Simulation of double-shell targets for experiments near to a threshold of thermonuclear ignition on megajoule laser

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SUMMARY

1. Advantages and disadvantages of double-shell target.
2. The ignition margin of double-shell targets at different time dependence of radiation temperature.
3. Effects of DT initial density on compression symmetry and thermonuclear burning parameters.
4. Simulations of double-shell targets taking into account spectral kinetic radiation transfer.
5. Simulation of the double-shell target with account of a turbulent mixing by the $k\varepsilon$-model.

CONCLUSION
Advantages and disadvantages of double-shell targets

ADVANTAGES:

- It is not required a careful tailoring of laser pulse
- The velocity of shell could be ~ 2 time lower
- The temperature of X-Ray radiation could be less 300 eV
- It is possible to use the $2\omega$ radiation of Nd-laser

DISADVANTAGES:

- The yield of thermonuclear energy is lower
- The strong development of RT-instability and turbulent mixing at inner shell surfaces

The 1D-simulation of gas-filled double-shell target ("base" target)

The shells have low aspect ratio: $A_{Au} = 6$ and $A_{Be} = 4$ to reduce a turbulent mixing influence on the compression and burn of DT-fuel.

The radiation temperature of 275 eV with front duration of 1-10 ns

Double-shell target could has ignition margin in 2 time more then one-shell target, but it convergent ration also high.

Questions to the optimization of double-shell targets

- Choice of a material, position and thickness of shells, composition and quantity of impurity in ablator.
- Influence of time dependence of radiation temperature on compression and burning of a double-shell target.
- Possibility to use liquid DT-fuel instead of DT-gas in double-shell target.
- Influence of hohlraum radiation asymmetry and turbulent mixing on ignition of a double-shell target.
The objective function under optimization is the ignition margin $W^*$:

$$W^* = (n-1) \int_{-\infty}^{t^*} \frac{dE_f / dt}{E} dt$$  \hspace{1cm} (1)$$

where: $dE_f / dt$ – rate of fuel heating by products of thermonuclear reactions, $E$ - energy of DT-fuel, $n$ - exponent in $\langle \sigma v \rangle \sim T^n$, $t^*$ - time of compression maximum.

The ignition margin taking into account the energy losses by a heat conductivity into a shell:

$$W^*_Q = \frac{W^* \cdot E^*}{W^* + E^*}$$  \hspace{1cm} (2)$$

where: $W^*$- ignition margin obtained by formula (1), $E^*$ - energy of DT-fuel, $Q^*$ - heat energy flux into shell at time $t^*$.

The 1D – simulations with different time dependence of radiation temperature by TIGR-OMEGA-3T code

<table>
<thead>
<tr>
<th>#</th>
<th>t₀</th>
<th>T_f, max</th>
<th>E_a</th>
<th>t*</th>
<th>ρ*</th>
<th>T_i*</th>
<th>M_a</th>
<th>V_max</th>
<th>W*</th>
<th>W_Q*</th>
<th>η (%)</th>
<th>ρ</th>
<th>T_i,max</th>
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Here: $E_a$ – target absorbed energy; $t^*$ - time of compression maximum; $\rho^*$ – density, $T_i^*$ - DT-ion temperature, $W^*$ and $W_Q^*$-ignition margins without and with account of energy losses at time $t^*$; $M_a$ – non-ablated part of Be-shell; $V_{max}$- velocity maximum of DT border; $\eta$ – tritium burn up; $\rho_{max}$ - density; $T_{i,max}$ – maximum of ion temperature at DT-burning.
The 2D - TIGR- OMEGA-3T code simulations for different $T_f(t)$ and radiation flux asymmetry in form of 4th-harmonic with amplitude $\gamma_4 = -1\%$

Ion temperature distribution at time of thermonuclear burn

$T_{f,\text{max}} = 265$ eV
$t_0 = 10$ ns

Density distribution at time of thermonuclear burn

$T_{f,\text{max}} = 250$ eV
$t_0 = 10$ ns
One-dimensional three-temperature calculations of double-shell target with liquid DT-fuel

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<tr>
<th>#</th>
<th>R1 (mm)</th>
<th>R2 (mm)</th>
<th>Vmax (mm/ns)</th>
<th>W* (g/cc)</th>
<th>WQ* (g/cc)</th>
<th>Tɨ* (keV)</th>
<th>DT ∫ρdr (g/cm²)</th>
<th>Au ∫ρdr (g/cm²)</th>
<th>ρmax (g/cc)</th>
<th>Ti,max (keV)</th>
<th>η (%)</th>
<th>Ndt (10¹⁷)</th>
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</table>

