Interaction of high-energy laser pulses with plasmas of different density gradients

J. Wolowski[1] , J. Badziak[1], A. Czarnecka[1], S. Gammino[2], J. Krása[3], L. Láska[3], A. Mezzasalma[4], P. Parys[1], M. Pfeifer[3], K. Rohlena[3] M. Rosinski[1], L. Torrisi[2,4], J. Ullschmied[3]
[1]*Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland*
[2]*INFN-Laboratori Nazionali del Sud, Catania, Italy*
[4]*Institute of Physics and PALS RC, ASCR, Prague, Czech Republic*
[5]*Università di Messina, Messina, Italy*

1. Introduction

The characteristics of the laser-produced plasma depend, among other factors, on distribution of the electron density during interaction of high-energy laser radiation with expanding plasma. First of all, different interaction mechanisms depend on electron density gradient in plasma, particularly, in the vicinity of a critical density (n_{cr}). But at densities lower than n_{cr} the efficiency of collisional absorption, as well as stimulated Brillouin and Raman scatterings (SBS and SRS) increase when the density gradient decreases. The SBS process is dangerous for the efficiency of indirect-driven laser fusion because it generates hot electrons in the high-Z plasma produced by laser beams on the inner surface of the Hohlraum capsule.

The plasma produced using a sub-nanosecond laser pulse at intensities of 10^{14}–10^{16} W/cm^2 emits ions with a broad range of charge states and with energies from hundreds of eV to hundreds of MeV as well as x-rays of energies from tens of eV to tens of keV, depending on the irradiated target material and the parameters of the laser used [1-8]. Experimental efforts in this field have concentrated on the influence of the pre-plasma produced by the prepulse on the characteristics of the x-rays emitted from laser-generated plasma [9-11]. Recently, the effect of a pre-pulse has been proposed [12] for investigating the relativistic self-focusing phenomenon accompanying very high intensity laser-plasma interactions.

In this paper, we present the results of investigations of the properties of laser-produced ion streams performed in the presence of pre-pulses of different parameters.

2. Equipment

The experiment was performed using the PALS iodine laser system at the PALS Research Center in Prague operating at a wavelength of 438 nm (3rd harmonics of fundamental frequency). The laser beam (up to 250 J in a 400-ps pulse) was focused onto a Ta target perpendicularly to the target surface, forming a laser spot with minimum diameter equal to ~70 μm. The measurements were performed using a fixed laser pulse energy, E_L = 140±10 J, corresponding to a power density of ~9×10^{15} W/cm^2. The main laser pulse was preceded by a pre-pulse having either 7% of the main-pulse energy, corresponding to pre-pulse energies $E_{p\text{-}L}$ of ~10 J. The main pulse was delayed by $\Delta t_{p\text{-}L}$, = 0, 0.33, 0.68, 1.4, 2.47, 3.34, 3.45, 3.76, 3.84 or 4.7 ns with reference to the pre-pulse.

In our experiments, we have used ion collectors (ICs) and a cylindrical electrostatic ion energy analyzer (IEA) for measuring the characteristics of the laser-generated ions [13]. Both of these diagnostics utilize the time-of-flight method. The IC measures a charge-integrated time-resolved signal of ions, from which the charge carried by the ions and ion velocity (energy) can be derived. Angular distribution of ion emission was measured using 5 ion collectors located at different distances (44, 50.5, 51.5, 54, and 61 cm) and different angles with respect to the target normal: 0° (IC_0), 25,6°, 34.4°, 45°, and 54°. The IEA makes it possible to identify the ion species produced, i.e. to determine their mass-to-charge ratios, energies, and abundance. The IEA was located at an angle of 30°.

3. Results

The ion collectors recorded groups of fast, thermal, and slow Ta ions. The characteristics of three ion groups depend on the different mechanisms of ion acceleration. The group of faster nonthermal Ta ions in the collector signal, if analyzed by the IEA, is found to be composed of the high charge state of ions. The ions slower than thermal ions were emitted from cooler plasma produced by x-rays generated in the hot laser-heated plasma.

