P.N.Lebedev Physical Institute of the Russian Academy of Science

Model of the Indirect Compression of Targets under Conditions at 1.5 MJ Energy

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Laser fusion facilities and lines of investigations worldwide

- USA: NIF 3ω 1.8 MJ,
  OMEGA 3ω 20 kJ,
  OMEGA EP 1ω 5 кJ 1 ps,
  LIFE – project of electric power station, including hybrid station (fusion+fission)

- France: LMJ (≈NIF) 3ω 1.8 MJ

- Europe: HiPER (fast ignition project),
  ELI 10^{25} W/cм^2

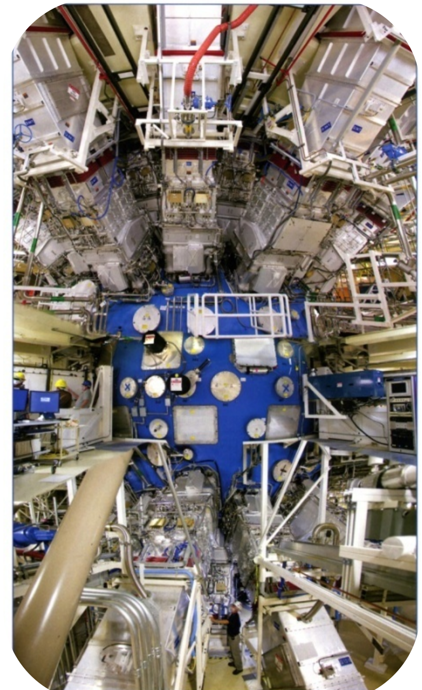
- Japan: FIREX (fast ignition project)

- Russia: UFL-2M 2ω 2.8 MJ

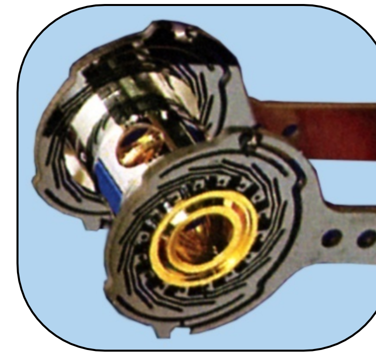
National Ignition Facility NIF (LLNL, USA)

Building

Interaction chamber



Hohlraum target

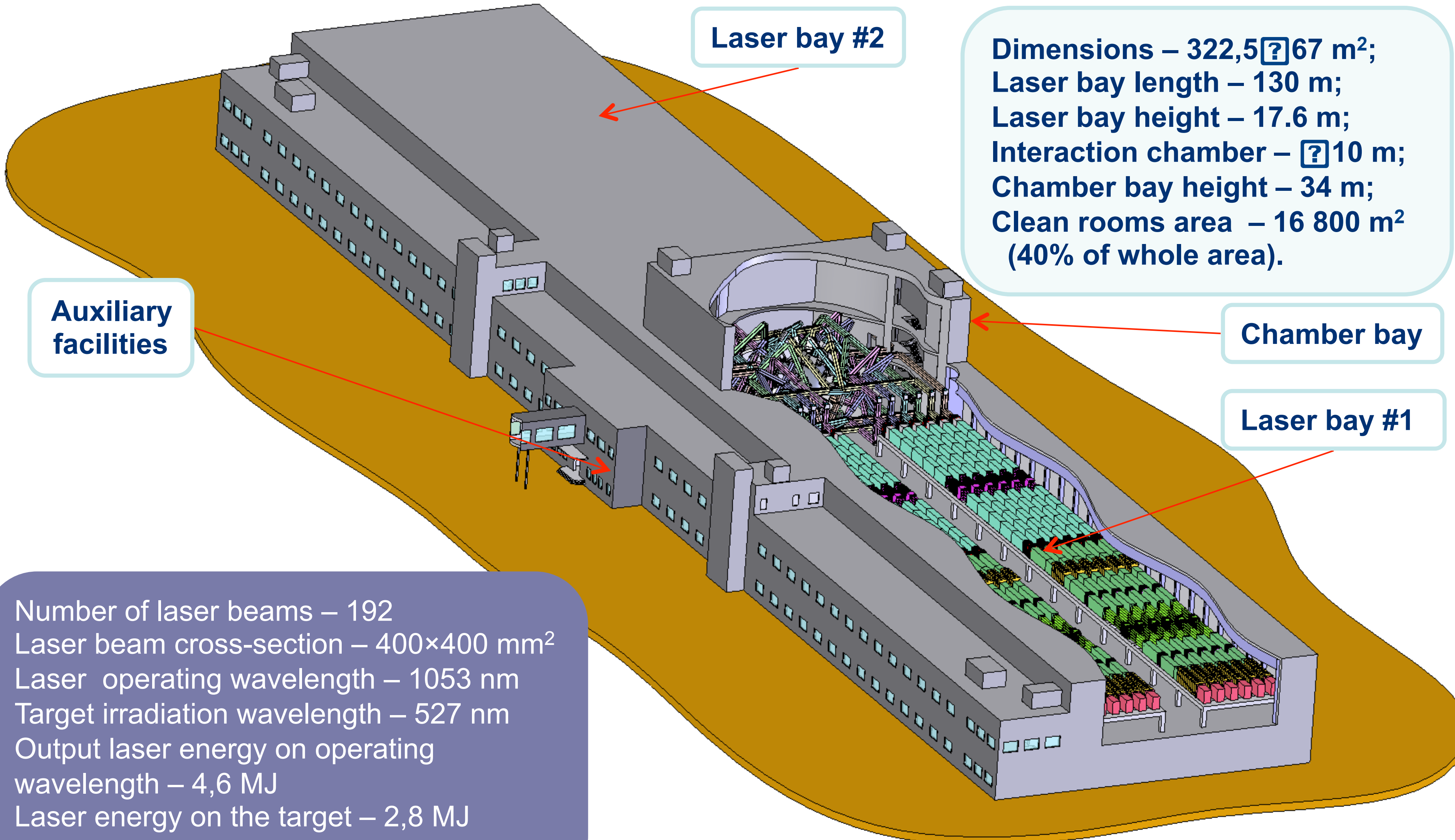


Параметры установки:

- **Number of Nd laser beams - 192**
- **Laser operation wavelength - 1,06 mcm**
- **Target irradiation wavelength - 0.356 mcm**
- **Output laser energy on operating wavelength – 4,6 MJ**
- **Laser energy on the target – 1,8 MJ**
- **Laser pulse time 5-20 ns**

NIF facility - $3.5billion
NIC(Nation.Ignition Campaigh) $109million in fiscal years 2011 and 2012 for ignition
2013: NNSA (National Nuclear Security Administration) has requested $84million for ignition. Another $15 million has been requested to carry out the non-ignition experiments at NIF.
Experiments: national security, fundamental science, and inertial fusion energy.

