Study of Inertial Fusion Energy via the Equation of State

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Abstract

A major breakthrough in inertial confinement fusion (ICF) occurred with the publication in 1972 of J. Nuckolls et al[1]. "Laser compression of matter to super-high densities: Thermonuclear applications". This important idea is a direct consequence of the equation of state (EOS) of matter at high density and temperature. Using for example[2] the Thomas Fermi EOS for the deuterium-tritium nuclear fuel, one gets that it is energetically "cheaper" to compress the fuel rather than to heat it. On the other hand, the nuclear reaction rate is proportional to the density square. Therefore, the fusion gain G (output energy/input energy) is significantly larger by compressing the fuel target while heating only a small portion of it.

The purpose of the target and driver designs in ICF is to obtain an appropriate fuel areal density (ρR) and temperature (T) in order to achieve nuclear ignition and high gain. For a variety of different ICF designs: (a) spark ignition, (b) volume ignition, (c) fast ignition with picosecond lasers or (d) impact fast ignition, one requires different domains of initial ρR and T values. Therefore the input energy for every scheme is in a domain set by the EOS and the mass of the fuel. Furthermore, the output energy is also a function of ρR and T and therefore for any given design the EOS fixes the gain in ICF.

1. Introduction

Many important physical phenomena are obtained by analyzing the equation of state of the system under consideration. For example, one can use the virial theorem and an ideal EOS to analyze the stars in a gravitational field. The ideal EOS is defined for a system of N particles in a volume V with a temperature T and internal energy E by: $PV = Nk_BT$ and $E = PV/(\gamma-1)$; k_B is the Boltzmann constant and γ is the ratio of the heat capacities at constant pressure and constant volume. In this case, it is concluded[2] that the star is unstable if $\gamma < 4/3$ and it is stable if $\gamma > 4/3$. Furthermore, while a stable star contracts its internal energy increases and it gets hotter. At the same time it radiates energy. For $\gamma = 5/3$, half of the potential energy decrease is used to heat the star and the other half is irradiated. As can be deducted from this simple example, one can get a lot of insight into the study of the stars through the EOS.

Two different schemes for controlled nuclear fusion have been investigated in the past fifty years: (1) Magnetic confinement fusion based on high intensity magnetic fields confining low density plasmas for long times, (2) Inertial confinement fusion based on rapid compressing[1] and heating the fusion fuel contained in a spherical target. At densities of about 1000 times solid density, for the hydrogen isotopes deuterium-tritium, and temperature above 5 keV the fusion reaction rates occurs efficiently before the plasma pellet disassembles. The compression and heating of the fuel is done with laser beams or ion beams. The compression is achieved by uniform direct illumination (**direct drive**) of the spherical pellet, or alternatively by converting the driver energy into soft x-rays in a cavity where the fusion pellet is placed (**indirect drive**).

The solution for the global energy problem by inertial confinement fusion (ICF) has been the subject of intense study [3-7] in many countries for the last 40 years. In order to achieve nuclear fusion ignition, mega-joule lasers with few nanosecond pulse durations are currently being constructed in USA and France. Furthermore, peta-watt (PW) lasers with time duration of the order of one picosecond have been operating in USA, UK, France, China and Japan, and are under development in other countries.

Nuclear fusion is potentially a safe and clean energy source. An ICF power plant has four major components: (a) the driver, laser or particle accelerator that delivers the energy to the fusion target, (b) the target factory, where deuterium tritium pellets are manufactured, (c) the reactor chamber where pellets and driver beams are brought together in order to produce nuclear fusion, and (d) the generator which converts the thermal energy into electricity.

The economics of the ICF power plant is determined by its power cycle. Electrical energy creates the driver energy with an efficiency η_d. The driver energy (E_d) is converted into thermonuclear energy by the target with a gain G, yielding an energy GE_d. The thermonuclear energy transforms to electricity with an efficiency η_T. A portion, the economical factor f, of this energy ($f\eta_T G\eta_d E_d = E_d$) must be recirculated to power the driver, thus completing the power cycle. The power cycle implies the basic formula for any ICF reactor: $G = 1/(\eta_d\eta_T f)$.

