Nuclear Energy without Radioactivity

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A fusion reaction of light hydrogen with boron-11 (HB11) generates less radioactivity per gained energy than burning coal. With the usual spherical laser compression scheme, the deuterium-tritium (DT) ignition may be demonstrated with the NIF laser, but the use of HB11 requires exorbitant compressions precluding this option; however, in contrast, the new petawatt-picosecond laser pulses, based on a recently discovered extreme anomaly, may permit a side-on ignition of uncompressed fuel differeing from the spherical compression scheme. In this case the HB11 reaction is only about 10 times more difficult than for DT and is in the next available range.

Energy topics

The mix of energy sources required for preventing a climatic catastrophe includes the nuclear option at a reasonable level of contribution despite its known problems and the advanced solutions required. There is no question that the emission of CO_2 has to be drastically reduced. 4 Billion tons per year, which was the level at 1950, are tolerable; nevertheless, even this limit guarantees that a large volume of Australian coal will still be mined in one hundred years. However, if CO_2 emission continues at more than 24 Billion tons per year, then ice will melt from Greenland, the Antarctic and glaciers. Melting half of the present Greenland ice, estimated to be equivalent to 500 meters depth over the whole island, will result in more than a 3 m increase in the level of the oceans.

Conversion of motorcars or aircraft to be driven by electricity, hydrogen or alternative fuel sources needs many years of research and development; however, mobility cannot be abolished in modern life. Energy waste can be reduced in lighting by using photodiodes increasing the efficiency by a factor ten while emitting the same light compared with conventional sources. Other methods of energy conservation are being developed. Alternative energy is coming from advanced solar-thermal power generation, and solar cell technology may drastically overcome the ongoing high price gap e.g. by using electron beam technology [1]. Wind energy is now economical since the French AREVA nuclear reactor producer has started investing money into offshore wind generators in the Baltic Sea.

Nuclear fission energy is the second largest producer of energy worldwide after fossil fuels. The most advanced EPR (European Pressure Reactor) dominates the market for new installations. A further question still open is whether fusion energy – different to fission - may be an important component as a future energy source. After more than 50 years development, magnetic confinement fusion is still being tested by the international ITER project aimed beyond 2015 at a cost of more than 10 Billion Euro. Critical problems need to be addressed such as wall erosion (disruption by Razumova effect) and many other challenges need to be overcome.

Laser driven fusion, using the largest laser NIF completed in early 2009 [2], aims to produce up to 10^{19} fusion neutrons from deuterium and tritium (DT) reactions with pulses of 1.1 MJ (gain 24) by the end of 2009; following this, the historic first controlled ignition of a fusion reaction on earth. The spherical laser compression of DT fuel may well reach the needed 2000 times solid-state density that had been measured in 1991; however, Steve Bodner [2] has predicted that the experiment "will fail to work". The critical solid-state density may occur using the complicated scheme of spark ignition, but the more simplified volume ignition [3] – discovered in 1977 in Australia – may work as confirmed in 1988 in underground reaction experiments. This alternative may even better fit the strategic goal of laboratory scale conditions for secondary fusion stage reactions with NIF [2,3].

Australian contributions to fission energy, apart from our domination of uranium resources, were highlighted by Dr. Selena Ng [4]. She first mentioned the Synrock method for storing long-lived nuclear waste where the use of ceramics is better than the French vitrification. Ng also highlighted the Silex isotope separation which is more advanced compared with other methods and is expected to be on the market in 2011.

Alternative scheme for fusion energy with lasers

The invention of the laser in 1960 led to the hope that it may ignite exothermal nuclear fusion reactions beginning with DT and resulting in neutrons and helium with a reaction energy about ten million times higher than from chemical reactions

$$D + T = n + {}^4He + 17.6\ \text{MeV} \qquad (1)$$

To ignite this reaction in DT plasma, it normally requires a temperature above 40 Million °C (about 4 keV). By 1969, lasers of a few Joules produced 1000 fusion neutrons and by 1996 100 Billion more were measured using about 10,000 times more energetic laser pulses (Soures et al 1996:[5] - references are in [5, 6]). The laser had to generate a spherical compression of the DT fuel and the design of the $3.5 Billion experiment NIF [2] followed along these lines of spherical compression for the next expected first manmade controlled ignition of fusion.

