Journal & Proceedings of the Royal Society of New South Wales, Vol. 140, p. 11–19, 2007
ISSN 0035-9173/07/010011–9 $4.00/1

Oral presentation at the 17th Australian National Physics Congress
Brisbane 3–8 December 2006

New Aspects for Low Cost Energy by Inertial Fusion Using Petawatt Lasers

FREDERICK OSMAN, HEINRICH HORA, GEORGE H. MILEY AND JAK C. KELLY

Abstract: The prospect of generating clean, safe, virtually unlimited, universally accessible and low cost energy from nuclear fusion has cost many billions of dollars over the last fifty years. The aim is to confine the hydrogen isotopes deuterium (D) and tritium (T) and hold them in this state for a sufficient length of time at temperatures of dozens of million degrees for the nuclei to fuse into helium. The predominant method used is the confinement of the reacting plasma by magnetic fields (MCF, magnetic confinement fusion) or confinement by the inertia of a fuel pellet after extremely fast heating and compression such that much more fusion energy is produced than one needed for this ignition (ICF, intertial confinement fusion). Prospects for such processes are reviewed.

Keywords: Fusion energy, Laser, Plasma, Ion currents.

INTRODUCTION

One of the leading experts on environment problems is James Lovelock FRS, who played a key role in detecting damage to the atmosphere caused by the chlorofluorohydrocarbon emission and succeeded in their worldwide banning. He was listed by the magazine *Prospect* in 2005 as one of the hundred most influential intellectuals in the world. In an interview with Ulli Kulke for the German newspaper *Die Welt* (March 23, 2006, p. 10), Lovelock maintained that all separate observations of environmental problems have to be combined. It is for instance suggested that ocean levels may rise during the next few decades not by several meters but by up to sixty meters. These catastrophic developments may be irreversibly on the way and it might be too late to stop them. Nevertheless, they may be delayed. Under the banner '*Das ist doch grüner Unsinn*' (this definitely is green nonsense) Lovelock favours nuclear energy, and very interestingly mentions fusion energy for the future (Hora 2007, 2007a).

For the very fast ignition of controlled fusion reactions, the laser was immediately considered as the preferred tool and suggested as such by Teller (1960) and Sakharov (1961). The prospect of laser powered fusion has driven the development of very high powered lasers, including the multibillion dollar facilities at NIF and LMJ (Gerstner 2007), opening developments up to conditions of the Hawking-Unruh radiation (Hora et al. 2002a, Stait-Gardner & Castillo 2006).

As always happens when increases of orders of magnitude are achieved, new physics has been revealed and old phenomena clarified. Currently available laser pulses of petawatt ($\mathrm{PW} = 10^{15}\,\mathrm{W}$) power and picosecond ($\mathrm{ps} = 10^{-12}\,\mathrm{s}$) duration permit new schemes for fast ignition. A basically new effect based on drastically anomalous measurements (Zhang et al. 1998, Badziak et al. 1999) was explained by a skin layer theory (Hora et al. 2002, Hora 2004, 2005) in combination with much earlier computations in Australia. This effect may be used for igniting virtually uncompressed solid DT fuel by PW-ps laser pulses to ignite a very high gain controlled fusion reaction wave, which, if confirmed by further research, may lead to very low cost fusion power stations.

This controlled ignition of weakly compressed DT fuel follows a scheme of Nuckolls & Wood (2002) where PW-ps laser pulses generate ultra-intense relativistic electron beams.

The new effect led to measurements of space charge neutral D-T-ion beam current densities exceeding $10^{11}\,\mathrm{A\,cm^{-2}}$, through which ion beams instead of the electron beams of Nuckolls et al. (2002) may lead to low cost, controlled ignition of fusion.

THE SOLUTION OF NUCKOLLS & WOOD (2002)

Nuckolls (2005) suggested in 1960 that laser pulses might be used to ignite solid or lightly compressed DT directly. This can be seen from the fact that a $10^{17}\,\mathrm{W\,cm^{-2}}$ laser intensity is comparable with 11 million degree (keV) Planck radiation. This ignition has not yet been achieved, as Kidder (2005) has critically remarked. However, with the advent of PW-ps laser pulses, the chance of success has been greatly improved. Nuckolls & Wood (2002) modified the fast igniter scheme (Tabak et al. 1994) so that they produce an intense 5 MeV electron beam such that an ignition of virtually uncompressed and large amounts of DT may result in 100 MeV fusion energy produced by a 10 kJ laser pulse of ps duration.

