Simple model for indirect target compression under conditions close to the NIF laser facility at 1.5 MJ energy

V.B. Rozanov, G.A. Vergunova
P.N. Lebedev Physical Institute of the RAS, Moscow, Russia.

35th International Workshop on Physics of High Energy Density in Matter
January 26th - January 30st , 2015
Waldemar-Petersen-Haus, Hirschegg, Austria

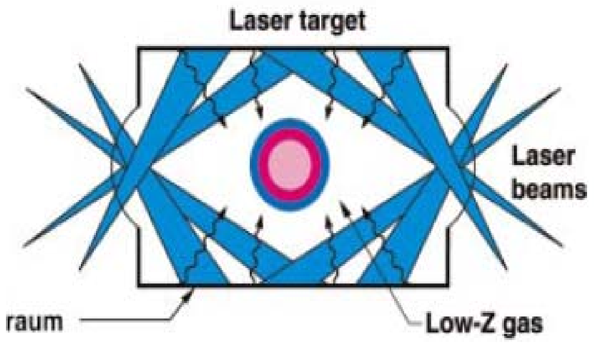
Introduction

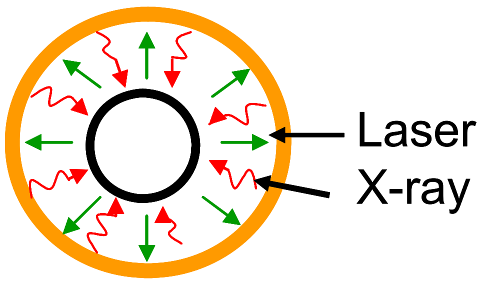
- A one-dimensional model for indirect target compression is proposed, which corresponds to the compression conditions of NIF facility, and allows one to analyze the experimental results. The model reproduces the known from literature data on the measured radiation temperature in the cavity and the shell motion velocity.
- The model is based on the RADIAN code. The mathematical model for description of physical processes in this code contains the equation of motion, equation of continuity, the equation of energy balance for electron and ion components, the matter equation of state for ions and electrons. The electron-ion exchange and a classical Spitzer heat conductivity are taken into account, and there is a possibility to decrease the heat conductivity aimed at better correspondence with the experimental results. A possibility is provided to use different equations of state. Spectral radiation transport is considered in a multi-group approximation, and the number of groups may reach 1300. 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.
- The model makes it possible to determine the temperature, density, Fermi adiabate and other parameters of the target at the stage of compression and burning, which affect the final thermonuclear yield

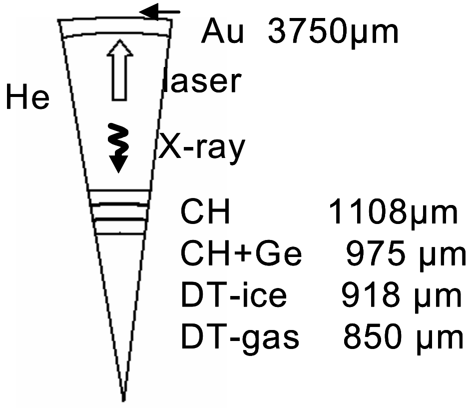
- Numerical modeling in 1D geometry though being inappropriate for a quantitative analysis of the experiment allows one to define the main parameters of target compression. An additional argument in favor of 1D geometry lies in the fact that the processes in the target begin as essentially non-dimensional ones, and in the end we have a small area which should be spherical.
- 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 target central part should be essentially one-dimensional. In 1D model the main energy balance, time characteristics and other parameters in the target should be fulfilled.

- We had at our disposal the optical constants obtained by the program THERMOS (Nikiforov A.F., Novikov V.G., Uvarov V.B. Quantum-statistical models of high-temperature plasma. Moscow, Phys.-math. Literature, 2000).
- In our 1D simulations we substitute a cylindrical converter for a spherical one. The capsule is placed in the center of this spherical converter. Taking into account the size of the converter, capsule, and holes in the converter, as well as the difference between the converter geometry in the NIF facility and the numerical simulation, we define the energy coming into the converter cavity, and then make numerical simulation of such a capsule compression.
- We made a series of simulations, which reproduce the main behavior and the published results from NIF simulation and experiments for the conditions when ignition was not observed. In this simulation we used different pulse energy, time duration and target design.

Energy balance equation







Laser radiation comes through the cylinder ends and is transformed into a soft x-ray radiation on the inner walls of the cylinder. The x-ray radiation evaporates the ablator of a spherical capsule. Part of the x-ray radiation comes out through the cylinder ends and is lost. In 1D model the stage of rlaser input is absent, the laser radiation comes onto the inner walls of the external shell, and there are no radiation losses through the entrance holes. Cylindrical and spherical targets are shown in Fig.1.

