Analysis of the symmetry of the direct-drive target implosion under laser pulse of a megajoule scale

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Abstract. The class of direct-drive targets for the laser pulse of a megajoule scale is considered in the work. A distinctive feature of the design of these targets is a relatively low aspect ratio (outer DT-shell radius/shell thickness, \(A \sim 10\)) to provide greater compression stability. The irradiation of the target surface is carried out by the shaped laser pulse on \(2\alpha\) of Nd-laser. The influence of laser energy absorption inhomogeneity on the parameters of compression and burning of thermonuclear fuel on the final stage of implosion is studied in the work based on 1D and 2D numerical calculations. The results of 2D modeling show that in the case of target’s offset from the point of beams crossing significantly greater reduction in the neutron yield is observed than in the case when only irregularities caused by the geometry of irradiation by the finite number of beams are taken into account.

1. Introduction

It is considered that the main obstacle to the achievement of high gain thermonuclear burning is a possible growth of various types of perturbations [1]. This is due to the fact that the precise compliance with the conditions for the irradiation symmetry, as well as capsule manufacturing without deviations from the nominal values of the parameters is difficult. In these conditions the possible approach is to look for such targets designs, which would provide maximum compression stability, accompanied by efficient DT-fuel burning. The class of such low aspect targets was proposed in [2–4]. In this work the efficiency of these targets for the different variants of inhomogeneity of the absorption of incident laser flux is evaluated. The cases which correspond to target irradiation by specific multi-beam laser system and target offset from chamber center will be considered. It should be noted that problem of target positioning i.e. placing it at the desired point is especially relevant for the prospects of the future fusion reactors where the capsules should be put in the core with a frequency of 1-10 Hz [5].

2. Target design and scheme of irradiation

The considered target is a system of nested shells and comprises an inner cavity with a radius of 1414 \(\mu\)m filled by DT-gas of density \(10^{-3}\) g/cc (the pressure is 0.2–0.4 atm at cryogenic temperatures). Then, the target consists of a layer of frozen DT-ice of 149 \(\mu\)m thick and a density of 0.253 g/cc. Finally, the target outside the DT-shell is surrounded by a polystyrene...
(C₈H₈)n of 34 µm thick and a density of 1.05 g/cc. Schematic representation of the target is shown on Fig. 1a. Irradiation of the target is carried out by 192 beams, united into clusters by 4 beams, which are located on the sides of the cube, as shown on Fig. 1b, the optical axes intersect at the center of the target. The total energy of the laser pulse is 2 MJ, a shape of the pulse is shown on Fig. 1c, the duration is 10 ns, the working wavelength is the second harmonic of the Nd-laser (λ_L = 0.53 µm). Under the conditions outlined above, total absorbed laser energy about 1.5 MJ and without taking into account angular dependency of the absorbed laser flux thermonuclear gain G = 20.8 and maximal areal density in DT-fuel (ρR)_{max} = 0.92 g/cm² [3] was obtained in 1D calculation.

3. Modeling of the inhomogeneity of laser energy absorption in the target
An assessment of inhomogeneity of laser energy absorption was done by using RAPID [6] and SEND [3,7] numerical codes. The first one solves equations of one-dimensional two-temperature hydrodynamics together with Maxwell’s equations to determine a part of incident laser energy absorbed in the target, the second one is responsible for the calculation of target heating uniformity by multi-beam laser system. On Fig. 2 the angular distributions of the total absorbed laser energy for the two cases described in the introduction are shown. It is clear that they differ significantly. Firstly, the uniformity of the absorption of laser energy η_E = E^min_t / E^max_t takes

![Figure 1](image1.png)

**Figure 1:** (a) Target dimensions, (b) scheme of target irradiation by multi-beam laser system, (c) shaped incident laser pulse.

