INTENSE ION BEAMS FROM RELATIVISTIC LASER PLASMAS – A PROMISING ACCELERATION MECHANISM

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Abstract

The acceleration of protons up to several MeV by the interaction of ultra-intense light with solid targets has been shown in several experiments[1,2,3,4]. With up to 10^{13} protons within 10 ps the beam intensity exceeds conventional accelerators by orders of magnitude.

Detailed studies at the LULI (laboratoire pour l'utlisation des laser intense) 100 TW laser have shown the excellent beam quality with smaller transverse emittance than conventional accelerators. The possibility of proton beam forming with structured targets and manipulation of the laser focal spot has also been demonstrated.

Due to the rapid development of ultra-intense lasers with high repetition rates the application of this accelerating mechanism for proton radiography, electrical field mapping, pulsed neutron sources, and as an injector for conventional accelerators seems to be feasible in the near future.

1 INTRODUCTION

In 1999 the interaction of intense lasers with plasmas in the relativistic regime at intensities above 10^{20} W/cm^2 was studied at the Petawatt laser system in Livermore, a 500 J laser with a pulse duration of around 0.5 ps.

During attempting to measure the relativistic electrons at the back side of thin gold and plastic foils the emission of a very intense proton beam was observed [1,5]. They found 10^{13} protons with energies up to 50 MeV. Due to the lifetime of the hot electrons the time for the emission was assumed to be less than 10 ps.

Measurements with proton spectrometers showed a Boltzmann like energy distribution with a temperature ($k_B T$) of 5 MeV.

In addition all experiments showed, that the emission was always normal to the rear surface of the target.

Unfortunately the Petawatt system was shut down soon after the first observation of these intense proton beams, so no more studies of this phenomena were possible there.

To study the phenomena more in detail, experiments were performed at the 100 TW laser system at LULI, a laser with 30 J in 500 fs and intensities up to a few times 10^{19} W/cm^2.

The following article summarizes the results of these experiments. In section 2 we will give a brief description of the acceleration mechanism, in section 3 the experimental setup is given. In section 4 we show the experimental results and section 5 presents some possible applications.

2 ACCELERATION MECHANISM

Soon after the discovery of the intense ion beams a model for the acceleration was developed: The target normal sheet acceleration (TNSA) [6].

The interaction of the ultra intense laser with the target produces an intense beam of hot electrons with a Boltzmann distribution corresponding to a temperature of several MeV. This beam is assumed to have a divergence of around 30°. Around 50% of the laser energy is transferred to these electrons.

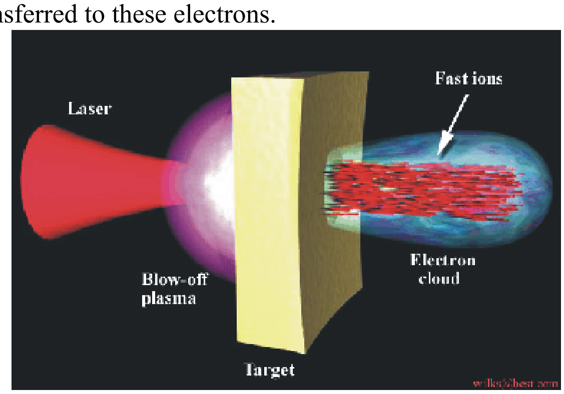

Figure 1: Schematic of the TNSA mechanism

These electrons then move through the target to the backside. The most energetic electrons escape from the target and the target is charged up to several MV. The less

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energetic electrons are confined inside the target by the electrostatic force. The equilibrium of the electrostatic forces and the thermal movement of the electron results in a small sheet on the backside of the target, a so called Debye sheet.

As the ions of the target have a very steep density gradient a large electric field is built up between the electrons in the sheet and the target bulk (MV/µm). The bulk material and especially hydrogen, which is contained in impurities of the surface layers and in the bulk material, is directly ionized by field ionization.

These ions are now accelerated in the electric field. As protons have the best charge/mass-ratio they achieve the highest acceleration. In this way they run in front of the ions, shielding the electric field of the electrons.

As electrons and ions are kept together the beam is current and space charge neutralized.

3 EXPERIMENTAL SETUP

The LULI 100 TW system is a laser with 30-50 J in 300-500 fs. The beam is focused with a f/3 off-axis parabola. In this way a peak intensity of 10^{19} W/cm^2 is obtained.