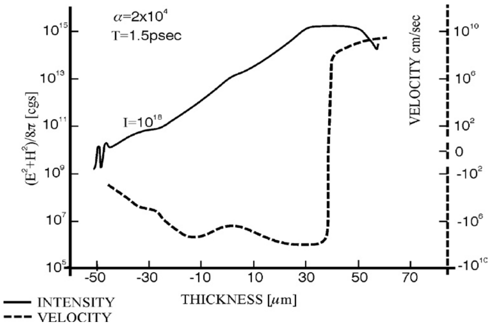

Fig. 1. Neodymium glass laser irradiation of 10^{18} W/cm^2 intensity from the right hand side on a deuterium plasma initially with low reflectivity bi-Rayleigh density profile located between 50µm and +50µm and initial temperature 100eV for plane geometry hydrodynamic very general computation. Result after 2 ps for the velocity (more than 10^9cm/s block with 18 vacuum wave length depth moving against the laser) and laser field energy density with dielectrically swelled field vectors, whose negative gradient determined the nonlinear (ponderomotive) force (from Figs. 10.18a and b of [10]). Negative velocity shows the block moving into the plasma interior.

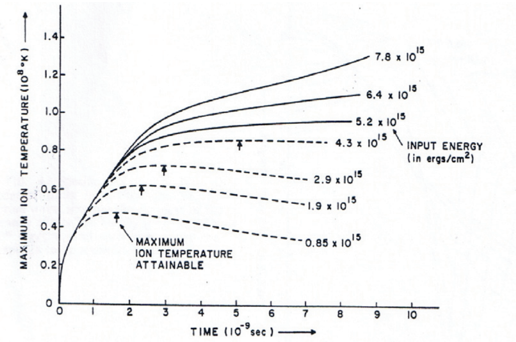

Fig.2. Characteristics of the maximum temperature T on time t for parameters E* of energy flux density in ergs/cm^2 for side-on fusion ignition of solid state DT from Fig. 2 of Chu [11].

Another scheme is called "fast ignition". When Azechi et al. (1991) demonstrated compression to 2000 times solid-state density with the then highest neutron gains of 10^{13}, the temperature of 3 Million degrees was disappointingly low. In this situation it was decided by E.M. Campbell (summarized in his Doctor of Science thesis at the University of Western Sydney: [6]) to use a laser pulse of picoseconds (ps) duration and petawatt (PW) power into the centre of the compressed DT plasma to generate the necessary ignition temperature. Based on the schemes to produce ps laser pulses of TW and finally PW power by 1999, experiments were followed up; however only 10^8 neutrons were gained by fast ignition due to complicating relativistic effects such as pair production of electrons, GeV ions, bursts of many 100 MeV electrons, and nuclear transmutations due to bursts of gamma radiation.

A modification of fast ignition, proposed by John Nuckolls et al. in 2002 [7], uses a very intense 5 MeV electron beam to ignite a larger volume of low density DT, compressed to only 12 times the solid-state, producing a fusion gain of 10^4. A laser of several PW needs to be fired into a plasma of high pre-compression produced prior by ns laser pulses.

Our new scheme is working alternatively without the need of a preceding plasma pre-compression. It uses extremely intense ion beams instead of the electron beams of Nuckolls et al. [7]. The new scheme is therefore a single step interaction PW-ps laser irradiation process and works with uncompressed DT fuel or with modest compression as in the scheme with electron beams.

The new scheme is based on measurements observed as an extreme anomaly at the interaction of ps or shorter laser pulses of more than PW power. This could be understood from much earlier numerical results for laser plasma interaction showing in one dimension (Ph.D. thesis of V.F. Lawrence, University of New South Wales, 1978:[6]) the action of the nonlinear (ponderomotive) force due to dielectric plasma effects [8]. The exact measurement of this acceleration was not discovered prior to Sauerbrey 1996: [5] because in all preceding measurements the plane of the geometry was violated by relativistic self-focusing [9] appearing in all relevant experiments before 1996. The very first time that relativistic self-focusing did not destroy the plane geometry was at the very anomalous experiment of Sauerbrey where the cut-off of any laser prepulse (contrast ratio 10^8) until less than 50 ps before the main pulse was used. This prevented the generation of a plasma cloud in front of the target that usually generates relativistic self-focusing, such that no beam filamentation could occur. The agreement of Sauerbrey's measurements with the nonlinear force theory was shown [5]. One example of the plane geometry computation with the dominance of the nonlinear force is seen in Fig. 1 extracted from the thesis of Lawrence:[10].

