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BREAKING THE 70 MeV PROTON ENERGY THRESHOLD IN LASER PROTON ACCELERATION AND GUIDING BEAMS TO APPLICATIONS

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Abstract

The acceleration of protons and light ions such as carbon by the interaction of intense laser beams with solid targets has been studied for more than 10 years. Since the discovery of the Target Normal Sheath Acceleration (TNSA) mechanism in 2000 by Snavely et al. [1] a lot of experiments and theoretical models have been used to understand the physical details underlying this mechanism and to characterize the resulting ion beam in terms of spatial and spectral energy distribution. While the required energy of the laser has been reduced by an order of magnitude and the targets have been optimized no experiment has exceeded energies around 70 MeV for protons in such experiments. With respect to the outstanding qualities of those laser accelerated ion beams, especially the low emittance, which allows for transport and focusing, many applications have been proposed. Recently new accelerating mechanisms have been proposed relying on the increasing laser intensity available with modern systems. Among them is the BOA (Break Out Afterburner) mechanism [2] first discovered at LANL in extensive computer simulations. The mechanism relies on the relativistic transparency of solids and has been first discovered experimentally at the LANL Trident laser system.

Most of the possible future applications also require the selection of a specific particle energy with ΔE=E < 1% and a focused or low-divergent beam. Here, several attempts have been taken in the past and the most promising results obtained with the use of small permanent-magnetic quadrupole devices [3,4] or pulsed high-field solenoids [5,6].

GETTING BEYOND THE 70 MEV BARRIER

Todays lasers are able to reach maximum intensities of more than $10^{21} W/cm^2$ [7]. The dominant ion acceleration starts off the rear, non-irradiated surface by a rapid charge separation. This mechanism is known as *Target Normal Sheath Acceleration* [8] and has been investigated for about a decade. Access to a higher energy range has been proposed by a set of new acceleration mechanisms, all based on ultra-intense laser-matter interaction. First, there is the so-called *Radiation Pressure Acceleration* (RPA) [9], and second the *laser Break-Out Afterburner* (BOA) [2,10,11].

The BOA mechanism has been discovered theoretically in 2006. The main difference between TNSA and BOA (or RPA) is the de-coupling of the ion acceleration from the driving laser field due to the thickness of the target. In contrast, for the RPA and BOA mechanism the electrons that are accelerating the ions are still interacting with the laser field. In order to couple to the maximum number of available electrons the target is required to be dense enough, so that the laser beam is not initially penetrating the target, but is coupling to the electrons. At some point the target has then to become relativistically transparent to the laser light, so that the light can directly interact with electrons, co-moving with the ions at the rear surface. So the BOA mechanism starts as normal TNSA, but then during the raising edge of the laser pulse the intensity couples to the already moving electron-ion front at the rear side of the target. A theoretical description is given in [10,11]. In those publications the interaction of an ultra-intense short pulse laser was investigated using Particle in Cell (PIC) simulations for very thin solid targets, where the thickness matches only a few times the skin depth. After the initial phase where the laser heats electrons, the product of critical density n_{cr} and Lorentz- factor γ equals the electron density of the solid, due to the mass increase of the swiftly oscillating electrons. The laser propagates through the target, continuously pushing the electrons, which transfer part of their kinetic energy to the ions via the onset of the Buneman-instability. The energy loss of the electrons to the ions is then compensated by the present light field until the total density drops due to the target expansion and the coupling becomes inefficient. Numerical simulations predict ion energies of hundreds of MeV for existing laser parameters and up to the GeV range for currently planned systems.

One important difference to TNSA is that in a mixture of target atoms, all of the accelerated ions propagate at the same particle velocity, governed by the slowest, i.e. the

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heaviest species present. Thus for high energy proton acceleration a pure hydrogen target is the ideal choice. For each laser pulse duration and intensity as well as for each target composition one can determine an optimum target thickness, based on the above mentioned physics. High-Z target materials require, due to their larger number of electrons per atom, extremely thin targets in the realm of only a few nanometer thickness. This in turn requires laser contrast parameters, which exceed the usually available values. For first systems like the LANL TRIDENT laser or the GSI PHELIX laser [12] the contrast has been demonstrated to exceed 10^{-10} using novel pulse cleaning techniques in the laser architecture. As TRIDENT has been for a while the only high energy short pulse laser at high contrast and BOA has been demonstrated there first [13,14], we started to do the experiments at LANL before changing to the PHELIX laser.

EXPERIMENTS

One of the two experimental setups is depicted in Figure 1. The experiments were carried out at the Los Alamos National Laboratory 200 TW TRIDENT laser facility and at the PHELIX laser system in Darmstadt, where the temporal contrast (ratio of unwanted laser irradiation compared to the peak intensity) was in excess of 10^{-10}. In two campaigns we used short parabolic mirrors close to normal incidence to focus typically 40-80J of 1.053 µm vertically polarized laser light in a clean 450-600 fs pulse to reach maximum intensities in between 10^{20} and 10^{21} W/cm^2. The laser pulse duration and beam parameters were carefully recorded during both campaigns. Plastic (CH2) or deuterized plastic (CD2) targets from 200 nm to 3.2 µm thickness were used to generate proton or deuteron beams. Copper activation techniques (nuclear activation imaging spectroscopy, NAIS) [15] were used to measure the proton and deuteron beam parameters for given laser energy and target thickness combinations.