The electron beams have to be produced by irradiation of the 10 kJ-ps laser pulse onto a plasma at pre-compression to more than 1000 times solid state density. Examples for ignition of DT are given for 10 times the solid state with the remark that for lower densities, even better conditions will be expected. This is all within a controlled energy generation and clearly different from an uncontrolled reaction. The close borderlines between controlled energy production and the uncontrolled case should not be used to bedevil laser fusion, as it was openly done by Tran (2004). Reporting on fusion energy to the UN-World Energy Conference in Sydney, he excluded laser fusion and reported only on the International Thermonuclear Experimental Reactor (ITER) using magnetic confinement fusion (MCF). Other objections to inertial fusion energy (IFE) are discussed elsewhere (Hora et al. 2005, 2007, 2007a).

To properly assess the position of ITER, the following facts have to be taken into account. This project, with funding of more than $16 billion, is scheduled to come to fruition in 2016 and the gain is still rather modest: a 500 MW electricity input should produce 500 MW fusion power during 500 seconds such that after conversion at 30 % efficiency in an electric generator, a gain of 0.3 may result (Tran 2004). The best measurement concerning magnetic confinement fusion (Keilhacker 1999) was with the JET (Joint European Torus), when a magnetically confined plasma torus during 2 seconds produced 16 MW of fusion power by irradiation of 21 MW neutral beam power and 3 MW heating by electromagnetic radiation. To this fusion gain of 0.66, one had to ignore the 100 MW of electricity which was needed to run the torus. If one takes the operation of JET into account, the gain of fusion energy is 0.129 and with 30 % conversion to electricity, the total gain is 0.042. ITER should then produce an increase of the gain by a factor only 7.4. It can be estimated that at least the same increase of gain is possible with the JET facility, if a number of additional neutral beam injectors were added. This would cost very much less than the projected ITER project cost and could be achieved in a much shorter time. However, this would be neutral beam fusion (Hora 2000, 2004) and contradict the Spitzer theorem of 1951.

The modified fast igniter (Nuckolls & Wood 2002) has still the disadvantage that the generation of the 5 MeV electron beams needs the interaction of a 10 PW-ps laser pulse with a plasma of very high (thousand times solid state) pre-compressed plasma. Then the electron beam ignites the voluminous low density DT fuel to produce 100 MJ fusion energy. This is the step to fulfil the initial dream that laser pulses may result in controlled ignition of virtually uncompressed solid DT fuel with very high gain.

A further step forward without any very high compression of plasma is to use space charge neutral ion beams instead of the relativistic electron beam as will be shown in the following section in order to completely fulfil the initial visions of Nuckolls (2005), with a plane geometry laser ignition of solid DT with PW-ps laser pulses.

EFFECT OF LASER DRIVEN PLASMA BLOCKS WITH VERY HIGH DT CURRENT DENSITIES

The following is a combination of the fast igniter concepts for laser fusion (Tabak et al. 1994) with the initial vision of Nuckolls (2005), in view of the recent development of petawatt-picosecond laser pulses. We underline the new aspects in this development, focussing on the fact that a new effect was found with the most anomalous measurements resulting from the interaction of laser pulses with a few TW-ps laser pulses (Sauerbrey 1996, Zhang et al. 1998, Badziak et al. 1999). Usually, these pulses produced extreme relativistic effects such as 100 MeV electrons, GeV highly charged heavy ions, extreme X-ray and gamma ray bursts with subsequent nuclear transmutations by the nuclear photo effect, pair production, and so on (Cowan et al. 1999). In strong contrast to this, the anomalous measurements showed very low X-ray emission (Zhang et al. 1998), very low ion energies (Badziak et al. 1999) and a rather transparent plane geometry plasma acceleration (Sauerbrey 1996). This could be combined with early numerical computations carried out around 1978 in Australia (Hora 1991) to explain these phenomena as a nonlinear force driven plasma block generation due to the avoidance of relativistic self- focussing by suppression of pre-pulses with extremely high contrast ratios (Hora et al. 2002, Hora 2003, Hora et al. 2005, Badziak et al. 2005).

We have first to return to the initial vision of Nuckolls (2005) as to whether irradiation of solid DT without pre-compression could result in ignition of a thermonuclear burn, or flame propagation. It has to be noted that the electron beam scheme of Nuckolls & Wood (2002) still needs very high plasma compression for generating the special electron currents and even the controlled fusion reaction in the large volume of DT of only 12 times solid state density needed the support of the highly compressed part of the fuel. We are aiming to use the ultra-intense ion beam following the skin-layer effect to avoid the requirement for very high compression.

