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Muonic and Polarized Fusion for Inertial Confinement Fusion?

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ERRATUM for KfK 3563

In German abstract

replace DR- by DT-

equation (6)

replace 1.55 by 3.5

following line

replace η^2 by $\hbar^2$

3rd line following equation (27)

replace comparison by compression

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Muonic and polarized fusion for inertial confinement fusion?[1]

*By Walter Seifritz and B. Goel**

Abstract

It is investigated whether or not the application of two novel concepts could facilitate the ignition of DT-pellet in the inertial confinement technique of fusion: The muonic fusion catalysis and the idea of polarized fusion. It seems that due to the overall energetics and inefficiencies involved the muonic fusion catalysis has no chance for a practical application and that in the case of the utilization of polarized DT-fusion material either for the spark region or in the highly compressed cold outer shell or in both pellet-regions the "gain of the gain" is only marginal. The driver energy requirement by the use of polarized fuel can, however, be reduced by a factor of 2.

Zusammenfassung

Myonen-Katalyse und polarisierte Fusion als Fusionsträgheitseinschluß?

Es wurde untersucht, ob die Anwendung von zwei neuartigen Konzepten den Zündvorgang von DR-Brennstoffkügelchen beim Fusionsträgheitseinschluß erleichtern kann: Durch Myonen-Katalyse oder durch die polarisierte Fusion.
Es scheint, daß aufgrund gesamtenergetischer Betrachtungen die Myonen-Katalyse kaum eine Chance besitzt und daß im Falle der Verwendung spin-polarisierter Fusionsmaterie entweder im Zündkern oder in der kalten hochkomprimierten Außenzone oder in beiden Pelletzonen der dadurch erzielbare Gewinn in Form eines höheren »Pelletgain« nur marginal ist. Die Treiberenergie kann jedoch um einen Faktor 2 reduziert werden.

INIS-EDB-PB-DESCRIPTORS

INERTIAL CONFINEMENT
THERMONUCLEAR IGNITION
BURNUP
GAIN
MUON BEAMS
CATALYSIS
DEUTERIUM
TRITIUM
MUONIC MOLECULES
IMPLOSIONS
SPIN ORIENTATION
POLARIZED TARGETS
ENERGY BALANCE

1. The ignition concept of classical inertial confinement fusion

In the classical Inertial Confinement Fusion Technique (ICF) the fusion fuel configuration at ignition is assumed to consist of a central hot region (spark) surrounded by highly compressed fuel at low entropy as shown schematically in Fig. 1.
Ignition occurs in the center. The temperature in the burning fuel increases rapidly from α-particle heating until the increase in the α-particle range with increasing temperature causes the α-particles escape into the surrounding cold fuel. Consequently propagation of the burning front becomes fast enough to advance more rapidly into the cold fuel than the hydrodynamic disturbance caused by the pressure increase of the thermal conduction front [2].

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In this process the energy required to initiate the burning process is substantially reduced from the requirement for uniform ignition. The propagating thermonuclear burn concept is essential to achieve high gain in inertial confinement fusion.
Fig. 1 shows a realistic ignition situation where the pressure is nearly constant over the total (hot and cold) fuel region [1; 12]. In this so-called "Modified Kidder-Bodner" gain model the following conditions have to be fulfilled:

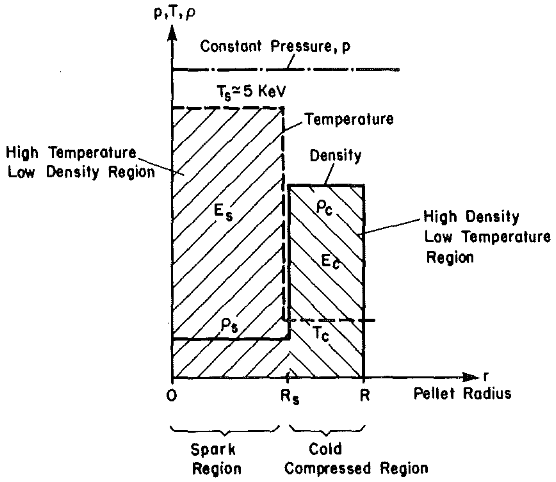

Fig. 1: The modified Kidder-Bodner ignition model [12] for inertial confinement fusion. The pressure over the spark and the surrounding cold compressed regions is assumed to be constant.

