Beam profiles of proton and carbon ions in the relativistic transparency regime

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Abstract. Ion acceleration from relativistic laser solid interactions has been of particular interest over the last decade. While beam profiles have been studied for target normal sheath acceleration (TNSA), such profiles have yet to be described for other mechanisms. Here, experimental data is presented, investigating ion beam profiles from acceleration governed by relativistic transparent laser plasma interaction. The beam shape of carbon C\textsuperscript{6+} ions and protons has been measured simultaneously with a wide angle spectrometer. It was found that ion beams deviate from the typical Gaussian-like shape found with TNSA and that the profile is governed by electron dynamics in the volumetric laser–plasma interaction with a relativistically transparent plasma; due to the ponderomotive force electrons are depleted from the center of the laser axis and form lobes affecting the ion beam structure. The results are in good agreement with high resolution three-dimensional-VPIC simulations and can be used as a new tool to experimentally distinguish between different acceleration mechanisms.

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1. Introduction

For more than a decade, intense short pulse lasers have been used to drive energetic ion beams [1–7]. These ion beams have compelling properties: high particle numbers of up to $10^{13}$ ions per laser pulse, energies up to several tens of MeV amu$^{-1}$ [8] (typically in an exponentially decaying energy distribution) and a low transverse emittance [9]. These properties are encouraging for advanced applications with laser-driven ion beams, including ion fast ignition [10, 11], hadron cancer therapy [12] or threat reduction (e.g. detection of fissile material) [13]. To date, the most extensively explored mechanism is the target normal sheath acceleration (TNSA) [1–3], where a laser beam with an intensity exceeding $10^{18}$ W cm$^{-2}$ is focused on $\mu$m-scale targets. Quasi-electro-static fields of order TV m$^{-1}$ at the rear and front of the target drive ions to tens of MeV. Recent increases in laser intensities and contrast allowed the exploration of acceleration with sub-micron targets, where high laser contrast reduces premature heating and prevents subsequent destruction of nm-scale targets prior to the arrival of the peak pulse. Simulations and recent experiments have shown improved efficiency, higher ion energies and the possibility of accelerating heavier ions. The break-out afterburner (BOA) [14–17] mechanism relies on a nm-scale target becoming relativistically transparent during the main interaction with a high contrast, short pulse laser with relativistic intensities well in excess of $10^{19}$ W cm$^{-2}$. Another promising mechanism, the radiation pressure acceleration (RPA) [18–22] takes an alternative approach, relying on the target staying mostly reflective and opaque to the laser light during the interaction. The whole target can then accelerate as light sail pushed by the laser. While the structure of TNSA beams has been studied in detail, the same is not true of these other mechanisms.

Here, we present experimental data comparing ion beam structure for TNSA and BOA accelerated carbon ions and protons. We use an ion wide-angle spectrometer (iWASP) to simultaneously measure proton and carbon C$^{6+}$ spectra with angular range covering approximately 25°. The results are in good agreement with high-resolution three-dimensional (3D)-PIC simulations and are consistent with theoretical predictions for acceleration in the BOA regime. Unique, distinct beam signatures have been identified that can be used to distinguish between different acceleration mechanisms. These results are necessary for designing advanced applications, especially when relying on (post-acceleration) tailoring and/or transport [23] of the laser-driven ion beams. In particular, for laser-based hadron cancer therapy, it may be necessary to guide the ion beam away from the main interaction to clean it from other particles,
**Figure 1.** (a) Sketch of experimental setup and geometry of wide angle spectrometer measurements. Measurements are taken along either the vertical or horizontal slit position marked in ‘ion beam front view’. (b) Typical iWASP spectrum with angular range of approximately 25°. The center of the laser beam propagating through the target onto the detector defines 0° in the spectrum.

γ- and x-ray radiation; this requires detailed knowledge of the initial ion beam structure and properties.

