Свойства плазмы, получаемой при облучении пористого вещества источником мягкого рентгеновского излучения

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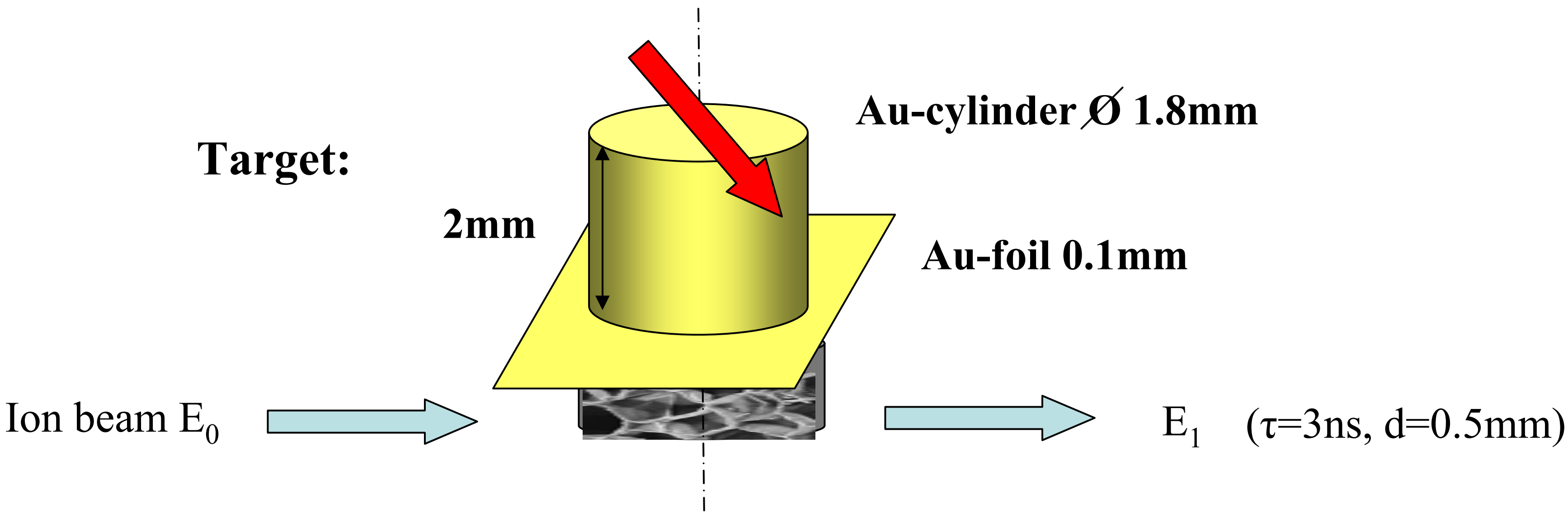
Experimental conditions

