

Ultrahigh Intensity Laser Physics at the LANL Trident Laser Facility

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Modern ultrahigh intensity lasers are able to reach focal intensities of the order of 10^{18} – 10^{21} W/cm² where laser-plasma interactions become relativistic, and a variety of new effects emerge into a completely new regime of physics. These processes include relativistic self-focusing of the laser beam, which results in even higher intensities, laser-induced particle acceleration to MeV energies on a micrometer scale, x-ray lasers, laser-induced nuclear physics, and even the production of antimatter and other exotic particles. These effects can be applied to a variety of physics studies and can potentially be used for a number of applications. Concepts under consideration are next-generation accelerators, the jump-starting of inertial confinement fusion (ICF) with fast ignition, various medical applications, and laboratory astrophysics. One of the three beams of the Trident laser facility at Los Alamos National Laboratory (LANL) has been converted to deliver ultrashort laser pulses at the above-mentioned intensities so that researchers can participate in this exciting new field at the forefront of today's physics. This beam is used to carry out a program that investigates the acceleration of ion bunches to MeV energies and MA currents and the interaction of these ions with different targets.

High-Irradiance Laser-Matter Interactions

An ultrahigh intensity laser pulse pointed at a solid target always interacts with a plasma because of its finite contrast ratio. Even in a laser with a relatively excellent

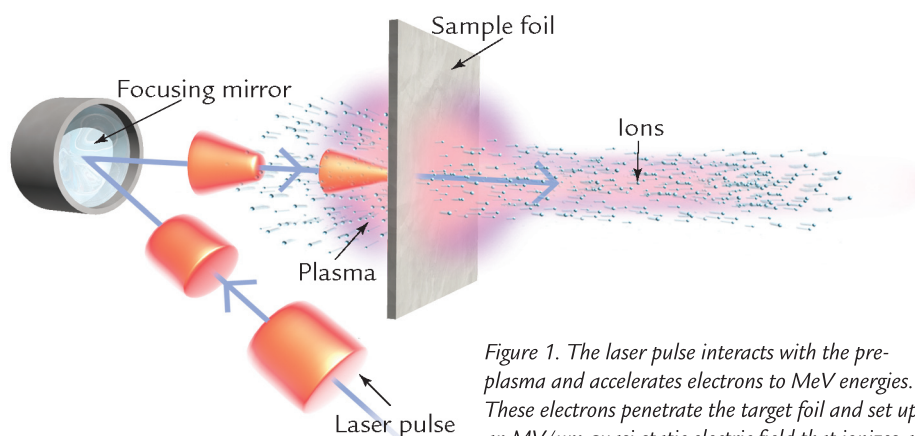


Figure 1. The laser pulse interacts with the pre-plasma and accelerates electrons to MeV energies. These electrons penetrate the target foil and set up an MV/ μ m quasi-static electric field that ionizes and accelerates the rear surface atoms.

contrast of $\sim 10^{-7}$ there will be a “pre-pulse” at 1–2 ns ahead of the main pulse with an intensity above 10^{12} W/cm², which is high enough to instantly create a plasma. The main pulse will therefore always interact with a plasma and never with a solid target. Furthermore, at these intensities, the laser-plasma interaction is relativistic, i.e., the electrons gain energy on the order of their rest mass when moving in the electro-magnetic field of the laser pulse. The laser transfers energy to the electrons and accelerates them in the laser-propagation direction through the target to multi-MeV energies. This process is due to the $\mathbf{v} \times \mathbf{B}$ force from the magnetic component of the electromagnetic

field, which becomes non-negligible when v approaches the speed of light. As illustrated in Figure 1, the electrons will penetrate a thin foil target, exit out the back surface, and set up a virtual cathode—a very strong electric field, exceeding field strengths of a few 10^{12} V/m (TV/m).