Equivalent to laser irradiation, it was considered that electron beam irradiation or irradiation by a beam of DT could be used for the flame ignition (Bobin 1974). It turned out that a DT ion beam current density under optimized conditions of

$$\mathrm{j} > \mathrm{j}^* = 10^{10}\ \mathrm{A\,cm^{-2}} \qquad (1)$$

was necessary and an energy flux density E given below was required.

$$\mathrm{E} > \mathrm{E}^* = 10^{8}\ \mathrm{J\,cm^{-2}} \qquad (2)$$

The condition (1) was many orders of magnitude beyond any particle beam technology and the condition (2) also was very extreme. It should be mentioned that by evaluation of the fusion detonation wave at spark ignition (Hora et al. 1998), the ignited core produced a value of $\mathrm{E} = 1.62 \times 10^9\ \mathrm{J\,cm^{-2}}$ for ignition of the high density low temperature outer DT shell. A correction of E^* in (2) to about ten times lower values may be possible (Hora 1983) if the interpenetration of the energetic particles into the low temperature fuel is considered, if the anomalous resistivity is included as expressed by the quantum correction of the classical collision frequency, and if the inhibition of the thermal conductivity is taken into account as given by the double layer between the hot and cold areas.

The fast ignitor scheme (Tabak et al. 1994) for laser fusion where the fuel is compressed to several thousand times the solid state density with ns laser pulses and the missing temperature in the centre for spark ignition was assumed to be provided by a ps-PW laser pulse, led to the development of these pulses. When studying the interaction of ps laser pulses of TW and higher power, the above-mentioned numerous relativistic effects (Cowan et al. 1999) were observed. If, however, the relativistic self focussing was avoided by suppressing any laser prepulse (high contrast ratio), the plane geometry of interaction within the *skin layer* of the plasma surface produced two plasma blocks. This is by nonlinear (ponderomotive) forces (SLA, skin layer plasma block acceleration by the nonlinear force), one moving with low sidewise expansion against the laser light and the other into the plasma (Figure 1), as expected from computations carried out prior to 1980, (Figure 2). This was first analysed from ion emission (Badziak et al. 1999, Hora et al. 2002) and confirmed in all details, both experimentally (Badziak et al. 2004) and numerically (Badziak et al. 2005).

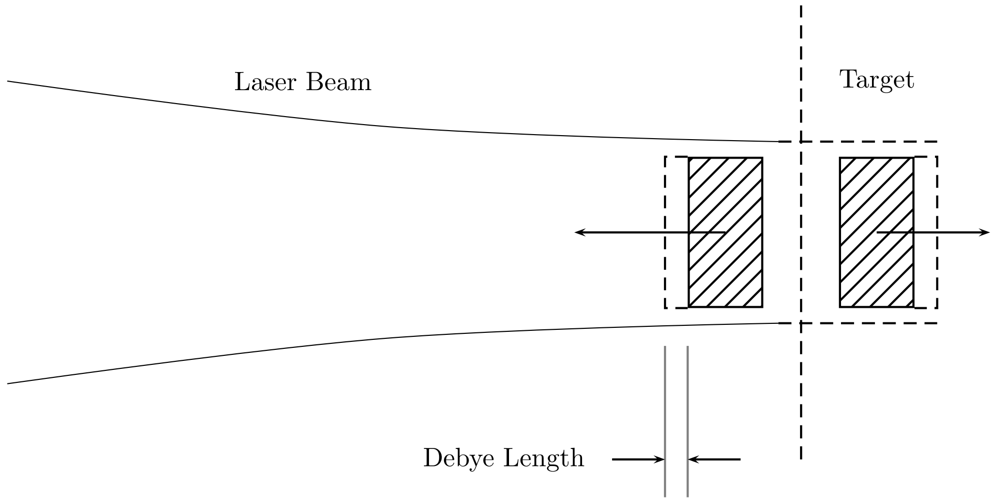

Figure 1. Fusion scheme where a laser beam irradiates solid DT producing a block of plasma moving against the laser light and another block moving into the target. Ignition requires extremely high DT current densities and energy fluxes of the blocks, equations (1) and (2).