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

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

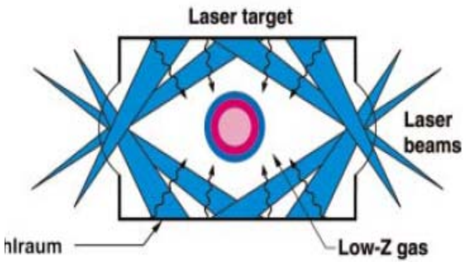
$$U_{rad}V_{rad} + \int_o^t W_{cap}S_{cap}\,dt + \int_o^t W_{LEH}S_{LEH}\,dt + E_{Au}(t) = E_{Las}(t) \qquad (1)$$

In a spherical model problem:

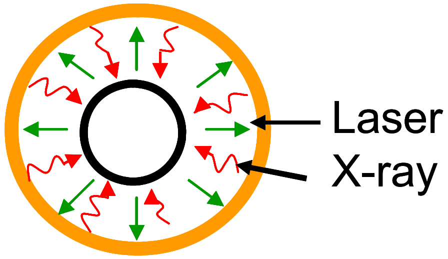
$$U_{rad}V_{rad} + \int_o^t W_{cap}S_{cap}\,dt + E_{Au}(t) = E_{sph}(t) \qquad (2)$$

Here U_{rad} is the x-ray radiation energy per unit volume; V_{rad}, the volume occupied by the radiation; W_{cap}, the radiation flux absorbed in a thermonuclear capsule; S_{cap}, the capsule surface; W_{LEH} and S_{LEH}, the the x-ray radiation coming through the entrance holes and the area of the holes, respectively (LEH – Laser Entrance Holes); $E_{Au}(t)$, the energy absorbed in the target walls by the time moment t; $E_{sph}(t)$, the energy coming into the spherical target. For a cylindrical target the real dimensions of one type of the target have been considered: the cylinder diameter, 5.45 mm; cylinder length, 9.5 mm; diameter of the laser radiation entrance holes, 2.275 mm; the capsule dimension is shown in Fig. 1. In many experiments the cylinder walls (hohlraum) were made of gold (Au). That is why just this material was used in the discussed 1D model. The model can be used to define the dependencies on the wall material, should there be available the characteristics and spectral coefficients of other materials in the database.

Energy balance equation



The laser energy absorbed on the walls of the target (Au) and the central capsule (CH) can be directly found from the simulations, the time dependence of the laser pulse being given or known. Since the experiments used a profiled pulse, the main contribution to the time integrals is made 5-3 ns before the end of the pulse, when the input energy is maximal. For a spherical target (Fig.1), when the radiation temperature T_{rad} falls over the range 270-340eV, the mentioned values are as follows: $E_{cap}/E_{sph}=0.34\text{-}0.28$, $E_{Au}/E_{sph}=0.62\text{-}0.7$. The energy associated with the volume filled with equilibrium radiation turns to be insignificant (2-4%). The energy balance for a spherical model may be written in the form:

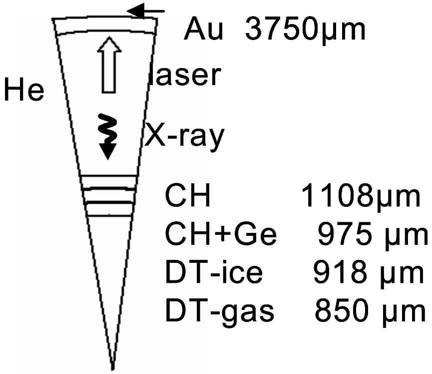


$$E_{sph}=E_{cap}+E_{Au}\,.$$

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.

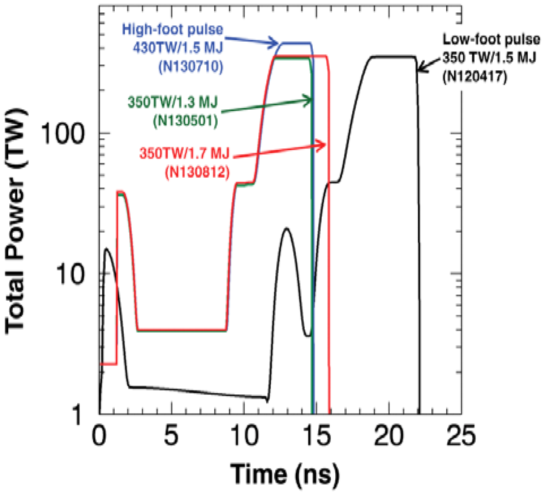


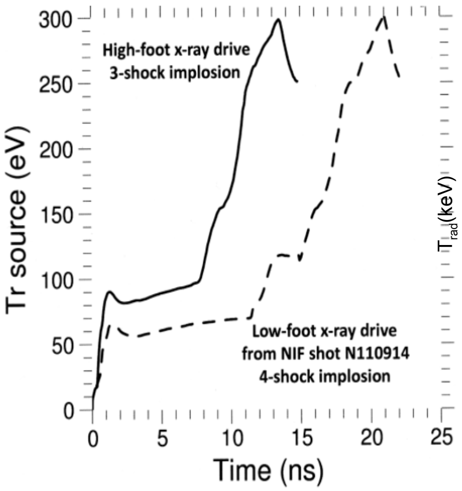
E_{sph}, МДж	T_{rad} , эВ	E_{cap}/E_{sph}	E_{Au}/E_{sph}	E_{LEH}, МДж	E_{las}, МДж
0.325	274	0.34	0.63	0.394-0.197	0.719
0.36	287	0.33	0.64	0.475-0.238	0.835
0.4	300	0.34	0.62	0.567-0.284	0.967
0.45	316	0.33	0.64	0.698-0.349	1.15
0.5	330	0.32	0.65	0.830-0.415	1.33
0.55	341	0.28	0.7	0.946-0.473	1.50

