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Computational optimization of indirect-driven targets for ignition on the Iskra-6 laser facility*

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Abstract

In Russia, the Iskra-6 laser facility with pulse energy of up to 300 kJ and nanosecond pulse duration was being planned (Kirillov *et al*., 2000). The possibility of thermonuclear ignition with this laser energy was a goal of the theoretical investigation at RFNC-VNIITF. Results of one-dimensional (1D) and two-dimensional (2D) modeling of indirect-driven targets for ignition on the Iskra-6 laser facility are presented. Sensitivity of cryogenic single-shell and non-cryogenic double-shell targets to radiation flux non-uniformity and shells roughness are studied.

Keywords: Indirect-drive targets; Thermonuclear ignition

1. INTRODUCTION

The NIF and LMJ high-power laser facilities with pulse energy as high as 2 MJ are being created in the USA and France (Campbell & Hogan, 2000; Andre, 2000). It was shown that the thermonuclear ignition of cryogenic direct- and indirect-driven targets can be achieved on these facilities (Lindl, 1995; Canaud *et al*., 2004). The implosion of spherical indirect-drive targets will be provided by blackbody X radiation with a temperature of up to 350 eV, which is generated when the laser radiation is focused into a cylindrical gold cavity.

In Russia, the Iskra-6 laser facility based on a solid-state laser with pulse energy of up to 300 kJ and nanosecond pulse duration is planned to be created at the Russian Federal Nuclear Center All-Russia Research Institute of Experimental Physics (Kirillov *et al*., 2000; Galakhov *et al*., 1999).

The Hohlraum-type pellet proposed at the Russian Federal Nuclear Center All-Russia Research Institute of Technical Physics (RFNC VNIITF) consists of a spherical gold shell with eight holes through which laser radiation is introduced, eight screens, and a multilayer spherical target at the center (Avrorin *et al*., 1997). Three-dimensional (3D) calculations of the radiation propagation inside the Hohlraum, as well as 1D simulations of the implosion and burning of the multilayer spherical target, were performed. These calculations and estimates indicate that the conditions necessary for a thermonuclear burst with a neutron yield of 10^{16} per pulse at laser energy lower than 1 MJ (Avrorin *et al*., 1997) can be achieved.

The possibility of thermonuclear ignition of the cryogenic target with a beryllium ablator (which is similar to the NIF target) on the Iskra-6 facility was investigated (Bradley & Wilson, 1999; Karlykhanov *et al*., 2004).

The 1D ERA code (Barysheva *et al*., 1982; Zuev, 1992) calculations resulted in the specification of optimal target parameters and radiation temperature dependence in time that needed to achieve ignition. The thermonuclear yield of 1.7 MJ was obtained in the ERA code simulation performed for targets with initial diameter of about 1.1 mm, the peak radiation temperature of 360 eV, and target absorbed energy of 30 kJ.

Important issues as the influence of the asymmetry of radiation on the target surface, and the roughness of the shell surface were not considered by Karlykhanov *et al*. (2004). Results of 2D calculations of cryogenic target for Iskra-6 are presented in this paper.

For the thermonuclear ignition on the NIF, non-cryogenic double-shell targets are offered as well (Amendt *et al*., 2002). These targets consist of the outer shell (pure or copper-doped beryllium) that impacts the gold inner shell filled with high-density DT gas at room temperature. Ignition experiments with double-shell targets can give the unique information for studying turbulent mixing.

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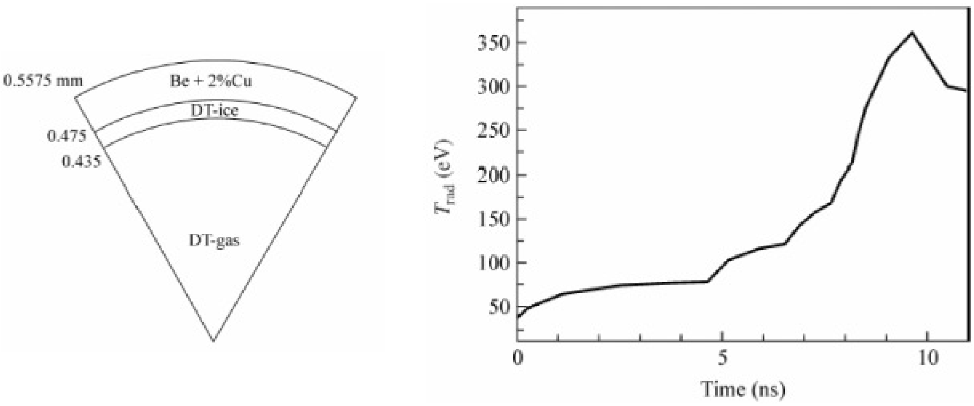

Fig. 1. Cryogenic target for the Iskra-6 facility (Karlykhanov *et al.*, 2004) and time dependence of radiation temperature on the target surface.