General view of UFL-2M facility (Sarov, Russia)



Dimensions – 322,5?67 m^2;
Laser bay length – 130 m;
Laser bay height – 17.6 m;
Interaction chamber – ?10 m;
Chamber bay height – 34 m;
Clean rooms area – 16 800 m^2 (40% of whole area).

Number of laser beams – 192
Laser beam cross-section – 400×400 mm^2
Laser operating wavelength – 1053 nm
Target irradiation wavelength – 527 nm
Output laser energy on operating wavelength – 4,6 MJ
Laser energy on the target – 2,8 MJ
Construction time – 2012 – 2020 years

Report Plan

1. Introduction
2. Energy balance in the target
3. Calculation of the compression of the target in the low foot regime
4. Calculation of the compression of the target in the high foot regime
5. Targets with high density carbon (HDC) ablator
6. Target ignition depending on the ablator radiation absorption
7. Discussion of results and conclusion

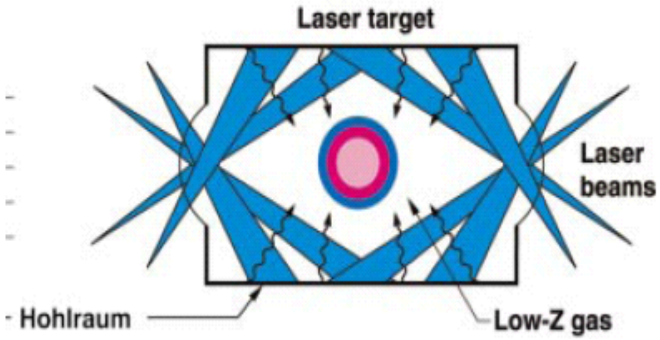
Introduction

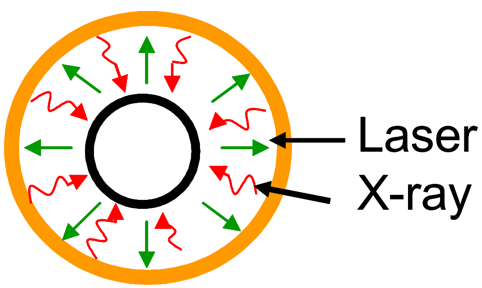
- The possibility of the analysis and interpretation of the reported experiments with the megajoule National Ignition Facility (NIF) laser on the compression of capsules in indirect-irradiation targets by means of the one-dimensional RADIAN program in the spherical geometry has been studied.
- Although the numerical simulation in the one-dimensional geometry cannot provide the strict quantitative analysis of experimental data, but it allows the determination of the main parameters of the compression process and a target, as well as tendencies in the variation of irradiation conditions, thus creating a platform for the interpretation of results.
- An additional reason in favor of the one-dimensional model is that the processes in a target for indirect irradiation begin with significantly non-one-dimensional processes and end with a one-dimensional almost ideal process.
- The model reproduces the known from literature data on the measured radiation temperature in the cavity and the shell motion velocity and correspond to the range of the observed parameters.

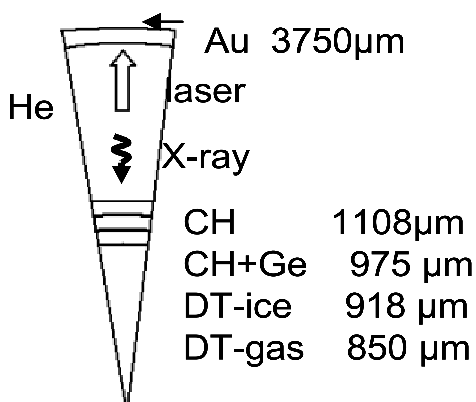
1D RADIAN code

- The physic mathematical model underlying the hydrodynamic RADIAN code includes the equations of two temperature hydrodynamics: equations of motion, continuity equation, equations of variation of the energy for the electron and ion components, and equations of state for ions and electrons. Electron–ion exchange and the classical or reduced Spitzer thermal conductivity are taken into account. The energy of laser radiation is absorbed through inverse bremsstrahlung. Laser radiation reaching the point with the critical density is completely absorbed at this point.
- Spectral radiation transport is considered in a multi-group, number of groups up to 1300. The simulations were performed with the equation of state of an ideal gas in order to reveal the behavior of quantities that weakly depend on the parameters of the equation of state and to test the possibility of performing independent simulations.
- Database of spectral radiation absorption coefficients are calculated by the THERMOS code (A.F.Nikiforov, V.G.Novikov, V.B.Uvarov, Inst.Applied Mathematics, Russian Academy of Sciiences). In particular, the existence of an optical database allows one to make use of this model for the analysis of the processes observed in thermonuclear targets, where the radiation is an important factor.

Energy balance equation

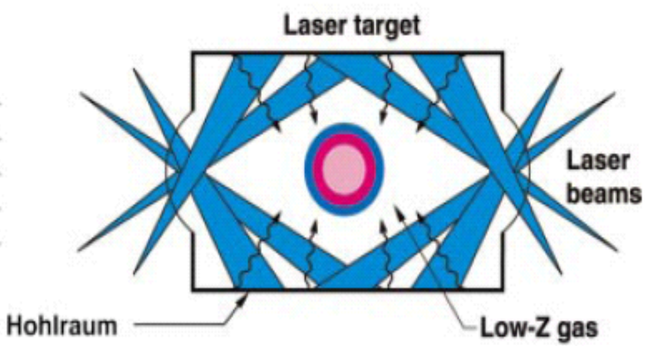


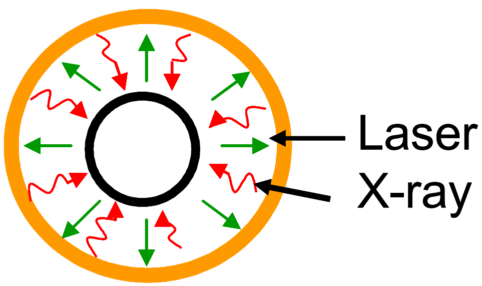


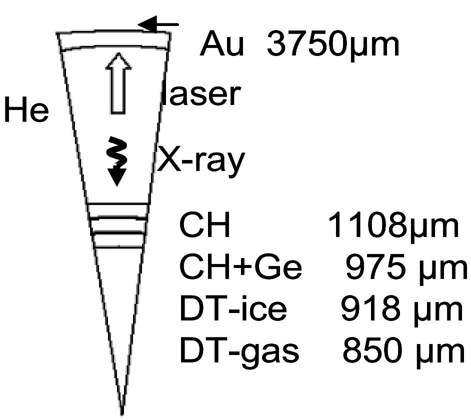


- In the indirect drive compression the primary laser pulse is transformed in the cavity on the inner walls of a gold target into a soft x-ray radiation. This x-ray radiation ablates and compresses the central part of the target with DT-fuel.
- These are, in fact, two- or three-dimensional problems. However, the compression of the central capsule should be essentially one-dimensional.

