H-^{11}B FUSION REACTION WITH EXTREME LASER PULSES FOR NON-LTE IGNITION

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Abstract

The just achieved laser technology for picosecond pulses of more than petawatt power permits pressures by the laser field to dominate over thermal pressures for igniting of the fusion of hydrogen with the boron isotope 11 (HB11 fusion). This is based on a combination of measurements with computational results. For a cylindrical trapping of the reaction volume of uncompressed solid state density fuel, the recently reached kilotesla magnetic fields in laser generated capacitor-coil pulses are necessary. For the fusion, non-thermalised conditions with elastic nuclear collisions for the avalanche of the three-alpha mechanism are necessary for the possible design of a reactor with negligible nuclear waste and low-cost operation. The preceding hydrodynamic computations for the ultrahigh acceleration of plasma blocks are supported by PIC computations with inclusion of the dielectric properties of plasmas near the critical density.

1. INTRODUCTION

The generation of extreme laser pulses [1] may lead to overcome the difficulty for generating nuclear fusion energy due to the fact that nuclear reactions are on an energy level of some million electron volts MeV compared with the eV for chemical reactions. This needs an ignition and a burn under thermal equilibrium at temperatures above dozens of million degrees compared with the several hundred degrees temperature for igniting chemical reactions e.g. with a match. The 15million degrees can be seen from the slow burning of hydrogen into helium at the center of the sun. This is the same with aiming a continuously burning fusion plasma in a the torus shaped plasma at magnetic confinement at the stellarator, where after 25 years of research, the first deuterium fusion was measured at temperatures of about 10 Million degrees (800 eV) at thermal equilibrium [2]. The temperatures for the tokamak [3] are considerably higher using the advantage of plasma currents of non-thermalised current densities of Mega-Amperes as explained as an improving condition [4]. This needs plasma densities of ten orders of magnitudes less than solids with very large scale equipment. Another improvement is by nonlinear phenomena [4] for which the alternative to continuous burning is given by the following considered pulsating micro-size controlled laser driven reactions.

2. PLASMA BLOCK ACCELERATION

Ignition of nuclear reactions below the astronomic high temperatures of dozens of million degrees are possible in the nuclear power stations that produce more than 10% of the global electric energy. Based on Otto Hahn's techniques to measure extreme low concentration of elements [5] it was discovered that the neutron capture of uranium produces fission into two nuclei with very high energy gain. Based on the measured neutron multiplication, Scillard's chain reaction could generate an explosive reaction with the astronomic high temperatures, but it was also possible in the nuclear power station by controlling of the neutron multiplication that the astronomic temperatures can be avoided with operation below manageable few hundred degrees centigrade in a reactor.

A similar way for ignition of fusion at low temperatures as in the fission generator, is based on the fact that the energy force density **f** in a plasma is not only determined by the thermokinetic pressure p from the plasma temperature and density but with an additional part f_{NL}

$$\mathbf{f} = \nabla p + \mathbf{f}_{NL} \qquad (1)$$

$\mathbf{f}_{NL}$ represents the forces due to electric and magnetic fields **E** and **H** of a laser pulse in the plasma. These fields are force quantities and are determining the force in the plasma in quadratic form as result of electromagnetic laser irradiation and are the gradients of the Maxwellian stress tensor

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

where $\mathbf{1}$ is the unity tensor. This expression of Eq.(2) defines the final, general, Lorentz and gauge invariant transient formulation of the equation of motion in a plasma of Eq. (1) in the plasma [6]. At plane wave geometry, the nonlinear force of Eq. (2) can be reduced to

$$f_{NL} = -(\partial/\partial x)(\mathbf{E}^2+\mathbf{H}^2)/(8\pi) = -(\omega_p/\omega)^2(\partial/\partial x)(E_v^2/n)/(16\pi) \qquad (3)$$

while general cases need all tensor components of Eq. (2) [7][8][9].