1.1. In the hot spark region

The spark region labeled with the subscript s can be described as an ideal gas. The condition for ignition is that the range of α-particles at ignition temperature is approximately equal to the radius of the spark region R_s, yielding a confinement parameter for the spark region, H_s, of

$$H_s = \rho_s R_s \gtrsim 0.4 \text{ g/cm}^2 \qquad (1)$$

where ϱ_s is the density of the fuel within the spark region. Furthermore, the ignition temperature, kT_s, for DT-fuel in the spark should fulfill the condition

$$kT_s \gtrsim 5 \text{ keV} \qquad (2)$$

Due to these ignition conditions, the pressure p and the internal energy of the spark region are given respectively by

$$p = \frac{2\, kT_s}{\mu_{DT}} \rho_s \qquad \text{g/cm}^2 \qquad (3)$$

$$E_s = 2 \cdot \frac{3}{2} kT_s \frac{M_s}{\mu_{DT}} \quad \text{ergs} \qquad (4)$$

where $M_s = 4\pi/3\, R_s^3\, \varrho_s$ is the fuel mass in the spark region and μ_{DT} is the ratio of the atomic weight of DT fuel to Loschmidt's number, i. e., $\mu_{DT} = 4.15 \times 10^{-24}$ g.

1.2. In the cold, highly compressed region

The relatively cold but highly compressed region surrounding the spark region and labeled with the subscript c can be described as a degenerate electron gas with the pressure given by

$$p \doteq \frac{2}{5} \alpha n_e \varepsilon_F = 2.34 \times 10^{12} \alpha \rho_c^{5/3} \quad \text{g/cm}^2 \qquad (5)$$

and the internal energy given by

$$E_c = \frac{3}{5}\alpha\varepsilon_F \frac{M_c}{\mu_{DT}} = 1.55\times10^{13}\, \alpha\, M_c \rho_c^{2/3} \text{ ergs} \quad (6)$$

where the Fermi energy is $\varepsilon_F = \hbar^2 (3\pi^2 n_e)^{2/3}/(2m_e)$ with the electron mass m_e, the electron density $n_e = \varrho_c/\mu_{DT}$, the mass of the highly compressed fusion fuel M_c and its density ϱ_c. The isentrope parameter α denotes the deviation from the completely degenerate electron gas and labels different isentropes ($\alpha \geq 1$).

1.3. Fuel and driver energies

The total fuel energy is

$$E = E_s + E_c \quad (7)$$

which has to be coupled into the fuel pellet by means of an external driver via the ablation effect producing a sequence of shocks. If the hydrodynamic efficiency of this procedure is denoted by η, then the energy of the driver beams is given by

$$E_{driver} = (E_s + E_c)/\eta \quad (8)$$

1.4. Burn-up, fusion energy and pellet gain

The burn-up of the thermonuclear burn wave is determined by the confinement parameter H_F of the total fuel (spark region and highly compressed region)

$$H_F = H_s + H_c = \rho_s R_s + \rho_c (R-R_s) \quad (9)$$

where R is the outer radius of the cold highly compressed region (see Fig. 1).

The burn-up fraction is

$$f_b = \frac{H_F}{H_o + H_F} \quad (10)$$

The reference confinement parameter H_0 for a *freely* burning and expanding DT-sphere is given by [2]

$$H_o = 8\mu_{DT} \frac{v_s}{\langle\sigma v\rangle} \quad (11)$$

since the effective burn time, i. e., the average time that the fuel ions are able to react before the rarefaction wave quenches burn, is

$$\tau_b = \frac{\int_o^{\tau_s} (4\pi\rho/3)\,(R - c_s t)^3\, dt}{(4\pi\rho/3)\, R^3} = \frac{R}{4v_s} \quad (11')$$

which takes account of the fact that in a spherical fuel pellet, half of the mass is beyond 80% of the radius [15; 16]. v_s and $\langle\sigma v\rangle$ are the sound velocity and reactivity parameter, respectively, at the burning temperature. Assume burning at 80 keV (nearly the maximum of $\langle\sigma v\rangle$) for which $v_s \simeq 3.5\times10^8$ cm/sec and $\langle\sigma v\rangle \simeq 10^{-15}$ cm³/sec the reference confinement parameter is $H_0 \simeq 11.6$ g/cm².