The electric field ionizes the rear surface and accelerates whatever ions are situated there to energies of many MeV. Protons have been accelerated to more than 60 MeV,¹ fluorine ions to above 100 MeV,² and lately high-Z Pd ions to 220 MeV.^{3,4} In many beam parameters, those ion pulses now exceed those of

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conventionally accelerated ions by orders of magnitude, exhibiting pulse durations in the sub-picosecond range, beam currents up to MA, and a transverse emittance $\epsilon_t < 0.001 \pi \text{ mm mrad}$.⁵ A typical conventional accelerator like, e.g., the CERN Super Proton Synchrotron (SPS) has an emittance of $\epsilon_t < 1 \pi \text{ mm mrad}$. These parameters have rekindled interest in laser-accelerated ion beams for applications like proton radiography,⁶ isochoric heating,⁷ fast ignition,⁸ and next-generation accelerators. The major difficulty for all these applications to date has been the large energy spread of the laser-accelerated ions, which typically exhibit a Maxwellian-like energy spectrum as shown in Figure 2. At LANL, we have demonstrated for the first time that quasi-monoenergetic ion beams can be generated by controlled target treatment

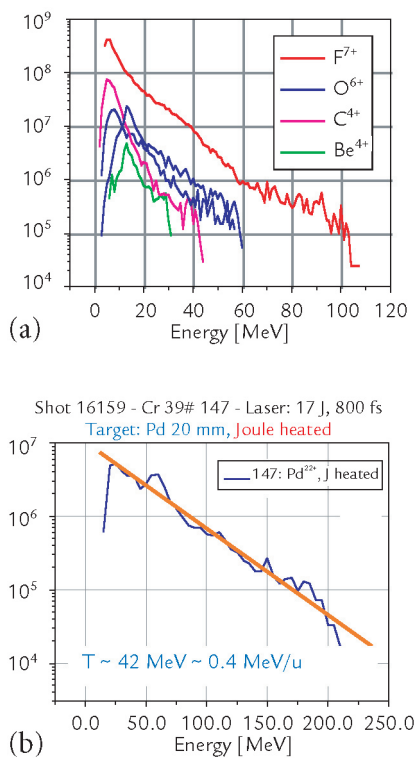


Figure 2. (a) Typical low-Z ion spectra from both the LULI 100-TW laser and Trident. (b) First mid-Z ion spectra (Pd 22+, $Z = 46$) from Trident.

before irradiating the metal foil target with an ultrahigh intensity laser. Furthermore, we also show the acceleration of a single charge state of one ion species directly in the forward target-normal direction. The accelerated C5+ ion bunch shown in Figure 3 exhibits a longitudinal emittance of $\epsilon_l < 2 \times 10^{-6} \pi \text{ eV s}$, exceeding that of conventional high-current accelerators by orders of magnitude. This new result shows the strong potential impact that ultrahigh intensity laser physics can have in many other areas of physics.

Accelerated Ions

Due to the vacuum conditions in ultrahigh intensity laser experiments, which typically are around 10^{-6} mbar , all target surfaces are coated with water vapour and hydrocarbon layers, e.g., pump oil. That means that no matter what target material is used, the outer layer always contains protons. Because of its low ionization potential and because protons exceed every other ion's charge-to-mass ratio by at least a factor of two, they are more efficiently produced and accelerated, drain the energy out of the acceleration process, and screen the accelerating electric field for the heavier particles. Accelerating other ions therefore requires the removal of the contaminating proton layers. This removal was demonstrated by Hegelich *et al.*² using the 100-TW laser at the École Polytechnique LULI research center with C and F ions. To achieve our goal of mid- to high-Z ion acceleration at LANL's Trident laser facility, we implemented the same kind of cleaning techniques in our ultrahigh intensity laser experiments. Trident delivers pulses of up to 30 J in as short as 600 fs, which corresponds to a power of $\sim 30 \text{ TW}$. As such, Trident is currently the highest-energy sub-picosecond laser in the U.S. The beam is aimed at an off-axis parabolic mirror within a vacuum chamber to focus the beam from its initial diameter of 6 in. down to a 20- μm spot on the target, achieving intensities in excess of