Energy balance equation







In the analysis the difficulty is to compare the 1D geometry with 2D and 3D one. The energy equation gives the way to solve this problem. To do this the balance of energy should be reproduce. Energy balance equation involves heating the walls and central capcule, filling the cavity by radiation, losses of the radiation energy through the ends of the cylinder target.

After that it is possible to link the energy in the spherical case with energy in real geometry.

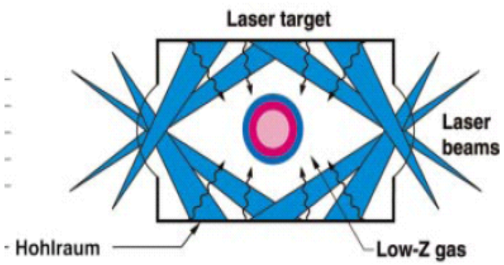
To compare a cylindrical and spherical description let us consider the energy balanc in the target.

In case of real cylindrical geometry, up to the time moment t we have:

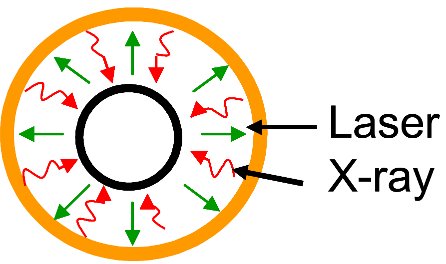
$$U_{rad}V_{rad} + \int_o^t W_{cap}S_{cap}dt + \int_o^t W_{LEH}S_{LEH}dt + E_{Au}(t) = E_{Las}(t) \qquad (1)$$

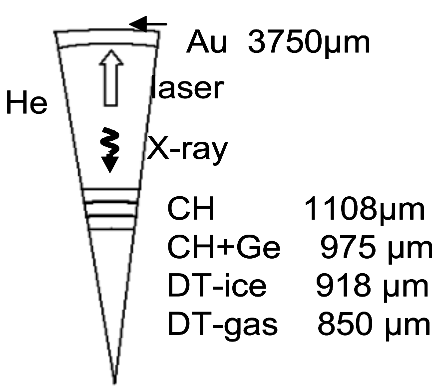
In a spherical model problem:

$$U_{rad}V_{rad} + \int_o^t W_{cap}S_{cap}dt + E_{Au}(t) = E_{sph}(t) \qquad (2)$$



Energy balance equation.
the result of adjustment





$$E_{sph} = E_{cap} + E_{Au} .$$

For real cylindrical geometry (Eq.1) one should add the energy losses connected with the windows E_{LEH} , namely:

$$E_{las} = E_{cap} + E_{Au} + E_{LEH} , \quad E_{LEH} = W_{LEH} \cdot S_{LEH} \cdot \Delta t .$$

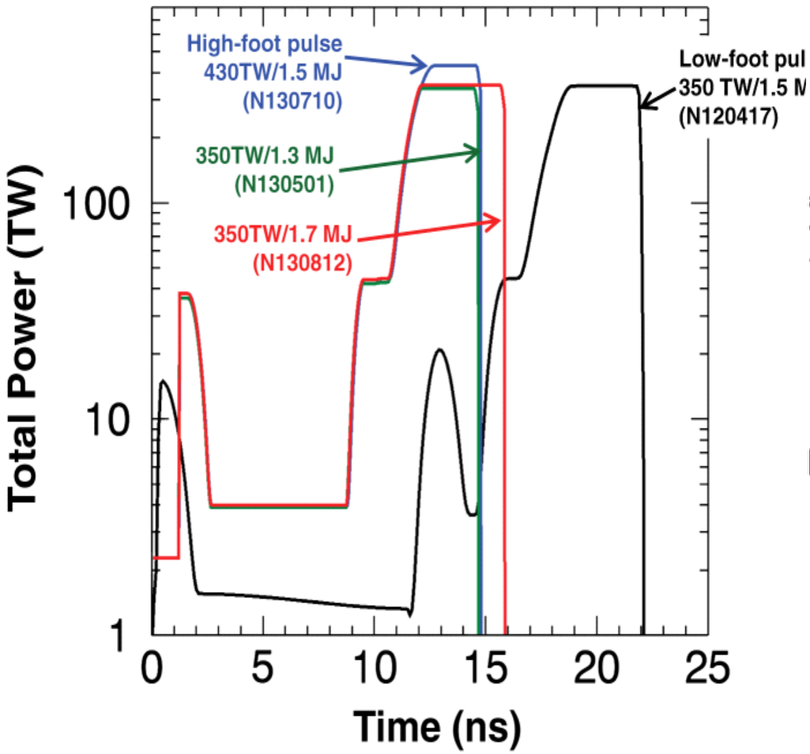
Table 1 illustrates the results of simulations and estimates.

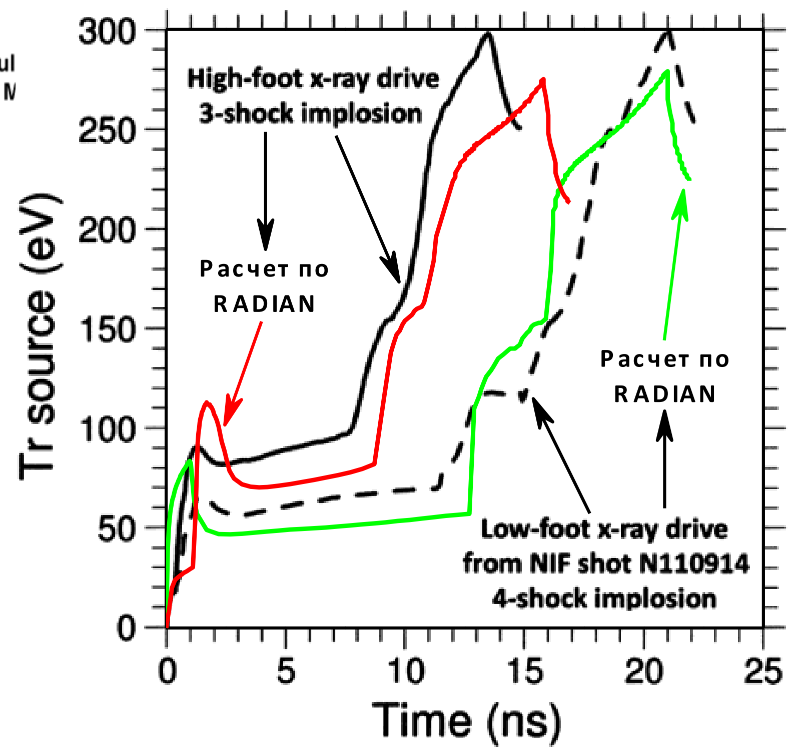
E_{sph}, МДж	T_{rad} . эВ	E_{cap}/E_{sph}	E_{Au}/E_{sph}	E_{LEH}, МДж	E_{las}, МДж
0.325	274	0.34	0.63	0.394-0.197	0.719
0.36	287	0.33	0.64	0.475-0.238	0.835
0.4	300	0.34	0.62	0.567-0.284	0.967
0.45	316	0.33	0.64	0.698-0.349	1.15
0.5	330	0.32	0.65	0.830-0.415	1.33
0.55	341	0.28	0.7	0.946-0.473	1.50

In Table 1: E_{sph} is the deposited energy in 1D simulation; T_{rad} , the radiation maximum temperature in the centre of He layer; E_{cap} and E_{Au} , the energy absorbed by the capsule and the wall of a spherical target; $E_{las} = E_{sph} + E_{LEH}$, the estimated laser energy for a cylindrical target based on the evaluation of energy losses E_{LEH}.

