*35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, O-4.043 (2008)*

Studies on proton beam generation for fast ignition-related applications

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Laser-driven proton fast ignition (PFI) of fusion targets requires collimated or focused proton beams of relatively low proton energy (mean energy $\bar{E}_i \approx 3-5\text{MeV}$) but of enormous power (P_i ~1PW) and intensity ($I_i \sim 10^{20}$ W/cm^2) [1]. Moreover, the laser-protons energy conversion efficiency (η) should be ≥ 15% (at ignition laser energy ~ 100kJ). Highly efficient generation of proton beams of such extreme parameters seems to be possible with the use of the method referred to as SLPA (skin-layer ponderomotive acceleration) [2] or RPA (radiation pressure acceleration) [3]. In this method, the ponderomotive pressure induced by a short laser pulse near the critical plasma surface drives forward a dense plasma (ion) bunch of ion density (n_i) higher than the plasma critical density. As $n_i > 10^{21} - 10^{22}$ cm^{-3}, even at moderate ion velocities (υ_i) and energies the ion beam intensities $I_i = n_i \upsilon_i E_i$ can be very high. The beam intensities can be increased further by the beam focusing using the curved target front surface [4].

This paper reports the results of studies of laser-driven generation of high-intensity proton beams performed on the LULI 100TW Nd:glass laser facility. In the experiment, a 350-fs, 1ω or 2ω laser pulse of high contrast ratio (~ 10^7 for 1ω and > 10^8 for 2ω) and intensity, I_L, up to 2×10^{19}W/cm^2 irradiated a thin (0.6 – 3μm) PS (polystyrene) or Au/PS (PS covered by 0.05 – 0.2μm Au front layer) target along the target normal. As the preplasma density gradient scale length near the critical surface, L_n, was relatively small ($L_n < 2 - 3$μm for 1ω [5] and $L_n < 1$μm for 2ω) and the laser beam diameter on the target, d_L, was ≈ 10 – 50μm, the condition $d_L >> L_n, \lambda_L, L_T$ required for SLPA [2] was rather well fulfilled, especially for larger d_L and/or 2ω laser beam (L_T is the target thickness). The proton beam characteristics were measured using the time-of-flight method (ion charge collectors), solid state track detectors (SSTDs) and radiochromic films (RCFs). The characteristics of protons of low ($E_p < 0.1$MeV) and moderate (0.1MeV ≤ E_p < 3MeV) energy were measured by four ion collectors (ICs) situated 80cm from the target at the angles 1°, 4°, 8° and 30° in respect to the target normal. SSTDs (CR 39 – PM 355 with Al filters) and RCF stacks measured with a sufficient resolution only high-energy protons (≥ 3MeV) as these detectors were strongly saturated by moderate-energy protons at the target-detector distances employed (L_{SSTD} = 123cm , L_{RCF} = 2.5cm).

