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Studies on laser-driven generation of fast high-density plasma blocks for fast ignition

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Abstract

The properties of plasma (proton) block driven by the laser-induced skin-layer ponderomotive acceleration (S-LPA) mechanism are discussed. It is shown that the proton density of the plasma block is about a thousand times higher than that of the proton beam produced by the target normal sheath acceleration (TNSA) mechanism. Such a high-density plasma (proton) block can be considered as a fast ignitor of fusion targets. The estimates show that using the S-LPA driven plasma block, the ignition threshold for precompressed DT fuel can be reached at the ps laser energy ≤ 100 kJ.

Keywords: Fast ignition; Ion beams; Laser; Nuclear fusion; Plasma

1. INTRODUCTION

Laser-driven proton fast ignition (FI) of fusion targets (Roth *et al.*, 2001) is a possible way toward inertial fusion energy (IFE) promising high efficiency and good control of the particle beam energy deposition in a compressed DT fuel (Deutsch, 2003, 2004). On the other hand, a critical point in the proton FI approach is the particle beam production efficiency, which is typically a few times lower than in the alternative approach using laser-driven electron beam (Kodama *et al.*, 2001). An extremely challenging task is attaining the proton beam parameters required for ignition (Atzeni *et al.*, 2002; Temporal *et al.*, 2002): the beam intensity, $\sim 10^{20}$ W/cm^2, the proton current density, $\sim 10^{13}$ A/cm^2, the beam power, ~1 PW (PetaWatt), the proton pulse duration, ~10 ps, and the mean proton energy, ~ 5 MeV. Potentially, such extreme proton beam parameters can be achieved by using the fast proton beams generated by the target normal sheath acceleration (TNSA) mechanism (Wilks *et al.*, 2001). Achieving the required proton beam intensities with sufficiently high efficiency with this method can encounter severe difficulties. One of the reasons is that the 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} (Snavely *et al.*, 2000; Hatchett *et al.*, 2000; Allen *et al.*, 2003), or lower. 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 following equation (Badziak *et al.*, 2005*b*):

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

(A is the atomic mass number), for near optimum proton energy, $E_i \sim 5$ MeV (Atzeni *et al.*, 2002; Temporal *et al.*, 2002), the required beam intensity, $I_i \geq 5 \times 10^{19}$ W/cm^2, can be attained at $n_i \geq 10^{22}$ cm^{-3}. To achieve such a proton density, the proton beam produced by TNSA at the rear target surface, has to be focused on a spot with diameter $d_{if} < (1/30) d_i$, where d_i is the beam diameter at the rear surface, and $d_{if} \leq 50\mu$m (Atzeni *et al.*, 2002; Temporal *et al.*, 2002). Assuming the proton production energetic efficiency is ~10% and a reasonable laser driver energy is ~100–200 kJ, we concluded that in order to deliver 10–20 kJ of energy to the compressed fuel for ignition (Atzeni *et al.*, 2002; Temporal *et al.*, 2002), 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-density ion beams (plasma blocks), having potential to be used for FI, is skin-layer ponderomotive acceleration (S-LPA) (Badziak *et al.*, 2004*a*, 2004*b*, 2005*a*, 2005*b*; Hora *et al.*, 2004; Hora, 2005). 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.

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2. PROPERTIES OF ION BEAMS PRODUCED BY S-LPA

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) (Badziak *et al.*, 2004*a*, 2004*b*, 2005*a*, 2005*b*). 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 toward 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.

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 Badziak *et al.*, 2004*b*, 2005*a*, 2005*b*, for details), with the ones achieved in recent TNSA experiments with relativistic intensities (Snavely *et al.*, 2000; Zepf *et al.*, 2003; Cowan *et al.*, 2004; Borghesi *et al.*, 2004) 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 (Badziak *et al.*, 2004*b*, 2005*b*):

$$j_s \approx Q/\tau_L S_s, \;\; I_{is}[\mathrm{W/cm^2}] \approx (1/z) j_s[\mathrm{A/cm^2}] \times E_i\,[\mathrm{eV}],$$

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 E_i is the mean energy of fast protons. The proton density at the source, n_i, was calculated from Eq. (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°, 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, and (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, for example, for the PW experiment is estimated to be $\sim 1.5 \times 10^{19}$ cm^{-3} (the beam divergence is $\sim$ 40° (Snavely *et al.*, 2000)).

