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Pressure of picosecond CPA laser pulses substitute ultrahigh thermal pressures to ignite Fusion

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Abstract: Nuclear reactions produce ten million times more energy than the chemical reactions e.g. from burning carbon, but the equilibrium thermal pressures for chemical reactions need temperatures of hundred ºC while nuclear burns need many dozens of million ºC. This is on the level for ITER or at NIF with using nanosecond laser pulses. In contrast, non-thermal pressures can be higher by lasers using nonlinear forces of picoseconds or shorter duration as computer results of 1978 had demonstrated by non-thermal plasma-block acceleration. This is in full agreement with the ultrahigh acceleration measured by Sauerbrey since 1996 thanks to his use of ultra-extreme powers of picosecond CPA-laser pulses. Even the very inefficient classical fusion of hydrogen with the ^{11}B can be used for the non-thermal reaction with sufficiently modest heating in a reactor for generation electricity.

1 Introduction

The ultra-powerful picosecond CPA laser pulses (D. Strickland and G. Mourou, 2018 Physics Nobel Prize [1]) have just reached the necessary condition for producing a turning point to overcome the difficulties in present schemes studied for an electricity generator using nuclear fusion reactions, where pressures for thermal equilibrium are needing temperatures of hundreds of Millions of ºC [2]. It is well known that these extreme conditions can be relaxed by using thermal non-equilibrium e.g. by partial involving ion beams [3] as e.g.in reverse-field arrangements in the cylindrical IEC-C-device reaction (Fig. 1 of [4]) but the astronomic temperatures are a handicap also in view of the energy losses by bremsstrahlung [5][6].

The solution has to consequently follow the nonlinear phenomena by the complete equation of motion with the interacting of the fields of the laser irradiation [7][8] for the DT reaction and the reaction of hydrogen H and ^{11}B

$$D + T = {}^{4}He + n + 17.3\ MeV \qquad (1)$$

$$H + {}^{11}Be = 3\ {}^{4}He + 8.9\ MeV \qquad (2)$$

The equation of motion of plasmas

$$\mathbf{f} = -\nabla p + \mathbf{f}_{NL} \qquad (3)$$

contains the plasma-dynamic pressure p with the density and the temperature T while then nonlinear terms - apart from a minor temperature dependence of the optical constants ***n*** are determined only on the electric and magnetic fields **E** and **H** with Maxwell's stress tensor **M** in the nonlinear force $\mathbf{f}_{NL} = \nabla\bullet\mathbf{M}$ [7][8]

$$\mathbf{M} = [\mathbf{EE}+\mathbf{HH}-0.5(\mathbf{E}^2+\mathbf{H}^2)\mathbf{1}+(1+(\partial/\partial t)/\omega)(\boldsymbol{n}^2-1)\mathbf{EE}]/(4\pi)-(\partial/\partial t)\mathbf{E}\times\mathbf{H}/(4\pi c) \qquad (4)$$

The recognizing of this result for the laser-plasma interaction was based on a number of observations.

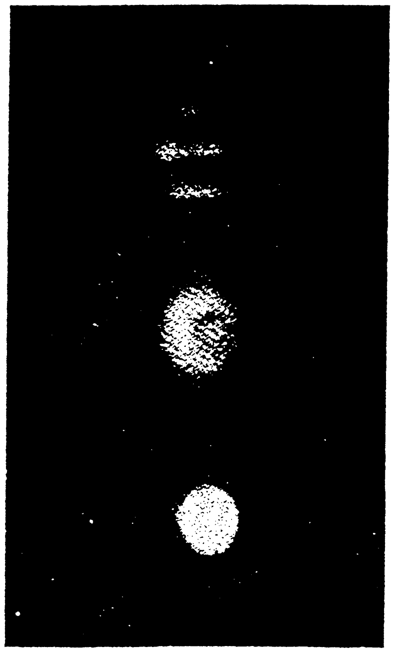

Fig. 1. Side-on framing camera picture of a plasma produced from an aluminum sphere of 80 μm radius at the time indicated after irradiation by a 30 ns ruby laser pulse focused to 0.4 mm diameter. The second frame shows the outer part of a rapidly expanding plasma and an inner spherical thermally expanding part [13][14].

