Crucial Non-Thermal Ignition for Gaining Electrical Energy from Laser Boron Fusion

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Abstract: Ignition of nuclear fusion reactions requires temperatures more than one million times higher than burning carbon to generate energy. Recently, this has been drastically changed since picosecond laser pulses with dozens of petawatts power have become available. Rather than thermal pressure, the nonlinear forces generated by such a laser can be used to ignite a fusion reaction. This has enabled an alternative to fission reactors for nuclear energy generation without the problems of radioactive waste. It has opened the possibility of a new clean, safe, low-cost and long-lasting electrical energy supply in the future.

Energy conservation and Thermal Equilibrium

Gaining electrical energy from chemical energy is most commonly achieved by burning fuel. The energy generated per molecule or atom is given in electron-volts (eV), representing about a volt from chemical batteries. Igniting petrol with a match produces temperatures of several hundred up to about one thousand degrees. In all cases the first law of thermodynamics holds - the total energy in the system is constant, whether this is chemical, electrical, optical, energy of mechanical motion at accelerating or slowing down the mass of a vehicle. Thermal energy has an additional restriction in that it can only flow from a higher to lower temperature and not the other way. This limits the exchange of thermal energy conversion to an efficiency number that is determined by the difference between high and low temperature.

In the steam engine of James Watt, this efficiency is only a 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 has to be shovelled into the fire. A petrol internal combustion engine is more efficient than coal, and diesel engine is nearly twice as efficient again producing half the carbon emissions for the same mechanical energy of the vehicle. An example of nearly 100% efficiency is the conversion of chemical energy into electric energy in a battery where thermal losses can nearly be neglected.

Nuclear Energy

Ernest Rutherford discovered that atoms are built by a electron cloud surrounding a much smaller nucleus in the centre. The energy needed to start nuclear reactions is not eV, as in chemistry, but more than one million times higher. Thus, temperatures required to ignite these reactions are in the order of one hundred million to one billion degrees. This is only observed in the universe within stars. The fire that slowly burns hydrogen into helium in the centre of the sun is about 15 million degrees. In a nuclear reaction the energy generated by changing one chemical element into another corresponds to a change of energy E from the mass difference M times c^2 according to Einstein's $E = Mc^2$ (using the speed of light c).

When listing the masses of the elements from the heaviest natural uranium to lighter elements, an increase of the binding energy of the particles to the nuclei is seen. When changing heavier elements from uranium to less heavy elements, down to iron, it results in an energy gain. This is the energy source of the nuclear fission reactors. For chemical elements lighter than iron the opposite is true. Reaction of light nuclei as hydrogen, helium, lithium, beryllium, boron etc. into heavier ones, up to iron, by fusing nuclei together, a fusion energy gain is seen.

This happens in the universe, as mentioned for the sun. Is there an alternative to achieving a fusion reaction without the need for temperatures above millions of degrees? For fission it was the most unique discovery in 1938 by Otto Hahn to achieve ignition at temperatures of power stations by hitting neutrons on uranium nuclei. Neutrons are particles like similar nuclei of hydrogen, however without the usual positive electric charge. When moving the uncharged neutrons towards uranium nuclei, they are not pushed back by the electric force from the uranium and can be captured by the uranium nucleus. This "neutron capture" excited the new heavier uranium nucleus and caused it to split into two nuclei and produce a huge amount of energy. Hahn could prove this by his unique technique to measure the extremely small number of generated chemical elements of the new nuclei. It could then be concluded that at the splitting (fission) of uranium, three further neutrons were generated, such that a chain reaction could occur creating an explosive reaction producing the extremely high temperatures. In the case of a power station this chain reaction is controlled to maintain manageable temperatures.

For nuclear fusion as a desired source of electrical energy a large amount of research was invested since 1950 for experiments that required temperatures much higher than 10 million degrees. One approach is a continuous reaction in a plasma torus at extremely low density confined by very high and constant magnetic fields. Examples are the Stellarator-Wendelstein experiment or the ongoing worldwide $20billion ITER project. The latter is not expected to generate energy before 2025 using the fusion of heavy and superheavy hydrogen isotopes deuterium and tritium (DT). Another approach is to use laser pulses for controlled micro-reactions. The best results have been achieved with the world's biggest laser at the National Ignition Facility (NIF) in Livermore (California) reaching gains of about one hundred times below the breakeven point of producing more fusion energy than had to be applied to start the reaction. In both cases the required ignition temperatures are considerably higher than 10 million degrees and have been reached where *local thermal equilibrium LTE* was determining the thermonuclear fusion reactions.

The Fusion ignition scheme at extreme non-thermal equilibrium

A recent experiment has confirmed a prediction made many decades ago that fusion can be achieved without the need for such high temperatures. Applied to a reaction of hydrogen and boron in non-local thermal equilibrium (non-LTE) conditions, nonlinear physics [1] dominated the reaction making it viable. This need to work with non-equilibrium conditions was formulated for a possible supporting the particle beams fusion proposal MIGMA, introduced by Meglich [2]. The non-equilibrium aspect was highlighted experimentally [3] in particular how nonlinear physics can drastically change the result – a change from no to yes, from wrong to right – completely even when neglecting very tiny properties. This is not a gradual change as an approximation, but a basic phenomenon discussed in detail in [4] with Richard Feynman [5] 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.