If there is pusher or tamper material around the fuel the free expansion of the sphere is tamped which increases the burn-up fraction. As a guess, the disassembly time for a DT-sphere with a pusher or tamper, possessing the (non-ablating) pusher mass $\tilde{M}$, is approximately

$$\tau = \tau_o \sqrt{1 + \tilde{M}/m} \quad (12)$$

(m = DT-fuel mass)

where τ_0 is the disassembly time of the freely expanding fuel ($\tilde{M} = 0$). Therefore, the burn-up of a tamped DT-sphere increases by the same factor $\sqrt{1+\tilde{M}/m}$ if there are no asymmetry effects degrading the burn.

The effective confinement parameter is

$$H_{eff} = \frac{H_o}{\sqrt{1 + \tilde{M}/m}} \quad (13)$$

For example, the non-ablated mass of the LiPb-pusher of the HIBALL pellet design in Ref. [1] is $\tilde{M} = 9.5$ mg and the DT-fuel mass is $m = 4$ mg. Introducing these numerical values in Eq. (13) gives $H_{eff} = 6.3$ g/cm² instead of $H_0 \simeq 11.6$ g/cm² for the freely expanding sphere. H_F in the case of the HIBALL pellet is (0.4+2.96) g/cm² $\simeq$ 3.4 g/cm² yielding a burn-up fraction of 35%. (In the HIBALL study, H_0 is assumed to be 7 g/cm², which gives a burn fraction of 33%, due to asymmetry effects and a burn-up fraction of 30% is recommended as a realistic figure).

The total fusion energy released during a thermonuclear microexplosion is

$$E_{fusion} = q_{DT} \cdot M \cdot f_b \quad (14)$$

with the specific DT-fusion energy $q_{DT} = 3.34\times10^{11}$ J per g of DT-fuel burnt and $M = M_s + M_c$ the total DT-fuel mass. The burn-up fraction f_b has to be introduced from Eq. (10).

Finally, the pellet gain is by definition

$$G = \frac{E_{fusion}}{E_{driver}} \quad (15)$$

Combining Eq. (15) with Eqs. (7), (8) and (14) gives the following standard expression for the pellet gain in classical inertial confinement fusion

$$G = \frac{q_{DT} \cdot M \cdot f_b}{(E_s + E_c)/\eta} \quad (16)$$

For example, in the HIBALL study the numerical values are: E_s = 57 kJ, E_c = 183 kJ, η = 0.05, M = 4 mg, f_b = 0.3 yielding a driver energy E_{driver} = 4.8 MJ and a pellet gain $G \simeq 83$.

2. The muonic ignition concept of inertial confinement fusion

The possibility of using muon catalysis of fusion reactions for the purpose of energy production has been a long-standing dream of physicists [3]. However, the possibility of using muons to facilitate ignition in inertial confinement fusion has not been discussed so far, in detail. The basic idea is to direct a pulse of muons into the pellet simultaneously with the driver beams. The muons should be slowed down in the outer part of the pellet and come to rest in the spark region. It has been estimated [4; 5] that each muon should be able to catalyse about 100 DT-fusion reactions during its lifetime even in a relatively cold DT mixture due to the screening effect of the Coulomb potential when a muonic DT-molecule (tμd) is being formed.

The energy released is therefore 100 times 17.1 MeV, but only the energy channeled into the α-particles, i. e. 100×3.5 MeV per muon = 0.35 GeV, can be recuperated in the spark region because this region is optically thick with respect to α-particles but not with respect to 14.1 MeV-neutrons.

If one denotes Z_μ as the number of muons which can be deposited in the spark region in the short time period available during the implosion process, the additional heating energy due to this effect in the spark region is

$$E_\mu = 0.35 \cdot Z_\mu \quad \text{(in GeV)} \quad (17)$$

Muons are produced by means of pions according to the decay equation

$$\pi \rightarrow \mu + \nu_\mu \qquad (18)$$

The pions themselves are produced by means of a proton accelerator in which protons are accelerated to 1–2 GeV producing pions in a heavy target. *Jackson* [6] has estimated a lower boundary of 10 GeV to produce one muon. At the Schweiz. Institut für Nuklearforschung (SIN), about 2×10^7 μ/sec can effectively be focussed onto a target corresponding to an input energy of 10^9 GeV per muon. Improvements in orders of magnitudes are, however, still possible.

