The properties of the plasma produced by the heating of a porous matter under X-ray irradiation

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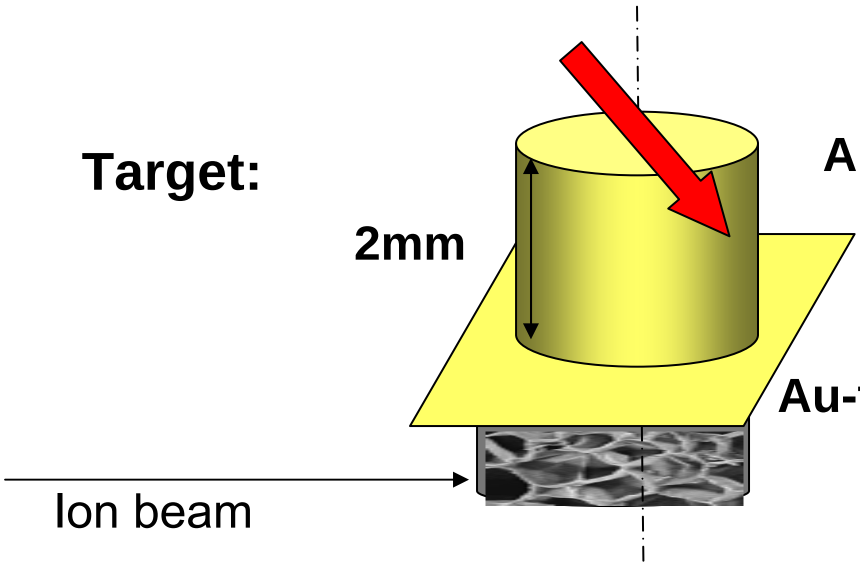
The purpose of our report is simulation and analysis of plasma parameters which are arising in foam matter under action of soft x-radiation

Experimental conditions

Target:



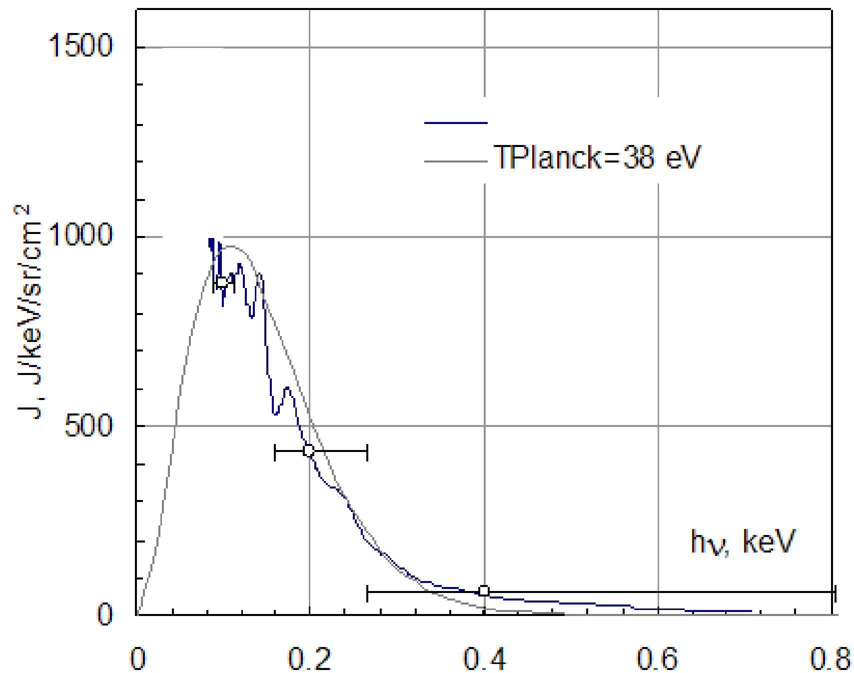
CH-foam 10-20 mg/cm^3 (1/100 of solid)

Areal density ρx=50-500 μg/cm^2

The experimental data are the following:

X-ray spectrum on the plastic foam layer was measured:

- T_{rad}=30-40 eV
- Transmitted energy makes 10-25% of the irradiation energy
- The incident radiation flux on the plasma layer (experimental data) is presented at the right
- The purpose is simulation of plasma parameters for ion beam deceleration .



Code RADIAN: two-temperature hydrodynamics plus radiation transfer equation

$$\frac{\partial r}{\partial t} = u(m,t), \quad dm = \rho r^n dr \qquad 0 \le m \le M \quad , \quad q \le t \le \infty \quad ,$$

$$\frac{\partial u}{\partial t} = -r^n \frac{\partial p}{\partial m} \quad ,$$

$$\frac{\partial}{\partial t}\left(\frac{1}{\rho}\right) + \frac{\partial}{\partial m}\left(r^n u\right) = 0$$

$$p = p_e + p_i \, ,$$

$$\varepsilon_e = \varepsilon_e(T_e), \quad p_e = p_e(T_e)$$

$$\varepsilon_i = \varepsilon_i(T_i) \quad p_i = p_i(T_i) \quad ,$$

$$\frac{\partial \varepsilon_e}{\partial t} = -p_e \frac{\partial r^n u}{\partial r} + \frac{\partial}{\partial m} r^{2n} \lambda \frac{\partial T_e}{\partial m} - K - \frac{\partial}{\partial m} r^n W \, ,$$

$$\rho \frac{\partial \varepsilon_i}{\partial t} = -p_i \frac{\partial r^n u}{\partial m} + K$$

n=0 – plane, n=2 – spherical geometry

Code RADIAN: two-temperature hydrodynamics plus radiation transfer equation

$$\mu\frac{\partial I_\nu}{\partial r}+\delta_{2n}\frac{1-\mu^2}{r}\frac{\partial I_\nu}{\partial \mu}+\chi_\nu I_\nu=2\pi\chi_\nu I_{\nu p}$$

$$W=\int_0^\infty d\nu\int_{-1}^{1}\mu I_\nu d\mu\,,\qquad \chi_\nu=\chi_\nu(\nu,\rho,\mathrm{T}_e),\qquad I_{\nu p}=\frac{4\pi h^2}{c^2}\frac{\nu^2}{e^{h\nu/kT_e}-1},$$

boundary conditions $I_\nu(r=0,\mu)=0$; $I_\nu(r=R,\mu\le 0)=I_0$.

u is the matter velocity; r, space coordinate; p_e and p_i, the electron and ion pressure; ρ, density; ε_e and ε_i, the electron and ion internal energy; K, the rate of energy exchange between the electrons and ions; T_e and T_i; W, the radiation energy flow of the matter; ν, the radiation frequency; μ, the cosine of the direction of the photon flight and the radius at the given point. It is possible to use about 1000 spectral groups.