Although the current densities and intensities of proton beams produced by S-LPA at subrelativistic laser intensities

Table 1. *Parameters of proton beams produced in various experiments. (a) Cowan et al., 2004; (b) Zepf et al., 2003; (c) Borghesi et al., 2004; (d) Snavely et al., 2000*

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} W/cm^{-2}	Proton density at the source estimated for 10° angle cone, 10^{18} cm^{-3}	Ref.
S-LPA	0.5 J/1 ps 10^{17} W/cm^2	0.017	26	0.44	900	This work
TNSA	30 J/0.35 ps 10^{19} W/cm^2 LULI	4	0.3	1.2	0.7	[a]
	50 J/1 ps 8×10^9 W/cm^2 Vulcan	4	0.4	1.6	0.9	[b], [c]
	500 J/0.5 ps 3×10^{20} W/cm^2 PETAWATT	6	0.5	3	0.9	[d]

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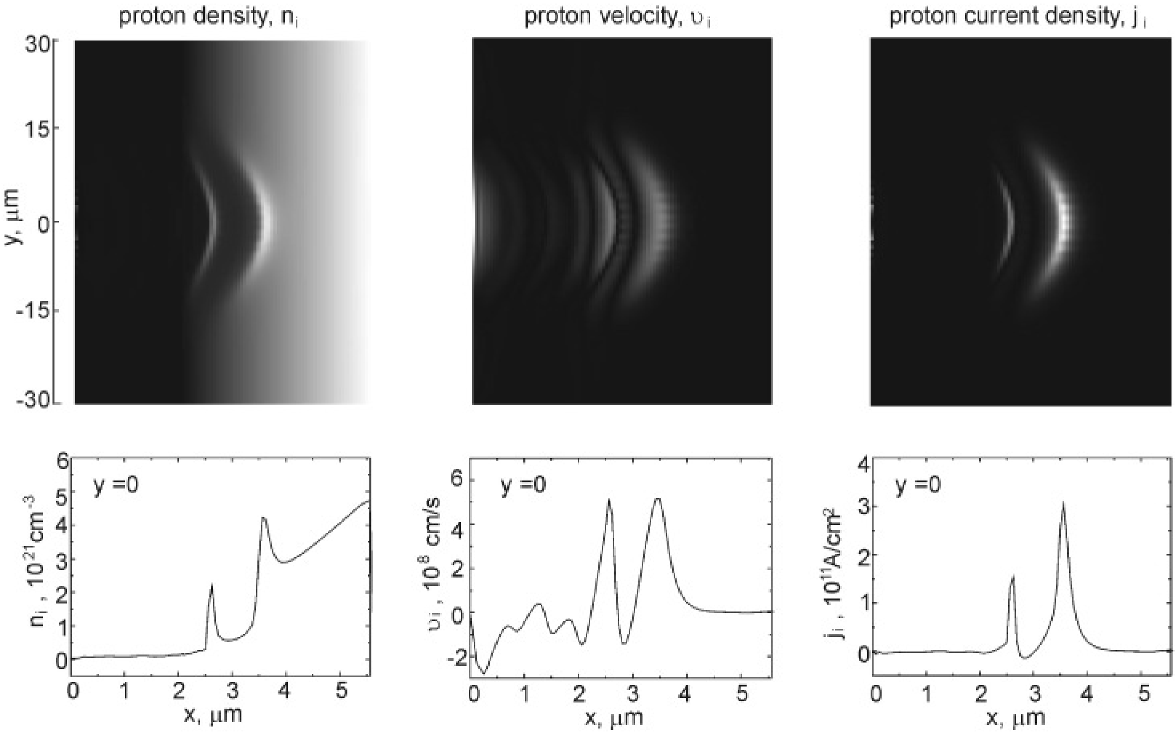

