РОСАТОМ

RFNC-VNIITF
after academician E.I. Zababakhin

ГОСУДАРСТВЕННАЯ КОРПОРАЦИЯ ПО АТОМНОЙ ЭНЕРГИИ «РОСАТОМ»

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

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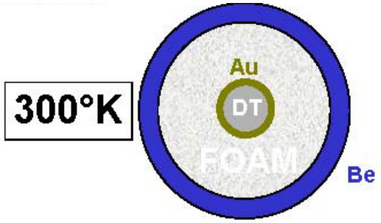
SUMMARY

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 *kε*-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 2ω 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**

P.Amendt et al. Physics of Plasmas, 9, 2221, 2002.

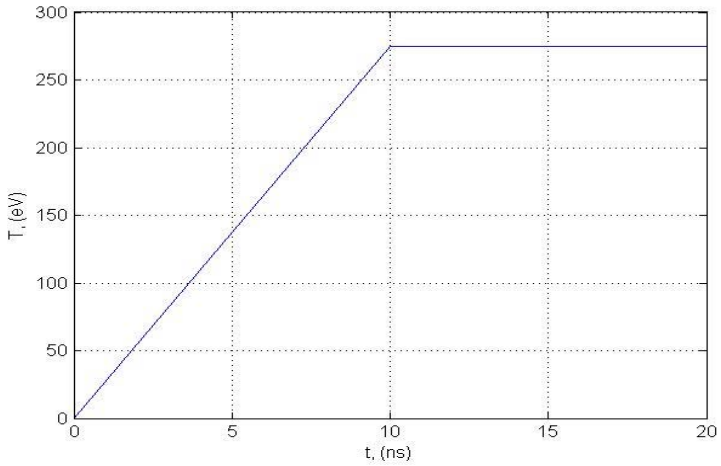
The 1D-simulation of gas-filled double-shell target (“base” target)

$D_{0.5}T_{0.5}$	Au	CH	$Be_{0.98}Cu_{0.02}$	$Be_{0.999}Cu_{0.001}$

R 0,25 0,30 0,90 0,95 1,2 mm

ρ = 0,07 19,3 0,07 1,94 1,84 g/cc

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 нс

Absorbed energy (kJ)	330
Maximum velocity of Au-shell (km/s)	310
Maximum of ion temperature (keV)	32
Maximum of fuel density (g/cc)	230
Tritium burn up (%)	48
Thermonuclear energy yield (MJ)	0,74
Neutron yield (10^{17})	2,6
Ignition margin (WQ*)	~ 4
Convergent ratio (R_0/r_{min})	~75

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

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*) V.A. Lykov, et al. The numerical simulations of indirect-drive targets for thermonuclear ignition on megajoule lasers. The 33-rd ECLIM Book of abstracts, p. 47 (Paris, France, August 31- September 5, 2014)

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 margin on thermonuclear ignition of ICF targets (Generalized Lawson Criterion)

The objective function under optimization is the ignition margin *W* *) :

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

where: dE_f/dt – rate of fuel heating by products of thermonuclear reactions, E- energy of DT-fuel, n - exponent in <σv> ~ T^n, t^*- time of compression maximum.

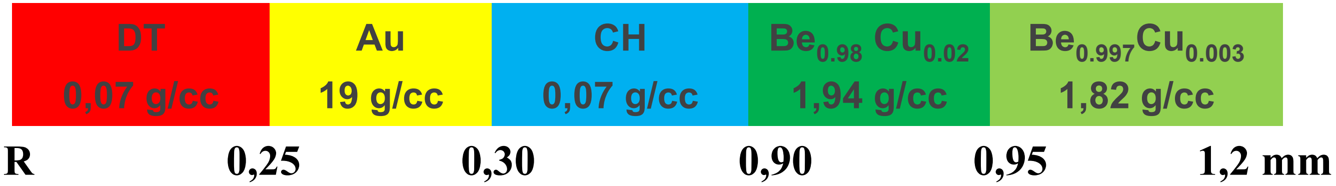
The ignition margin taking into account the energy losses by a heat conductivity into a shell:

$$W_Q^* = \frac{W^* \cdot E^*}{W^* + E^*} \qquad \textbf{(2)}$$

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

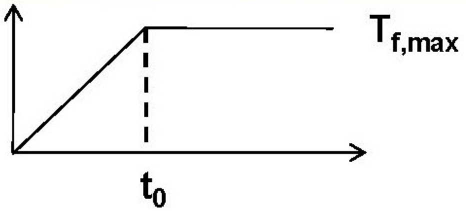
***) Vakhrameev Yu.S., Mokhov V.N., Popov N.A., Atomnaya energiya, 49, 121 (1980)**

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



DT 0,07 g/cc | Au 19 g/cc | CH 0,07 g/cc | $Be_{0.98}$ $Cu_{0.02}$ 1,94 g/cc | $Be_{0.997}Cu_{0.003}$ 1,82 g/cc

R 0,25 0,30 0,90 0,95 1,2 mm



#	t_0 ns	$T_{f,max}$ eV	E_a kJ	t* ns	ρ* g/cc	T_i* keV	M_a	V_{max} mm/ns	W*	W_Q*	η (%)	ρ g/cc	$T_{i,max}$ keV
1	10	275	327	13,9	569	3,8	0,17	0,31	22	7,7	47	190	22
2	10	265	310	14,4	536	3,7	0,20	0,29	17	6,3	47	239	33
3	10	250	283	15,2	420	3,3	0,24	0,26	9,9	4,1	44	214	28
4	1,0	275	365	6,6	309	3,2	0,1	0.25	8,9	3,0	28	173	18
5	1,0	265	350	7,1	433	3,4	0,11	0,27	15	4,9	43	192	25
6	1,0	250	318	8,0	501	3,4	0,16	0,25	13	5,2	48	239	33

Here: E_a – target absorbed energy; t* - time of compression maximum; ρ* –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}- velosity maximum of DT border; η – tritium burn up; $ρ_{max}$ - 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 γ_4 = -1%