2. Experimental setup

The experiments have been carried out at the Los Alamos National Laboratory Trident laser facility [24]. In short pulse mode, Trident can produce a 550 fs, 80 J pulse at 1.053 μm. An f/3 off-axis parabolic mirror is used to focus the linearly polarized beam. The on-target focus has been measured to be ~6 μm in radius (1/e²-condition, containing > 60% of the laser energy) with a peak intensity of 5 × 10²⁰ W cm⁻². The laser pulse duration and beam parameters were carefully recorded during the whole campaign. Thin, free-standing, artificially grown diamond foils with thicknesses from 30 nm to 5 μm were used to generate ion beams in both the TNSA and BOA regime. Trident has an exceptionally high temporal laser contrast of 10⁻⁷ at −4 ps (relative to arrival of the main pulse) and this enables interaction of the peak laser pulse with a highly overdense target even for nm-thicknesses (N ≫ 1, with N = nₑ/nₑ and nₑ the electron density and nₑ = mₑω₀²/(4πe²) the critical electron density); see figure 1(a)) for a sketch of the setup.

In order to analyze the ion beam profiles, both carbon ion and proton spectra were measured simultaneously. Since commonly used stacks of radio-chromic film are not feasible for simultaneous detection of carbon and proton spectra with high energy resolution due to the hugely different stopping power, here we used the iWASP described in [25]. The iWASP is a spectrometer based on particle deflection in a wedged magnetic field of order 0.4 T; species separation is achieved by exploiting the hugely different stopping power of carbon ions and protons in a stacked detector. The detector consists of a 32 μm Al layer for laser light shielding, followed by a 1 mm thick CR39-plate [26] and then a standard BAS-TR image plate (IP) [27]. The CR39 is used to detect carbon ions above 33 MeV (the energy needed to pass the Al layer); it is ‘transparent’ to protons above 11 MeV, i.e. protons above that energy leave no countable

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6 Applied Diamond Inc. (www.usapplieddiamond.com).

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tracks on the CR39 (unless etched for several hours). The IP is used to detect protons above 11 MeV (the energy needed to pass the Al-layer and the CR39). Carbon ions above 230 MeV are not stopped within the CR39—though they still leave tracks in it—and will also be detected on the IP. In the configuration used here, the iWASP has a lower instrument resolution of \( \ll 100 \mu \text{rad} \) and of 5% for protons and 8% for carbon \( \text{C}^6^+ \) at energies 50 and 40 MeV per nucleon, respectively. For the ion energies measured during this experiment, the detector setup and magnet dispersion gave a clear separation of the proton and carbon signal, i.e. no overlap of their signals on either the CR39 or the IP (see [25] for details).

It should be noted that the iWASP has no electric field and cannot resolve different charge states of carbon ions. Measurements using Thomson parabolas have shown that for the laser conditions employed, sub-micron targets have a high degree of carbon ionization; \( \text{C}^6^+ \) is typically the dominant charge state (see [25]). For thicker targets (\( \gg 500 \text{ nm} \)), where TNSA is dominant, lower carbon charge states are also accelerated and detected and the overall \( \text{C}^6^+ \) abundance is significantly reduced. Here, for the purposes of investigating general angular properties of the ion beams, we shall assume that all carbon ions are \( \text{C}^6^+ \). This approach is justified by the fact that distinct features only appear for thicknesses where ionization into \( \text{C}^6^+ \) is very high (see figures 3(b) and 6(a)).

It should furthermore be noted that analyzing angular beam properties with common Thomson parabolas [28, 29] with a satisfying accuracy is very challenging due to their very limited solid angle. In our setup, the iWASP covers a solid angle of 0.4 msr, 3–5 orders of magnitude higher than conventional Thomson parabolas. Spectra are measured covering an angular range from \(-2.5^\circ \) to \(22.5^\circ \) in a plane either parallel or perpendicular to the laser polarization axis (see sketch in figure 1(a)); \(0^\circ \) corresponds to the laser propagation axis.

