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Application of laser-accelerated high-energy protons for isochoric heating of matter

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The possibility of producing, in a controlled way, matter at solid density (1-10 g/cm3) while maintaining it at a high temperature (1-100 eV) has been for a long time a desired goal. Studying matter in these conditions would provide an array of information useful for a variety of problems [1] that range from fundamental physics (dense and relatively cold matter at the frontier of plasma physics) to astrophysics (matter in the planetary cores) through applications like ICF (stopping power of particles in warm dense matter).

To achieve this, energy has to be deposited in a short time scale before heating-induced expansion decreases the density of the heated matter, i.e. isochorically. The heated material is then inertially confined. Up to now, attempts to achieve isochoric heating have been pursued using either short-pulses lasers or short-duration laser-produced x-rays (through inner transitions induced in solids by laser-accelerated hot electrons). Optical frequencies are very limited in their penetration of solid matter, typically some nm of skin depth in Al for 1 μm light. Therefore only a surface layer is directly heated [2] while the inner part of the sample gets heated on a much longer time scale through heat conduction accompanied by thermal expansion. This does not allow maintaining a high density and temperature. Therefore, high intensity laser pulses incident on a thin foil cannot create an uniform, hot dense plasma.

In comparison, ions have a much higher penetration depth, allowing *volumetric heating*; for example the Bragg peak in Al is at a depth of 5 μm for a 0.5 MeV proton and 200 μm for a 5 MeV proton. Ions deposit energy directly and deeply in matter and can create isochoric heating provided that the energy deposition time is shorter that the heating-induced expansion time. In typical large ion accelerators such as GSI, much higher ion energies can be produced than with lasers, but in much longer bunches (tens of ns) that prevent the deposition of the energy before hydrodynamic expansion.

There is a specific interest for this purpose in using ultra-intense laser-accelerated ions and protons [3], even if of relatively modest energies compared to the beams produced by accelerators, i.e. in the MeV range. Indeed, they have the superior advantage of being produced in a very short time, < 1ps. After 300 µm of propagation, there is only ~ 20 ps of debunching time within the proton beam (between 0.5 MeV and 5 MeV), so that energy can be deposited potentially in a shorter time scale than the expansion time of matter heated to a few eV, allowing the possibility to create isochoric heating over a large volume of matter [4].

We have carried out on the 100TW laser at LULI, Ecole Polytechnique, France an experiment to test these concepts and measure the heating that can be induced by a laser-accelerated proton beam on a solid cold target. The experimental set-up is shown below.

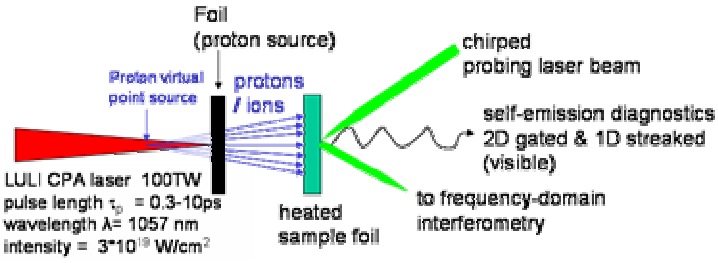

Figure 1: schematic of the experiment. A proton focused beam is incident on a thin foil that is heated.

The emissivity of the heated sample has been measured to determine the sample temperature. The measurement was made in the visible range by using time-resolved 1D imaging by a streak camera (to resolve the fast heating induced by the beam from the subsequent heat wave that travels much slower through the sample foil) and a 2D gated imager, the ensemble being absolutely calibrated. The OTR (Optical Transition Radiation), induced in the second foil by the MeV range electrons leaving the primary target, could be detected and partially separated from the later heating signal due to proton stopping in the foil. Figure 2 shows the emissivity of a target taken by a fast 1D streak camera with a ~2 ps resolution. In subplot a) the intense higher spot is due to the OTR of the fast electrons and, after the crossing time of the protons, the heating they induce is visible. Subplot b) shows that the OTR can be isolated from proton heating by tilting the second target (here the streak camera has only a ~30 ps resolution). In fact, the protons will be accelerated normally to the tilted surface whereas the electrons will continue their propagation parallel to the incident laser pulse.

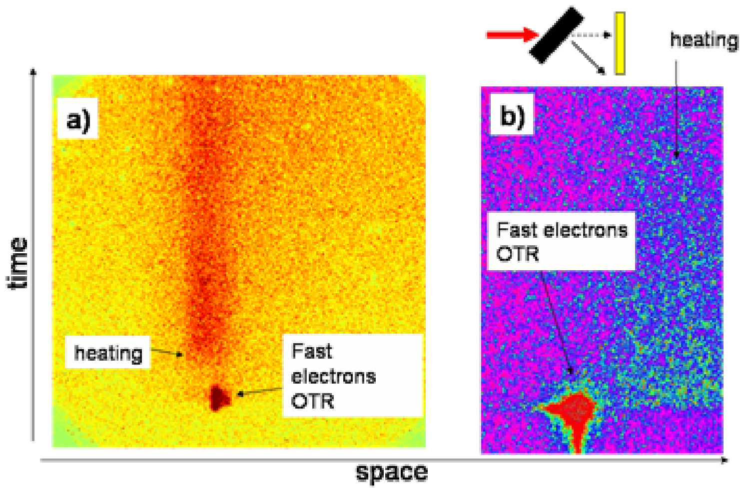

Figure 2: Separation of the OTR signal induced by fast electrons from the proton heating signal a) in time using a fast streak camera b) in space, using a tilted target.