2 Identifying the Nonlinearity

A significant case of nonlinear deviation from classical linear physics was seen by the measurements, how the laser opened the door to the principle of nonlinearity and could be seen from the effect measured by Linlor [9] followed by others (see [7] p. 31) when irradiating solid targets with laser pulses of several ns duration. At less than one MW power, the pulses heated the target surface to dozens of thousand ^{o}C and the emitted ions had energies of few eV as expected in the usual way following classically. When the power of the nanosecond laser pulses was exceeding a significant threshold of few MW, the ions – suddenly – had thousand times higher energies. These keV ions were separated with linear increase on the ion charge indicating that there was not a thermal equilibrium process involved

The MW threshold was identified as the beginning of ponderomotive self-focussing [10], well following a ponderomotion as realized by Askaryan and well indicated by Bulanov et al [11] in a qualitative way, but it was clarified only by adding two further equations, the condition of refraction and the relation of diffraction for the beam filament to result in the exact reproduction of the threshold of about few MW [10].

The non-linearity as an electro-dynamic process could be seen in the photos of Fig. 1 as shown from many hundred side-on pictures from free falling aluminium spheres when irradiated from the left by laser pulses in the range of 10 ns duration [12]. Evaluation [13][14] of expansion velocities related to the power and duration of the pulses showed that there was a spherical core of plasma expanding with classical plasma hydrodynamics from heating by few dozens of eV temperatures, but there were the half-moon like plasmas with nonlinearly increased expansion velocities up to keV ion energies.

For the following it is important to find conditions in Eq. (3), where the properties of laser pulses have such high laser intensities that its fields produce a non-thermal (cold) pressure by the nonlinear forces that are higher than the thermal pressures p. This can be seen from the numerical evaluation of Fig. 2. The results of the nonlinear force permitted a numerical study for the interaction of a laser pulse of intensity 10^{18}W/cm^2 on a slab of deuterium plasma of density close but below the critical value. The very general time dependent motion was calculated including the local variation of temperature and density that resulted within 1.5ps in the motion of a plasma blocks achieving a velocity of above 10^9 cm/s directed against the laser light. Such an ultrahigh acceleration of more than 10^{20}cm/s^2 was hundred-thousand times higher than measured from the thermal irradiation by lasers on solids. For this numerical result of 1977 (summarized in Fig. 8.4 of [8]), the laser intensities were then just available but were many orders of magnitudes longer than a picosecond with a confirmation of numerical stability

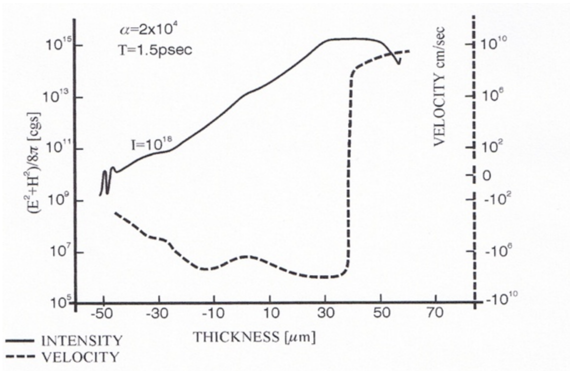

Fig.2. *10^{18} W/cm^2 neodymium glass laser is incident from the right hand side on an initially 100 eV hot very low reflecting bi-Rayleigh deuterium plasma profile at initial time t=0, results at time t=1.5 ps of interaction is a velocity distribution v(x) on the depth x and in an energy density of the laser field ($\boldsymbol{E}^2+\boldsymbol{H}^2$)/8π. The dynamic development had accelerated the plasma block of about 20 vacuum wave length thickness of the dielectric enlarged skin layer moving against the laser and another block into the plasma showing ultrahigh >10^{20}cm/s^2 acceleration [7][8].*

The result of Fig. 2 can be summarized schematically in Fig. 3 that the dielectric constants ***n*** of the plasma around the critical plasma density deviating from unity are causing an explosion between the two plasma blocks, one moving against the irradiated laser pulse and the other towards the plasma interior. The ultrahigh acceleration of the block moving against the beam is seen from the velocity measured by the Doppler shift of the spectral lines.