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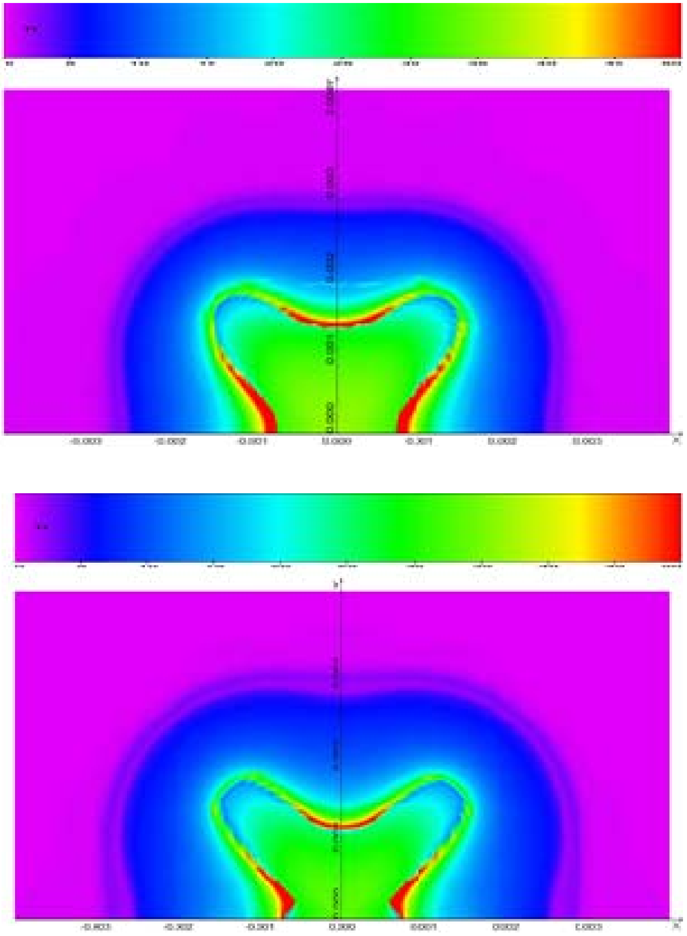
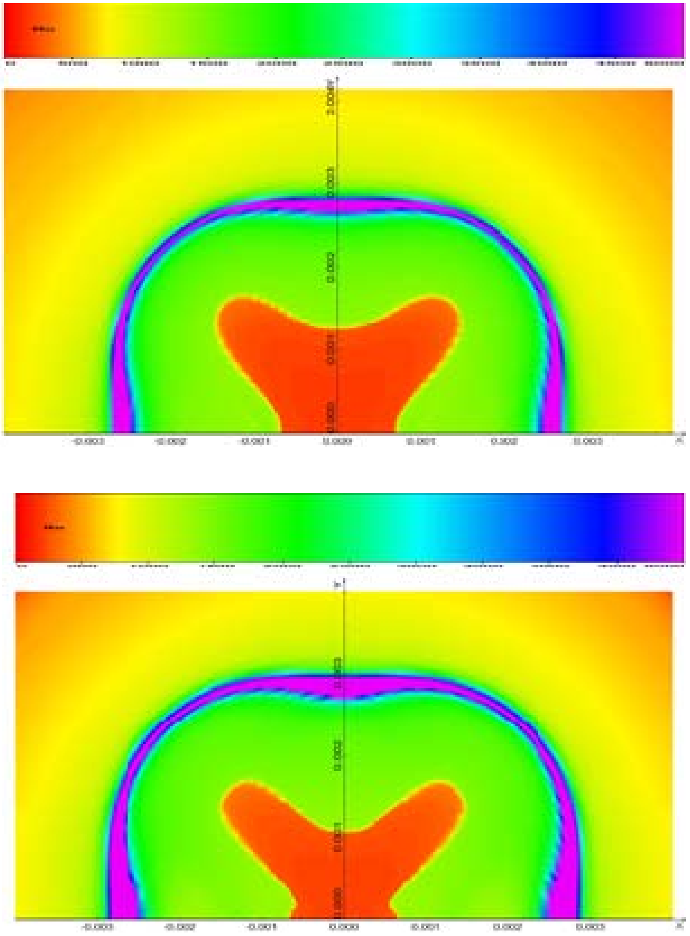


Ion temperature distribution at time of thermonuclear burn



Density distribution at time of thermonuclear burn

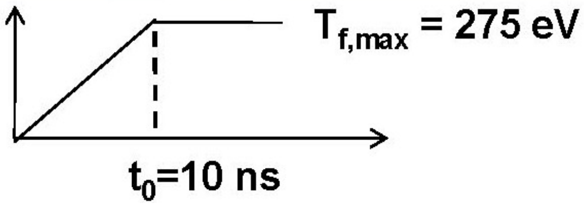
$T_{f,max}$=265 eV

t_0=10 ns

$T_{f,max}$=250 eV

t_0=1,0 ns

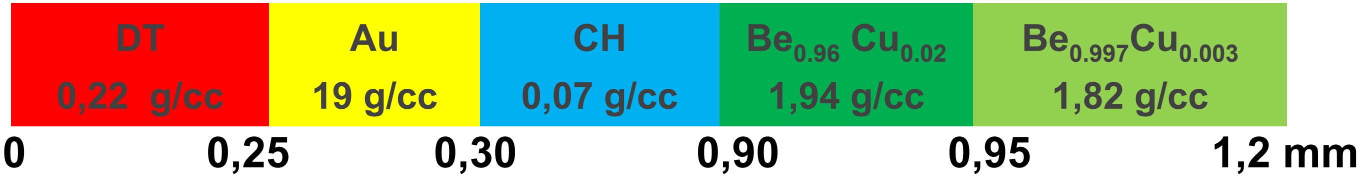
One-dimensional three-temperature calculations of double-shell target with liquid DT-fuel



