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Polarization: A Must for Fusion

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Abstract. Recent realistic simulations confirm that the polarization of the fuel would improve significantly the DT fusion efficiency. We have proposed an experiment to test the persistence of the polarization in a fusion process, using a terawatt laser hitting a polarized HD target. The polarized deuterons heated in the plasma induced by the laser can fuse producing a ^3He and a neutron in the final state. The angular distribution of the neutrons and the change in the corresponding total cross section are related to the polarization persistence. The experimental polarization of DT fuel is a technological challenge. Possible paths for Magnetic Confinement Fusion (MCF) and for Inertial Confinement Fusion (ICF) are reviewed. For MCF, polarized gas can be used. For ICF, cryogenic targets are required. We consider both, the polarization of gas and the polarization of solid DT, emphasizing the Dynamic Nuclear polarization (DNP) of HD and DT molecules.

1 Introduction

The polarization of D and T nuclei should increase their reactivity when used as fuel material in fusion processes induced either by magnetic or by inertial confinement. The fusion reaction:

$$D + T \rightarrow \alpha + n + 17.6\ MeV \tag{1}$$

goes mainly through the excitation of an $^5He\ 3/2^+$ intermediate state, resulting from the coupling of the spins 1 and $1/2$ of the D and T nuclei to a total spin $S = 3/2$. Without polarization of D and T, the statistical distribution of the six possible states gives four $S = 3/2$ and two $S = 1/2$ states. Only the $3/2$ states can produce the intermediate $3/2$ resonance. With 100% parallel polarization of D and T, all states would contribute to the fusion, increasing the reactivity by 50%. In addition, the polarization allows the control of the direction in which the reaction products are emitted, the neutron having a $\sin^2\theta$ distribution. This can be very useful to reduce damage or activation of costly equipment. Theoretical considerations have indicated that the polarization should persist as well in MCF [1] as in ICF [2]. In addition, recent realistic simulations show that the required hot-spot temperature (T) and areal density (ρR) can be reduced by about 15 % for fully polarized nuclear fuel.

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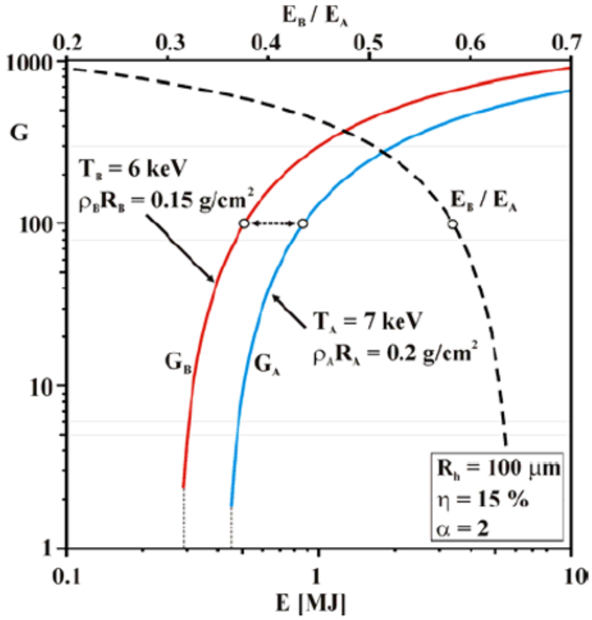


Fig. 1. Isobaric model: energy gain G as a function of the driver energy E (solid lines) and energy ratio E_B / E_A as a function of gain G (dashed line). Subscripts A (blue) and B (red) refer respectively to un-polarized and polarized DT fuel.

