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Laser-ablation treatment of short-pulse laser targets: Toward an experimental program on energetic-ion interactions with dense plasmas*

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Abstract

This new project relies on the capabilities collocated at Los Alamos in the Trident laser facility of long-pulse laser drive, for laser-plasma formation, and high-intensity short-pulse laser drive, for relativistic laser-matter interaction experiments. Specifically, we are working to understand quantitatively the physics that underlie the generation of laser-driven MeV/nucleon ion beams, in order to extend these capabilities over a range of ion species, to optimize beam generation, and to control those beams. Furthermore, we intend to study the interaction of these novel laser-driven ion beams with dense plasmas, which are relevant to important topics such as the fast-ignition method of inertial confinement fusion (ICF), weapons physics, and planetary physics. We are interested in irradiating metallic foils with the Trident short-pulse laser to generate medium to heavy ion beams ($Z = 20$–45) with high efficiency. At present, target-surface impurities seem to be the main obstacle to reliable and efficient acceleration of metallic ions in the foil substrate. In order to quantify the problem, measurements of surface impurities on typical metallic-foil laser targets were made. To eliminate these impurities, we resorted to novel target-treatment techniques such as Joule-heating and laser-ablation, using a long-pulse laser intensity of $\sim 10^{10}$ W/cm^2. Our progress on this promising effort is presented in this paper, along with a summary of the overall project.

Keywords: Charped-particle sources; Ion beams; Laser-plasma acceleration; Laser-plasma interactions; Plasma-diagnostic techniques

1. INTRODUCTION

This new project involves two important areas presently at the frontier of plasma physics: relativistic laser-matter interactions (Pegoraro *et al.*, 2004; Chirila *et al.*, 2004) and the properties of dense plasmas (Gericke, 2003). The project relies on the capabilities collocated at Los Alamos in the Trident laser facility of long-pulse laser drive, for laser-plasma formation, and high-intensity short-pulse laser drive, for relativistic laser-matter interactions experiments. Presently at Trident, the short-pulse (C) beam may deliver up to ~ 30 J of 1.054 micron light (limited by the compression-grating fluence limit B-integral in the air pulse-compressor) in a pulse as short as 0.5 ps, while each of the two long-pulse beams (A and B) may deliver up to ~ 200 J of 0.527 micron light in ~ 0.1 to 2 ns pulses in conventional operation.

We are working to understand quantitatively the physics that underlie the generation of laser-driven MeV/nucleon ion beams, in order to extend these capabilities over a range of ion species, to optimize beam generation, and to control those beams. We aim to acquire sufficient quantitative understanding to allow effective optimization and control of laser-driven ion beams. We would like to achieve a high conversion efficiency of the laser energy (> 1%) into ion beams with sufficiently high atomic number ($Z > 20$), sufficiently high ionization state ($Z_{eff} > 15$), and sufficiently high directed energy (> 1 MeV/atomic mass unit [AMU]). Beyond our plans, with present-generation lasers using the TNSA acceleration mechanism (explained below), future laser advances promise even better ion-acceleration

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capabilities based on other mechanisms (Shorokhov & Pukhov, 2004).

Furthermore, we intend to study the interaction of these novel laser-driven ion beams with dense plasmas, which are relevant to important topics such as the fast-ignition method of inertial confinement fusion (ICF), weapons physics, and planetary physics. These interactions are sufficiently complex that *ab inito* methods are not likely to be feasible in simulations of realistic experimental systems. Therefore, we are most interested in validating emerging reduced models of the many relevant physical processes. These processes include the atomic physics necessary to describe the evolution of the charge state (Z_{eff}) of beam ions in dense plasmas, such as ionization, charge exchange, and recombination. We anticipate that diagnosing the experiments proposed will be extremely challenging (Renner *et al.*, 2004). We are also interested in validating models for collisions of the beam heavy ions with the lighter background ions (knock-on cascades). Moreover, we need the validation of models describing beam-ion collisions with electrons, which are responsible for most of the beam-energy loss (Gericke & Schlanges, 2003), and likely control the range of the ions in these plasmas. Beam-energy deposition modeling in dense plasmas is most challenging for "slow" ions, that is, MeV/nucleon ions near the end of their range.

