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Extreme CPA Laser Pulses for Igniting Nuclear Fusion of Hydrogen with Boron-11 by Non-thermal Pressures for Avoiding Ultrahigh Temperatures

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Abstract: Ten million times more compact energy than from burning carbon can be obtained from nuclear fusion reactions corresponding to equilibrium temperature reactions in the range above 100 million degrees. Following the energy gain in stars, one has to gain nuclear energy from slamming very light nuclei where however the extremely high temperatures above 100 million degrees are needed for the sufficient pressures at thermal equilibrium ignition. A radically new option works with non-thermal pressures of picosecond laser pulses at ultrahigh optical powers by nonlinear forces of ponderomotion. The nuclear fusion of hydrogen with the isotope 11 of boron produces primarily harmless helium and has no problems with dangerous radioactive waste and excludes any catastrophic melt-down as fission reactors, it has the potential to be of low costs and can supply the Earth for more than 10,000 years with electricity.

Key words: Laser boron fusion, non-thermal ignition, plasma block acceleration, CPA pulses.

1. Introduction

Nuclear fusion reactions are one possible option to substitute burning carbon as energy source for avoiding an irreparable climatic change with existential global consequences. Dr. Ursula von der Leyen (Leyen 2019), President of the European Commission, mentioned in her inauguration speech on 3rd of December 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 emission, 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, so that this may be reached by nearly impossible present means only. One way is thanks to Lord Rutherford and Otto Hahn, to focus on nuclear energy for generators of electricity, based on the milion times higher energy per reaction than chemical energy from burning carbon. Fission of uranium under the most extreme control produces now more than 10% of all electricity but the problem of dangerous nuclear radiation or catastrophic accidents as Chernobyl can not 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 dozens of million degrees Celsius. The sun burns hydrogen into helium at more than 15 million degrees. To repeat this in power stations is tried since 60 years but “fusion always seems to be 30 years away”, see Windridge (2019).

In this situation, a summary is given how an absolutely radical alternative may be possibly now based on the extensive research of the 50-year

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research that was leading to non-thermal pressures in plasmas due to the most extreme laser pulses, as a new direction for producing low-cost, unlimited electricity in nuclear reactors without problems of dangerous nuclear radiation or melt-down catastrophes of reactors. This should be reached by using the just existing technology for laser pulses. The discussion includes reference to the achievements of the world's biggest laser NIF at Livermore/California and with discoveries of laboratory technologies and basic physics as the extreme states of matter and discoveries of extreme laser pulses (Strickland and Mourou 1985) or on basic developments of Nonlinear Physics (Feynman 1987, see Hora 1996; 2000). But they then reached laser pulses of picoseconds or shorter duration and powers at or above dozens of petawatt that were not available before but have been opened and discovered by research beyond linear physics (Hora 1969; 1981; 2016).

The key point presented here in this direction is the fact, that the extreme laser pulses opened the door for working at conditions of extremely non-thermal equilibrium or non-LTE (Local Thermal Equilibrium). This is in contrast to all fusion concepts including the extremely low plasma density at magnetic torus confinement as ITER etc., but also with lasers as NIF by using nanosecond laser pulses on thermal equilibrium conditions of dozens of million temperatures (°C). The way to the turning point was indeed hard research during very many years as has been well documented, but can now be reached with just available very extreme picosecond laser pulses (Hora et al. 2020, Margarone et al. 2020). Before describing these present achievements, the numerous different steps have to be described in the following summary needing for acknowledging the finally achievement of the overturning radical change with modest ignition temperatures as underlined at the event of the following presentation.

Ninety-nine percent (99%) of experts in plasma physics when being asked about nuclear fusion energy as alternative to energy generation in contrast to burning carbon fuel to avoid subsequent polluting the atmosphere and causing a climatic catastrophe with rising ocean levels etc., will answer that gaining fusion energy needs more than further 20-year research with costs of more than $50 billion. These facts are a reality and the question is why nuclear fission (in difference to fusion) can be so much more successful as source of nuclear energy in well working power stations producing now more than 10% of all electricity on earth, and why fusion energy is so much more difficult for energy generation in reactors. There is a crucial change on the way to overcome the obstacle of the million degrees (°C) temperature conditions for igniting fusion reactions thanks only now to the present achievements of high power laser technology and the many years exploration of the nonlinear physics of laser-plasma interaction.

The first point of consideration is about energy conservation and equilibrium. Gaining electric energy from chemical energy is mostly done by burning of the fuel. The chemical energy per involved molecule or atom is given in electron-volts (eV) showing an amount of about one Volt one gets from a chemical battery. Igniting petrol with a match produces the needed temperatures of several hundred up to about thousand degrees. All this energy conversion follows the law of strict energy conservation for any kind of involved energy whether this is chemical, electrical, optical, energy of mechanical motion at accelerating or slowing down the mass of a vehicle. One additional restrictive condition only is for thermal energy because it can only flow from a higher to lower temperature level and not the other way. This limits the exchange of thermal energy conversion to efficiency that value is determined by the difference between higher and lower temperature.

In the steam engine of James Watt, this efficiency is only few percent of the energy from burning coal into mechanical energy of motion. For the work of a steam locomotive, a huge amount of coal had to be shovelled into the fire. The combustion engine with petrol is more efficient and the use of the higher temperature in a Diesel engine again has additionally a nearly twice higher efficiency producing two times less carbon pollution to the atmosphere for the same mechanical motion of a vehicle. An example of nearly 100% efficiency is at conversion of chemical energy directly into electric energy in a battery if thermal losses can nearly be neglected.

1.1 Nuclear Energy

Ernest Rutherford discovered that atoms are built by a surrounding electron cloud and a much smaller central nucleus. The energy needed for nuclear reactions is not eV as in chemistry but above million times higher (mega electron volts MeV). The fire to ignite these reactions is then in the order of hundred to thousand million degrees centigrade as it can be observed in the universe within stars or other objects. The fire for very slowly burning hydrogen into helium in the center of the sun is above 15 million degrees. Taking the binding energy E per nucleon in a nucleus depending on the nucleon number A of the chemical elements, there are few different values. Changing one chemical element into another that corresponds to a change of energy E expressed by a mass difference M according to Einstein's result $E = Mc^2$ (using the speed of light c) again is showing the million times higher energy in eV than from chemical reactions.

When listing the masses of the elements from the heaviest natural uranium with 238 nucleons into elements with lower weight, an increase is seen (Fig. 1). When changing heavier elements from uranium to less heavier ones down to iron, it can result in gaining energy. This is the energy source of the nuclear fission reactors. For lighter chemical elements than iron this is the other way. Reaction of light nuclei as hydrogen, helium, lithium, beryllium, boron etc. into heavier ones up to iron by fusing of nuclei together, fusion energy is possible to be gained.

This happens in the universe, as mentioned for the sun. Can one do this without needing a nuclear burning with temperatures above dozens of million degrees? For fission it was following the discovery by Otto Hahn (1938) for achieving ignition without the mentioned extremely high temperatures by hitting neutrons on uranium nuclei, following the studies by Enrico Fermi, Lise Meitner and others (see from p. 138 of Teller 2001). Neutrons are particles like the nuclei of hydrogen, however, without the usual positive electric charge of all nuclei of chemical elements. When moving the electrically uncharged neutrons towards uranium nuclei, these are not pushed back by the electric force from the uranium, and can then be captured into the uranium nucleus. This earlier well-known "neutron capture" excited then the generated heavier uranium nucleus and caused its breaking into two nuclei of middle weight and produced a huge amount of energy. Hahn could prove this by his technique to measure the extremely small amounts of generated chemical elements of medium weight. It could then be concluded that at this splitting (fission) of uranium, three further neutrons were generated (Scillard 1939), so that a multiplying avalanche or chain reaction could happen for an explosive reaction producing the extremely high temperatures, or by a controlled reaction by moderating the neutrons for slow energy generation at temperatures that could be managed in a nuclear fission power station.

