LASER-PROTON ACCELERATION AS COMPACT ION SOURCE

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Abstract

Preparatory work is presented in the context of the upcoming LIGHT project, which is dedicated to build up a test stand for injecting laser accelerated protons into conventional accelerator structures, located at GSI Helmholtzcenter for Heavy Ion Research (Darmstadt, Germany). In an experimental campaign in 2010, a beam of 8.4×10^9 protons with 170 ps pulse duration and (6.7±0.1) MeV particle energy could be focused with the use of a pulsed high-field solenoid. Collimation and transport of a 300 ps proton bunch containing 3×10^9 protons with (13.5±0.5) MeV particle energy over a distance of 407 mm was also demonstrated. Parallel simulation studies of the beam transport through the solenoid are in good agreement with the experiment.

INTRODUCTION

Proton acceleration from sub-ps, high-intensity laser-irradiated thin foils in the TNSA [1, 2] regime has attracted much attention during the past decade. However, the proton energy distribution is of an exponential shape with a currently achievable cut-off energy of 78 MeV [3] and the beam shows an energy depended envelope-divergence (maximum 50 to 60 degrees). The radiochromic film (RCF) imaging spectroscopy (RIS [4]) enables a full characterization of the proton beam, which provides large particle numbers (10^{12}) and a small emittance. The unique beam parameters of laser accelerated ions meet the conditions for several applications, for example creation of high energy density matter [5], proton fast ignition [6] or its use as a compact accelerator source [7]. The last possibility includes the use as an alternative injector for post-acceleration structures. For most of those applications, collimation and transport of a selected proton energy interval is required.

First experiments of capturing laser accelerated protons used laser-driven microlenses [8]. This technique requires a more complex setup with two synchronized laser beams and the proton capture efficiency is low. In addition, the microlens is destroyed in each shot. In the following, permanent quadruple magnets were investigated [9]. However, those suffered from a small acceptance and low particle transmission. Consecutive experiments, carried out at the PHELIX laser (Petawatt High Energy Laser for Ion eXperiments [10]) at GSI, explored the use of pulsed, high-field solenoids, which showed promising results [11]. For a following experimental campaign the first prototype solenoid was substituted with a specially optimized solenoid, developed at the high-field laboratory of Helmholtzcenter Dresden-Rossendorf (HZDR). The new solenoid provided a larger and more homogeneous magnetic field. The experimental results are supported by simulations with the WarpRZ particle-in-cell (PIC) code [12].

The experimental and numerical studies provide the basis for the development of a test stand to capture, transport and bunch-rotate laser-accelerated proton beams, initiated by the TU Darmstadt and located at the GSI accelerator facility. The collaboration of several laser and accelerator laboratories (TU Darmstadt, GSI, Helmholtz Institute Jena, Uni Frankfurt, HZDR) provides the essential laser technology and accelerator expertise for this project, namely the **LIGHT** project: **L**aser **I**on **G**eneration, **H**andling and **T**ransport.

The LIGHT project covers the overall process from generation of laser accelerated ions to the possible post-acceleration. The separate areas that are investigated in theory, simulation and experiment are:

1. Laser pulse shaping. Manipulation of the TNSA field using an optimized intensity distribution of the laser focus.
2. Optimizing the target geometry. Development of high efficiency (laser energy to proton energy), low divergency targets.
3. Collimation, transport and energy selection using ion optical devices, e.g. the pulsed high-field solenoid.
4. Bunch-rotating and compression of a selected proton energy interval.

The necessary unique conditions for those experiments are at present provided only at the GSI facility. At the experimental area Z6, there is a fully equipped ion beamline of the UNILAC accelerator available and since January 2011 a 100 TW laser beamline of the PHELIX

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laser, combined with a multitude of laser-, plasma- and ion-diagnostics and the necessary expertise on each field.

SIMULATION

Extensive simulation work was done with the WarpRZ PIC code [13]. The code was developed to study high-current ion beams and provides the possibility of including external fields – in this case the maximum calculated magnetic field of the pulsed solenoid (7.7 T) – and customized particle sources. As particle source a typical proton spectrum of a TNSA experiment was chosen: 1.85×10^{12} protons with an exponential energy spectrum in the range of 3.4 to 23 MeV. In the simulations, those were represented by 10^6 macro particles. There have been no measurements of the co-moving ($v_{electron} = v_{proton}$) electron spectrum at this point, but a quasi neutral plasma expansion is proposed [14]. Therefore, a strictly co-moving electron spectrum of the same shape was used; i.e. electron energies from 1.9 to 12.5 keV.