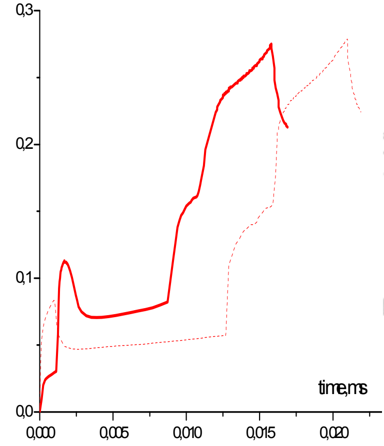
In Table 1: E_{sph} is the deposited energy in 1D simulation; T_{rad} , the radiation maximum temperature in the centre of He layer; E_{cap} and E_{Au} , the energy absorbed by the capsule and the wall of a spherical target; $E_{las}=E_{sph}+E_{LEH}$, the estimated laser energy for a cylindrical target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

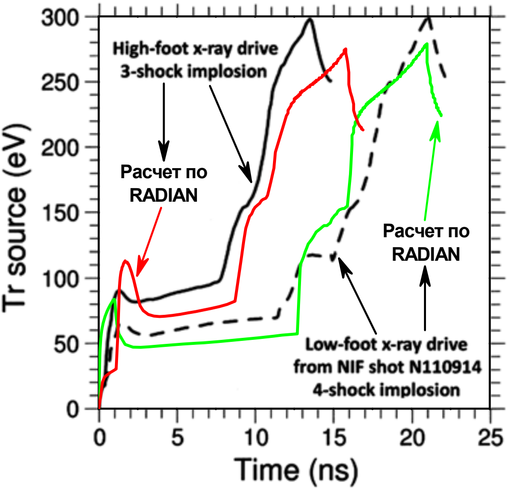
Description of typical laser pulses and course of radiation temperature in “low foot” “high foot” experiments

- The results of numerical simulation of radiation temperature T_{rad} in the cavity at “low foot” and “high foot” regimes by the RADIAN code. It is seen that the discussed model reproduces the radiation temperature in both regimes.



