Proton acceleration from ultrahigh-intensity short-pulse laser-matter interactions with Cu micro-cone targets at an intrinsic \(\sim 10^{-8}\) contrast

S. A. Gaillard\textsuperscript{1,2}, K. A. Flippo\textsuperscript{2}, M. E. Lowenstern\textsuperscript{3}, J. E. Mucino\textsuperscript{3}, J. M. Rassuchine\textsuperscript{1}, D. C. Gautier\textsuperscript{2}, J. Workman\textsuperscript{2} and T. E. Cowan\textsuperscript{1}

\textsuperscript{1} Forschungszentrum Dresden-Rossendorf, P.O. Box 510119, Dresden, Germany
\textsuperscript{2} Los Alamos National Laboratory, P-24, MSE526, Los Alamos, NM, USA
\textsuperscript{3} Atmospheric, Oceanic & Space Sciences, University of Michigan, Ann Arbor, USA

Corresponding author: sandrine.gaillard@gmail.com

Abstract. In this paper, we report on experiments comparing various geometries of conical Cu targets to Cu flat foils, which were performed on the 200 TW Trident laser (\(\sim 80\) J, 600 fs, \(\sim 7\) \(\mu\)m spot size, S-polarization and \(\sim 1.5\times10^{20}\) W/cm\(^2\)) at an intrinsic (to the system’s regenerative amplifier) ASE contrast of \(10^{-8}\). The current work builds on previous results obtained on Trident (\(\sim 20\) J, \(\sim 14\) \(\mu\)m spot size, P-polarization, \(\sim 10^{19}\) W/cm\(^2\), also at the intrinsic contrast of \(10^{-8}\)) demonstrating enhanced proton energies and laser-proton conversion efficiencies (\(\eta\)) using Flat Top Cone (FTC) targets \cite{1}. An electron spectrometer and a Cu K\(\alpha\)/g302 imaging diagnostic were added to respectively assess the electron population, and determine the characteristics of laser absorption in FTCs. Results indicate a linear correlation between electron temperatures and proton energies, as well as laser absorption taking place in a preplasma filling the cone, preventing the previously observed enhancement in proton energies.

1. Motivations and introduction

In previous experiments performed on the Trident laser at \(\sim 20\) J and at the intrinsic \(10^{-8}\) contrast, we found that flat-top cone (FTC) targets yielded an increase in proton energy from 19 MeV to \(>30\) MeV and in laser-proton conversion efficiency (\(\eta\)) from 0.5 % to 2.5 %, as compared to flat-foil targets \cite{1}. These results could be due to improved laser guiding toward the cone tip, which would yield higher laser intensities and hotter electrons. Improved electron production and transport can lead to an increase in the electron density and temperature at the flat-top. In addition, a longer electron confinement on the flat-top can lead to reduced mass target (RMT) effects such as resistive/confining edge fields and enhanced target/top charge up. Finally, when the laser is misaligned and cannot reach the cone tip, or is absorbed farther from the flat-top due to an excess in preplasma, the proton acceleration is neither as efficient nor as energetic.

The experiment described here was performed after the Trident laser energy upgrade from \(\sim 20\) J to \(\sim 80\) J to verify whether the enhanced proton energy would scale with laser energy and whether the predictions (from simulations) concerning the effect on the preplasma level in the FTC neck were correct \cite{1}. To diagnose the laser absorption zone inside the FTC, Cu targets were used, as well as Cu-K\(\alpha\) 2D imaging. Indeed, if the lower energy end of the hot-electron population deposits its energy in the FTC neck, then K\(\alpha\)-x-ray emission is direct indication of preplasma filling the cone tip \cite{2}. In
this paper, we show that, with this laser energy enhancement, the spot size decrease (due to the addition of a deformable mirror) from ~14 μm down to ~7 μm FWHM (with 47 % of the energy in the spot), and the resulting intensity increase from ~10^{19} W/cm^{2} to ~10^{20} W/cm^{2}, at the intrinsic contrast level, the laser is able to propagate to the top of both the FTC and the Funnel Cone (FC) targets, i.e. Cu Kα emission is observed from the cone tip. However, most of the emission originates at the cone walls (i.e. cone wall emission or CWE is predominant), due to a relatively large preplasma. This preplasma prevents the laser from being efficiently absorbed closer to the cone tip [2, 3]. The hot electron population is generated in the preplasma region, and not close to the flat-top. This negatively impacts the proton acceleration, especially in the case of thin FTC necks [1]. Electron spectroscopy indicates that the temperature of the escaping electrons correlates linearly well with proton energy.

