Transport of laser accelerated proton beams and isochoric heating of matter

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Abstract. The acceleration of intense proton and ion beams by ultra-intense lasers has matured to a point where applications in basic research and technology are being developed. Crucial for harvesting the unmatched beam parameters driven by the relativistic electron sheath is the precise control of the beam. We report on recent experiments using the PHELIX laser at GSI, the VULCAN laser at RAL and the TRIDENT laser at LANL to control and use laser accelerated proton beams for applications in high energy density research. We demonstrate efficient collimation of the proton beam using high field pulsed solenoid magnets, a prerequisite to capture and transport the beam for applications. Furthermore we report on two campaigns to use intense, short proton bunches to isochorically heat solid targets up to the warm dense matter state. The temporal profile of the proton beam allows for rapid heating of the target, much faster than the hydrodynamic response time thereby creating a strongly coupled plasma at solid density. The target parameters are then probed by X-ray Thomson scattering (XRTS) to reveal the density and temperature of the heated volume. This combination of two powerful techniques developed during the past few years allows for the generation and investigation of macroscopic samples of matter in states present in giant planets or the interior of the earth.

Introduction

The realization of intense and energetic laser pulses has resulted in enormous scientific activity over the past decade due to many potential applications including the generation of giga-electron-volt, narrow band electron pulses [1], intense x-ray pulses [2], laser-driven nuclear phenomena [3], inertial fusion energy [4,5], as well as the acceleration of protons from hydrocarbon impurities and heavy ions to mega-electron-volt energies from thin foil targets [6–9]. These ion beams (particularly protons) are generated in a very robust and reproducible way with up to 10^{13} protons by the target normal sheath acceleration mechanism [10]. The ions are accelerated, forming a quasineutral plasma with an exponential energy spectrum that exhibits a sharp cutoff at its maximum energy [11]. Unlike conventionally accelerated ion beams, they contain very high particle numbers in short, picosecond pulses and have unprecedented emittance; i.e., the beams expand in a very laminar fashion [12]. These features make them useful as a diagnostic tool (e.g., proton radiography of transient processes [13]) and they could have applications as compact particle accelerators [14] for the creation of high-energy density (HED) matter [15] or for proton fast ignition [5]. Because of the high intensity and the volumetric energy deposition of the proton beams in solid material, large samples of Warm Dense Matter (WDM) can be produced. This exotic state of matter between solid and plasma state is of high interest and relevant for astrophysical research and possible industrial applications.

Ion beam transport

The interaction between an ultra-intense laser pulse (I $>10^{18}$ W/cm2) and a thin target foil leads to an acceleration of protons up to kinetic energies of several tens of MeV. In the short acceleration time of a few picoseconds up to 10^{13} protons and ions are accelerated. Well defined, smooth beams with transverse emittances up to hundred times smaller than in conventional accelerators are observed in experiments [12,16]. This remarkably good beam quality motivates the injection into conventional accelerators. However, such an application requires further investigations to reduce the half-opening angle of the beam which is up to 40 degree and to minimize the energy spread. An external magnetic field as a collimation and energy filtering method decouples the acceleration process and the transport providing the opportunity of independent optimization of both processes[17].
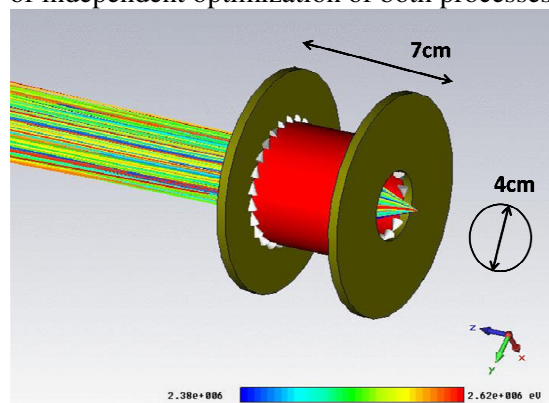

Figure 1: The figure shows a simulation with CST Studio. The solenoid magnet used in the experiments has a length of 7cm and an open inner diameter of 4 cm. A magnetic flux density of 8 T in the solenoid collimates protons with an energy of 2.5 MeV.