To minimize the cost of electricity f has to be as small as possible. A typical estimated value for f is about 0.25. The value of η_T is limited by thermodynamics, therefore for an economical ICF power plant one requires $G > 10/\eta_d$. This relation implies that for a driver with an efficiency of 10% the pellet gain should exceed 100. For example, taking f = 0.25, $\eta_T = 0.4$, $\eta_d = 0.1$, G = 100, and using a laser system with energy of 3.3 MJ per shot and with a frequency of 10 Hz, one gets a driver with a power of 0.033 GW, the thermonuclear power is 3.3 GW, the gross electricity power is 1.3 GW where 0.3 GW is recirculated to driver while **1GW goes to the electric power utility**.

Between the all possible fusion reactions the **deuterium tritium (DT) fuel** seems to be the first candidate for the reactor since it has the highest cross section for low energies (few keV). The DT reaction products and energy excess is given by $D+T \rightarrow \alpha + n + 17.59 MeV$, where α and n are the helium4 nucleon and the neutron accordingly. For this reaction, the fusion energy overcomes the bremsstrahlung losses at temperature larger than 4 keV, therefore the maximum theoretical gain is G_{max} = 17590 [keV]/{ $4 \times (3/2) \times 4[keV]$ } ≈ 730, where in the denominator the ideal equation of state (EOS), E = (3/2)T was used for the two ions and the two electrons D+T+2e with a temperature T = 4 keV in energy units.

If such a high gain can be achieved then what is the problem? The real gain is much smaller since one has to take also into account the following efficiencies: the driver absorption by the pellet η_A, the hydrodynamic efficiency from the absorbed energy to the heating energy η_H and the fraction of the nuclear fuel ϕ that burns before the pellet breaks apart. Therefore the gain G is

$$[1] \qquad G = \frac{\eta_A \eta_H \phi q_{DT}}{q_{th}} < G_{\max} = \frac{q_{DT}}{q_{th}} = \frac{3.39 \cdot 10^{11} [J/g]}{1.16 \cdot 10^{8} T_{keV} [J/g]} = 2922$$

where q_{DT} and q_{th} are accordingly the fusion energy yield per gram and the ideal EOS for heating the fuel to a temperature T in keV units. For a realistic example η_A = 0.8, η_H = 0.1, ϕ = 0.3 and for the temperature required to overcome the bremsstrahlung T = 4 keV, one gets a gain of G= 17.5. This is not a very good gain taking into account that a power plant requires G > 100.

This problem was solved by designing the target and the driver pulse shape in such a way that only a spark (ξM, where M is the mass of the fuel) at the center of the compressed fuel is heated and ignited. The rest of the fuel is heated by the α particles produced in the DT reaction. For this to happen it is necessary that the density of the fuel (ρ) times its radius R is larger than 0.3 g/cm^2. For the example, using the above values it is sufficient to heat only a fraction ξ =0.175 of the fuel in order to increase the gain from 17.5 to 100. However, due to hydrodynamic instabilities[5,7], such as Rayleigh – Taylor and Richtmyer- Meshkov, and preheat of the nuclear fuel, this scheme of ICF is not very promising.

Fast ignition[8,9] avoids some of the severe obstacles mentioned above by triggering ignition not in a central self-produced spark, but in a secondary interaction of an igniting driver of a very short duration, such as a multi peta-watt (PW) laser beam. With this concept, much less energy is required in order to obtain nuclear ignition and high gain.