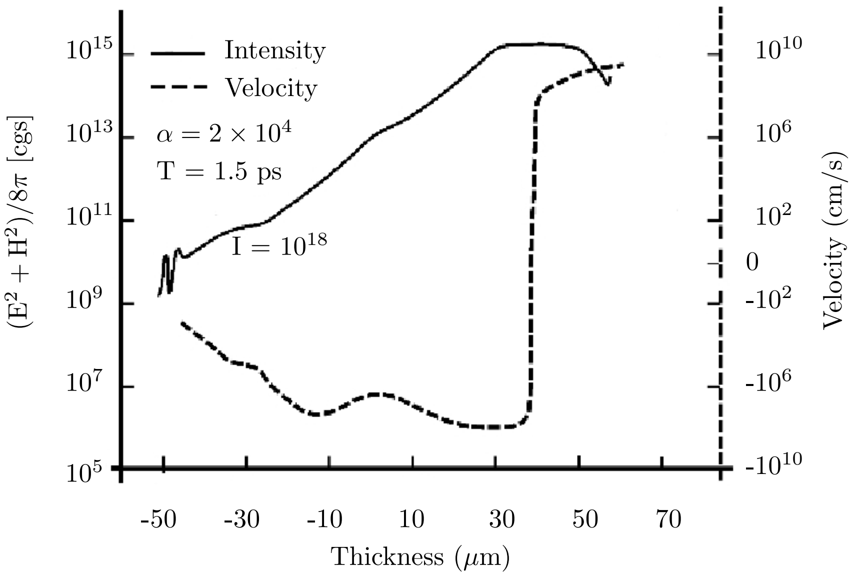

Figure 2. Generation of blocks of deuterium plasma moving against the neodymium glass laser light (positive velocities, v, to the right) and moving into the plasma interior (negative velocities) produced upon irradiation by a neodymium glass laser of 10^{18} W cm^{-2} intensity onto an initially 100 eV hot and 100 μm thick bi-Rayleigh profile (Hora 1991) with minimum internal reflection. The electromagnetic energy density $(\mathbf{E}^2+\mathbf{H}^2)/(8\pi)$ is shown at the same time of 1.5 ps after beginning constant irradiation (Cang et al. 2005).

The suppression of the self-focussing was indirectly confirmed (Hora et al. 2002) from the measured intensity independence of the accelerated ion numbers (Badziak et al. 1999). The suppression of the self-focussing channel (Hora 1975, 1991, Häuser et al. 1992) was ingeniously measured by Zhang et al. (1998) where TW-100 fs laser pulses were clean with a contrast ratio of 10^8; the need for a pre-pulse generated plasma plume for the relativistic self-focussing was demonstrated by detecting the emitted X-rays changing from very low values without self-focussing into very high values if a femptosecond pre-pulse was irradiated at least 70 ps before the main pulse.

It is very important to underline the fact that SLA-plasma-block acceleration was observed previously, without the later realized connections, by Sauerbrey (1996), confirming in retrospect that his 350 fs TW laser pulses were sufficiently clean. The pulses were produced by the Schäfer-method, amplifying 350 fs dye-laser-pulses through an activated KrF laser medium (Schäfer 1986) without the need for gratings or pulse compression as with Mourou's chirped pulse amplification CPA method (Mourou & Tashima 2002). Sauerbrey (1996) measured an acceleration, A, in a carbon plasma front moving against the laser by the Doppler effect, produced by a 350 fs TW KrF laser pulse at 3.5×10^{17} W cm^{-2} as follows:

$$A_{exp} = 10^{20}\ \mathrm{cm\,s^{-2}} \tag{3}$$

This corresponds to an electric field $\mathbf{E}^2 = 2.9\times10^{15}$ erg cm^{-3} and a density, $n_i m_i$, of the accelerated plasma layer of 5.4×10^{-3} g cm^{-3} at the critcal density $n_i = 1.6\times10^{21}$ cm^{-3} for C^{6+} ions. The nonlinear force for the simplified plane geometry (Hora 1991) is given in (4).

$$\begin{aligned} f_{NL} &= -\,(\partial/\partial x)\ (\mathbf{E}^2 + \mathbf{H}^2)/(8\pi) \\ &= n_i m_i A \\ &= -(1/16\pi)(\omega_p/\omega)^2(\partial/\partial x)\ \mathbf{E}^2 \end{aligned} \tag{4}$$

Assuming for simplification $\partial x = \Delta x = 10\,\mu$m and a swelling of S = 2 (the experiments of Badziak et al. (2004, 2005, 2006) for ps pulses resulted in S = 3.5), we find the theoretical value given in (5).

$$A_{NL} = 1.06\times10^{20}\ \mathrm{cm\,s^{-2}} \tag{5}$$

Applying this result to the accelerated plasma blocks of DT with a critical density at $n_e = 10^{21}$ cm^{-3} and an ion velocity above 10^8 cm s^{-1} shows that the plasma blocks have an ion current density above 10^{10} A cm^{-2}, therefore fulfilling condition (1) for flame propagation. A very detail numerical confirmation of this fact using the genuine two-fluid model has been provided (Badziak et al. 2005, Cang et al. 2005, Glowacz et al. 2006).