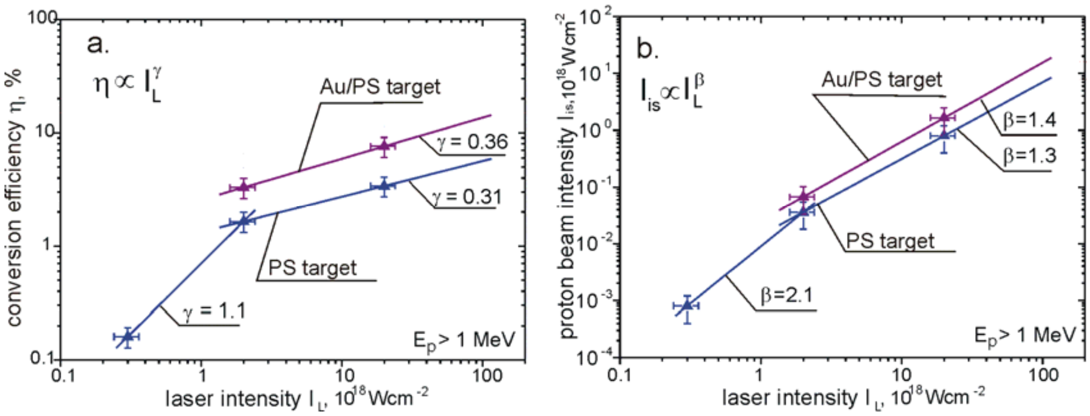

Fig. 1. The laser-protons energy conversion efficiency and the proton beam intensity at the source as a function of laser intensity for PS and Au/PS targets. Points – the results of IC measurements, lines – the results of approximation by a power function.

The dependences of laser-protons energy conversion efficiency and intensity at the source of the proton beam generated from 1.8-μm PS target and Au/PS target with 0.2-μm Au layer on the laser intensity, for protons of energies 1MeV < E_p < 3 MeV, are presented in Fig.1. The proton beam intensity at the source was calculated from the IC measurements using the formula [2]: $I_{is} \approx \overline{E}_p Q / e \tau_s S_s$, where Q is the total charge of protons of mean energy $\overline{E}_p$ (in the considered energy range), τ_s is the proton pulse duration at the source, S_s is the proton beam area at the source and e is the elementary charge. As for SLPA ions τ_s is approximately equal to the laser pulse duration τ_L and S_s is close to the laser focal spot area $S_L = \pi d_L^2$ [2, 3, 6], so to calculate I_{is} we assumed $\tau_s \approx \tau_L$, $S_s \approx S_L$.

It can be seen that for moderate-energy protons the conversion efficiency η for the Au/PS target is twice as high as for the PS target and reaches 8% at $I_L = 2\times10^{19}$W/cm^2. A similar increase in η for the Au/PS target was also observed for high-energy protons (>3MeV). Assuming that the scaling laws shown in Fig.1 are correct for laser intensities > 2×10^{19}W/cm^2, the value η ≈ 15% required for PFI could be achieved at $I_L \approx 10^{20}$W/cm^2. At such I_L the proton beam intensity at the source $I_{is} \approx 1.5\times10^{19}$W/cm^2, so, to attain the ignition threshold the proton beam must be focused to increase the intensity by 5 – 10 times. Potentially, the values of η and I_{is} required for PFI can be achieved even at lower laser intensities by further optimization of the target and using longer laser pulses (in the 5 – 10ps range) [7].

To reach relatively high laser pulse contrast ratio needed for effective SLPA proton generation in PFI experiments and for better matching of a proton energy spectrum to PFI requirements, a 2ω (second harmonic) laser beam for proton generation can be used as an alternative to the usually considered option with 1ω beam driver. A comparison of preliminary measurements of proton beam parameters performed for 1ω and 2ω beam of the LULI 100TW laser is presented in Fig.2. In the case when $I_L\lambda_L^2$ for the 1ω beam is equal to that for the 2ω beam, the beam intensity of protons of energy 1-3MeV (Fig. 2a) is nearly 10 times higher and the conversion efficiency is about 50% higher for the 2ω beam than that for the 1ω beam, in spite of the fact that the 2ω laser beam energy was more than twice as low. Also, the number (per cm^2) of high-energy (>3MeV) protons is higher for 2ω (Fig. 2b). However, for $I_L^{1\omega} \approx I_L^{2\omega}$, the beam intensities of 1-3MeV protons are comparable for 1ω and 2ω and the laser-protons conversion efficiency is lower for the 2ω beam.