The present study continues the investigations on inertial confinement fusion (ICF) carried out at the RFNC VNIITF. The aim of this work is to study the possibility of igniting a non-cryogenic double-shell target on the Iskra-6 facility. Calculations were carried out by using the 1D Era code, which was developed for simulating physical processes occurring in ICF targets. The energy and momentum transport by non-equilibrium radiation was taken into account in the multi-group diffusion approximation. In simulations, we used the tabulated spectral absorption coefficient calculated by the mean atom model (Nikiforov *et al.*, 2000). Influences of 2D effects were studied by using 2D code TIGR-Ω (Shushlebin *et al.*, 1995; Neuvazhayev *et al.*, 1998).

2. RESULTS OF 1D-MODELING

Double-shell non-cryogenic targets are the possible alternative to cryogenic single-shell targets. The double-shell target design is proposed in the work of Amendt *et al.* (2002) at the Lawrence Livermore National Laboratory (LLNL). This design requires constant radiation temperature in Hohlraum $T_R = 200$ eV.

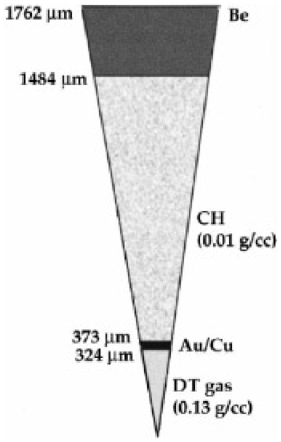

Fig. 2. Double-shell non-cryogenic target design for thermonuclear ignition on the NIF (Amendt *et al.*, 2002).

In 1D LLNL simulations of the target, the thermonuclear yield was about 3.2 MJ at a thermal radiation energy absorbed by the target of 500 kJ. Laser-target energy conversion efficiency η was about 30% in Hohlraum made from a (cocktail) mixture of high-Z elements (Amendt *et al.*, 2002).

The fusion energy yield calculated from the LLNL double-shell target by the ERA code coincides with that calculated by the LASNEX code, accurate to 10%. This confirms the reliability of the methods used at the RFNC VNIITF and LLNL to calculate thermonuclear targets.

In RFNC VNIITF, the possibility of ignition of the double-shell target (which is similar to LLNL target) was investigated. We started with the cautious assumption that the Hohlraum construction of the same type efficiency of laser energy transfer to a target could reach a value 20%. In this case, the target absorbs energy:

$$E_{abs} = E_{las} \cdot \eta = 0.2 \cdot 300 \text{ kJ} = 60 \text{ kJ}.$$

The energy absorbed by the target is described by the following approximate relationship:

$$E_{abs} \cong \sigma T_R^4 \cdot 4\pi R^2 \cdot \Delta t,$$

where R is the outer radius of the target, and Δt is the duration of implosion process.

Implosion time is proportional to the target radius: $\Delta t \sim R$ (Amendt *et al.*, 2002), so $E_{abs} \sim R^3$. The two-fold decrease in the radius R should lead to a decrease in the absorbed energy by a factor of 8: from 500 kJ for the LLNL target to 60 kJ for the scaled target. Considered in this paper, double-shell target for the Iskra-6 was obtained from the LLNL target by scaling $R_i \rightarrow R_i/2$.

In the Era code, calculations of the scaled double-shell target, the thermonuclear yield equal about 280 kJ. This value is close to the output energy of the Iskra-6 facility. Target absorbs energy of about 60 kJ. The DT-fuel burning-

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Table 1. *Parameters of the implosion and burning of cryogenic single-shell (Karlykhanov et al., 2004) and non-cryogenic double-shell targets for the Iskra-6 facility calculated by the 1D ERA code*

Target	Double-shell	Single-shell
Peak radiation temperature (eV)	200	360
Absorbed energy (kJ)	60	31
Implosion velocity (km/s)	250	400
Peak ion temperature (keV)	36	40
Peak fuel density (g/cm^3)	250	700
$\langle \rho R \rangle_{fuel}$ (g/cm^2)	0.3	0.8
$\langle \rho R \rangle_{total}$ (g/cm^2)	2.7	1.1
Fuel burning-out (%)	36	19
Fusion energy yield (MJ)	0.28	1.7
Neutron yield (10^{17})	1	6
Required laser energy (kJ)	300 ($\eta = 20\%$)	300 ($\eta = 10\%$)

out is about 36%. The peak fuel density reaches 250 g/cm^3. Ion temperature at burning exceeds 30 keV.