Our quest to extend laser-driven acceleration to heavy ions builds on recent work on proton acceleration. As demonstrated at several facilities worldwide (that is, Nova PW, LULI, Vulcan, Trident), the interaction of high-energy sub-ps lasers with foil targets can result in efficient acceleration of protons to multi MeV energies. In the experiments with the highest laser-energy to date, done at the Nova PW laser, an energy conversion efficiency of laser to ions of up to $\sim 10\%$ was observed with gold-foil targets (Snavely *et al.*, 2000). The protons come from impurities adsorbed on the surface of untreated metal foils. Smooth metal-foil targets yield proton beams with an ultra-low transverse emittance, which represents a crucial advantage of using lasers for ion-beam generation. Experiments on Trident have recorded the lowest transverse emittance of a high-current proton beam, 0.0025 π mm-mrad at 8 MeV (Cowan *et al.*, 2004), compared to the more typical $\sim \pi$ mm-mrad of the CERN LINAC injector. On Trident, the dominant proton-acceleration mechanism was characterized (Fuchs, 2004). This mechanism predominantly accelerates protons on the rear surface of the target along the laser-propagation direction, consistent with the so-called target normal surface acceleration (TNSA) mechanism described in one-dimensional (1D) approximation (Hatchett *et al.*, 2000). The laser acts as a source of relativistic electrons (characterized by a "hot" temperature T_{h}) that are pushed forward through the target. These electrons create an electric sheath near the rear surface of the target, with an electric field of order $\sim T_{\text{h}}/e\lambda_{\text{D}}$, where λ_{D} is the Debye length of the relativistic electrons. This electric field ionizes and accelerates preferentially the ion species on the target surface with the highest charge-to-mass ratio. This is typically the light-ion impurities (especially protons, if present), not the ions of the metallic-target matrix.

The next step in harnessing short-pulse lasers to produce beams of heavier ions has been the use of in situ Joule heating to evaporate loosely bound surface impurities that contain hydrogen (Hegelich *et al.*, 2002), first tried on the LULI laser. With such targets, the proton content in the beam (and the energy thus consumed) can be made negligible. Unfortunately, this technique cannot remove other impurities with binding energies in the eV range, such as metal oxides. Therefore, we are left with two alternatives. One alternative is using the few metals that are highly resistant to oxidation, such as Pd. The other alternative is to use an active method to clean the impurities off the target surface in situ, and shoot the short-pulse laser before impurities have a chance to re-stick (in less than 1 s, given the typical $\sim 10^{-6}$ torr vacuum level in our target chamber). We have tried both methods, as described below, and the results are guiding our upcoming experiments.

2. EXPERIMENTAL CONFIGURATION

The experimental configuration is shown in Figure 1. There are two principal diagnostics, which are common in short-pulse laser-plasma experiments nowadays. The first one is a stack of radiochromic film (RCF), which allows a diagnosis

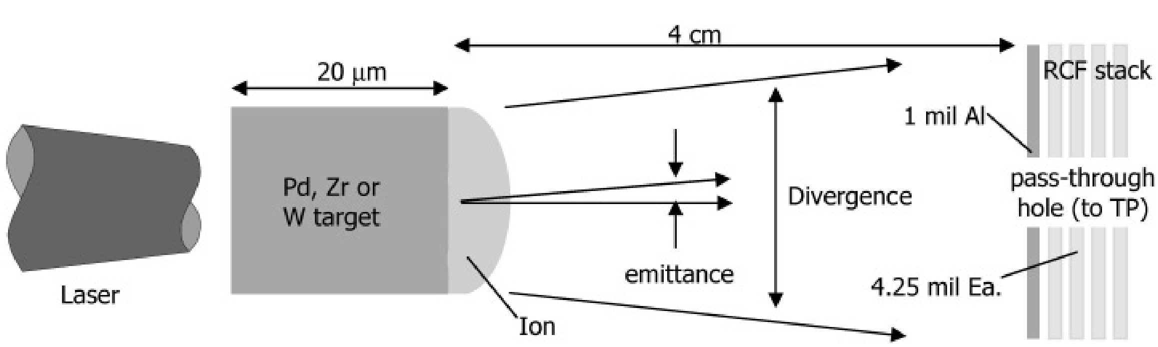

Fig. 1. Experimental configuration used on typical Trident short-pulse experiments.