ENERGY FLUX DENSITY FOR FUSION FLAME PROPAGATION

We now discuss how condition (2) could be fulfilled with ps laser pulses of TW power or several PW by defocussing to large areas and interacting with the DT in order to produce moderate ion energies, since the optimized DT fusion cross sections require 80 keV only. Experiments (Badziak et al. 1999, 2004, 2005) provided E values for (2) of nearly 10^6 J cm^{-2}.

For the compressing block, the whole maximum quiver energy of the electron is converted into translation energy of the ions. For the DT interaction, use of an oscillation energy of 80 keV for the resonance maximum of the DT reaction may not necessarily be the best choice. Since this is close to the relativistic threshold intensity I_{rel} we have to use the general quiver energy (Hora 1991)

$$\varepsilon_{osc} = m_o c^2\ [(1 + 3SI_{vac}/I_{rel})^{1/2} - 1] \tag{6}$$

where the maximum intensity $I_{max} = SI_{vac}$ due to the dielectric swelling near the critical density is expressed by the factor S with the laser intensity I_{vac} in vacuum at the target surface.

For the general analysis we have to be flexible about the chosen values of the applied maximum (dielectrically swelled) oscillation energy ε_{osc} into the translation DT ion energy ε_{trans} in adjustment of fusion cross sections. We further leave open the value of the energy flux density $E^* = I_{vac}/\tau_L$ for reaction condition (2) [possibly even a lower value depending on future research on interpenetration mechanisms (Hora 1983)] to find the correct value of E* where the laser pulse duration τ_L will have to be in the range of ps. According to numerical studies (Cang et al. 2005, Badziak et al. 2005, Glowacz 2006), in agreement with estimations, this value could well be a few ps. From (7)

$$I_{vac} = E^*/\tau_L \tag{7}$$

we arrive at the function for the laser wave length given in (8) where m_o is the rest mass of the electron.

$$\lambda(\varepsilon_{trans}, E^*, \tau_L, S) = [\tau_L I^*_{rel}/3SE^*]^{1/2} \{[(\varepsilon_{trans}/m_o c^2) + 1]^2 - 1\}^{1/2} \tag{8}$$

Using as a special case $\tau_L = 3\,$ps, $E^* = 2 \times 10^7$ J cm^{-2}, $\varepsilon_{trans} = 80\,$keV, we arrive at (9).

$$\lambda = 0.516/S^{1/2}\,\mu\text{m} \tag{9}$$

The nonlinear force driven two-block skin layer interaction model (Figure 1) works for swelling, S, considerably larger than 1, as was the case automatically from detailed analysis of the measurements (Hora 2003) with S = 3. The lowest possible case with S = 1 is that without any dielectric swelling where the whole laser pulse energy is transferred, as in the simple case of radiation pressure to the (nonlinear-force dominated, nearly collisionless) absorbing plasma. We conclude that the condition (2) could well be fulfilled for the ignition of uncompressed solid DT fuel when applying shorter laser wave length than that of the neodymium glass laser; this is well in reach of present technology. For the pessimistic case of Bobin (1974), the numerical factor in (9) is 0.105, such that with S = 1 just the borderline of higher harmonics CPA (Mourou & Tashima 2002) or of excimer lasers (Schäfer 1986) would be covered. Further research on lower values of E^* and numerical studies for slightly longer laser pulses may further relax the conditions, and longer laser wave lengths would be possible. Figure 3 shows the dependence of the necessary laser wave length for a pulse length of 3 ps and swelling S = 1 which one needs for a desired ion translative energy in multiples of $m_o c^2$, if the threshold E^* is given. Maybe there is a narrow gap for successful conditions.