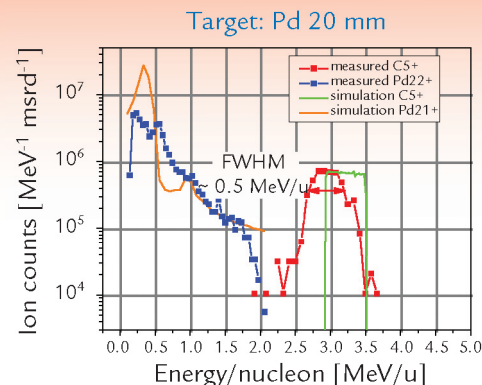


Figure 3. Measured ion energy spectra and simulations using BILBO.

10^{19} W/cm^2 . A sketch of a typical setup is shown in Figure 4.

To clean the target, we rely on two methods: Joule heating using either a strong direct current (dc) that is passed through the foil or a continuous-wave (cw) laser. Both methods are capable of heating the target to temperatures in excess of $1,000^\circ\text{C}$, which remove all H-bearing contaminants. With no H present, remaining species on the rear surface are ionized by the electric field. The charge state with the highest charge-to-mass ratio is predominantly accelerated. Experiments on the LULI 100-TW laser and on the Trident laser successfully accelerated a wide range of low-Z ions to multi-MeV/nucleon energies. Figure 2(a) shows the spectra for He-like Be, C, O, and F.

Moving from low-Z ions to mid- or high-Z ions proves to be more difficult. Although contaminants like water vapour can be cooked off by heating the target, heating cannot clean metal oxides, carbides, and nitrides on the surface—these contaminants usually have binding energies in the eV range. To overcome this problem we are working on two different approaches. The first approach is to use a second pulsed laser at relatively low intensity ($\sim 5 \times 10^{10} \text{ W/cm}^2$) to ablate the rear surface thus removing

the contaminating oxides, etc. Although this approach worked in principle, the technical details are tricky and remain a subject of ongoing study. The second approach is to use a “magic” material that does not form oxides or other compounds. This approach is the easier solution; however, it limits the available target materials. One such “magic” material is Pd. With an atomic mass of 106, Pd ($Z = 46$) does not easily form oxides. As shown in Figure 2(b), we succeeded for the first time to accelerate a mid- Z material into a multi-MeV/nucleon ion bunch using an ultrahigh intensity laser. In future experiments, we hope to improve this result, increasing the energy and the particle number and achieving greater control of the beam properties, e.g., ballistic focusing as shown in Figure 3. Once these goals are achieved, the Pd beam can be used to study isochoric heating in matter, effectively recreating in the laboratory conditions that are otherwise only found in the interior of large Jovian planets.

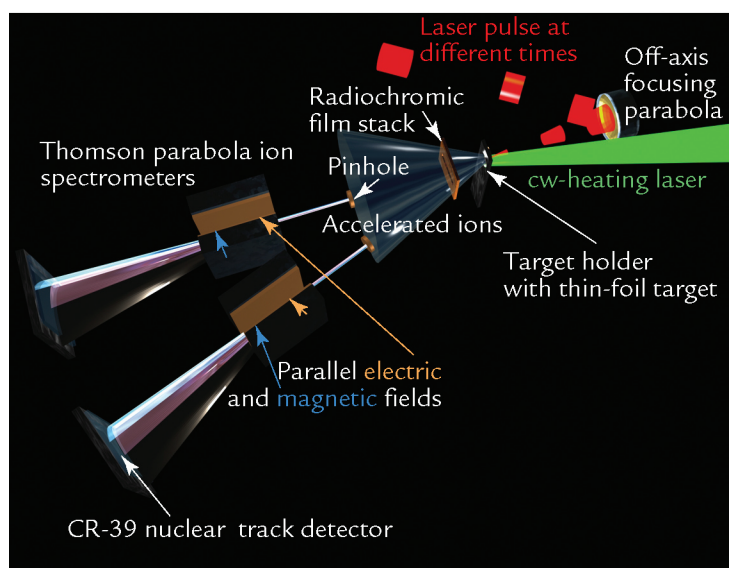


Figure 4. Typical setup of a laser-ion-acceleration experiment. The target is typically a ~ 10 -mm-thin metal foil, the diagnostics consist of various films, track detectors, and spectrometers. A green cw laser is used to clean the target of hydrocarbon contaminants.

