Studies of Phenomena Related to Fast Ignition of a Fusion Target by Laser-Driven Proton Beams

J. Wolowski 1), J. Badziak 1), S. Jablonski 1), P. Parys 1), M. Rosinski 1), A. Szydlowski 2), P. Antici 3), J. Fuchs 3), A. Mancic 3)

1) Institute of Plasma Physics and Laser Microfusion, EURATOM Association, Warsaw, Poland
2) The Andrzej Soltan Institute for Nuclear Studies, Swierk, Poland,
3) LULI, Ecole Polytechnique, CNRS, CEA, UPMC; Route de Saclay, Palaiseau, France

e-mail; wolowski@ifpilm.waw.pl

Abstract. Generation of high-current proton beams of parameters scalable to those required for fast ignition of a fusion target was studied numerically and experimentally. Using a hydrodynamic relativistic 2D code, it was found that laser-induced skin-layer ponderomotive acceleration (SLPA) makes possible to produce collimated proton beams of MA currents and TA/cm^2 current densities at relativistic laser intensities above 10^{19}W/cm^2. The production of proton beams of such extreme parameters was demonstrated in the experiment performed on the LULI 100TW laser facility, in which a subpicosecond laser pulse of intensity up to 2x10^{19}W/cm^2 was used as the proton beam driver. Based on these results, a concept of ICF fast ignition using SLPA-produced proton beams was proposed.

1. Introduction

Laser-driven proton fast ignition of fusion targets [1] requires collimated proton beams of moderate proton energy ($\leq$ 10MeV) but of enormous proton current ($\geq$ 100MA) and current density ($\geq$ 10TA/cm^2) [2, 3]. Generation of proton beams of such extreme parameters seems to be possible using the method referred to as skin-layer ponderomotive acceleration (SLPA) [4 – 7]. 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}, the ion current density $j_i = zen_i\upsilon_i$ can be very high even at moderate ion velocities (υ_i) and energies (z is the ion charge state, e is the electron charge).

2. Results

Using a two-dimensional relativistic hydrodynamic code, production and focusing of proton beams driven by the SLPA mechanism at relativistic laser intensities was analyzed. It was shown that the key parameter determining the spatial structure and angular divergence of the proton beam is the ratio d_L/L_n, where d_L is the laser beam diameter and L_n is the plasma density gradient scale length. When $d_L >> L_n$, a dense highly collimated megaampere (MA) proton beam of the proton current density approaching TA/cm^2 can be generated by SLPA at laser intensities above 10^{19}W/cm^2.

The SLPA-driven high-current proton beams can be effectively focused by curving the target front surface. The focused beam parameters essentially depend on the density gradient scale length of the preplasma L_n and the surface curvature radius R_T (see FIG.1.). When $L_n \leq 0.5\lambda_L$ (λ_L is the laser wavelength) and R_T is comparable with the laser beam aperture d_L, a significant fraction of the accelerated protons is focused on a spot much smaller than d_L, which results in a considerable increase in the proton fluence and current density [8].