The PW laser is supposed to form a channel during a few tens picoseconds in the plasma atmosphere in such a way that at the stagnation point of the implosion this laser pulse delivers about 10^{20} W/cm^2, 10 ps duration and energy of the order of 10 kJ. Such a laser has been built at Osaka University in Japan. The problem is that the laser does not penetrate directly into the compressed pellet. The laser penetrates only up to the critical surface where the electron density is $n_e = \gamma_r 10^{21} cm^{-3}/\lambda_\mu^2$, γ_r is the relativistic factor ~ 10 and λ_μ is the laser wavelength in microns. Since the laser cannot penetrate the compressed fuel ($n_e \sim 10^{24}\ cm^{-3}$ or more), the laser energy is converted into high energy electrons[10] or protons[11] that cause strong local heating followed by a fusion burn wave throughout the compressed fuel. However, the heating is not properly confined and in order to avoid the undesired preheating of the DT fuel, a gold (ρ_{Au}/ρ_{DT} ~100) cone–stuck spherical pellet as shown in figure 1 was suggested[12]. Imploding such a shell Kodama et al[12] measured about 10^7 neutrons by using nine beams of the Osaka University (Japan) laser system operated at a wavelength of 0.53 μm and with energy of 2.5 kJ for 1.2 ns flat top pulses, and using a 0.5 PW laser for the fast heating,. This result was an enhancement about three orders of magnitude

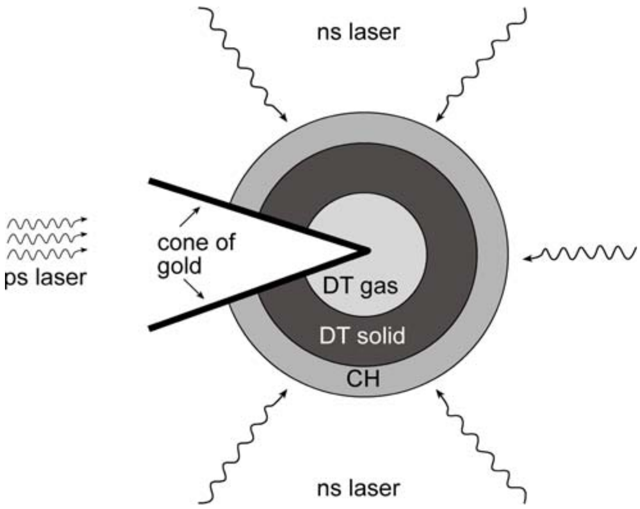

Figure 1: A schematic configuration for fast ignition. The pellet is compressed by few nanosecond laser pulses while the spark heating is done with a few tens of picosecond laser pulse after the compression.

Besides this scheme other fast ignition ideas exist. For example, fast ignition by plasma jets[13-15] that are induced by the main laser system that compresses the target. In other proposals[16,17] the fuel is ignited by using a plasma flow created from a thin exploding pusher foil. Recently Murakami[18] revived the old impact fusion ideas within the context of fast ignition (see figure 2).

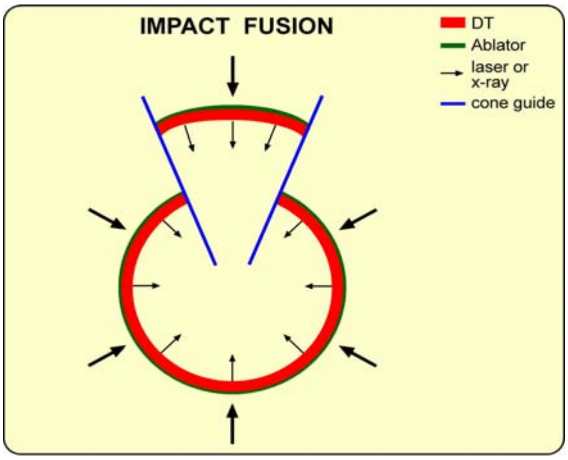

Figure 2: schematic of impact fast ignition fusion.