The simulation box covered 500 mm in propagation direction. As the particle density rapidly goes down in time, the time steps of the simulation were chosen adjustable from 75 fs to 1 ps.

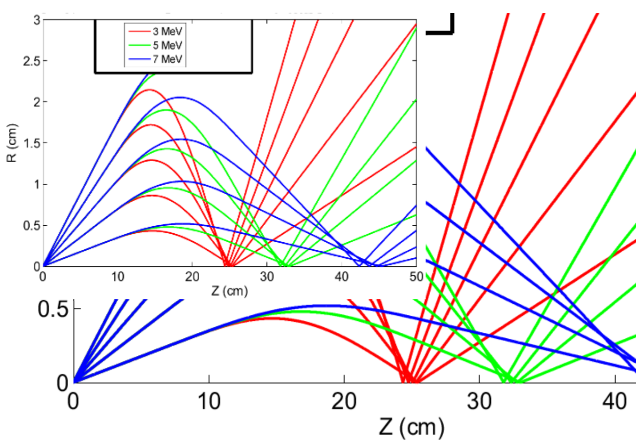

Figure 1: Spherical and chromatic aberrations of protons in the solenoidal ion optic. The black bold lines mark the solenoid edges.

Fig. 1 shows chosen particle trajectories of protons influenced by the magnetic field of the solenoid with a maximum value of 7.5 T. The chromatic aberration of this ion optic leads to the fact, that different proton energies are focused in different places. This gives the opportunity of energy selection via a pinhole of a few millimetres diameter placed in a distance, where the desired proton energy is focused. In this way, most particles with energies different from the focussed particles' one can block out.

As a second effect, spherical aberrations can be observed, too. They occur due to the fact, that the particles enter the field under different divergence angles and propagate through a spatially slightly different magnetic field. As a consequence, the focus of one specific particle energy is smeared out, resulting in a growth of beam emittance.

EXPERIMENT

The simulation results could be verified in an experimental campaign at the laserbay of the PHELIX facility at GSI in 2010. In the short pulse operation mode, PHELIX provided about 100 J of laser energy in 500 fs. With a focal spot diameter of about 15 µm this is equivalent to 5×10^{19} W/cm^2. The achievable contrast is 60 dB. As targets, 5 to 25 µm thin gold foils were used.

The targets were placed 95 mm before the solenoid. This is necessary to avoid induced eddy currents in the target when pulsing the solenoid. Earlier experiments [10] showed that the target foil is bent up to 18° due to those currents and so directly affects the propagation direction of the target normal accelerated proton bunch. The solenoid itself had a length of 150 mm, an aperture of 48 mm and consisted of 108 copper wire windings. The detector (RCF in stack configuration [7]) was placed behind the solenoid and in a 407 mm distance to the target.

Focussing and collimation of protons could be demonstrated for different energies, using different field strengths in the solenoid. Fig. 2 (left side) shows the image of the different RCF layers of one shot with a maximum magnetic field of 7.7 T of the solenoid. The films are in stack configuration and different proton energies have their Bragg peak (and consequently maximum deposited energy) in different layers. The Bragg peak energy for each film is also indicated in fig 2.

The lower energetic protons (3.7 MeV, first film) are over-focused and the beam shows strong filamentation. A focussing of protons could be observed in the second film (6.6 MeV). At FWHM the focus profile was 1.2 mm times 1.7 mm and contained 8.4×10^9 protons.

The collimated proton beam necessarily has the beam diameter of the solenoid aperture (48 mm) and was calculated to be at (13.5±0.5) MeV with 3×10^9 protons in this energy interval via analysis of the RCFs.

COMPARISON OF SIMULATION AND EXPERIMENT

Fig. 2 shows the experimental results in comparison to the results of the simulation. To compare the simulation with the experiment, the spatial profile of the simulated proton beam (more specifically the theoretically deposited energy in RCFs) at 407 mm behind the target is plotted.

The simulations are in perfect agreement with the experiment concerning the focussing (~6.6 MeV) and collimation (~14 MeV) energies. However, due to co-moving electrons, an additional proton focus on beam axis is observed in the simulations only. Also, the strong filamentation of the over-focussed protons is not predicted by the simulations.