Controlling nuclear fission in power stations is not fully free from catastrophic incidences known as "reactor meltdown" from the case of three-miles Island. This happened (see Jungk 1979) when the controlling of the chain reactions was intentionally reduced for premature generation of power requested before completion by the investors for selling electricity. This case did not cause any loss of lives. The more severe similar accidents at Chernobyl happened by turning down some controlling equipment in order to finish the service procedures on time. The Fukujima

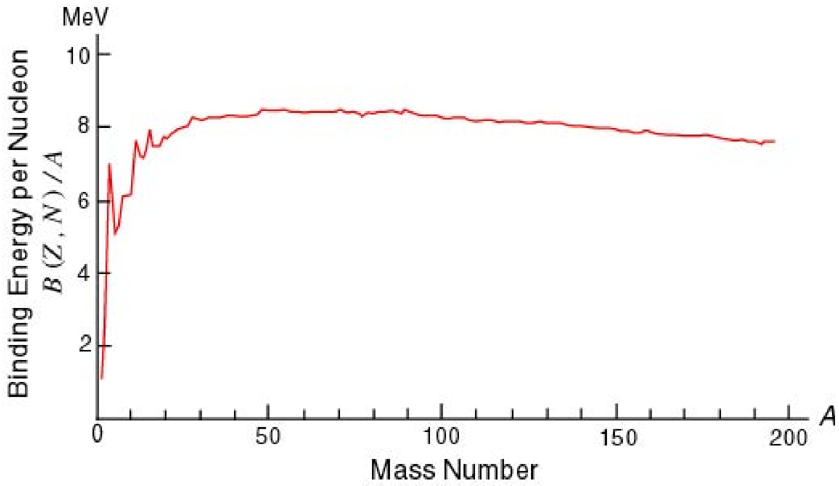

Fig. 1 Binding energy per nucleon depending on the nucleon number *A* in nuclei given by their mass number (modified from Google).

case was a builder's mistake having built the wall against the tsunami 25 cm too low. To avoid these kinds of accidents, Edward Teller (2016) designed an autonomously working fission reactor to be underground 100 m in hard rock.

The measurement of nuclear fission (Hahn et al. 1938) was rather unexpected. Even Hahn's colleague Lise Meitner was sceptical who must have been the closest to know all techniques of Hahn. Hahn and Meitner were credited by IUPAC (2018) in 1949 as discoverers of protactinium but were not honoured with the Nobel Prize as usual for discovering a new element. Hahn must have known the scepticism of colleagues when he got his discovery published during the Christmas season of the journal. Even honouring Hahn by giving his name (Hahnium) for the element 105 was long time under attempted by the Americans. The first measurements of element 105 by the discoverers at Berkeley/California have fully entitled to give the name Ha105. Another name was against the clearly invalid and wrong claim—according to Wikipedia—about insufficient measurements in Dubna near Moscow.

For nuclear fusion from the lightest, hydrogen H up to iron as desired source of electric energy to prevent the climatic catastrophe, a large amount of research was invested since 1950 where one had to use a way of reactions at temperatures much higher than 10 million degrees. One way was for continuous reactions in a plasma torus at extremely low density confined by the highest possible constant magnetic fields as in the Stellarator-Wendelstein experiment or the ongoing worldwide funded ITER project (Bigot 2017), costing more than \$20 billion with producing fusion for energy generating reactions of heavy and superheavy hydrogen deuterium and tritium (DT) not before the year 2037 (Green 2018). The very stationary plasma at the Wendelstein experiment resulted in the very first fusion neutrons after 25 years work for a stellarator, when a temperature of 800 eV, about 10 million degrees, was measured (Grieger et al. 1981). The diffusion of the plasma across the magnetic field was 20 times faster than classical. This factor is exactly the result for the quantum correction of the collision frequency in deuterium (see Section 2.6 of Hora 1991). After 38 years, the temperature in the billion Euro experiment Wendelstein 7-X had climbed up to 4 times higher temperatures—40 million degrees centigrade (Milch 2018) —while the Tokamak produces higher temperatures.

The other way to fusion energy is to use laser pulses for controlled micro-reactions that have best results with the world's biggest laser NIF at Livermore (California) reaching respectable gains

(Hurricane et al. 2014) that however were about hundred times below the breakeven for delivering exothermic energy. In both cases of the continuous as well as for the pulsed nanosecond pulse ignited fusion reaction, the temperatures are considerably above several 10 million degrees well reached where local thermal equilibrium LTE was determining the thermonuclear fusion reactions, but this is not long enough.

For the need to prevent a climatic catastrophe, reference is given to Buchal (2018), after the increased melting of ice glaciers in the Himalaya, or Greenland or the Antarctic and the rising of ocean levels is evident. The COP Clima-Conference in Bonn/Germany 2017 had 25,000 participants and 200 billion Euros was invested against the change of the climate. Even in politics it was noticed how against all democratic rules, the tsunami at Fukujima in March 2011 caused changes. Buchal (2018) from the Peter Grünbert Institute in Jülich mentioned how the German federal chancellor in order to keep her staying in power through favouring a radical position, ordered the shut-down of nuclear power stations despite the unchanged situation with difficulties for providing electric power.

1.2 The Fusion Ignition Scheme at Extreme Non-thermal Equilibrium

The crucial or fundamental change of all these developments of controlled fusion energy did arrive in very recent results of laser boron fusion by the experimental confirmation of the long theoretically predicted initiating of the fusion reactions at modest temperatures. The crucial point is to use conditions different from local thermal equilibrium (NLTE) being the basis together with nonlinear physics (Hora 1988). The need to work with non-equilibrium conditions was formulated for a possible support of the particle beam fusion proposal MIGMA, introduced by Maglich (1988) with his ion-beam fusion based fusion reaction scheme for magnetic field confined torus configurations of continuously working very low particle density fusion reactions. The non-equilibrium beam fusion aspect may be also the key property for the continuously working low density HB11 fusion in the tri-alpha-energy project (Rostoker et al. 1996). The non-equilibrium aspect was also guided from discussing the experiment (Boreham et al. 1979) as a typical property revealed from the discovery of the laser. One should not forget the basic discovery of the stimulated or enforced emission of radiation discovered by Einstein (1917) for the laser in order to directly demonstrate Planck's discovery of quantization of action. The discovery of this principle of laser is essential for nonlinear physics that can drastically change the result of linear physics towards nonlinear physics—a change from no to yes, from wrong to right—even when neglecting very tiny properties. This is not a gradual change as an approximation, but a basic phenomenon as discussed in details with Richard Feynman (1987) also arguing about Steven Hawking's or Carl Friedrich von Weizsäcker's assumption of a saturation of physics and ending of physics research. In contrast, nonlinearity is opening a whole new dimension of discoveries and effects (Hora et al. 2000).

For our topic this is similar as the conversion of chemical into electrical energy in a battery without heating. In our case needing mechanical energy of motion of plasma, this is not only produced by thermal pressure given by temperature and density, but can be done dominantly and non-thermally by the pressure due to extremely energy density of laser pulses. This pressure by the laser field is expressed by the nonlinear force given by the special variation of the energy density of the laser pulse in the plasma.

2. Direct Observation of Nonlinear Conversion of Optical Energy into Mechanical Energy

How the laser opened the door to the principle of nonlinearity could be seen from the effect measured by Linlor (1963) followed by Isenor (1964), Schwarz et al. (1965) and others. When Linlor irradiated solid targets with laser pulses of few ns duration at less than 1 MW power, these heated the surface to dozens of thousand degrees and the emitted ions had energies of few eV as expected classically. When the power of the nanosecond laser pulses was exceeding few MW, the ions—suddenly—had thousand times higher energies above thousand eV. But these ions were separated with linear increase on the ion charge indicating that there was not a thermal equilibrium process, but an electro-dynamic process. Fig. 2 shows one of many hundred side-on photos from free falling aluminium spheres when irradiated from the left by laser pulses in the range of 10 ns duration (Sucov et al. 1967). Evaluation of expansion velocities related to the power and duration of the pulses showed that there was a spherical core of plasma expanding from heating by few dozens of eV temperatures but there were the half-moon like plasmas with nonlinearly increasing expansion velocities up to keV ion energies.

The question of nonlinearity and the crucial importance not to neglect very tiny quantities of linear physics appeared with the measurement of Fig. 4. Focusing a laser beam into low density helium produced ionization and subsequent radial acceleration of the electrons with the energy in the range of keV exactly following from the nonlinear force. One problem appeared when the linear polarized beam had only transversal electric and magnetic fields as usually assumed and is correct at infinite plane waves.

