Plasma Mirror for High Contrast Picosecond Laser Pulses for Fast Ignition Fusion.

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Abstract. Application of a unique anomaly of ps laser pulses with powers above TW for driving plasma blocks for fast ignition is based on very high contrast ratios produced by plasma mirrors of which the mechanisms involved are discussed. A recent plasma mirror experiment is evaluated in view of the optical momentum transfer where the measurements are reproduced from the nonlinear (ponderomotive) force acceleration of the electrons with the usual electrostatic coupling of the ions.

1. Introduction

Very unexpected anomalies of laser-plasma interaction were measured when ps laser pulses of TW and higher power irradiated solid targets [1]. The usually occurring relativistic self-focusing of the laser beams in the plasma plume could be suppressed and a plane-geometry interaction with nonlinear-force-driven skin layers produced highly directed plasma blocks with ion current densities above \(10^{10}\) Amp/cm\(^2\) moving against the laser or into the target. This may open a new modification of the fast ignition scheme [2] similar to the thermally driven plasma blocks (fast impact ignition [3]). The nonlinear force driving in contrast to the thermal driving is essential for the anomaly as it could be established from the various observations (see Sauerbrey, Zhang et al. in [1]) specifically from the fact [4] that the number of accelerated ions does not vary at 30 times change of the laser intensity. From this fact a very specific skin layer process was concluded [5].

A necessary condition for the fast ignition by these nonlinear force driven blocks [1,2] is that the laser pulses are extremely clean where only the suppression of prepulses by a factor \(10^8\) (contrast ratio) can prevent the usually occurring relativistic self-focussing [5,6]. This is achieved by using plasma mirrors within the irradiating laser pulse. The concept of these mirrors is based on transparent dielectric materials which have a very low reflection of the laser beam from solid state materials for separating any lower intensity prepulse until a threshold laser intensity produces plasma with a very high reflectivity. These plasma mirrors were introduced by Anisimov, Basov and Prokhorov et al., (see references in the subsequent improvements by Schmiedberger and Vrbova [7]). Since these early developments, a number of new phenomena have been discovered as the electric double layers [8], the stochastic
pulsation [9] and their suppression by smoothing of the laser beams by broad band [10] or visibly demonstrated by Labaune et al [11] using random phase plates [12].

2. Mechanisms involved in plasma mirrors

For the nonlinear force driven plane plasma fronts without relativistic self-focussing two different ways for generating ps laser pulses are available, that of Chirped Pulse Amplification, CPA [13], and that of the Schäfer method [14] where a sub-picosecond dye laser pulses is amplified in a KrF laser medium to generate the TW or PW laser powers. For the first case as an example of the numerous preceding cases, the experiments by Neely et al [15] with contrast ratios of $10^9$ are discussed in the section 4, while the second case was based on contrast ratios of $10^{10}$ as first used for x-ray emission [16,17].

Several mechanisms of laser-plasma interaction have first to be discussed for the application of plasma mirrors. When the intensity $I$ of the laser resulting in an electron quiver energy $\varepsilon_{osc}$ equal to $mc^2$, this relativistic threshold energy is $I=I_r=4.05\times10^{18}/\lambda^2$ W/cm$^2$ where $\lambda$ is the laser wavelength in $\mu$m. The quiver energy (see Eq. 6.76 of [18]) is then the temperature of the hot electrons given in the corrected form [19]

$$\varepsilon_{osc} = T_{hot} = \{(1 + 3IS/\lambda^2/(n|4.05\times10^{18}|)^{1/2} - 1\}511 \text{ keV}$$

where $S$ is the dielectric swelling [18], and the thermalization for the hot electrons by collisions needs the quantum correction as shown from the Gitomer ambipolar acceleration of energetic ions [6]. Relativistic self focussing is due to the change of the refractive index $n$ of the plasma at relativistic quiver motion and occurs at much lower intensities $I$ than the relativistic threshold [20]

$$I > 10^3 I_r$$

A further mechanism is the generation of electric double layers [8] since the laser radiation accelerates the electron cloud in the plasma by the nonlinear (ponderomotive) forces and the ions follow by electrostatic attraction by which way the ions are split in sections by the ion charge number $Z$. The separated ion cloud is attracted by the electrons over an effective Debye sheath. This is incorrectly called Coulomb acceleration and automatically appears in collisionless single particle simulations of laser-plasma interaction which model was improved by Wilks et al [21] working with Particle In Cell (PIC) codes. These computations arrived at similar moving plasma blocks as Target Normal Sheath Acceleration (TNSA) similar to the PIC derived “pistons” [22] as a particle description of the earlier derived hydrodynamic generation of blocks of plasmas partially separated by precursing electron clouds (see Fig. 1 of Ref. [6]).