#	R_1 mm	R_2 mm	V_{max} mm/ns	W*	W_Q*	ρ* g/cc	T_i* keV	DT $\int\rho dr$ g/cm²	Au $\int\rho dr$ g/cm²	ρ_{max} g/cc	$T_{i,max}$ keV	η %	N_{dt} (10^{17})
1	0,20	0,24	0,28	8,3	5,2	454	3,46	0,65	4,66	252	34	45	4,0
2	0,20	0,25	0,30	9,2	5,6	471	3,48	0,64	5,20	249	34	47	4,2
3	0,20	0,26	0,28	9,7	5,7	463	3,40	0,66	6,10	244	33	48	4,3
4	0,26	0,30	0,29	7,8	5,0	384	3,18	0,78	4,75	206	40	48	9,3
5	0,25	0,30	0,29	7,8	5,0	399	3,18	0,77	5,48	219	40	49	8,4
6	0,24	0,30	0,28	8,2	5,0	373	3,20	0,70	5,90	198	35	48	7,4
7	0,30	0,34	0,28	6,5	4,2	303	2,97	0,78	4,40	169	41	47	14,2
8	0,30	0,35	0,27	5,3	3,3	257	2,82	0,70	4,62	151	36	46	13,8
9	0,30	0,36	0,23	3,9	2,3	188	2,57	0,57	4,39	118	25	40	11,9
10	0,36	0,40	0,26	2,7	1,8	168	2,33	0,64	3,32	125	30	38	19,6
11	0,35	0,40	0,25	2,2	1,3	140	2,25	0,55	3,46	110	15	18	8,6
12	0,34	0,40	0,21	1,5	0,9	112	2,03	0,46	3,40	94,0	2,9	0,5	0,23

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 $\gamma_4 \cdot P_4(\mu)$



DT 0,22 g/cc

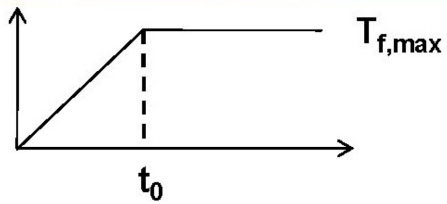
Au 19 g/cc

CH 0,07 g/cc

$Be_{0.96}Cu_{0.02}$ 1,94 g/cc

$Be_{0.997}Cu_{0.003}$ 1,82 g/cc

0 — 0,25 — 0,30 — 0,90 — 0,95 — 1,2 mm



#	t_0 ns	$T_{f,max}$ eV	γ_4 %	ρ_{dt} g/cc	η %	ρ_{max} g/cc	$T_{i,max}$ keV	N_{dt} 10^{17}	W*	W_Q*
1	10	265	0,0	0,07	47	239	33	2,6	17	6,3
2	10	265	-1,0	0,07	39	322	25	2,1	-	-
3	10	265	0,0	0,2	48	210	45	7,5	8,0	4,4
4	10	265	-1,0	0,2	45	205	43	7,1	-	-
5	10	265	-1,5	0,2	43	212	37	6,7	-	-
6	1,0	250	0,0	0,07	48	239	33	2,7	13	5,3
7	1,0	250	-1,0	0,07	37	367	22	2,1	-	-
8	1,0	250	0,0	0,2	50	228	47	7,8	5,8	3,3
9	1,0	250	-1,0	0,2	48	227	44	7,5	-	-
10	1,0	250	-1,5	0,2	45	226	40	7,1	-	-

Here: γ_4 – amplitude of radiation flux asymmetry in form of 4-th harmonic; ρ_{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:$T_{f,max}$=250 eV, t_0=1,0 and γ_4= -1%