Comparison of the experimental and simulation data in the “low foot” and “high foot”

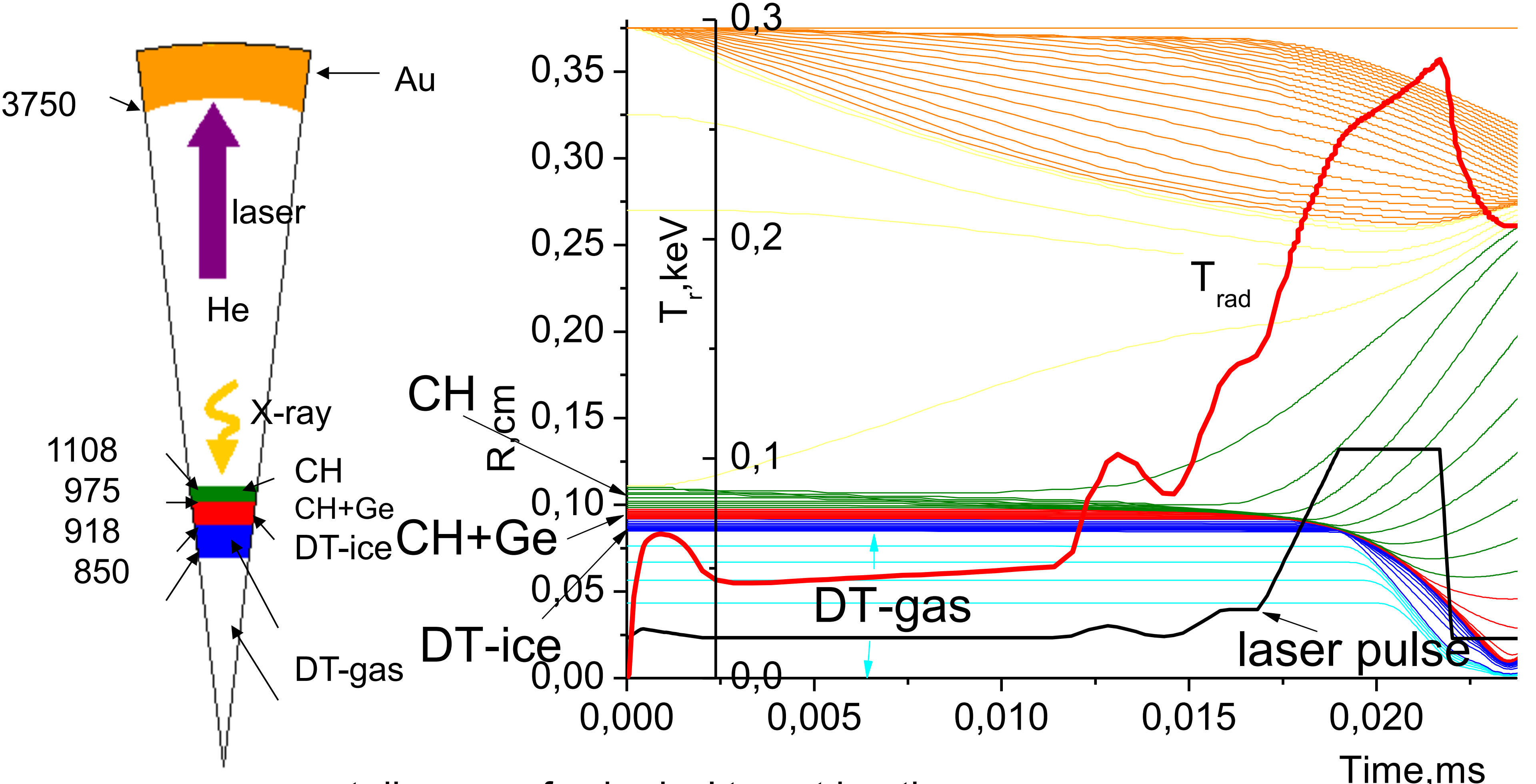
- High foot regime laser pulse is shorter and radiation temperature on the first stage is higher.
- It is seen that the discussed model reproduces the radiation temperature in both regimes.





Phys.Rev.Lett.112, 055001 (2014). Phys.Rev.Lett., 112, 055002 (2014)

Low-foot simulation



r-t diagram of spherical target heating

Low-foot simulation

M. J. Edwards et al. Phys. of Plasmas 20, 070501 (2013)

	LLNL				RADIAN simulation E_{sph} (МДж)		
	Predicted range in simulations	Maximal experimental value	N120321 "no coast"	N111215 "coast"	0.325 "no coast"	0.325 "coast"	0.45 "no coast"
T_{rad}(eV)	305	320	303	292	282	290	316
V_{max}(км/s)	370	352	310	312	270	285	290
$T_{ion\text{-}gas}$(кeV)	3.5	4.3	3.1	3.6	3-5	3.6-5.1	3.8-5.2
N_n(+?)	$3.4 \cdot 10^{17}$	$8.5 \cdot 10^{14}$	$5 \cdot 10^{14}$	$8.5 \cdot 10^{14}$	$6 \cdot 10^{15}$	$2 \cdot 10^{15}$	$5.9 \cdot 10^{15}$
N_n	$3.5 \cdot 10^{15}$				$4 \cdot 10^{15}$	$1.7 \cdot 10^{15}$	$4 \cdot 10^{15}$
P (Gbar)	375	197	156	103	37	18	27

- The reported data confirm that 1D simulations can reproduce a number of characteristics established in 2D or 3D processes
- One can improve the correspondence between 1D simulations and more complete calculations (or experiments) by means of the iteration in order to select energy and time dependence Esph.
- The quality of selection should be controlled by comparing Trad(t) of 1D simulations with the experimental results or the data of more accurate calculations.