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of the shape of the ion beam, particularly its divergence. The beam divergence is caused by the radial decay of the TNSA electric field. The divergence is not entropic and can be compensated by strategies such as shaping the target, in contrast to the transverse emittance which is irreversible. The ion ranges in the RCF are such that the typically abundant 10 MeV protons traverse over 10 layers of RCF, whereas a heavy ions range out in the first layer (see Fig. 2).

A hole in the RCF allows a fraction of the ions to pass and to enter the second diagnostic, a Thomson parabola. This instrument subjects the incoming beam to strong transverse electric and magnetic fields (pointing in the same direction) over a length of a few cm. Once past these fields, ions are detected on a flat piece of CR39 plastic. The setup is illustrated in Figure 3. An ion flying through the fields deflects transversely along the electric field, as well as in the perpendicular transverse direction due to the magnetic field. Any ion with a given charge-to-mass ratio is deflected such that its trajectory will intersect the detector surface at a point lying on a specific parabolic curve, regardless of the directed ion energy. The strike point along the parabola is determined by the ion energy. The most energetic ions will be deflected least, lying closest to where an undeflected-ion would hit, at the common base of the parabolas for all charge states.

On Trident, a single shot generates typically 500,000 ion counts on our Thomson parabola diagnostic, typically distributed among 15–20 tracks. These are automatically counted using a high-resolution computer-controlled microscope.

3. CHARACTERIZATION OF UNTREATED TARGETS

The presence of laser-target surface contaminants can be deduced from the ion acceleration results commonly obtained in laser facilities worldwide. However, we are not aware of any prior examples, where the contamination has been actually measured. The area density of contaminant ions on typical foil-target materials (Pd, Zr, and W) was determined at Los Alamos National Laboratory by a diagnostic that relies on Rutherford backscattering of a beam of He^{2+} incident on the target surface. Oxygen and carbon measurement makes use of well known lab specific energies which exceed the Coulomb barrier and offer greater sensitivity. The enhancement for carbon and oxygen using a helium beam occurs at 7.6 and 5.6 MeV, respectively. The hydrogen measurement was conducted by forward recoil spectrometry with 1.5 MeV $^{4}He^{+}$ beam. The detector angle was 30 degrees and the target angle was 75 degrees. A piece of 6 μm thick Mylar was placed in front of the detector to stop the forward scattered helium particles. A hydrogenated amorphous silicon film was used as a hydrogen standard in the measurement. The results are shown in Table 1 for three