2. Why compression?

In ICF the "name of the game" is compression. The laser energy E_L that heats the DT fuel within a sphere with radius R_C and particle density n_C is given by

[2]
$$\eta_H \eta_A E_L = (3n_C T)\left(\frac{4}{3}\pi R_C{}^3\right)$$
$$\Rightarrow E_L = \left(\frac{1}{\eta_H \eta_A}\right)\left(\frac{4\pi}{2.5 m_p \rho_0{}^2}\right)(\rho_C R_C)^3 T \left(\frac{\rho_0}{\rho_C}\right)^2$$

where the ideal gas EOS has been used, m_p is the proton mass, $\rho_0 = 0.2$ g/cm^3 is the initial DT density, ρ_C is the compressed DT density, the temperature T is in energy units and η_H, η_A are the hydrodynamic efficiency and the laser absorption coefficient accordingly. Solving explicitly the nuclear rate equations in the domain of temperatures (5 – 20) keV, one obtains the fraction of the nuclear fuel ϕ that burns before the pellet breaks apart,

[3]
$$\phi \approx \frac{\rho_C R_C}{\rho_C R_C + 7[g/cm^2]}$$

From this equation one can see that $\phi = 30\%$ for $\rho_C R_C = 3$ [g/cm^2]. This last number can be translated into Lawson' criterion for ICF: $n_C \tau_C = 2\times10^{15}$ [s/cm^3], where τ_C is the confinement time. From equations [2] and [3] one gets the following necessary laser energy that heats the plasma to the threshold temperature of 4 keV (fusion energy equals the bremsstrahlung losses) and inducing a 30% burn of the nuclear fuel

[4]
$$E_L[MJ] = \left(\frac{1.3\times10^6}{\eta_H \eta_A}\right)\left(\frac{\rho_0}{\rho_C}\right)^2$$

Taking typical values of $\eta_H = 0.1$ and $\eta_A = 0.8$, the ICF ignition and nuclear burn require a pulsed (few nanoseconds) laser system with an energy

[5] $$E_L[J] = 1.6\times 10^{13}\left(\frac{\rho_0}{\rho_C}\right)^2$$

It is evident from this result that without compression one requires an unrealistic pulse laser with energy of 16 Giga-Joules, while a 3000 compression (i.e. 600 g/cm^3, a density already achieved experimentally at Osaka University in Japan[19]) **reduces the laser energy to 1.75 Mega-joules**. Therefore, it is not surprising that the two largest laser systems under construction at Livermore (the National Ignition Facility) in USA and the Mega-joule laser in France will have energy of about 2 Mega-joules!

Another important parameter is the mass M of the nuclear fuel, given by

[5] $$M = \frac{4}{3}\pi R_C{}^3\rho_C = \frac{4.19}{\rho_C{}^2}\left(\rho_C R_C\right)^3 \approx \frac{113}{\rho_C{}^2}[g]$$

where $\rho_C R_C = 3$ was used. Without compression $\rho_C = 0.2$ g/cm^3, and the last equation implies a nuclear DT mass of about 2.8 kg, an undesired value for the controlled fusion reactor. However, a compressed fuel with density $\rho_C = 600$ g/cm^3 needs a pellet with only 1.0 mg DT fuel ($\phi = 0.3$ was taken, consistently with $\rho_C R_C = 3$ g/cm^2).

3. Energy gain.

We here focus on the fast ignition. Below we consider simple model for optimization of target gain in fast ignition scheme. The total driver energy E_d splits into two, i.e., the compression energy for the main fuel E_{com}, and the ignition energy E_{ign}, which are given respectively by[20]:

[6] $$E_{ign}[kJ] = 140\left[\rho/\left(100g/cm^3\right)\right]^{-1.85}; E_{com}[kJ] = 330\alpha M_c\rho^{2/3},$$
$$\mathrm{E_d = E_{ign} + E_{com}}$$

where ρ is the fuel density (isochoric fuel profile is assumed). The ideal EOS for the DT yields a pressure P_C of the compressed fuel: $P_C = n_iT + n_eT = 2n_eT$, where n_i and n_e are the ion and the electron densities respectively. However, the electrons are degenerate and therefore the ideal gas EOS for them is not justified. If the electrons would be fully degenerate then their pressure is $P_{deg} = (2/5)n_e\varepsilon_F$, where ε_F is the Fermi energy ($\sim \rho_C{}^{2/3}$) and the main fuel compressed density is $\rho_C = (2.5m_p)n_e$. α in equation [6] is called the isentrope parameter as it is defined by the ratio $\alpha = P_C/P_{deg} = 5T/\varepsilon_F$, taken to be ~ 3. The mass of the fuel and the burn fraction ϕ are

[7] $$\mathrm{M_c = 4\pi H_c^3/3\rho_c;\ H_C = \rho_C R_C;}\ \phi \approx \frac{\mathrm{H_C}}{\mathrm{H_C + 7[g/cm^2]}}$$

where $H_c \equiv \rho_c R_c$ is the areal mass density of the main DT sphere with a compressed radius R_C. Once the hot spot is successfully ignited, a burn wave is expected to propagate through the main fuel causing a burn fraction estimated by ϕ. The energy gain is finally evaluated to be

[8] $G = 3.4\text{x}10^{18}[\text{erg/g}]\phi M_C/E_d$

where the small fraction of the thermonuclear energy released from the hot spot is ignored for simplicity.

Figure 3 shows the driver energies versus the fuel density. Since the compression energy and the ignition energy have opposite behavior with respect to the density, one can easily find that the total driver energy has a minimum at certain value of the density (see Fig.3). In particular, it should be stressed that there exists an optimum relation for E_{com}/E_{ign}, to minimize the total driver energy by setting,

[9] $$\frac{\partial E_d}{\partial E_{com}} = 0 \Rightarrow$$

[10] $$E_d = \left(\frac{\alpha M_c}{\eta_c}\right)^{\nu/(\nu+1)} \left(\frac{a\nu}{\eta_i}\right)^{1/(\nu+1)} \left(1+\frac{1}{\nu}\right); \quad \nu=2.85$$

where η_C and η_i are the efficiencies from driver (e.g. laser) to thermal energy of the igniter (i.e. hot spot) and the compressed fuel accordingly. Therefore, using the above approximations the optimum ratio is given by $E_{com}/E_{ign} = \nu = 2.85$.

Finally, Fig.4 shows the energy gain versus the compressed fuel density for different fuel mass. As one can see there is an optimum gain as a function of compression.

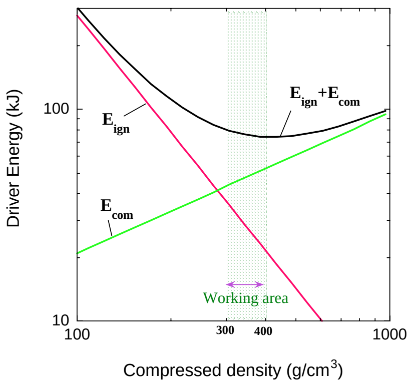

Fig 3: Driver energy versus the compressed fuel.