Measurements of the ions by Badziak et al 1999:[5] under the same anomalous conditions resulted in maximum energies of 0.5 MeV while relativistic self-focusing usually produced 22 MeV ions. The anomalous effect was shown also in the experiment by Zhang et al. 1998: [5] from x-emission. The explanation in 2002 [5] was the nonlinear force acceleration of the dielectrically enlarged skin layer as later confirmed in many details experimentally and numerically [5]. The highly directed ions were in space charge neutral plasma blocks with ion current densities above 10^{10} Amps/cm^2. The use of such ion beams for igniting laser driven fusion was formulated in 2002 by the first author (Hora) and was declassified when a similar case with electron beams was disclosed [7].

The use of the nonlinear force driven plasma blocks from PW-ps laser-plasma interaction permits a come-back of the side-on ignition of uncompressed DT as studied with hydrodynamics by Chu [11] and fully confirmed in 1974 by Bobin 1974:[6] including the losses by bremsstrahlung emission. A typical result is shown in Fig. 2. Irradiation by ps pulses with an energy flux density E* (in ergs/cm^2) results in a time dependence of the triggered detonation wave. If the temperature decays after a few ns, no ignition happens. The result is that ignition appears for higher temperatures T than the ignition temperature T_{ign} where the curves do not decrease in time with a threshold E_{th}* if

$$E^* > E_{th}^* = 4.3\times10^8\ \mathrm{J/cm^2} \text{ for temperatures } T > T_{ign} = 7.4\ \mathrm{keV\ (DT)} \quad (2)$$

This extremely high ignition threshold for E* prevented the side-on ignition of uncompressed DT in 1972 and laser fusion followed the scheme of spherical compression of the fuel by lasers for ignition.

With the now available nonlinear force driven plasma blocks using PW-ps laser pulses the situation was changed [6]. The conditions of the side-on ignition of uncompressed DT now appear to be an option for laser fusion after the NIF experiment (Moses 2008:[6]) confirms ignition. Chu's computations were fully reproduced (Ghroanneviss, Malekynia et al.:[6]) and the effects of thermal conduction inhibition due to the double layer and the collective stopping power following Denis Gabor 1952:[6] (not known to Chu [11] in 1972) resulted in a 20 times lower threshold E* for ignition [12]. It was estimated [6] that this one step side-on ignition of solid density DT should be possible with ps laser pulses of several PW subject to further detailed research. This is close to the present capacity of lasers after 2 PW pulses of about ps duration were realized in 1999 (Cowan et al:[5,6]).

The dream fusion reaction of light hydrogen with boron-11

From the beginning of fusion research, a dream reaction is

$$p + {}^{11}B = 3\,{}^{4}He + 8.8\ \mathrm{MeV} \quad (3)$$

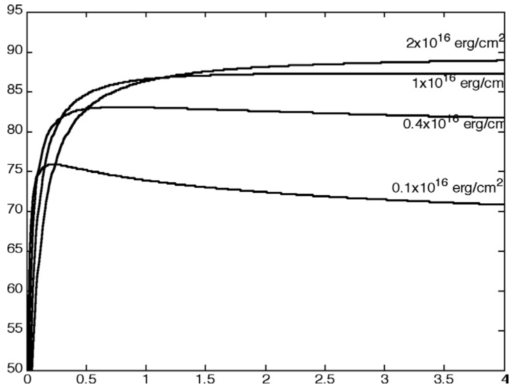

Fig. 3. Side-on ignition characteristics for HB11 at the same conditions as in Fig. 2 resulting in Eq. (4).