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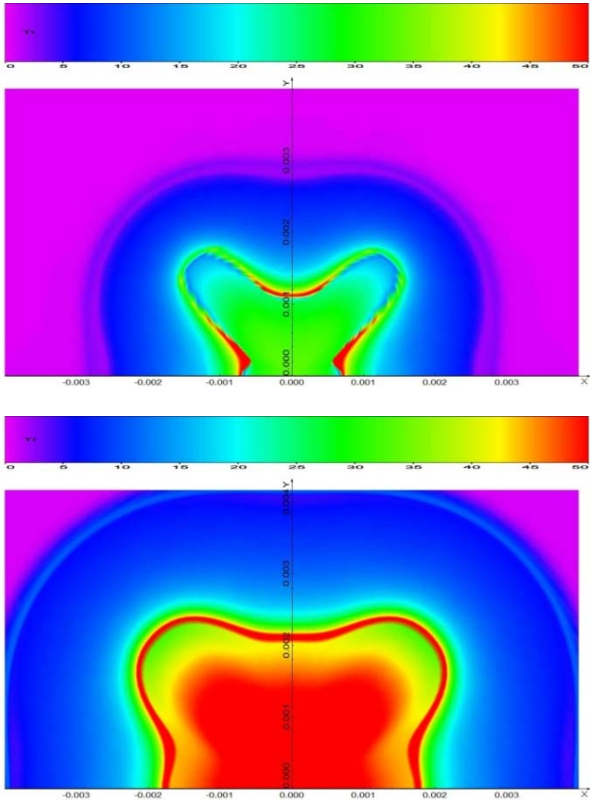
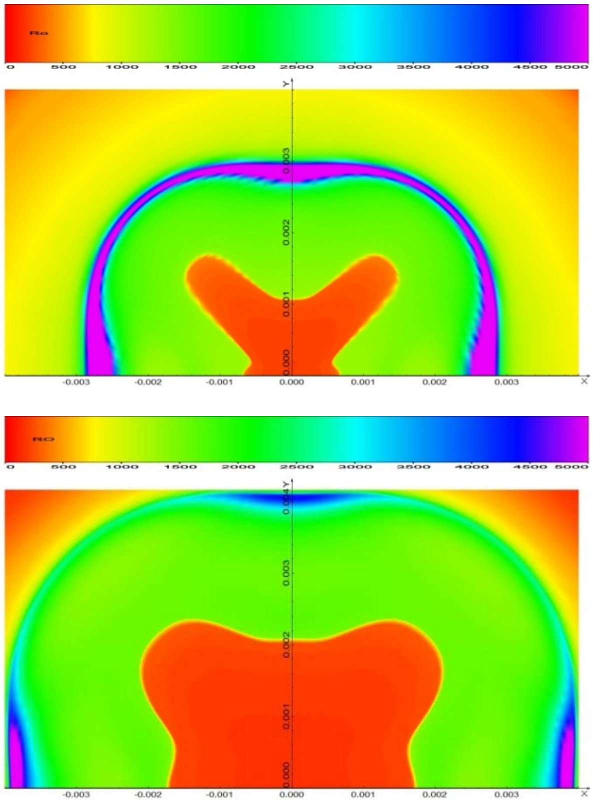


Ion temperature distribution at time of thermonuclear burn



Density distribution at time of thermonuclear burn

DT-gas (ρ_{dt}=0,07 g/cc)
N_{dt} decreases for 17%
in 2D-calculation

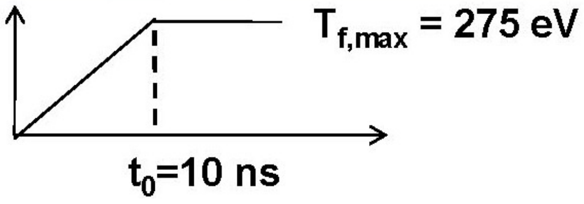
DT-liquid (ρ_{dt}=0,2 g/cc)
N_{dt} decreases for 5%
in 2D-calculation