3. Relativistic transparency regime acceleration

Using the Trident laser with intensities of \( 10^{20} \text{ W cm}^{-2} \), diamond targets with thickness less than \( \sim 700 \text{ nm} \) become relativistically transparent during the peak laser interaction; with Tridents contrast and a target density of \( \sim 3 \text{ g cm}^{-3} \), conditions for relativistic transparency are readily met for these thicknesses, where \( N/\gamma \lesssim 1 < N \) with \( \gamma \) the electron Lorentz factor [30]. (Note that because significant target heating occurs prior to relativistic transparency, our condition for the onset of transparency is based on the electron thermal Lorentz factor and not on laser intensity \( a_0 \) as reported by Vshivkov et al [31]; the former condition is found to be in good agreement with our PIC simulations of the BOA.) We found that in this thickness range, the BOA mechanism [32] is operative. In particular, the initial laser penetration into the target is limited to the skin depth \( l_s \propto c/\sqrt{\pi e} \). As hot electrons are produced in the laser field at the front side and the target starts expanding longitudinally along the laser propagation axis, the electron density decreases, while the Lorentz factor increases. The laser evanescent field thus reaches deeper into the still opaque target, further enhancing hot electron generation. For a sufficiently thin target, the laser eventually converts all electrons into a hot electron population with highly relativistic energies through this process of volumetric heating and the target turns relativistically underdense. Relativistic transparency is the most prominent characteristic of the BOA mechanism, and also marks a boundary condition to where RPA cannot be operative anymore. Note that when transparency occurs, the plasma reflectivity \( R(\omega) \) drops substantially and the radiation pressure (and thus the efficiency of the RPA) decreases significantly [33].
Figure 2. Plasma evolution for Trident relevant parameters as seen in a 2D-VPIC simulation (see [34] for simulation details). Plotted is the electron $\gamma_e$ (red), electron density $n_e/n_{cr}$ (blue) and normalized laser amplitude (green) as a function of time. After $t_1$ the plasma is classically overdense, yet relativistically transparent with $n_e/n_{cr} < 1$. After $t_2$ the plasma turns classically underdense with $n_e/n_{cr} < 1$.

In the BOA, on the other hand, the laser energy is dominantly transferred to the ions between time $t_1$, when the target becomes relativistically transparent, and time $t_2$, when peak target density relaxes to the non-relativistic critical density [34]. These dynamics are depicted in figure 2. Before $t_1$, an electric field $E_x$ determined by the distribution of hot electrons produced at the front side of the target accelerates the ions. In the simulations, ions gain approximately 10% of their final kinetic energy until $t_1$ [34]. Between $t_1$ and $t_2$, when the target is relativistically transparent, electrons accelerated toward the rear of the target in the intense laser field set up a strong longitudinal electric field that co-moves with the ions accelerating them to extreme energies. In this period, the laser volumetrically interacts with the whole target and laser energy is efficiently mediated to the ions through the electrons.

A plausible explanation for how this occurs was advanced by Albright et al [15], who proposed that a beam-plasma instability from a relativistic, drifting electron population (in this case, with the drift induced by the laser) could generate an unstable plasma mode characterized by the growth of large-amplitude, longitudinal electric fields that co-propagate with the ions. The Buneman instability has been studied extensively in non-relativistic plasma, including laboratory and space settings ([35], also Reitzel and Morales [36]). In the non-relativistic plasma literature, the Buneman instability is known to be one of the fastest growing instabilities in plasma, growing so rapidly that it is actually considered a reactive quasi-mode, a condition when the instability growth rate is comparable to or exceeds the real part of the frequency; the mode has a rather low phase speed and in both the non-relativistic and relativistic cases, efficiently transfers momentum from drifting electrons to ions. Unlike space settings or laboratory plasma, in the BOA, the laser can continue to impart forward momentum to the electrons (and thus the ions).
When the target eventually becomes classically underdense (at time $t_2$) acceleration of ions decreases significantly due to the low coupling efficiency of laser light into the low density plasma. For fixed laser parameters, these times are strongly target thickness dependent. For too thin a target, $t_2$ is reached before arrival of the peak pulse, limiting energy transfer and hence acceleration of ions via the BOA mechanism. For too thick a target, $t_1$ will come after the peak pulse arrival (or not at all for very thick targets). Optimal ion acceleration is obtained when the peak laser intensity falls within a time window between $t_1$ and $t_2$.