Heating of low Z foams by means of hohlraum radiation

PHELIX Laser: 1ω, 1.4ns, 250J, Ø~200-300μm, 10^{14} W/cm²



CHO-foam 2-20 mg/cm³

Areal density x=50-500 mg/cm²

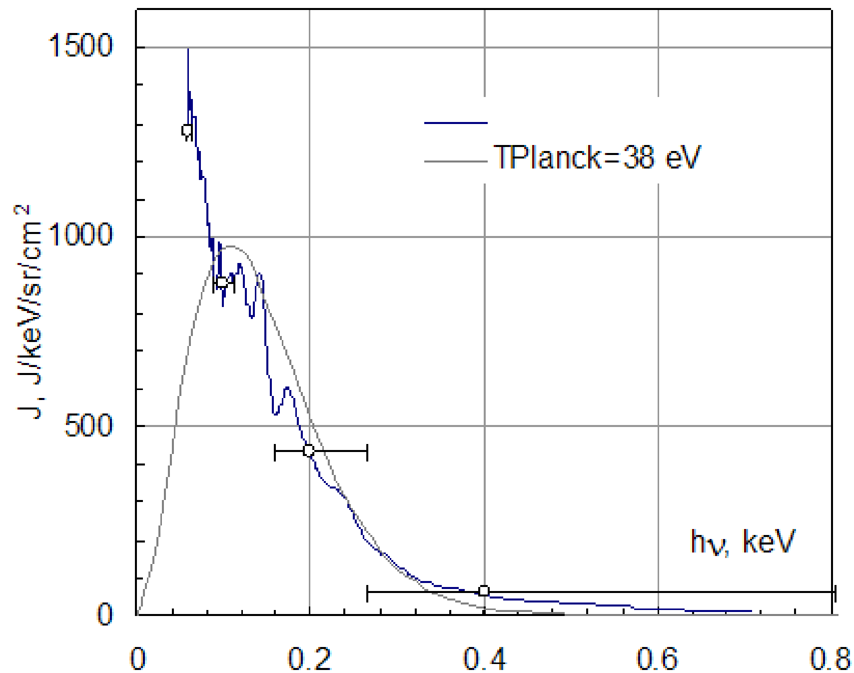
The purpose of our report is analysis and simulation of plasma parameters which are arising in foam matter under action of soft x-radiation

В данной работе теоретически исследуется образование плазмы в плоском слое полимерной пены (с плотностью ρ=0.002g/cm^3, толщиной 800 μm) под действием внешнего источника мягкого рентгеновского излучения в условиях экспериментов на установке PHELIX.

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 flow (experimental data) is presented at the right
- The purpose is simulation of plasma parameters for ion beam deceleration.



Code RADIAN:
two-temperature hydrodynamics plus radiative transfer equation

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

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

$$p = p_e + p_i ,$$

$\varepsilon_e = \varepsilon_e(T_e)$, $\quad p_e = p_e(T_e) \quad \varepsilon_i = \varepsilon_i(T_i) \quad p_i = p_i(T_i)$, n=0 – plane, n=2 – spherical geometry

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

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

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

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

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.

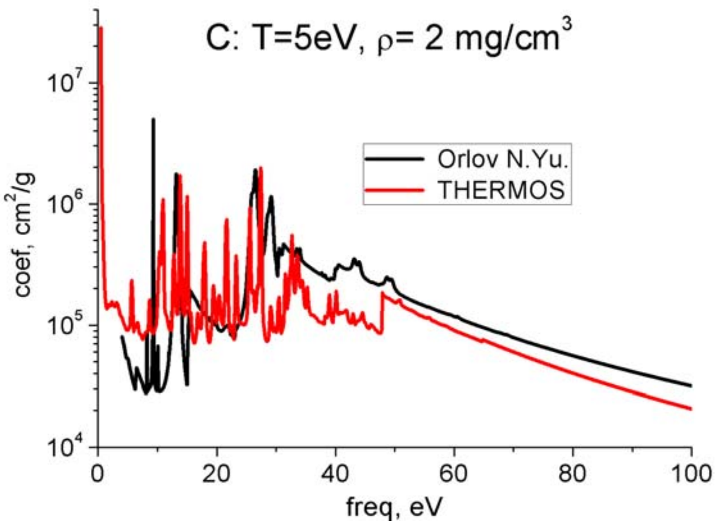
We use optical constants from code THERMOS (Inst. of Appl.Math.), DESNA (Lebedev Phys.Inst.) for CH_2. These constants we indicate below as “real”. We compare the absorption coefficient for C with the coefficients simulated by Prof. Orlov N.Yu. (T=5 and 10 eV). They prove to be similar.