Fig. 1. Results of a numerical simulation of high-density plasma (proton) block generation by S-LPA obtained with the use of 2D two-fluid relativistic hydrodynamic code. The laser pulse of $\tau_L = 0.25$ ps, $\lambda_L = 1$ μm, $I_L = 3 \times 10^{18}$ W/cm^2 and $d_f = 20$ μm interacts with hydrogen preplasma of 3 μm thickness at the critical density.

are fairly high, to achieve MeV proton energies and beam intensities $\geq 5 \times 10^{19}$ W/cm^2 required for FI, 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 one-dimensional (1D) and two-dimensional (2D) two-fluid relativistic hydrodynamic codes for $I_L \lambda_L^2$ up to 10^{19} Wcm^{-2} μm^2. Figure 1 and Figure 2 present the results of 2D simulations for the cases when the Gaussian laser pulse of $\tau_L = 0.25$ ps, $I_L \lambda_L^2 = 3 \times 10^{18}$ Wcm^{-2} μm^2 and $d_f = 20$ μm (Fig. 1) or $d_f = 5$ μm (Fig. 2) interacts with hydrogen preplasma of a linear density profile and of 3 μm thickness at $n_e = n_{ec}$. For both cases, near the laser beam axis, there are produced high-density ($\sim 5 \times 10^{21}$ cm^{-3}) proton beams of the proton energy ~ 150 keV, the proton current density $\sim 3 \times 10^{11}$ A/cm^2, and the proton beam intensity $\sim 5 \times 10^{16}$ W/cm^2. However, the spatial structure of the proton beam essentially depends on the ratio d_f/L_{pre}. In the case of $d_f = 20$ μm, when the necessary condition for S-LPA, namely $d_f \gg L_{pre}$, is fulfilled quite well, we observe a low-divergence proton beam of Gaussian-like spatial structure. On the other hand, at $d_f = 5\,\mu$m ($d_f \sim L_{pre}$) a fairly complex multi-bubble structure of the proton beam is formed. Such proton beam structure is a consequence of the complex structure of the laser field in plasma, which is created, first of all, due to reflection of the light wave by the curved overdense plasma surface of the small radius of curvature. Fortunately, the proton beam spot diameter required for FI is estimated to be ~ 30–50 μm (Temporal *et al.*, 2002), so fulfilling the condition $d_f \gg L_{pre}$ is feasible at realistic contrast ratio of a laser pulse driving the proton beam.

3. FAST IGNITION OF A FUSION TARGET BY A PLASMA BLOCK

The potential of a plasma (proton) block as a fast ignitor was tested for the FI by Plasma Blocks (FIPB) scheme (Badziak *et al.*, 2005*b*) presented in Figure 3. In the considered case of FIPB, the laser beam (beams) driving the plasma (proton) block is focused on the planar target, placed in the vicinity of the tip of a guiding cone protecting both the laser beam and the plasma block against the influence of DT plasma, while it is compressed (Norreys *et al.*, 2000; Kodama *et al.*, 2001). For the above scheme, we estimated the intensity, I_h, the total energy, E_h, the pulse duration, τ_h, and the mean proton energy, E_i, of the proton flux heating the compressed DT fuel by using the formulae (Badziak *et al.*, 2005*b*):

