First dominating non-thermal pressures by CPA-laser pulses in contrast to billion degree thermal pressures for fusion

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Abstract: The experiment by Steinke et al. proves that sub-picosecond CPA laser pulses produce energy densities above 10^{12} J/cm^3 for generation of non-thermal, nonlinear-force driven pressures that are much higher in contrast to the thermal pressures above 50Million $^{\circ}$C temperatures usually needed for fusion energy in power reactors.

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Fusion energy generation is based on following equation of motion for the force density **f**

$$\mathbf{f} = -\nabla p + \mathbf{f}_{NL} \tag{1}$$

where p is the gas-dynamic thermal pressure given by the product of plasma density and temperature T and a second term of the nonlinear force $\mathbf{f}_{NL}$ caused by electric and magnetic laser fields **E** and **H**, the plasma frequency ω and the optical refractive index *n.* This is given as $\mathbf{f}_{NL}= \nabla \bullet \mathbf{M}$ with Maxwell's stress tensor **M**

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

These forces $\mathbf{f}_{NL}$ are nonlinear, because they relate the mechanical force density with the squares of force quantities **E** and **H** of the electric and magnetic laser field respectively. Usually the pressure in the plasma p is given by the temperature T. For fusion, T has to be around or far above 50 Million degrees Celsius. During the last 60 years, these temperatures have been reached in laboratories, however not long enough to build a generator for electricity.

When the laser was discovered in 1960, its very extreme energy density during extremely short times and in very small volumes was the hope, that the second term in Eq. (1) may produce a pressure high enough to be larger than the thermal pressure p by the nonlinear force $\mathbf{f}_{NL}$ at a laser interaction with plasma.

Since 1963, measurements showed the nonlinear force and plasma motion at laser interaction separately to the expected linear processes of plasma heating [1][2]. The CPA (Chirped Pulse Amplification) was discovered [3], honoured with the 2018 Physics Nobel Prize to Donna Strickland and Gerard Mourou, providing now laser pulses of picosecond and much shorter durations having a power of 10 Petawatt equal to about thousand times of the power of all global electricity generators together during the time of a picosecond.

Computations of the nonlinear force in 1978 showed that the nonlinear force can dominate according to Eq. (1) over thermal forces in plasmas of million degrees (see Figs. 10.18a&b in [1], or drawn together in Fig. 8.4 of [2]) resulting in nearly solid density plasma blocks by the ultrahigh acceleration of about 100,000 times higher than from thermal heating and expansion of plasma under thermal pressures using the largest laser on earth. Sauerbrey [4] had to use CPA laser pulses with results close to the predicted earlier calculated [1] accelerations.

The case that for nuclear fusion the nonlinear, non-thermal forces result in higher pressures than usual thermal pressures have directly been evaluated from an experiment [5] where subpicosecond laser pulses of 1.2 Joule energy were completely converted in a 18nanometer diamond layer into highly energetic directed ions as result of the dielectric caused plasma block acceleration [6]. The energy density E in the interaction volume was

$$E \ = \ 6.55 \times 10^{12} \mathrm{J/cm^3}. \tag{3}$$

These processes are from experiments [5] when a 45fs laser pulse of 810 nm wave length and 3×10^{19} W/cm^2 intensity was hitting a diamond layer of 18nm thickness. Within 2.3% of the laser vacuum wave length more than 99% of the laser energy was converted into plasma energy, detected with directed C^{+6} ions of 71MeV energy. The nonlinear force driven plasma block acceleration by a dielectric explosion worked with a swelling factor of 5 [6]. The whole energy of 1.2 J of the laser pulse was converted into the uncompressed solid state diamond layer. The electromagnetic energy density in the volume with a focus diameter of 3.6 μm had a volume of 1.83×10^{-13} cm^3 of the interaction volume corresponding to an energy density E of Eq. (3).

This is a clear case of the predominance of the nonlinear-force determined non-thermal pressure acceleration and is orders of magnitudes higher than thermal equilibrium pressures at fusion temperatures. It is another experimental example of Eq.(1) where the equation of motion is not determined by the first term of the RHS of (1), as it was seen form the numerical results of Fig. 8.4 of [2], in agreement with the subsequent measured ultrahigh plasma acceleration of Sauerbrey [4], repeated by Földes et al [7] and the clearly nonlinear measurements of Badziak et al. [8] dominating over the differing linear thermal properties [9]. It is a further example [10][11] that the nonlinear plasma block acceleration at conditions with high dielectric swelling factors close to the critical density needs the inclusion of the dielectrictic effects in PIC computations [12].

These results confirm in retrospect the design of a laser boron fusion reactor, Fig. 16 of [13] based on the use of CPA laser pulses where the co-authorship of Mourou was essential. The plasma block acceleration results in a five orders of magnitudes elevated energy gain above the classical thermal-equilibrium boron fusion [14][15]. This has to be added up to the increase by further four orders due to the avalanche multiplication of the boron reaction [16] to confirm a nine orders increase of the fusion gains over the classical values [16] as measured [13][17]. This increase of the fusion gain by measured nine orders of magnitudes above the classical values leads to the road map [18] for an environmentally clean, safe, low-cost and abundant laser boron fusion reactor design for electricity generators [19].

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