Taking the optimistic figures for the energy necessary to produce one muon either from *Jackson* (10 GeV/μ) or from *Petrov* [4] (5 GeV/μ) it is obvious that muonic fusion in the classical sense, namely to irradiate DT-fusion material with a muon beam, is energetically senseless; one muon can catalyse 100 DT reactions, only 1.76 GeV of energy (100×17.6 MeV/DT-reaction) are released, whereas about 5 to 10 GeV were necessary to produce the muon itself. The whole process is therefore endothermic.

However, if muons are used as a means to facilitate ignition in the spark region in Inertial Confinement Fusion, as indicated for the first time by *Tan* [8], the energetic treatment of the problem is different from the above because the energy needed to ignite a thermonuclear burn wave may be small compared with the total energy yield of the whole thermonuclear burn process.

In the following it will be estimated whether or not muonic fusion would increase the pellet gain of fusion targets in the microexplosion concept of inertially confined spherical plasmas.

If one denotes with ε the above-mentioned efficiency to produce one muon ($\varepsilon \simeq$ 5–10 GeV/μ), then the energy which has to be invested for the process to deposit additional heating energy in the spark region, as expressed in Eq. (17), is given by

$$E_p = \varepsilon\, Z_\mu \text{ (GeV)} \qquad (19)$$

The denominator in the pellet gain formula, Eq. (16), should now be modified in such a way that the additional investment of energy E_p due to the muonic production mechanism is added. Then the heating effect in the spark region, E_μ, given by Eq. (17), can be substracted from the spark energy E_s because it is not necessary for the driver to deliver enough energy to the spark region to reach the ignition temperature of about 5 keV. Qualitatively speaking, the entropy production of the collapsing shock waves could be lower.

If the temperature of the spark region would not reach the ignition temperature by the ablation process alone, the α-particle heating due to muonic fusion would deliver additional energy and entropy, respectively, so that the spark region could reach the ignition temperature anyway. The evolution of the entropy in the spark region for a typical implosion is shown in Fig. 2.

The compression energy, E_c, however, can only be delivered by the ablation process; muons can only be used to produce heat and therefore entropy but not to perform isentropic compression of fusion fuel. E_c remains unchanged.

The input energy modified by muons, therefore, has to be compared with the original input energy of the classical gain-formula of Eq. (16).

$$\frac{(E_s - 0.35\, Z_\mu) + E_c}{\eta} + \varepsilon\, Z_\mu \gtrless \frac{E_s + E_c}{\eta} \qquad (20)$$

(E_s, E_c in GeV).

According to Eq. (16), the pellet gain of a microexplosion target increases if the denominator, i. e. the driver energy, decreases. Introducing the above modified input energy, the pellet gain increases with the help of muons if the left-hand side (= mixed input energy) is smaller than the right-hand side (input energy without muons) of Eq. (20).

This condition is obviously fulfilled if

$$\boxed{\varepsilon\eta < 0.35 \text{ GeV}} \qquad (21)$$

Introducing the above-mentioned optimistic values for ε=5 to 10 GeV it turns out that muonic fusion topping gives only sense if the hydrodynamic efficiency of the ablation process η is substantially smaller than 7 to 4 percent. The theoretical upper limit of η is about 8 percent; a typical value taken in pellet designs [1] is 5 percent.