$$I_h \approx \frac{I_{is}}{g[1 + l_{th}/\tau_L \upsilon_i]} \tag{2}$$

$$E_h \approx \pi r_h^2 I_h \tau_h \tag{3}$$

$$\tau_h \approx \tau_L + l_{th}/\upsilon_i \tag{4}$$

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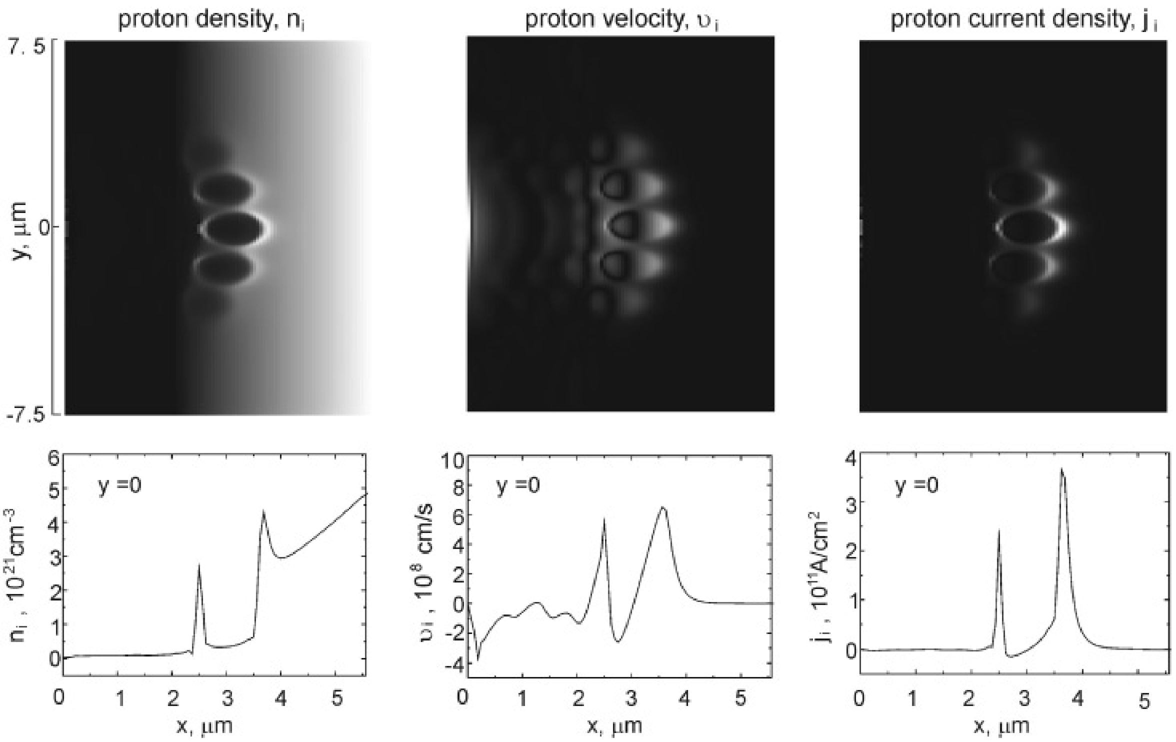

Fig. 2. As in Figure 1 but at $d_f = 5\,\mu$m.

$$E_i \approx 511(z/2)(\gamma - 1), \quad [\mathrm{keV}] \tag{5}$$

$$j_s \approx 1.2\times10^{11}(z/A)^{1/2}\lambda_L^{-2}\gamma(\gamma-1)^{1/2}, \quad [\mathrm{A/cm^2}, \mu\mathrm{m}] \tag{6}$$

$$I_{is} \approx (1/z)j_s E_i \approx 3.1\times10^{16}(z/A)^{1/2}\lambda_L^{-2}\gamma(\gamma-1)^{3/2}, \quad [\mathrm{W/cm^2}, \mathrm{A/cm^2}, \mathrm{keV}, \mu\mathrm{m}], \tag{7}$$