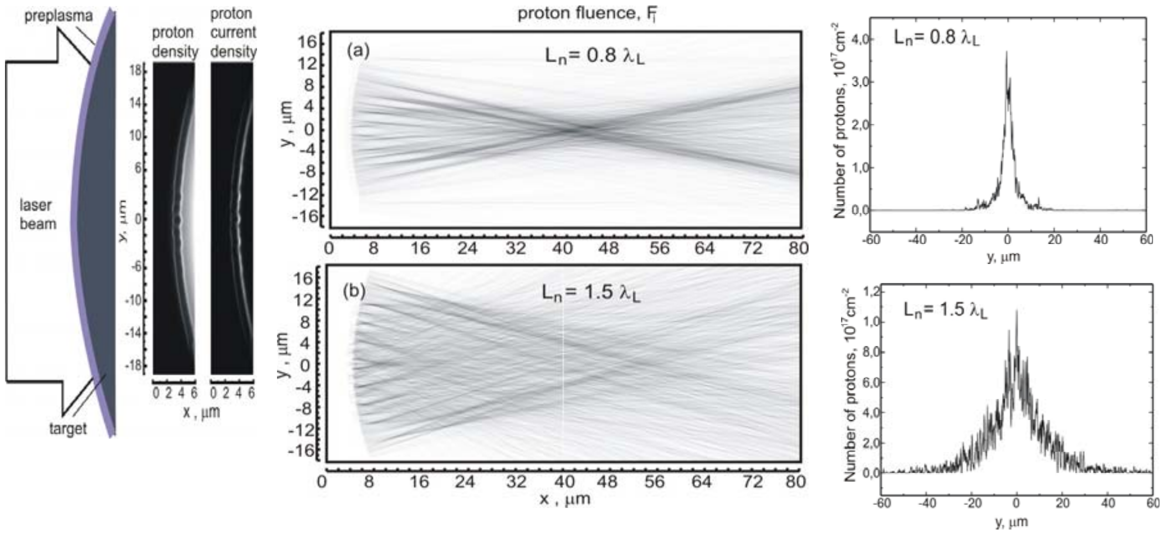

FIG. 1. Effect of the preplasma density gradient scale length L_n on focusing quality. I_L= 3 × 10^{18}W/cm^2, τ_L = 0.25 ps, d_L = R_T = 40μm.

In the experiment, performed on the LULI 100TW laser facility [9], a 350-fs, 1.05-μm high-contrast (~10^7) laser pulse of energy up to 15 J and intensity up to 2×10^{19}W/cm^2 irradiated a thin (1–3μm) PS (polystyrene) or Au/PS (PS covered by 0.05–0.2μm Au front layer) target along the target normal. The proton beam characteristics were measured using the TOF method (ion charge collectors, ICs), solid state track detectors (SSTDs) and radiochromic films (RCFs).

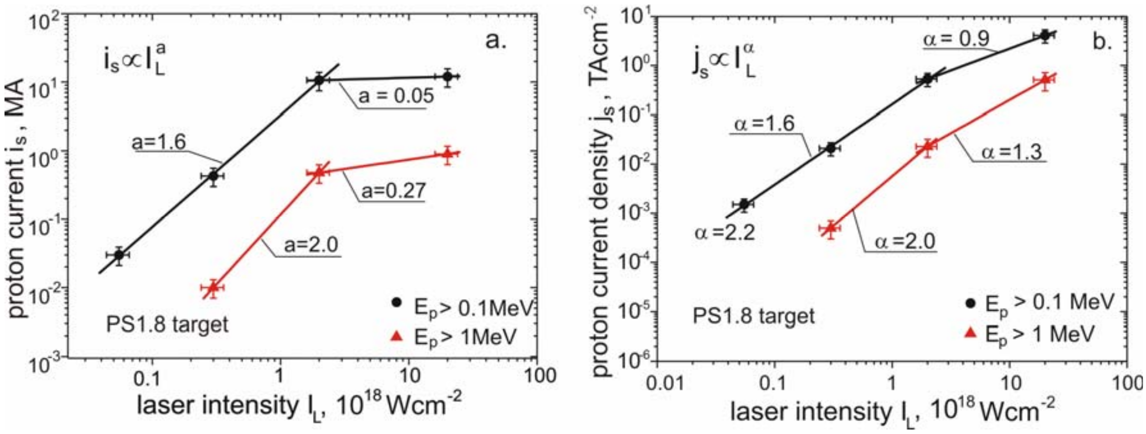

FIG. 2. The proton beam current (a) and current density (b) at the source as a function of laser intensity. Points – the results of IC measurements; lines – the results of approximation by a power function.

The dependences of the proton current and current density at the source (calculated from IC measurements) on the laser intensity, for protons of energy > 0.1 MeV and > 1MeV are presented in FIG.2. It can be seen, that for relativistic laser intensities the current and current density of MeV protons approach 1MA and 1 TA/cm^2, respectively, and they attain multi-MA and multi-TA/cm^2, respectively, when sub-MeV protons are included to the proton flux. Parameters of the proton beam remarkably depend on the target structure. In particular, using a double-layer Au/PS target results in two-fold higher proton currents and laser-protons energy conversion efficiencies than in the case of a plastic target (see FIG.3.).