As diagnostics we used proton spectrometers to measure the energy distribution, Thomson parabolas to distinguish the different ion species, and stacked radiochromic film (RCF) for the transverse beam profile at different proton energies. The proton spectrometers and the Thompson parabolas could be mounted at different angles for measurements of the spatial distribution.

Neutron TOF and neutron activation were used to investigate beam properties with the products of nuclear reactions, mainly DD-reactions, of the ion beam.

4 BEAM PROPERTIES

Although the energy of the LULI laser is ten times less than the energy of the Petawatt, the acceleration mechanism obviously still works. We obtained the same forward peaked emission of a very intense ion beam from the back side of the target [7].

4.1 Energy distribution

With the data of the proton spectrometers we found a

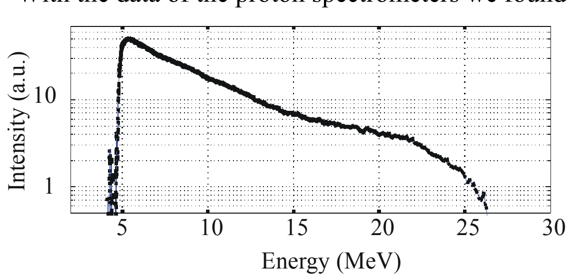

Figure 2: Energy distribution of the protons

Boltzmann like energy distribution with a maximum energy around 25 MeV. Overall there were 10^{12} protons emitted.

The spectrum in Fig. 2 could be reproduced the best when assuming two components with two different temperatures of 2 MeV and 6 MeV respectively.

4.2 Transverse beam profile

As already seen in the Petawatt experiments the ion beam has a energy dependent divergence of 8°-30° full angle. First measurements of the emittance with classic methods were limited by the detector resolution. Only a upper limit of 0.53 π mm mrad for the normalized emittance was given.

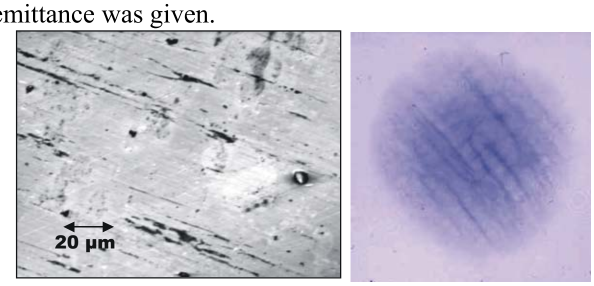

Fig. 3: Structures on the backside surface shape the beam

Analyzing the beam profile more in detail, some of the features in the beam profile were traced back to structures on the backside surface of the target. These structures change local the electron sheet on the rear side of the target which results into a structure of the ion beam. These structures are then mapped to the detector with a huge magnification. As the structure is unperturbed , the ion beam propagation is laminar.

Systematic investigation of this phenomenon with micro structured targets showed that this structures on the backside are mapped with a resolution down to the sub-micrometer range. These data gave a new upper limit for the normalized emittance: 0.06 π mm mrad.

These experiments also showed the possibility of beam shaping with suited targets. The principle was demonstrated with several shapes: grids, lines, crosses, quadratic structures and more.

4.3 Laser focus

The experiments demonstrated the possibility of ion beam shaping by tailoring the laser focus. As seen in Fig. 4 an astigmatic focus produces an ion beam with a astigmatism perpendicular to the focus.

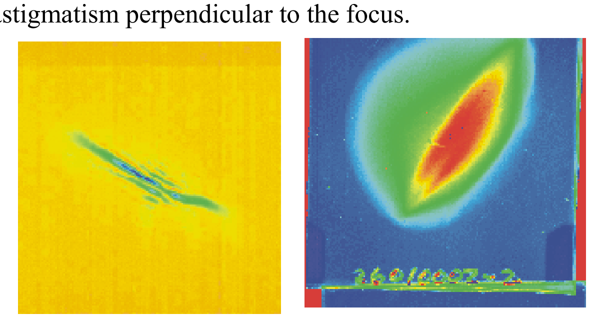

Figure 4: The ion distribution (right) depends on the shape of the focus (left)

These results can be explained assuming an electron beam shaped as the focus, propagating unperturbed through the target and leading to a focus like shaped electron sheet on the backside. As the curvature in the direction of the smaller diameter is stronger, the angular spread is higher.

The experiments show, that beam shaping with a suited focus shape is possible, especially ion beam focusing.