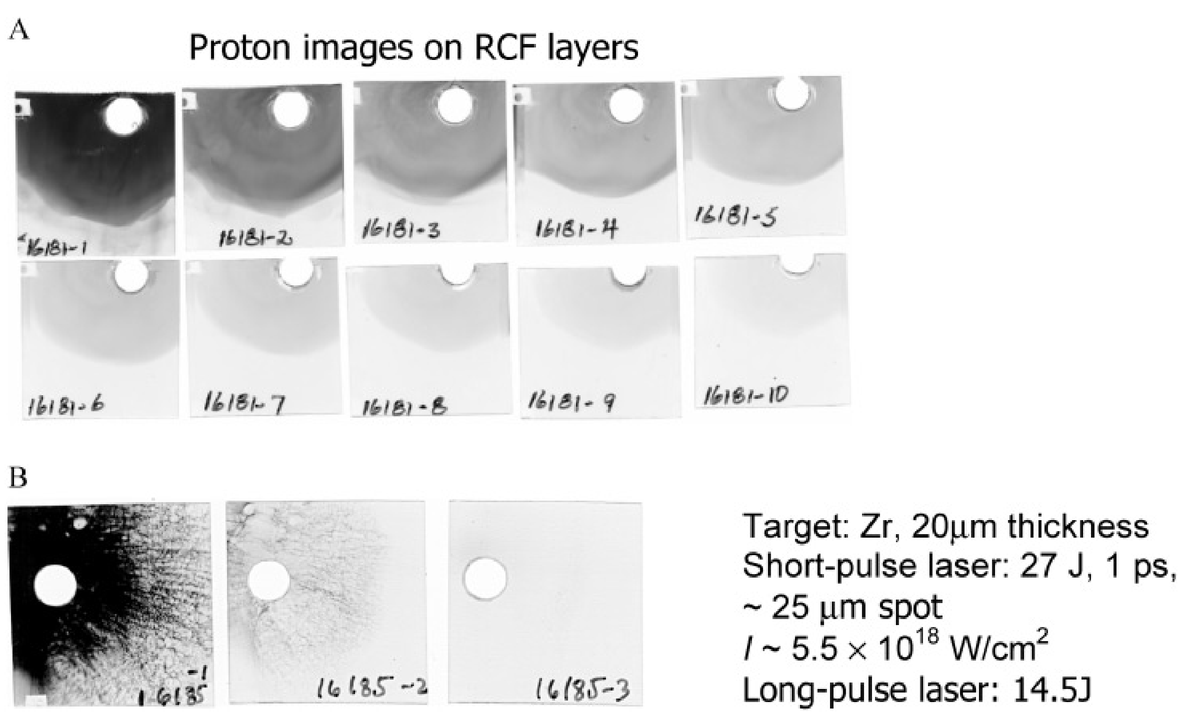

Fig. 2. RCF images of two shots with Zr-foil targets, 20 μm thick, on Trident. On the top, the target is untreated, and the image is mostly due to protons with a cutoff energy exceeding 10 MeV. The short-pulse laser beam delivered on target an energy of 27 J, a pulse length of 0.825 ps and a ~ 25 mm spot, resulting in a laser intensity of $I \sim 6.7 \times 10^{18}$ W/cm^2. The bottom RCF images come from a target which pre-ablated with a 527 nm, 0.1 ns beam with 14.5 J and a laser intensity on target of 0.64×10^{10} W/cm^2. The short-pulse laser intensity on target was $I \sim 5.5 \times 10^{18}$ W/cm^2. The fewer layers of exposed RCF are consistent with production of heavier ions and the elimination of the dominant proton beam.

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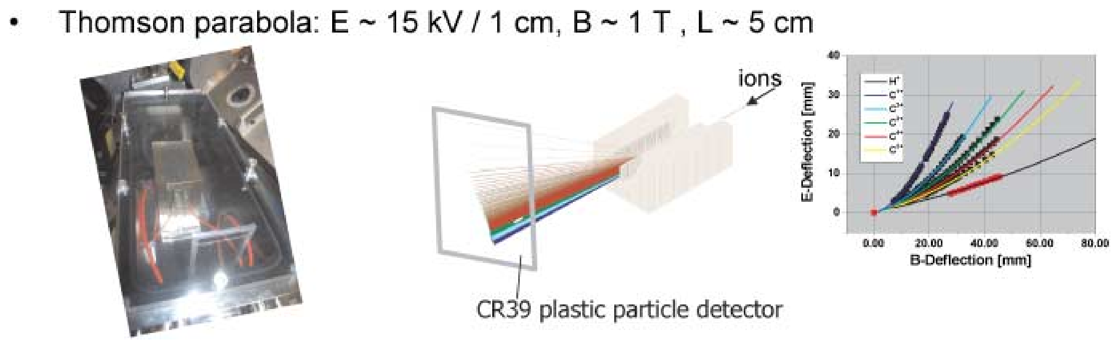

Fig. 3. (Left) A photograph of the Thomson parabola diagnostic; (center) schematic of the parabola showing the flight of ions with a given charge-to-mass ratio for a range of energies; (right) parabolic locus of ion-strike points at the detector plane for protons and various charge states of C.

metal foils nominally 20 μm. Typically, these targets have abundant C, O, and H surface impurities, each with area densities of order 10^{16} atoms/cm^2.

