accelerating sheath shape, and can be adjusted by adjusting the amount of curvature. This efficiently produces a beam with extremely relevant characteristics to fast ignition (Nakamura *et al.*, 2007), laser based accelerators (Dunne, 2006), proton beams for proton radiography of plasmas (Borghesi *et al.*, 2002, 2010; Kodama *et al.*, 2004), isochoric heating (Patel *et al.*, 2003) shocks (Koenig *et al.*, 2004), proton therapy (Bulanov & Khoroshkov, 2002; Fourkal *et al.*, 2002; Noda *et al.*, 2002; Pegoraro *et al.*, 2004; Nishiushi *et al.*, 2009, Yogo *et al.*, 2009), micro-beam radiation therapy (Slatkin *et al.*, 1992), positron emission tomography (Spencer *et al.*, 2001), focused ion beam milling machines (Reyntjens & Puers, 2002), ion beam microscopes (Li, 2007), and dual beam electron/ion microscopes (MoberlyChan, 2009). For applications such as proton therapy, control of the characteristics of the beam are important (Toncian *et al.*, 2006) and a micro-magnetic device (Schollmeier *et al.*, 2008) separates the electron and or proton beam from the X-rays, or focus them (Nishiuchi *et al.*, 2002; Kanazawa *et al.*, 2009). An ion-milling machine that includes electron microscopy capabilities to image the object, and non-destructive X-rays radiographs of the same object would be a possibility. With high repetition rate (Tümmler *et al.*, 2009) and high-energy high-repetition rate lasers (Bayramian *et al.*, 2007; Burns *et al.*, 2009) as well as targets that are on the verge of cost effective mass production (Renard-Le Galloudec *et al.*, 2006; Alexander *et al.*, 2007, 2009; Higginson *et al.*, 2006), cost effective compact applications can be readily envisioned.

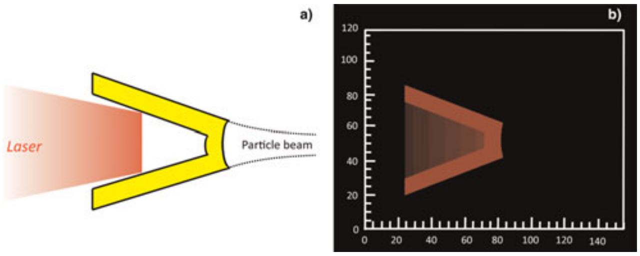

Fig. 1. (Color online) Conceptual schematic of the curved cone target (**a**) and simulated target (**b**).

3. A NEW SHAPE FOR PARTICLE BEAM GENERATION

Because the new target shape proposed here has not been fabricated yet, we used the two-dimensional (2D) particle-in-cell (PIC) code PICLS (Sentoku *et al.*, 2007) to run collisionless simulations and assess the electro-magnetic fields structures and proton beam characteristics in comparison with flat targets. We ran several intensities to span the range available to short pulse lasers. Figure 2a shows the simulated cone target as a dotted line. The inner and outer tip diameters are respectively 10 and 30 μm. They are both curved. The target itself is 10 μm thick. The simulations box is 150 μm long to capture the emitted particles. The incident laser pulse (1 μm, 40 fs, 21 μm full width at half maximum transverse spot size at 3×10^{18} W/cm^2) has a Gaussian temporal and transverse spatial profile. The pulse is injected to the left of a 120 × 150 μm box. The laser interacts with the target at normal incidence, with its polarization in the simulation plane. The peak of the pulse enters the box 80 fs after the beginning of the calculation. The initial target density is

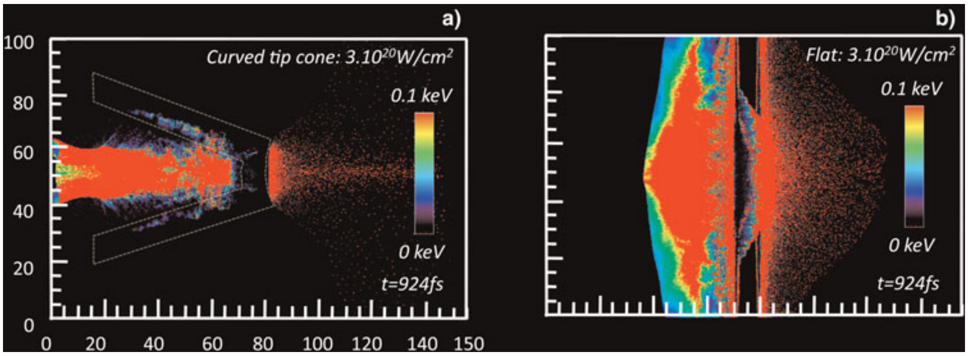

Fig. 2. (Color online) Proton energy density for the cone target at 3×10^{20} W/cm^2 (**a**) and for the flat target for the same laser intensity (**b**).