because no neutrons are produced and the resulting alpha particles are mono-energetic of 2.9 MeV being ideal for high-efficient direct conversion into electricity or after redirecting with magnetic fields for space propulsion (Miley et al 2008:[6]). Secondary reactions lead to radioactivity but this is less per produced energy than burning coal due to its natural contents of 2 ppm uranium and may be considered as negligible (Weaver et al 1973:[13]). However, it was evident from the beginning that this fusion reaction is more difficult than using deuterium-tritium fusion fuel, as seen from the spherical laser compression of HB11 needing densities of 100 000 times the solid-state (Hora 1975:[13]) and input laser pulses of some 10 MJ energy to produce modest energy gains per laser energy of less than 25 (Scheffel et al 1997:[13]). These conditions are exorbitant and have excluded any hope for laser driven HB11 fusion by spherical compression.

This situation changed, when instead of the spherical laser compression scheme, the side-on ignition with Petawatt-picoseconds laser pulses was studied following the DT results [6]. To be consistent with the results of Chu [11] with DT fuel, computations were first performed based on his assumptions. Using the HB11 fusion cross-sections, the hydrodynamic calculation resulted in the time dependence of the plasma temperature shown in Fig. 3 in analogy to the characteristics plots of Fig. 2 for DT. The parameter of the curves is the energy flux density E*. The aim is to find the value of $E_{th}*$ of the ignition threshold where the plasma temperature T merges into a constant value in the dependence on time t. The determination of the threshold conditions needs a very detailed and highly precise numerical evaluation following up on the detailed curves of Fig. 3 to exclude the very slight time decay. This value is found to be for HB11, with ignition temperature T_{ign}, given by the curve in Fig. 3 with the parameters

$$E^* > E_{th}^* = 1\times10^9\ \mathrm{J/cm^2} \quad \text{at} \quad T_{ign} = 87\ \mathrm{keV} \qquad (\mathrm{HB11}) \qquad (4)$$

These results are remarkably modest compared with the values for DT in Eq. (2) and within a factor of only ten more difficult than the DT fusion, Eq. (2). In view of the exorbitant difference between DT and HB11 for volume ignition using spherical pellet compression, it is surprising how much easier the ignition of HB11 works with a side-on generated thermonuclear reaction front.

Bremsstrahlung emission is automatically included in the hydrodynamic computations following the treatment of Chu [11]. Separate outputs of the bremsstrahlung have confirmed this result. The side-on ignition is a kind of shock wave process and is practically two dimensional in difference to the three dimensional processes at spherical compression. This fact requires that the temperature for DT needs to be larger than 4 keV and for HB11 larger than 60 keV, as confirmed by the results (2) and (3). Electron and ion temperatures and many further details are evaluated separately.

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References

[1] H. Hora, Klimakatastrophe Überwinden (Overcoming the Climatic Catastrophe) Roderer Publisher, Regensburg/ Germany 2007
[2] D. Kramer, Physics Today, May 2009, p. 28
[3] P.A. Amendt et al. Phys. Rev. Lett. 94, 065004 (2005)
[4] S. Ng, (Australian Representative for the French AREVA nuclear reactor company) Four Societies Lecture in Sydney, February 24, 2009
[5] H. Hora, J. Badziak et al, Physics of Plasmas 14, 072701 (2007)
[6] H. Hora, Laser and Particle Beams 27, 207 (2009)
[7] J.H. Nuckolls et al in Edward Teller Lectures, Imperial College Press, London 2005, see pages 13-14
[8] H. Hora, Phys. Fluids 12, 182 (1969)
[9] H. Hora, J. Opt. Soc. Am. 65, 882 (1975)
[10] H. Hora, Physics of Laser Driven Plasmas, Wiley New York, 1981
[11] M.S. Chu, Physics of Fluids 15, 412 (1972)
[12] H. Hora et al. Appl. Phys. Letters 93, 011101 (2008)
[13] N. Azizi et al. Laser and Particle Beams 27, 201 (2009); H. Hora, G.H. Miley et al., Laser and Particle Beams 27, No.3 (2009) doi: 10.1017/SO26303460999022X

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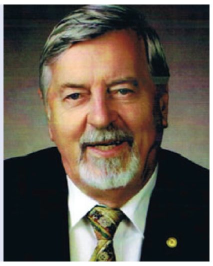

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