As mentioned above, in situ Joule heating the target to ~ 1000 °C, have been used successfully to remove surface impurities rich in hydrogen (Hegelich *et al*., 2002). Unfortunately, this technique cannot remove other impurities with binding energies in the eV range, such as metal oxides. Therefore, we are left with two alternatives. In the next section, we discuss the results with the first alternative, using Pd targets, a metal highly resistant to oxidation. The other alternative, removing the impurity by other means, is discussed in Section 5.

4. ACCELERATION RESULTS WITH PD TARGETS WITH AND WITHOUT JOULE-HEATING

The Thomson-parabola results from a Trident shot with an untreated Pd-foil target, 20 μm thick, are shown in Figure 4. The dominant proton trace is suppressed for clarity. Low charge states of Pd are seen along with C, but no O ions are observed. This encouraging result is consistent with the resistance to oxidation of Pd. However, Pd is an excellent getter, requiring Joule heating to eliminate all traces of Hydrogen.

The application of Joule heating (a few W) to a similar foil target changes the results significantly. The proton beam is not present anymore. Pd charge states up to Pd^{22+} are observed. Figure 5 shows the ion energy spectrum of the Pd^{22+} charge state, compared to the C^{4+} charge state from the previous shot with an untreated-target. Assuming conservatively a 10° beam, about 7×10^8 Pd^{22+} ions with energy $\geq$ 1 MeV/AMU were produced (0.1% of the laser energy), whereas a total of 8.5×10^9 Pd^{22+} ions were produced with energies above 0.2 MeV/AMU (0.4% of the laser energy).

In spite of these encouraging results, there remain difficulties with this approach. The first is that a simple scaling law that we developed to estimate ion-acceleration performance versus laser-energy, indicates that Trident has too little energy to produce the electric fields necessary to ionize and accelerate such heavy ions, to the desired high energies with high efficiency. Therefore, at the next opportunity, we intend to test ion acceleration with lighter metallic species, such as Chromium, more in line with the available laser energy. The second problem is that our present implementation of Joule heating (literally driving a 60 Hz AC current through the target, controlled with a Variac) is not sufficiently reproducible. Specifically, a subsequent, nominally identical shot failed to produce Pd^{22+} ions. This implementation of target heating suffers from the irreproducibility of the electrical resistance of the target contacts. To solve this problem, we intend to implement a different method of target heating, described in Section 6 (below). Finally, relying exclusively on inert target metals, limits our choices of constituent ions of our laser-driven beams. Therefore, an active target-treatment method applicable to any metal is desired. Our pursuits along those line ρ are described below.

Table 1. *Areal density of H, C, and O in surface contaminants on typical laser-target rolled metal foils*

Metal	H (atoms/cm^2)	C (atoms/cm^2)	O (atoms/cm^2)
Pd	4.5×10^{16}	2.4×10^{16}	3.8×10^{16}
Zr	3.1×10^{16}	5.4×10^{16}	4.2×10^{16}
W	2.9×10^{16}	0.25×10^{16}	0.8×10^{16}

5. ACCELERATION RESULTS USING LASER ABLATION FOR TARGET CLEANING

Active surface treatment of our laser targets is very challenging. Since most laser facilities in practice do not operate in ultrahigh vacuum, it takes less than a second of exposure of a cleaned target surface to the target-chamber environment to get re-coated with water vapor, hydrocarbons, etc. Therefore, the method has to be operable ρ in situ and