In the case of laser ignition of a hydrogen-boron reaction, mechanical energy in the motion of a plasma is not only produced by thermal pressure but also by non-thermal pressure due to the energy density of laser pulses. This pressure generated by the electromagnetic field of the laser is expressed by the nonlinear force given by the special variation of the energy density of the laser pulse in the plasma.

Forces and Motion of Plasma

The hydrodynamic equation for motion of fluids like plasmas (all matter of temperatures above thousands of degrees) began with Leonard Euler in the eighteenth century. It needed the later defined electric and magnetic fields (Maxwell's stress tensor) and properties of plasma, (Langmuir's plasma frequency or the Debye-Milner length [6], all achievements by Nobel Laureates of the 20th century). The rather complicate derivation of the equation of motion was not complete in 1966. From laser-plasma interaction experiments one first could derive nonlinear effects due to local changes of the optical refractive index of plasmas resulting in the nonlinear forces. It was a merit in the preceding equation of motion that one nonlinear term had been discovered, but the final missing two nonlinear terms were not known before the publication [7].

The completed equation of motion permitted a numerical study for the interaction of a laser pulse of intensity 10^{18}W/cm^2 (Watts per square centimetre) on a slab of deuterium plasma of density close to the critical value. The very general time dependent motion was calculated including the local variation of temperature and density that resulted within 1.5ps (picoseconds = millionth of a millionth of a second) in the motion of a plasma block 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 one 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 [4]), the laser intensities were then just available but were many orders of magnitude longer than a picosecond – the lasers required to test this theoretical result simply didn't exist yet.

A most dramatic development in laser technology was achieved with chirped pulse amplification CPA [8] which produced the picosecond and shorter pulses of extreme power. Their first use for ultrahigh acceleration was measured by Sauerbrey in 1996 [9] and were very close to the computer simulations of 1977 using the blue Doppler shift of the spectral lines in the plasma block moving against the laser pulse. These measurements needed very clean laser pulses of high contrast to avoid relativistic self-focusing. This was demonstrated by Jie Zhang and his team [10] in a most exceptional way.

Following these and related experiments studying picosecond laser pulse interactions with solid density fusion targets, hydrodynamic computations were performed [11][12] including an IAEA coordinated research project [13]. This all confirmed the dominance of the non-thermal, nonlinear force driven ultrahigh acceleration of plasma blocks by picoseconds laser pulses of extremely high power. The very first measurement of fusion gains under these conditions was from deuterium [14] by nonlinear force driven plasma block acceleration that were nearly four orders of magnitudes higher with picosecond laser pluses than the measurements from numerous laboratories based on thermally dominated fusion. It is a real merit that the measurements of Norreys et al. [14] inspected the low target temperature confirming that the reacting plasma of the accelerated blocks had a remarkably low temperature such that the nearly four orders of magnitudes increase of the fusion gain was not caused by a thermal effect.

Non-thermal ignition of Laser Boron Fusion

Most of the fusion studies were directed on the easiest of all reactions, that of DT, the heavy and superheavy hydrogen isotopes deuterium and tritium. This produces each a harmless helium nucleus but also a neutron. Neutrons decay with a half life of 14.69 minutes into a harmless electron and a hydrogen nucleus, but before their decay, they move nearly unchanged through all materials over long distances. Neutron capture can happen with any harmless stable nucleus, changing it into a radioactive nucleus resulting in unwanted radioactive waste. In contrast, "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. This HB11 reaction produces three helium nuclei – also called alpha particles - of equal energy.

This aneutronic reaction was most interesting from the beginning of the research field, however it was considered much more difficult than DT. Energy generation with HB11 is impossible at thermal equilibrium conditions, thus approaches using continuous magnetic confinement fusion as ITER or Wendelstein are not viable. This is also the case for pulsed laser driven fusion with pulses of nanosecond duration that are determined by LTE conditions where the energy gain is very low. The energy gain of HB11 is five orders of magnitude below that of classical DT fusion. However, experimental evidence that laser pulses shorter than 100 picosecond and above 600 Joule have ignited the HB11 reaction at solid fuel density [16]. In these experiments the measured gains were even higher than for DT fusion [17]. In this case of thermal non-equilibrium, the gains were one billion times higher than the classical case. This experimental result could be completely explained by the non-LTE conditions [18] and by the four orders of magnitude increase by an avalanche multiplication (chain reaction) as three alphas were generated at each reaction [19].

Electricity from absolutely clean, low-cost and lasting laser boron fusion

The Laser Boron Fusion Reactor offers a basically new approach with the "potential to be the best route to fusion energy" [20]. It carries the opportunity that development will be short term relative to other (thermal) fusion approaches which have become some of the world's most complicated and expensive experiments, which are still being pursued given their potential impact on climate change if they are to work.