4.4 Acceleration of heavy ions

As explained before the acceleration of heavy ions is inhibited by the accelerated protons. When removing the hydrogen by heating the target several minutes with around 1000 °C the emission of heavy ions was increased significantly. For example we obtained 10^9 F^{7+}-ions with an energy of 3 MeV/nucleon [8].

5 APPLICATIONS

The excellent beam profile and the temporal structure of the ion beam offers some interesting applications for this type of acceleration.

5.1 Proton radiography

Proton beams can be used to shadowgraph objects. Due to the stopping process of protons also a detection of light materials in a environment of high Z-material is possible. In this way proton radiography is complementary to x-ray radiography.

Due to the excellent beam profile and the short emission time of laser accelerated protons they are ideal for investigations with high spatial and temporal resolution. In our experiments we were able to obtain a spatial resolution down to less than 10 µm.

Another speciality of proton beams is their sensitivity to electric fields. In this way proton beams are also a tool for field mapping with high temporal resolution [9].

5.2 Pulsed neutron source

Pulsed neutron sources are also feasible with laser accelerated ions. Using D-D or (p,n) reactions we could obtain a few times 10^8 neutrons in a single shot. The temporal structure is similar to the ion beam's, e.g. an emission time in the ps range.

5.3 Proton fast ignitor

One approach for inertial confinement fusion is the "fast ignitor" [10]. The basic idea is to ignite a fusion capsule by fast deposition of energy inside a pre-compressed fuel. Due to their penetration depth proton beams are better suited than lasers. The construction of a classic ion accelerator with necessary intensities is a major problem of this concept. Laser accelerated ions could reach the intensity needed for this concept[11].

5.4 Injector for accelerators

Laser accelerated ions are an alternative as an injector for normal accelerators. For example as injector for a synchrotron or in general for all high intensity accelerators. Apart from the beam parameters this is also interesting due to the smaller size and less required operation staff.

For practical reasons a laser with a higher repetition rate than today is necessary. As the phase space of the laser accelerated ions is different to the acceptance of typical accelerators, a proper phase space matching is also needed. The high space charge in addition requires a drift space in which the beam can spread up to lower the ion density. Therefore large apertures are necessary.

The low repetition rate of high intensity lasers toady is due to the high thermal load caused by inefficient pumping of the lasing material with flash lamps. The efficient pumping with laser diodes is a possibility to reduce the thermal load and to obtain higher repetition rates. A petawatt laser with 0.1 Hz repetition rate is currently under construction [12].

The transverse phase space matching can be done with available techniques. For the reduction of the divergence a quadrupole with magnetic fields of less than 2.5 Tesla is sufficient. The chromacity can be corrected with a normal sextupole.

For the longitudinal phase space matching a high gradient accelerator is necessary to reduce the energy spread. In addition the accelerator must accept a high beam load due to the huge currents. For this task a special kind of induction linac, a dielectric wall accelerator (DWA) is proposed, more detailed studies are under work.

An alternative approach is only to take a small part of the ions with a limited energy spread. A simulation shows, that the injection of 5×10^9 protons with a mean energy of 20 MeV into a high current Alvarez structure fits into the longitudinal acceptance. Although this technique would loose a lot of intensity it's still interesting due to the beam quality as described above.

REFERENCES

[1] R.A. Snavely *et al.*, Phys. Rev. Lett. **85**, 2945 (2000)
[2] A. P. Fews *et al.*, Phys. Rev. Lett. **73**, 1801 (1994)
[3] K. Krushelnick *et al.*, Phys. Rev. Lett. **83**, 737 (1999)
[4] A. Maksimchuk *et al.*, Phys. Rev. Lett. **84**, 4108 (2000)
M. Zepf *et al.*, Phys. Plasmas **8**, p. 2323 (2001)
[5] S. P. Hatchett *et al*., Phys. Plasmas **7**,2076 (2000)
[6] S.C. Wilks *et al*., Phys. Plasma **8**,542 (2001)
[7] M. Roth et al., accepted for publication in PRST-AB
[8] M. Hegelich *et al*., submitted to Phys. Rev. Lett
[9] M. Borghesi *et al*., Plas. Phys. and Contr. Fusion **43**, A267 (2001)
[10] M. Tabak *et al*., Phys. Plasma **1**, 1626 (1994)
[11] M. Roth *et al*., Phys. Rev. Lett. **86**, 436 (2001)
[12] www.physik.uni-jena.de/qe/Forschung/Eng-FP-Petawatt.html