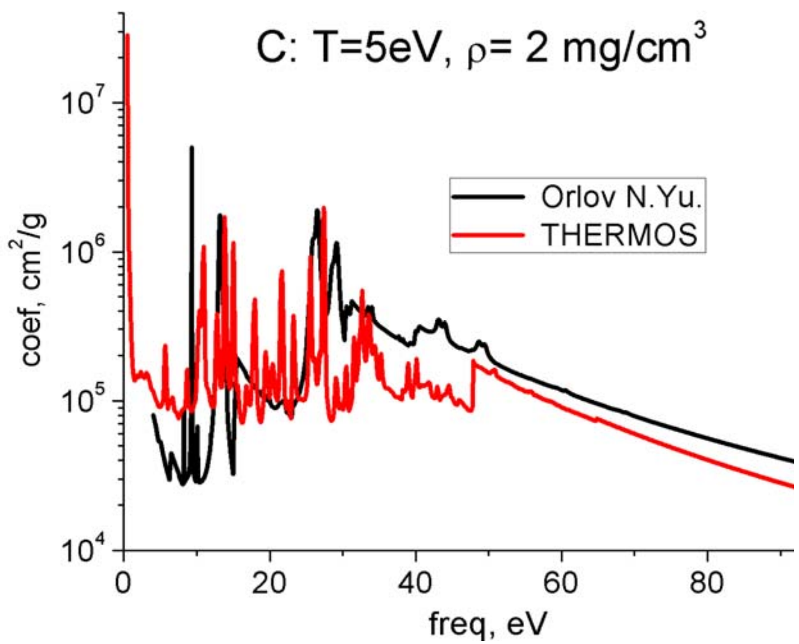
Optical coefficient used in simulation

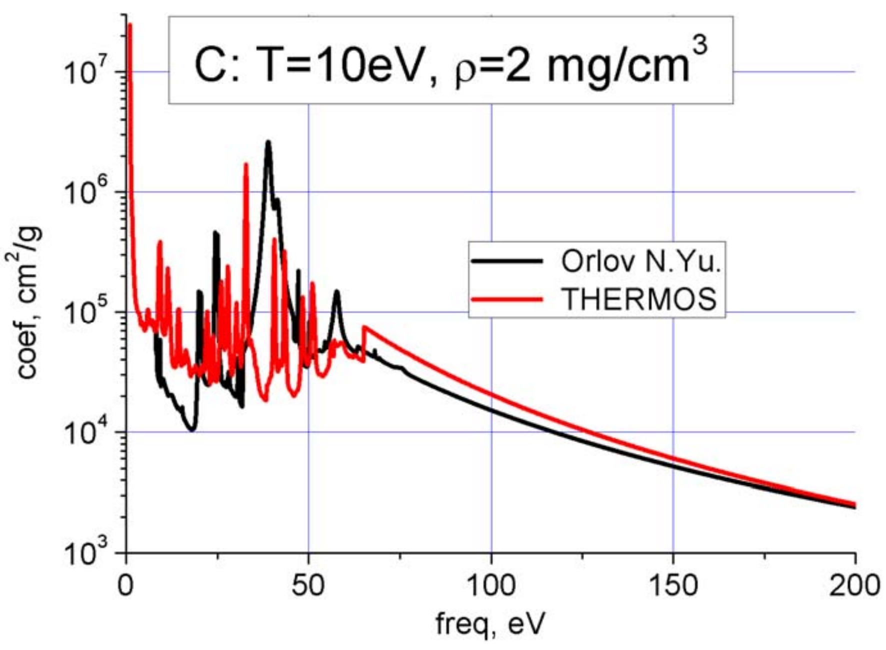
We use optical constants from the codes THERMOS (Inst. of Appl.Math.) and DESNA (Lebedev Phys.Inst.) for CH_2. These constants we indicate below as "real". We compare the absorption coefficient for C with the coefficients simulated by Prof. Orlov N.Yu. (T=5 and 10 eV). They prove to be similar.

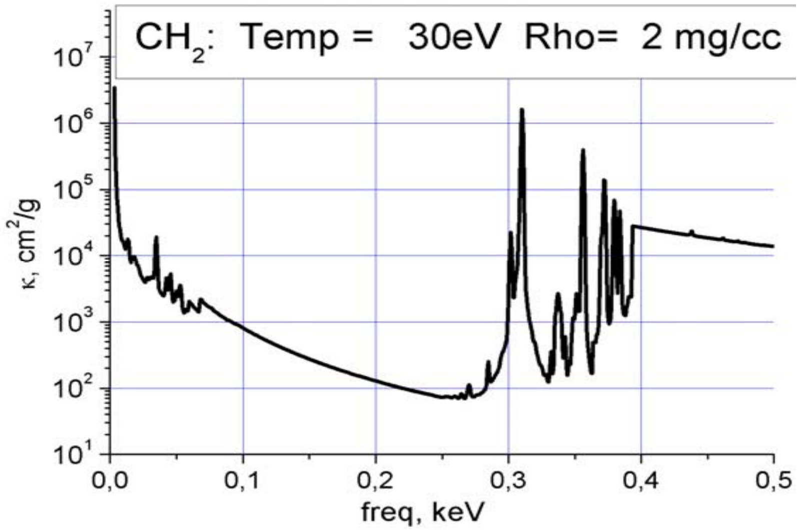
It is seen that the absorption coefficient drops with the temperature increase.