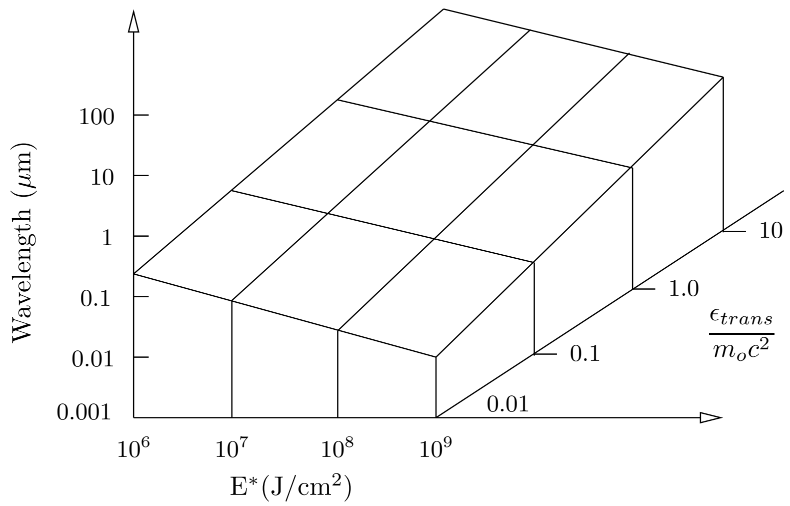

Figure 3. Relation between the laser wave length, aimed ion energy ε_{trans} in multiples of $m_o c^2$ and the necessary energy flux density for ignition of uncompressed DT following (8) for S = 1 and a laser pulse duration of 3 ps.

DISCUSSION

To produce energy at five times lower cost than all the existing energy sources on earth is potentially achievable if the laser could ignite solid state DT without the complicated precompression step. It is remarkable that Nuckolls & Wood (2002) developed the option of the fast igniter where very intense 5 MeV electrons would ignite large quantities of nearly solid state (or moderately compressed) DT and where some 10 kJ of laser energy produces more than 100 MJ of fusion energy. It can be assumed that this ignition scheme involves controlled laser fusion processes quite differently to uncontrolled fusion reactions. A similar scheme may be reached with nonlinear force driven skin layer acceleration SLA plasma blocks (Hora 2002). The necessary condition (1) for 10^{11} A cm^{-2} and higher DT ion current densities for this have been verified (Hora et al. 2002, Badziak et al. 2005) for optimum ion energies of 80 keV. For condition (2), the possibilities seem to be in reach since the value E^* will be considerably reduced in view of modifications that have not yet been fully explored. The final question is whether the necessary laser intensities of 10^{17} to 10^{18} W cm^{-2} of few ps duration provide comparable conditions for igniting the fusion flame in a way similar to radiation ignition (Nuckolls 2005), which refer to uncontrolled reactions with similar intensities of Planck radiation (11 million K).

With several preliminary estimations concerning fusion, apart from solid experimental and theoretically based results on plasma block generation, the present study may provide the framework for further evaluation of Particle in Cell (PIC) computation results for generation of plasma blocks (pistons) covering conditions (1) and (2) (Esirkepov et al. 2004). We must find out how to avoid relativistic self-focussing and how to optimise DT ion energies for the fusion flame. Our present position from the side of sub-relativisitc conditions may be an alternative approach leading to a very simplified low cost laser fusion reactor.

If this laser-plasma block controlled ignition (LABIG) scheme becomes a serious method of producing energy at very low cost, nonproliferation problems associated with uranium fission would be greatly reduced (Hora 2002). The benefits in reducing global warming would be much greater than the risks of a suggested increase in the number of fission reactors. Unlike the finite supply of uranium, the availability of hydrogen and its isotopes is essentially unlimited.

The problems to be clarified are the new theoretical aspects of the interpenetration process for Bobin's (1974) fusion flame and techniques for producing sufficiently thick highly directed and low temperature plasma blocks by the skin layer effect. The use of radially driven layers with shrinking width and increasing thickness are currently being discussed (Badziak et al. 2006).

CONCLUSIONS

Interaction of TW-ps laser pulses with plasma results in a skin layer mechanism for nonlinear (ponderomotive) force driven two dimensional plasma blocks (pistons). This mechanism relies on a high contrast ratio for suppression of relativistic self-focussing. Space charge neutral plasma blocks are obtained with ion current densities larger than 10^{10} A cm^{-2}. Using ions in the MeV range results in 1000 times higher proton or DT current densities than the proposed proton fast igniter requires (Roth et al. 2005). This should result in better conditions of this fast ignitor scheme. The ballistic focusing of the generated plasma blocks and then short-time thermal expansion increases their thickness but maintains high ion current densities. As shown here, this approach then provides conditions that are very favourable for efficient fast ignition of a fusion target. If successful, this approach to fast ignition could significantly simplify operation of an IFE plant, leading to very attractive energy production costs.

ACKNOWLEDGEMENTS

This paper is based on an oral presentation at the 17$^{\text{th}}$ Australian National Physics Congress 2006, Brisbane 3–8 December 2006. Support by the Australian Institute of Nuclear Science and Engineering (AINSE) is gratefully acknowledged.