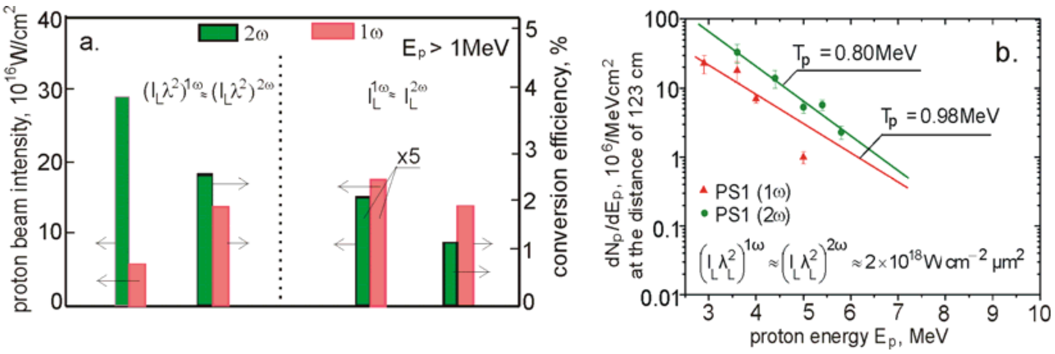

Fig. 2. A comparison of parameters of moderate-energy (1 – 3MeV) (a) and high-energy (>3MeV) (b) proton beams generated by a 1ω or 2ω laser beam. $I_L^{1\omega} \approx 2\times10^{18}$W/cm^2. For part (b): points – the results of SSTD measurements, lines – the results of approximation by the Maxwellian energy distribution with the temperature T_p.

We compared the experimental results presented above with 1D particle-in-cell (PIC) simulations performed for the fully ionized hydrogen target with the preplasma ramps of different density gradient scale length (L_n). It was found that for a laser pulse of $I_L = 2\times10^{19}$W/cm^2 , τ_L = 350fs, λ_L = 1.05μm and L_n in the range from λ_L to $2\lambda_L$, the proton beam peak intensities were within the range (1.3 – 2.1)$\times10^{18}$W/cm^2. It is in fairly good agreement with the values estimated from our measurements using the SLPA model (Fig. 1). We also observed that for the case $(I_L\lambda_L^2)^{1\omega} = (I_L\lambda_L^2)^{2\omega}$ the beam intensity of protons generated by a 2ω beam was higher than that for a 1ω beam though the differences was slightly smaller than in the experiment.

In conclusion, it has been shown that 1-3MeV proton beams of intensity ~ 10^{18}W/cm^2 at the source can be produced at relativistic laser intensities (>10^{19}Wcm^{-2}μm^2) when the laser-target interaction condition approach the SLPA requirements. The laser-protons energy conversion efficiency and proton beam parameters remarkably depend on the target structure and can be significantly increased with the use of a double-layer Au/PS target. The intensity of a proton beam generated by the 2ω laser beam is at least several times higher than that produced by the 1ω beam with the same value of $I_L\lambda_L^2$, while these intensities are comparable when $I_L^{2\omega} \approx I_L^{1\omega}$.

Acknowledgements. The authors acknowledge the LULI laser team for its expert support to this experiment. The access to the LULI 100TW laser facility has been supported by the European Commission under the *LASERLAB-Europe Integrated Infrastructure Initiative (contract No. RII3-CT-2003-506350).* This work was also supported in part by the IAEA RCP project under Contract No. 13794, Grant No. E1127 from Région Ile-de-France as well as the IPPLM contribution to the HiPER project.

References

1.M. Temporal et al., Phys. Plasmas 9, 3098 (2002).
2. J. Badziak et al., Plasma Phys. Control. Fusion 46, B541 (2004) ; J. Badziak et al., Appl. Phys. Lett. 89, 061504 (2006); J. Badziak, Opto-Electron.Rev. 15, 1 (2007) and references therein.
3. T.V. Liseikina and A. Macchi, Appl. Phys. Lett. 91, 171502 (2007).
4. J. Badziak and S. Jabłoński, Appl. Phys. Lett. 90, 151503 (2007).
5. J. Fuchs et al., Phys. Plasmas 14, 053105 (2007).
6. H. Habara et al., Phys. Plasmas 10, 3712 (2003).
7. L. Robson et al., Nature Phys. 3, 58 (2007).