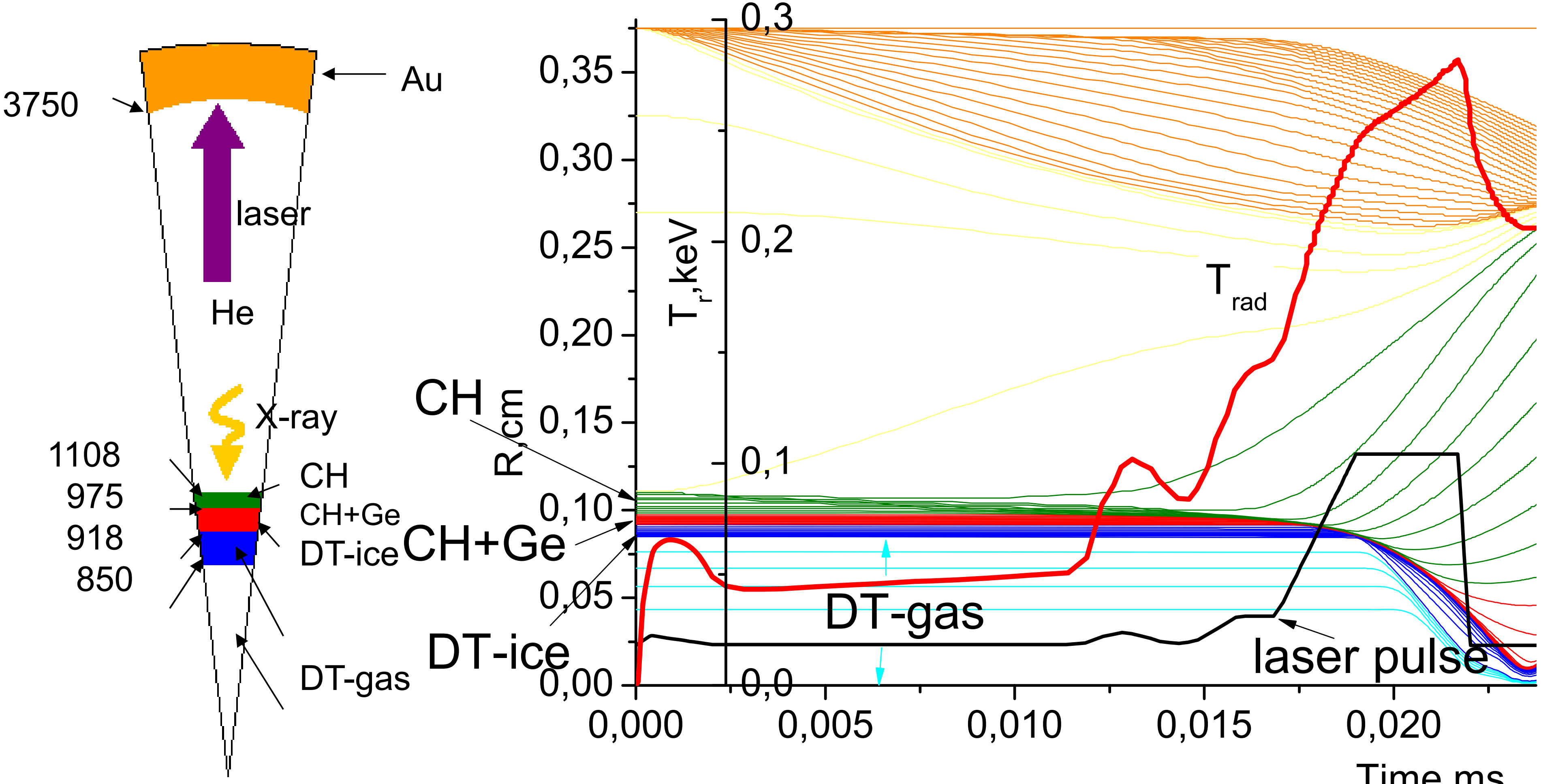






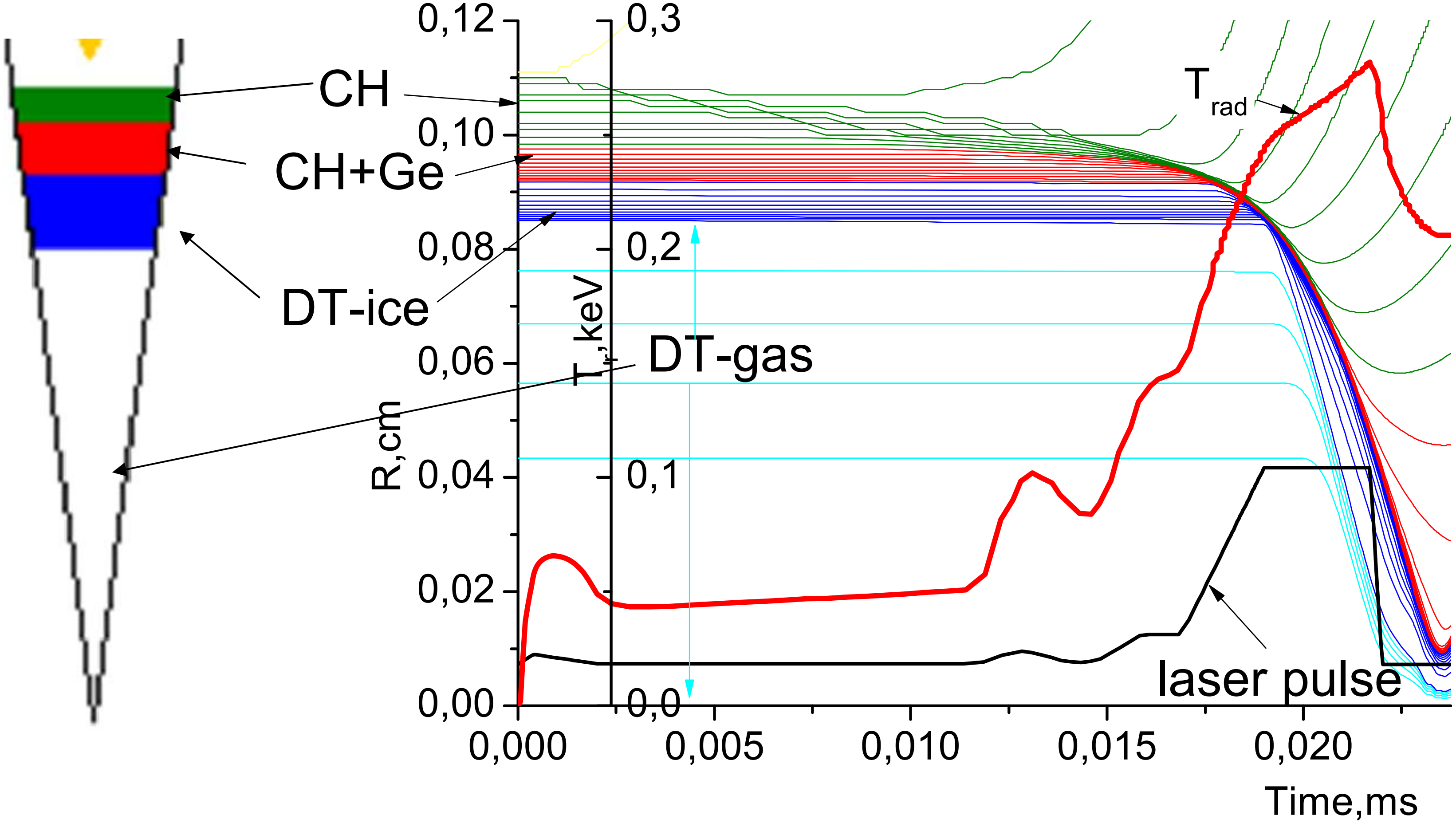
Phys.Rev.Lett.112, 055001 (2014). Phys.Rev.Lett., 112, 055002 (2014)

