Investigation of the Ignition Conditions of Polarized DT fuel for Inertial Confinement Fusion

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In Direct Drive Inertial Confinement Fusion (ICF) a spherical capsule containing the Deuterium-Tritium (DT) thermonuclear fusion fuel is irradiated by several laser beams. The laser energy deposition generates an expansion of the low-density corona and induces the implosion of the inner payload. The laser power profile is designed to produce a series of shock waves properly timed to generate a central core of plasma at high-temperature and relatively low-density. The ignition of the DT nuclear fusion reactions takes place in this plasma, usually called the ignition hot-spot, and under given conditions a fusion burn wave propagates through a fraction of the fuel allowing for high energy gain. Recently, an alternative to this central ignition scheme [1] has been proposed, the shock ignition (SI) scheme [2]. In this latter scheme it is supposed that an additional high power pulse is added at the end of the compression phase providing an inward shock that should supply the necessary confinement and compression to initialize the DT nuclear fusion reaction. The advantage of the SI is a relaxation of the laser energy deposition uniformity requirements with respect to the central ignition scheme. In all these schemes the ignition condition depends essentially on the nuclear fusion cross section of the fuel nuclei. Indeed, the fuel envisaged to be burned in both ICF as well as in Magnetic Confinement Fusion is DT because it provides the highest cross section at relatively low temperature (10-100 keV).

It is well known that the nuclear fusion cross-section depends on the spins of the interacting nuclei [3]. In the case of the Deuterium-Tritium the products of the fusion reaction are a neutron and an alpha particle with associated Q-value of 17.6 MeV. The intermediate state of this reaction is the compound nucleus ^{5}He characterized by a spin 3/2. Because the Deuterium has a spin 1 and the Tritium spin 1/2, the statistical weight associated to formation of the ^{5}He is only 2/3. The fusion cross section could be approximated by

$\sigma = (a + 2 b / 3 + c / 3) \sigma'$, where σ' is the full cross section associated to the ^{5}He (J = 3/2) state. The parameters a, b and c depend of the spin polarizations of the D and T nuclei: $a = d_+ t_+ + d_- t_-$, $b = d_0$, $c = d_+ t_- + d_- t_+$, where d_+, d_0 and d_- are the probabilities associated with the 3 possible orientations of the D spin and t_+, t_- those associated with the Tritium spin. Thus, for an unpolarized DT fuel we have $d_+ = d_0 = d_- = 1/3$, $t_+ = t_- = 1/2$, giving the unpolarized cross-section $\sigma_0 = 2 \sigma'/3$, while for a fully polarized fuel $d_+ = t_+ = 1$, $d_0 = d_- = t_- = 0$, giving $\sigma = \sigma'$. Thus, the cross-section increases by a factor $\delta = \sigma / \sigma_0 = 1.5$ if the two nuclei are polarized along the same direction.

In the context of the ICF scenario the direct consequence of the increased nuclear cross section is a higher energy gain $G = E_{tn} / E$, where E is the driver energy and $E_{tn} = q_{DT}\, m_{DT}\, \phi$ is the output thermonuclear fusion energy which increases with the DT mass, m_{DT}, and is proportional to the burn fraction ϕ, where the fusion energy yield per unit mass is q_{DT}. The burn fraction can be estimated by $\phi = \rho R / (\rho R + H_B)$, where ρR is the fuel areal density and H_B is the burn parameter which is usually approximated as 7 g/cm^2. The burn parameter is inversely proportional to the reactivity $<\sigma v>$ [4], H_B [g/cm^2] $\approx 9\, T^{1/2} / <\sigma v>$, thus its minimum reduces from 7 to about 5 g/cm^2 when the cross section increases by 50%. The reduction of the burn parameter implies a larger fraction of mass burned and consequently a larger fusion energy E_{tn}. Moreover, the increased cross section reduces the ignition threshold which allows for lower driver energy E which in turn increases the gain G.