The shape of the part of the IC signal recorded at the angle of 0^o corresponding to the fast Ta ions changes with increasing $\Delta t_{p\text{-}L}$ as shown in Fig. 1. In particular, the fast ion peak at ~2 ns for $\Delta t_{p\text{-}L}$ = 4.7 ns is narrower in comparison with the wider fast ion signals for shortest $\Delta t_{p\text{-}L}$, although, the velocity (energy) of fast ions at $\Delta t_{p\text{-}L}$ = 4.7 ns is considerable lower then in the case of shorter $\Delta t_{p\text{-}L}$. The maximum Ta ion current and the peak energy of fast ions at 3.5 ns < $\Delta t_{p\text{-}L}$ < 4.7 ns do not change significantly. It was observed that the large number of slow ions recorded at $\Delta t_{p\text{-}L}$ = 0 by IC_0 (proportional to slow ion current density) falls sharply up to undetectable amount for $\Delta t_{p\text{-}L}$ = 4.7 ns. The maximum and peak ion energies calculated on the basis of the IC signals attain maximal values at $\Delta t_{p\text{-}L}$ <1.2 ns and decrease for longer delay times.

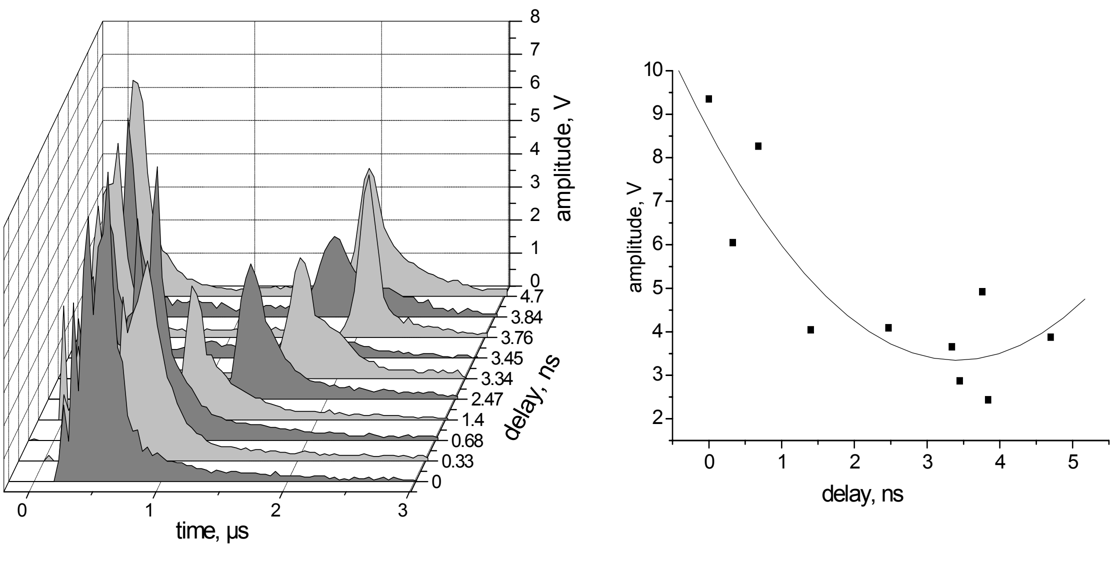

Fig. 1. Typical IC signals for fast Ta ions recorded at 0° and for different delay times and dependence of the amplitude of fast ion peak on the delay time.

The angular distributions of the fast ion currents, estimated for plasma produced by the main laser pulse without pre-pulse and with pre-pulse preceding the main pulse, for $\Delta t_{p\text{-}L}$ = 4.7 ns are shown in Fig. 2. In the pre-pulse case, the ions expand with smaller angular divergence than in the case without pre-pulse. In the first case the group of fast Ta ions was significantly slower then for $\Delta t_{p\text{-}L}$ = 0 and was recorded only by IC located at an angle of 0°.

Examples of ion spectra recorded at 30° using the IEA with a deflecting potential of 30 kV are shown in Fig 3, for time intervals between the pre-pulse and the main laser pulse ($\Delta t_{p\text{-}L}$). = 0, 0.6, 1.2 and 4.6 ns. The relative abundance of different Ta ion species depends significantly on $\Delta t_{p\text{-}L}$. The diagram shows that for a deflecting potential of 30 kV selecting the high energy ions (E_i = 30z keV, where: z – ion charge state) the highest ion charge states (z_{max} ~50+) occur for $\Delta t_{p\text{-}L}$ = 0, 0.6 and 1.2 ns. For $\Delta t_{p\text{-}L}$ = 2.3 ns the maximum ion charge state was only z_{max} ~ 25+, while for $\Delta t_{p\text{-}L}$ = 4.6 ns only z_{max} ~ 3+ was recorded.