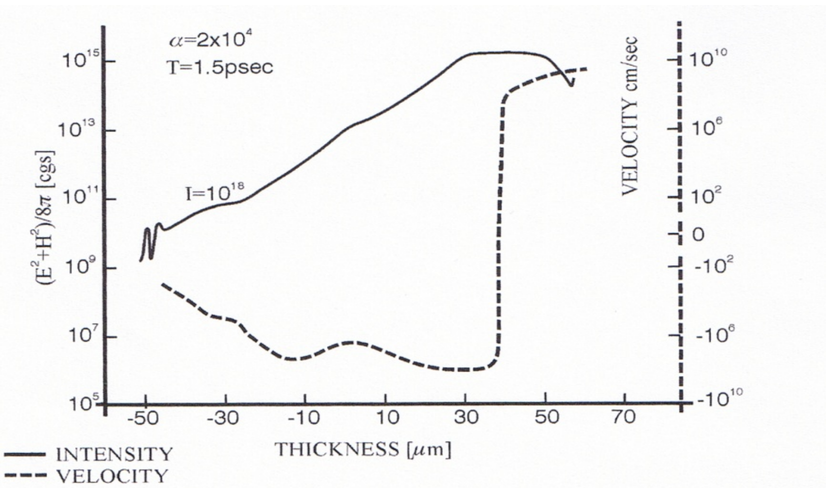

FIG. 1. 10^{18} W/cm^2 neodymium glass laser is incident from the right hand side on an initially 100 eV hot very low reflecting bi-Raleigh deuterium plasma profile at initial time t=0, resulting at time t=1.5 ps of interaction in a velocity distribution v(x) on the depth x and in an energy density of the laser field $(\mathbf{E}^2+\mathbf{H}^2)/8\pi$. The dynamic development had accelerated the plasma block of about 20 vacuum wave length thickness of the skin layer moving against the laser and another block into the plasma showing ultrahigh >10^{20}cm/s^2 dielectric enlarged acceleration [8].

The computation result of Fig. 1 of 1977 (from Figs. 10.18a&b of [8]) was performed with similar parameters as the measurements of Sauerbrey 1996 [10]. This shows a rather good agreement confirming the five orders of magnitudes higher acceleration than at thermal conditions at NIF, repeated by measurements by Földes. et al [11] or related non-thermal results [12]. The measurements by the team of Jie Zhang [13] clarified that all these ps laser pulses had to be of highest quality with a high level of contrast ratio to avoid pre-pulse generation of a plasma blume and subsequent relativistic self-focusing. This confirmed the plasma block acceleration by the nonlinear forces – one moving into the target and one moving against the laser being proved by the measured strong blue shift of spectral lines. Plasma-hydrodynamic computations confirmed shock generation in agreement with the Rankine-Hugeniot densities where details of initially large internal electric fields explained why the shock compression was delayed by about one nanosecond after the initiating picosecond laser pulse. Many theoretical studies followed these experimental results that were summarized [14] [15] including support from the IAEA [16]

3. APPLICATION TO HYDROGEN-BORON 11 FUSION AND DESIGN OF A HB11 FUSION REACTOR

Up to this step we considered fusion especially of the DT reaction

$$D + T = {}^{4}He + n + 17.6\ MeV \qquad (4)$$

where neutrons n are being generated at each reaction. These causes radioactivity in the reaction waste. The mentioned HB11 reaction of the of hydrogen and the boron isotope 11 is primarily absolutely clean form radioactivity

$$H + {}^{11}B = 3\ {}^{4}He + 8.7\ MeV \qquad (5)$$

Expanding the computations from DT fusion to HB11 fusion – that under classical LTE equilibrium has five orders of magnitudes lower energy gains – surprisingly [17] arrived at the same gains as DT if in contrast, the extreme non-equilibrium is used. After high HB11 fusion gains were measured [18], about 1000 higher gains were measured [19]. When adding the three-alpha avalanches of HB11 [20], Eq. (5), the increase of the energy gain by 9 orders of magnitude was above the measured classical value HB11 fusion gain as theoretically explained [21]. From comparing with results from DT it was concluded [20] that a scheme of Fig. 2 for a HB-fusion may be designed, where ps laser pulses of more than 30 PW power can produce energy in helium nuclei (alpha particles) of 300 kWh from the reaction of 14mg boron. A necessary condition is that the cylindrical fuel hast to be trapped (Fig. 3) in a kilotesla magnetic field that is generated about one nanosecond long by a condenser loop at irradiation by a kJ-ps laser pulse [22].

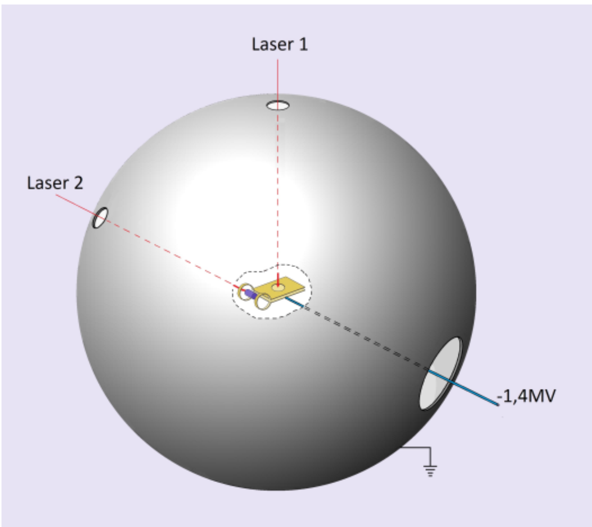

FIG. 2. Scheme of an economic electric power reactor for production of boron-fusion, with no problem of dangerous nuclear radiation with the estimated possibility of a power station producing low cost electricity [20]. The reaction unit in the center is described in Fig.3.