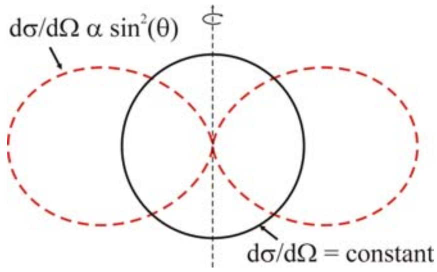

Fig. 1. Angular distribution of the neutron and alpha particle for a unpolarized DT fuel (isotropic) and for fully polarized plasma [$\sin(\theta)^2$].

The spin polarization of the incoming nuclei not only modifies the cross section but also change the angular distribution of the produced particles. It has been found that in the case of unpolarized DT plasma the angular distribution of the products, neutron and alpha in our case, is isotropic. On the other hand, for fully polarized fuel they are emitted following a $\sin(\theta)^2$ angular distribution [3] (see Fig.1). In order to evaluate the possible consequences for the ignition energy a set of 2D simulation have been performed with the DUED code [5]. A 3D

Monte-Carlo package has been developed in order to take into account the alpha energy deposition. A hot-spot spherical core with areal density of 0.3 g/cm^2 confined by a dense and cold shell has been considered. We varied the core temperature to find the threshold between the non-igniting and igniting case. The parameter δ was set to 1 and we have been considered the two cases: isotropic and sin(θ)^2 angular distribution. The results indicate that the isotropic and sin(θ)^2 distribution provide almost the same thermonuclear output power as a function of time, thus indicating that the angular distribution does not modify the ignition energy.

We have studied the change of the ignition conditions due to the increased cross-section as a function of the polarization factor δ using the 1D MULTI code [6] for a direct drive capsule implosion.

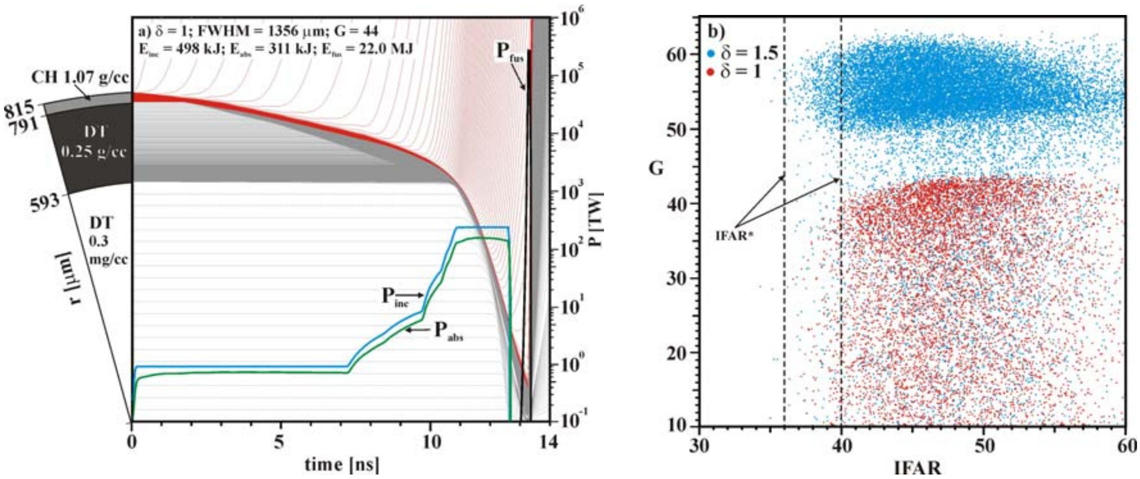

Fig. 2. a) Direct Drive capsule and Lagrangian radial profiles provided by the Multi-1D code. Laser incident power, absorbed power and fusion output power are also shown. b) Energy gain G as a function of the in flight aspect ratio IFAR.