Low-foot simulation



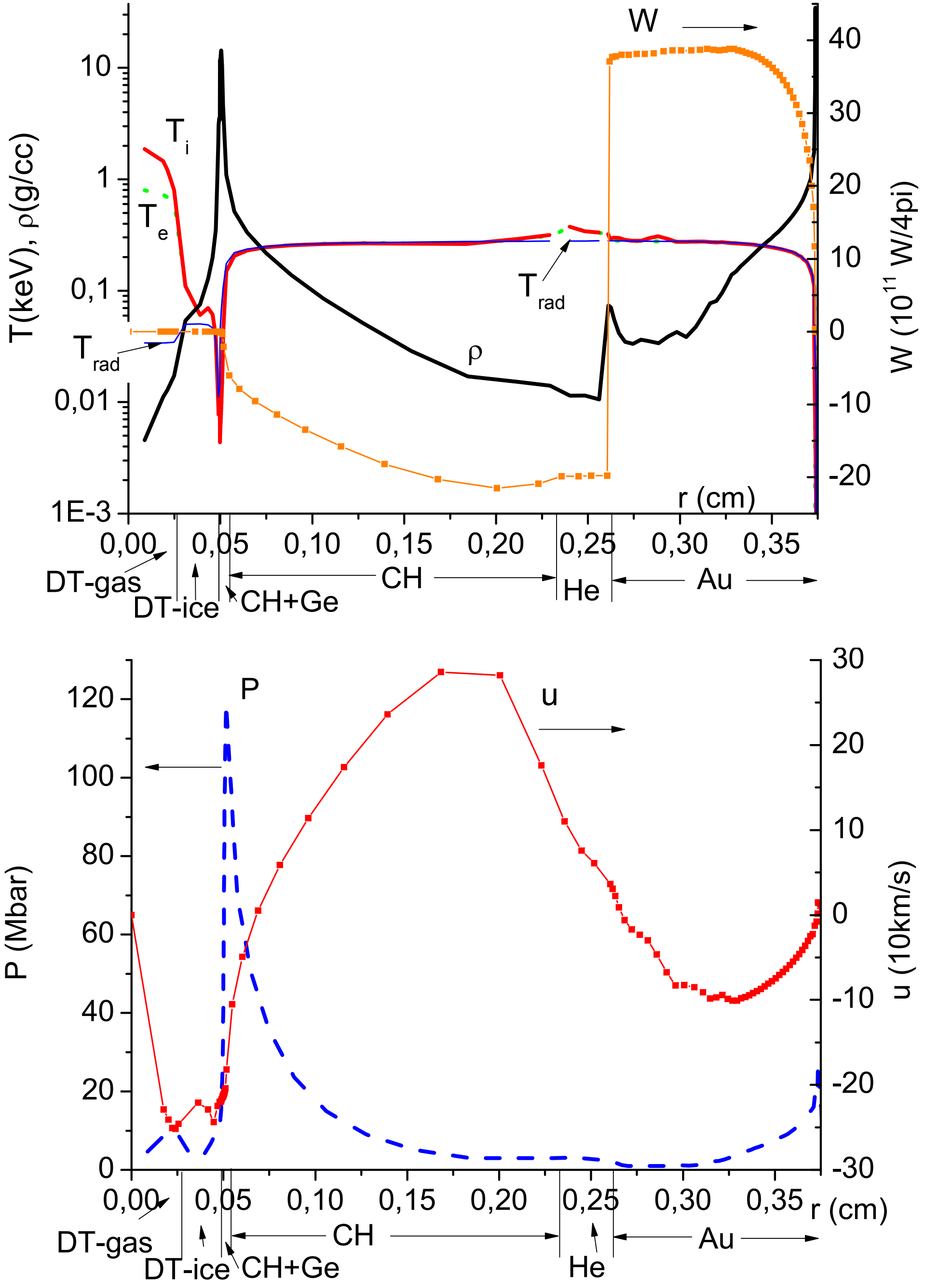
r-t diagram of spherical target heating

Low-foot simulation



r-t diagram of the inner shell capsule compression

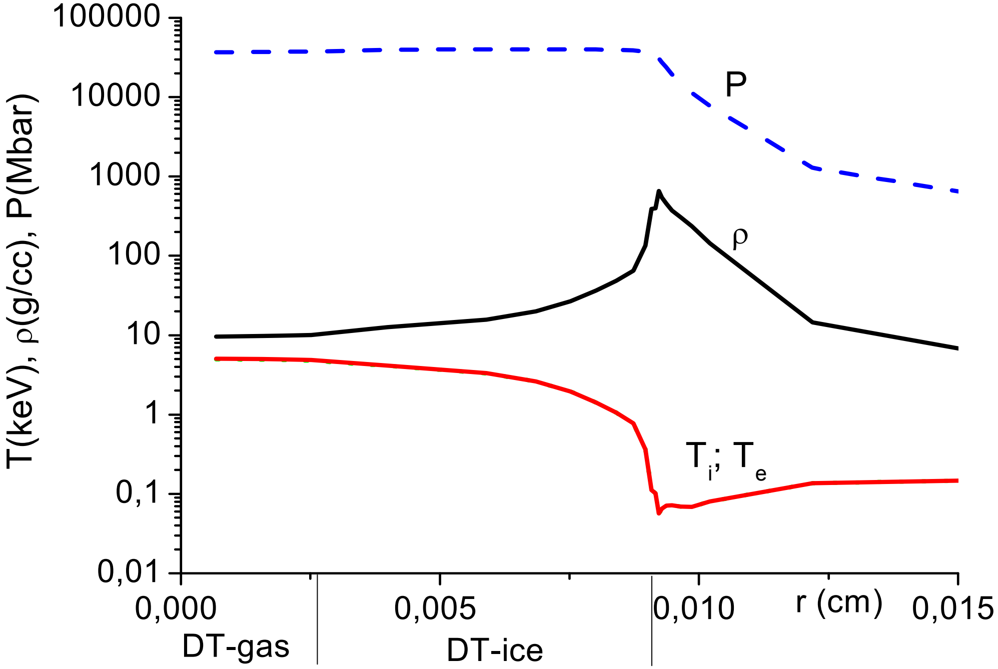
Low-foot simulation



The electron, ion and radiation temperature, the density and the radiation flux heating the inner shell at the time moment 21.5 ns. The negative value of the radiation flux corresponds to the flux coming into the capsule.

d) Pressure and velocity distribution in the target at 21.5 ns.

Low-foot simulation



The distribution of electron and ion temperature, the density and pressure at 23.5 ns.