$40n_c$ and remains higher than the relativistic critical density $a_0 n_c$, where a_0 is the normalized laser amplitude and n_c is the critical density ($n_c = 1.1 \times 10^{21}/\lambda^2(\mu\mathrm{m})^2$ cm^{-3}, λ is the laser wavelength). The plasma, composed of D ions, protons, and electrons, is initially fully ionized. The mesh size is $\Delta x = \Delta y = 40$ nm with 40 D ions or 40 protons and 40 electrons per cell. Two types of targets were investigated: cone D targets (shown in Fig. 1b) and flat D foils, both with a thin layer of protons at the back. An exponential pre-plasma consisting of protons and electrons is located inside the cone in the first case, or in front of the flat foil for the second case. It has a density 1% to n_c over 50 µm with a characteristic length of 1 micron. The time step is equal to 0.132 fs.

Figure 2 represents the 2D proton energy density for a 10 µm thick curved-tip cone in a high intensity case at 3×10^{20} W/cm^2. Figure 2b represents the same 2D proton energy density for a 10 µm flat target at the same intensity. We clearly see that the protons are a lot more confined in the cone than in the flat target where they tend to diffuse laterally. The protons emitted from the cone are much more collinear to the laser axis compared to the flat target where they expand perpendicularly to the sheath.

Figure 3 shows the proton divergence (py/px) as a function of the longitudinal position at 924fs for the cone (Fig. 3a) and the flat target (Fig. 3b) for 3×10^{20} W/cm^2. In both cases, the average divergence is small, especially for the high-energy protons (those with a position from 120 to 140 µm). The cone target controls the divergence much better than the flat target over a wider range of energies. The curvature also allows to focus the most energetic protons in a specific location, and thus to deposit through the ions a higher energy in a smaller volume than in the case of a flat target, which is of special interest to isochoric heating.

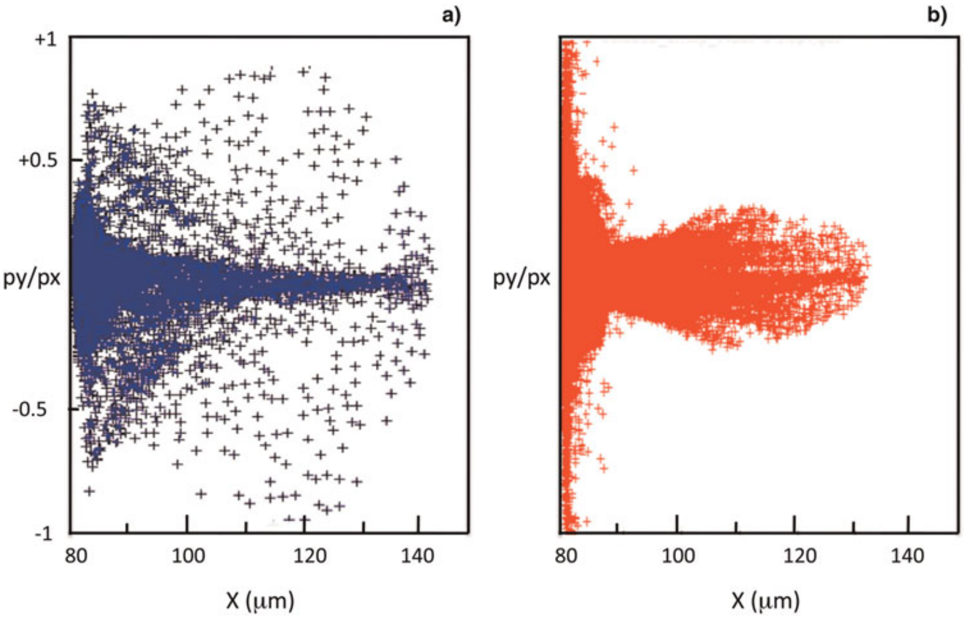

Fig. 3. (Color online) Proton divergence (py/px) as a function of the longitudinal position at 924fs for the cone (**a**) and the flat target (**b**) for 3×10^{20} W/cm^2.