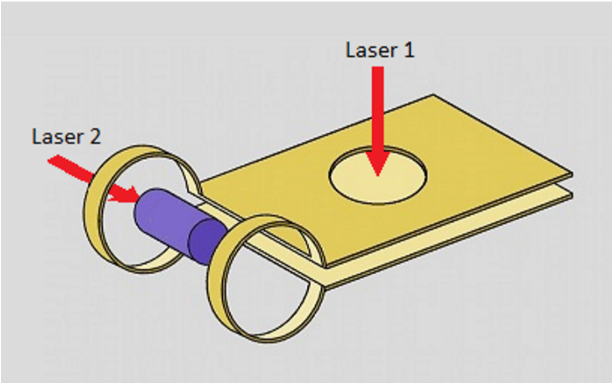

Fig 3. *Reaction unit in the center of the reactor of Fig. 2 using "capacitor coil fields" producing a cylindrical magnetic field of kilotesla [22]. The cylindrical target with the HB11 fuel is co-axially located in a coil where during a ns the kilotesla magnetic field is produced by a kJ-ns laser pulse 1. A ps-30kJ laser pulse 2 initiates the non-thermal ignition of the fusion in the fuel.*

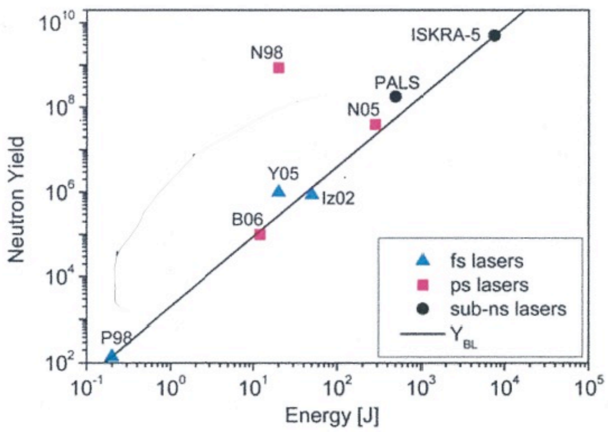

FIG. 4. Neutrons from irradiation of laser pulses of duration between femtoseconds and 0.1 nanoseconds on the irradiated energy from targets with deuterium as fusion fuel (Krasa et al. [25]).

To the initial question about astronomic temperatures above dozens of million degrees for thermal equilibrium fusion reactions, the laser boron fusion with the reactor of Fig. 2 can lead to the crucial result of a low temperature initiation of controlled fusion, similar to the fission power stations. The continuously working reactors as ITER-tokamak or the wendelstein-stellarator are all based on the astronomic high temperatures. Also at the laser fusion like NIF with nanosecond pulses the astronomic high equilibrium temperatures were measured. The hope that the conditions of equation (1) with non-thermal cases and not dominating thermal pressures p has now been verified with the dominating nonlinear forces due to the fields for the extreme picoseconds laser pulses for ignition. This was clearly shown by the dominance of the block acceleration as in Fig. (1) and with the measured blue Doppler shift of spectral lines [10][11] using high quality laser pulses with avoiding relativistic self-focusing [13].

4. EVALUATION OF FRST NON-THERMAL PLAMA-BLOCK FUSION IGNITION AND CONCLUSION

The very first experiment with ultrahigh plasma block acceleration by picosecond laser pulses with dominance of the nonlinear force where fusion reactions were studied, can be mentioned in retrospect [23][24][25]. The measurements based on thermal equilibrium for laser pulses between femtoseconds and nanoseconds were all on a straight line, see Fig. 4, with exception only of the nearly ten thousand times increased neutron generation from deuterium fusion measured by Norreys et al. [23] using picoseconds laser pulses. It was especially confirmed that the plasma temperature in the range of the reaction was significantly low, clearly showing that the DD reactions were based on non-thermal conditions. In retrospect one can conclude that this was a case of non-LTE plasma-block acceleration with dominance of the nonlinear force in Eq. (1).

The reactor design of Fig. 2 was especially arriving at the condition, that the initiation of the nuclear fusion did not require the ultrahigh equilibrium temperatures needed for ITER or with fusion using nanosecond NIF-laser pulses. The further significant advantage was by using boron with sufficiently suppressing of any problems of radioactive radiation (for the ten-thousand times less neutrons than primary reactions from secondary reactions, a mantle outside the reactor of Fig. 2 can eliminate any intolerable radioactivity [26]). The domination of the pressure by the laser fields against thermal pressures is arriving then at the low temperature operation condition like in the nuclear fission reactors. The level of laser pulses of the necessary capacity has practically been achieved [27][28] based on a reactor design with the CPA (Chirped PulseAmlification) laser technology [29].

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