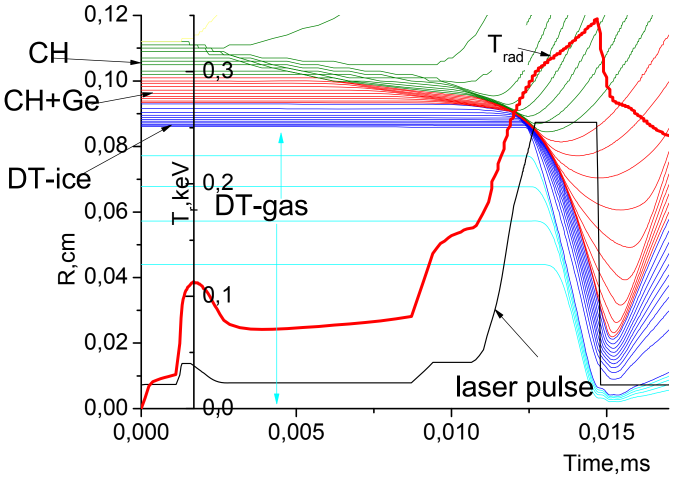
Low-foot simulation

	LLNL				RADIAN simulation E_{sph} (MJ)		
	Predicted range from simulations	Maximum value in the experiments	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}(km/s)	370	352	310	312	270	285	290
$T_{ion-gas}$(keV)	3.5	4.3	3.1	3.6	3-5	3.6-5.1	3.8-5.2
N_n (no ignition)	$3.5\cdot10^{15}$	$7.5\cdot10^{14}$	$4.2\cdot10^{14}$	$7.5\cdot10^{14}$	$4\cdot10^{15}$	$1.7\cdot10^{15}$	$4\cdot10^{15}$
P (Gbar)	375	197	156	103	37	18	27

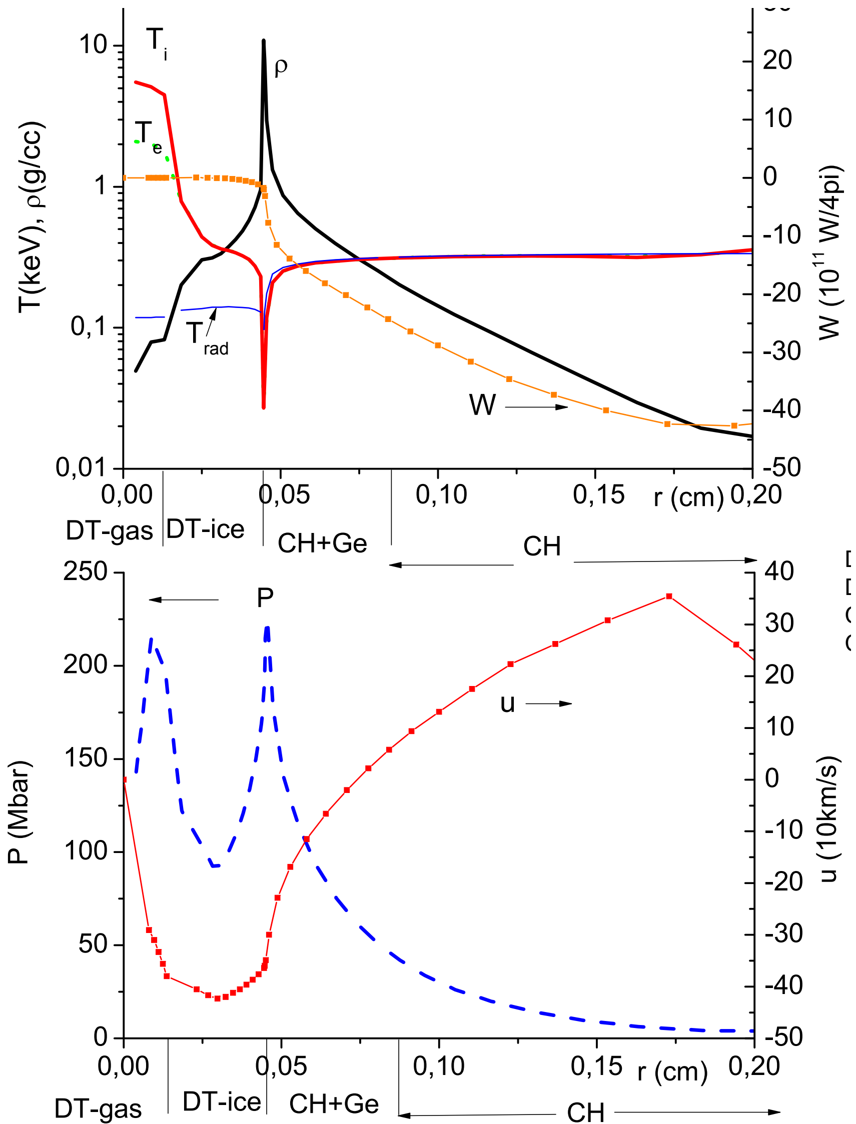
M. J. Edwards et al. Phys. of Plasmas 20, 070501 (2013)