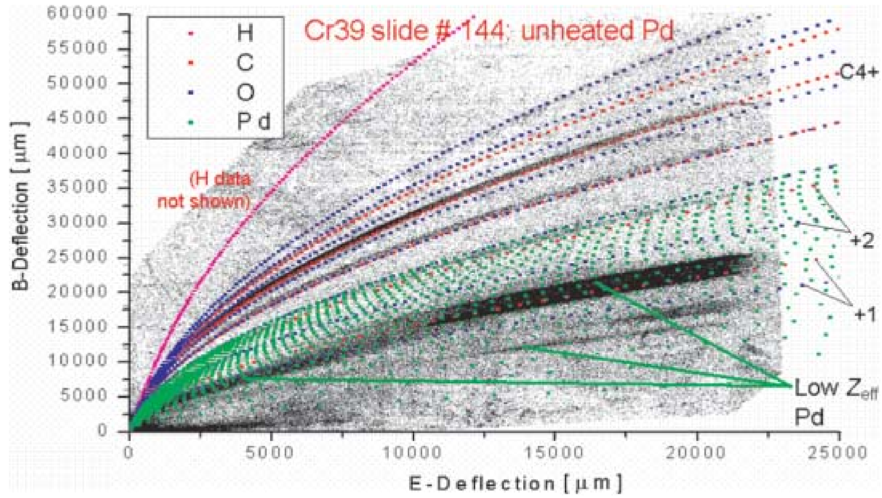

Fig. 4. Plot of beam ion locations detected on the plane of the Thomson parabola diagnostic. Individual ions cannot be resolved in this plot due to the high number of particles detected. This target was an untreated Pd foil, irradiated by a 21 J, 1 ps pulse.

remotely. Moreover, it has to be pulsed and yet be gentle enough to preserve the integrity of the delicate laser targets. Ablation of target-surface material driven by a pulsed optical laser is an attractive alternative satisfying all the requirements. It has been well-known for many years that irradiating a material surface with laser intensity in the range of 10^9–10^{11} W/cm^2 may ablate part of the surface material without destroying the target, depending on the details of the target and the laser pulse.

We have implemented laser-ablation cleaning of the target on Trident, using the A long-pulse Trident beam, frequency-doubled to a wave length of 527 nm, and sub-aperture in order to ensure that only the rear target surface is irradiated, as opposed to the target holder and other surfaces. (The "front" target surface is irradiated by the short-pulse beam.) In order to keep the irradiance low enough, this beam line was operated in a highly de-rated fashion, using 0.1 ns pulses with an energy of ~10 J to yield an intensity on target of order 10^{10} W/cm^2. The A beam is fired 6 μs prior to the short-pulse beam (C). This interval is chosen because it is within the range possible with the existing Trident configuration, it allows sufficient time for the ablated material to clear the vicinity of the target, and it should result in negligible impurity re-sticking.

In order to establish an upper bound for the desired laser intensity, we utilized glass slides with a known area density

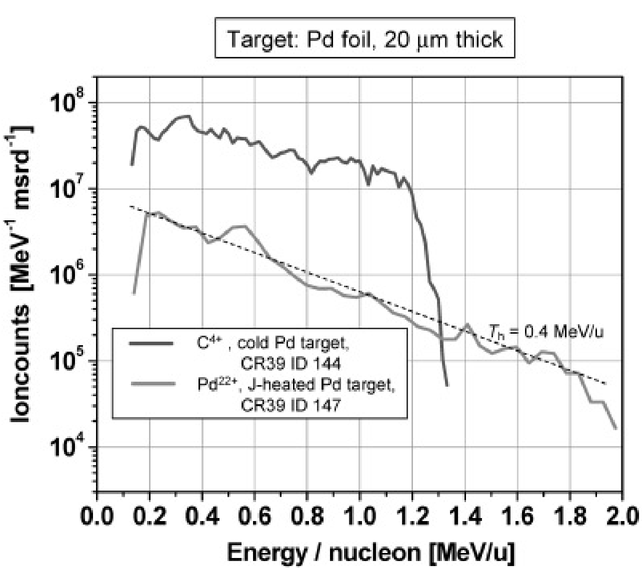

Fig. 5. Pd^{22+} spectrum from a Pd foil target irradiated by a 17 J, 0.8 ps pulse, compared with the C^{4+} spectrum from the shot in Figure 4.