It should be noted that whether the Buneman instability is indeed the dominant mechanism for the energy transfer has not been determined unambiguously and this is subject for future study.

Self-cleaning [14] occurring early during the acceleration typically causes most protons to be removed from the target prior to the main acceleration phase. Electrostatic fields present throughout the interaction accelerate protons the most due to their high charge to mass ratio [37–39]. In thin nm-scale targets, this can lead to bulk protons being effectively removed from the target early in the interaction as seen in PIC simulations; this effect is even more pronounced with targets where the initial bulk proton concentration is very low and when protons are only present on the surface due to contamination.

For thicknesses exceeding $\sim 500$ nm, the intensity and pulse duration of the focused Trident laser is insufficient to turn the target relativistically transparent and $N/\gamma > 1$ throughout the whole peak laser pulse interaction. Acceleration is then mostly governed by the TNSA mechanism; electrons heated in the laser field on the front side of the target set up quasi electrostatic fields on the front and rear side of the target and accelerate ions normal to the surface. Here, protons, accelerated first due to their low inertia and high charge-to-mass ratio, shield the longitudinal electric fields to heavier ions and impede their acceleration as compared with the BOA mechanism.

4. Experimental results

To identify the angular ion beam structure, the iWASP has been used in two configurations, ‘vertical’ and ‘horizontal’, i.e. parallel and perpendicular to the laser polarization axis (see figure 1(a)). A typical spectrum is shown in figure 1(b); the high resolution, angularly resolved proton spectrum was obtained from a 150 nm diamond target, measured in the horizontal plane of the ion beam (intensity is color coded and in PSL MeV$^{-1}$ msr$^{-1}$ where PSL is the photo stimulated luminescence of the IP). In order to visualize the angular dependence in terms of the ion flux, the measured spectra have been integrated along the energy axis. Figure 3 shows the measured integrated particle numbers $n_i$ for different target thicknesses (55 nm, 190 nm, 600 nm and 25 μm) for protons (a) and for carbon C$^{6+}$ (b). Integrated spectra measured in the horizontal plane are shown from $0^\circ$ to $22.5^\circ$; the corresponding spectra for the vertical plane are not shown as they yield no significant differences. In fact, we found that in over 100 shots the general angular ion flux is almost independent of the measured plane for equal thicknesses, indicating a rotational symmetry of the ion beam around its center (0$^\circ$ in the spectra) for most energies. For this reason, spectra have been mirrored with respect to 0$^\circ$ on to the negative angle axis as a guide for the eye.

However, for different target thicknesses and hence different acceleration mechanism, the ion flux yields significant differences in its shape. Starting with a thickness of 25 μm (red solid line with triangles), where acceleration is purely TNSA dominated, a Gaussian-like distribution
Figure 3. Integrated particle numbers as a function of the angle for different target thicknesses for protons (a) and carbon ions (b). The measurement is from 0° to 22.5°; as a guide for the eye, the measurement has been mirrored to the negative angle region (shaded area, see text for details). Particle numbers for protons are in PSL. Typical angular distributions are shown for sub-optimal BOA targets at 55 nm (yellow squares), an optimum BOA target at 190 nm (blue stars), mixed dynamics target at 600 nm (green circles) and a target for pure TNSA interaction at 25 µm (red triangles). The table lists the integrated number of particles measured in the spectrometer for each of the spectra.