We report on an experiment carried out at the PHELIX laser system at GSI. PHELIX (Petawatt High Energy Laser for Ion eXperiments) is a high energy laser system operating at 1µm using large scale Nd:glass amplifiers. In its current state it delivers up to 150 J in 700 fs to reach focused intensities of 5 x 10^{19} W/cm^2. In the experiments we used a pulsed high field solenoid to collimate and focus the

proton beam and further increase the proton flux density. Since the solenoid focuses the beam in all transverse directions it can be used as a compact single device. Thus, higher transmission of protons through the solenoid can be achieved in comparison to quadrupoles. The strong magnetic flux densities of up to 15 T were generated by some of the capacitors normally used to trigger the flash lamps of PHELIX. The solenoid was placed 17 mm behind the target to make sure that all protons enter the solenoid's aperture of 44 mm. The simulation with CST Particle Studio in figure 1 shows the behavior of the proton beam in the magnetic field. For this we took the actual beam divergence from experiment as input parameters for the CST simulation. A magnetic flux density of 8 T leads to a collimation of protons with a kinetic energy of 2.5 MeV. The measured particle numbers detected behind the solenoid at a magnetic flux density of 8 T was compared to the initial particle numbers. Therefore the detector was placed 240 mm behind the target and had a size of (5 x 5) cm (see Figure 2). As the simulation suggests, the 2.3 MeV protons are slightly focused, so that the beam diameter behind the solenoid is smaller than the detector size.

Figure 2: Example of the effect of the solenoid on proton beams. Proton beam image of two consecutive shots measured at a distance of 240 mm behind the target. Whereas no significant energy deposition is visible without energizing the coil a clear proton beam signal can be seen on the right part of the image.

About (95 +5 -19)% of the initial particles could be detected. In comparison to laser-proton-acceleration without beam parallelization by the solenoid only 23% of the initial protons can be detected in the RCF due to the strong divergence of the beam. Since the magnetic field is not strong enough to collimate protons with energies higher than 2.5 MeV the amount of detected particles in comparison to the initial particles decreases strongly with increasing proton energy.

In summary we have demonstrated collimation of laser accelerated proton beams with a pulsed high field solenoid. For the designed particle energy almost the entire beam could be detected. As can be seen in Figure 2 the beam is not really homogeneous. We verified that the proton beam accelerated off the laser target was a smooth laminar one, so the distortions in the beam were caused by the interaction of the ion with the magnet. Two main aspects are currently investigated in more detail. First, the loss of quasi neutrality, because the co-moving electrons are forced on the solenoid axis, thereby generating an electrostatic lens inside the magnet. This also is assumed to be the reason for an enhanced focusing capability, which was observed, compared to numerical simulations taking into account the influence of the B-field only. Second, there was observed an interaction of the ions (or plasma) with the inner wall of the solenoid causing local surface discharges which certainly influenced the homogeneity of the B-field. The analysis of the spatial structure of the transported ion beam is currently investigated and will be presented soon.

Driving Warm Dense Matter

The unmatched beam intensity and excellent beam quality results in important applications like ion source development, radiography, the concept of proton driven fast ignition and the generation of exotic states of matter. The latter is of particular importance due to the different interaction mechanism of ions compared to lasers. Whereas lasers only interact with the surface of a sample, ions can penetrate deep into the material of interest thereby generating large samples of homogeneously heated matter. The short pulse duration of laser produced ion beams furthermore allows for the investigation of equation of states close to the solid state density, because of the material's inertia preventing the expansion of the sample within the interaction. In addition to these unique characteristics, the interaction of ions with matter dominantly is due to collisions and does not include a high temperature plasma corona as it is present in laser matter interaction. The absence of a large radiation background is of importance to the experiment as will be explained later. Large conversion efficiencies have been observed and significant energy can be transferred from the ultra intense laser via the ion beam into the sample of interest. Because of the high beam quality, ballistic focusing has been demonstrated, allowing for an increase in local energy deposition and thus to higher temperatures.

The generation of large homogenous samples of warm dense matter is, as challenging as it is, accompanied by the even more challenging task to diagnose this state of matter, as usual diagnostic techniques fail under these conditions. The material density results in a huge opacity and the relatively low temperature does not allow traditional spectroscopic methods to be applied. Moreover the sample size, deposited energy and lifetime of the matter state are strongly interrelated and dominated by the stagnation time of the atoms in the probe. Thus high spatial and temporal resolution is required to gain quantitative data in those experiments. XRTS as the second technique developed in the recent years is ideally suited for these conditions.