The parameters of optimum double-shell targets with DT-fuel as liquid or gas are close
2D - TIGR- OMEGA-3T code simulations of double-shell target for radiation flux asymmetry as $\gamma_4 \cdot P_4(\mu)$

Here: $\gamma_4$ – amplitude of radiation flux asymmetry in form of 4-th harmonic; $\rho_{dt}$ - DT initial density;

Cryogenic targets tolerate the irradiation asymmetry in ~1,5 times bigger than gas-filled targets despite decrease in ignition margin also in ~1,5 times.
2D-TIGR-OMEGA-3T code simulations of double-shell targets with DT-gas and DT-liquid at radiation parameters: $T_{f,\text{max}} = 250 \text{ eV}$, $t_0 = 1.0$ and $\gamma_4 = -1\%$

- **DT-gas** ($\rho_{\text{dt}} = 0.07 \text{ g/cc}$): $N_{\text{dt}}$ decreases for 17% in 2D-calculation.

- **DT-liquid** ($\rho_{\text{dt}} = 0.2 \text{ g/cc}$): $N_{\text{dt}}$ decreases for 5% in 2D-calculation.

Ion temperature distribution at time of thermonuclear burn

Density distribution at time of thermonuclear burn

The compression symmetry improves in ~ 1.5 time and the decrease of neutron yield is considerably less in targets with DT-liquid than with DT-gas.
The 1D-simulations with account of radiation transfer in spectral kinetic and three-temperature approximations (the choice of Cu-concentration in Be-ablator)

<table>
<thead>
<tr>
<th>#</th>
<th>X_{Cu} %</th>
<th>Radiation Approx.</th>
<th>E_a kJ</th>
<th>t* ns</th>
<th>ρ* g/cc</th>
<th>T_i* keV</th>
<th>M_a</th>
<th>V_{max} m/ns</th>
<th>W*</th>
<th>W_Q*</th>
<th>ρ_{max} g/cc</th>
<th>T_{i,max} keV</th>
<th>η %</th>
<th>N_{dt} 10^{17}</th>
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<tr>
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<td>226</td>
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<td>10</td>
<td>14</td>
<td>0,8</td>
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<td>3T; f=1/4</td>
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<td>2,6</td>
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<td>199</td>
<td>23</td>
<td>42</td>
<td>2,3</td>
</tr>
</tbody>
</table>

Here: X_{Cu} – copper atomic concentration in Be-ablator;
S.K.- spectral kinetic and 3T-three- temperature approximations for radiation transfer;
f – parameter in formula for limit of radiation energy flux: \( q_f^* = f \cdot c \sigma T^4 \)

The optimal copper concentration near to \( \sim 0,3\% \) for that the ignition margin \( W_Q^* \approx 4 \).
1D-simulations of double-shell targets with account of spectral kinetic radiation transfer and turbulent mixing by the $k\varepsilon$-model *)

Here: $\{\alpha\}$ - the set of $k\varepsilon$-model constants for self-similar law of light fluid penetration into heavy one: $L_b = \alpha A g t^2$, $A$ - Attwood number, $g$-acceleration, $t$ - time; $M_{cl}^*$ – “pure“ fuel part (without Au-impurity).

Turbulent mixing reduces the ignition margin $W_Q^*$ in ~ 1,5 times to $W_Q^* \approx 2-3$

1. The ignition margin $WQ^* \sim 4$ at convergence ratio $R_0/r_{\text{min}} \sim 70$ are obtained in 1D-calculations of gas-filled double-shell targets for radiation temperature $\sim 270$ eV and energy absorbed by target $\sim 300$ kJ.

2. The more low values $R_0/r_{\text{min}} \sim 50$ were attained in 1D-calculations of double-shell targets with DT-liquid but ignition margin decreased to $WQ^* \sim 2.5$.

3. The 2D-simulations show that admissible asymmetry of radiation flux in form of 4th harmonic follows $\gamma_4 \sim (R_0/r_{\text{min}})^{-1}$ and for cryogenic targets is: $\gamma_4 \leq \pm 1.5\%$.

4. The account of turbulent mixing by the $k\varepsilon$-model leads to considerable degradation of double-shell target compression and thermonuclear burning.

5. The considering of possible sources of compression asymmetry and turbulent mixing result in conclusion about impossibility to achieve a reliable ignition of considered targets with energy $\sim 2.8$ MJ in the 2nd harmonic of the Nd-laser.

6. However, experiments with double-shell targets would give the unique information on high energy density physics.
THANK YOU FOR ATTENTION