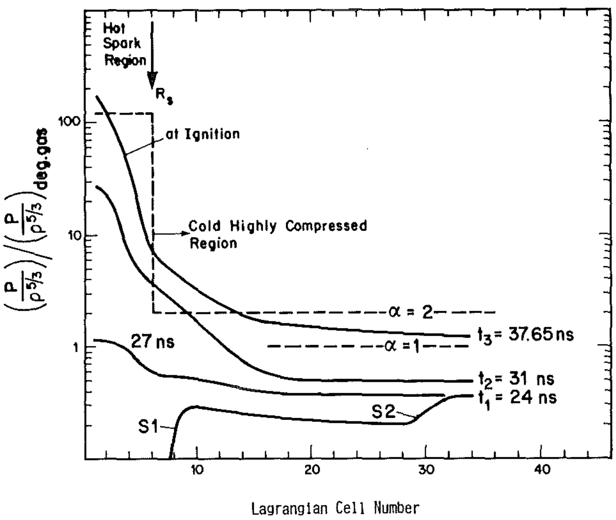

Fig. 2: Entropy evolution in the spark region for a typical implosion in the inertial confinement fusion technique [1].

Thus even from a theoretical point of view there is no benefit to use muons as a help to facilitate the ignition process of microexplosions. In addition, from a practical point of view it seems to be impossible to focus muons into the spark region possessing a volume of only a fraction of a cubic millimeter.

Nevertheless, let us apply the above theoretical treatment to a practical case: In the HIBALL study [1] the following energies of the pellet implosion mechanism were determined to be:

Spark energy:	E_s = 57 kJ
Energy in the highly compressed region:	E_c = 183 kJ
Hydrodynamic efficiency:	η = 0.05
Heavy ion driver energy:	$(E_s + E_c)/\eta$ = 4.8 MJ (22)

Let us assume that in the spark region the entropy production is not high enough (Fig. 2) and the ignition temperature of 5 keV cannot be reached, and, for instance, only two thirds of the necessary energy is achievable. The spark energy is therefore reduced to 3/5 of 57 kJ or 34.2 kJ. So, 22.8 kJ/η or 456 kJ is saved in driver energy. If this energy gap in the spark region of 22.8 kJ is filled by muonic

α-particle heating according to Eq. (17), $22.8\times10^3\times 6.24\times10^9/0.35 = 4.1\times10^{14}$ muons have to be deposited into the spark region ($1\ J = 6.24\times10^9$ GeV).

The spark region has a radius of only 77 μm and it would be extremely difficult, if not impossible, to focuse and deposit the muons in such a small spot. Furthermore, the catalytic fusion mechanism of muons works only if the muons are bound to the hydrogen atoms. Since the binding energy of a muon to a hydrogen atom is ~ 2.7 keV, (about 200 times more than the electron) and the ignition temperature is ~ 5 keV the muons heating mechanism is only applicable in the lower temperature range. The muons therefore have to be delivered and deposited prior to the collapse of the shock waves so that the entropy increase of the latter ones adds up to the "bottoming heating" of the muons. If this timing is not precise one gets either "preheating" by muon heating degrading the isentropic compression, or the muonic heating mechanism fails if the muons arrive too late. It is therefore extremely uncertain that muons can be successfully applied at all.

In any case, according to Eq. (19) using an optimistic ε-value of 5 GeV/μ one would need 2.05×10^{15} GeV $\simeq$ 325 kJ to produce the muons. The "gain" of this operation $\overline{G}$ is

$$\overline{G} = \frac{\text{driver energy saved}}{\text{additional energy to produce muons}} = \frac{456\ \text{kJ}}{325\ \text{kJ}} \simeq 1.4 \qquad (23)$$

Taking into account the energy losses in the accelerator it turns out that the effecitve value of $\overline{G}$ is smaller than unity. Thus, it is energetically senseless to apply muons in this case.

2.1. *The problem of the time scale during the implosion phase*

There is another problem with respect to the time scale of the implosion of the inertial confinement fusion. The classical scheme of mesocatalysis is shown in Fig. 3 with the notation [4]:

- τ_0 = (2.2×10^{-6} sec) muon lifetime
- τ_{dt} = time a muon is transferred from deuterium to tritium ($= 3.7\times10^{-9}$ sec)
- $\tau_{dt\mu}$ = time a mesonic atom ($t\mu^-$) collides with a deuterium to form a mesic molecule ion $(dt\mu^-)^+$ ($\lesssim10^{-8}$ sec);
  τ_{dt} and $\tau_{dt\mu}$ are large compared with the fusion time τ_f ($= 10^{-12}$ sec) and with the time of muon slowing down and capture τ_a ($= 10^{-10}$ sec)
- c = probability that a muon forms a mesic atom ($d\mu^-$) or ($t\mu^-$)
- W_s = probability that a muon is captured by an α-particle and stays there until it decays, alternatively ($1-W_s$) is the probability that the muon slows down during the time τ_a and again catalyses the fusion ($W_s \lesssim 10^{-2}$)