The scattering of externally generated x-rays off electrons has demonstrated excellent diagnostic quality [18-22]. It is not only able to penetrate deep into the matter revealing the properties in the bulk material, but it also simultaneously results in the most wanted parameters temperature and density with highest precision. The challenge is the small cross section for the interaction which requires a powerful x-ray source as well as low background radiation level as well as high resolution spectrometers with high efficiency.

We combined these two new techniques for the first time to investigate the transformation of solid, low-Z material into the state of warm dense matter. For this we used the 60 J, 1 ps CPA beam to generate an intense proton beam to heat the sample of interest, and the 200 J, 20 ps beam 8 of the VULCAN laser to drive an x-ray source to scatter off the proton driven sample. In a second campaign we used the high contrast short pulse beam of the LANL Trident laser to drive a powerful proton beam and the remaining two long pulse beams to drive thermal Chlorine backlighter radiation. By varying the distance of the proton source to the warm dense matter sample we shaped the pulse length of the proton beam due to the dispersion caused by the energy distribution of the ions. We also shaped the ion source target in order to collimate the ion beam onto the sample for maximising the energy deposition. One advantage of the presented concept is that we can separate the ion driver from the sample and therefore can apply sufficient shielding to explore the material conditions in absence of a large radiation field.

This experiment also served as a demonstration experiment for the concept of proton driven fast ignition, where the low-Z material is to be heated to fusion conditions by a short pulse laser driven proton beam. The complex targets necessary for these experiments were produced in a collaborative effort between the RAL target laboratory and the one at Technische Universität Darmstadt.
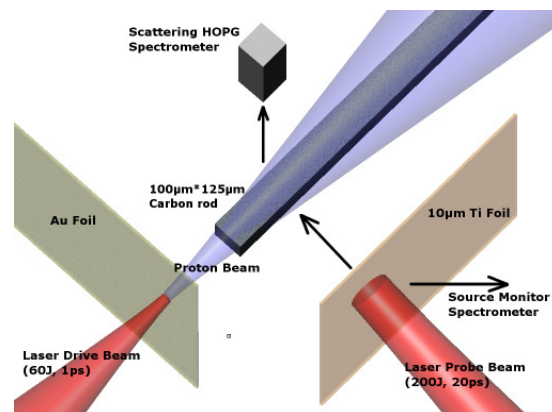
Figure 3: Target design for the RAL campaign. The 100 TW laser from the lower left part hits the gold foil to accelerate protons to heat the solid carbon rod. From the right the 20 ps 200 J backlighter beam irradiated the Titanium foil. The scattered radiation is detected at an angle of 90 degree through a slit in the shield at the bottom of the target.

The energy deposited by the proton beam was measured by the analysis of the part of the proton spectrum that missed the target. Because of the high intensity of the proton beam in addition to RCF, a new method based on nuclear activation was used to determine the proton beam energy content. Based on the deposited energy the temperature of the driven carbon sample was calculated. Figure 4 shows the temperature distribution of the RAL experiment in the carbon sample together with the measured region. The calculation was based on actual proton particle spectra from the experiment and used tabulated stopping power data and EOS to simulate the temperature distribution.
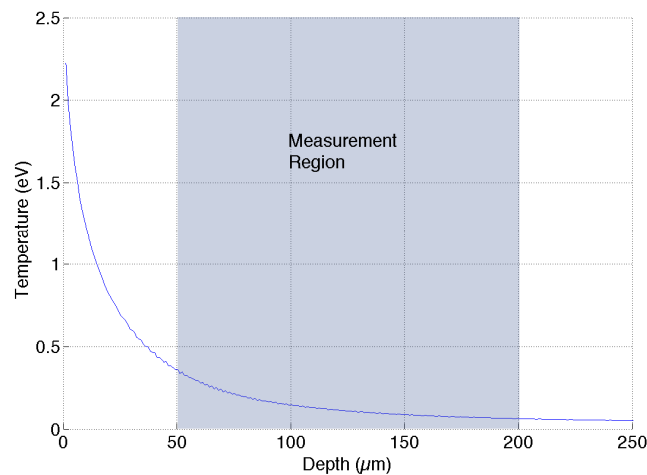

Figure 4: Temperature distribution in the solid carbon sample based on the measured proton spectrum. The shaded area represents the measured region, covering the temperature range of the solid – liquid phase transition.