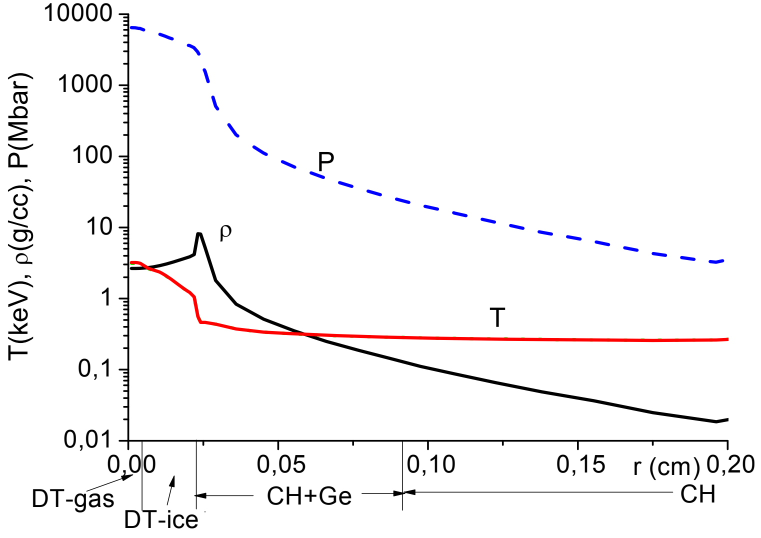
The presented data confirm a possibility to reproduce in 1D simulations some of the results of 2D and 3D character. One should note that the last stage of the capsule compression is (at least should be) , to a high degree, one-dimensional. One can improve the correspondence of 1D and more complete simulations (or experiments) using the iterations to fit the energy and time dependence E_{sph}. The fitting quality must be controlled by comparing the $T_{rad}(t)$ dependence from 1D simulation with the experimental data or the data from more accurate simulations.

High-foot simulation Phys.Rev.Lett..112, 055001 (2014)



R-t diagram for the experiment N130710





Distribution of electron and ion temperature, density and pressure at the time moment 15.3 ns.

The electron and ion temperature, density and radiation flux heating the inner capsule at the time moment 14.4ns. c) Pressure and velocity distribution in the capsule at the time moment 14.4ns.

High-foot simulation

	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

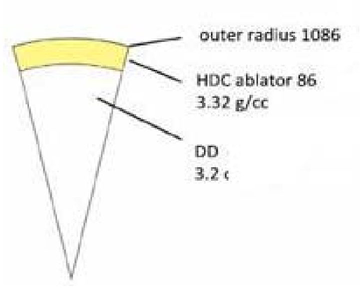
High-foot simulation

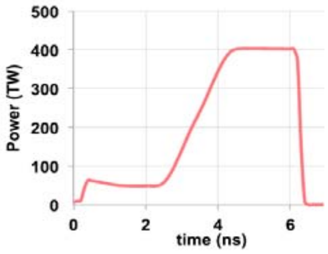
- As a whole, the correspondence of the results (LLNL – simulations and experiments, RADIAN - simulations) for the “high-foot” regime seems to be better compared to the “low-foot” regime. Higher heating at the initial stage of the process, higher value of Fermi adiabate P/P_F, shorter time of compression, and a smaller factor of hydrodynamic instability growth promote adequacy of 1D description and lessen the sensitivity to the details in the description of the characteristics of the matter and processes available in the database of the used programs.
- However, the results of burning with account for hydrodynamic instabilities and mixing can be obtained only in 2D and 3D simulations.

High-density carbon (HDC) capsule simulation.

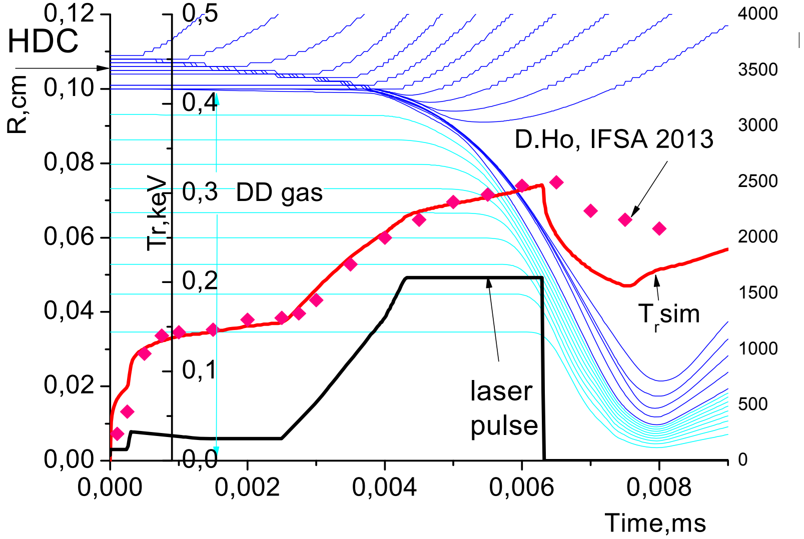
Capsule with an ablator made of high-density carbon (diamond phase, ρ=3.32g/cm3).