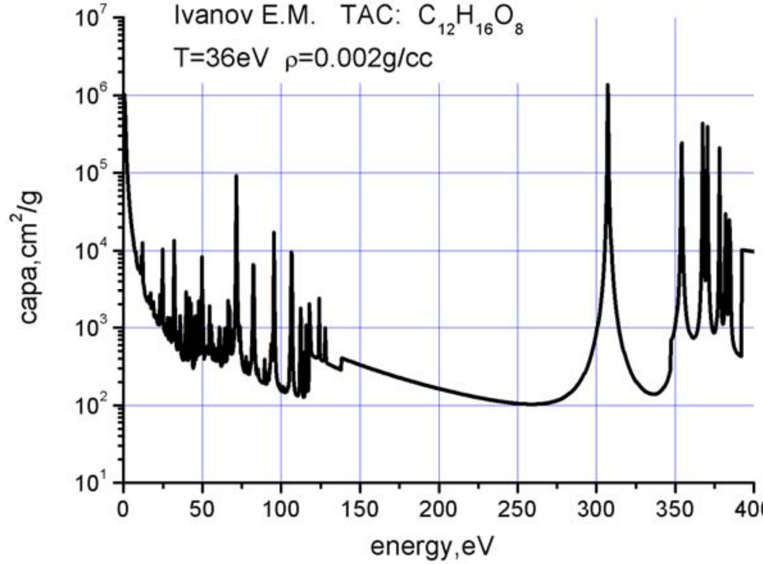
To determine the sensitivity of the simulation results to the radiation constant variation we use also

1) the spectral Bremsstrahlung coefficient, and
2) the model coefficient obtained from the "real" constants by multiplication by number 1/5-2

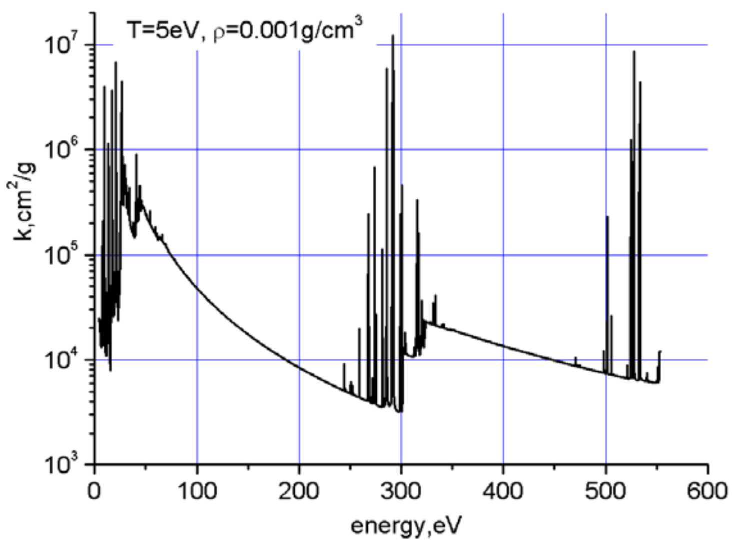








The absorption coefficient TAC ($C_{12}H_{16}O_8$) calculated by the Prof. N.Yu. Orlov. It coincides with CH_2, by an order of magnitude. The absorption coefficients differ structurally due to the presence of oxygen in TAC

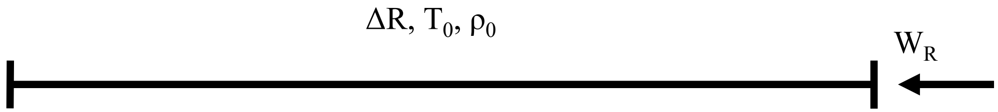


We can predict before demonstration the following numerical results:

- 1) An increasing radiation temperature T_{rad} of the incident flux leads to higher plasma heating. As the temperature rises the absorption coefficient drops, so the transmitted radiation energy increases.
- 2) The results will depend on the absorption coefficients. The greater are the coefficients, the smaller is the transmitted energy.

- There are two possibilities to control the plasma parameters:
- 1) The lower the external temperature T_{rad} of the incident flux , the more optically transparent the coefficients.
- 2) The higher the external temperature T_{rad} , the more optically opaque the coefficients.

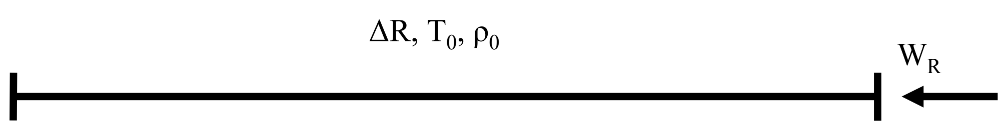
Geometry of simulation



- A plane layer (thickness, 800-1000 μm; density, 2 mg/cc) of polystyrene foam was irradiated by X-ray sources (Planckian) T_{rad}, W_{rad}, t_{rad}.
- The penetration depth of the external source radiation depends on the incident radiation frequency. Lower frequencies are absorbed more effectively than the higher ones.

The table of simulation examples

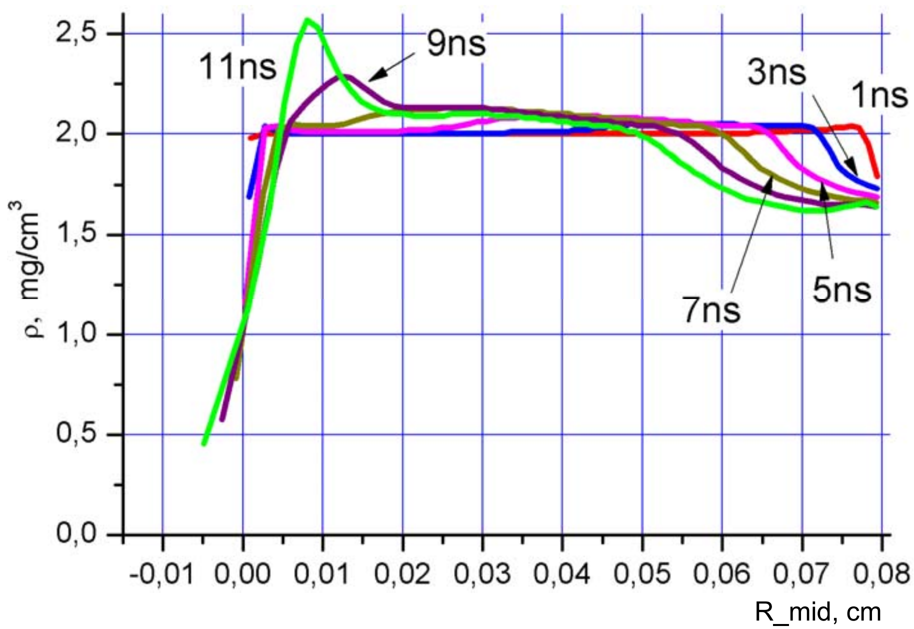
N	T_{rad}, eV	τ_{rad}, ns	W_{rad}, 10^{11} W/cm^2	coef	E_{out} /E_{rad}
169	20	5	0,17	“real”	0.04
172	20	5	0,17	Bremss.	0.95
175	20	5	0,17	1/5* “real”	0.15
176	25	5	0.39	“real”	0.15
171	30	5	0.83	“real”	0.32
174	30	5	0.83	2* “real”	0.10
170	40	5	2.6	“real”	0.64