The nonlinear forces from laser fields in plasmas due to dielectric effects were treated in an abbreviated way as shown in Fig. 3. The forces were formally identical with Thomson's (1845) ponderomotive forces in electrostatics, see the arrows in Fig. 3 due to inclusion of the optical refractive index of plasmas. Kibble 1966 used the expression "E^2 field-gradient force" and had the correct and intriguing view that

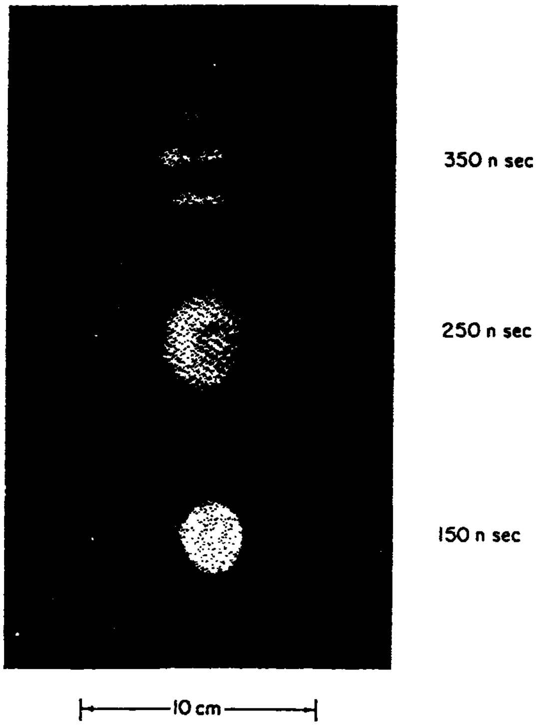

Fig. 2 Side-on framing camera picture of a plasma produced from an aluminum sphere of 80 μm radius at the time indicated after irradiation by a 30 ns ruby laser pulse focused to 0.4 mm diameter. The second frame shows the outer part of a rapidly expanding plasma with the inner spherical thermally expanding part [Engelhardt et al. (1970); Hora (1968; 1971)].

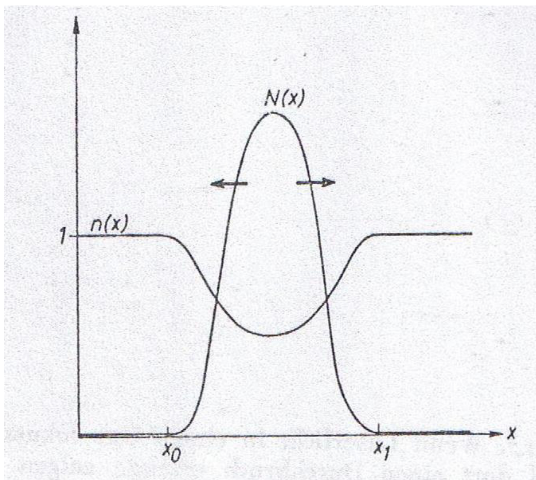

Fig. 3 A laser pulse arriving from the left hand side on a plasma slab of density *N*(*x*) with the schematic drawn curve for the optical constant *n*(*x*) within the plasma decreasing below the value unity causes nonlinear (ponderomotive) forces (arrows) in the plasma equation of motion tearing the slap in parts (see arrows) one part moving against the laser beam and another in the laser beam direction (Hora et al. 1967).

electrons hitting a laser beam experience “an electron optical refraction”, a view which is fully justified. This result of no longitudinal wave components was later one of the great triumphs of Maxwell’s theory of electrodynamics which experimental fact could not be understood before. The Maxwellian exact beam with finite radius was indeed resulting in a very tiny longitudinal component. This was shown exactly for a special beam (Hora 1981, see Chapter 12.3) into the direction of E-polarization. However, into the B-direction no acceleration could be calculated when using only the two transversal components of the laser beam. But this result changed totally when the very tiny longitudinal laser field component was included. A more realistic evaluation was with using a beam with Gaussian radial intensity dependence (Cicchitelli et al. 1991). The final results could be reached by successive up to 13 iterations to arrive at the same acceleration into the B-direction as measured. An example with not sufficient iteration is in Figs. 6.4 and 6.5 of Hora (2016) proving that the very tiny longitudinal component needs to be included in the nonlinear theory from an essential change.

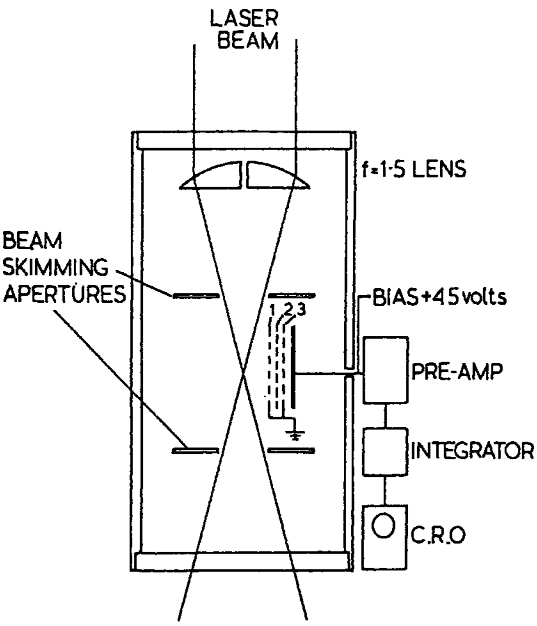

Fig. 4 The Boreham experiment (Boreham et al. 1979) focusing a neodymium glass laser beam to 10^{16}·W = cm^2 in 10^{-6} to 10^{-3} Torr helium with radial emission of electrons of up to keV energy.

3. Forces and Motion of Plasma

For the theoretical description of plasmas, several options are given. One can consider about one million electrons and ions in their individual motion and interaction in computer programs where a leading example is given by Kruer (1988). One problem is to cover the Coulomb collisions where the large distances need a large computer capacity to be covered by the latest supercomputers if not simplifying assumptions are used.

The other way is to summarize parts of the plasma by distribution functions for the methods of kinetic theory. There again, the Boltzmann collision term can only be expressed by first approximations. Mathematical methods with PIC (particle in cells) lead to interesting thermal non-equilibrium results (Buneman 1959) to give a lot of interesting answers as long as particle collisions are not essential to the studied topics. The use of classical hydrodynamics for plasmas including heat transfer by collisions during the plasma motion under forces was to be studied, leading to many sufficient results in comparison with experiments, but one has to be aware that the temperatures either under equilibrium or by cases separately for electrons and for ions and equipartition exchanges need assumptions with sufficient acceptance of Maxwell-Boltzmann thermal distributions.

In most cases, these classical thermal distributions are justified, though one has to be aware from Fig. 5, that classical statistics may in some cases be not valid nor Fermi-Dirac statistics, but also a modification of the statistics for electrons with mass (m) coupling to black body radiation at temperatures above mc^2 towards intermediary statistics (Gentile 1940: Hora et al.1961; Eliezer et al. 2004). The classical statistics is then a rather narrow range between the different statistics.

The hydrodynamic equations for motion of fluids like plasmas (all matters of temperatures above thousands of degrees are plasmas) began with Leonhard

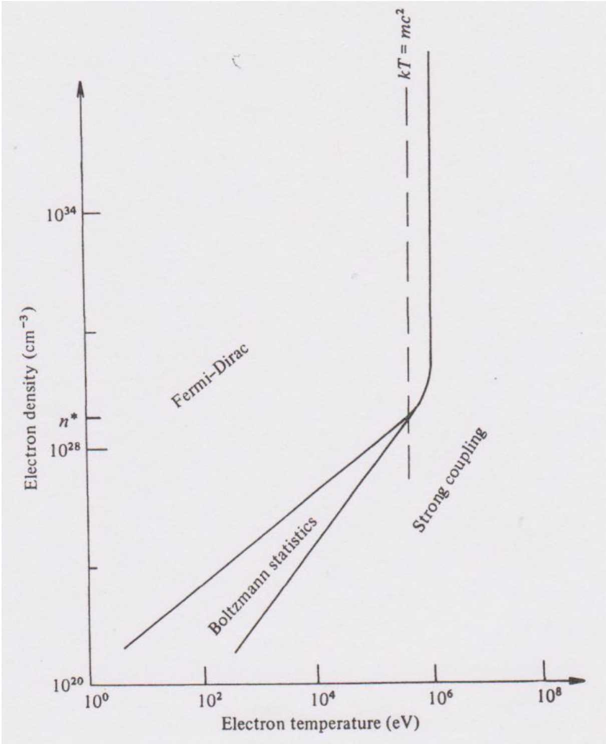

Fig. 5 Ranges for different statistics for electrons (Eliezer et al. 2004).