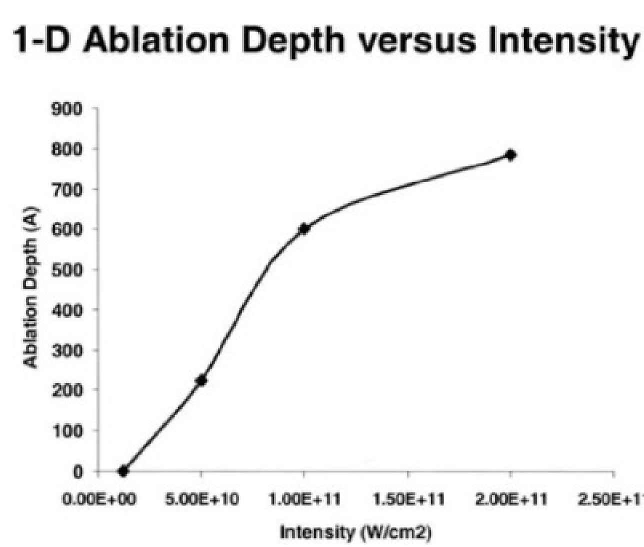

Fig. 6. Amount of Vanadium metal ablated from a foil target coated with impurities (see text) versus incident laser intensity at 527 nm wave lengths.

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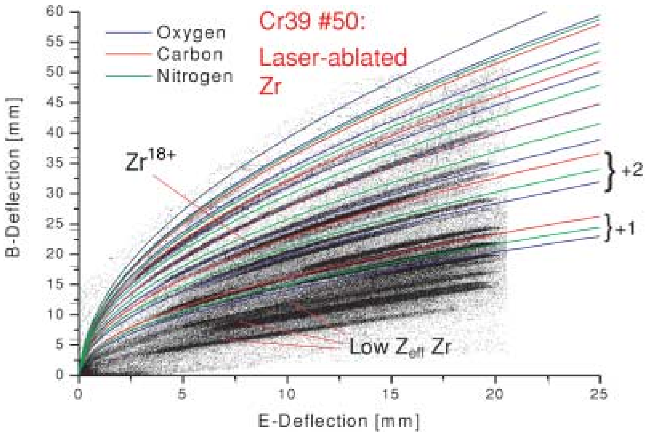

Fig. 7. Plot of beam ion locations detected on the plane of the Thomson parabola diagnostic for a Zr-foil target illuminated by the laser-ablation beam prior to short-pulse irradiation. The short-pulse laser pulse had energy of 17 J and duration of 1 ps.

of deposited Carbon. The highest C density tested was 5 μg/cm^2 (2.5 $\times$ 10^{17} C atoms/cm^2). We verified that a laser intensity of 8.1 $\times$ 10^{10} W/cm^2 (normal incidence) is sufficient to remove that much C without destroying the glass surface. A calculation (1D) with the hydrocode LASNEX was also performed to investigate the desired ablation intensity for upcoming experiments with V-foil targets. The simulation assumes that the laser encounters a 125 Angstrom layer of water and a 50 Angstrom layer of C before encountering a 50 mm V target foil. The simulation clearly shows that there is a point within the target that remains approximately stationary. Beyond that point, toward the laser side, the Lagrange zones are ablated with speeds exceeding 10 km/s, whereas on the other side, a thermal wave is launched into the substrate. In this particular case, a laser intensity of 2 $\times$ 10^{10} W/cm^2 is necessary for the breakpoint to lie within the V foil, rather than within the impurity overcoat, as shown in Figure 6.

In our first experiments, we tried laser-ablation cleaning on Zr foils 20 μm thick. Because of geometry constraints, the laser was incident on the target at 82 degrees. In this initial run, we used a conservatively low ablation-laser intensity to ensure target survivability. For shot #16188, we employed a laser intensity of 1.15 $\times$ 10^{10} W/cm^2 on the rear target surface, without any Joule heating. The good news is that the proton trace on the Thomson parabola was suppressed. Unfortunately, the ablation-laser intensity appears to be too low to completely eliminate all impurities, and a significant number of light ions from impurities (C, N, and O) are observed. We appear to have created up to Zr^{18+}, but the presence of these impurities appears to have limited the cutoff energy for Zr^{18+} to 0.3 MeV/AMU. The Thomson parabola traces are shown in Figure 7.