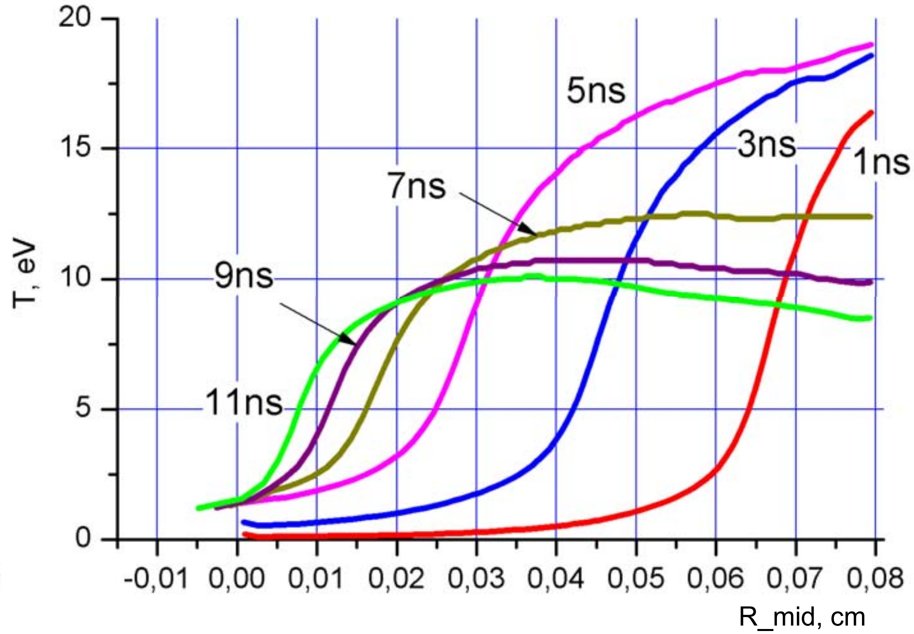


The picture illustrates the results of modeling:
T_{rad}=20eV, $W_{rad}=1.7\cdot10^{10}$ W/cm^2, t=5ns.

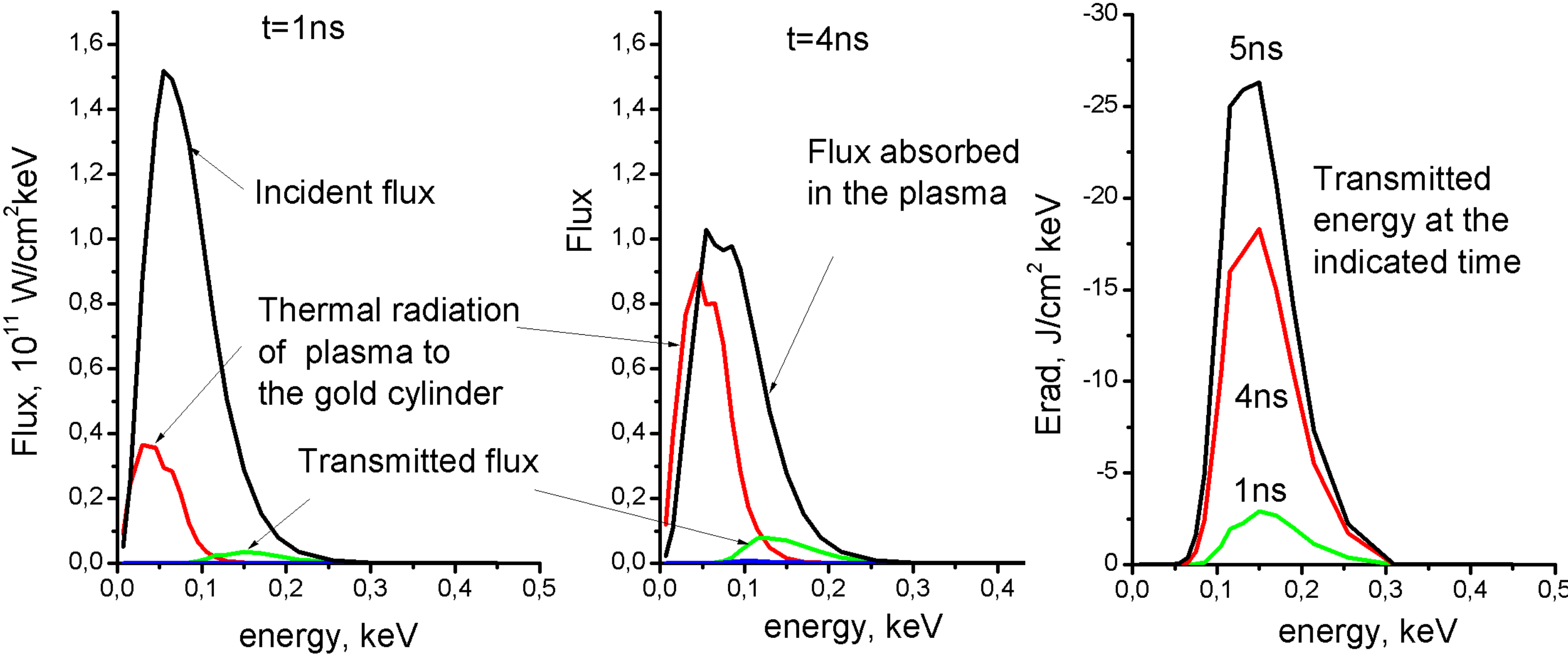
It is seen that during 5 ns the plasma is heated by the external source flow. About 500 μm of the foam is heated. After the end of the external source action the heat transfer is realized by the electron heat conductivity flow. The plasma temperature drops from 17 to 10 eV. In this case the thermal wave heats up the matter for ~250 μm during 5 ns.