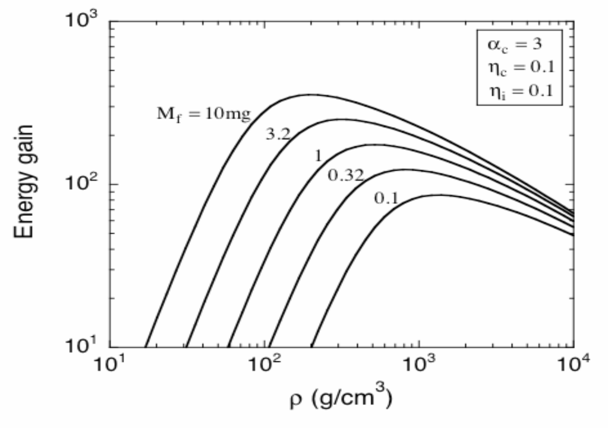

Figure 4: energy gain versus the compressed fuel density for different fuel mass

4: Bremsstrahlung , degeneracy and the pB11 problem

Bremsstrahlung is one of the most important energy loss mechanisms in achieving nuclear fusion ignition. In the classical approach, it is necessary to heat the ions to a temperature high enough to overcome radiation emission, independent of the plasma density. The independence of plasma density follows from the fact that the fusion energy (E_{fus}) as well as the bremsstrahlung energy losses (E_{bre}) are proportional to density square ($E_{fus} \sim \rho^2$ and $E_{bre} \sim \rho^2$). This is the case in magnetic confinement where plasma density is very low ($\rho \sim 10^{-9}$ g/cm^{-3}) and in inertial confinement where plasmas density is very high ($\rho \sim 10^3$ g/cm^{-3}). The requirement $E_{fus} > E_{bre}$ implies that the temperature for deuterium-tritium ($DT \rightarrow n\alpha$) fusion has to be larger than $T_{DT} \sim 4$ keV, while the temperature for the proton-boron11 fusion ($p^{11}B \rightarrow 3\alpha$) has to be larger than $T_{pB11} \sim 150$ keV. The fusion $p^{11}B \rightarrow 3\alpha + 8.7$ MeV is of major importance since it is the cleanest nuclear reaction to produce energy (practically no neutrons are created).

Quantum degeneracy is defined by the dimensionless ratio between the temperature (in energy units) T of the electrons and the Fermi energy ε_F, $\eta = \varepsilon_F/T$. For $\eta << 1$, the degenerate case, the electrons are described by Fermi-Dirac statistics with a distribution equal to one between zero and the Fermi energy. For $\eta >> 1$, the classical case, the electrons are described by the Maxwell-Boltzmann statistics. The ratio between the degenerate and the classical bremsstrahlung radiation losses[21] is

[11] $$\frac{W_{deg}}{W_{class}} = \left(\frac{\sqrt{\pi}}{2F_{1/2}(\eta)}\right)\left\{F_1(\eta) - \frac{1}{2}\left[\ln\left(e^{\eta}+1\right)\right]^2\right\}$$

where W is the total radiation power per unit volume [Watt/m^3] and $F_k(\eta)$ is the Fermi-Dirac integral defined by

$$F_k(\eta) = \int_0^{\infty} \frac{x^k dx}{\exp(x-\eta)+1}$$

This general equation yields for the degenerate case

[12] $$\eta \equiv \frac{T}{\varepsilon_F} << 1 \Rightarrow \frac{W_{deg}}{W_{class}} = \frac{\pi^2\sqrt{\pi}}{8}\left(\frac{T}{\varepsilon_F}\right)^{3/2}$$

For example, if $T/\varepsilon_F = 0.1$ then the bremsstrahlung loss is about 7% of the radiation loss from a classical plasma at the same temperature. Bremsstrahlung is inhibited in degenerate plasmas because transitions are forbidden by Pauli's principle. The problem is to reach the extremely high densities required for the electron quantum degeneracy. An estimation of the density is derived by analyzing the Fermi energy

[13] $$\varepsilon_F = \left(3\pi^2\right)^{2/3}\left(\frac{\hbar^2}{2m_e}\right)n_e^{2/3} \Rightarrow \varepsilon_F = \varepsilon_{F0}\left(\frac{Z}{Z_0}\right)^{2/3}\left(\frac{\rho}{\rho_0}\right)^{2/3}$$

$\hbar$ is Planck constant divided by 2π, m_e and n_e are the electron mass and density accordingly, ρ_0 and ρ are the initial and the final (compressed) densities having accordingly an ionization state of Z_0 and Z. ε_{F0} is the Fermi energy of the pre-compressed target, usually of the order of few electron volts.