M. J. Edwards, P. K. Patel, J. D. Lindl et al(117authors)
PHYSICS OF PLASMAS 20, 070501 (2013)

Integral estimation of situation of LLNL autors themselves is:

" … the highest neutron yield obtained has been 8.5 ? 10^{14}, resulting in a hot spot heating rate a factor 10x below that for which alpha deposition would begin to cause bootstrap heating leading to ignition. The neutron yield is also a similar factor below detailed post shot 2D&3D simulation".[1]

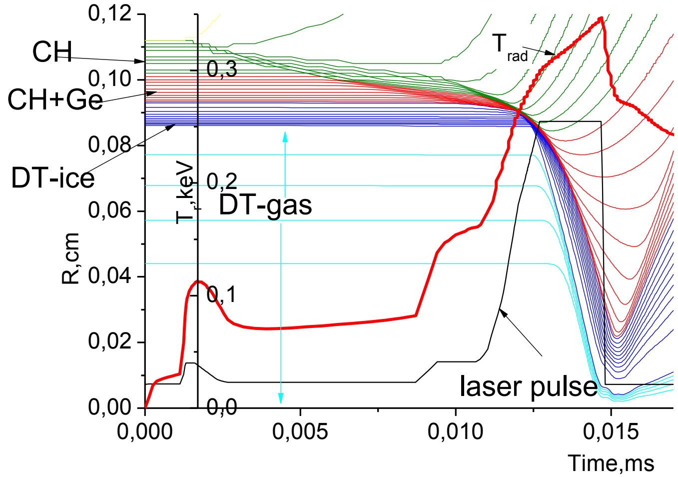
-"In the best performing implosion in which there was little mix of ablator into hot spot (low mix experiment), data analysis indicate that the hot spot density was ~2-3 x below these post shot simulation while the temperature were compatible".[2]

For a full explanation of the experimental results do not have enough knowledge of the range of existing parameters of the laser and target.

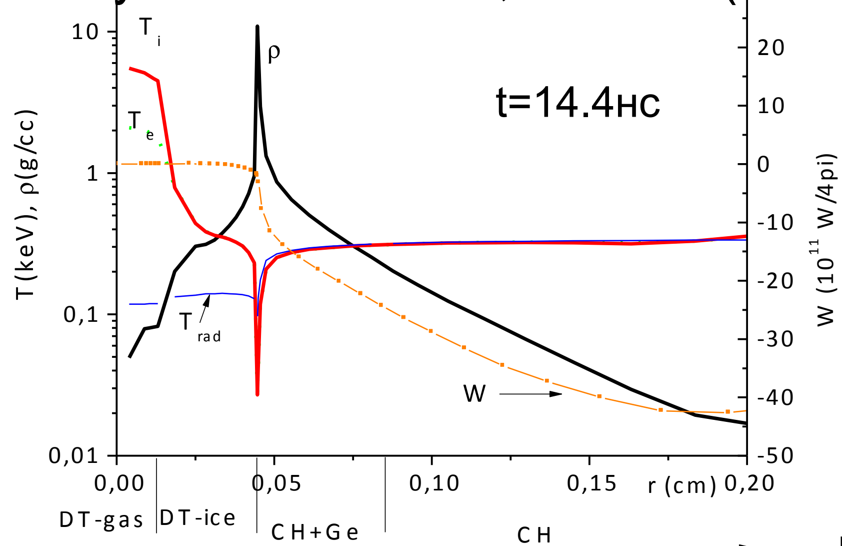
To date, the target parameters need adjustment and exposure.

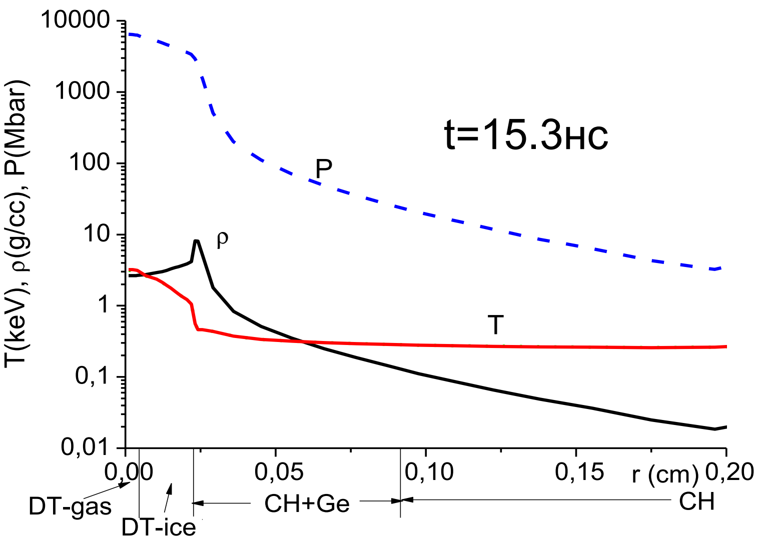
High-foot simulation

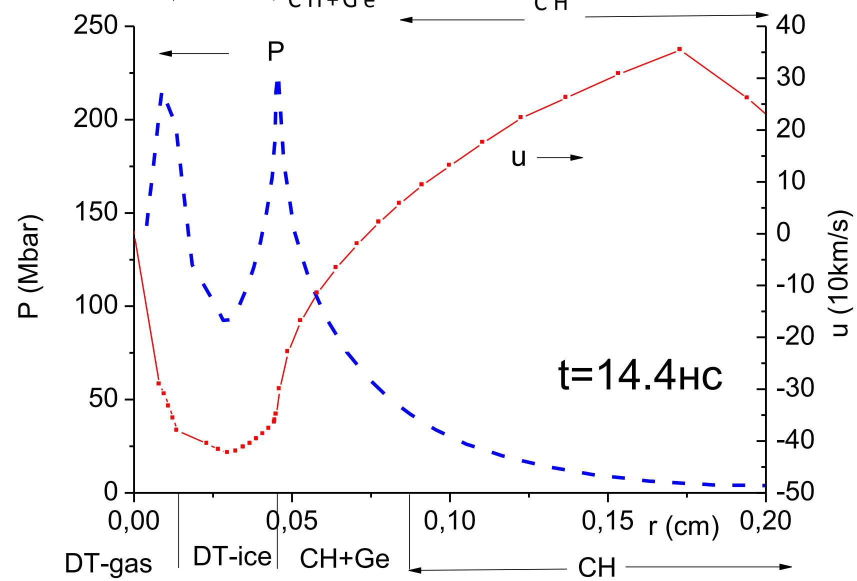
Phys.Rev.Lett..112, 055001 (2014)



R-t диаграмма для эксперимента 130710







Distribution of electron and ion temperatures, density and pressure at 15.3 ns.

- Electron and ion temperatures, density and radiative flow heating up an inner capsule at the time
- Pressure and velocity distribution over the capsule at 14.4 ns.

Agreement between the results (LLNL simulations and experiments and RADIAN simulations) is better in the high-foot regime than in the low-foot regime.