A more recent experiment performed on Trident with an enhanced contrast (>10^{-10}) shows that proton energies are increased to 67.5 MeV at only ~80 J of laser energy [4], versus previous petawatt laser records of 58 MeV at ~400 J. It also shows that not only is it crucial to obtain laser absorption at the tip (note that tip heating is dependent on laser contrast and intensity [2]), but it is even more important to find the optimum balance [4] between CWE wall versus top emission (TE).

2. Description of the targets and of the experimental set-up
The experimental set-up and diagnostics are pictured in Figure 1 (left). The various cone targets shown in Figure 1 (right), i.e. funnel cones (FC) (a-c) and an FTC (d), as well an RMT that were the ~10 μm thick, 300 μm diameter broken-off tops of FTCs (d-2), were all shot at normal (0˚) incidence. Regular large flat foils (2×7 mm^2 for all target thicknesses, except the 1 μm case which was ~1×1 mm^2) were shot at 22.5˚ incidence to avoid back-reflections and damage to the focusing parabola.

Figure 1: (left) Set-up of the Aug. 2008 Trident Cone beamtime; (left inset) actual image of an FTC target shot (Photo credit: J. S. Cowan); (right) Various geometries of cone targets shot, i.e. 3 types of FCs (a-c): (a) pure Cu (b) 500 nm of Ti above the Cu, (c) 500 nm of Ti above and below the Cu; and FTCs (d). RMTs were also shot, which were the broken-off tops of the FTC (d-2).

3. Proton energies, conversion efficiencies η, and Cu Kα emission of the various targets
Table 1 shows proton energy ranges and η (using RIS [5] on a MicroD) for various target geometries. Note the ~5 MeV variation in the maximum proton energy from 10 μm thick flat foils between shots with similar laser energies; and the much greater deviation (i.e. ~10 MeV) for the RMTs with fairly constant laser conditions. The proton energies reported in Table 1 are the energies of the proton beams accelerated from the target via the target sheath normal acceleration (TNSA) mechanism, observed with RadioChromic Film (RCF) stacks, and in the case of cone targets, accelerated from the top of the cone. This top beam, emitted normally from the top of the FTC or the FC, is almost always
round and uniform; while the side beam, emitted from the cone walls, tends to emit as an annular non-uniform spray and is ignored, given that the electrons involved do not reach the spectrometer.

Table 1: Proton energy ranges and conversion efficiencies \( \eta \) for flat-foil targets and cone targets.

| Target type | Thickness | Proton energy variation | range J, shot number; or e.g. | Respective \( \eta \) |
|-------------|-----------|-------------------------|-------------------------------|------------------|
| Flat        | Large     | 1 μm – 150 μm           | 58.5 MeV [6] – ~25 MeV         | 90 J, 20549 – 97 J, 20542 | 3.73 % – 1.32 % |
|             | Large     | 10 μm                   | ~50 MeV to ~55 MeV             | 92 J, 20534 to 94 J, 20537 | 1.35 % & 1.6 % |
|             | RMT       | 10 μm                   | ~32 MeV to ~44 MeV             | 88 J, 20552 to 82 J, 20508 | 2.15 % & 2.12 % |
| Cone        | FC        | 10 μm                   | ~12 MeV to ~47 MeV             | e.g. 26.7 MeV at 76 J, 20518 | 0.79 % |
|             | FTC       | 10 μm                   | ~5 MeV to ~30 MeV              | e.g. 27.8 MeV at 86 J, 20532 | 1.62 % |