Results of 1D-modeling of cryogenic and non-cryogenic targets for Iskra-6 are presented at Table 1. Thermonuclear yield from the single-shell target is six times higher than from the double-shell target. But fuel burning-out is about twice as lower in the single-shell target. It could be explained by higher $\langle \rho R \rangle_{total}$ in the double-shell target. For the ignition of the cryogenic targets much higher radiation temperature is required. Implosion velocity of double-shell target is less about 1.6 times. Reachable ion temperature is close for both targets. Nevertheless, peak fuel density of single-shell target is three times higher. Energy absorbed by double-shell target is two times higher. Therefore, laser-target energy conversion efficiency must be also two times higher.

3. RESULTS OF 2D MODELING

Influences of radiation asymmetry and shells roughness on implosion and burning of indirect-driven targets for the Iskra-6 facility were studied by using 2D three-temperature code TIGR-Ω.

Table 2. *Results of 2D modeling of non-cryogenic target for the Iskra-6 with perturbed temperature*

Harmonics number k	0	4	4
Amplitude a_0	0	0.0025	0.005
Peak fuel density (g/cm^3)	350	360	400
Peak ion temperature (keV)	32	29	23
Fuel burning-out (%)	36	34	30

Table 3. *Results of 2D modeling of cryogenic target for the Iskra-6 with perturbed temperature*

Harmonics number k	0	4	4
Amplitude a_0	0	0.00125	0.0025
Peak fuel density (g/cm^3)	740	660	560
Peak ion temperature (keV)	36	25	9
Fuel burning-out	19	14	3

3.1. Targets sensitivity to radiation asymmetry

In calculations, the radiation temperature on outer boundary was set by the formula:

$$T_{rad} = T^*_{rad} \cdot (1 - a_0 \cos(k\theta)),$$

T^*_{rad} − Unperturbed temperature, a_0—amplitude of perturbation, k—harmonics number. Perturbations in a thermal flux and radiation temperature are bound by the formula: $\delta q/q = 4 \cdot \delta T/T$. Therefore full amplitude of thermal flux perturbation equals $8 \times a_0$.

In Tables 2 and 3, some results of calculations with perturbed radiation temperature are presented. With growth of perturbation amplitude, the considerable decrease of DT-fuel burning-out in the cryogenic target is observed. At asymmetry in the radiation flux $\delta q/q = 0.02$, the thermonuclear yield from target equals only 18% from the 1D yield.

In Figure 3, dependences of thermonuclear yield from the targets on amplitude of perturbation are presented. Cryogenic single-shell target is too much more sensitive to radiation asymmetry than non-cryogenic double-shell.

3.2. Targets sensitivity to shells imperfections

We have tested the influence of outer surface roughness for cryogenic and non-cryogenic targets. In calculations, the outer radius of ablator was set by the formula:

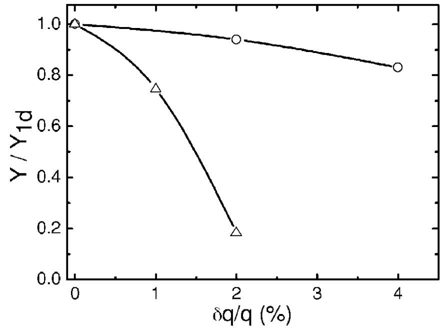

Fig. 3. Decrease of thermonuclear yield from cryogenic (triangles) and non-cryogenic (circles) targets versus full amplitude of thermal flux perturbation.

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Table 4. *Results of 2D modeling of non-cryogenic target for the Iskra-6 with perturbed outer surface of ablator*

Harmonics number k	0	12	12
Amplitude δ_0 (nm)	0	13	26
Peak fuel density (g/cm^3)	350	360	370
Peak ion temperature (keV)	32	31	29
Fuel burning-out (%)	36	35	34

$$R(\theta) = R_0 + \delta_0 \cos(k\theta),$$

R_0—initial radius, δ_0; amplitude of perturbation. Some results of calculations with perturbed outer ablator surface are presented in Tables 4 and 5.

Sensitivity of targets for the Iskra-6 facility to outer ablator surface roughness is presented.

At the full amplitude of geometrical perturbation $2 \times \delta_0 = 52$ nm reduction of the thermonuclear yield equals 2% for the single-shell target and about 5% for the target with two shells.

In Figures 4 and 5, calculated distribution of ion temperature in fuel at the moments of ignition and peak burning are submitted.

We also have carried out some calculations with perturbations on the outer surface of gold shell on the non-cryogenic capsule. Results are presented in Table 6. At the full amplitude of geometrical perturbation $2 \times \delta_0 = 26$ nm reduction of the thermonuclear yield is about 3 %.

