Carbon ion beam focusing using laser irradiated, heated diamond hemispherical shells

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\textbf{Abstract.} Experiments preformed at the Los Alamos National Laboratory’s Trident Laser Facility were conducted to observe the acceleration and focusing of carbon ions via the Target Normal Sheath Acceleration (TNSA) mechanism using hemispherical diamond targets. Trident is a 200 TW class laser system with 80 J of 1 \( \mu \)m, short-pulse light delivered in 0.5 ps, with a peak intensity of \( 2 \times 10^{20} \) W/cm\(^2\). Targets where Chemical Vapor Deposition (CVD) diamonds formed into hemispheres with a radius of curvature of 400 \( \mu \)m and a thickness of 5 \( \mu \)m. The accelerated ions from a hemisphere were diagnosed by imaging the shadow of a witness copper mesh, located 2.4 mm behind the target, onto a film pack located 5 cm behind the target. Ray tracing was used to determine the location of the ion focal spot. The TNSA mechanism favorably accelerates hydrogen found on the targets. To make the carbon beam detectable, targets were first heated to several hundred degrees Celsius using a CW, 532 nm, 8 W laser. Imaging of the carbon beam was accomplished via an auto-radiograph of a nuclear activated lithium fluoride window in the first layer of the film pack. The focus of the carbon ion beam was determined to be located 630 \( \pm \) 110 \( \mu \)m from the vertex of the hemisphere. LA-UR 09-06918

\textbf{1. Introduction}

The goal of this work was to observe the focused carbon ion beam produced by the TNSA [1, 2] mechanism. The focusing of a high energy carbon ion beam into a micron scale spot size has applications ranging from Inertial Confinement Fusion (ICF) Fast Ignition (FI) to cancer radiotherapy [3]. Carbon ions have a narrower Bragg peak than protons, and thus deposit more energy in a smaller volume. It has also been proposed that a carbon beam could be used to perturb the surface of an imploding ICF capsule. Ion beam acceleration from micron thick, solid targets irradiated by ultra-intense, ultra-short pulse lasers has been studied at great length [4, and references therein]. Experiments have demonstrated that curved foil targets can be used to focus the beam [5]. Most of the work that has been done has concentrated on diagnosing...
the proton beams. This is primarily because of the difficulty in detecting other ion species with detectors like RCF packs. Spectrometers, which can identify different charge to mass species such as Thomson parabola spectrometers, have provided information of the ion beam in small solid angles. The full beam profile has been typically measured using stacks of radiochromic film [6, 7] or nuclear activation [8]. The problem with most of these techniques for detecting ions heavier than hydrogen is that they cannot discriminate between species. Placing filters in front of the detector to block the hydrogen is not possible because protons have a greater range in the filter material than heavier ions.

In this work, Chemical Vapor Deposited (CVD) synthetic diamond targets were irradiated with laser light from the Trident short-pulse beam at Los Alamos National Laboratory. Targets were pre-heated using a CW laser in order to remove water and hydrocarbon contaminants. The abundance of each ion species emitted is highly dependent upon the target surface composition [9, 10, 11]. The CVD targets were hemispheres with a radius of 400 \( \mu m \) and a shell thickness of 5 \( \mu m \). The spatial profile of the resulting carbon ion beam was measured using a novel nuclear activation technique, whereby a 1 \( mm \) thick lithium fluoride plate in the ion beam path reacted with the carbon beam to produce radioactive nuclides. The number of nuclides per unit area is proportional to the incident ion flux, thus the beam profile could be measured via an autoradiograph of the activated LiF plate. Nitrogen-13 produced in the \( ^{12}C \left( Li^7, He^6\right)^{13}N \) reaction provided a means of further distinguishing carbon ions from any remaining protons. Using a witness copper mesh and ray tracing, the focus of the carbon beam was determined to be at 630 \( \pm 110 \mu m \) from the vertex of the hemisphere.

2. Experimental set-up

The experiment was conducted at the Trident laser facility at Los Alamos National Laboratory using the short-pulse beam. The laser is a 200 TW class system which delivers 80 \( J \) on target with a FWHM pulse length of 0.5 ps with a peak intensity of 2 \( \times 10^{20} \) W/cm\(^2\). The wavelength is 1053 nm. The target was positioned so that the focal plane of the \( f/3 \) off-axis parabolic mirror was centered on the outer surface of the CVD diamond shell at normal incidence. A copper witness mesh with a grid spacing of 127 \( \mu m \) was located 2.4 mm downstream of the laser focal plane. A second laser beam was used to heat the target to several hundred degrees prior to the Trident beam firing in order to remove the contaminants. The laser was a Coherent Verdi V18 CW laser with an output of up to 18 W at 532 nm. The beam was focused to a spot size of about 1 \( mm \) and was typically run between 4 W and 8 W for several minutes prior to firing the Trident short-pulse. The heating laser was stopped after the shot was completed.