6. FUTURE WORK

We intend to continue our dual track approach to demonstrate efficient laser-driven production and acceleration of heavy ion beams. We intend to improve the performance of heated inert metal targets, by implementing a more reliable and reproducible method based on CW laser heating. The heating performance was tested using a portable CW laser at

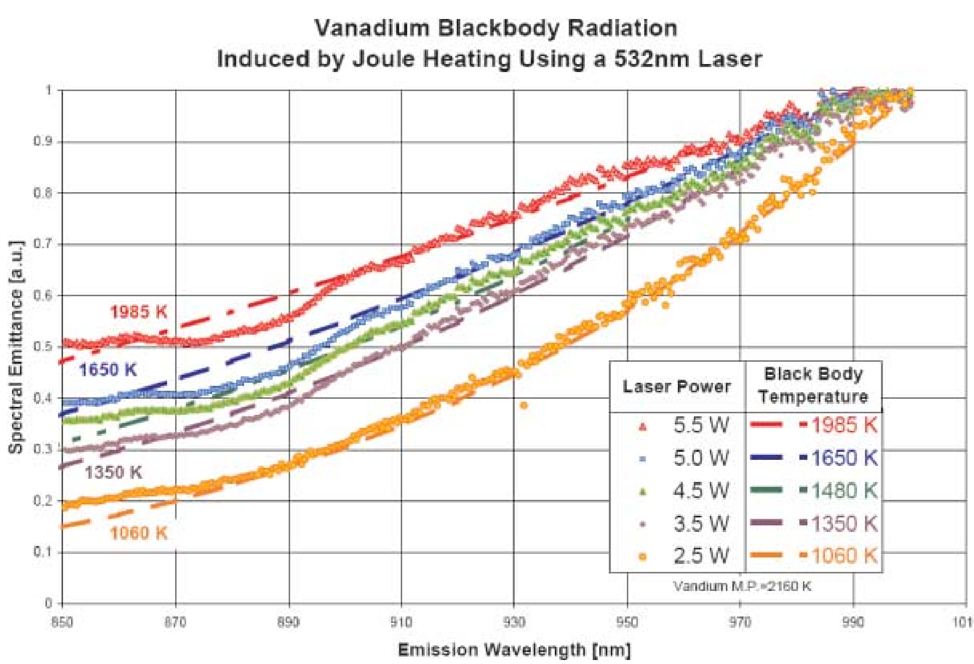

Fig. 8. Black-body spectra from a V-foil target (20 μm thick) heated with a CW laser.

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a wave length of 532 nm using a V target in the Trident target chamber. As shown in Figure 8, a laser power above 2.5 W is sufficient to heat the target above the desired target of 1000° C. We intend to implement this method in our next experimental run. We intend to continue development of laser-ablation to eliminate target surface impurities. Guided by LASNEX simulations and our results to date, we intend to increase the ablation laser intensity to $\sim 5 \times 10^{10}$ W/cm^2 on the rear target surface.

7. SUMMARY AND CONCLUSIONS

We are working to understand quantitatively the physics that underlie the generation of laser-driven MeV/nucleon ion beams, in order to extend these capabilities over a range of ion species, to optimize beam generation, and to control those beams. In the future, we intend to study the interaction of these novel laser-driven ion beams with dense plasmas, a plasma physics frontier relevant to important projects such as the fast-ignition method of ICF. We are pursuing our immediate goal in experiments where thin metallic foils are irradiated with the Trident short-pulse laser to generate medium to heavy ion beams ($Z = 20$–45) with high efficiency. Presently, target-surface impurities seem to be the main obstacle to reliable and efficient acceleration of the metallic ions in the foil substrate. We have measured the surface impurities on laser targets. To eliminate these impurities, we have resorted to novel target-treatment techniques such as Joule-heating and laser-ablation using a long-pulse laser intensity of $\sim 10^{10}$ W/cm^2. Our progress on these efforts has been presented. We conclude that we are well on our way to demonstrate efficient production and acceleration of ion beams with the desired parameters.

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