1ns < time < 11ns



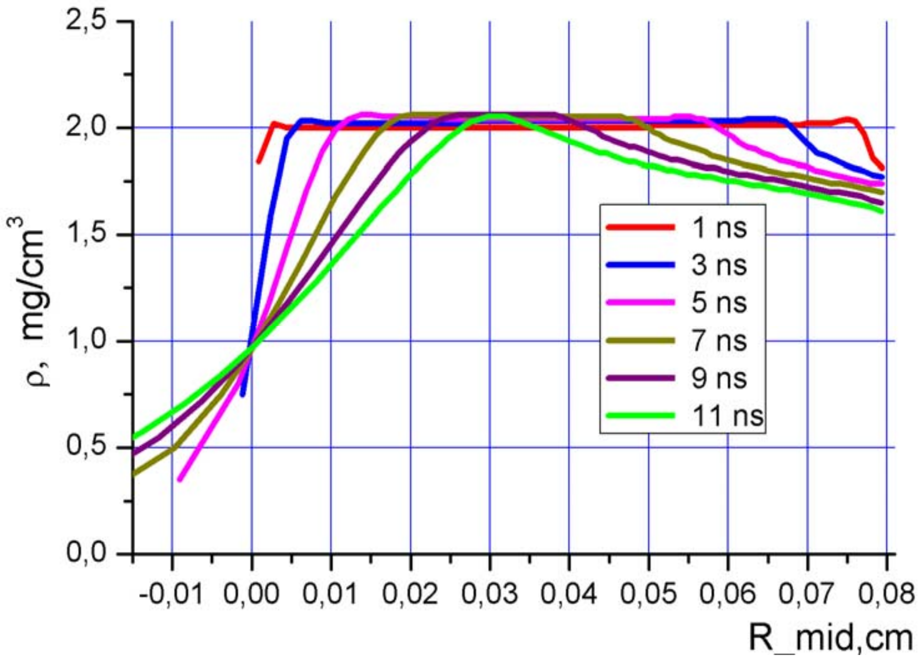


The plasma radiation spectra. Run: T_{rad}=20eV, W_{rad}=1.7·10^{10} W/cm^2, t=5ns.



The results of simulation: T_{rad}=30eV, $W_{rad}=0.83 \cdot 10^{11}$ W/cm^2, t=5ns.

Plasma layer heated by incident radiation up to 5 ns.
Heated plasma extended and its density dropped.

