

Studies on Laser-Driven Generation of Fast High-Density Plasma Blocks for Fast Ignition

J. Badziak¹, S. Głowacz¹, H. Hora², S. Jabłoński¹, P. Parys¹, J. Wołowski¹

¹*Institute of Plasma Physics and Laser Microfusjon, EURATOM Association, Warsaw, Poland*

²*Department of Theoretical Physics, University of New South Wales, Sydney, Australia*

Proton fast ignition (FI) of fusion targets [1] requires ps proton beams of PW power and of extremely high proton current densities ($j_i > 10^{12}$ A/cm²) and proton beam intensities ($I_i > 10^{19}$ W/cm²) [2, 3], which are not attainable at present even with the biggest conventional accelerators [4]. Potentially, such extreme proton beam parameters can be achieved using ballistic focusing of fast proton beams generated by the target normal sheath acceleration (TNSA) mechanism [5] driven by a short (≤ 1 ps) laser pulse of relativistic intensity. Achieving required proton beam intensities with sufficiently high efficiency with this method can encounter, however, severe difficulties. One of the reasons is relatively low density of accelerated protons at the source (in a close vicinity of the rear target surface), which typically is $\sim 10^{19}$ cm⁻³ [6 – 9] or less (see further). As the relation between the ion beam intensity, I_i , the ion density, n_i , and the ion (mean) energy, E_i , can be expressed by the equation (see e.g. [9]):

$$n_i \approx 4.52 \times 10^3 A^{1/2} I_i E_i^{-3/2}, \quad [\text{cm}^{-3}, \text{W/cm}^2, \text{MeV}] \quad (1)$$

(A is the atomic mass number), for near optimum proton energy $E_i \sim 5$ MeV [2, 3] the required beam intensity $I_i \geq 5 \times 10^{19}$ W/cm² [2, 3] can be attained at $n_i \geq 10^{22}$ cm⁻³. To achieve such a proton density, the proton beam produced at the rear target surface has to be focused in the spot of diameter $d_{if} < (1/30)d_i$, where d_i is the beam diameter at the rear surface and $d_{if} \leq 50\mu\text{m}$ [2, 3]. Assuming the proton production energetic efficiency $\sim 10\%$ and a reasonable laser driver energy $\sim 100 - 200$ kJ, we arrive at the conclusion that in order to deliver of 10 – 20 kJ energy to the compressed fuel, demanded for its ignition [2, 3], significantly more than 50% of the total number of produced protons should be focused in the required spot. Taking into account the angular and energetic dispersion of the produced protons it seems to be a very difficult task.

The other laser-based method of producing collimated high-intensity ion beams, having potential to be used for FI, is Skin-Layer Ponderomotive Acceleration (S-LPA) [9 – 11]. In this paper, basic properties of proton beams produced by S-LPA are described and the possibility of using such beams for FI is considered.

S-LPA employs strong ponderomotive forces induced at the skin-layer interaction of a short laser pulse with a thin preplasma layer (of $L_{pre} \ll d_f$) produced by the laser prepulse in front of a solid target (L_{pre} – the preplasma layer thickness, d_f – the laser focal spot diameter) [9 – 11]. The main short laser pulse interacts most intensely with the plasma in the skin layer near the surface of the critical electron density n_{ec} and the geometry of the interaction is almost planar (since $L_{pre} \ll d_f$). The high plasma density gradient in the interaction region induces two opposite ponderomotive forces which break the plasma and drive two thin plasma blocks towards the vacuum and the plasma interior, respectively. As the ion density of the forward-accelerated plasma block is $n_i \geq n_{ec}/z$, (z is the ion charge state), even at moderate mean ion velocity, the ion current density and the ion beam intensity of the block can be very high. The time duration τ_{is} of the ion flux flowing out of the interaction region (being the ion source) is approximately equal to the laser pulse duration τ_L and the block area S_s is close to the area of the laser focal spot S_f . Due to almost planar acceleration geometry, the angular divergence of the ion beam is small.

Table 1. Parameters of proton beams produced in various experiments.

method	laser beam	mean proton energy, MeV	proton current density at the source estimated for 10° angle cone, GAcm^{-2}	proton beam intensity at the source estimated for 10° angle cone, 10^{15}Wcm^{-2}	proton density at the source estimated for 10° angle cone, 10^{18}cm^{-3}	Ref.
S-LPA	0.5J/1ps 10^{17}Wcm^{-2}	0.017	26	0.44	900	this work
TNSA	30J/0.35ps 10^{18}Wcm^{-2} LULI	4	0.3	1.2	0.7	[12]
	50J/1ps $8 \times 10^{19}\text{Wcm}^{-2}$ VULCAN	4	0.4	1.6	0.9	[13, 14]
	500J/0.5ps $3 \times 10^{20}\text{Wcm}^{-2}$ PETAWATT	6	0.5	3	0.9	[6]