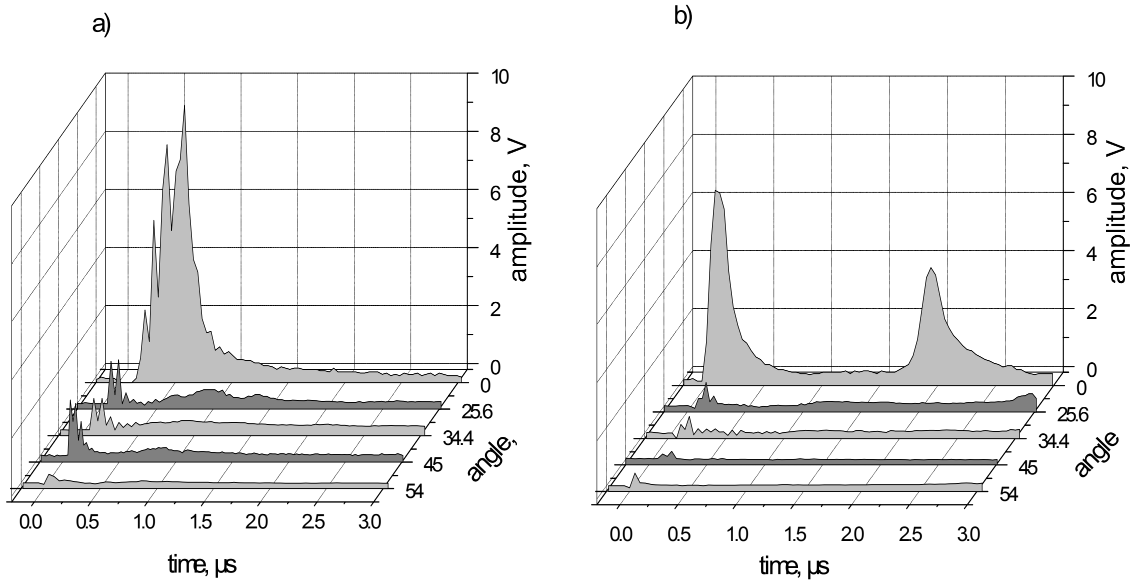

Fig.2. Angular distributions of fast Ta ion emission for $\Delta t_{p\text{-}L}$ = 0 (a) and $\Delta t_{p\text{-}L}$ = 4.7 ns (b).

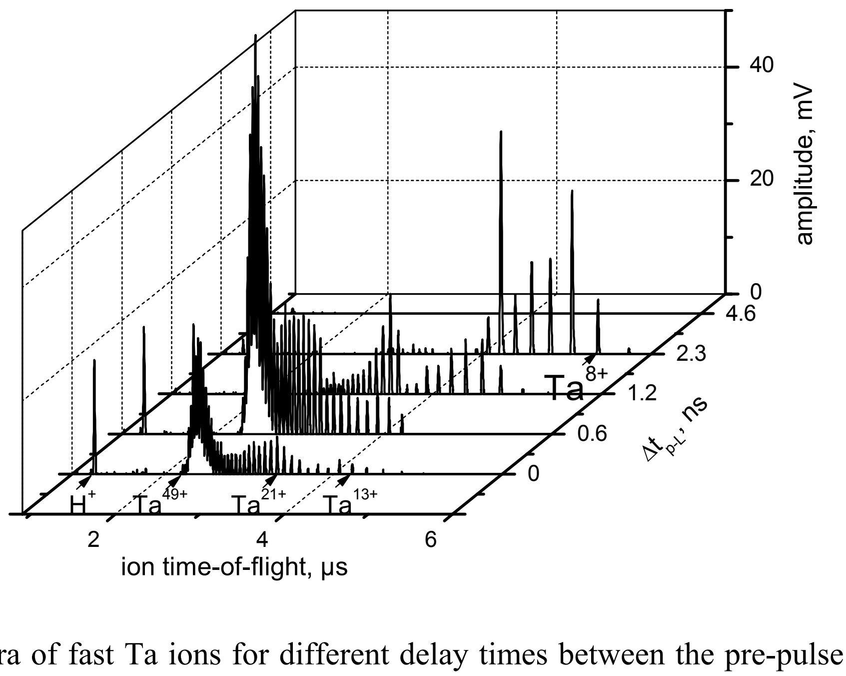

Fig. 3. Spectra of fast Ta ions for different delay times between the pre-pulse and the main laser pulse, recorded at 30 kV deflecting voltage.