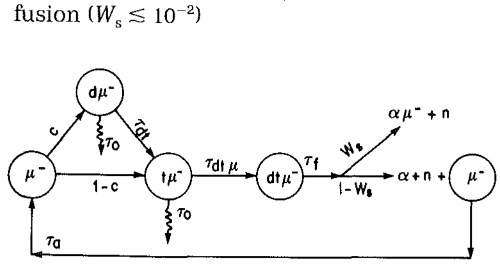

Fig. 3: The scheme of the mesonic cycle (the abbreviations are explained in the text).

Due to this scheme the number of cycles, Z, which a muon has time to catalyze is

$$1/Z = c \cdot \frac{\tau_{dt}}{\tau_0} + \frac{\tau_{dt\mu}}{\tau_0} + W_s \qquad (24)$$

Since τ_{dt} and $\tau_{dt\mu}$ are small compared with the muon lifetime τ_0, $Z \approx W_s^{-1} \approx 100$.

However, in the case of the microexplosion technique there is another time which controls the process: the implosion time τ_{imp} of the spark region. According to Fig. 2, the order of magnitude of this time is $\tau_{imp} \approx 10$ nsec $= 10^{-8}$ sec which is two orders of magnitude smaller than the muon lifetime τ_0. Thus, τ_0 in Eq. (24) has to be replaced by τ_{imp}. Since $\tau_{dt} < \tau_{imp}$, but $\tau_{dt\mu} \simeq \tau_{imp}$ and $\tau_{dt\mu}/\tau_{imp} \gg W_s$, the number of cycles is $Z \approx \tau_{imp}/\tau_{dt\mu} \approx 1$. In other words, a muon in an imploding spark region does not have enough time to perform 100 caetalyzed fusion reactions as required in the stationary DT-fuel case.

The times given for τ_{dt} and $\tau_{dt\mu}$ in brackets above correspond to liquid hydrogen density 4.25×10^{22} cm^{-3}. It is assumed that both τ_{dt} and $\tau_{dt\mu}$ are inversely proportional to the density. If the spark region is compressed by at least a factor of 100 the most sensitive time $\tau_{dt\mu}$ is reduced by the same factor. Thus, $\tau_{dt\mu}/\tau_{imp}$ reduces to 10^{-2}, i. e., to the same order of magnitude like W_s. Since τ_f and τ_a are still small compared with the density corrected $\tau_{dt\mu}$, it may be possible to get about 100 muon cycles. This is only a theoretical speculation and is correct only if the spark region is compressed about 100 times before the muons are deposited there.

In conclusion it seems that from an energetical point of view the muonic fusion idea may have practical sense only in the schemes proposed by *Petrov* [4] and *Takahashi* [11], namely in combination with an electro-breeder [4]. In that scheme the muons are "energetically free" because the main purpose of the proton beam is to produce spallation neutrons to breed fissile materials like Plutonium or Uranium-233 from Uranium and Thorium, respectively. The muons are a by-product and if they are collected and directed into DT-material, they provide an additional 14-MeV neutron source which can sustain the breeding process.

3. The ICF-ignition concept using polarized matter

An increase of 50% in the nuclear DT-fusion cross section when the reacting deuterium (D) and tritium (T) nuclei have parallel spins compared with isotropic spin orientation has recently been reported [13]. In addition, [14] et al. have shown that in inertial confinement plasmas with up to 10^4 times solid densities the relaxation time of nanoseconds for the spin-oriented state is sufficiently long compared with the essential reaction time of the pellet. In the following it will be investigated whether or not the use of polarized matter in an ICF-pellet will decrease the driver energy input or simultaneously will increase the pellet gain.

The utilization of polarized DT-fuel for an ICF pellet can be accomplished in three ways: 1. Only the spark region is made of polarized DT-fuel. 2. Only the highly compressed region surrounding the spark region consists of polarized DT-fuel. 3. Both regions are made of polarized DT-fuel.

In the following the effect of each of these configuations on the pellet gain is discussed.