A comparison of parameters of a forward-accelerated proton beam at the source, attained in our S-LPA experiment with 0.5- μm polystyrene target at subrelativistic laser intensities (see [] for details), with the ones achieved in recent TNSA experiments [6, 12 – 14] with relativistic intensities is presented in Table 1. For calculation of the proton current density, j_s , and the proton beam intensity, I_{is} , at the source from experimental data we used the expressions [9, 11]: $j_s \approx Q/\tau_L S_s$, $I_{is} [\text{W/cm}^2] \approx (1/z)j_s [\text{A/cm}^2] \times \bar{E}_i [\text{eV}]$, where Q is the total charge of fast protons measured in the far expansion zone, S_s is the fast proton source area, τ_L is the laser pulse duration, and \bar{E}_i is the mean energy of fast protons. The proton density at the source, n_i , was calculated from (1). As the angle cones within which the protons were recorded were essentially different in different experiments, the values of the proton beam parameters were recalculated to the same angle cone fixed as 10° (only protons with relatively small angular divergence, say $\leq 10^\circ$, are expected to be focused in the required small spot). From the results of the comparison presented in Table 1 the following conclusions can be reached: (a) the proton beam intensities at the source generated within a fixed angle cone by subrelativistic S-LPA are comparable to those produced (within the same angle cone) by TNSA at relativistic laser intensities and much higher laser energies, (b) the proton current densities at the source generated within a fixed angle cone are significantly higher for S-LPA than those for TNSA, (c) the proton densities at the source produced by S-LPA are about a thousand times higher than those generated by TNSA within the same angle cone. It is worth noting that the “useful” (for focusing) part of the proton density in the TNSA beams is distinctly smaller than the “total” proton density, which e.g. for the PETAWATT experiment is estimated to be $\sim 1.5 \times 10^{19}\text{cm}^{-3}$ (the beam divergence is $\sim 40^\circ$ [6]).

Though the current densities and intensities of proton beams produced by S-LPA at subrelativistic laser intensities are fairly high, to achieve MeV proton energies and required beam intensities $> 10^{19}\text{W/cm}^2$, S-LPA at relativistic laser intensities has to be used. The possibility of production of a high-density plasma (proton) block in such a regime was examined with the use of 1D and 2D two-fluid relativistic hydrodynamic codes for $I_L \lambda_L^2$ up to $10^{19}\text{Wcm}^{-2} \mu\text{m}^2$. Fig 1 shows the plasma block produced near the (relativistically shifted) critical surface by the interaction of the laser pulse of $\tau_L = 300\text{fs}$ and $I_L \lambda_L^2 = 3 \times 10^{18}\text{Wcm}^{-2} \mu\text{m}^2$, with preplasma of a linear density profile.

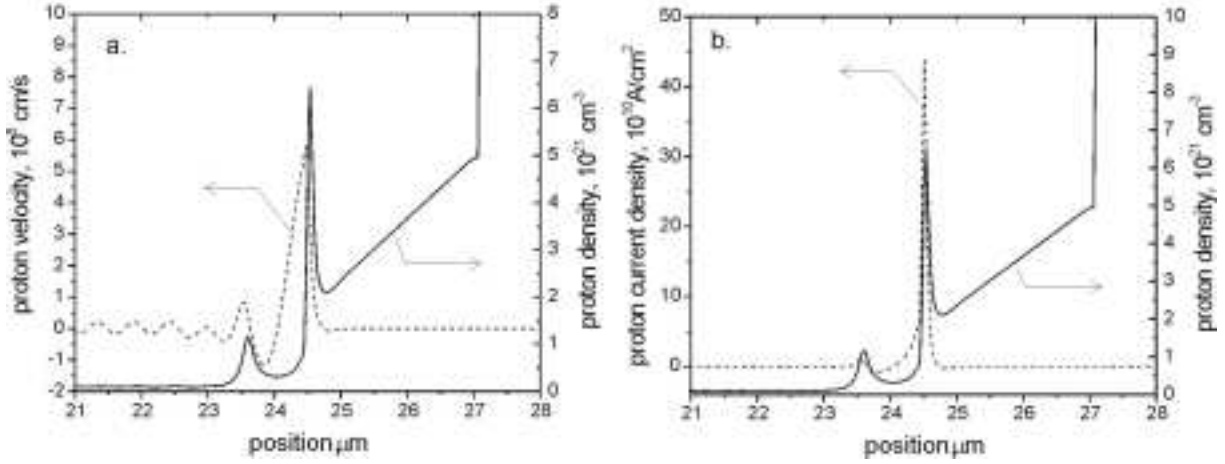


Fig. 1. Results of a numerical simulation of high-density proton beam generation by S-LPA obtained with the use of 1D two-fluid relativistic hydrodynamic code. The laser pulse of $\tau_L = 300\text{fs}$ and $I_L = 3 \times 10^{18}\text{W/cm}^2$ interacts with hydrogen preplasma of $3\mu\text{m}$ thickness at the critical density. Behind the critical surface a dense, forward-accelerated proton (plasma) block of the proton energy $E_i \approx 150\text{keV}$, the proton current density $j_s \approx 4 \times 10^{11}\text{A/cm}^2$ and proton beam intensity $I_{is} \approx j_s[\text{A/cm}^2] \times E_i[\text{eV}] \approx 6 \times 10^{16}\text{W/cm}^2$ is formed.