	Experiments LLNL			Simulations RADIAN		
	N130501	N130710	N130812	N130501	N130710	N130812
E_{sph}, MJ				0.48	0.55	0.61
E_{las}, MJ	1.292	1.484	1.693	1.3	1.5	1.7
Velocity, km/s	296	337	312	310	370	320
Compression time t_f, ns	16.76	16.46	16.75	15.68	15.35	15.7
Δt, ns	2.1	1.8	0.9	0.9	0.6	0.4
N_n	$7.67 \cdot 10^{14}$	$1.05 \cdot 10^{15}$	$2.40 \cdot 10^{15}$	$2.12 \cdot 10^{15}$	$1.48 \cdot 10^{15}$	$2.82 \cdot 10^{15}$
P, Gbar	81	53	108	11	8	30
T_{ion}, keV	3	3.5	4.2	3.5	4	4.2

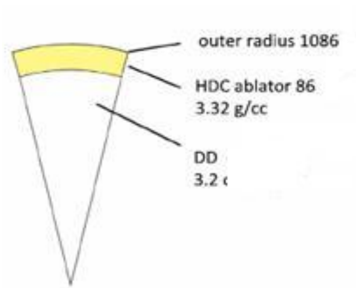
Phys.Rev.Lett.112, 055001 (2014)

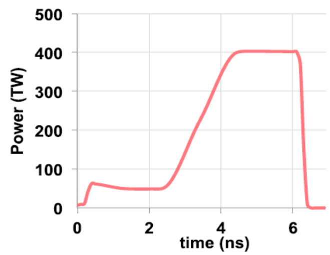
Post shot simulation

High-density carbon (HDC) capsule simulation.

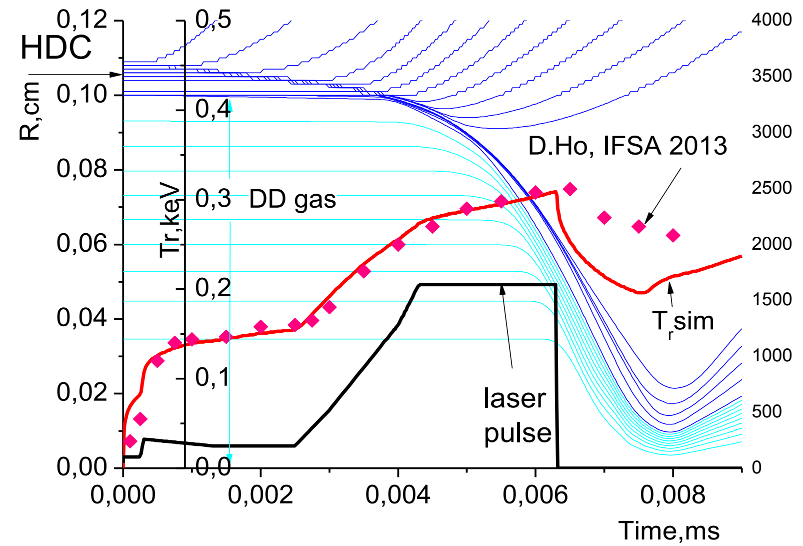
Capsule with an ablator made of high-density carbon (diamond phase, ρ=3.32g/cm3).

D.Ho, IFSA 2013, shot 130813; Phys. of Plasmas 21, 056318 (2014).



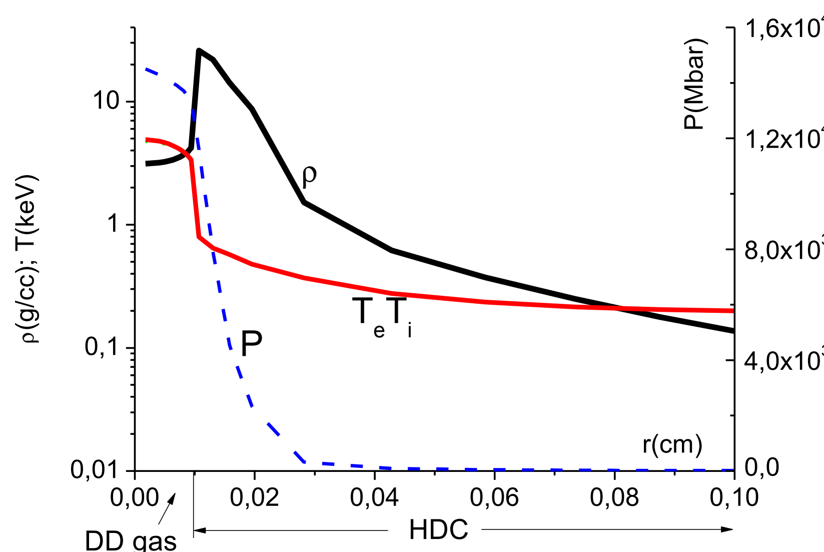


2-shock pulse shape



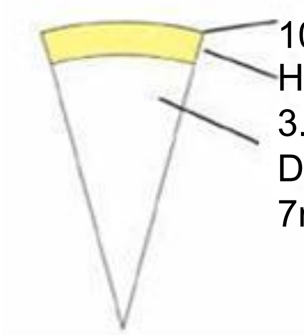
86 mcm thick capsule for experiment N130813 contains DD gas (density, 3.2mg/cc)

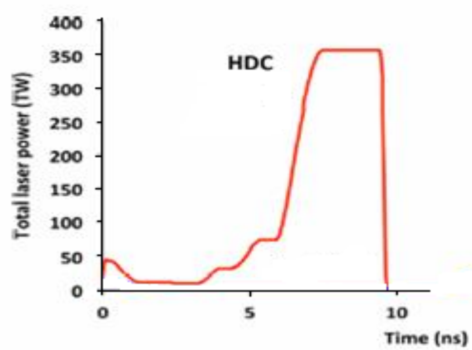
	LLNL, N130813		RADIAN
	эксперимент	расчет	расчет
N_{neutr}	$2.3\cdot10^{13}$	$2.4\cdot10^{13}$	$5\cdot10^{13}$
T_{ion}(кэВ)	3.4	3.3	3.6
Bang time (нс)	7.77	7.75	7.95
R_{min} (mcm)	91	101	96.7
V_{max} (km/s)	-	440	400



High-density carbon (HDC) capsule simulation. Capsule with high-density carbon ablator (diamond phase, ρ=3.32g/cm3).

D.Ho, IFSA 2013, shot 130813; Phys. of Plasmas 21, 056318 (2014).