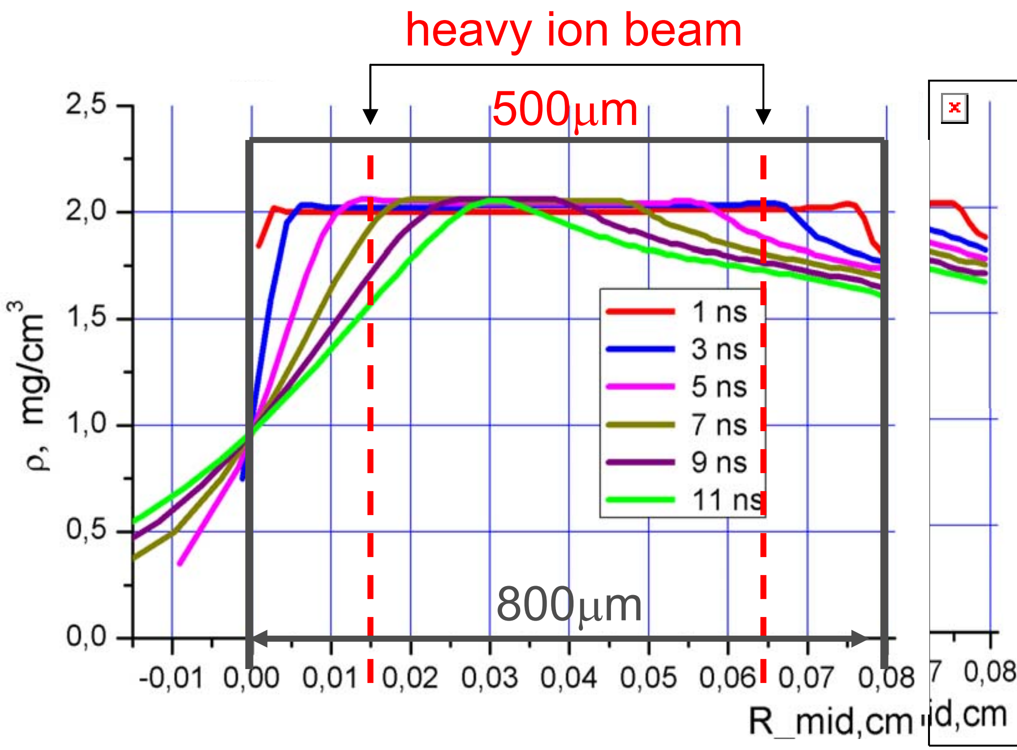


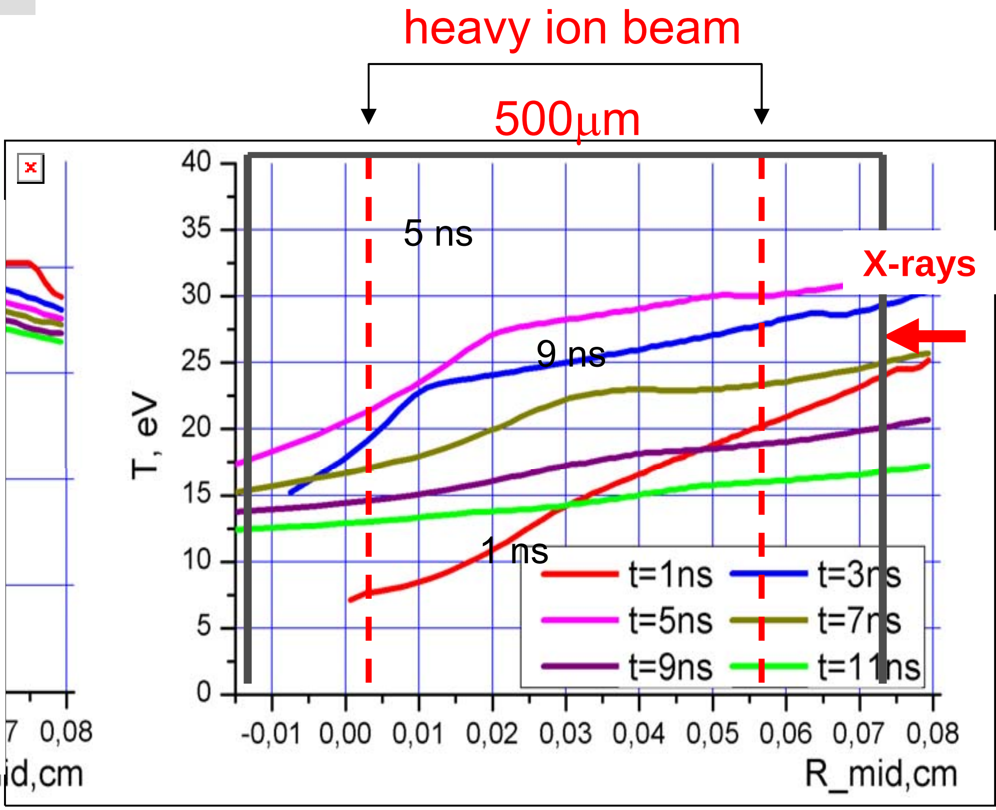
Hydrodynamics of CHO-foam heated by the external X-ray source

Run 170: Planck T_{rad}=40eV; $t_{x\text{-}rays}$= 5ns; TAC 2 mg/cc, 800μm

Density :
Slow 1-D expansion starts at 3-5ns.
Only 15% density fluctuations
in the interaction region of 500μm

Temperature:
time =3-9ns Te=15-25eV





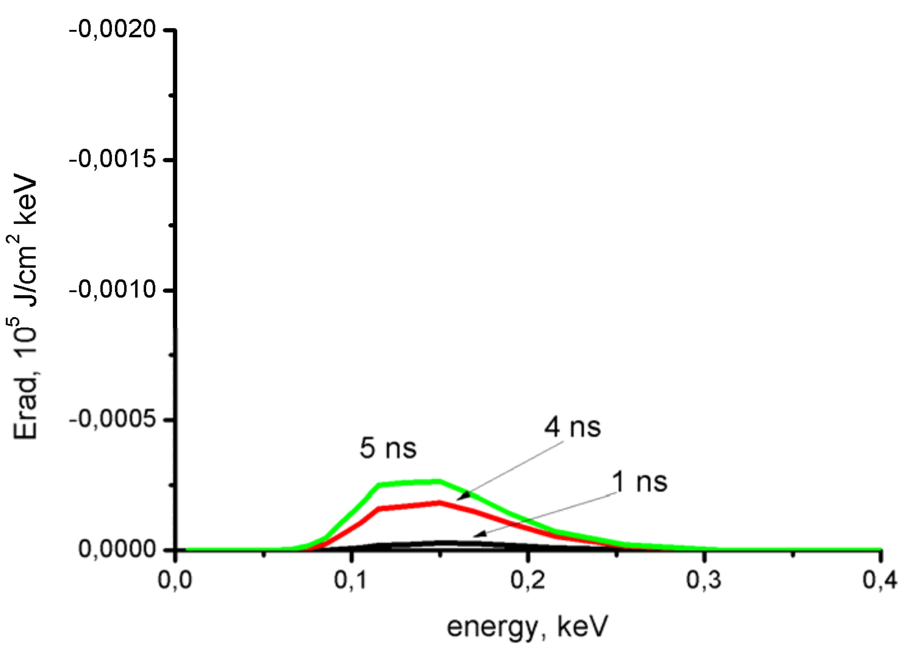
Sensitivity of the calculation results relative to the optical constants

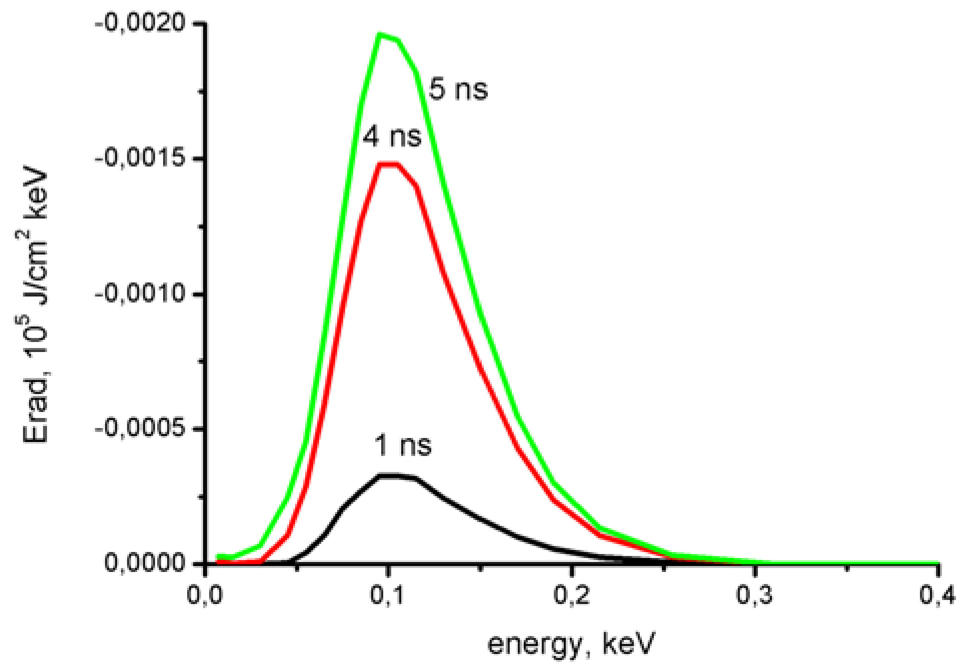
- Decrease in the optical constants (opacity) leads to a decrease in the average temperature of plasma and an increase in the plasma re-emitted energy.
- Maximum of the spectral intensity is shifted to a softer region.