Approximate scaling laws for parameters (E_i, j_s, I_{is}) of ion beams accelerated forward by the S-LPA mechanism at relativistic laser intensities are given by the formulae [9]:

$$E_i \approx 511(z/2)(\gamma-1), \quad [\text{keV}] \tag{2}$$

$$j_s \approx 1.2 \times 10^{11} (z/A)^{1/2} \lambda_L^{-2} \gamma(\gamma-1)^{1/2}, \quad [\text{A/cm}^2, \mu\text{m}] \tag{3}$$

$$I_{is} \approx 3.1 \times 10^{16} (z/A)^{1/2} \lambda_L^{-2} \gamma(\gamma-1)^{3/2}, \quad [\text{W/cm}^2, \mu\text{m}] \tag{4}$$

where $\gamma = (1 + 3SI_L/I_{rel})^{1/2}$ is the relativistic Lorentz factor S is the dielectric swelling factor, I_L is the laser intensity in vacuum and $I_{rel} \approx 4.1 \times 10^{18}/\lambda_L^2$, $[\text{W/cm}^2, \mu\text{m}]$ is the relativistic intensity. The above scaling laws were verified with 2D hydrodynamic code for $I_L \lambda_L^2 \leq 10^{19}\text{Wcm}^{-2}\mu\text{m}^2$ and fairly good quantitative agreement (better than 50%) between numerical and analytical calculation was found. Then, these scaling laws were used for a rough estimate of parameters of the proton flux heating a precompressed DT fuel according to the Fast Ignition by Plasma Blocks (FIPB) scheme presented in Fig. 6 of the paper [9].

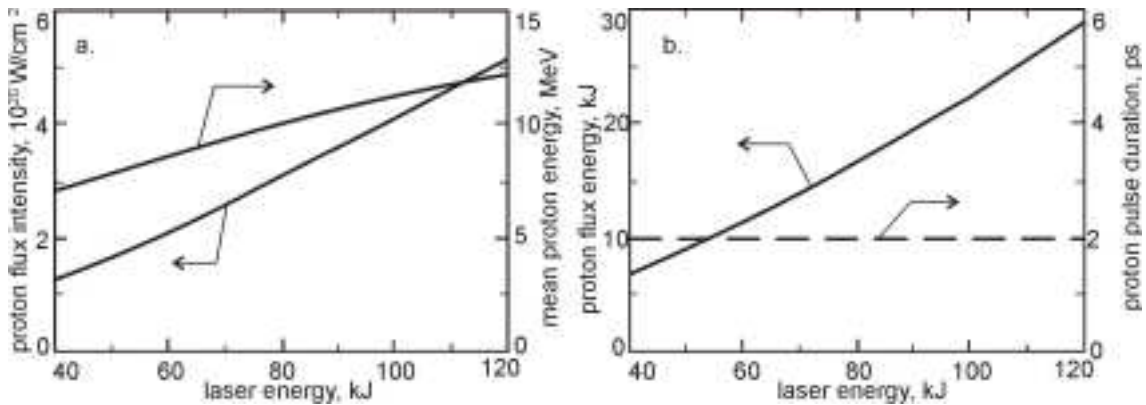


Fig. 2. Parameters of proton flux heating the fuel in the FIPB scheme.

In the considered case of FIPB, all laser beams of the fast ignition driver are focused on the planar target placed in the close vicinity of the guiding cone tip, situated near the high-density fuel core. We assumed that the laser focal spot radius is equal to $30\mu\text{m}$, $z/A=1$ (protons), $S=1.5$, $\lambda_L=1\mu\text{m}$ and $\tau_L=2\text{ps}$. It can be seen that parameters of the proton flux ($E_{\text{beam}} \sim 10 - 20 \text{ kJ}$, $I_{\text{beam}} \geq 10^{20} \text{ W/cm}^2$, $E_i \sim 5 - 10 \text{ MeV}$) required for ignition of the precompressed ($\rho \sim 300 - 400 \text{ g/cm}^3$) DT fuel [2, 3] are achieved at laser energy $\sim 70 - 90 \text{ kJ}$. We are aware, however, that this promising result has to be proved by detailed numerical and experimental studies.

In conclusion, it has been shown that S-LPA makes it possible to produce collimated proton beams of the proton density about a thousand times higher than the ones produced with the TNSA method. The rough estimates indicate that using such proton beams, the ignition of precompressed DT fuel can be reached without the beam focusing at laser energy $\leq 100 \text{ kJ}$.

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