Experiments for laser driven DT fusion were based on spherical irradiation of laser beams. The laser amplifiers of the National Ignition Facility (NIF) are the size of three football fields using 192 beams to be collected by a 10-meter diameter sphere that are focused onto a fusion fuel pellet of less than one centimetre diameter.

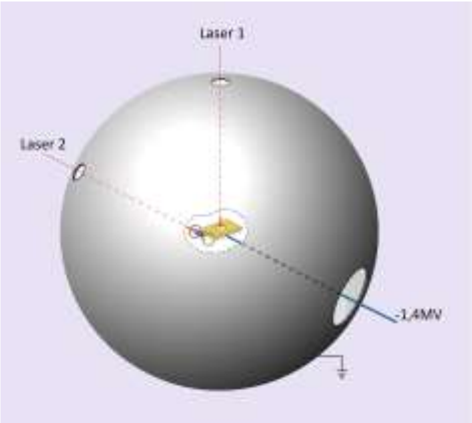

Fig. 1. *Schematic of a boron-fusion reactor and electric power generator, which generates low-cost energy and does not produce dangerous nuclear radiation [21][22][23]. The reaction unit in the center is described in Fig. 2.*

For laser boron fusion, the reactor is spherical, Fig. 1, and ignition of the reaction only requires one laser beam. The wall of the reactor sphere is at least one-meter in radius. This sphere would collect helium nuclei (alpha particles of 2.9 MeV energy) generated by the HB11 fusion reaction to generate about 300 kWh energy per shot. The sphere has to be made of steel or a similar material of at least few millimetres thickness. The shock produced by the fusion reaction corresponds to that of a chemical explosive of about 50 grams. This comparably low shock is due to the fact that it is caused by 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 relative to a chemical explosion.

The reaction unit in the center is designed for a cylindrical geometry of the fusion fuel Fig. 2. If the unit is at the same potential as the sphere, the energy of the alpha particles is absorbed in the wall sphere and has then to be converted thermally for use in electric generators.

Another advantage is that nuclear energy of the mono-energetic alphas can be changed directly into electricity with a minimum of thermal loss if the unit is held at a negative potential of less than but close to 1.4 Megavolts. The alphas are then slowed down as they approach the outer wall and the gained electrostatic energy can then directly be converted into DC current. 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.

The lasers that have made the HB11-reactor a possibility may become commercially available within few years. In 2018 lasers with 0.17 ps, 10 PW power and one shot per minute are in use [25] and advances to one shot per second should be developed within the range of present day technology [26], driven in part by prospective technologies such as laser boron fusion. The optical technology for guiding the 30PW-ps pulses of high contrast and modest focusing, which has been more advanced for use in facilities such as NIF, can also be used.

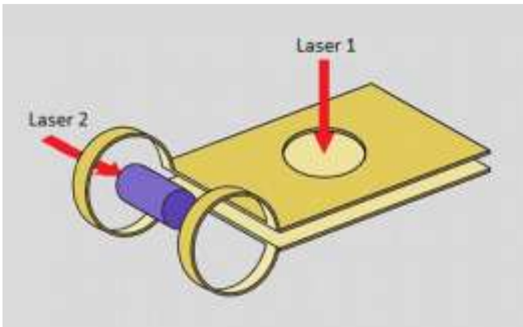

Fig 2. *Reaction unit in the centre of the reactor of Fig. 1 using "capacitor coil fields" producing a cylindrical magnetic field of kilotesla magnitude [24]. The cylindrical target with the HB11 fuel is co-axially located in a coil where, for a ns, the kilotesla magnetic field is produced by a kJ-ns laser pulse 1. A ps-30kJ laser pulse 2 initiates the*

non-thermal ignition of the fusion in the fuel (result of 1977, see Fig. 8.4 of [4]).

The physics of the generation of the ultrahigh magnetic fields in the coils [24] has been explored. Nevertheless, study of the field properties, the time dependence, and further improvements will continue to be developed by the research field.

The mechanical guiding of the reaction unit to the rector center is another detail required for this technology that will need to be addressed in the future, as will the positioning of the unit into the reactor center to achieve a series of reactions - one event per second were following solutions based on technologies envisaged by Erhard Gaul [27].

It has to be underlined that the energy generation by burning carbon resources – the historic way we have to appreciate that was enabled age of wealth and comfort of the human civilization since the invention of the steam engine – has to be most gratefully considered. In reducing carbon emissions into the atmosphere to less than 20% of the present level, i.e. to reach 1950's levels [28], this hydrogen-boron fusion energy source may be indispensable in the future. The aim is to gain more than one million times more compact nuclear energy density than chemical energy without producing dangerous radioactive waste, which is possible with hydrogen boron fusion. This is based on the direct conversion of energy by a non-thermal laser pulse for ignition. By this approach the generation of thermal energy can be drastically reduced by applying non-thermal equilibrium and using the nonlinear physics of laser-plasma interaction.

**Scientific Director together with four Advisors of HB11 Energy Pty.Ltd. (Presented to Board Meeting, July 2018 with Managing Director Warren McKenzie and Financial Director Jan Kirchhoff)

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