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



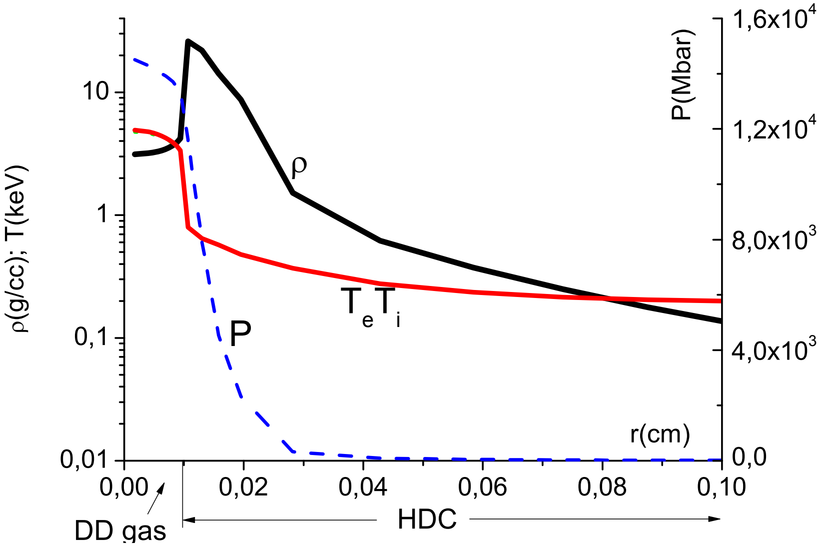


2-shock pulse shape



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

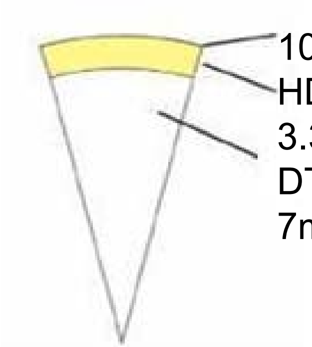
	LLNL, N130813		RADIAN
	эксперимент	расчет	расчет
N_{neutr}	$2.3\cdot10^{13}$	$2.4\cdot10^{13}$	$5\cdot10^{13}$
T_{ion}(кэВ)	3.4	3.3	3.6
Bang time (нс)	7.77	7.75	7.95
R_{min} (mcm)	91	101	96.7
V_{max} (km/s)	-	440	400



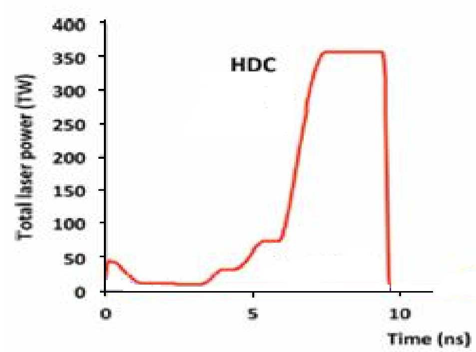
High-density carbon (HDC) capsule simulation.

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

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



1076mcm
HDC ablator 76mcm thick
3.32g/cc
DT gas
7mg/cc

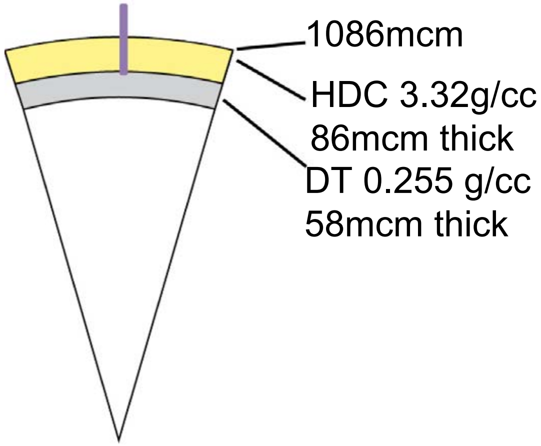


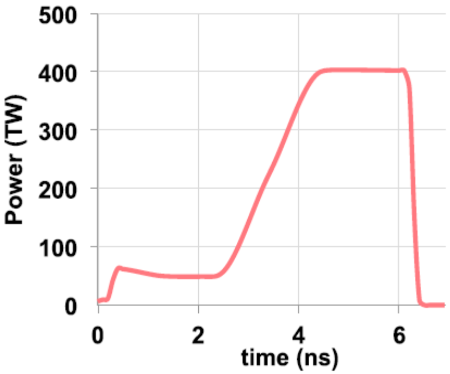
4-shock pulse shape

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	$1.8 \cdot 10^{16}$
RADIAN	320	400	$4.2 \cdot 10^{15}$

Conclusions

- The simulation results are in satisfactorily agreement with the measurement results, and correspond to the range of observed parameters. However, they do not give a complete quantitative description of the experiments.
- The range of compared results may be widened, to obtain, in particular, a more detailed picture of the target parameters in the vicinity of maximum capsule compression. 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 (and, of course, an answer to this question, if to be found)): which part of the observed discrepancies (simulation/experiment) is of 1D character (inadequacy of databases, defects and drawbacks of the modeling codes, lack of knowledge of the parameters, etc.), and which one requires to consider 2D and 3D processes, and make simulations with account of hydrodynamic instabilities and mixing?
- We believe that compression 1D modeling can be useful in establishing the boundary when 2D and 3D modeling will turn to be absolutely necessary.

- Thank you for attention

Conclusions

- A possibility to analyze and interpret the experiments on indirect capsule compression made with a mega-joule NIF laser with the help of 1D RADIAN code in spherical geometry has been studied. The problem of energy balance in the target has been considered, as well as the definition of the laser energy to be used in a spherical model of the target; the analysis of the results from the pulses which differ in energy and time dependence ("low foot" and "high foot" regimes) is presented; the compression parameters for the targets with HDC ablator are obtained (HDC – high-density carbon).
- The simulation results are in satisfactorily agreement with the measurement results, and correspond to the range of observed parameters. However, they do not give a complete quantitative description of the experiments.
- The range of compared results may be widened, to obtain, in particular, a more detailed picture of the target parameters in the vicinity of maximum capsule compression. 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 (and, of course, an answer to this question, if to be found)): which part of the observed discrepancies (simulation/experiment) is of 1D character (inadequacy of databases, defects and drawbacks of the modeling codes, lack of knowledge of the parameters, etc.), and which one requires to consider 2D and 3D processes, and make simulations with account of hydrodynamic instabilities and mixing?
- We believe that compression 1D modeling can be useful in establishing the boundary when 2D and 3D modeling will turn to be absolutely necessary.