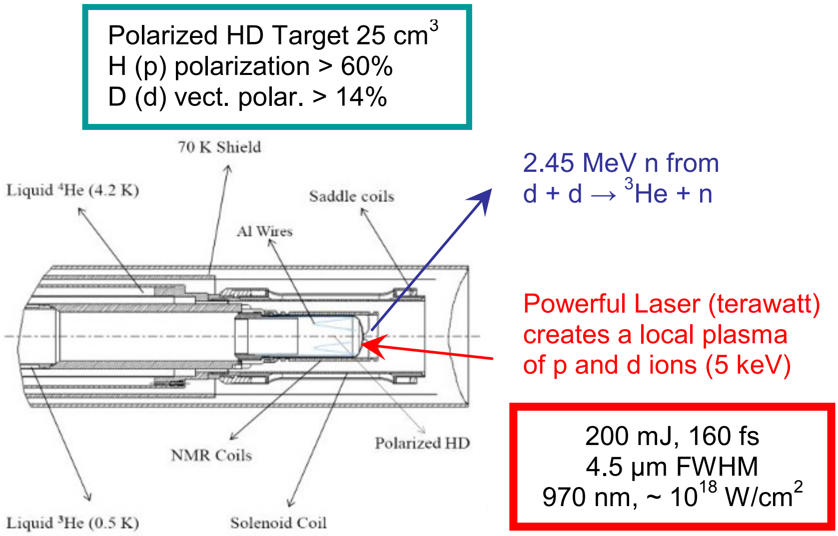
Moreover, numerical simulations of a directly driven capsule show that the required laser power and energy to achieve high gain are significantly reduced, while the maximum achievable energy gain scales roughly as the fusion cross section [3]. Figure 1 from [3] summarizes those results. It is found that for an invested energy of 1 MJ, the estimated gains are G_A (1MJ) = 130 while G_B (1MJ) = 300 for un-polarized and polarized DT fuel respectively. Moreover, for a fixed gain G, the ratio E_B / E_A is always smaller than 0.7, decreasing as the gain increases (see the dashed line in figure 1) and indicating a decrease of the required invested energy E_B for polarized fuel. As an example, for a gain G = 100 the driver energy is E_A = 880 kJ while a smaller energy E_B = 510 kJ (E_B / E_A = 0.58) is required. Obviously, very high gains can only be achieved with polarized *DT* fuel. It should be noted that the $\sin^2\theta$ distribution of the polarized reaction products was not taken into account in the above simulation. A narrower concentration of the heat due to such an anisotropic distribution should further favour the generation of hot spots.

2 Persistence of the polarization

We have proposed to investigate the polarization persistency using the reaction:

$$D + D \rightarrow {}^3He + n + 3.3\ MeV \qquad (2)$$

induced by fusion of polarized deuterons heated in a plasma. It is anticipated that the angular distributions of the neutrons as well as significant changes in the fusion rates can be measured and related to the persistence of the polarization. Details on the setup and the experiment features are given in Ref. [4]. Here, we show only a sketch of the experiment.



Polarized HD Target 25 cm^3
H (p) polarization > 60%
D (d) vect. polar. > 14%

2.45 MeV n from
$d + d \rightarrow {}^3He + n$

Powerful Laser (terawatt)
creates a local plasma
of p and d ions (5 keV)

200 mJ, 160 fs
4.5 µm FWHM
970 nm, ~ 10^{18} W/cm^2

Fig. 1 Tentative set-up showing a typical arrangement of a polarized *HD* target in a cryostat maintaining the target temperature below 1 *K* under a holding field of 1 *T*. The target is bombarded by a terawatt laser producing a localized plasma. Neutrons are generated in the plasma, by fusion reactions between polarized deuterons.

The above described experiment uses only existing equipment: polarized *HD* targets are currently produced by static polarization [5] and the polarization can be accurately measured [6], on the other hand terawatt lasers and neutron detectors are easily available. A signal of 10-20% on the neutron yield due to the persistence of the polarization should be measurable. We collaborate with a Russian-German group to perform precise measurements of all the observables of the double polarized fusion reaction (2) at the PNPI laboratory in Gatchina [7]. On the other hand, the laser fusion investigation is underway: a proposal has been made at the Institute for Laser Engineering (ILE) in Osaka, Japan and has been accepted as the POLAF project (Polarization in Laser Fusion) [8]. The experiment is going on using the ILE equipment, in particular the MANDALA neutron multi-detector. Assuming that the persistence of the polarization in a fusion process has been demonstrated, there remains the problem of the polarization of the *DT* fuel.

3 Polarization of Hydrogen isotopes

The experimental polarization of *DT* fuel is a technological challenge. For MCF, polarized gas can be used. Atomic beams of *H* and *D* are currently produced with high polarization, but their intensity is too low by 3 orders of magnitude [9]. It has been proposed to polarize Hydrogen molecules, which allows the production of molecular beams with a satisfactory intensity of 10^{20} molecules/s [10]. This is barely enough to feed ITER. For ICF, cryogenic targets are required. The symmetries of H_2, D_2 or T_2 Hydrogen isotopes in their homo-molecular form (two fermions or two bosons), trapped as long lived meta-stable states in the solid, complicate the polarization of corresponding targets. However *HD*, a hetero-molecular form of Hydrogen has no symmetry and can be polarized [11]. The static polarization (high field and low temperature) using distilled *HD* has been achieved [5], opening the possibility to produce polarized *DT* molecules [12]. High static polarization of *DT* cannot work, because of the heat generated by the Tritium radioactivity (~ 640 mW/g). Therefore, one has to count on the Dynamic Nuclear Polarization (DNP) of solid *DT* which, compared to the DNP of *HD*, presents specific additional difficulties [13]. Still, the DNP of *HD* itself was investigated in the past with only moderate success [14]. Therefore, although quite possible in principle, the polarization of *DT* fuel will require huge technological developments. Figure 3 shows the standard scheme of DNP polarization of *HD* or *DT*: the high static polarization of electrons is transferred to *H* or *T* nuclei by RF transitions (see [12] for more detail). For efficient DNP, long relaxation times T_1^H and T_1^D for the nuclei and short relaxation times T_1^e for the electrons are required. This is normally the case for distilled *HD* [5]. Therefore, Solem's experiment should be repeated in order to define a protocol for optimum DNP polarization of *HD* molecules that could possibly be applied to *DT* molecules which have the same magnetic and molecular configurations as *HD*.