![Figure 2](image2.png)

**Figure 2:** The angular distributions of the total absorbed laser energy: (a) inhomogeneity due to target irradiation geometry, (b) inhomogeneity due to target offset along X-direction on 80 µm.
value 0.9663 in the first case and 0.8714 in the second one. Secondly, the dominant modes $l_\phi$ of induced perturbations are $8 \div 10$ and 1, respectively. It should be noted that when the target is displaced from the chamber center on $80 \, \mu m$ the efficiency of laser energy absorption slightly decreases in comparison with the standard conditions of target irradiation while the rate of uniformity drops significantly. This is due to the fact that on the opposite sides of the target located on the axis of offset, the values of absorbed energy change in opposite directions, creating a large difference between the target heating.

4. Target implosion efficiency

Investigations of target implosion efficiency were carried out using numerical programs DIANA [8] and NUTCY [9, 10] in the 1D and 2D geometry, respectively. One-dimensional calculations can be represented as points on the distributions shown on Fig. 2, two-dimensional – in the form of straight line segments. Modeling of the compression and burning of thermonuclear fuel with the help of DIANA program, i.e. spherically symmetric formulation, for different pairs of angles ($\theta, \phi$) led to the ranges of variation of the thermonuclear gain $G$ from 8 to 14 for standard irradiation conditions and from 4 to 16 in the case of target offset by $80 \, \mu m$ along one of the axes if the center of coordinate system is placed in the center of the chamber. Omitting details, we only note that in the case of the shifted target variation of obtained values is significantly higher than without considering such an offset.

The next step of the study of the target performance is investigation of the efficiency of target compression and burning in the 2D geometry. The initial state for 2D calculations is formed from a set of one-dimensional profiles, taken at time $t = 10 \, ns$, which corresponds to the end of the laser pulse. Modeling for different segments on the maps of absorbed energy leads to the following ranges of variations of $G$: from 2.82 to 5.85 under standard target irradiation conditions and from 0.07 to 5.4 in the case of target offset on $80 \, \mu m$ along the X-direction. Thus, in the first case, a two-fold reduction of thermonuclear gain is observed, and in the second case worsening of the burning takes place until its termination. On Fig. 3 the distributions of density and temperature at the time of peak compression for standard irradiation conditions and for the case of shifted target with different resulting values of the gain which correspond to different line segments on Fig. 2 are shown.

Analysis of 2D distribution shows that in the case of target offset from the point of beam crossing the temperature of central area is lower than at standard irradiation conditions due to the fact that because of presence of significant low mode perturbations the transform of kinetic energy of accelerated DT-shell into internal energy doesn’t occur effectively. This leads to a reduction in the rate of main fusion reaction. This circumstance, together with a reduction in the maximal value of areal density in the DT-fuel is the reason for decreasing DT burnout which directly affects the value of thermonuclear gain degrading it.

5. Conclusion

The influence of inhomogeneities of laser radiation absorption associated with both the geometry of the irradiation by the laser system and the offset of the target from the point of beams focusing on the implosion efficiency was investigated. It is shown that the geometry of the target irradiation has no significant effect on the values of the thermonuclear gain compared with a spherically symmetric case. Target offset from the chamber center on the contrary can lead to situations with not burning DT-fuel even when the shift amount is not more than 5% of the initial radius of the target. Thus low mode perturbations have much greater impact on the thermonuclear yield than ones associated with the geometry of the irradiation by the laser system.
Figure 3: Distributions of density (a), (b), (c) and temperature (d), (e), (f). The first column refers to standard irradiation conditions at time moment $t = 11.1$ ns with resulting gain 2.82 ($\theta = 0^\circ - 90^\circ, \varphi = 46^\circ$), the second and third columns – to the case of shifted target at time moment $t = 11.14$ ns with resulting gain 0.07 ($\theta = 90^\circ, \varphi = 0^\circ - 180^\circ$), and at time $t = 11.24$ ns with resulting gain 5.4 ($\theta = 0^\circ - 180^\circ, \varphi = 0^\circ$) respectively.

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