Run # 169: T_{rad}=20eV; ”real”

Run # 175: T_{rad}=20eV; 0.2*”real”

Transmitted flux





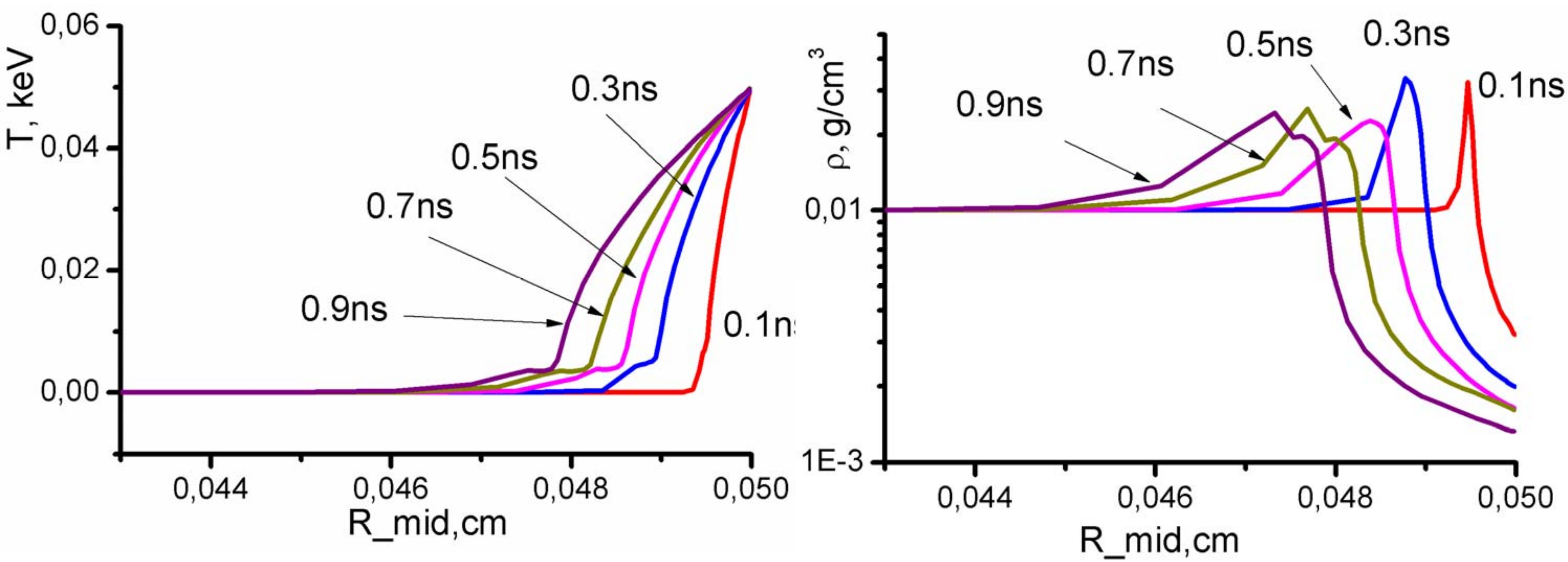
External source has narrow spectral range.

Suppose that an external radiation source is not a “black body” and radiates in a more narrow spectral range. Then the energy absorption takes place in a more narrow plasma spatial region corresponding to the above spectral range. In our calculations we simulate this case as a single spectral group radiation. The energy is absorbed in a relatively narrow spatial region. A shock wave is formed in plasma. It surpasses a thermal wave and makes the matter heated and compressed. As a result, an essentially non-homogeneous plasma is produced.

The same situation occurs if the energy transfer by electron heat conductivity wave is dominating.

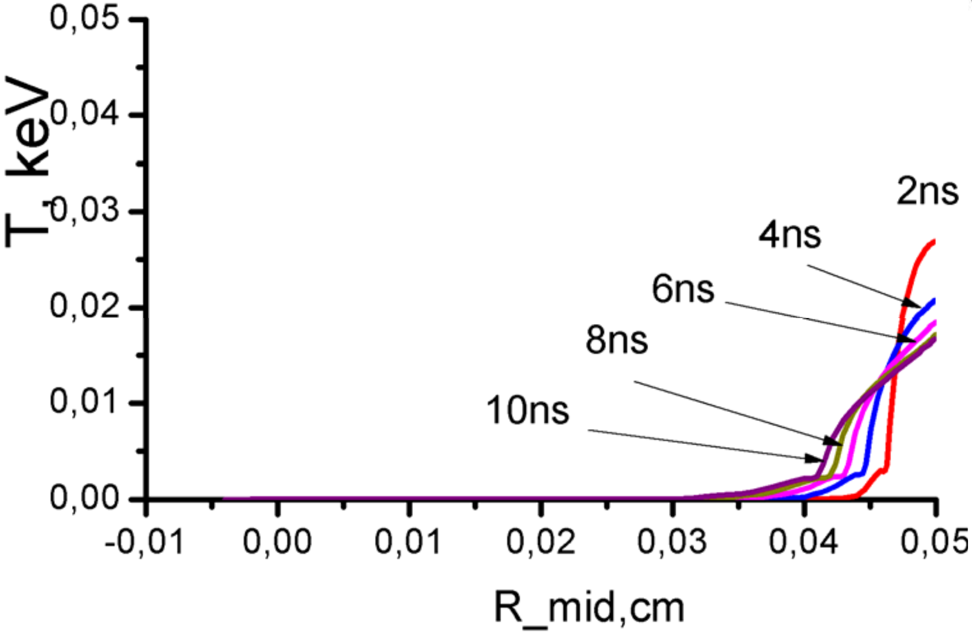
Heating of matter due to a heat transfer from a hot wall (run #117). The temperature is maintained at 50 eV during one nanosecond at the right-hand boundary of a plane polyethylene layer of 500 μm thickness and 10 mg/cm^3 density.

