Comparison and analysis of the results of direct-driven targets implosion

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Abstract. The article presents calculation results, which were received for the implosion of the typical cryogenic thermonuclear direct-drive targets that are intended for use at the OMEGA facility, NIF and Russian laser facility. The compression and burning characteristics, which were obtained using various numerical codes of different scientific groups, are compared. The data indicate good agreement between the numerical results. Various sources of target irradiation inhomogeneity and their influence on the implosion parameters are considered. The nominal scales of these disturbances for various facilities are close to each other. The main negative effect on the efficiency of compression and burning is due to the accidental offset of the target from the center of the chamber.

1. Introduction

In recent years, considerable efforts have been made to resolve the issue that causes a discrepancy between numerical and experimental results in solving problems of laser thermonuclear fusion. This is primarily due to the failure of the National Ignition Campaign (NIC) and subsequent campaigns to achieve ignition at the National Ignition Facility (NIF). Numerous attempts by various scientific groups to explain the results have not yet been successful.

One area of research along this path is to compare the results of numerical calculations obtained using various numerical codes, analyze the differences that arise and determine possible causes for the discrepancies. This allows us to evaluate the influence of various physical processes and mathematical models, which are used for their description, on the implosion of thermonuclear targets in general. The existence and development of this trend is evidenced by the publications in recent years, which are devoted to the study of various aspects of laser thermonuclear fusion in the context of a particular laser facility.

In this paper, the authors provide and compare the modeling results of implosion of the direct-drive targets in one- and multi-dimensional formulations [intended for the OMEGA facility, NIF for the polar direct-drive (PDD) and Russian laser facility], which were obtained by the corresponding scientific groups using various numerical codes. The aim of this comparison is to determine the degree of influence of various approaches on the physical and mathematical description of the implosion process on the dynamics of compression and burning of thermonuclear fuel. In addition, possible
sources of irradiation of target surface inhomogeneities and their effect on the ignition of thermonuclear fuel are analyzed. It is known that even under indirect action of the laser radiation, low-mode perturbations appear on the target, which substantially reduce the total neutron yield [1].

The given data allow one to speak about good agreement between the values of compression and burning characteristics of the capsules in various numerical calculations, as well as the similarity of the approaches used for the investigation of laser fusion problems.

2. Modeling results. Comparison and analysis

In this section, we consider typical (cryogenic) direct-drive targets and the laser pulses that are used in some operating and planned laser facilities. The results of numerical calculations that are obtained using various programs are presented.

2.1. OMEGA facility

We should start with the OMEGA facility, which implements the direct-drive approach and operates on a regular basis at the Laboratory for Laser Energetics (LLE) at the University of Rochester (USA). The total laser energy is \( \sim 26 \text{ kJ} \), the number of beams is 60, the operating wavelength is \( \lambda_L = 0.351 \text{ \mu m} \) (Nd:Glass, 3rd harmonic of neodymium laser \( \omega_3 \)). To compare the numerical results, we use the target and laser pulse from [2] for which there are experimental data. Table 1 lists the values of some parameters that are available for comparison from [2].

|               | LILAC | ASHER | DIANA | SND  | Exp. |
|---------------|-------|-------|-------|------|------|
| \( t_c \), ns | 2.72  | 2.70  | 2.67  | 2.57 | 2.68 | 2.72 |
| \( f_{abs} \) | 0.542 | 0.536 | 0.540 | 0.480| 0.542| 0.542|
| \( N_n \times 10^{14} \) | 0.662 | 0.735 | 1.10  | 2.27 | 2.88 | 1.98 | 0.454 |

These data indicate good agreement between the results of various calculations, which is also confirmed by comparing the density, pressure, and temperature profiles at the time of maximum compression (see figure 1). A noticeable discrepancy in the neutron yield is due to the exponential (explosive) nature of the development of thermonuclear reactions in targets and the high sensitivity of the result to the parameters of the formed plasma.
The calculation using the SND code gives the target collapse time that is closer to LILAC and demonstrates a less stressful state of the matter compared with the DIANA calculation (see table 2 and figure 1), and, as a consequence, a smaller neutron yield.