Disabling space charge effects in the simulations leads to a vanishing of this feature in the proton beam. Having a

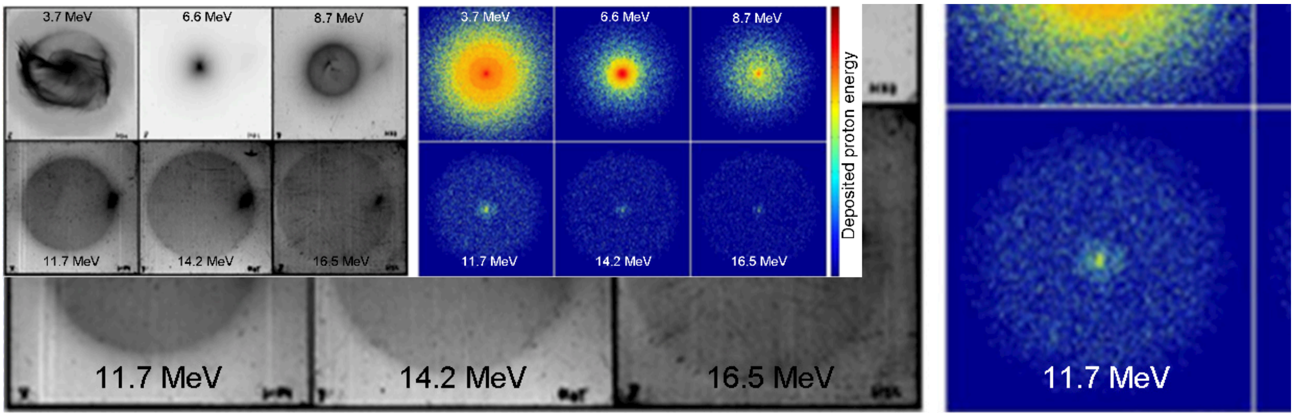

Figure 2: Comparison of experiment (left) and simulation (right). In both cases, the deposited energy in RCFs is shown. For each RCF of the stack the proton Bragg peak energy is shown. The black spot on the right side of the RCFs in the experiment is the signal of high energetic electrons.

closer look on the electrons while propagating through the solenoid reveals that, due to their lower mass, the co-moving electrons are tightly focused on beam axis in the solenoid. And although about 80% of the electrons are reflected by the magnetic mirror effect, the on-axis electron aggregation has an influence on the protons via Coulomb force. As this effect could not be verified by the experiment, the assumed co-moving electron spectrum has to be questioned. In addition, the filamentation of the over-focused proton beam is most likely also caused by space charge effects.

A magnetic spectrometer was designed to investigate the co-moving electrons. First experimental data could be gathered during a laser ion acceleration experiment at the Callisto laser facility at Lawrence Livermore National Laboratory, California, USA. The preliminary results show a non-exponential feature in the electron spectrum around 5 keV electron energy (fig. 3).

Further experiments are planned during 2011 to fully determine the low energy electron spectrum in TNSA

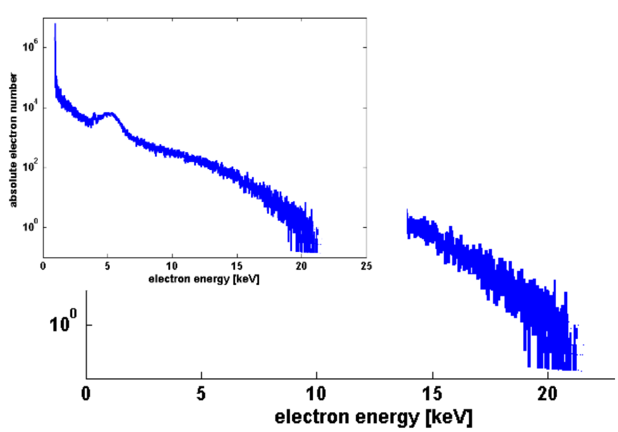

Figure 3: Spectrum of co-moving electrons in a TNSA experiment. An unpredicted non-exponential feature has been discovered in a small energy interval. The steep rise in electron numbers to lowest energies is only due to entering the critical sensitivity of the detector.

experiments and the degree of quasi-neutrality during the plasma expansion. These data will then serve as new input parameters for simulations.

CONCLUSION

First experiments demonstrated transport of large particle numbers (about 10^{12} in total and some 10^{9} in small relevant energy intervals) of laser accelerated protons over a distance of 407 mm. Simulations are in good agreement. Only determining the real co-moving electron spectrum is a current problem; a beamtime in autumn 2011 is planned to investigate this issue.

The results about collimation and transport of protons provide the basis for the further investigation of laser accelerated particle sources as injector for conventional accelerator structures. The upcoming LIGHT collaboration is dedicated to realize a test stand for those studies within the following months.

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