4. Discussion of results and conclusions

At a laser pulse energy of ~140 J (laser intensity of ~9×10^{15} W/cm^2) wavelength of 438 nm, pulse duration of 400 ps) heating the plasma without a pre-pulse produced high energy (up to several MeV) highly-charged Ta ions and hard x-rays similar to our previous experiments [6,7,8,14]. A laser pre-pulse, which creates a pre-plasma, changes the laser-matter interaction considerably, in particular the efficiency of fast ion acceleration.

The maximum and mean energies of the fast ions, as well as the yields of both hard and soft x-rays, attain their highest values for delay times in the range of ~ 0 – 1.2 ns and decrease for longer delay times. The ion current density also decreases for $\Delta t_{p\text{-}L}$ >1 ns but, after attaining a shallow minimum at a delay time of ~2.5 ns, than it increases. It can be supposed that, within the range of delay times from 0 to ~1 ns, there exist the optimum conditions for maximizing the fast ion energies and the yields of hard x-rays at considerably high fast ion current density. At longer delay times, the pre-pulse plasma effectively screens the target surface and the main pulse interacts, in fact, with the plume of the expanding plasma, which results in decreasing amounts and energy of thermal, fast, and slow ions. However, at $\Delta t_{p\text{-}L}$ >3.5 ns, intense streams of fast ions expanding close to the target normal, with lower mean energy $E_{i,p}$ ~ 200 keV were observed. In this case, surely, other mechanisms of ion acceleration along the laser beam axis should be taken into consideration.

The essential characteristics of the laser-generated fast ion streams and hard X-rays depend on, among other factors, of the distribution of the electron density during interaction of the high-intensity laser radiation with the plasma produced by the leading edge of the laser pulse. For instance, both parametric Brillouin and Raman backscattering (BBS and RBS) [15] are more efficient at low electron concentration and low gradient of plasma density, even at lower laser power density than that occurring at shorter $\Delta t_{p\text{-}L}$.

Further studies of phenomena accompanying intense laser pulse interaction with pre-plasma produced by a pre-pulse preceding the main laser pulse will be continued at the PALS Research Centre in Prague and at IPPLM in Warsaw.

Acknowledgements

This work was supported by the EU (project PALS00029) within the Contract No HPRI-CT-1999-00053) and by the International Atomic Energy Agency in Vienna under Contract No 1153.

References

[1] H. Haseroth and H. Hora Laser and Particle Beams **14** (1996) 393
[3] F.P. Boody et al.: Laser Part. Beams **14** (1996) 443
[2] L. Laska et al.: Rev. Sci. Instrum. **69** (1998) 1072
[4] E.L. Clark et al.: Phys. Rev. Lett. **85** (2000) 1654
[5] J. Badziak et al.: Appl. Phys Letters **78** (2001) 1823
[6] J. Wolowski et al.: *Plasma Phys. Control. Fusion* **44** (2002) 1277
[7] L. Ryc et al.: *Plasma Phys. Control. Fusion* **45** (2003) 1079
[8] L. Torrisi at al.: Appl.Surf. Sci. 220 (2003) 1087
[9] D. Kuhlke et al.: Appl. Phys. Lett. **50** (1987) 1785
[10] U. Teubner et al.: Appl. Phys. **B 54** (1992) 439-499
[11] P. Zhang et al.: Phys. Rev. **E 57** (1998) R3746-R3748
[12] H. Hora et al.: Opt. Commun. **207** (2002) 333
[13] E. Woryna et al.: Laser Part. Beams **14** (1996) 293
[14] L. Láska et al.: Plasma Phys. Control. Fusion, **45** (2003) 585
[15] W.L. Kruer et al.: Phys. Fluids **25** (1982) 2324.