Euler in the eighteenth century including the equation of continuity, that of energy conservation and that of motion for the involved forces. It needed the later to be defined with electric and magnetic fields and Maxwell's stress tensor and properties of plasma with Langmuir's plasma frequency, or the Debye-Milner length, see Gabor 1953 (achievements by Nobel Laureates of the 20th century). The rather complicate derivation of the equation of motion was not complete in 1966.

The completed equation of motion:

$$f = -\nabla p + j \times H/c + E\nabla\cdot E/(4/\pi) - \omega_p^2(1 + i\nu/\omega)E\nabla\cdot E/[4\pi(\omega^2 + \nu^2)] - \omega_p^2(1 + i\nu/\omega)E\cdot\nabla E/[4\pi(\omega^2 + \nu^2)] - EE\cdot\nabla\ \omega_p^2(1 + i\nu/\omega)/[4\pi(\omega^2 + \nu^2)] \quad (1)$$

is formulated with the nonlinear force $f_{\rm NL}$ (Hora 1969).

$$f = -\nabla p + f_{\rm NL} \quad (2)$$

It contains the thermokinetic pressure p given by the plasma density and temperature T. j is the electric current density in the plasma, E and H the electric and magnetic field, ω the laser frequency, ν the collision frequency, and ω_p the plasma frequency. It was a merit that the second-last term as a nonlinear term had been derived by Schlüter (1960). The derivation of the third-last term and of the last term was possible only later (Hora 1969) based on momentum conservation at laser-plasma interaction and the condition that the time variation of the laser intensity was very much slower than the time of the oscillation of the laser field (non-transient condition).

The transient case was first approached by Klima et al. (1972) and then 6 different derivations by a number of authors were derived with different results. Of all these controversial formulations, the closest to the truth was by Zeidler et al. (1985) where still a small logarithmic term was missing. This could be clarified from symmetry relations (Hora 1985) so that the final formulation of the nonlinear force—expressed in terms of the Maxwellian stress tensor M (Hora 1981; 1991; 2016) is

$$f_{\rm NL} = \nabla M \quad (3)$$

with

$$M = [EE + HH - 0.5(E^2 + H^2)\mathbf{1} + (1 + (\partial/\partial t)/\omega)(n^2 - 1)EE]/(4\pi) - (\partial/\partial t)E \times H/(4\pi c) \quad (3a)$$

where $\mathbf{1}$ is the unity tensor. This expression with Eq. (2) is the final, general, Lorentz and gauge invariant formulation of the equation of motion of a plasma at laser irradiation. This confirmed also as final fact that plasma is neither para- nor diamagnetic (Rowlands 2006) as answer to Harald Grad's (1968) formulation "Yes Virginia, plasma is paramagnetic if you believe in Santa Claus". The general result of the nonlinear force of Eq. (3) can be reduced to Eq. (4) for plane wave geometry if a laser pulse is irradiated along the x-direction at perpendicular incidence to the force in propagation direction of the laser arriving at:

$$f_{\rm NL} = -(\partial/\partial x)(\mathrm{E}^2 + H^2)/(8\pi) = -(\omega_p/\omega)^2(\partial/\partial x)(E_v^2/n)/(16\pi) \quad (4)$$

This shows immediately how the electromagnetic energy density of a laser pulse is working by the nonlinear force in a similar way as thermo-kinetic pressures p in Eqs. (1) or (2) for accelerating plasma. In special cases (Cicchitelli et al. 1990) all components of the stress tensor are necessary. Eq. (4) is related to the ponderomotive force in electrostatics (Thomson 1845) while the stress tensor formulation is of fundamental value in Physics.

4. Very Extreme Laser Pulses to Overcome Thermal Pressures

Following Eq. (2) we have to find conditions, where the properties of laser pulses have such high laser intensities that the 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 evaluations of Fig. 6. 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 1.5 ps in the motion of plasma blocks achieving a velocity of about 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 theoretical result of 1977 (summarized in Fig. 8.4 of Hora 2016, following Fig. 6), the laser intensities were then just available but were many orders of magnitudes longer than a picosecond.

The computation had at each time step to calculate the new density and temperature profiles of the plasma including the resulting optical constants with the varying collision frequency for local heating through absorption of laser radiation and thermal conduction in the plasma. The numerical stability of the computation was checked by evaluating the amount of the energy transferred for the kinetic energy of the plasma motion and the collisional absorption of laser radiation. After correct results of the computations until 2 ps, numerical instabilities appeared.

Fig. 7 shows schematically the generation of the plasma blocks whose ultrahigh acceleration is due to the nonlinear forces of the laser pulse that is dominating over the heating from the absorption of the laser radiation by electron collisions. The densities and temperatures result in a Debye length that is sufficiently small for the application of the one.

This result of 1977 (Hora et al. 1979; Hora 1981) can be compared in the following with the experiments of Sauerbrey (1996) though the background theory of plasma-hydrodynamics may not be fully perfect as mentioned, but the agreement between the computation and the measurement is evident. The explosive dielectric plasma block acceleration can be seen also from PIC computations (Fig. 8). Without the dielectric response of the plasma, only ordinary radiation pressure acceleration in the direction of the laser pulse is resulting. The explosive block generation (Fig. 7), is due to the dielectric properties.

Experiments for the just mentioned conditions of ultrahigh acceleration of plasma blocks by the nonlinear force were possible after a most significant discovery that led to a radical turning point in laser development with the Chirped Pulse Amplification (CPA) (Strickland et al. 1985; Mourou et al. 1998) for generating laser pulses of picoseconds or shorter duration and extremely high powers arriving at two petawatts (Key et al. 2000; Wilks et al. 2001; Barty et al 2004; Chen et al. 2005) measuring pair production with a record of positron emission (Chen et al. 2009).

With initial laser powers of 10^{18} W/cm^2 it was possible for the very first time (Sauerbrey 1996) to measure the ultrahigh acceleration of the plasma block moving against the irradiating laser pulse as seen from the blue Doppler shift of spectral lines. The measured acceleration of 10^{20} cm/s^2 was exactly in the range of the computations of 1977. Similar measurements with drastic deviations from the usually observed thermal computations of 1977 (Fig. 6) were repeated with similar theoretical agreement (Földes et al. 2000).

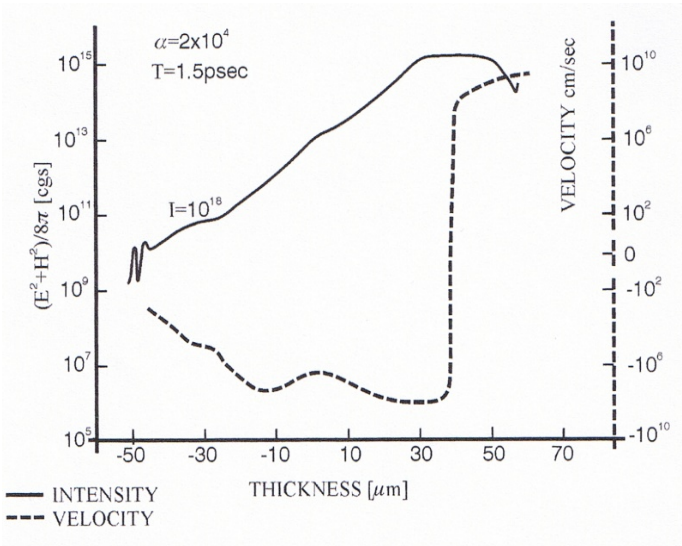

Fig. 6 10^{18} W/cm^2 neodymium glass laser is incident from the right hand side on an initially 100 eV hot very low reflecting bi-Raleigh deuterium plasma profile at initial time $t = 0$, results at time $t = 1.5$ ps of interaction is a velocity distribution $v(x)$ on the depth x and in an energy density of the laser field $(E^2 + H^2)/8\pi$. 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 (Hora et al. 1979, Hora 1981).