where: I_{is} and j_s are the proton beam intensity and the proton current density at the source, respectively; υ_i—the mean ion velocity, τ_L—the laser pulse duration, l_{th}—the distance from the target to the high-density fuel, r_h—the radius of heated fuel, $g = f(l_{th}/d_f, \theta_i)$—geometrical factor, θ_i—the proton beam angular divergence, $\gamma = (1 + 3SI_L/I_{rel})^{1/2}$—the relativistic Lorentz factor, S—the dielectric swelling factor, I_L—the laser intensity in vacuum and $I_{rel} \approx 4.1 \times 10^{18}/\lambda_L^2$, [W/cm^2, μm]—the relativistic intensity. The scaling laws Eqs. (5)–(7) were verified with 2D hydrodynamic code for $I_L\lambda_L^2 \leq 10^{19}$ Wcm^{-2} μm^2 and reasonable quantitative agreement (within the factor 2) between numerical and analytical calculations was found. Then, Eqs. (2)–(7) were used for a rough estimate of the parameters of the proton flux heating a precompressed DT fuel according to the scheme presented in Figure 3. For the calculations, we assumed: $l_{th} = 100$ μm, $d_f = 40$ μm, $\tau_L = 5$ ps, $\lambda_L = 0.53$ μm, $S = 1.5$, $\theta_i = 5°$, $z/A = 1$ (protons). We calculated the proton flux parameters as a function of energy of the laser pulse driving the proton beam generation. The result of the calculations is presented in Figure 4. It can be seen that parameters of the proton flux required for ignition of the precompressed ($\rho \sim 300$–400 g/cm^3) DT fuel, namely $E_h \sim 10$–15 kJ, $I_h \sim 10^{20}$ W/cm^2, $E_i \sim 5$–8 MeV (Atzeni *et al.*, 2002; Temporal *et al.*, 2002), are attainable at laser energy ~ 80–100 kJ. This laser energy can be even lower, if we take into account the fact that part of directed energy of laser-produced fast electrons, which is not used up for proton acceleration, can potentially be utilized for addi-

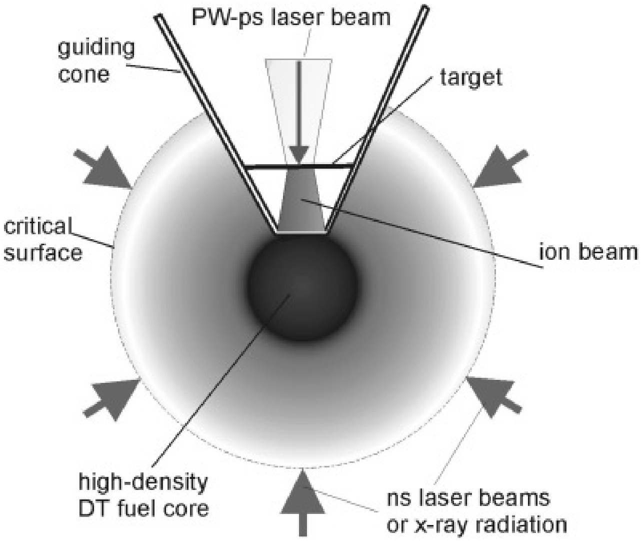

Fig. 3. The idea of FI by plasma block produced by S-LPA.

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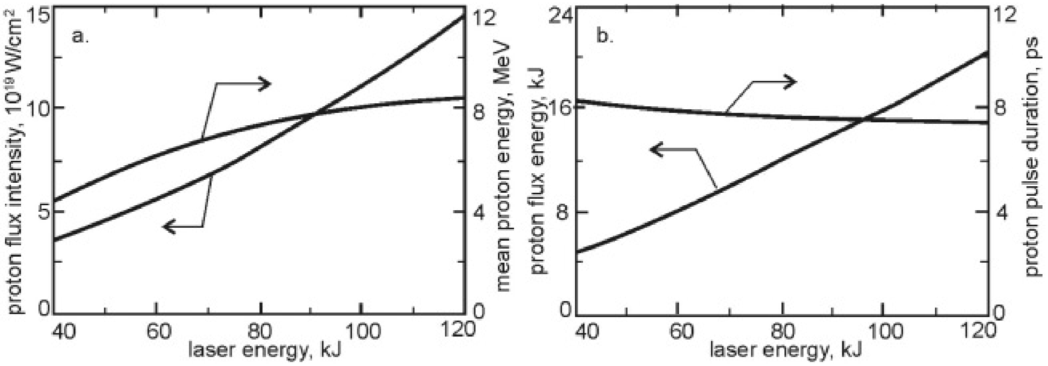

Fig. 4. Parameters of proton flux heating the fuel as a function of ps laser energy.

tional heating of the fuel. However, consideration of such hybrid, proton-electron FI scheme is beyond the scope of this paper.