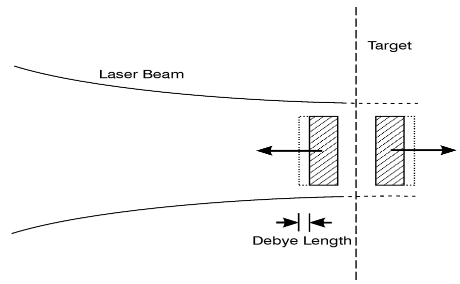

Fig. *3. Scheme of skin depth laser interaction where the non-linear force accelerates a plasma block moving against the laser beam and another block towards the target interior as a kind of dielectric explosion. In front of the blocks are electron clouds of the thickness of the effective Debye lengths for the conditions of Fig. 2*

This computed result of Fig. 2 in 1977 [7] was fortunately done with parameters that could be compared in the following with the experiments in 1996 of Sauerbrey [17] showing a rather high degree of agreement. The fact of the ultrahigh acceleration of the ions in the plasma block moving against the irradiated laser pulse was seen from the blue Doppler shift of spectral lines according to Fig. 3 causing the dielectric explosion of plasma blocks basad on the refraction index close to the critical density as essential mechanism in Fig. 2.

This indicates that the laser interaction worked by the forces at densities close to the critical plasma density. When using lower plasma densities, the specrtal lines were only red shifted showing a pushing of the plasma as a simple "radiation force acceleration" as seen also from PIC computations due to a refractive index close to unity [18] without the strong dielectric response of the plasma at near-critical density. Only the ordinary "radiation pressure acceleration" in the direction of the laser pulse is resulting. The explosive block generation with the ultrahigh acceleration is the result of the dielectric explosion property [18].

Experiments for the just mentioned conditions of ultrahigh acceleration of plasma blocks by the nonlinear force were possible only after a most significant discovery that led to a radical turning point in laser development with the Chirped Pulse Amplification CPA [1][19]. With initial laser powers of 10^{18}W/cm^2 it was possible by Sauerbrey [17] for the very first time to measure the ultrahigh acceleration of the plasma block moving against the irradiating laser pulse as shown by the blue Doppler shift of spectral lines [17] and measured as acceleration of 10^{20}cm/s^2 exactly in the range of the computations of 1977 [7]. Similar measurements with ultrahigh accelerations deviating from the usually observed thermal computations did result by computations in 1977 (Fig. 2) arrived at similar theoretical agreement [20].

For the repetition of these experiments, one critical point was the need of very high quality of the laser pulses with respect to the contrast ratio for the time development of the pulse. It turned out that this was a question how to exclude relativistic self-focusing [21] that could be solved only in a most sophistic way [22].

Numerous measurements with red and no blue Doppler shift occurred at lower plasma densities than critical and were essentially only pushing the electron cloud into the direction of the irradiated laser beam as ordinary radiation pressure. This "radiation pressure acceleration" is essentially different from the dielectric explosion process of the plasma blocks well having the acceleration given by the transverse normal sheath acceleration TNSA mechanisms as it was a basically general result [23] from plasma hydrodynamics reproduced also from ion adequate single particle PIC models with a quiver drift of the eight-like electron motion (see Fig 8.1 of [24] and [25]) and further evaluations [26][27].

This fact of agreement between Fig. 2 and the measurement of Sauerbrey [17] bridges the different presumptions between Maxwell's energy distributions of hydrodynamics and the usual neglecting of dielectric and collisional effects [18][27] in PIC [28] techniques to give a basic validity of the computational result of Fig. 2 and the measurements [17][20].

3) Nonlinear force accelerated plasma blocks to avoid ultrahigh fusion temperatures

The numerical result of Fig. 2 with irradiation of initially 100 eV hot deuterium plasma by a 10^{18}W/cm^2 laser intensity with the rather comparable measurements of Sauerbrey [17] is a sufficient condition for the dominance of the second term in Eq. (3) against the first term with the thermal pressure p. The measured ultrahigh acceleration by [17] and repeated by Földes et al. [20] using the needed very high contrast ratio laser pulses [21]. It was seen also by the skin layer acceleration of Badziak et al. [29][30] and by Norreys et al [31] following the diagram by Krasa [32][33] (Fig. 4).

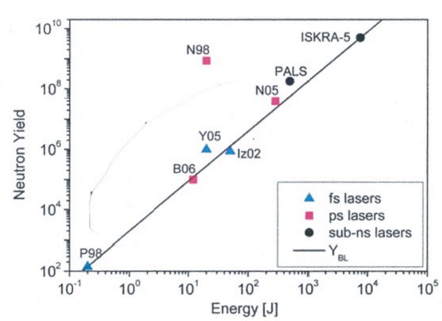

Fig. 4. Fusion neutrons from irradiation of laser pulses of duration between femtoseconds and 0.1 nanoseconds on the irradiated energy from targets with deuterium as fusion fuel [72].