Interaction processes were measured (Badziak et al. 1999) differing to the usual observation that could be understood by nonlinear force acceleration (Hora et al. 2002, 2002a, 2003). The detailed comparison with respect to the dielectric swelling factor and consequently gained experimental results led to the summary of the involved processes (Hora et al. 2007, Hora 2009).

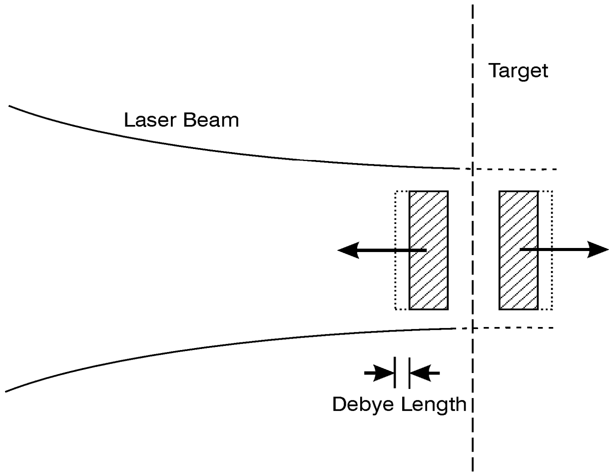

Fig. 7 Scheme of skin depth laser interaction where the non-linear force accelerates a plasma block moving against the laser beam and another block towards the target interior as a kind of dielectric explosion. In front of the blocks are electron clouds of the thickness of the effective Debye lengths for the conditions of Fig. 6.

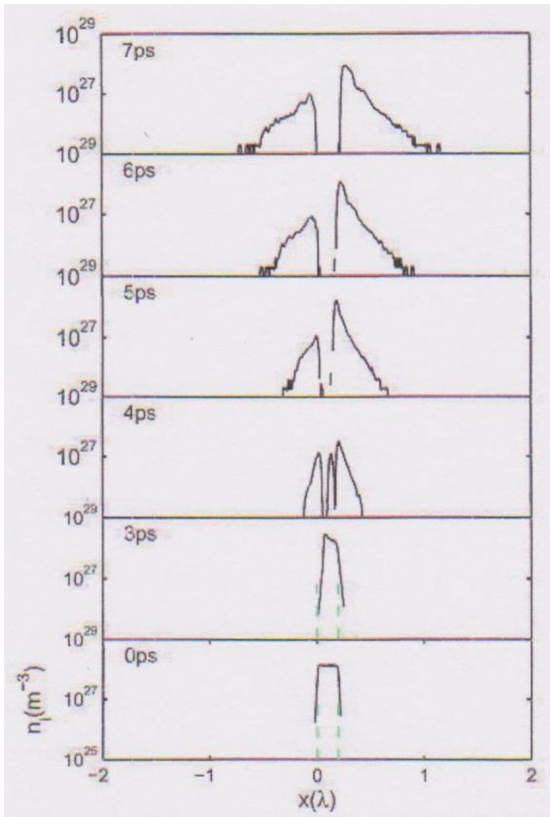

Fig. 8 PIC computations of the density depending on the depth of a plasma slab of initial thickness at time zero at density close to the critical density at laser irradiation by 10^{15} W/cm^2 from the left hand side (Hora et al. 2018; Xu et al. 2018).

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 that was solved in a most exceptional way (Zhang et al. 1998). Zhang was familiar with relativistic self-focusing (Hora 1975) that was a long time not accepted, even not by Basov et al. (1978). A well known authority at the Kurtchatov Institute could not understand how a 4 joule nanosecond laser pulse by A. Rode on phosphorus could produce 11 times ionized phosphorus. Using the formula (Hora 1975) gave immediately the measured result, though it took then more than 2 years before the publication in JETP was out. Even in Russia it was possible to block scientific publications under the claim of being a military secret, delaying Rode's PhD.

In 1995, all centers measured the relativistic self-focusing with the understandable high X-ray emission of short wave length. An exception was noticed only by Jie Zhang at the Rutherford Appleton laboratory in England. He noticed that with PS-CPA laser pulses there were rare cases, when no high intensity X-rays were seen. When he returned to China, he was able with a most sophistic team to perform an experiment with resolution of the motion of plasma blocks of terahertz sequence to proof, that the suppression of relativistic self-focusing (Hora 1075) can be brought under control and to breathtakingly measure the plasma motion in shorter time resolution of ten picoseconds could show how and when relativistic self-focusing could be excluded—indeed at these cases when no powerful X-rays were emitted (Zhang et al. 1989). This most extreme experimental result was so important at the time of 1998.

To the problems of self-focusing, this refers to the before mentioned significant increases of ion energies at measurements of Linlor (1963). When initial irradiation of several nanosecond long laser pulses on solids produced heating to dozens of thousand degrees corresponding to an energy of few eV of the emitted thermalized ions as expected classically if the laser pulse was of less than MW power. This was suddenly changing to ions with energies up to thousand times higher (keV) and more if laser pulses with a little higher than MW power, were incident. These keV ions were not from a thermalized equilibrium but their energy was separated by the number of the electric ion charge if the laser pulse was above the threshold power of about MW. An electrodynamic acceleration was evident but the fact of the thousand times higher ion energy was made understandable only after the ponderomotive self-focusing theory was derived (Hora 1990a).

This self-focusing theory was subrelativistic. After the relativistic quiver energy of electrons in a laser field was derived (Hora 1973), the relativistic self-focusing was discovered (Hora 1975) to result as in Fig. 9a, where the prepulse generated a plasma plume in front of the target causing an optical shrinking of the laser pulse to wavelength diameter.

This was then measured (Luther-Davies et al. 1976) showing ions of more than MeV energy by incidence of few Joule nanosecond laser pulses. Similar MeV energy could indirectly be concluded from measurements with carbon dioxide laser pulses by Ehler (1975). This was then repeated in many cases but not accepted e.g. by a celebrity at the Kurchatov Institute in Moscow who blocked the acceptance of the PhD thesis of Andrew V. Rode saying "it is impossible that few Joule laser pulses can produce phosphorus ions of more than 10 MeV energy". But this was measured and the rather transparent theory (Hora 1975) exactly agreed with the measurement very easily (Basov et al. 1987). The measurement of very highly charged ions of energies far above 100 MeV became then common knowledge. As seen in Fig. 9a, the very high laser intensity in the relativistically squeezed laser beam caused very intense and short wave length x-ray emission as expected.

Using picoseconds laser pulses, there were very rare cases, where none of mentioned extreme x-ray pulses were emitted apart from oft x-rays. Zhang as specialist in x-rays followed up this question (Zhang et al. 1998). Irradiating not extremely focused sub-picosecond laser pulses on a target (Fig. 9b) after a much less energetic same pre-pulse was irradiated at a time τ before the main pulse arrived, no extreme x-rays were emitted. Increasing τ to 70 ps, was still with low x-ray emission, but for larger times, the same happened as in Fig. 9a with relativistic self-focusing. The 70 ps were just needed for generating the plasma plume. This was the proof that with shorter τ, no self-focusing happened as a necessary condition for the ultrahigh acceleration in the experiment of Sauerbrey (1996). This result could work only with the highest quality laser pulses where the sub-picoseconds laser pulses had a very high contrast ratio. The laser pulses in the experiments for reproducing the measurement of Sauerbrey (1996), similar to Norreys et al. (1998), Badziak et al. (1999), Földes et al. (2000) and a few others had the sufficiently high quality laser pulses. This is the reason why in numerous other experiments, Sauerbrey's measurements—as essential points for the here considered laser boron fusion—could not be reproduced. The used laser pulses had not the sufficiently high quality. This discovery under guidance of Zhang (Zhang 1998) for recognizing and to disqualify experiments using low quality laser pulses is the most important on the way to the following laser boron fusion for the possible solution of the global energy problem.