4. CONCLUSIONS

In conclusion, it has been shown that S-LPA makes it possible to produce plasma (proton) blocks of proton densities about a thousand times higher than those of proton beams produced by the TNSA mechanism. Such a high-density plasma (proton) block driven by S-LPA at relativistic laser intensities can be considered as a fast ignitor of fusion targets. The rough estimates show that using the plasma block, the ignition threshold for precompressed DT fuel can be reached at the picosecond laser energy ≤ 100 kJ. Contrary to the scheme of Roth *et al*. (2001), the ignition seems to be feasible without ballistic focusing of the proton beam. In the case of increasing heating beam intensity, the focusing of the S-LPA beam using a shaped target or employing several overlapped beams generated from planar targets (Badziak *et al*., 2005*b*) can be considered.

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REFERENCES

Allen, M., Sentoku, Y., Audebert, P., Blazevic, A., Cowan, T., Fuchs, J., Gauthier, J.C., Geissel, M., Hehelich, M., Karsch, S., Morse, E., Patel, P.K. & Roth, M. (2003). Proton spectra from ultraintense laser-plasma interaction with thin foils: Experiments, theory, and simulation. *Phys. Plasmas* **8**, 3283–3289.

Atzeni, S., Temporal, M. & Honrubia, J.J. (2002). A first analysis of fast ignition of precompressed ICF fuel by laser-accelerated protons. *Nucl. Fusion* **42**, L1–L4.

Badziak, J., Głowacz, S., Jabłoński, S., Parys, P., Wołowski, J. & Hora, H. (2005*a*). Generation of picosecond high-density ion fluxes by skin-layer laser-plasma interaction. *Laser Part. Beams* **23**, 143–148.

Badziak, J., Głowacz, S., Jabłoński, S., Parys, P., Wołowski, J. & Hora, H. (2005*b*). Laser-driven generation of high-current ion beams using skin-layer ponderomotive acceleration. *Laser Part. Beams* **23**, 401–409.

Badziak, J., Głowacz, S., Jabłoński, S., Parys, P., Wołowski, J. & Hora, H. (2004*a*). Production of ultrahigh-current-density ion beams by short-pulses skin-layer laser-plasma interaction. *Appl. Phys. Lett.* **85**, 3041–3043.

Badziak, J., Głowacz, S., Jabłoński, S., Parys, P., Wołowski, J. & Hora, H. (2004*b*). Production of ultrahigh ion current densities at skin-layer subrelativistic laser-plasma interaction. *Plasma Phys. Cont. Fusion* **46**, B541–B555.

Borghesi, M., Mackinnon, A.J., Campbell, D.H., Hicks, D.G., Kar, S., Patel, P.K., Price, D., Romagnani, L., Schiavi, A. & Willi, O. (2004). Multi-MeV protons source investigations in ultraintense laser-foil interactions. *Phys. Rev. Lett.* **92**, 055003-1–055003-4.

Cowan, T.E., Fuchs, J., Ruhl, H., Kemp, A., Audebert, P., Roth, M., Stephens, R., Barton, I., Blazevic, A., Brambrink, E., Cobble, J., Fernández, J., Gauthier, J.-C., Geissel, M., Hegelich, M., Kaae, J., Karsch, S.L., Sage, G.P.Le., Letzring, S., Manclossi, M., Meyroneinc, S., Newkirk, A., Pépin, H. & Renard-leGalloudec, N. (2004). Ultralow emittance, multi-MeV proton beams from a laser virtual-cathode plasma accelerator. *Phys. Rev. Lett.* **92**, 204801-1–204801-4.

Deutsch, C. (2003). Transport of megaelectronvolt protons for fast ignition. *Laser Part. Beams* **21**, 33–35.

Deutsch, C. (2004). Penetration of intense particle beams in the outer layers of precompressed thermonuclear fuels. *Laser Part. Beams* **22**, 115–120.