**Table 2.** Values of the additional characteristics of the thermonuclear target implosion, which are intended for the OMEGA facility: $\eta_{\text{max}}$, hydrodynamic efficiency; $\rho R$, DT areal density; $\rho_{\text{max}}$, maximum DT density; $E_r$, self-radiation losses of the plasma; $E_{\text{TN}}$, total thermonuclear energy; $\alpha = p / p_F$, Fermi adiabat. The values $\eta_{\text{max}}$, $E_r$ and $E_{\text{TN}}$ are given for the moment of calculation completion, i.e., 5 ns. $\rho_{\text{max}}$, $\rho R$ – at the moment of maximum compression $t_c$.

|          | $\eta_{\text{max}}$, % | $\rho R$, g/cm² | $\rho_{\text{max}}$, g/cc | $E_r$, kJ | $E_{\text{TN}}$, kJ | $\alpha = p / p_F$ |
|----------|------------------------|-----------------|-----------------|---------|-----------------|-----------------|
| DIANA    | 10.4                   | 0.24            | 212.0           | 0.3     | 0.81            | 3.7             |
| SND      | 9.34                   | 0.17            | 151.0           | ~0      | 0.56            | 3.3             |

2.2. **NIF, Direct-drive targets**

The failure of achieving ignition using indirect irradiation schemes led to the development of an approach for the organization of direct target irradiation using the current configuration of NIF (Nd: Glass, $3\omega$, 192 laser beams) - PDD [6]. This idea has significant difficulties that are associated with the peculiarities of the location of laser ports, which were originally designed to work within the framework of indirect irradiation schemes. To achieve an acceptable homogeneity of irradiation and laser energy absorption, scientific groups resort to beam repointing, which varies the total beam energy and the shape of the focal spot depending on the proximity to the equatorial region of the target. In addition, for the redistribution of energy between beams, it is proposed to use different wavelengths for the beams that have different polar angles of the optical axes that are slightly different from the nominal one ($3\omega$) [7].

To compare the results of 1D calculations, we will use a relatively standard value of the integral fraction of laser absorption at 60%, not taking into account the specificity of PDD. Consider the characteristic cryogenic target used, for example, in [8], with the CH ablator, which can be obtained by scaling the targets that are used at the OMEGA facility to a larger amount of absorbed energy, and
also resembles the baseline target for the Russian laser facility, which will be discussed in the next section. The beam parameters and dependence of the laser pulse power are given in [8]. Table 3 shows the calculations results, which are obtained using various one-dimensional numerical codes.

Table 3. Characteristics of target compression and burning, which are considered in section 2.2; $G$ is the thermonuclear gain, $V_i$ is the implosion velocity, and $\Phi$ is the burnout.

|       | $G$, % | $V_i$, km/s | $\alpha = p/p_e$ | $\Phi$, % |
|-------|--------|-------------|------------------|----------|
| LILAC | 74.6   | 361         | 2.2              | 15.9     |
| DIANA | 99.2   | 390         | 1.8              | 20.9     |

It can be seen that the values of various compression and burning characteristics are similar, considering the initial formulation uncertainties. The variation of the absorption fraction without changing the pulse duration leads to the fact that the value $f_{abs}^{0.89}$ (0.89 without CBET, see [7]) provides the value of the gain factor of ~76 in the calculation of the DIANA program.

2.3. Russian laser facility

The total number of beams is 192, which are grouped into clusters of 4. The significant difference between the planned Russian laser facility and those considered in the previous sections is the operating wavelength of the laser radiation $\lambda = 0.527 \mu m$ (Nd:Glass, 2nd harmonic of the neodymium laser 2$\omega$). This circumstance leads to a decrease in the radiation conversion loss and, as a consequence, to a greater value of available energy that is incident on the target. In this case, the regime of laser interaction with the target material changes, and as a result, the radiation absorption decreases. Previous studies [9, 10] have shown that the transition from the 3rd to the 2nd harmonic makes the values of the coefficient comparable to those obtained using the 3rd harmonic radiation, namely, ~20. Thus, the baseline target has been chosen, the parameters of which are given in [9]. Another important peculiarity is that the absorption occurs at a density that is less than critical, which reduces the thermonuclear yield by approximately 2 times.

3. Inhomogeneities of target irradiation at various facilities

It is known that direct-drive targets are more susceptible to the influence of hydrodynamic instabilities. Shortwave perturbations are stabilized at the ablation stage [11], and of interest are the perturbations with moderate and low modes that can be induced by the irradiation inhomogeneity or inaccuracy of positioning of a target in a chamber. The scale of various sources of inhomogeneities and the degree of their influence on the target compression at various facilities will be discussed in this section.