We analyze two cases: (I) the DT fusion and (II) the pB11 fusion[22-24]. The ions are described by an ideal gas EOS while the electrons are degenerate and obey[2] the Fermi-Dirac EOS. Assuming $Z = Z_0$ in equation [13] one gets $\varepsilon_F \sim (6\text{eV})\times(\rho/\text{g/cm}^3)^{2/3}$. We further assume that $T << \varepsilon_F$, and for numerical estimate we take $\varepsilon_F = 5T$. Since bremsstrahlung is negligible in the degenerate case one has to take a temperature that gives a reasonable fusion cross section. For this consideration we take T = 2 keV for DT fusion and T = 100 keV for pB11 fusion. In these cases we obtain the following estimate for the maximum theoretical gain, for degenerate,$(G_{max})_{deg}$ and classical,$(G_{max})_{clas}$, defined as the ratio

[14]

$$\text{(a)}\quad G_{max}\left(DT2e\right)_{deg} = \frac{17{,}600\text{keV}}{2\varepsilon_F + 2\times\left(3T/2\right)} \approx \frac{17{,}600\text{keV}}{2.6\varepsilon_F} \approx 677$$

$$\text{(b)}\quad G_{max}\left(DT2e\right)_{clas} = \frac{17{,}600\text{keV}}{4\times\left(3T/2\right)} \approx \frac{17{,}600\text{keV}}{6\times 4\text{keV}} \approx 733$$

Comparing the degenerate case 14(a) with the classical estimation 14(b) it seems that it is not very useful to go to the degenerate case. However, it should be emphasize that for the degenerate case the ions can be heated to temperatures lower than the minimum 4 keV required in the classical case due to the bremsstrahlung losses. Both results in [14] are very optimistic therefore a more accurate estimation, like the one given above in section 3, is necessary before concluding about the favorite scheme.

However, for the pB11 clean fusion even the most optimistic results suggest that this clean fusion is not viable in any scheme. In particular,

$$\text{(a)}\quad G_{max}\left(pB^{11}5e\right)_{deg} = \frac{8,700\text{keV}}{5\varepsilon_F + 2\times\left(3T/2\right)} \approx \frac{8,700\text{keV}}{5.6\varepsilon_F} \approx \frac{8700}{2800} \approx 3.1$$

$$[15]\quad \text{(b)}\quad G_{max}\left(pB^{11}5e\right)_{clas} = \frac{8,700\text{keV}}{7\times\left(3T/2\right)} \approx \frac{8,700\text{keV}}{10.5\times 100\text{keV}} \approx 8.2$$

$$\text{(c)}\quad G_{max}\left(pB^{11}5e\right)_{\text{ion only}} = \frac{8,700\text{keV}}{2\times\left(3T/2\right)} \approx \frac{8,700\text{keV}}{300\text{keV}} \approx 30$$

For the DT case we need a density ~ 5×10^4 g/cm^3, while for pB11 the density has to as large as ~ 2×10^7 g/cm^3! But even for this huge density the cleanest of all fusion, pB11 $\rightarrow 3\alpha$, is not going to work since a gain smaller than 3 seems to be useless for inertial fusion energy reactor. The classical result 15(b) is also not practical since one has to multiply the Gain with the burning factor (ϕ ~0.3) and the different efficiencies as given by equation [1]. It seems that the only way to improve the Gain in this reaction is a scheme to heat (directly ?) only the ions while the energy transfer to the electrons are inhibited (again by degeneracy of the electrons). The maximum theoretical gain is defined in [15(c)] and optimistically estimated to be 30. This gain is not a very useful number taking into account the present efficiencies and burning fraction.

In summary, using the present knowledge of pB11 cross section and bremsstrahlung losses together with the EOS knowledge, one concludes that the desired clean fusion reaction pB11 $\rightarrow 3\alpha$ is not suitable for a magnetic confinement or inertial confinement (at any density) reactor.

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