The principal diagnostic was a film pack which consisted of stacked layers of Gafchromic HD-810 radiochromic film, a 1 \( mm \) thick LiF window and filters made of Kapton polimide film or aluminum foil. The film pack was placed 5 cm behind the target and had diameter of 5 cm. The layers from front to back (front facing the target) were 7 \( \mu m \) of Kapton, 1 \( mm \) of LiF, 90 \( \mu m \) of Kapton, 13 \( \mu m \) of aluminum, 1 piece of HD-810 film, 1 \( mm \) of aluminum and 1 piece of HD-810. The HD-810 film is multi-layered with a 0.75 \( \mu m \) gelatin layer in the front, a 7.5 \( \mu m \) active layer and a 95 \( \mu m \) polyester base. With this configuration, protons had to have a minimum incident energy of 14 MeV to reach the first HD-810 film layer and needed 0.5 MeV to reach the LiF. Carbon ions required 300 MeV and 10 MeV for the same. A Thomson parabola spectrometer was located behind the target and could be used when the LiF/RCF pack was not used. The spectrometer was used to measure the relative abundance of protons in the beam and the effectiveness of heating.

After a shot was complete, the LiF/RCF pack was disassembled so that the LiF layer could be scanned. The LiF was placed in direct contact with a FujiFilm BAS-SR imaging plate in order to auto-radiograph the activation. This method has been used to measure proton beam profiles using copper as the activated plate [8]. The initial time for scanning was 10 minutes.
after irradiation and integrated for about 20 minutes. This time window was chosen because the signature nuclide, due to the carbon beam, comes from the $^{12}C^{12}(Li^{7}, H e^{6})N^{13}$ reaction. The $N^{13}$ is a positron emitter with a half-life of 9.8 minutes. After 10 minutes, all nuclides with half-lives of a minute or less decayed to background levels and longer lived nuclides did not have enough activity to contribute significantly with the exception of $C^{11}$ and $F^{18}$. The production of $C^{11}$ is unlikely. The data could have been confused, however, by the production of $F^{18}$ (half-life of 110 minutes) which can be produced protons. In one scenario, $N^{18}$ would decay rapidly into $F^{18}$ after being produced by the $(p, 2n)$ reaction with $F^{19}$ in the LiF. The $F^{18}$ nuclide could also be produced directly by $(p, d)$ and $(p, p + n)$ reactions. The lowest threshold for these reactions is $8.6 MeV$. Thus, the requirement for heating the targets was that the peak proton energy fall below this threshold. The nuclide abundance during the scan window was determined by simultaneously placing the LiF window and imaging plate between two scintillators and making a coincidence counting measurement of the 511 keV gamma-ray produced by the positron decay. The relative abundance was inferred from the average half-life of the LiF decay.

3. Results and discussion

For targets which were not heated by the CW laser, the proton energies were above $40 MeV$ and made profiling the carbon beam unfeasible. Data from the coincidence counter revealed a typical average half-life of about 1 hour, likely from the decay of $F^{18}$ and $N^{13}$ combined. However, when the target was heated, the average half-life dropped to 10 minutes, consistent with a nearly pure $N^{13}$ decay (figure 1). Thomson parabola data confirmed that when the target was heated the peak proton energy went from the usual $40 MeV$ to $3 MeV$. This is still energetic enough for the $(p, n)$ reaction with $Li^{7}$. However, this produces $Be^{7}$ which has a 53 day half-life and a thousandth of the activity of $N^{13}$. Reasonable fits to the coincidence counting data were achieved with either $97\%$ $N^{13}$ and $3\%$ $Fe^{18}$ or $98\%$ $N^{13}$ and $2\%$ $Be^{7}$.

![Figure 1. Half-life Fits: Heated target shown in gray, blue and dashed green, Unheated shown in dashed red.](image1.png)

![Figure 2. Autoradiograph of the activated LiF from a heated target.](image2.png)

The auto-radiograph from the heated target showed a clear picture of the shadow cast by the copper witness mesh (figure 2). Ray tracing techniques [7] were used to locate the position of the ion beam focus. Figure 3 shows the image collected on the imaging plate and the ray tracing, which matched points on the mesh to points on the image. The point where the rays cross nearest to one another (the solution to the linear least squares problem) was identified as the focus. For a hemisphere with a 400 $\mu m$ radius, the focus was found to be $630 \pm 110 \mu m$ from the vertex of the hemisphere (figure 3). The uncertainty in the position is dominated by the uncertainty in the relative spacing between the target and the witness mesh; assumed to be
within 100 \( \mu m \). This focal distance is consistent with the \( 1.6 \times R \) proton focusing observed in past works [5].

**Figure 3.** Ray tracing from a heated CVD diamond hemisphere. Figure is zoomed so that the target and mesh positions can be seen relative to the ion focus. Purple disks are the plus minus range of the focal position, the orange disk diameter is the maximum radius made by a ray, and the yellow oval is the RMS radius of 35 \( \mu m \).

The edge sharpness of the mesh lines in figure 2 suggests a source size that is between 60 \( \mu m \) and 100 \( \mu m \) in diameter, with the caveat that the source is much larger than the mesh bar size (40 \( \mu m \)). The RMS distance of the rays from the focal point was 35 \( \pm 20 \mu m \). The uncertainty is the standard deviation of radii about the focal point.

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