| Target Thickness | Proton (PSL) | Carbon |
|------------------|-------------|--------|
| 55nm             | 2.80E+06    | 1.13E+08 |
| 190nm            | 3.88E+07    | 3.12E+08 |
| 600nm            | 2.63E+07    | 2.82E+08 |
| 25µm             | 1.32E+07    | 4.68E+07 |

can be seen for the carbon and proton beams. For both the flux peaks at 0°, which agrees well with previous results on TNSA showing acceleration normal to the target surface [40]. It can also be seen that acceleration of carbon ions is strongly suppressed and TNSA works dominantly on protons due to their high charge-to-mass ratio and low inertia. In particular, the proton beam half-angle is 20°, twice as large as for carbon ions and the total number of accelerated carbon ions is very low, almost a factor of 10 less than with thinner targets.

Around 600 nm, the laser is still unable to penetrate the whole target and turn it relativistically transparent [30]. Acceleration is likely to be a mix of early-phase BOA and TNSA (also called enhanced TNSA); a significant fraction of the target electrons is already subject to intense heating by the laser. For this thickness, the carbon ion beam cone angle is doubled and is similar to that of the proton beam; the number of accelerated particles increased by a factor of 6 (see table in figure 3). At the same time, proton numbers only doubled; assuming that the main source of protons is surface contamination, their total number can be considered to be mostly independent of the original target thickness. More interestingly, at about ±10°, wings appear that break the Gaussian-like character of the angular distribution obtained with micron-thick targets. With 190 nm thickness, the target is within the optimum thickness range for the BOA mechanism using the Trident laser; the target is relativistically transparent (yet classically overdense) for most of the peak pulse interaction, with $N/\gamma < 1 < N$ [32, 34].
Figure 4. Integrated particle numbers as a function of the angle for different energy bands for carbon C\textsuperscript{6+} ions. The measurement is from 0° to 22.5° and 190 nm of diamond as shown in figure 3(b)) for all energies. Shown are plots (from left to right) for particles with energy between 30 and 100 MeV (black), 100 and 150 MeV (red), 150 and 200 MeV (blue) and energies above 200 MeV (orange).

(Measurements of the target transparency are shown and discussed in detail in [30].) Numbers of carbon ions have increased by a factor of 8 over the ion numbers obtained at 25 μm where TNSA is dominant, while the number of available carbon ions in the focal volume (with constant area) of the target has been reduced by a factor of 130 (measurements have not shown a significant increase of the source size with changing target thickness [32]). At this thickness, the wings are most pronounced. While for protons, the particle flux still peaks at 0°, for carbon ions, peak particle numbers within the wings exceed numbers on-axis. This is shown in more detail in figure 4 where integrated numbers for carbon C\textsuperscript{6+} for this shot (190 nm) are shown for different energy bands rather than all energies. Integrated particle numbers are shown for particles with energy between 30 and 100 MeV (black), 100 and 150 MeV (red), 150 and 200 MeV (blue) and energies above 200 MeV (orange). For all energy bands the ring structure is retained, while particle numbers significantly decrease on-axis with increasing energies. This distinct feature of the BOA mechanism is discussed in more detail in the next two sections.

For thicknesses around 55 nm, the target turns relativistically transparent very early in the rising edge of the main pulse [30]; acceleration with the BOA mechanism is thus less efficient as the target expands and turns classically underdense with \( N < 1 \) well before the peak pulse interacts with the plasma [34]. For both species, the opening angle is reduced to 10–15°. Proton numbers have dropped by a factor of 10 and carbon numbers by a factor of three.