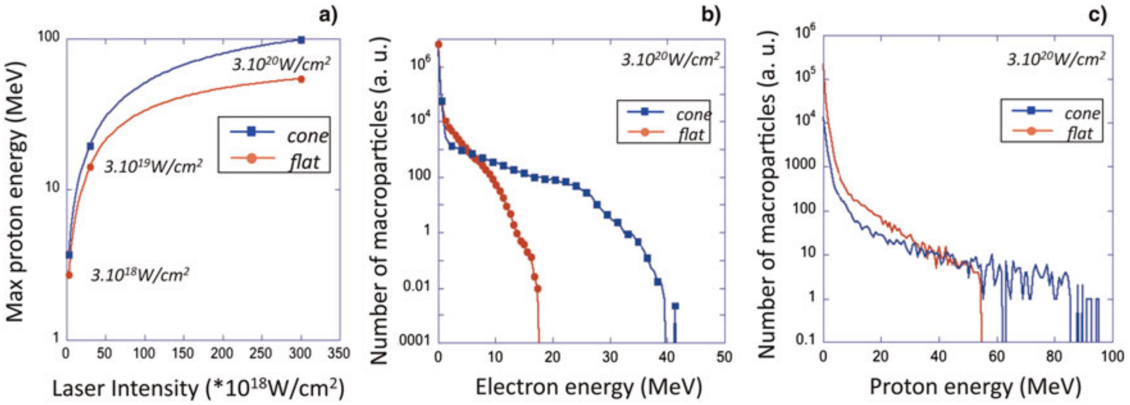

Fig. 4. (Color online) Maximum proton energies for three laser intensities from both the cone target and the flat target (**a**). Electron energy spectrum (**b**) for both cone and flat target at 660 fs, and proton energy spectrum (**c**) for both cone and flat target at 1.98 ps.

Figure 4 confirms that the cone is a much more efficient structure over a range of intensities. Figure 4a shows the maximum proton energy expected for both the cone target and the flat target over a range of intensities. We see that as we increase the intensity the maximum proton energy increases in general regardless of the target but the cone target clearly shows higher maximum proton energy than the flat target for all intensities. That difference increases with intensity. Especially evident at 3×10^{20} W/cm^2 is, that both electrons (Fig. 4b) and protons (Fig. 4c) are accelerated to higher energies in a higher number for the cone target. Enhanced laser interaction results in much higher maximum proton energies at high intensities. Laser absorption is greatly increased in cone targets. It reaches 75.7% for the cone target and only 42.1% for the flat target in the high intensity case (3×10^{20} W/cm^2). For the low intensity case (3×10^{18} W/cm^2), the absorption reaches 83.4% for the cone target compared to 65.8% for the flat target. In the high intensity case, laser intensity reaches a maximum of 2.4×10^{21} W/cm^2 in the tip of the cone (6×10^{20} W/cm^2 for the flat target), highlighting the micro-focusing effect of the cone. The longitudinal electric field, the one accelerating the protons, reaches in this case 100 TV/m (17 TV/m for the flat target). In the low intensity case, laser intensity reaches a maximum of 4.3×10^{18} W/cm^2 for the cone (7×10^{18} W/cm^2 for the flat target) with a longitudinal electric field at 5 TV/m (3.6 TV/m for the flat target). In the low intensity case, the large preplasma present in both cases tends to give similar laser parameters evolutions, similar electric fields and a moderate increase of maximum proton energy. In the high intensity case, the laser intensity and the longitudinal electric field reach significantly larger values in the cone leading to an important increase in maximum proton energy. Note here that as the laser intensity increases, very often, so does the prepulse. It also becomes more difficult to contain the entire laser energy in the focal spot. In the case of having best focus toward the base of the cone, all the laser energy gets in and gets micro-focused by the cone shape into the tip. Additional studies need to be performed to further quantify the divergence, the effect of the pulse duration, laser intensity and prepulse.

4. CONCLUSION

In conclusion, we show that a new conical target shape has the potential to produce proton beams of a higher maximum energy and a lower divergence. Because of the appropriate use of the cone structure itself, by using the faces leading to the tip, nor the laser imprint or the focal spot size have an impact on the particle beam characteristics. The contrast of the laser can also be mitigated and finally the f-number of the focusing optic is superseded by that of the cone target itself. All these parameters increase the potential for various groups to join in the research endeavor and pursue exciting new applications.

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