This is a case where the laser pulses had sufficiently high quality, as can be mentioned in retrospect [31] where the exceptional way the unexpected four orders of magnitudes increase of fusion gains is a fact. It was the merit of these measurements that the temperature of the generated plasma were performed to confirm the significantly low heating and to prove the non-thermal conditions of the fusion reaction. In retrospect from the resent results, it may be concluded that the four orders of increased neutron gains are a typical non-thermal equilibrium fusion by nonlinear force accelerated plasma blocks.

After the experimental results of the plasma block acceleration by Sauerbrey [17] with clarification of avoiding relativistic self-focusing [21] and the numerous measurements [29] of very different non-thermal laser-plasma interaction [33], numerical studies were performed [34] to explain the increased neutron gains of [31] as a typical non-thermal equilibrium fusion by nonlinear force accelerated plasma blocks. These results pointed to consider the laser driven boron fusion, Eq. (2) as a case of block ignition. It is well known, that ablation compression of spherical HB11 fusion arrives at five orders of magnitudes lower energy gains than the DT reaction (Chapter 9.6 of [8]). When applying the computations of plane wave ignition with picoseconds laser pulses [34] on solid density fusion fuel, the resulting need of an energy flux E* of 4×10^8J/cm^2 for DT was nearly the same as for HB11 [35]. This was a surprising gain increase for HB11 by five orders of magnitudes though only binary nuclear reactions as in the case of DT were used for comparison. The reaction of Eq. (2) producing three ^4He (alpha particles) resultd in an avalanche reaction and using elastic plasma collisions for the exceptionally preferred energy range around 600 keV resulting in a further increase of the energy gains by four orders of magnitudes [36]. These are all together one billion times higher reaction gains than the classical HB11 fusion as measured.

The very first measured HB11 reaction with picosecond CPA laser pulse irradiation [37] resulted in thousand reactions. Irradiating a laser pulse together with a second one for producing an intense particle beam (see the general advantage of [3]) resulted in more than one million reactions [38] and experiments with a single lase beam of entirely few dozens of ps arrived at billion reactions [39] agreeing with the calculated just mentioned gain increases [36]. In all experiments, the temperature could be estimated below values of 100 eV, or at least many orders of magnitudes lower than of the thermal equilibrium pressures above 100 Million °C.

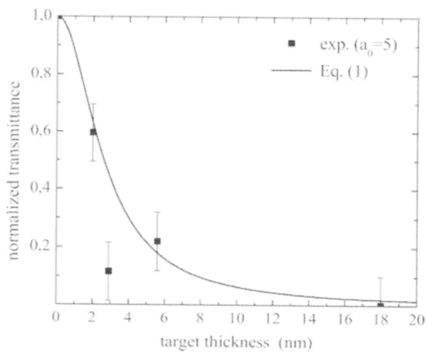

Fig. 5. Points are the transmission laser energy incident of 810 nm wave length CPA pulses of 1.2 J and 45fs duration per incident laser energy at a diameter of 3.6 μm of diamond layers of varying thickness [41] (with permission of the publisher).

Fig. 5 shows the strangely and unexpectedly measured optical transmission of laser pulses irradiated on diamond layers of varying thickness. At a thickness of 18 nm (2.2% of the vacuum laser wavelength) all laser energy had been absorbed by conversion into plasma, mostly of ions. It was from the beginning evident, that this was nonlinear force acceleration of which the details could be estimated [42]. The interaction volume was 1.83×10^{-13} cm^{-3} such that the energy density of the interaction was

$$E_d = 6.55\times10^{12} J/cm^3 \quad (5)$$

The generated pressure corresponds to a value far above the pressure of the astronomically high equilibrium thermal pressure of the plasma.

5 Conclusion

Using the knowledge of numerously elaborated and experimentally confirmed cases of interaction of CPA laser pulses in the sub-picosecond range and powers above petawatt, the ignition of fusion of hydrogen with the boron isotope 11 (HB11 fusion) is of high energy gain [2][5][40]. Experiments indicated energies above 10^{12} J/cm^3 for non-thermal pressures.This is the basis for the design (Fig. 16 of [5]) of an environmentally clean, safe, low-cost and abundant generator of electricity [40]. The equation of motion for the ignition is dominated by the non-thermal term of the nonlinear force $\mathbf{f}_{NL}$ in Eq.(3), for avoiding the thermal pressures that are in the range above temperatures of 100 million °C.

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