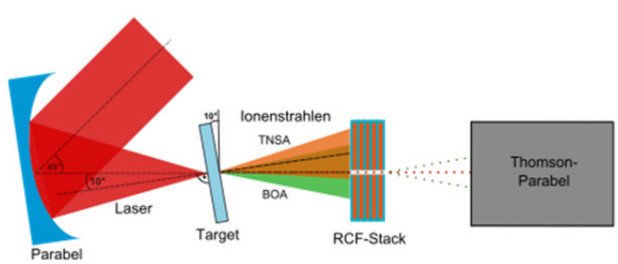

Figure 1: Setup of the PHELIX Experiment.

We first tested the BOA mechanism using CH2 and CD2 targets and the iWASP [16] spectrometer to measure the yield of deuterons and protons for the two target types. While for 300 nm targets the ion distribution resembles the bulk concentration, the 3 µm target only showed surface protons with very little deuterium contribution. We then used the NAIS diagnostics to detect the maximum proton energy. A clear signal was visible even after penetrating a solid copper stack of 2.5 cm. Given the energy loss inside the copper and the required activation threshold of 4 MeV the proton energy in the beam must have exceeded 130 MeV. Coincidence activation counting and a gamma spectroscopy verified the signal to originate indeed from Cu(p,n)Zn reactions.

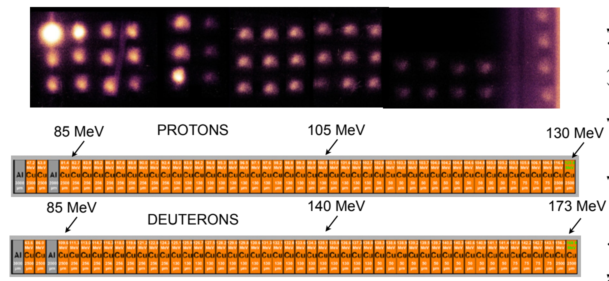

Figure 2: NAIS image of proton and deuteron activated copper. The energies correspond to the endpoint energies to excite the Cu(p.n)Zn reaction. In the experiment activation in all layers confirmed ion energies exceeding 130 MeV.

For the PHELIX experiments, the laser was focused with an F = 1.7 parabolic mirror to a focal spot size of 3, 5 µm (FWHM) containing 25 % of the energy which results in an on target intensity of $8 \cdot 10^{20}$ W/cm^2. Pre-ionization of the target was precluded by using the new PHELIX high contrast mode [12] with a noise level that is 10 orders of magnitude below the maximum up to 100 ps before the main pulse. The vertically polarized laser irradiated the target at an angle of $10^{\circ} \pm 1^{\circ}$ with respect to the target normal direction (see Fig. 1). The main idea was to distinguish between TNSA accelerated particles and BOA particles by separating the two beams spatially. TNSA ions always are emitted normal to the target's rear surface whereas BOA ions propagate predominantly in the laser direction. As targets we used polymethylpentene-foils at different thicknesses ranging from 200 nm to 1200 nm. Radiochromic films (RCF) in stack configuration served as our main diagnostic to evaluate the spectrum as well as the spatial shape of the accelerated proton beam [17]. Each stack was composed of 16 active layers separated by copper and nickel foils of different thicknesses to extend the detection range up to a maximum measurable energy of 70 MeV.

RESULTS

For the TRIDENT experiments a clear transition from the classic TNSA to the BOA regime was visible. Not only in terms of higher energies, but also and more interesting in terms of a visible change from surface acceleration of contaminants to bulk acceleration. From a CD_2 target the transition from predominantly protons from surface contaminants to the deuterium acceleration from the bulk material clearly revealed the change in the acceleration mechanism. At PHELIX we could observe the change from the TNSA proton emission off the target

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normal to the formation of a second jet at much higher energies in the laser propagation direction as predicted for the BOA process. Details will be published elsewhere, but with two experimental groups at two laser systems the experimental foundation for the BOA mechanism can be regarded as demonstrated.

GUIDING BEAMS TO APPLICATIONS

As stated above, a well understood and widely-used mechanism for laser-based ion acceleration is the TNSA mechanism. It is most efficiently used for accelerating protons and shows excellent beam properties with respect to bunch intensity and emittance [18]. However, the beam suffers from large envelope divergence and a continuous energy spectrum, while for most applications a low divergent, mono-energetic bunch is necessary. Therefore, much effort has been taken to face these problems during the last years. Most promising results could be achieved by applying magnetic fields for chromatic focusing, thus collimate the beam and provide for a first energy selection at the same time. Pulsed solenoids [5] and permanent magnetic quadrupoles [3,4] have been reported as suitable options. Still, the energy spread of the obtained bunches is high and energy compression necessary.

In Germany, the LIGHT collaboration [19] has built such a test beamline at the GSI Helmholtz center for heavy ion research as a central part of the collaboration's agenda.