Usually, when the laser is misaligned (Figure 2 (left)), the side beam is more energetic than the top beam, but never greater than that from a flat foil (i.e. in the best case, see Figure 3(b), >47.2 MeV compared to 55 MeV). Top beams are always accelerated from the tip of FCs, unless the neck diameter is too small (<~ 20 μm outer diameter neck), and/or the neck is too long, such that, even when the laser is well aligned, no proton beam can form off the tip and there only is all the proton emission comes from the walls (Figure 2 (right)). As the neck becomes larger (~25 μm), the top beams are accelerated to higher proton energies, and the ratio of the top beam / side beam proton maximum energies increases.

Figure 2: (left) Shot 20515, FC, laser misaligned, \( E_p \) side beam > \( E_p \) top beam; (right) Shot 20512, FC, laser aligned, neck too small such that there is no normal proton beam emission at high energy.

Figure 3 compares Cu Kα images and RCF stacks obtained from two FCs and an FTC. In the aligned cases (Figure 3(a)&(c)), Cu Kα imaging confirms that the cone is filled with preplasma, and thus the laser penetrates poorly to the tip. However the protons are accelerated in nice, uniform top beams, but with no proton energy increase. Note in (c) that the fairly strong electron beam emitted from the flat top in the normal direction does show the presence of hot electrons, mainly in the same direction as the protons. Also, even if the laser is aligned and reaches the tip, yielding Cu Kα TE, it does not mean that the proton energy will be enhanced. This suggests there has to be the right balance of CWE and TE [4], which is unachievable in the intrinsic contrast case, where CWE >> TE. In Figure 3(b), Cu Kα imaging confirms that the laser misalignment is responsible for the proton side beam. The top beam is hard to distinguish (2\(^{nd}\) to last detector on the 2\(^{nd}\) row of RCFs) and has a relatively low energy (27.8 MeV), while the side beam is very energetic (> 47.2 MeV). Lastly, the
very energetic oblique (upper left to lower right) cone wall spray from the FC indicates that the electrons born on the cone wall are emitted normal to all its length.

4. Correlation between electron temperature and proton energy

Figure 5 (left) shows the electron population from the electron spectrometer [7] as well as how the lower (T₁) and higher (T₂) electron temperatures are obtained. In the case of the cones (Figure 5 (right)), the average of the lower and higher temperatures (T₁+T₂)/2 correlates better linearly with proton energies (of the top, not the side, beam) rather than T₁ alone. For the flat foils (various thicknesses), the proton energies are higher, but there is a much weaker linear correlation with electron temperature (not shown here). In all cases, the linear correlation between proton energy and electron temperature is in agreement with the Wilks scaling [8].

Figure 5: Electron temperatures as a function of proton energy: (left) example of an electron spectrum: T₁ is obtained using the red data points, T₂ using the orange ones; (right) T₁ and (T₁+T₂)/2 temperatures of the various cones. The T₁ values are represented by the smaller data points (lighter colored trendline). The (T₁+T₂)/2 values are represented by the larger shadowed data points (darker purple trendline).

5. Summary

The four-fold increase in laser energy from ~ 20 J to ~ 80 J at the intrinsic 10⁻⁸ contrast seems to considerably increase the plasma pre-fill inside the FTC, as indicated by the Cu Kα x-ray absorption images. This prevents further proton energy enhancement even with higher laser energy and FTC targets. In terms of proton energy, flat foils actually perform better than aligned or misaligned FTCs. To obtain an increase in proton energy at ~ 80 J, a higher contrast must be used [4]. The FTC proton energies appear to correlate well with the electron temperatures, suggesting that the electron acceleration in a plasma-filled cone is not of sufficient temperature to support higher energy ions.

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