During the experiment, we have explored a range of parameters by varying the thickness of the sample heated foil, using targets of different Z like aluminum or gold, varying the heated temperature by moving the sample out of focus and using curved targets.

Figure 3 shows the time-resolved 1D optical emission from the rear-surface of various proton-heated targets. One can see that the heating decreases as the target thickness increases and that heating increases with the Z of the target, as expected. This, since the stopping power of the protons increases with higher Z targets.

Experimental data are compared to simulations using a 2D hydrocode (DUED) [5] and having as input the known accelerated proton energy distribution. This distribution is made out of two temperatures, one for the low energy protons (T=0.9MeV) and one for the high energy protons (T=5.4MeV). For both, the number of protons decreases exponentially, the high energy proton distribution having a higher temperature, but a smaller number of protons (i.e. there are 2 orders of magnitude between the number of protons at 0.5 and 5 MeV). The main contribution of the heating is predominantly due to the low energy protons. Figure 4 shows how the target can be heated in a few picoseconds to temperatures of a few eV. Moreover one can clearly see the initial isochoric heating and, after some tens of picoseconds, the adiabatic expansion. Also a radial profile of heating is detectable. On the back side of the target, where no protons are arriving, the adiabatic expansion is visible.

Concerning curved targets [4], we were able to better concentrate protons on the target, but did not see a substantial increase of the heating. It seems hence better to focus the laser with its full intensity on a flat target than to irradiate a larger curved spot which is necessary to focus the protons but causes a too large decrease in the number of accelerated protons.

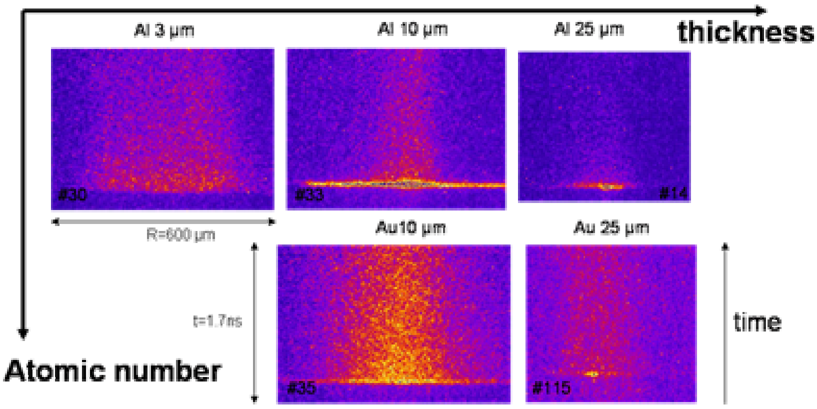

Figure 3: Time-resolved 1D images of the rear-surface of a proton-heated foil. Time goes up.

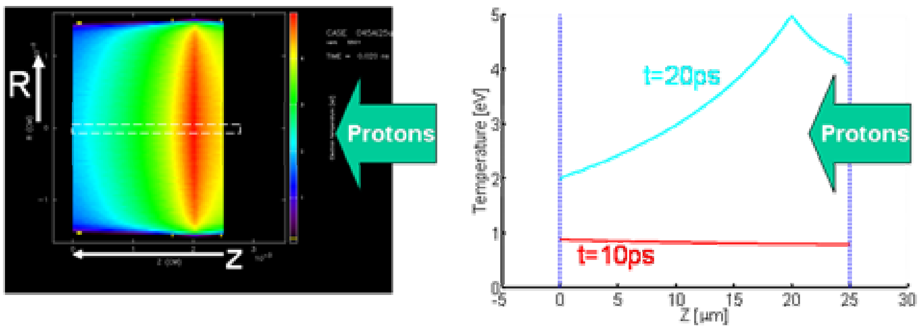

Figure 4: DUED Simulation for a 25µm aluminum foil heated by protons, 20ps after the irradiation starts. a) shows the 2D temperature map whereas in b) is shown in abscissa the longitudinal target depth, in ordinate the mean temperature around the central point (±15µm). The Bragg peak one can see at 20 ps is mainly due to protons of about 0.5MeV, which cross the distance between the two targets of about 200µm in 20ps.

The results show that accelerated protons can indeed be used to achieve heating of solid targets. This method is promising as a way either to measure the equations of state of materials in poorly known conditions (a few eV, solid density) or as a way to measure the stopping power of higher Z ions (other than protons) which is not well known.

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References:

[1] http://www-hasylab.desy.de/conferences/WDM/content-3.html#wdm
[2] P. Audebert *et al.*, Phys. Rev. Lett. **89**, 265001 (2002).
[3] R. Snavely *et al.*, Phys. Rev. Lett. **85**, 2945 (2000); S. C. Wilks *et al.*, Phys. Plasmas **8**, 542 (2001) ; S. Hatchett *et al.*, Phys. Plasmas **7**, 2076 (2000) ; M. Hegelich *et al.*, Phys. Rev. Lett. **89**, 085002 (2002).
[4] P. K.Patel et al., Phys. Rev. Lett. **91**, 125004 (2003)
[5] S. Atzeni et al., Comput.Phys.Commun doi:10.1016/J.cpc.2005.03.03