Variance of DD-neutron yield in laser fusion experiments

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Abstract — This contribution deals with experimental observations of the yield of DD fusion in deuterated plastic targets irradiated by 300-ps 3-TW laser system PALS. To perform the analysis of variance for neutron yield values, Y_n, in the range of 10^5 - 10^9 observed in a relatively narrow range of laser energy E from 500 - 700 J, the observed yield values were included in a neutron-yield – laser-energy (Y_n–E) diagram showing general trends in the energy yield scaling Y_n (E). This dependence is characterized by a power law, $Y_n = Q\ E^{1.65}$, where Q is the parameter reflecting possible dependence on the pulse duration, laser intensity, laser contrast ratio, focal geometry, target structure, etc. [1]. The analysis we present shows that, despite shot-to-shot fluctuations, the variance of Q values from 14 – 5.2×10^4 for the narrow range of laser energy obtained in PALS experiments can be elucidated by the influence of some nonlinear processes affecting ion acceleration.

The law of laser energy scaling for the yield of neutrons, Y_N, generated by intense lasers is derived from a series of experiments performed on various laser systems [1]. In general, this law is related to the energy and number of fusion ions. Y_N depends on the number densities of reacting nuclei and the fusion averaged reactivity, $<\sigma v>$, where $\sigma(v)$ is the cross section defined as the number of reactions per target nucleus per unit time when a unit flux of projectile particles hits the target [2,3].

It is generally known that it is not possible to directly obtain experimental information on the flow of ionized species accelerated forward into the target volume, and to determine the number densities of reacting nuclei. Only in the case, for example, of deuterons is it possible to estimate retrospectively the number of fusion deuterons from the measured neutron yield [4, 5]. The properties of particles accelerated in the target volume are generally assessed on the basis of the measured characteristics of ions and electrons accelerated into the vacuum, from both the front and rear surfaces of the target.

Laser intensity scaling for the maximum proton energy also does not show a simple dependence, as a number of different nonlinear processes are involved in plasma production [5]. This was demonstrated by the dependence of maximum proton energy on the laser intensity, which was expressed in form:

$$E_p \approx 4.85 \times 10^{-4} \frac{d[\mu\mathrm{m}]}{\lambda[\mu\mathrm{m}]} \sqrt{\chi\, I\lambda^2\ [\mathrm{Wcm^{-2}\mu m^2}]}\ [\mathrm{MeV}], \tag{2}$$

where χ is a difficult-to-predict coupling parameter expressing the amount of laser intensity transferred to E_p, d is the diameter of the laser focal spot, λ is the laser wavelength, I is the laser intensity. The χ value can be determined by fitting of (2) to experimentally observed dependence of E_p on $I\lambda^2$. For example, a set of experiments with 300 fs-1 ps lasers gives χ=1, PLAS experiments (τ_{FWHM} = 350 ps, λ=1.315 μm) give $\chi \approx 0.6$ [5].

Although the E_p value is an important indicator of the efficiency of laser fusion, the main parameter affecting Y_N is the average fusion reactivity, which depends on the velocity distribution function $f(v)$. As demonstrated by a number of experiments [6], $f(v)$ is the shifted velocity distribution function, where the centre-of-mass velocity, u_{com}, is determined by the acceleration voltage, U, resulting from the separation of charges:

$$u_{com} = \sqrt{2eq(U + U_0)/m_i}, \tag{3}$$

where U_0 is the voltage representing the initial ion velocity in the direction of observation. If we assume that the motion of ions is characterized by a Maxwell-Boltzmann shifted distribution function, then the most probable velocity v_{mp} of accelerated ions is:

$$v_{mp} = \frac{1}{2}\left(u_{com} + \sqrt{u_{com}^2 + 4v_T^2}\right). \tag{4}$$

The PALS experiments found $T_i \approx 1.1$ keV and $U \approx 800$ keV for $I \approx 6\times10^{15}$ W/cm^2 [6]. This indicates not only a small contribution of the most probable thermal velocity, v_T, but a dominant role for u_{com} in $<\sigma v>$. The dependence of Y_N on the laser energy could therefore be elucidated in the context of the beam-controlled fusion by taking into account the u_{com}, which is easily determined when ions are emitted by the front target's surface. The value of u_{com} depends significantly on nonlinear laser-plasma interaction.

Three different DD-fusion experiments with the PALS laser were performed, as Fig. 1 shows.