REFERENCES

Badziak, J., Kozlov, A.A., Makowksi, J., Parys, P., Ryc, L., Wolowski, J., Woryna, E. and Vankov, A.B., 1999. Investigation of ion streams emitted from plasma produced with a high-power picosecond laser, *Laser and Particle Beams*, **17**, 323–329.

Badziak, J., Glowacz, S., Jablosnki, S., Parys P., Wolowski, J. and Hora, H., 2004. Production of ultrahigh-current-density ion beams by short-pulse laser-plasma interaction, *Applied Physics Letters*, **85**, 3041–3043.

Badziak, J., Glowacz, S., Jablonski, S., Parys, P., Wolowski, J. and Hora, H., 2005. Laser-driven generation of high-current ion beams using skin-layer ponderomotive acceleration, *Laser and Particle Beams*, **23**, 401–410.

Badziak, J., Glowacz, S., Hora, H., Jablonski, S. and Wolowski, J., 2006. Studies of laser driven generation of fast-density plasma blocks for fast ignition, *Laser and Particle Beams*, **24**, 249–254.

Bobin, J.L., 1974. Nuclear fusion reactions in fronts propagating in solid DT, In Schwarz, H. and Hora, H. (Eds), *Laser Interaction and Related Plasma Phenomena*, Vol. 4B, pp. 465–494. Plenum Press, New York.

Cang, Y., Osman, F., Hora,H., Zhang, J., Badziak, J., Wolowski, J., Jungwirth, K., Rohlena, J. and Ullschmied, J., 2005. Computations for nonlinear norce driven plasma blocks by picosecond laser pulses for fusion, *Journal of Plasma Physics*, **71**, 35–51.

Cowan, T.E., Parry, M.D., Key, M.H., Dittmire, T.R., Hatchett, S.P., Henry, E.A., Mody, J.D., Moran, M.J., Pennington, D.M., Phillips, T.W., Sangster, T.C., Sefcik, J.A., Singh, M.S., Snavely, R.A., Stoyer, M.A., Wilks, S.C., Young, P.E., Takahashi, Y., Dong, B., Fountain, W., Parnell, T., Johnson, J., Hunt, A.W. and Kuhl, T., 1999. High energy electrons, nuclear phenomena and heating in petawatt laser-solid experiments, *Laser and Particle Beams*, **17**, 773–783.

Esirkepov, T., Borghesi, M., Bulanov, S.V., Mourou G. and Tajima, T., 2004. Highly efficient relativistic-ion generation in the laser-piston regime, *Physical Review Letters*, **92**, 1–4.

Gerstner, E. 2007. Editorial *Nature* **446**, 16

Glowacz, S., Hora, H., Badziak, J., Jablonski, S., Cang, Y. and Osman, F, 2006. Analytical description of rippling effect and ion acceleration in plasma produced by a short laser pulse, *Laser and Particle Beams*, **24**, 15–25.

Häuser, T., Scheid, W. and Hora, H., 1992. Theory of ions emitted from a plasma by relativistic self-focusing of laser beams, *Physical Review A*, **45**, 1278–1281.

Hora H., 1975. Theory of relativistic self-focusing of laser radiation in Plasmas, *Journal of the Optical Society of America*, **65**, 882–886.

Hora, H., 1983. Interpenetration burn for controlled inertial confinement fusion by nonlinear forces, *Atomkernenergie*, **42**, 7–10.

Hora, H., 1991. *Plasmas at High Temperature and Density.* Springer, Heidelberg.

Hora, H., 2000. *Laser Plasma Physics: Forces and the Nonlinearity Principle.* SPIE-Books, Bellingham, WA.

Hora, H., 2002. *Fusion reactor with petawatt laser*, German Patent Application 103308515.3 (declassified 5 Sept. 2002).

Hora, H., 2003. Skin-depth theory explaining anomalous picosecond-terawatt laser-plasma interaction, *Czechoslovak Journal of Physics*, **53**, 199–217.

Hora, H., 2004. Developments in inertial fusion energy and beam fusion at magnetic confinement, *Laser and Particle Beams*, **22**, 439–449.

Hora, H., 2005. Ideal Energy Source by Mark Oliphant's Beam Fusion, *Journal and Proceedings of the Royal Society of New South Wales*, **138**, pp. 13–29.

Hora, H. and Miley, G.H., (Eds) 2005. *Edward Teller Lectures: Lasers and Inertial Fusion Energy.* Imperial College Press, London.

Hora, H., Azechi, H., Kitagawa, Y., Mima, K., Murakami, M., Nakai, S., Nishihara, K., Takabe, H., Yamanaka, C., Yamanaka M. and Yamanaka, T., (1998) Measured laser fusion gains reproduced by self-similar volume compression and volume ignition for NIF conditions, *Journal of Plasma Physics*, **60**, 743–760.