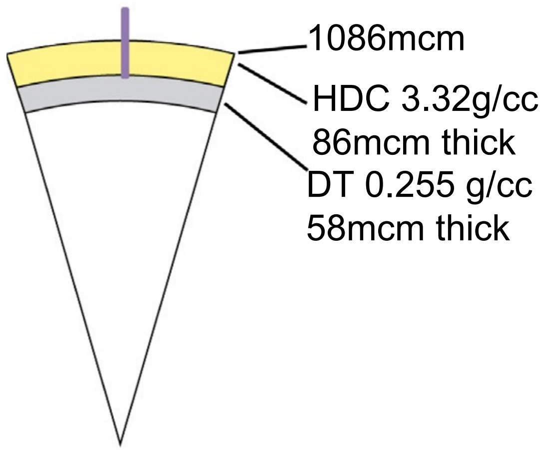


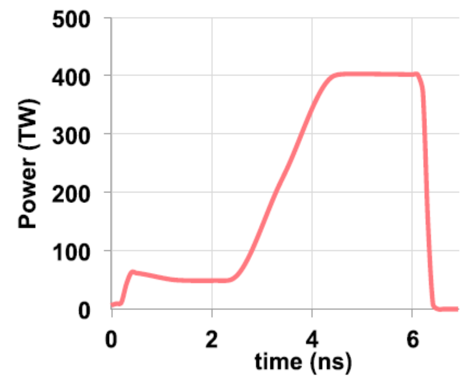
4-shock pulse shape

76 mcm thick capsule for experiment N130628 contains DT gas (density, 7mg/cc)

	Measured	LLNL calculated	RADIAN
N_n	$1.67\cdot10^{15}$	$1.74\cdot10^{15}$	$2.2\cdot10^{15}$
T_{ion} (keV)	2.85	2.56	3.2
V_{max} (10^7 cm/s)	2.5	2.35	3.2
Bang time (ns)	12.56	12.58	10.76

High-density carbon (HDC) capsule simulation. Capsule with high-density carbon ablator (diamond phase, ρ=3.32g/cm3) with DT-ice (2 pics. D.Ho, IFSA 2013, shot 130813; Phys. of Plasmas 21, 056318 (2014).



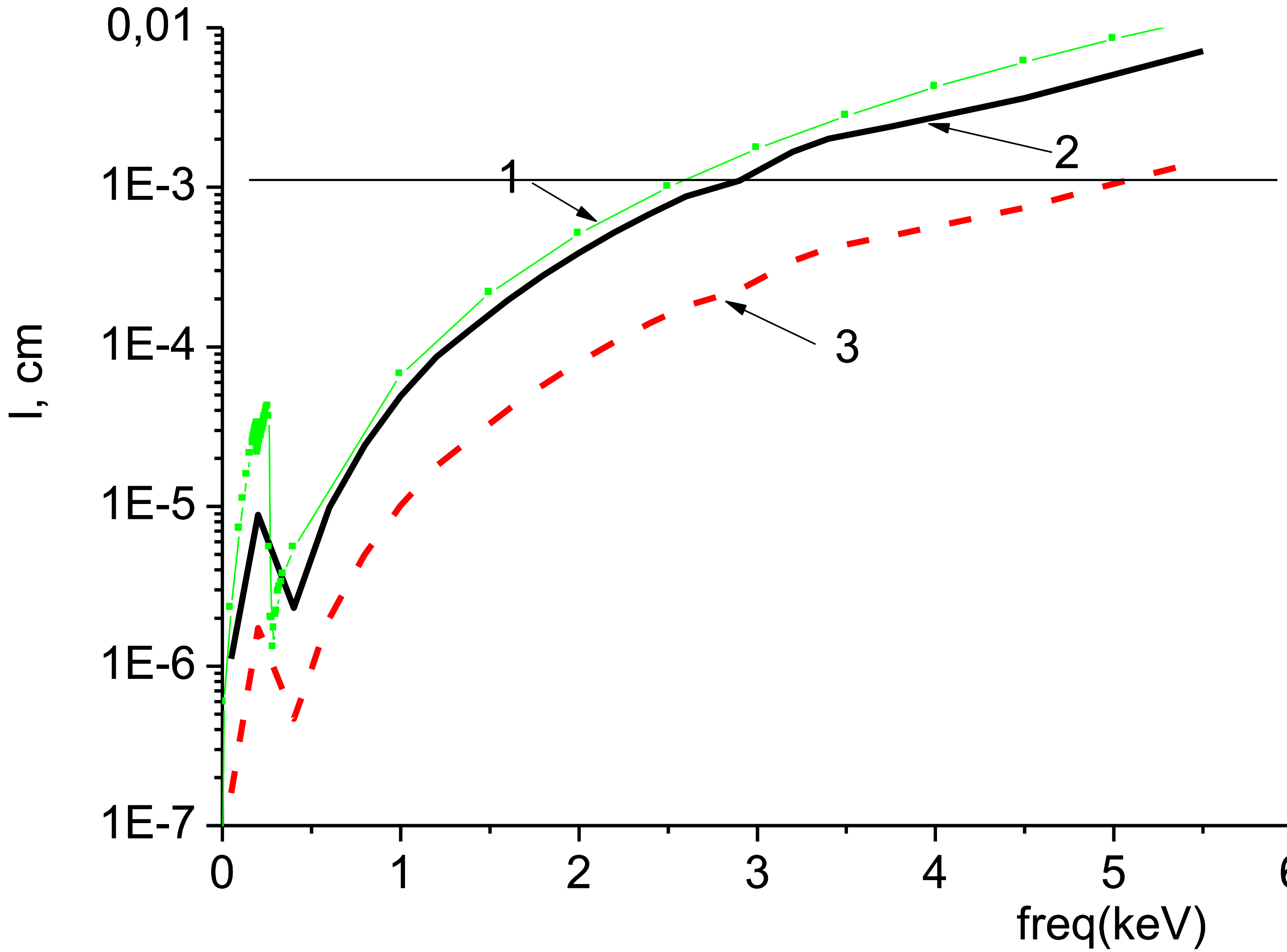


2-shock pulse shape

	T_{rad} (eV)	v_{max}	N_n
LLNL	300	390	1.8 ? 10^{16}
RADIAN	320	400	4.2 ? 10^{15}

Continuing the calculations we found tangible relationship between the compression of the target and Ge impurities.

Suppose that our spectral lengths permit deviation from the lengths in the real experiment several times. The figure shows the dependence of the radiation lengths from the photon energy.



Spectral path of the radiation within the range of temperatures 6-11eV and densities 10-15g/cm3 .THERMOS code simulations [20] – curve 1. One quarter of the radiation spectral path –