4.1. Theory and simulations

For a simple, heuristic explanation of the wings appearing at ±10° in the optimal BOA target thickness range consider the motion of a single electron in a tightly focused, relativistic laser beam. The electron is expelled from the laser focus by the ponderomotive force of the linearly polarized laser pulse. The collective expulsion of electrons then leads to radial electrostatic fields and ions accelerated in these fields will carry away this information with a finite angular spread. Especially when working with targets on the nm-scale, target denting is likely to contribute to the angular spread as well.
Figure 5. (a)–(d) 3D-VPIC simulation results of BOA at time $t = 180.9$ fs during the relativistic transparency. Panel (a) shows isosurfaces of C$_{6}^{+}$ energy between 400 and 700 MeV at time $t = 241$ fs = $t_2$ and the laser at the center. Note that the geometry is rotated by 90° with respect to the experiment indicated by the labels for ‘horizontal’ and ‘vertical’. The laser polarization is along the arrow marked with ‘vertical’. (b)–(d) ($x = 6–7$ µm), (c) ($8–9$ µm) and (d) ($9–11$ µm); (b1) to (d1) show averages of $n_e$ and in (b2) to (d2) is the kinetic energy for carbon C$_{6}^{+}$ $E_k$ displayed.

Figure 5 shows results from a 3D simulation of the BOA. Simulation parameters are close to Trident parameters, but use a shorter pulse duration to facilitate computing time within available bounds. The simulation is rotated by 90° with respect to the experiment and is carried out in a spatial volume $20 \times 25 \times 25$ µm with $n_e/n_{cr} = 660$ initially. The laser pulse has a duration of $\tau_{\lambda} = 312$ fs, is polarized along the white arrow in (a) marked with ‘vertical’ and has a Gaussian profile $E_y \sim \exp[-(y^2 + x^2)/w^2]$, where $w = 4$ µm. The simulation cell size is $1.7\lambda_D$ (5.95 nm) in $x$ and $3.4\lambda_D$ (11.9 nm) in $y$ and $z$; 14 $\times$ 10$^9$ cells and 21 $\times$ 10$^9$ particles are used (500 particles per cell for each species); more details can be found in Yin et al [41]. Figure 5(a) shows a frame at $t = t_2 = 241$ fs with carbon C$_{6}^{+}$ between 300 and 700 MeV (see colormap) and the laser field in the center. Frames (b)–(d) show cut-planes from this snapshot orthogonal to the laser axis at different distances $x$ to the original position of the irradiated target. Upper panels (b1) to (d1) show electron densities and the lower panels (b2) to (d2) carbon C$_{6}^{+}$ ion densities. Panels (b) are averaged over $x = 6–7$ µm, panels (c) over $x = 8–9$ µm and panels (d) over $x = 9–11$ µm with the original target position at $x = 3$ µm and hence show densities at different energy ranges. Panels (b) and (c) show a ring structure with a clear azimuthal/rotational symmetry of the beam with an opening angle of about 15°, which is in good agreement with our experimental results. The electron density plots have an area of strong depletion in the center, which is imprinted onto the ion beam. The results are in good agreement with the particle plots in figure 3 that show the same signature for targets in the optimum BOA thickness range.

4.2. Angular energy dependence

Another detail, visible in panel (d2), which represents the most energetic carbon ions, is a broken azimuthal symmetry. The ring structure is not closed along the polarization axis of
Figure 6. Overall maximum energies (red triangles) and cutoff energies seen on-axis at 0° (blue circles) for carbon C\textsuperscript{6+} ions (a) and protons (b). For protons maximum energies are emitted on-axis regardless of the target thickness, whereas maximum carbon ion energies are emitted off-axis in BOA (≪ 1 µm) and on-axis in the TNSA regime (> 1 µm).