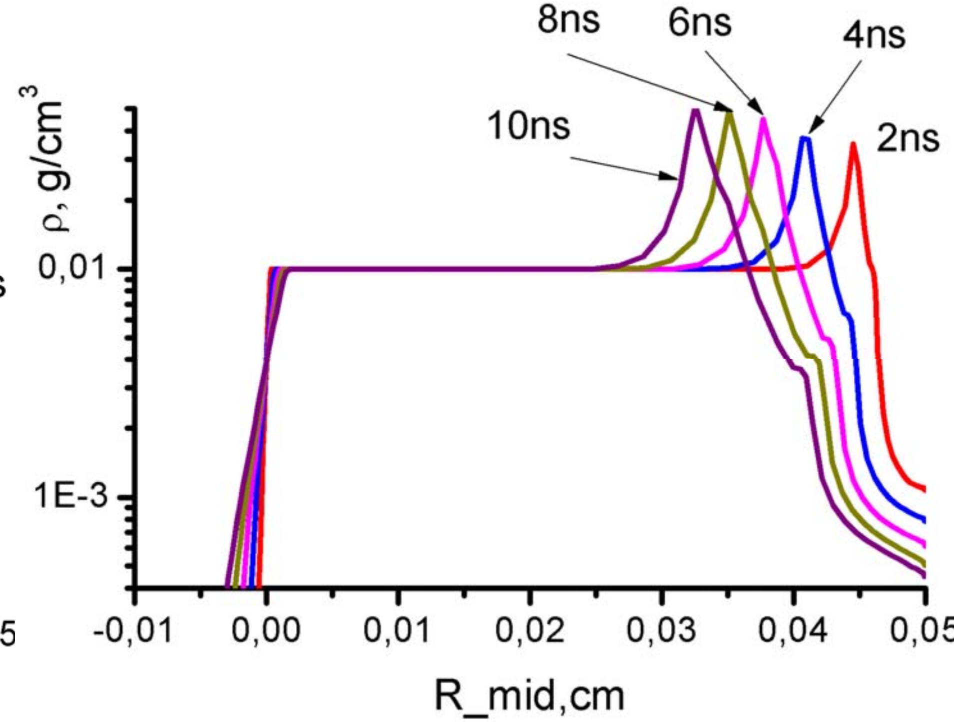
Time is up to 0.9 ns



Heating of matter due to a heat transfer from a hot wall (run #117, continued). After 1 ns the temperature falls. The density profile is not uniform. Only a 200 μm layer is heated.

Time is 1-10 ns





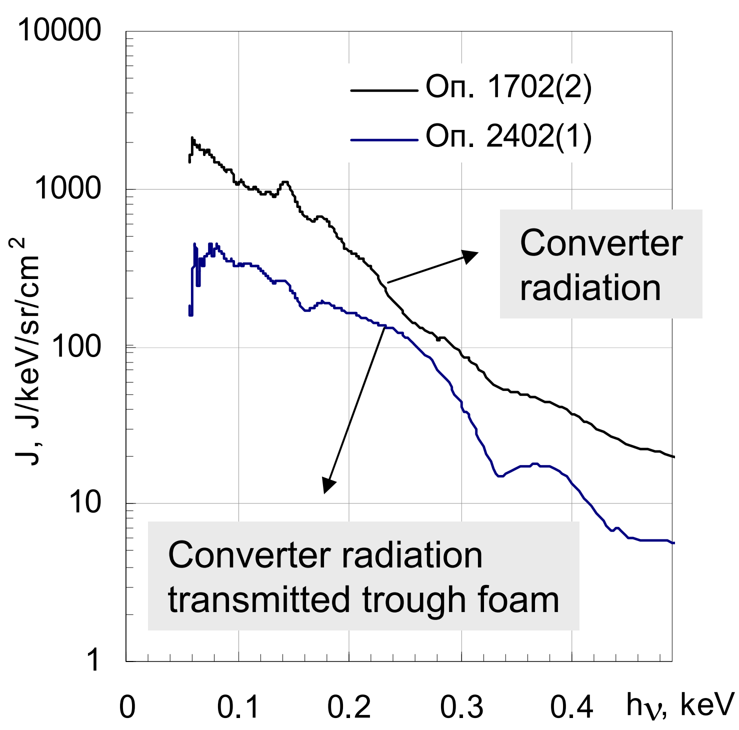
Shot 24.02.10(1) E=130J

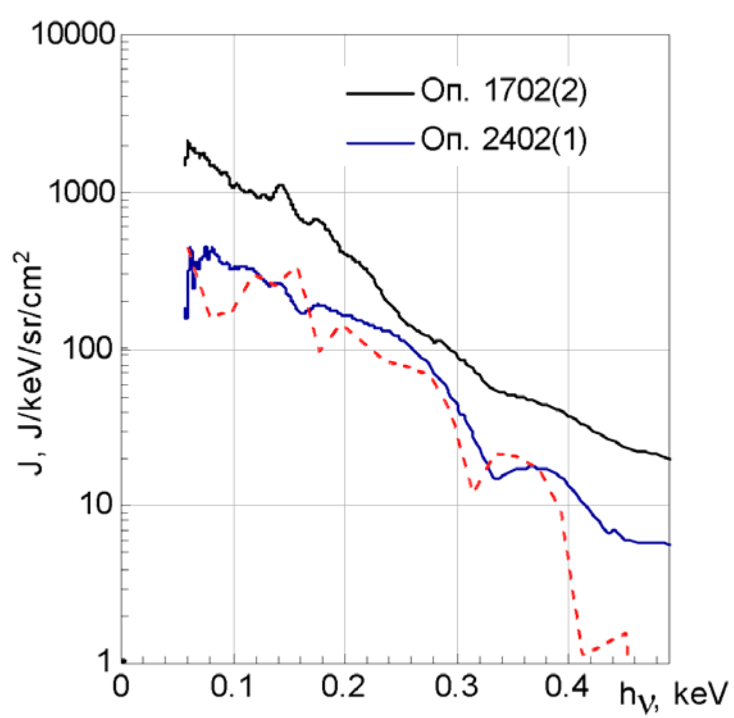
Target: converter d=1.7mm,h=1.7mm, wall 10 μm Au, bottom Au 168μg/cm^2 + 0.002g/cc 800mm TAC

Black and blue curve – experimental curves of falling and passing X-ray.

Red dot curve – results of numerical simulation with initial experimental falling spectrum. Passing through foam energy is 25% falling energy.

four fold absorption in foam





results N. Suslov, VNIEF, Sarov

Conclusions

- Our analysis and simulations demonstrate that it is possible to produce such plasma layer parameters (temperature, density and their distributions) that will be needed in future experiments on deceleration of ions in plasma with the density 2 mg/cm^3 and temperature T=15-25eV.
- The calculation results are sensitive to the plasma optical constants. It is practical to perform preliminary experiments for determination of plasma optical characteristics.

Thank you for your attention