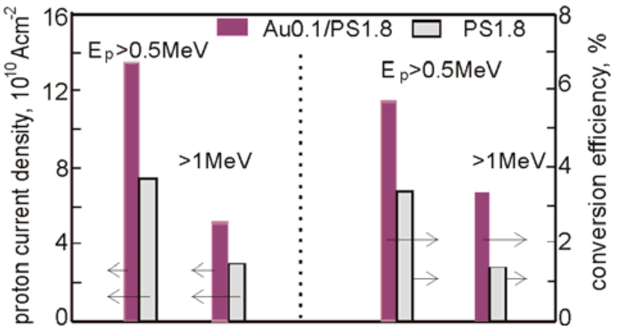

FIG. 3. A comparison of the proton current density at the source and the laser-protons energy conversion efficiency for Au/PS and PS targets. $I_L = 2\times10^{18} W/cm^2$.

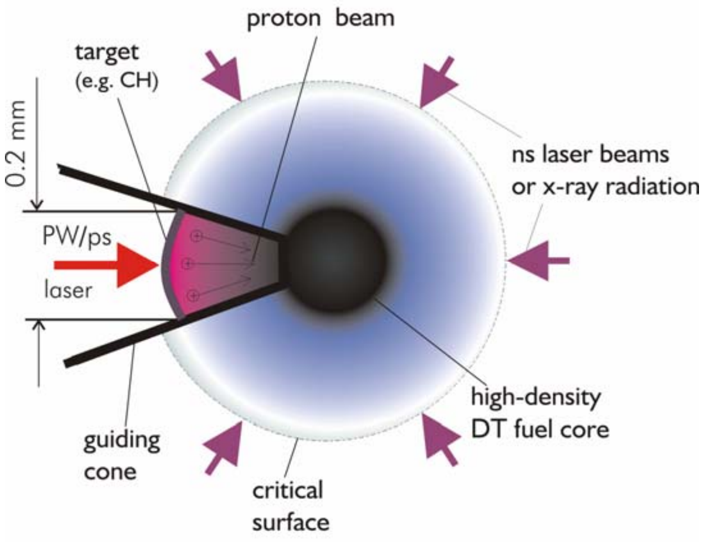

FIG. 4. The concept of fast ignition with SLPA-driven proton beam: a dense focused proton beam generated at the interaction of a PW laser with a dielectric hydrogen-rich target of the curved front surface ignites the DT fuel compressed by cone-guided implosion [3].

Based on the above results, a concept of ICF fast ignition using SLPA-driven proton beams was proposed (see FIG.4.) [3]. According to this concept, the DT fuel compressed to the density of 300 – 400g/cm^3 by cone-guided implosion is ignited by an ultraintense, focused proton beam generated at the interaction of a high-contrast multi-PW/ps laser beam with a dielectric hydrogen-rich target of the curved front surface. As the density of SLPA-driven protons at the source is high, the required current densities of protons heating the fuel can be achieved with only a slight focusing of the proton beam. The beam can be generated from a fairly thick (several μm) solid density layer, which means that the proton source area can be relatively small (S_s < 0.05mm^2) and the proton source-fuel distance can be small as well ($d_{sf} \leq$ 0.3mm). As a result, the proton velocity dispersion does not cause non-acceptable elongation of the proton pulse, so a non-monoenergetic beam can be used. To achieve the ignitor (proton beam) and fuel parameters required for the ignition, an implosion laser of energy ~ 200kJ and an ignition (PW/ps) laser of energy ~ 100kJ is necessary [3].

3. Conclusions

- SLPA makes it possible to produce highly collimated (or focused) dense proton beams of extremely high currents and current densities which are significantly higher than those produced by other methods currently known. In particular, the proton beams of MA currents and TA/cm^2 current densities at the source can be produced at laser energy only ~ 10J and laser intensity ~ 10^{19} W/cm^2.
- Parameters of SLPA-driven proton beams (current, intensity, mean energy etc.) as well as the laser-protons energy conversion efficiency can be significantly improved by using structured (eg. double-layer) targets.
- The production of SLPA-driven MeV proton beams of proton currents and current densities approaching those required for fast ignition of ICF targets (i.e. $i_p > 100$ MA, $j_p > 10$ TA/cm^2), seems to be feasible at the near future when high-contrast multi-PW laser pulses will be available.

3. References

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