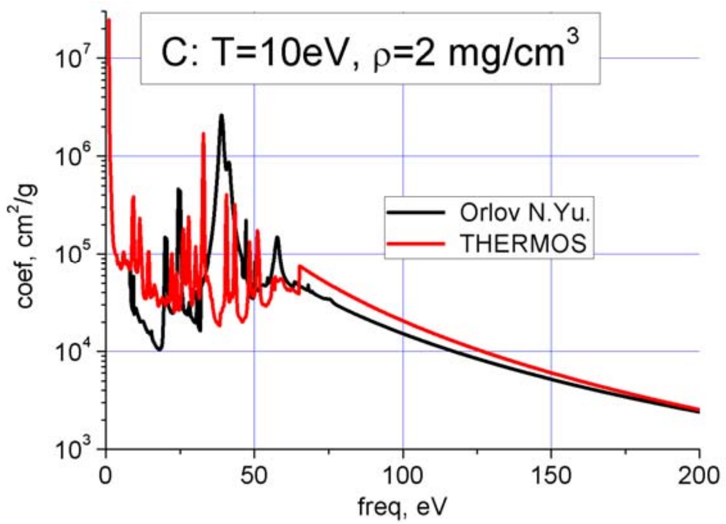
It is seen that the absorption coefficient drops with the temperature increase.

To determine the influence of the constants on the simulation results we use also

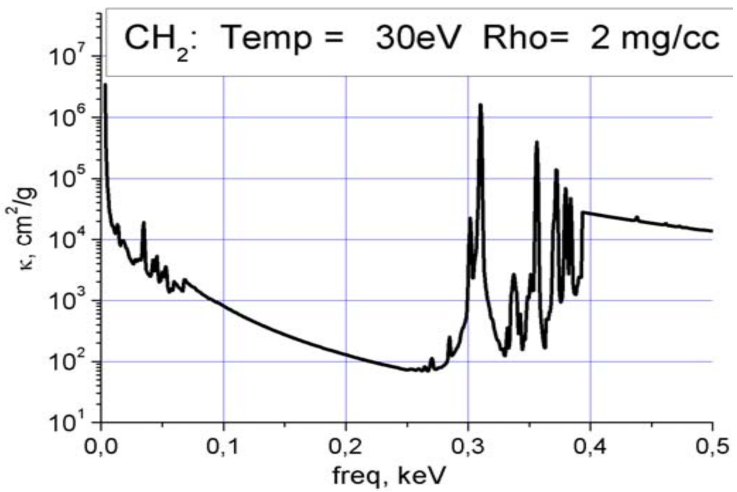
1) the spectral Bremsstrahlung coefficient, and

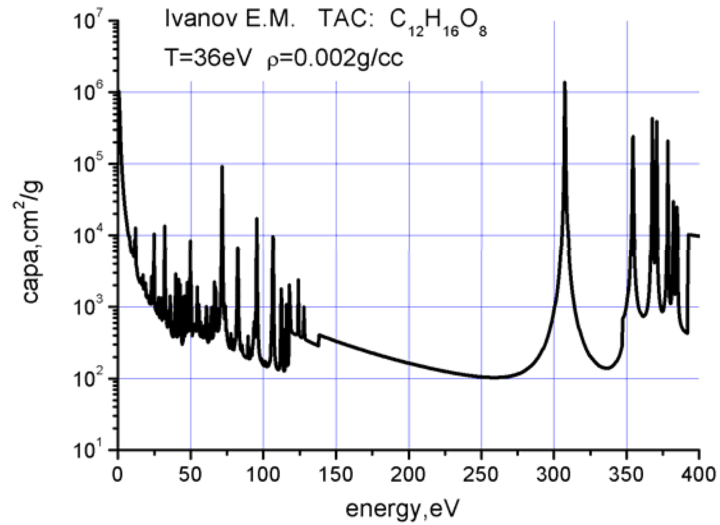
2) the model coefficient is obtained from the “real” coefficients by multiplication by number 1/5-2