Further attention is given to stochastic pulsation at laser-plasma interaction where within several ps interaction, the laser has a mirror reflection at the critical density accelerating the corona by nonlinear forces to the $10^8$ cm/s$^2$ velocities. This is interrupted by the generated partial standing wave in the corona leading to a density ripple causing a von-Laue-Bragg phase reflection of nearly 98% at the outermost corona to interrupt the net plasma acceleration. This is followed up by thermal washing out of the density ripple within 5 to 20 or more ps when again a mirror reflection is possible for another block of a $10^8$ cm/s corona layer being then interrupted again after few ps by density rippling and phase reflection. This was experimentally proved in details by Maddever et al [9] and the stochastic sequence of this
pulsating interaction was numerically reproduced in all details [10]. It was shown numerically, how a broad-band laser field avoids this pulsation [10] leading to a highly efficient transfer of optical energy into the plasma at low reflectivity by avoiding the phase reflection. The same can be achieved with random phase plates as shown directly from framing picture diagnostics by Labaune et al. [11] how the random phase plates [12] suppressed filamentation as well as suppressing the plasma blocks perpendicular to the filaments. These mechanisms led to an increase of laser fusion gains by a factor 20 and more [23] with the highest compression density and a reduction of parametric instabilities by more than a factor 100 [11].

3. Consequences for the picosecond operation of plasma mirrors

Following these rather complicate phenomena of laser-plasma interaction, it is important to summarize, what of these facts are of importance for the operation of the plasma mirrors for the initially mentioned important applications to nonlinear force driven plasma blocks for a new fast ignition scheme for laser fusion [2] and related applications. The result of Eq. (2) restricts that the laser beam at the plasma mirror needs to be wide enough such that the intensity is lower than $10^{-4}$ times of the relativistic threshold. This seems to be easily fulfilled since these intensities are far above the longer than ps laser pulses for generation of plasma from the transparent dielectric mirror material. However it is well known, that the threshold for damage and plasma generation in dielectrics is considerably higher for ps and fs than for longer laser pulses.

For ps laser pulses, the generation of ponderomotive self-focussing [24] at the threshold of 1 MW is not longer valid, since this kind of filament need moving plasma out of the beam axis needing much longer time than ps, in some cases up to nanoseconds. Being aware of the 5 to 30 ps stochastic pulsation and the low reflectivity at phase reflection, it can be concluded, that no beam smoothing is advisable for the operation of the mirror, since the establishing of the high reflectivity by phase reflection within few ps is very favourable.

4. Application to an example of plasma mirror operation

The recent publication [15] of ps 170 J laser pulse interaction with a 40 nm silicon layer using a plasma mirror to provide a contrast ratio of $10^9$ can be used for the following considerations. The measured forward acceleration of 990 MeV ions may mostly be caused by the momentum of the incident laser pulse though the question remains how nevertheless some swelling of the laser pulse may happen and a generation of two layers moving against the laser pulse and with the laser pulse are generated. It was evaluated what a collisionless absorption by the nonlinear forces in thin plasma layers with fs and ps laser pulses can be achieved [25].