5. Crucial Measurement of the Nonlinear-Force Driven Plasma-Block Acceleration

At this point, one diagram of 1978 is very important in Fig. 6. It shows how a 200 micrometer deep initially 100 eV temperature bi-Rayleigh density deuterium plasma slab with collisions and central closest to critical central density plasma slab is irradiated by 10^{18} W/cm^2 laser intensity from the right hand side with the printout after 1.5 ps of the resulting electromagnetic energy density distribution and the generated plasma velocity is shown. The genuine two-fluid computation shows that the electromagnetic field density is increasing up to a 15 times maximum higher than the vacuum value resulting in a nonlinear force by the radient to lower density. After this time, the plasmas had an acceleration to a velocity of more than 1,000 km/s against the laser light. Measurements by Sauerbrey (1996) were not far away from these parameters and showed blue-shift measurements of spectral lines from plasmas moving against the laser light clarified by the before mentioned measurements of the team of Zhang et al. (1998). The effective skin layer acceleration is different from similar TNSA sheath acceleration (see Badziak et al. 2005) and was close to the earlier computed values. Similarly the plasma block acceleration is shown schematically

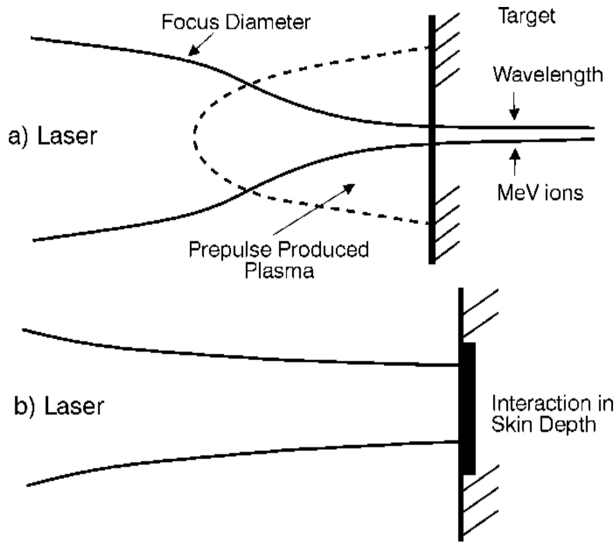

Fig. 9 Scheme for demonstration of the essential different geometry of the laser-plasma interaction for subsequent non-thermal nonlinear driven electron acceleration. (a) The pre-pulse generated plasma before the target causes instantaneous relativistic self-focusing of the laser beam to shrink to less than a wave length diameter with very high acceleration due to the strong gradient of the laser field density (Hora 1975). (b) The nearly not present or too thin plasma in front of the target permits only plane geometry interaction in the skin depth with much lower ion energies but without relativistic self-focusing.

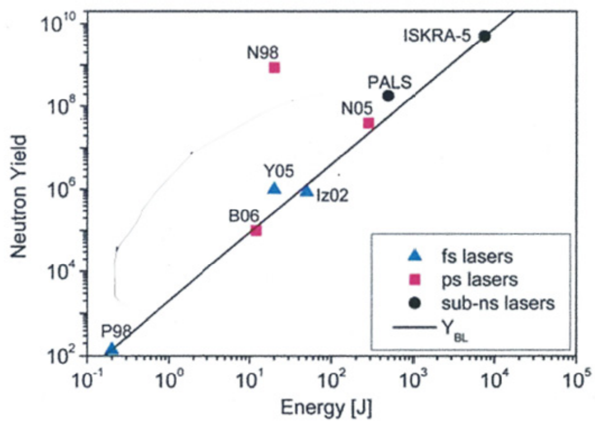

Fig. 10 Neutrons from irradiation of laser pulses of duration between femtoseconds and 0.1 nanoseconds on the irradiated energy from targets with deuterium as fusion fuel (Krasa et al. 2013).

in Fig. 7 though the complete nonlinearity theory of the plasma block is shown in Fig. 8.

One case where the laser pulses had sufficiently high quality can be mentioned in retrospect (Norreys et al. 1998) where a confusing and exceptional way an unexpected extremely highly increased nuclear fusion gain was measured. When compiling the results of numerous authors with the linear dependence in Fig. 10, the result of Norreys et al. (1998) (see N98 of Fig. 10) shows a nearly four-order-magnitude higher fusion gain using ps laser pulses of 10 J energy. It was the merit of these measurements that the temperature of the generated plasma was performed to confirm the significantly low heating and to prove the non-thermal conditions of the fusion reaction. Few years later (NO5 in Fig. 10), an experiment with picoseconds laser pulses of 300 J energy irradiating a sandwich target with deuterium resulted in a neutron gain well on the usual line measured for reactions at thermal equilibrium. In retrospect from the resent results (Picciotto et al. 2014; Margarone et al 2015), it may be concluded that the four orders of increased neutron gains of Norreys et al. (1998) are a typical non-thermal equilibrium fusion by nonlinear force accelerated plasma blocks.

After the experimental results of the plasma block acceleration by Sauerbrey (1996) with clarification of avoiding relativistic self-focusing (Zhang et al. 1998) and the numerous measurements by Badziak et al. (1999) of very different non-thermal laser-plasma interaction (Hora et al. 2002; Hora 2003), numerical studies were performed (Hora et al. 2002a; 2005; 2007; 2011; Cang et al. 2005; Jablonski et al. 2005; Miley et al. 2005; 2008; Sadighi et al. 2010; 2010a). The four orders of increased neutron gains of Norreys et al. (1998) are a typical non-thermal equilibrium fusion by nonlinear force accelerated plasma blocks.

6. Non-thermal Ignition of Laser Boron Fusion

Most of the laser-fusion studies were based on the easiest of all reactions, that of DT, the heavy and superheavy hydrogen deuterium D and tritium T.

$$D + T = {}^{4}He + n + 17.6 \text{ MeV} \quad (5)$$

This produces each a harmless helium nucleus but also a neutron. Neutrons decay with a half life of 14.69 min into a harmless electron and a hydrogen nucleus, but before their decay, they move nearly unchanged through all materials over long distances. Neutron captions can happen with any harmless stable nucleus, changing it into a radioactive nucleus resulting in unwanted radioactive waste. In contrast, the desire of "aneutronic" fusion without any primary neutron generation is possible if the usual light hydrogen H has a fusion with the isotope 11 of boron B-11.

$$H + {}^{11}B = 3\,{}^{4}He + 8.7 \text{ MeV} \quad (6)$$

This HB11 reaction produces three helium nuclei—also called alpha particles—of equal energy if the colliding energy is low (Oliphant et al. 1933). For collision energies especially above 4 MeV the produced alphas have not longer an equal energy distribution.

7. Shock Generation and Volume Reactions after Ignition

This aneutronic reaction was from the beginning the most interesting, however it is much more difficult than DT. Energy generation with HB11 at thermal equilibrium conditions needs temperature above 800 MeV at continuously working magnetic confinement fusion with very high losses of bremsstrahlung and at ITER or Wendelstein because the losses of energy by cyclotron radiation are higher than the gained fusion energy. The energy gain of HB11 is five orders of magnitudes below that of classical DT fusion. The only boron fusion reactions have been measured at laser interaction. The first 1,000 reactions, just above the measuring threshold, were by Belyaev et al. (2005) per irradiation of a ps CPA laser pulse. More than million reactions were detected by Labaune et al. (2013) and more than a billion by Picciotto et al. (2014) and more at repetition (Giuffrida et al. 2020) and Margarone et al. (2020) where the avalanche multiplication is essential (Hora et al. 2015) as evaluated in details with inclusion of elastic collisions (Eliezer et al. 2016).

Shorter than 100 picosecond laser pulses can be used above 600 J for igniting the HB11 reaction at solid fuel density (Picciotto et al. 2014) where the measured gains are even close to those from DT fusion at adjusted laser pulses (Hora et al. 2015).

In the case of thermal non-equilibrium, the measured gains were one billion times—or nine orders of magnitudes—higher than in the classical case. The first five orders were the result of upgrading of the computations by Chu (1972) similar to Bobin (1974) how to ignite solid density DT by laser pulses. The initial result was that the laser pulses had to be shorter than a picosecond and the energy flux density had to be above a threshold of $E^* = 4 \times 10^8$ W/cm^2. The updating was for the then not known inhibition of thermal conduction, the collective stopping for electrons and for quantum modifications of the collision frequency resulting in a reduction of the thresholds by about one order of magnitude (Hora 2009). When these computations were performed for the HB11 reaction (Hora et al. 2010; 2011a) the very surprising result was that the threshold E^* was close to the value of DT, bridging five orders against the classical value. These computations covered only binary collisions for HB11 as this is valid for DT. When evaluating the triple production of alphas for HB11, Eq. (6), an avalanche or chain reaction was possible for an increasing gain by four further orders of magnitudes (Eliezer et al. 2016) arriving at an agreement with the measurements based on elastic nuclear collisions for the specially high fusion reaction cross section at 605 keV. This is based on the highly non-ideal state of the reacting plasma (Hora 2015) as known from the theory of Fortov (see Hoffmann et al. 2016; 2017; 2018). The experimental result (Margarone et al. 2015) could be completely explained by the non-LTE conditions.