Hora, H., Badziak, J., Boody, F., Höpfl, R., Jungwirth, K., Kralikova, B., Kraska, J., Laska, L., Parys, P., Perina, P., Pfeifer, K. and Rohlena, J., 2002. Effects of picosecond and ns laser pulses for giant ion source, *Optics Communications*, **207**, 333–338.

Hora, H., Badziak, J., Glowacz, S., Jablonski, S., Sklandanowski, Z., Osman, F., Cang, Y., Zhang, J.I.E., Miley, G.H., Peng, H., He, X., Zhang, W., Rohlena, K., Ullschmied, J. and Jungwirth, K., 2005. Fusion energy form plasma block ignition, *Laser and Particle Beams*, **23**, 423–432

Hora, H., 2007. New aspects for fusion energy using inertial confinement, *Laser and Particle Beams* **25**, 37–45.

Hora, H., 2007a. *Klimakatastrophe Überwindern.* S. Roderer Verlag, Regensburg.

Hora, H., Osman, F., Castillo, R., Collins, M., Stait-Gardner, T., Chan W.-K., Hölss, M., Scheid, W., Wang, J.X.,, and Ho, Z.-K. 2002a. Laser-generated pair production and Hawking-Unruh radiation, *Laser and Particle Beams* **20**, 79–86.

Keilhacker, M., 1999. High fusion performance from deuterium-tritium plasma in JET. *Nuclear Fusion*, **39**, 209–221.

Kidder, R.E., 2005. Book review, *Laser and Particle Beams*, **23**, 597.

Mourou, G. and Tashima, T., 2002. Ultrahigh power laser pulses, In Tanaka, K.A., Meyerhofer, D.D. and Vehn, J.M. (Eds), *Inertial Fusion Science and Applications 2001*, pp. 831–836. Elsevier, Paris.

Nuckolls, J.H., 2005. Edward Teller Medal: Acceptance Remarks. See Hora et al. (2005).

Nuckolls, J.H. and Wood, L., 2002. *Future of inertial fusion energy,* Lawrence Livermore National Laboratory Preprint, UCRL-JC-149860.

Roth, M., Brambrink, E., Audebert, B., Blayevic, A., Clarke, R., Cobble, J., Geissel, M., Habs, D., Hegelich, M., Karsch, S., Ledingham, K., Neelz, D., Ruhl, H., Schlegel, T. and Schreiber, J., 2005. Laser accelerated ions and electron transport in ultra-intense laser matter interaction, *Laser and Particle Beams*, **23**, 95–100.

Sakharov, A., 1961. See Hora et al. (2005), p. 3.

Sauerbrey, R., 1996. Acceleration of femtosecond laser produced plasmas, *Physics of Plasmas*, **3**, 4712–4716.

Schäfer, F.-P., 1986. Excimer laser for very short laser pulses, *Applied Physics*, **B39**, 1–7.

Stait-Gardner, T., and Castillo, R. 2006. Difference between Hawking and Unruh radiation derived from studies about pair production by lasers in vacuum. *Laser and Particle Beams* **24**, 579–603.

Tabak, M., Glinsky, M.N, Kruer, W.L., Wilks, S.C., Woodworth, J., Campbell, E.M., Perry, M.D. and Mason, R.J., 1994. Ignition of high-gain fusion with ultrapowerful lasers, *Physics of Plasmas*, **1**, 1626–1634.

Teller, E., 1960. See Hora et al. (2005), p. 3

Tran Minh Quang, 8 September 2004. Physics Colloquium, Sydney University.

Zhang, P., He, J.T., Chen, D.B., Li, Z.H., Zhang, Y., Wong, L., Li, Z.H., Feng, B.H., Zhang, D.X., Tang, X.W. and Zhang, J., 1998. X-ray emission from ultraintense-ultrashort laser irradiation, *Physical Review*, **E57**, 3746–3752.

---

* Frederick Osman, Mathematics Department, Trinity College, Summer Hills, NSW, Australia. Email `fosman@trinity.nsw.edu.au`

§ Heinrich Hora, Department of Theoretical Physics, University of NSW, Sydney, Australia.

§ George H. Miley, Fusion Studies Laboratory, University of Illinois, Urbana-Champaign, USA.

§ Jak C. Kelly, School of Physics, Sydney University, Sydney, Australia.

* Author for correspondence.

(Manuscript received 14.08.2006, accepted 30.01.2007)