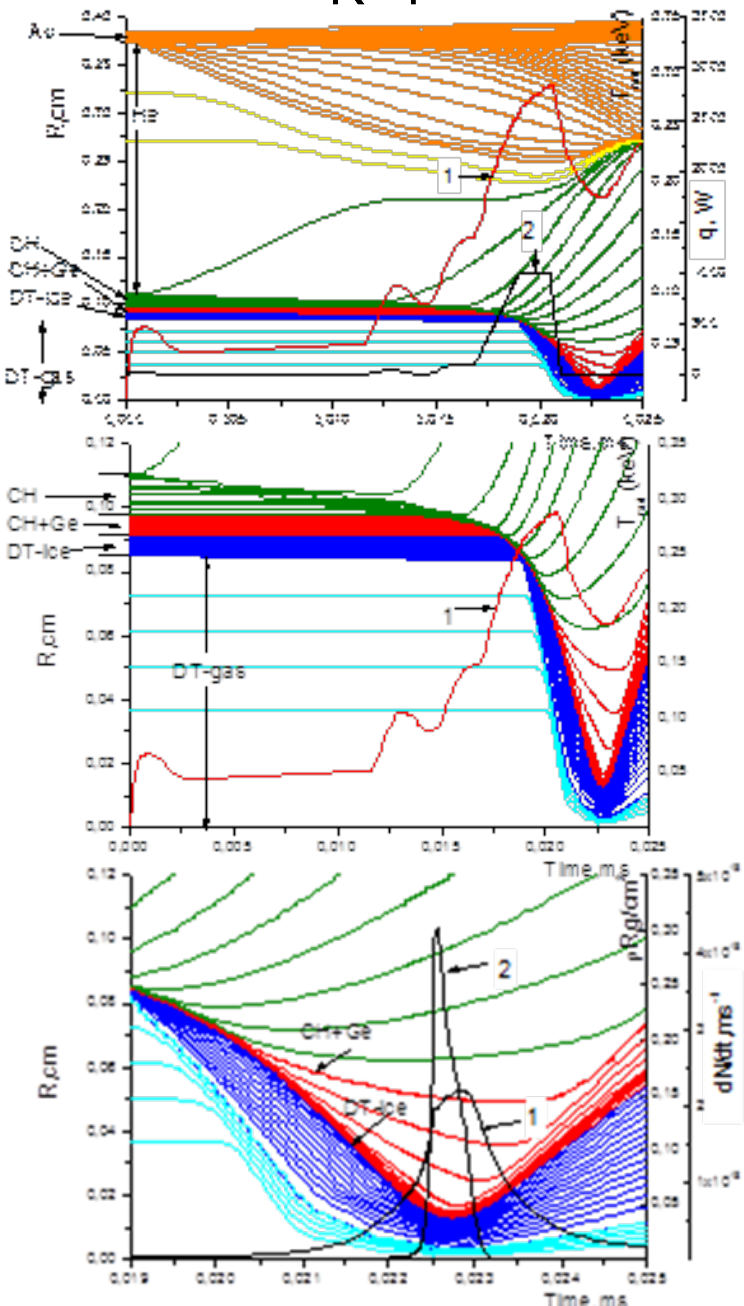
Results of simulation with reduced lengths are shown in the table. Changes in the spectral length relate to the small volume targets.

Table 1a.

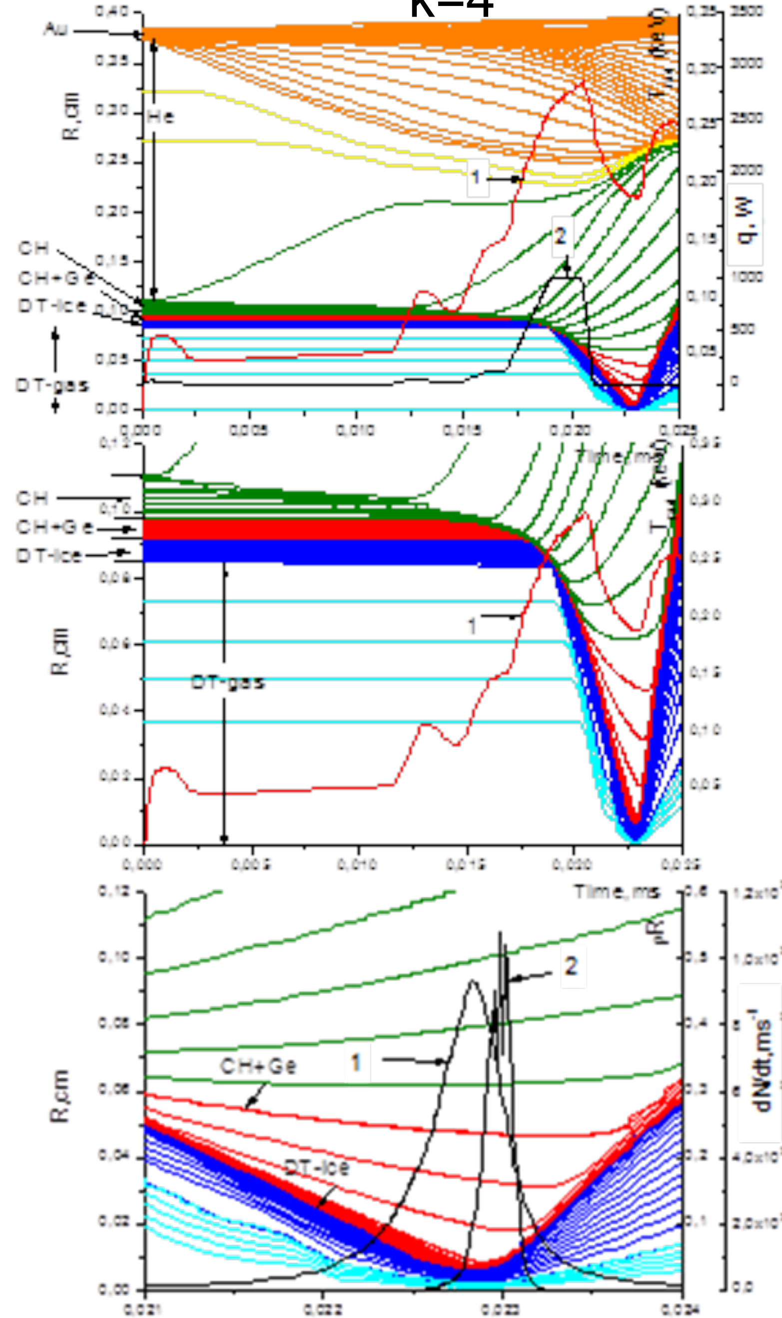
k	**1**	**3**	**3.5**	**4**	**7**	**10**	**20**
$N_{нейтр}$, 10^{15}	1.46	25.6	54.6	187	5560	6000	6440
$E_{тя}$, 10^3 J	4,2	72	154	525	15600	16800	18100

Difference can be seen in the dynamics

K=1



k=4



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Conclusion

- The simulation results ("low foot" and "high foot" regimes, compression of targets with HDC ablator) are in a satisfactory agreement with the measurement results and correspond to the range of the observed parameters. However, they do not give a complete quantitative description of the experiment.
- A physical basis for a possibility to use 1D description lies in the fact that the last stage of capsule compression is close to 1D process.
- In this connection there arises an interesting question: what part of the observed discrepancies between simulation and experiment is of 1D character (inadequacy of databases, defects and drawbacks of the modeling codes, unknown parameters, etc.), and what part of them requires consideration of 2D and 3D processes and the performance of simulations with account of hydrodynamic instabilities and mixing? The papers published in literature do not give answer to this question.
- We believe that 1D modeling of compression can be useful in establishing of some boundary, beyond which the 2D and 3D modeling will prove to be absolutely necessary.

ИНСТИТУТ
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Ф И А Н

- Thank you for attention