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)

DT	Au	CH	$Be_{0.98}Cu_{0.02}$	$Be_{1-X}Cu_X$
0,07 g/cc	19 g/cc	0,07 g/cc	1,94 g/cc	1,82 g/cc

0 0,25 0,30 0,90 0,95 1,2 mm



#	X_{Cu} %	Radiation Approx.	E_a kJ	t* ns	ρ* g/cc	T_i^* keV	M_a	V_{max} m/ns	W*	W_Q^*	ρ_{max} g/cc	$T_{i,max}$ keV	η %	N_{dt} 10^{17}
1	0.0	S.K.	335	14,0	226	3,0	0,06	0,24	5,0	2,5	140	10	14	0,8
2	0.0	3T; f=1/4	347	13,8	555	4,0	0,20	0,32	17	7,7	266	28	48	2,6
3	0.0	3T; f=3/8	360	12,8	537	5,2	0,12	0,33	18	7,4	244	26	45	2,5
4	0,3	S.K.	342	15,0	334	3,2	0,19	0,24	7,6	4,1	182	21	38	2,1
5	0,3	3T; f=1/4	296	15,3	396	3,7	0,29	0,23	7,7	4,0	220	23	42	2,3
6	0.3	3T; f=3/8	311	14,6	413	3,2	0,25	0,25	8,7	4,5	226	24	43	2,4
7	0,9	S.K.	290	15,8	359	3,1	0,28	0,23	6,9	4,0	199	23	42	2,3

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 ~ 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 *kε*-model *)

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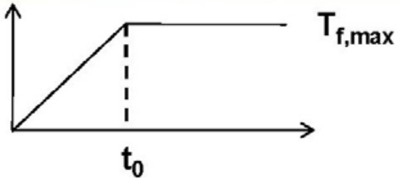

#	t_0 ns	$T_{f,max}$ eV	ρ_{dt} g/cc	{α}	E_a kJ	ρ* g/cc	T_i^* keV	V_{max} mm/ns	M_{cl}^*	W_Q^*	ρ_{max} g/cc	$T_{i,max}$ keV	η %	N_{dt} 10^{17}
1	10	275	0,07	-	342	334	3,2	0,24	-	4,1	182	21	38	2,1
2	10	275	0,07	0.04	-	366	3,0	-	0,44	2,7	246	9,5	13	0,8
3	10	275	0,22	-	342	263	2,6	0,23	-	2,5	182	32	44	7,8
4	10	275	0,22	0.04	-	255	2,5	-	0,70	1,8	200	12	12	2,1
5	1,0	250	0,07	-	314	299	2,8	0,20	-	2,6	198	18	32	1,8
6	1,0	250	0,07	0.04		371	2,6		0,41	2,0	274	5,0	3,0	0,2
7	1,0	250	0,22	-	313	257	2,2	0,19	-	1,2	221	24	37	6,3
8	1,0	250	0,22	0.04	314	289	2,1	0,19	0,51	0,9	253	2,7	0,4	0,1

Here: {α} - the set of kε-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 $W_Q^* \approx 2\text{-}3$

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*) V.E.Neuvazhaev, V.G. Yakovlev, Calculation of gravitational turbulent mixing by *kε*-model. VANT, series: Mathematical simulation of physical processes. Issue 1, pp. 28-36, 1989.

CONCLUSION

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1. The ignition margin $WQ^* \sim 4$ at convergence ratio $R_0/r_{min} \sim 70$ are obtained in 1D-calculations of gas-filled double-shell targets for radiation temperature ~ 270 eV and energy absorbed by target ~ 300 kJ .
2. The more low values $R_0/r_{min} \sim 50$ 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 $\gamma_4 \sim (R_0/r_{min})^{-1}$ 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 ~ 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