The laser (note that the simulation is rotated by 90° with respect to the experiment). Hence, the most energetic ions are piled up off-axis, perpendicular to the laser polarization axis. This is caused by a symmetry break in the radial ponderomotive force that leads to a pile up of electrons perpendicular to the polarization axis. An analytical derivation for this effect is given in Yin et al [41]. In short, the perpendicular momentum $\vec{p}_\perp$ of the electrons by the secular (non-oscillatory) part of the ponderomotive force shows a $m = 2$ variation with $\cos(2\theta)$. This variation manifests in a non-azimuthally symmetric radial flow in the electron continuity equation, which leads to a transient period over which electron density lobes form. Successively, fastest ions are accelerated into lobes, too, as observed in the simulation (panels (d1) and (d2)). For the panels (b) and (c), which show slower ions, the symmetry break is canceled by the electrostatic force of the ion background overcoming the electron ponderomotive motion. The symmetry break has been seen in high resolution 3D VPIC simulation for Trident similar parameters (again with a shorter $\tau_\lambda = 312$ fs to reduce computing time) as shown figure 5(a). The snapshot shows iso-energy surfaces of carbon C\textsuperscript{6+} ions with energies between 400 and 700 MeV (see color bar of the figure, lower energies are not shown) and the laser electric field in the center; the time of the snapshot is at the end of the BOA phase when the target has just turned classically underdense with $N < 1$. The particles are gathered almost symmetrically around the laser in a ring-like structure, but the azimuthal symmetry is broken along the polarization axis of the LP laser pulse of the simulation for these energies (white arrow marked with ‘vertical’ in figure 5(a)).

We tested the validity of the simulations by identifying where highest energies have been measured in the experiment. In figure 6, maximum energies from angularly resolved energy spectra for thicknesses of 30 nm–25 µm are plotted; the plots show the maximum energy measured on-axis (blue circles) and the overall maximum energy measured in the entire angularly resolved spectrum between 0° and 22.5° (red triangles) for carbon ions (left frame) and protons (right frame). The measurements reveal that carbon C\textsuperscript{6+} maximum ion energies are emitted off-axis in the optimum BOA thickness range around 200 nm; maximum
energies are typically found between 5° and 15°. In this thickness range, the energies measured on-axis are typically lower by a factor of 2. For targets exceeding 1 µm, where the acceleration starts to be dominated by the TNSA mechanism, maximum energies are emitted on the laser axis at 0°. At the same time, maximum proton energies are always found at target normal at 0° regardless of the target thickness, as depicted in figure 6(b). This is most likely caused by the self-cleaning of the target, which causes the protons to be mostly removed from the main interaction region and thus do not experience the full BOA mechanism dynamics. This angular dependence also shows that measurements of maximum ion energies with conventional Thomson parabolas can be misleading when not picking the ‘optimum’ angle and may result in measuring a maximum energy that is not the global maximum ion energy achieved in the interaction.

5. Summary

We presented a first study of carbon and proton beam profiles from acceleration in the BOA regime and compared the measurements with acceleration in TNSA and also with 3D-VPIC simulations. The results reveal distinct signatures in the beam shape for BOA dominated acceleration. The measured beams for proton and carbon ions indicate a ring-like structure, which is in good agreement with 3D-VPIC simulations. The simulations show that the ponderomotive force of the relativistic laser causes depletion of electrons in the laser focus center and the formation of electron lobes. These lobes are imprinted onto the ion beam, which hence has a ring-like structure with an azimuthal/rotational symmetry around the laser focus center. Highest ion energies are typically emitted off-axis rather than on-axis, a key signature of the BOA mechanism. In contrast, for TNSA dominated acceleration, ion beams have a Gaussian-like distribution with energies and particle flux peaking on-axis. These unique and distinct beam signatures have been examined, indicating a means of distinguishing between different acceleration mechanisms. They are important for designing laser systems for advanced applications, such as hadron cancer therapy or ion fast ignition or any other application where post-acceleration tailoring and transport of the laser-driven ion beams is required. While it remains to be determined how the beam structure changes, when acceleration is dominated by other mechanisms such as the RPA, first theoretical work has already been done, in order to investigate manipulation and control of ion beam structure in the broader BOA scheme. In order to facilitate a less divergent and more collimated beam, Huang et al [42] propose a double target scheme to reduce further broadening of the beam. A flat top intensity distribution could also be envisioned for the BOA scheme to achieve a more uniform beam structure by reducing excessive stripping/depletion of electrons in the center, which could also result in highest energy to be distributed over the entire beam.

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