A Direct Drive capsule [7] (see Fig. 2a) characterized by an external radius of 815 μm, a 24 μm thick plastic CH ($\rho_{CH} = 1.07$ g/cm^3) absorber and a total DT mass of 300 μg ($\rho_{DT} = 0.25$ g/cm^3) has been considered. A series of thousands of numerical simulations have been performed with the Multi-1D code, the incident laser power profile is defined by a 7 point profile [t_i, P_i, $i \in 1 = 7$] and in each simulation these points were varied randomly inside a predefined range. The laser focal spot is Gaussian with a full width at half maximum (FWHM) of 1356 μm and a 3D ray-tracing package with inverse bremsstrahlung energy laser deposition is used.

In order to estimate the influence of the increasing of the cross section in the robustness of the capsule implosion the in-flight-aspect-ratio, IFAR = Max[0.5 $(r_{out} + r_{in}) / (r_{out} - r_{in})$] has been evaluated in each simulation. The inner (r_{in}) and outer (r_{out}) radius of the compressed shell used to evaluated the IFAR have been set to the positions where the density is $\rho = \rho_{max} / 10$. In the Fig. 2b are shown by red and blue points the gain as a function of the IFAR for the cases of unpolarized and fully polarized fuel, respectively. The minimum IFAR* that realizes a gain $G > 0.9\ G_{max}$ are indicate by vertical dashed lines in Fig. 2b. It is found that this minimum in flight aspect ratio could be reduced by about 10% for the enhanced cross-section ($\delta = 1.5$) leading to more robust implosion with less sensitivity to hydrodynamic instabilities.

δ	G_{max}	P* [TW]	E_{abs}* [kJ]
1.0	44.2	215	290
1.1	48.3	200	285
1.2	52.1	192	275
1.3	56.1	185	265
1.4	59.5	175	255
1.5	63.8	170	248

Table I. Maximum gain G_{max}, laser peak power P* and absorbed energy E_{abs}* evaluated for different values of the polarization factor δ.

A large number of 1D numerical simulations have been performed varying the polarization factor from $\delta = 1$ (unpolarized fuel) to $\delta = 1.5$ (fully polarized fuel). For each value of δ the maximum gain G_{max}, as well as the minimums of the laser peak power (P*) and of the absorbed energy E_{abs}* that realize a gain $G > 0.9\ G_{max}$ have been calculated. The results are summarized in Table I. In summary, it have been found that the maximum achievable energy gain increases as $G_{max} \propto \delta^{0.9}$ [8], while the required laser power P* scales as $\delta^{-0.6}$ and the absorbed laser energy decreases as $E_{abs}^* \propto \delta^{-0.4}$.

References

[1] J. H. Nuckolls, L. Wood, A. Thiessen and G. B. Zimmermann, Nature 239, 129 (1972)
[2] R. Betti, C. D. Zhou, K. S. Anderson, L. J. Perkins, W. Theobald A. A. Solodov, Phys. Rev. Lett. 98, 155001 (2007)
[3] R. M. Kulsrud, H. P. Furth, E. J. Valeo and M. Goldhaber, Phys. Rev. Lett. 49, 1248 (1982)
[4] S. Atzeni and J. Meyer-ter-Vehn, The Physics of Inertial Fusion (Oxford University Press, 2004)
[5] S. Atzeni, Comput. Phys. Commun. 43, 107 (1986)
[6] R. Ramis, R. Schmalz and J. Meyer-ter-Vehn, Comput. Phys. Commun. 49, 475 (1988)
[7] V. Brandon, B. Canaud, M. Primout, S. Laffite and M. Temporal, Random walk optimization of laser pulse shape for direct-drive target design for Inertial Confinement Fusion EPJ-D submitted (2012)
[8] M. D. Rosen, J. D. Lindl and A. R. Thiessen, Laser Program Annual Report UCRL-50021-83 Lawrence Livermore National Laboratory, Lawrence pp. 3-5–3-9 (1983)