3.1. Scales of irradiation inhomogeneities

Let us analyze the possible sources of target irradiation inhomogeneities at various facilities. Using the data on the configuration of a laser system and the target irradiation geometry (OMEGA [2], PDD on NIF [12, 13], the Russian laser facility [10, 14]), the surface radiance of the capsule was calculated. The corresponding normalized values of intensity distributions are given in figure 2.
Their harmonic analysis leads to the following values of the dominant modes \( l_d \): (a) \( l_d = 10 \) and (b) \( l_d = 6, 8 \). The value of the root-mean-square deviation of the intensity \( \sigma_0 \) from the mean value over the sphere, which is calculated from the distributions in figure 2, is given in table 4. It can be seen that irradiation geometry induces perturbations with moderate wavelengths and small amplitudes, which means that their influence on the compression symmetry will not be significant. Table 4 also consists of nominal values of the energy imbalance in the beams \( \sigma_E \), beam mispointing \( \sigma_m \), accident offset of the target from the target center \( \sigma_s \), and beam mistiming, \( \sigma_\tau \). To take into account the possible inhomogeneities in 2D and 3D formulations, the approach that is proposed in [15] is used in this paper, except that instead of the radiance distributions, the absorbed energy in a spherically symmetric corona is used [9].

Table 4. Comparison of the scales of inhomogeneities at various laser facilities. The values for NIF are obtained by scaling the values for OMEGA (\( \sim E_k^{1/3} \)). For some of them, the values from [16] are given in parentheses.

| Facility        | \( \sigma_0, \% \) | \( \sigma_E, \% \) | \( \sigma_m, \mu m \) | \( \sigma_\tau, ps \) | \( \sigma_s, \mu m \) |
|-----------------|---------------------|---------------------|------------------------|----------------------|----------------------|
| OMEGA [2]       | 0.22                | 10                  | 10                     | 5                    | 10                   |
| NIF             | –                   | 10(5)               | 40                     | 20                   | 40(50)               |
| Russian laser facility | 0.72                | 8                   | 160                    | \( \leq 100 \)        | \( \leq 80 \)        |

By comparing the relative values of inhomogeneities, it can be concluded that the nominal values given here are similar to each other, which ultimately should lead to similar characteristics of implosion when investigating the influence of various factors on the efficiency of the process.

3.2. **Influence of irradiation inhomogeneity on the compression and burning characteristics**

As was demonstrated in [2], based on the three-dimensional calculations using the ASTER code, the complex accounting of possible irradiation inhomogeneities within the nominal expected values does not make it possible to achieve a convergence of the experimental and numerical results. A consecutive individual increase in the scale of a particular source of disturbances leads to the fact that a target offset has a defining negative influence on the neutron yield, namely, a twofold increase in the displacement compared with the nominal one leads to the experimental values.
Earlier, the same conclusion was made in [17] based on a series of one- and two-dimensional calculations. For more details, see [18]. The accidental beam mispointing, as shown by numerical calculations, has the second largest effect on the efficiency of compression and burning, which is expected, because the agreed mispointing of the beams is, in fact, the target offset.

Table 5. Values of the gain (min/max) in the series of one- and two-dimensional calculations, which take into account various sources of irradiation inhomogeneities of the baseline target surface, for the Russian laser facility.

| Nos. | \( \sigma_E \), % | \( \sigma_m \), \( \mu m \) | \( \sigma_s \), \( \mu m \) | \( G_{1D} \) | \( G_{2D} \) |
|------|------------------|------------------|------------------|-------------|-------------|
| 1    | –                | –                | –                | 12.54       | –           |
| 2    | –                | –                | –                | 8.6/13.5    | 2.82/5.85   |
| 3    | 8                | –                | –                | 8.1/13.0    | 4.98/5.74   |
| 4    | –                | 160              | –                | 6.0/13.8    | 0.1/6.5     |
| 5    | –                | 80               | 80               | 3.7/16.5    | 0.07/5.4    |

The thermonuclear gain, which is shown in table 5, illustrates the influence of certain types of irradiation inhomogeneities of a baseline target at the Russian laser facility. The first line corresponds to a spherically symmetric formulation of the problem. The second one takes into account the geometry of irradiation. The other lines take into account the geometry of irradiation and some individual sources of inhomogeneity.

4. Conclusions

The paper compares the results of numerical calculations of implosion of various thermonuclear targets in a spherically symmetric formulation. The direct impact of laser radiation on the target is a common consideration for all simulations. The comparison of corresponding numerical results for these problems obtained by different scientific groups using various numerical codes demonstrates their good agreement between themselves.

The scales of various sources of irradiation inhomogeneity, namely, the imbalance of energy in the beams, the mispointing of laser beams and errors in the positioning of the capsule inside the chamber, as well as their effect on the compression efficiency and the possibility of fusion of thermonuclear targets are analyzed. Regarding the baseline target at the Russian laser facility, it was shown that the accidental offset of the target from the center of the chamber has the most negative effect. This conclusion is consistent with the results of the analysis of the influence of inhomogeneities on the OMEGA targets, which is based on the ASTER three-dimensional code.

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