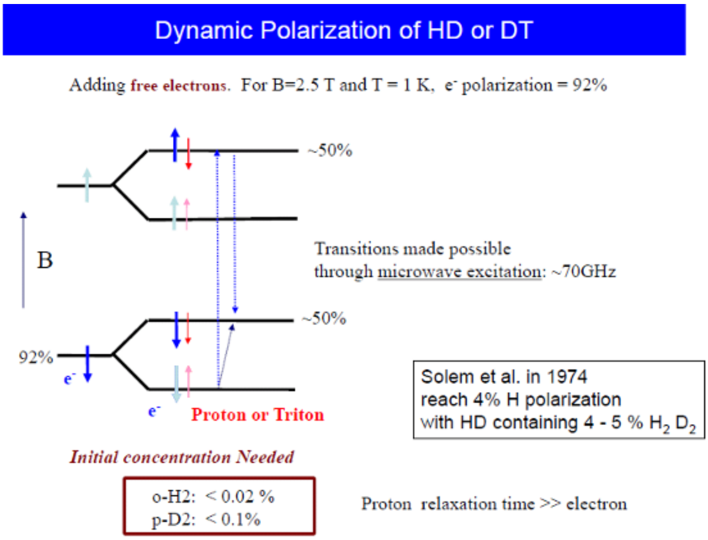


Fig. 3. Scheme showing the DNP polarization of Protons or Tritons.

The moderate success of Solem should not be discouraging. He has used commercial *HD* containing several percents of H_2 and D_2, which are trapped as *ortho*-H_2 (o-H_2) or *para*-D_2 (p-D_2) long living metastable states in the solid *HD*. Those magnetically actives species reduce the nuclear T_1 relaxation times and limit the DNP process. Highly distilled *HD* or *DT*, with impurities contaminations less than 10^{-4} should be used [5]. It has been pointed out that the energetic electrons due to the radioactivity of Tritium would dissociate *DT* molecules allowing the *D* and *T* ions to recombine in D_2 and T_2 poisoning quickly any purified *DT* gas [13]. However, the equilibrium configurations of those Hydrogen isotopes at low temperature are o-D_2 and p-T_2 which do not allow thermal connection between the lattice and the spin reservoir and have therefore little impact on the T_1 spin-lattice relaxation times. As a benefit, the huge abundance of free electrons in *DT* should be a big help for the DNP process. Another difficulty is that the e-DNP (DNP from electrons) of *D* nuclei gives rise to low *D* polarizations of the order of 40%, while the polarization of *H* nuclei (protons) can approach 100 %. Therefore, the n-DNP (DNP from nucleons) should be used to increase the *D* polarization. This process called “Adiabatic Fast Passage” is used to increase the *D* polarization in polarized *HD* targets by transferring the *H* polarization to *D* [15]. The *H* polarization is lost, but can be regenerated by e-DNP and the whole process repeated several times to reach high *H* and *D* polarizations [16]. In US, there is a project to inject 55% polarized *D* (from *HD* molecules) and polarized ^3He in the DIII-D Tokamak of San Diego, in order to see a 15% increase of the emitted protons by the fusion reaction: $D + {}^3He \rightarrow {}^4He + p + 18.35\ MeV$ due to the fuel polarization [17].

The relatively high *D* polarization of 55% would be obtained by a single n-DNP process at the expense of the *H* polarization, after static polarization of the solid *HD* [18]. Finally, one should note that solid polarized targets can be injected in MCF reactors, as proposed in [17].

4 Conclusion

A considerable effort is under way to produce energy using controlled fusion either by MCF or ICF. Polarized fusion fuel is of great interest, both to increase the fuel reactivity and to control the direction in which reaction products are emitted. The question to know if the polarization will persist in a fusion process can be answered using existing experimental equipment, and neutron detection. The corresponding investigation is underway at ILE (Osaka). The ongoing measurements at Gatchina for the double polarized *DD* fusion at low energy will provide the necessary experimental data to analyze the Osaka results. Finally, the polarization of the *DT* fuel is a huge problem, but the impact of the polarization on fusion is so important that a revival of the field is absolutely needed. The successes with the static polarization of *HD* allow big hopes for the DNP of *HD* and *DT*. The production of high intensity polarized molecular beams is another way to pursue.

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