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About Thermal and Non-thermal Ignition of NuclearFusion Reactions

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Dr. Ursula von der Leyen, President of the European Commission, mentioned in her inauguration speech 1st DEC 2019 in Portugal that one of her two priorities is the decarbonisation of energy generation. This is not only to prevent a catastrophe but is a problem of *existential survival*. The attempt to use renewables is acknowledged but for reaching low carbon, this is nearly an impossibly monstrous task. Apart from the expected doubling of energy demand within the next 30 years it is of such a gigantic volume that this can never be fully reached by present measures. One way is thanks to Lord Rutherford and Otto Hahn, to focus on nuclear energy for generators of electricity based on ten milion times higher energy per reaction than chemical energy as from carbon. Fission of uranium under extreme control produces now more than 10% of all electricity but the problem of dangerous nuclear radiation or catastrophic accidents as Chernobyl cannot be excluded by 100%.

What remains is nuclear fusion from the energy by joining together very light nuclei to heaviers. This is the energy source of myriades of the stars. The more than million times higher nucelar reaction energy than from burning carbon needs then ignition temperatures of many million degrees Celsius. The sun burns hydrogen into helium at 15 million degrees. To repeat this in power stations is tried since 60 years but „...Fusion always seems to be 30 years away“, see J.M. Windridge in [1].

A radical change of this situation is now neverless open thanks to getting rid of the temperatures above of the million degrees Celsius by using the just reached ultra-extreme CPA (Chirped Pulse Amplification) laser pulses for LASER BORON FUSION without the problems of dangeous nuclear radiation. The equation of motion for the force density **f** in high-temperature plasmas is given by hydrodynamics for nuclear fusion

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

consists of a first term with the gas dynamic pressure p given by the density and the thermal equilibrium temperature T. This is in the range below eV (electronvolt = 8135 ^{o}C) as chemical energy when burning coal, but is at about ten million times higher for nuclear energy. For ignition, this range is of many dozens of million degree Celsius ^{o}C and was well reached with magnetic plasma confinement in tokamaks or stellarators or in aimed billion degrees in reverse field tri-alpha-energy configurations or in laser driven spherical compression with lasers of nanosecond pulses, but for too short times than needed for building a reactor for generating electricity.

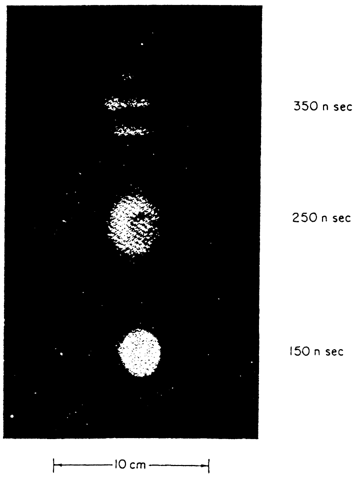

Fig. 1. *Side-on framing camera picture of a plasma produced from an aluminum sphere of 80 μm radius at the time indicated after irradiation from the left hand side by a 30 ns ruby laser pulse focused to 0.4 mm diameter at the mentioned times after irradiation. The second frame shows a rapidly expanding half-moon-like plasma and a inner spherical part [5].*

Apart from the first term with the thermal pressure p in Eq.(1), the presence of electric and magnetic fields and plasma-optical responses can generate the non-thermal electromagnetic nonlinear force $\mathbf{f}_{NL}$. This could directly be seen in the experiments by Sucov et al. [2] at laser interaction in Figure 1 resulting first in the non-transient equation of motion Eq. (10) with Maxwell's plasma stress tensor needing additional nonlinear terms in Schlüters earlier formulation seen from momentum conservation [3]. Finally for the general transient case clarifying six controversal solutions, the Lorentz and gauge invariant Eq. (6b) [4] was derived.

Evaluating about 500 pictures like Fig. 1 [5] for different laser pulse energies, pulse durations and sphere diameters showed the central plasma thermally expanding with temperaures around 20 eV fully following the expected thermal plasma propeerty of the heated sphere taking the varying energy depending on the cases of the interacting laser energy of the cross section of values of about 90%.

The maximum energy of the ions in the half-moons were in the range up to 5 keV showing a non-thermal behaviour [5]. This definitely could not be from bremsstrahlung in the corresponding range of 20 MeV tempeature. Very detailled hydrodynamic computation of plane geometry condition of deuterium plasma at 10^{17} W/cm^2 laser intensity up to the critical density during 1.5 ps laser irradiation showed a plasma block acceleration of 10^{20} cm/s^2 [6]. This ultrahigh acceleration against the direction of the laser beam was measured from blue Doppler-shifted spectral lines by Sauerbrey [7] using CPA laser pulses [8] for which discovery the 2018 Physics Nobel Prize was awarded to Donna Strickland and Gerard Mourou. The nonlinear force driven acceleration [7] was about 100,000 times higher than thermal acceleration by the world's largest NIF laser.

One highlight of non-thermal energy density by nonlinear force conditions against the thermal energy density with plasma temperaures of hundred Million °C is the measururement by Sven Steinke where 18nm thin diamond films absorbed 99% energy of laser pulses and produces an energy density of 6.55x10^{12} J/cm^3 [9][10]. This is much higher than the hundred million degrees of thermal equilibrium ignition especially for the very low gains of hydrogen H with the boron isotope 11 (HB11 reaction) that is primarily environmnatally clean without radioacitvity. This supports the design (Fig. 16 of [11]) for an absolutely clean, safe, low-cost and abundant electricity generator.

The new result is not only that a way was found to a drastic reduction of the carbon energy by remembering the ten million times higher nuclear reaction energy. The HB11 Energy has on top the advantage to be free from radioacitivity with keeping the very minor secondary reactions sufficiently easily under control. The main new achievement is that the difficulty of thermal equilibrium of hundred million degrees tempearures for fusion is now overcome by nonlinear forces from CPA laser pulses for using non-thermal ignition [12].

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