The evolution of the plane irradiation front of the target by the picoseconds laser pulse at energy flux densities above E^* into the shock generation of the uncompressed solid density fusion fuel could be calculated using the genuine two-fluid code with the separated ion and electron fluid including the generated electric fields given by the Poisson equation (Lalousis et al. 1983; Hora et al. 1984). This was used also in the sophisticated later computations by Cang et al. (2005).

The generation of a shock ignition is seen from an example of DT in Fig. 11. After 4 ns, the shock has been finally generated with four times of the initial fuel density in agreement with the Rakine-Hugoniot theory for a collionless shock. The complete hydrodynamics with heating and collisions show how the thickness of the shock front is growing due to thermalising collision processes.

The delay of the shock generation until more than a nanosecond in Fig. 11 could be clarified by Fig. 12. This is due to the fact that the ps of very high deposition of the laser pulse is first moving the block of the electrons followed by the ion block. Fig. 12 is the printout of the very high electric fields at early times until about 2 ns. This result could only be seen from the genuine plasma hydrodynamics with separate electron and ion fluids connected by the Poisson equation (Lalousis et al. 1983, Hora et al. 1984). For completion, Fig. 13 shows the amount of the fusion rate coming from the whole generated and still reacting plasma though the initial density close to the ps initial laser interaction surface is slowly decaying during the dynamic motion of the plasma.

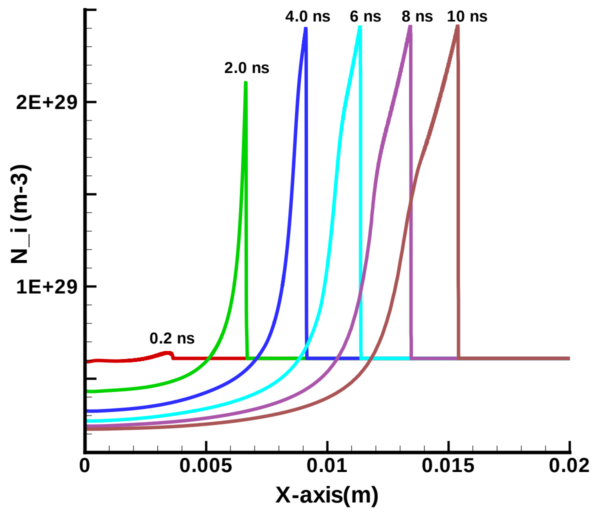

Fig. 11 Ion density n_i depending on the depth x of the propagating fusion flame at different times after a picoseconds laser pulse of 10^{20} W/cm^2 initiated the fusion reaction front.

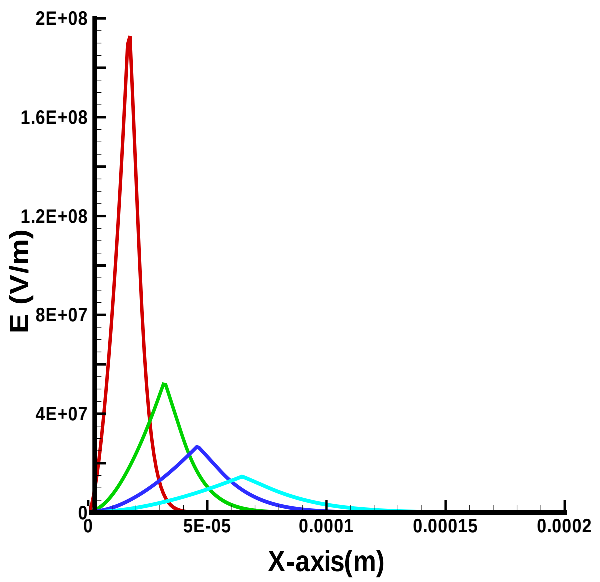

Fig. 12 Longitudinal electric field E in the plasma depending on the depth x in the fusion fuel close to the interaction range of the ps laser pulse with an energy flux E^* = 10^8 J/cm^2 for the cases of Fig. 11, for the times with decreasing maxima: 40 ps; 400 ps; 1 ns; 2 ns.

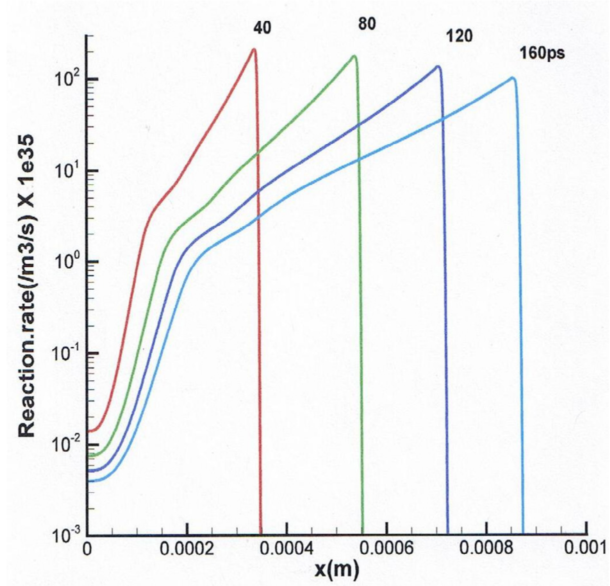

Fig. 13 HB11 reaction rate von rates in different depth x in 1D computations parallel to the magnetic field at times in after the ps after the generation of the ps fusion flame was initiated by a 10^{20} W/cm^2 KrF laser picosecond laser pulse.

8. Electricity from Absolutely Clean, Low-Cost and Lasting Laser Boron Fusion

The Laser Boron Fusion Reactor offers basically new properties with the "potential to be the best route to fusion energy" (Haan 2010) where the possibility of a comparably very short-term development for the market may overcome the problems of the climatic catastrophe. Experiments for laser driven DT fusion were based on spherical irradiation of laser beams. The laser amplifiers of the NIF experiment cover most of the size of three football fields using 192 beams to be collected by a 10 m diameter sphere to be focused into the center on fusion fuel of less than centimetre diameter. The techniques of correct guiding, focusing and temporal scheduling of the laser beams were mastered. Any possibility of a catastrophic meltdown accident of fission reactors is excluded.

For the laser boron fusion, the reactor (Hora 2014) is of spherical shape, Fig. 14, but with the basic simplification that the ignition of the reaction is produced only by one laser beam. The wall of the reactor sphere of at least one meter radius for generation of helium nuclei (alpha particles of 2.9 MeV energy) of 300 kWh

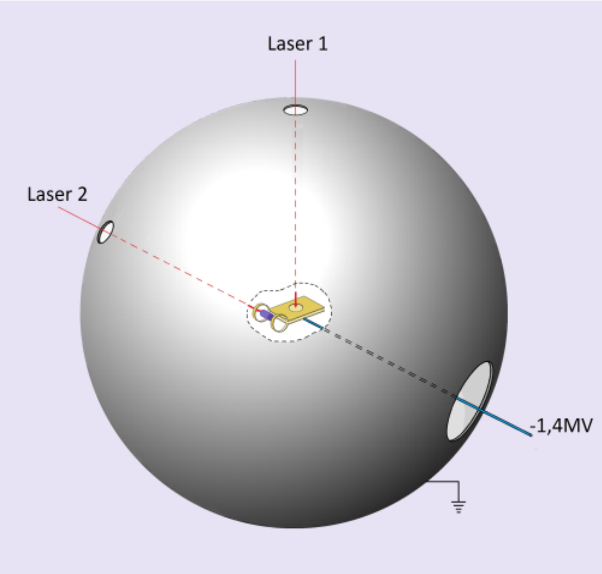

Fig. 14 Scheme of an economic electric power reactor for production of boron-fusion, absolutely free from the problem of dangerous nuclear radiation with the estimated possibility of a power station producing electricity at a very high profit (Hora 2014). The reaction unit in the center is described in Fig. 15.

energy per shot. The sphere has to be of steel or similar material with elimination of secondary low energetic neutron generation (Eliezer et al. 2017, Hora et al 2018a) of at least few millimeters thickness (Hora et al. 2017; 2017a; Lan et al. 2017). The shock produced by the fusion reaction corresponds to that of a chemical explosive of about 50 g. This comparably low shock compared with chemical reactions is due to the fact that this depends on the energy of the generated particles. This is given by the square root of the ratio between nuclear and chemical energy, reducing the nuclear explosion shock by a factor of few thousands against the chemical explosion apart from a softening to the shock front of the alphas.