4. CONCLUSION

1D-calculations have shown the principal possibility for the thermonuclear ignition of the non-cryogenic double-shell target (similar to LLNL target) on the Iskra-6 scale laser facility. The thermonuclear yield about 0.3 MJ was obtained in the ERA code simulation. Energy absorbed by target was about 60 kJ. Target transferred about 20% from 300 kJ of the Iskra-6 energy.

Table 5. *Results of 2D modeling of cryogenic target for the Iskra-6 with perturbed outer surface of ablator*

Harmonics number k	0	12	12
Amplitude δ_0 (nm)	0	13	26
Peak fuel density (g/cm^3)	740	710	690
Peak ion temperature (keV)	36	30	26
Fuel burning-out (%)	19	17	14

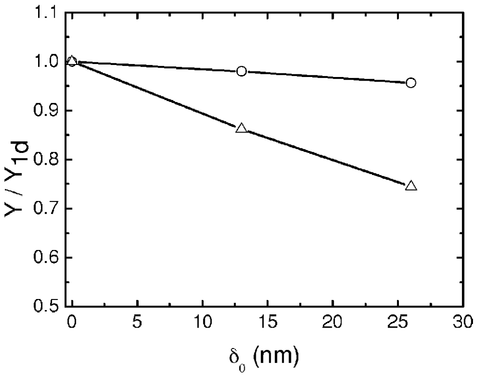

Fig. 4. Decrease of thermonuclear yield from cryogenic (triangles) and non-cryogenic (circles) targets versus amplitude of outer ablator radius perturbation.

Hohlraum radiation temperature for double-shell target is 200 eV that is much less than peak temperature 360 eV for offered before single-shell target for the Iskra-6.

TIGR-Ω 2D calculations shown that the thermonuclear yield from non-cryogenic target with two shells is close to the 1D at amplitude of perturbation as 12th harmonic on the exterior surface of shells from gold and beryllium up to 50 nm. Full amplitude of radiation drive asymmetry should be less than 4% for perturbation as 4th harmonic.

The cryogenic target can tolerate the asymmetry of a thermal flux as 4th harmonic less than 1%. The amplitude of perturbation as 12th harmonic on an exterior ablator surface should be less than 25 nm.

In this paper, we did not consider such important issues as the influence of mixing. This problem will be the subject of our further investigations.

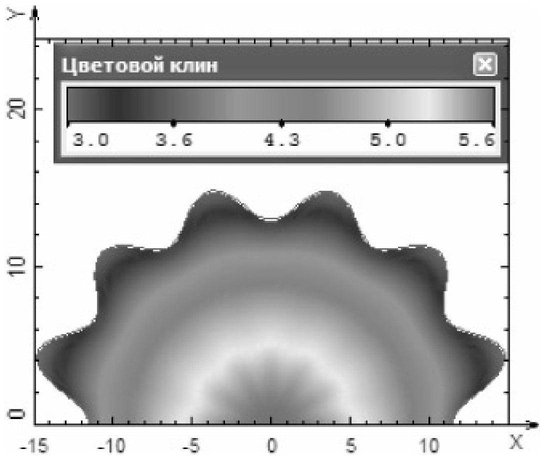

Fig. 5. Ion temperature distribution in DT-fuel of non-cryogenic target at the moment of the ignition. Perturbation of outer ablator surface with $k = 12$ and $\delta_0 = 26$ nm was applied (X, Y – μm).

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Table 6. *Results of 2D modeling of non-cryogenic target for the Iskra-6 with perturbed outer surface of gold shell*

Harmonics number k	0	12
Amplitude δ_0 (nm)	0	13
Peak fuel density (g/cm^3)	350	360
Peak ion temperature (keV)	32	30
Fuel burning-out (%)	36	35

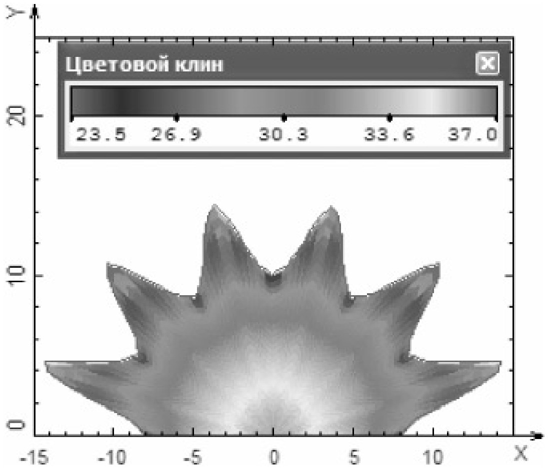

Fig. 6. Ion temperature distribution in DT-fuel of non-cryogenic target at the moment of the peak burning. Perturbation of outer ablator surface with $k = 12$ and $\delta_0 = 26$ nm was applied (X, Y − μm).

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