Hatchett, S.P., Brown, C.G., Cowan, T.E., Henry, E.A., Johnson J.S., Key, M.H., Koch, J.A., Langdon, A.B., Lasinski, B.F., Lee, R.W., Mackinnon, A.J., Pennington, D.M., Perry, M.D., Phillips, T.W., Roth, M., Sangster, T.C., Singh, M.S., Snavely, R.A., Stoyer, M.A., Wilks, S.C. & Yasuike, K. (2000). Electron, photon, and ion beams from the relativistic interaction of Petawatt laser pulses with solid targets. *Phys. Plasmas* **7**, 2076–2082.

Hora, H. (2005). Difference between relativistic petawatt-picosecond laser plasma interaction and subrelativistic plasma block generation. *Laser Part. Beams* **23**, 441–451.

https://doi.org/10.1017/S0263034606060368 Published online by Cambridge University Press

Hora, H., Osman, F., Cang, Y., Badziak, J., Jabłoński, S., Głowacz, S., Miley, G.H., Hammerling, P., Wołowski, J., Jungwirth, K., Rohlena, K., He, X., Peng, H. & Zhang, J. (2004). TW-ps laser driven blocks for light ion beam fusion in solid density DT. *Proceedings of SPIE* **5627**, 51–63.

Kodama, R., Norreys, P.A., Mima, K., Dangor, A.E., Evans, R.G., Fujita, H., Kitagawa, Y., Miyakoshi, T., Miyanag, N., Norimatsu, T., Rose, S.J., Shozaki, T., Shigemori, K., Sunahara, A., Tampo, M., Tanaka, K.A., Toyama, Y., Yamanaka, T. & Zepf, M. (2001). Fast heating of ultrahigh-density plasma as a step towards laser fusion ignition. *Nature* **412**, 798–802.

Norreys, P.A., Allott, R., Clarke, R.J., Collier, J., Neely, D., Rose, S.J., Zepf, M., Santala, M., Bell, A.R., Krushelnick, K., Dangor, A.E., Woolsey, N.C., Evans, R.G., Habara, H., Norimatsu, T. & Kodama, R. (2000). Experimental studies of the advanced fast ignitor scheme. *Phys. Plasmas* **7**, 3721–3726.

Roth, M., Cowan, T.E., Key, M.H., Hatchett, S.P., Brown, C., Fountain, W., Johnson, J., Pennington, D.M., Snavely, R.A., Wilks, S.C., Yasuike, K., Ruhl, H., Pegoraro, F., Bulanov, S.V., Campbell, E.M., Perry, M.D. & Powell, H. (2001). Fast ignition by intense laser-accelerated proton beams. *Phys. Rev. Lett.* **89**, 436–439.

Snavely, R.A., Key, M.H., Hatchett, S.P., Cowan, T.E., Roth, M., Phillips, T.W., Stoyer, M.A., Henry, E.A., Sangster, T.C., Singh, M.S., Wilks, S.C., MacKinnon, A., Offenberger, A., Pennington, D.M., Yasuike, K., Langdon, A.B., Lasinski, B.F., Johnson, J., Perry, M.D. & Campbell, E.M. (2000). Intense high-energy proton beams from petawatt-laser irradiation of solids. *Phys. Rev. Lett.* **85**, 2945–2948.

Temporal, M., Honrubia, J.J. & Atzeni, S. (2002). Numerical study of fast ignition of ablatively imploded deuterium-tritium fusion capsules by ultra-intense proton beams. *Phys. Plasmas* **9**, 3098–3107.

Wilks, S.C., Langdon, A.B., Cowan, T.E., Roth, M., Singh, M., Hatchett, S., Key, M.H., Pennington, D., MacKinnon, A. & Snavely, R.A. (2001). Energetic proton generation in ultra-intense laser-solid interactions. *Phys. Plasmas* **8**, 542–549.

Zepf, M., Clark, E.L., Beg, F.N., Clarke, R.J., Dangor, A.E., Gopal, A., Krushelnick, K., Norreys, P.A., Tatarakis, M., Wagner, U. & Wei, M.S. (2003). Proton accelerations from high-intensity laser interactions with thin foil targets. *Phys. Rev. Lett.* **90,** 064801-1–064801-4.

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