SETUP

The experiments were performed at GSI Darmstadt with the PHELIX laser [20], which is able to accelerate protons to multi-MeV energies from thin foil targets via the TNSA mechanism. A pulsed high-field solenoid is used for collimation and transport of the bunch. A detailed description of this first stage of the beamline including a full characterization of the proton bunch can be found in a previous publication [21]. Similar targets (5 and 10 μm thin flat gold foils) and laser parameters (laser pulse duration τ =650 fs, focal spot size 3.5×3.5 μm^2 (at FWHM) and 10-15 J of laser energy on target, thus laser intensities exceeding 10^{19} W/cm^2) were used.

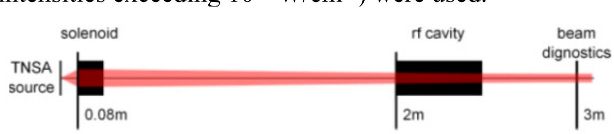

Figure 3: The 15 cm long pulsed solenoid is located 8 cm behind the laser target. It is set to focus 9.6 MeV protons at a 3m distance. At 2m a RF cavity is located followed by a diagnostics box and a magnetic dipole detector.

RESULTS

The characterization of the bunch at 3 m distance to the source is performed by two independent methods. A diamond detector is used for time-of-flight (ToF) measurements and a stack of radiochromatic films (RCF) is used to fully characterize the spatial and spectral information of the protons.

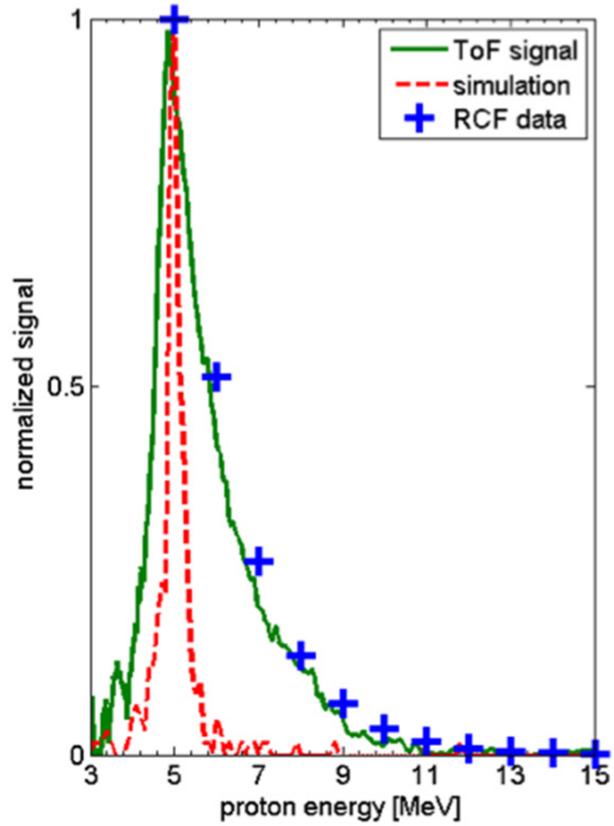

Figure 4: Normalized ToF results of the diamond detector (at 2.2 m from source) for focusing of 5 MeV with a 5 mm pinhole. The dashed graph is the corresponding expected spectrum from simulations. The blue crosses show the exponential decaying spectrum for the high energies obtained from the RCF data.

Figure 4 shows the energy spectrum of a 5 MeV proton beam just using the chromatic focusing of the solenoid through a pinhole to limit the energy spread. The discrepancy between the idealized simulation and the measurement originates from deviations of the magnetic field inside the solenoid from an ideal one due to the presence of co-moving electrons inside the coil.

Energizing the RF cavity allows for further energy spread reduction and modification dependent on the relative phase of the RF to the incoming ion bucket.

We were able to further shrink the energy spread for protons of the designated energy of 9.6 MeV from 18% for the ions passing the entrance aperture of the cavity to less than 3% behind the energized cavity.

We also have been successful showing not only a reduction of the energy distribution but also a reversal, meaning that we can slow down the head of the bunch with respect to its tail. This will allow in the near future to use simple ballistic focusing to obtain an ion bunch with expected bunch length of less than a few hundred picoseconds, while still having large particle numbers available. Details of the latest results and the upcoming experiments will be published elsewhere.

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CONCLUSION

A TNSA based compact (total length: 3m) proton beamline has been successfully commissioned at GSI Darmstadt, using the PHELIX laser as driver of the proton acceleration. A pulsed high-field solenoid provides for beam capturing and energy selection and a rf cavity provides for energy compression, thus accessing smallest energy spread (or in future experiments shortest bunch duration via phase focusing) at high particle current. In the presented experiments from the latest campaign at this new beamline, intense proton bunches at 9.7MeV energy and with particle numbers within the FWHM of the bunch of 1.7×10^9 (±15%) and an energy spread of (2.7±1.7)% have been measured. Further optimization of this beamline is planned to increase the proton numbers, reach shortest possible bunch durations and implement additional (transverse) focusing elements to the beamline to access highest intensities.

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