The reaction unit in the center of the sphere is of such kind that is not for a spherical irradiation of plasma beams but for a cylindrical geometry of the fusion fuel (Fig. 15). If the unit is at the same potential as the sphere, the energy of the alphas is absorbed in the wall sphere and has then to be converted thermally for use in electric generators.

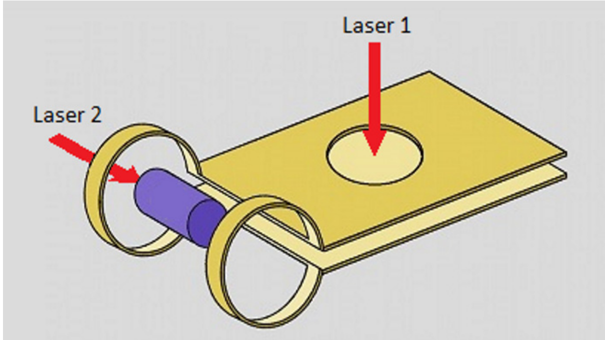

Fig. 15 Reaction unit in the center of the reactor of Fig. 14 using "capacitor coil fields" producing a cylindrical magnetic field of kilotesla (Fujioka et al. 2013). The cylindrical target with the HB11 fuel is co-axially located in a coil where during a ns the kilotesla magnetic field is produced by a kJ-ns laser pulse 1. A ps-30 kJ laser pulse 2 initiates the non-thermal ignition of the fusion in the fuel, see Fig. 6.

Another advantage is that nuclear energy of the mono-energetic alphas can be changed directly into electricity with a minimum of thermal losses, if the unit is charged on a negative potential of less than but close to 1.4 megavolts. The alphas are then slowed down when flying against the positive wall potential and the gained electrostatic energy can then directly be converted into three-phase electric currents by techniques well developed by the HVDC high voltage direct current transmission. This direct conversion of nuclear energy into electricity is indeed possible only if plasma discharge losses between the unit equipped with Faraday screening and the reactor wall can be sufficiently reduced, otherwise the energy conversion of the alphas is possible only by the heating of the wall material.

This is well expectable within few years. In 2018 lasers with 0.17 ps, 10 PW power and one shot per minute are in use following Ditmire (2017) and upgrading to the other specifications with one shot per second should be developed within the range of present day technology (Kiriyama 2018). The necessary and very high contrast profiles (Danson et al. 2018) have been achieved for the necessary high quality laser beams driven also for the other most important applications apart from laser boron fusion.

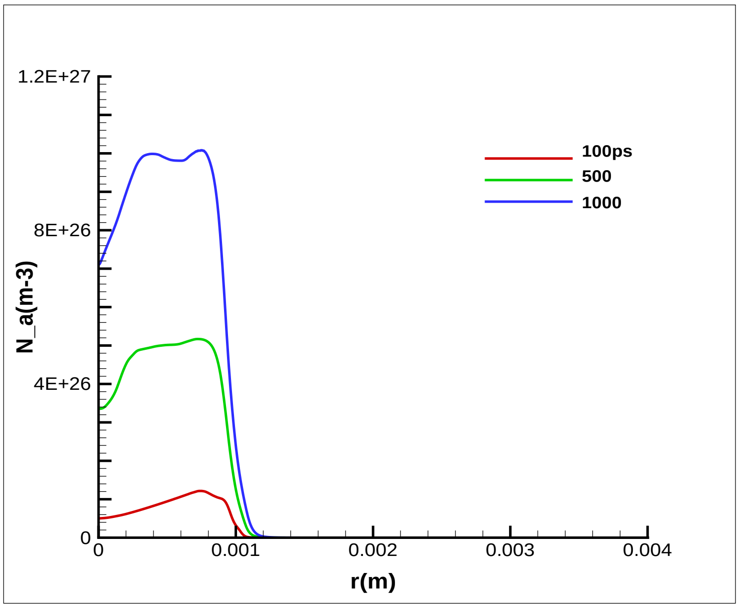

Fig. 16 Cylindrical trapping by a cylinder-parallel kilotesla magnetic field for a HB11 solid density fusion by a plane wave incidence one ps laser pulse of intensity of 10^{20} W/cm^2 intensity on the cylinder end. The generated fusion generated alpha particles of density n_a at different times shows ignition from the increasing alphas on time while these with the plasma are trapped within the initial cylinder radius of 1 mm.

The optical technology for guiding the 30 PW-ps of high contrast and modest focusing is on a much more sophisticated level developed (Barty 2004) for the case of NIF and can be taken over.

The physics of the generation of the ultrahigh magnetic fields in the coils (Giuffrida 2016) has been explored. Nevertheless the studying of the field properties, the time dependence, and further improvements are a technology for laboratory projects on usual level. Fig. 16 is a result showing the computation for trapping of cylindrical volume of the solid density HB11 reacting plasma.

The mechanically guiding of the reaction unit to the rector center is indeed not an easy topic but should be of less difficulty than the similar problems in the technology of micro-electronics and may be taken over from there. The technology for repeating the positioning of the unit into the reactor center for one event per second was following solutions based on technologies envisaged by Gaul (2017).

If by whatever reason the here described laser boron fusion with exclusion of any radioactive waste problem would not be possible, the modest temperature picosecond nonlinear force driven ultrahigh plasma block acceleration can be used for irradiation of DT targets (frozen or as polyethylene component) for intense neutron source for controlled fusion-fission hybrid energy generation (Hora 2018).

It has to be underlined that the energy generation by burning carbon resources—the historic way we have to realize that this was opening the age of wealth and comfort of the human civilization since the invention of the steam engine—has to be the most gratefully appreciated. This carbon energy source can well be used and is definitely indispensible in the future, if the carbon emission into the atmosphere has to be less than 20% of the present level of 2020, i.e. to be reduced to the level of 1950 (Hora 2010) or lower. Furthermore, there is absolute no question, that solar energy mostly based on advanced photovoltaics or wind energy can partly be the economically best solution in specific cases—one may consider e.g. the Australian outback. The aim beyond is only for gaining the main global high demand for electric energy generation, where the more than million times more compact nuclear energy density than chemical energy without producing dangerous radioactive waste by using boron fusion may become the key option. This is based on the now opened direct non-thermal conversion of laser pulse energy for ignition. By this way the generation of extreme heat for ignition can be drastically reduced by applying non-thermal equilibrium and using the nonlinear physics of laser-plasma interaction to reach the established success of nuclear fission but without the problems of dangerous nuclear waste and the catastrophic reactor meltdowns.

Achievements

This is a 40-year scientific story, but it is not more than a first beginning for one of the options for preventing the problem of climate change while keeping a clean and economic global production of energy.

The handicap for fusion energy for power stations has been overcome by using non-thermal pressures for ignition with picosecond CPA laser pulses of ultra-extreme powers. The ignition by thermal pressures with temperatures of dozens of hundred million ^{o}C is then obsolete (Hora et al 2020).

The otherwise very difficult fusion of hydrogen with Boron-11 (HB11 fusion) is then possible without any primary production of radioactive radiation and a small secondary neutron generation can be suppressed (Eliezer et al. 2017).

Against the earlier measurement of very low laser boron fusion, very many orders of energy gains were bridged (Hora et al 2015) thanks to the avalanche reaction (Eliezer et al 2016) arriving toward break-even to the similar level at NIF at Livermore/CA (Giuffrida et al 2020) as expected with petawatt laser pulses (Margarone...Fujioka et al 2020). A further strong increase of the gain can be expected from the dielectric plasma block explosion (see Fig. 6) based first on the measurements by Sauerbrey (1996) with ultrahigh acceleration by the nonlinear force.

The measurements are guided to the low-cost, environmentally clean, safe, and abundant electricity generation from laser boron fusion.

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