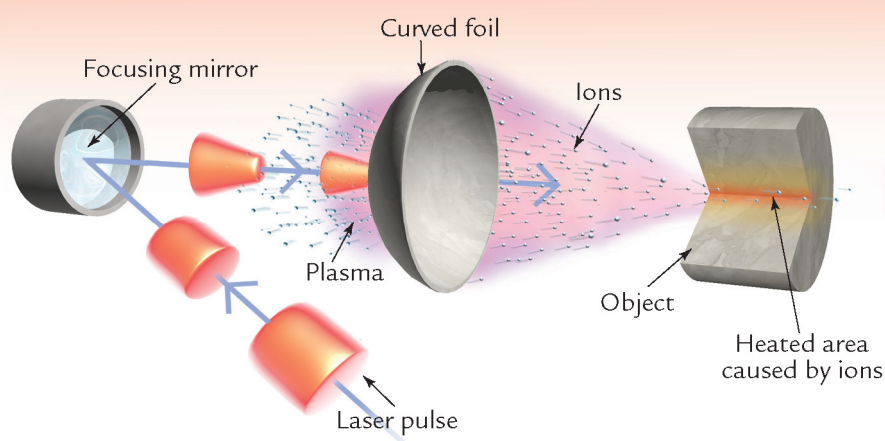


Figure 5. Ballistic focusing of a laser accelerated ion beam into a secondary target. The secondary target will be heated isochorically to high temperatures while remaining at high density, recreating conditions found in the core of Jovian planets.

Monoenergetic Ions and Modeling

As mentioned to earlier, we were the first to accelerate a monoenergetic MeV-ion bunch with a laser. When heating the Pd target to remove the H, a thin monolayer of C atoms remained at the rear surface. Because these C layers are very localized, all C atoms see the same field at the peak of the pulse and are ionized to the same charge state and instantly accelerated. As the field decreases after ~ 100 fs, all the C atoms are at the front of the ion expansion, in a position trailing the hot electrons, which

effectively conserves their volume in phase space. The full width half maximum (FWHM) of 0.5 MeV per nucleon in the Thomson parabola spectrum shows a longitudinal emittance of this C5+ bunch smaller than 2×10^{-6} eV seconds—about six orders of magnitude better than for the CERN SPS. We have used the one-dimensional hybrid code BILBO (Backside Ion Lagrangian Blow-Off) to help us understand this result. BILBO solves a Vlasov-Maxwell system analytically, calculating the boundary conditions for a nonlinear Poisson solver. The solver yields the electron density and electric fields and propagates the ions as kinetic particles. The code uses a threshold ionization model with atomic data for ionization energies of C and Pd and hot-electron-cooling models to account for the extraction of energy used to accelerate the ions. Using BILBO, we reproduced the measured spectra qualitatively (Figure 3) and seek to derive better models to understand and optimize beam production.

Conclusion

Future experiments will be directed towards better understanding of the underlying acceleration physics and towards the use of the accelerated ions for a number of different applications. Because of the modest integrated energy of the ions, they must be focused to one point, which can be achieved by using curved targets (Figure 5). The long-term goal of our project is to study transport and stopping mechanisms of high-current ion beams in cold, dense plasmas. These experiments require the use of Trident's other beam lines to create the target plasma while the short-pulse beam generates the ion pulse. For these experiments and for other short-pulse physics applications, more energy in the short pulse beam is desirable and in some cases even necessary. Therefore, the Trident short pulse arm will be upgraded over the next 18 months to deliver pulses of ~ 115 J in less than 500 fs. This 200-TW upgrade puts P Division even more firmly at the forefront of modern science and opens new opportunities for programmatic research. It keeps Trident among the best of the existing short-pulse lasers in the world and makes even more exotic new physics accessible.

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