3.1. *Polarized spark region*

In this case the main effect is the reduction of the ignition temperature due to the increased reaction parameter $<\sigma v>$. Below a temperature of 10 keV the reaction parameter is given by

$$<\sigma v> \sim a\ T^{-2/3} \exp\left(-19.02\ T^{-1/3}\right) \quad (25)$$

where a is a constant and T is the temperature in keV. The power density of the plasma is proportional to this expression. On the other hand, the loss of the bremsstrahlung of the plasma is proportional to $T^{1/2}$. Equating both terms one gets an ignition temperature of $T_s \simeq 5$ keV for isotropic DT-fuel. For polarized DT-fuel the factor a in Eq. (25) is increased by a factor of 1.5 and the same procedure results in the modified ignition temperature of the spark region consisting of polarized fuel of

$$T_s' \simeq 4.3 \text{ keV} \quad (26)$$

According to Eq. (4) the internal energy of the spark region is reduced correspondingly. In the HIBALL example $E_s' = 49$ keV instead of $E_s = 57$ keV. Since all other parameters remain practically constant in this case the driver energy is reduced by 3.5% from 4.8 MJ to (49+183) kJ/0.05 = 4.64 MJ and the pellet gain increases only by about 2%.

3.2. *Polarized highly compressed zone*

Due to the 50% increase in the fusion cross section the confinement parameter H_0 of Eq. (11) and with it H_{eff} of Eq. (13) reduces from 6.3 g/cm² to 4.2 g/cm². The corresponding reduction in the case of HIBALL H_0 is from 7 g/cm² to 4.7 g/cm². The straightforward consequence of this reduction is the increase in burn fraction from Eq. (10) by ~30%, i.e. from 0.33 to 0.42.

The HIBALL cavity is designed to accomodate a pellet yield of 400 MJ. If this constraint is set on the pellet performance, i.e. burn fraction is fixed at 0.33, Eq. (10) gives a value of 2.3 g/cm² for H_F. The size of spark zone is determined by the α-particle range to be 0.4 g/cm². Hence,

$$H_c = 2.3 - 0.4 = 1.9 \text{ g/cm}^2. \quad (27)$$

This corresponds to a density of about 180 g/cm² instead of 630 g/cm² assumed in the HIBALL study. Thus, a much lesser degree of comparison is required if polarized fuel is used. From Eq. (6) one obtains

$$E_c' = 79 \text{ kJ} \quad (28)$$

Thus, if only the compressed fuel zone is polarized the total driver energy requirement is

$$(57 + 79) / 0.05 = 2.72 \text{ MJ} \quad (29)$$

This is about 40% lower than the energy required for unpolarized fuel. As a consequence of reduced driver energy pellet gain is increased by 80%.

3.3. *Polarized matter in both regions*

If the whole pellet consists of polarized fuel the ignition temperature of the spark region is lower and the burn up fraction of the highly compressed region, being mainly determined by its reactivity, is increased.

According to Eq. (16) the modified pellet gain for polarized matter is given by

$$G' = \frac{q_{DT}\ M\ f'}{(E_s' + E_c)/\eta} \quad (30)$$

the overall effect relative to the isotropic fuel case is

$$\frac{G'}{G} = \frac{f'}{f}\ \frac{1 + E_c/E_s}{E_s'/E_s + E_c/E_s} \quad (31)$$

For the above example $f'/f = 1.4$, $E_c/E_s = 3.21$ and $E_s'/E_s = 0.86$. Thus, $G'/G = 1.45$.

Again if the pellet yield is kept at the level of HIBALL design the driver energy requirement is given by

$$(E_s' + E_c')/0.05 = (49 + 79)/0.05 = 2.56 \text{ MJ} \quad (32)$$

Thus, the driver energy is reduced and the gain is increased by a factor of ~2 by the use of polarized fuel.

In conclusion it can be stated that the use of polarized fuel does not dramatically increase the pellet gain. The reduction in driver energy by a factor of 2 means that ion current flowing through RF-LINAC is also reduced by this factor. This can considerably reduce the cost of ion source and RF-LINAC. Since LINAC is the major cost factor of the driver, the total cost of the HIBALL driver may be reduced by about 20%.

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