The momentum of the laser pulse is $5.7 \times 10^2$ gcm/s. The optical interaction is with the electrons having a maximum quiver energy of 1.69 MeV from Eq. (1) at the neodymium glass laser intensity of $2.1 \times 10^{19}$ W/cm$^2$. If these are accelerated towards the vacuum behind the target by the density gradient by the nonlinear force, they will then with a large effective Debye layer accelerate the silicon ions according to their charge number $Z$ of 13 or 14 (as preferently measured) to energies of Z times the nonrelativistic value as derived before [20] according to 41 MeV corresponding to 1.1 MeV per nucleon. This is much too less than observed. The other mechanism is the acceleration the electrons in vacuum by lasers [26] where the generated electric field leads to the Z-times higher ion energies. The main momentum transfer goes then into these ions. This arrives at 7.6 MeV per nucleon if the
momentum transfer would have gone into the complete foil and arrives at 30.4 MeV per nucleon if the momentum transfer would have gone into half thickness of the foil in agreement with the measurements (Fig. 7 of Ref. [15]) where nearly all ions were accelerated to the range of the first value. In conclusion, the experiment shows a direct conversion of the optical energy of the laser pulse into the motion of the silicon layer. Indeed many details of this process need to be clarified.

References:
[1] Hora H., Badziak J., M.N. Read Li Yu-Tong et al. 2007 Phys. Plasmas 14, 072701
[2] Hora H., Badziak J., Glowacz S., et al. 2006 Journal de Physique IV 133, 219 (2006)
[3] Murakami M., Nagatomo H., Ayechi H., F., Perlado M., Eliezer S. 2006 Nucl. Fusion 46, 99
[4] Badziak J., Kozlov A.A., Makowski J., et al. 1999 Laser & Part. Beams 17, 323
[5] Hora H., Badziak J., et al. 2002 Opt.Commun. 207, 333
[6] Hora H. 2003 Czech. J. Phys. 53, 199; Hora H. 2005 Laser & Part. Beams 23, 441
[7] Schmiedberger J., Vrbova M. 1996 Laser & Part. Beams 4, 427
[8] Hora H., Laloupis P., Eliezer S. 1984 Phys. Rev. Lett. 53, 1650; Eliezer S., Hora H. 1989 Physics Report 172, 339
[9] Maddever R.A.M. et al. 1990 Phys. Rev. A 41, 2154
[10] Hora H., Aydin M. 1992 Phys. Rev. A 45, 6123
[11] Labaune C. et al. 1992 Phys. Fluids B4, 2224; Hora H. 2006 Laser & Part. Beams 24, 35
[12] Kato Y., Mima K., et al. 1984 Phys. Rev. Lett. 53, 1057
[13] Strickland D., Mourou G. 1985 Opt. Commun. 56, 219; Mourou G., Tajima T. 2002 Inertial Fusion Science and Applications 2001 (Paris: Elsevier) p. 831
[14] Schäfer, F.-P. 1986 Appl. Phys. B39, 1
[15] Strangio C., Caruso A., Neely D., et al. 2007 Laser & Part. Beams 25, 85
[16] Teubner U., Bergmann J., Wonthergem B. van, Schäfer F.-P. 1993 Phys. Rev. Lett. 70, 794
[17] Amendt P., Eder D.C., Wilks C.S. 1991 Phys. Rev. Lett. 66, 2598; Amendt P.A., Robey H.R. et al. 2005 Phys. Rev. Lett. 94, 065004
[18] Hora H., 1981 Physics of Laser Driven Plasmas (New York: John Wiley)
[19] Chen H., Wilks C.S. 2005 Laser & Part. Beams 23, 411
[20] Hora H. 1975 J. Opt. Soc. Am. 65, 882; Häuser T., et al. 1992 Phys. Rev. A 45, 1278
[21] Wilks S.C.,Krue W.L., Tabak M., Langdon A.B. 1992 Phys. Rev. Lett. 69, 1383
[22] Esikepov T., BorghesiM., Bulanov S.V., Mourou et al. 2004 Phys. Rev. Lett. 92, 175003
[23] Azechi H., Jitsuno. T., Kanabe, M. Mima, K. 1991 Laser & Part. Beams 9, 193
[24] Hora H. 1969 Zeitschr. f. Physik 226, 156
[25] Batchelor M.T., Stening R.J. 1985 Laser & Part. Beams 3, 189
[26] Hora H. 1988 Nature 333, 337 (1988), Glinec Y. et al 2005 Laser & Part. Beams 23, 161; Lifshitz A.F., Faure J., Glinec Y., Malka V., Mora, P. 2006 Laser & Part. Beams 24, 255