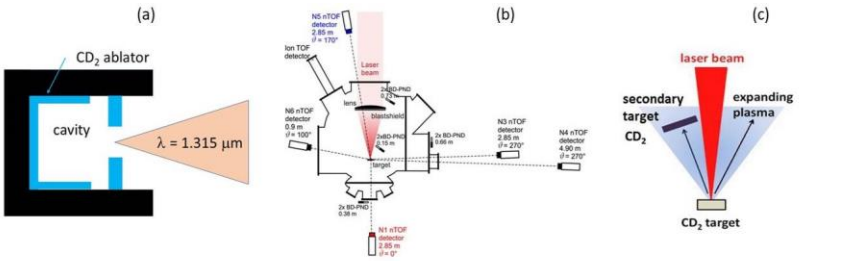

Fig. 1 Experimental setup schemes:
(a) PALS RAS-target [7,8],
(b) thick foil target [4,6],
(c) pitcher-catcher scheme [4].

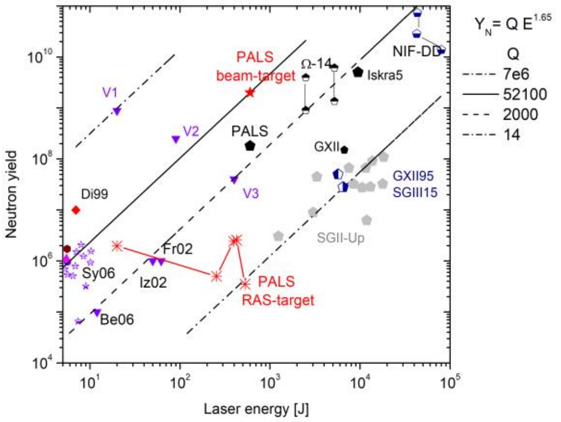

Fig. 2 Selected DD-fusion experiments associated with laser energy dependence of fusion neutron yields obeying the power law $Y_N = Q{\cdot}E^{1.65}$, where Q is the parameter reflecting possible dependence on the pulse duration, laser intensity, laser contrast ratio, focal geometry, target structure, etc. Sorting the values of the neutron yields obtained in various experiments shows that the power law $Y_N = Q\,E^{1.65}$ is suitable to determine lines in the Y–E diagram each of them [1]. The Y_N values labelled PALS Ras-target were obtained in experiments with specific cavity targets by applying a "Reversed Acceleration Scheme" (RAS) [7,8].

In the "PALS RAS-target" experiment, a laser pulse heated the interior of a cavity as it passed through a hole in the front of the cavity, as shown in Fig. 1a [8]. The walls of the cavity were made of CD_2 foils of 10-15 µm in thickness. The plasma produced on the bottom wall and sides of the cavity expanded into the cavity and hit the top input foil. The range of achieved neutron yield was $\approx 0.3\text{-}4.6\times10^6$, as the points labelled "PALS-RAS-target" show in Fig. 2. The dominant part of the DD fusion reactions occurred inside the cavity and in its frontal side. The results of this experiment are generally consistent with the results of numerical modelling that takes into account model of elastic–plastic solids, Johnson–Cook's model with Mises yield criterion, equation of state (EOS), modelling of the propagation of shock wave fronts, thermal conductivity, ionization and recombination of a medium, radiation losses, inverse bremsstrahlung, and the multiplayer structure of irradiated targets. There is no nonlinear laser-plasma interaction taken into account. Three points at the laser energy of 400-500 J lie at a straight line $Y_N = 14\,E^{1.65}$, which links this data with data obtained on experiments performed at the ShenGuang-II Upgrade (SGII-Up) [9], SG-III prototype (SGIII15) [10], and GEKKO XII (GXII95) [11] laser facilities, where the non-thermal contribution to neutron production may not have been very beneficial. But, Fig. 2 shows that a nonlinear interaction occurred when a lower laser energy of 20 J was applied in the RAS experiment.

However, when a thicker target of sub-millimetre thickness is used (see Fig. 1b), the ion energy may increase due to the occurrence of nonlinear laser-target interaction (e.g., self-focusing). In this case, the neutron yield increased by a factor of about 350, as data labelled PALS in Fig. 2 show. When deuterons accelerated in the backward direction with respect to the laser beam were cached with a large area CD_2 catcher (see Fig. 1c), then the beam-target fusion achieved a yield of 2×10^9, which is 52,100 times higher than the RAS-target yield, see label PALS-beam-target in Fig. 2. Thus, Y_N is apparently very strongly influenced by nonlinear phenomena occurring during laser plasma production.

In conclusion, the sorting of Y_N shows up to 4 orders of magnitude difference in yields found in different PALS experiments, which can be characterized by the value of the parameter Q for a given laser energy. Due to the easy feasibility and the large number of DD fusion experiments performed, the general Y_N-E diagram gives the possibility to analyse in a broader context processes that are dominant in electron and ionic acceleration and that significantly affect the yield of neutrons.

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