The temperature in these first experiments was limited by the available proton beam energy. It covers the range between liquid carbon and the excited solid phase, a region of high interest. The change in temperature results in a strong decrease of the Thomson scattered signal elastic component. This was observed in the experiment and excellent agreement with theory could be demonstrated. Details as well as the results from the LANL experiments are still subject to analysis and will be published soon. However in the RAL experiments the predicted temperature could be demonstrated, showing the feasibility of the method for the first time.

Summary

We have successfully demonstrated the efficient capture and transport of laser accelerated proton beams using pulsed high field solenoid magnets. Almost the entire particle number could be guided through the ion beam transport system for the design particle energy. In these experiments a novel version of a nuclear temperature measurement was developed using giant resonance excitation of different isotopes. In two experimental campaigns laser accelerated proton beams were used to isochorically heat a solid carbon sample. The temperature was measured using x-ray Thomson scattering and showed good agreement with the predictions based on state of the art equation of state parameters. Finally a new diagnostic for very intense ion beams based on nuclear activation with high spatial and spectral resolution was successfully tested.

References

[1] W. P. Leemans, B Nagler, A. J. Gonsalves, Cs. Toth, K. Nakamura, C. G. R. Gedes, E. Esarey, C.B. Schroeder and S.M. Hooker , Nature Phys. **2**, 696 (2006).
[2] M. M. Murnane, H. C. Kapteyn, M. D. Rosen and R. Falcone, Science **251**, 531 (1991).
[3] K.W. D. Ledingham, P. McKenna, R. P. Singhal, Science **300**, 1107 (2003).
[4] M. Tabak, J. Hammer, M. E. Glinsky, W. L. Kruer, S.C. Wilks, J. Woodworth, E. M. Campbell and M. D. Perry, Phys. Plasmas **1**, 1626 (1994).
[5] M. Roth, et al. , Phys. Rev. Lett. **86**, 436 (2001).
[6] R.A. Snavely, et al., Phys. Rev. Lett. **85**, 2945 (2000).
[7] E. L. Clark, et al., Phys. Rev. Lett. **84**, 670 (2000).
[8] A. Maksimchuk, S. Gu, K. Flippo, D. Umstadter, V. Yu. Bychenkov, Phys. Rev. Lett. **84**, 4108 (2000).
[9] M. Hegelich, et al., Phys. Rev. Lett. **89**, 085002 (2002).
[10] S.C. Wilks, et al., Phys. Plasmas **8**, 542 (2001).
[11] J. Fuchs, et al., Nature Phys. **2**, 48 (2006).
[12] T. E. Cowan, et al., Phys. Rev. Lett. **92**, 204801 (2004).
[13] L. Romagnani, et al., Phys. Rev. Lett. **95**, 195001 (2005).
[14] A. Pukhov, Phys. Rev. Lett. **86**, 3562 (2001).
[15] P. K. Patel et al., Phys. Rev. Lett. **91**, 125004 (2003).
[16] F. Nürnberg, et al., Rev. Sci. Instr., Vol. 80 (3), p. 033301 (2009)
[17] M. Schollmeier, et al., Phys. Rev. Lett. **101**, 055004 (2008).
[18] G. Gregori *et al.,* Phys. Rev. E **67** 026412 (2003).
[19] S. H. Glenzer *et al*., Phys. Rev. Lett. **90**,175002 (2003).
[20] S. H. Glenzer *et al*., Phys. Rev. Lett. **98,** 065002 (2007).
[21] A. L. Kritcher *et al*., Science **322**, 69 (2008).
[22] E. Garcia Saiz *et al.,* Nature Physics **4**, 940 (2008).
[23] R.J. Clarke et al., Nucl. Instr. and Meth. A -585, 117-120 (2008)
[24] P. McKenna, et al., Phys. Rev. E, 70, 036405 (2004)