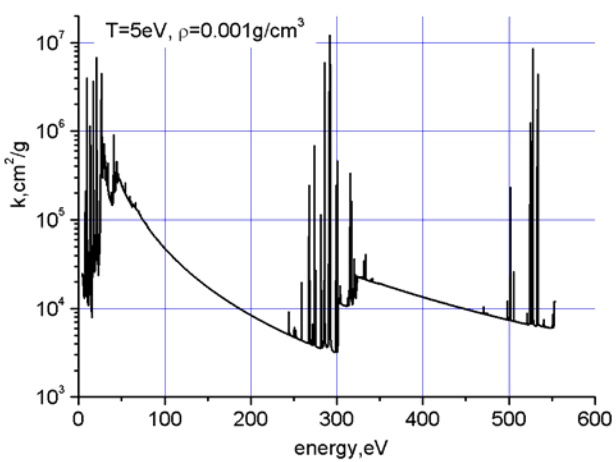


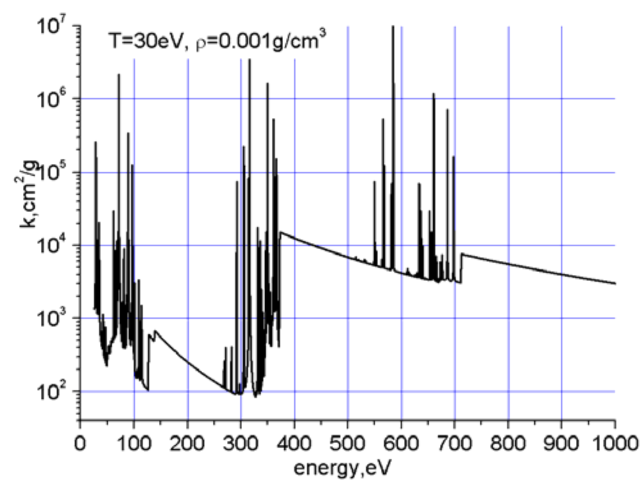


The absorption coefficient TAC ($C_{12}H_{16}O_8$) calculated by the prof. N.Yu. Orlov. It coincides with CH_2, by an order of magnitude. The absorption coefficients differ structurally due to the presence of oxygen in TAC









We can predict before demonstration the following numerical results:

- 1) An increasing radiation temperature T_{rad} of the incident flux leads to a 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. If the coefficients are greater the transmitted energy is smaller.

- 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.

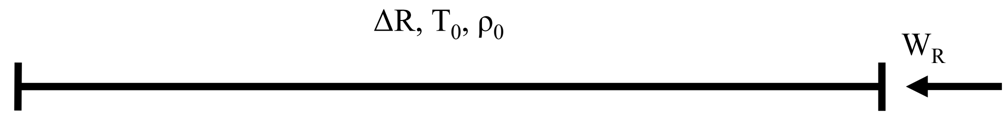
Предварительный анализ параметров падающего потока излучения и зависимостей оптических констант показывает существенно нелинейную картину взаимодействия внешнего потока рентгеновского излучения с мишенью и образования плазмы.

- С одной стороны увеличение радиационной температуры падающего потока излучения ведет к увеличению нагрева и повышению температуры плазмы. С другой стороны увеличение температуры плазмы ведет к уменьшению коэффициента поглощения излучения и увеличению доли прошедшего через плазму излучения

- Параметры плазмы и прошедшего сквозь мишень излучения могут контролироваться за счет изменения двух факторов:

  температуры внешнего потока рентгеновского излучения и оптической прозрачности плазмы, например, за счет выбора ее состава и/или плотности.

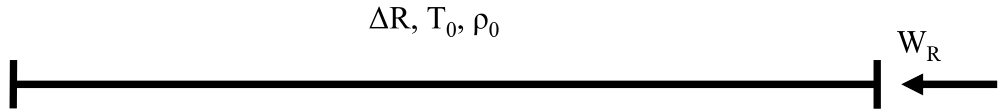
Постановка расчетов: плоская геометрия



- Плоский слой низкоплотной полимерной пены (толщиной 800 μm, плотностью 2 mg/cc) облучается Планковским источником рентгеновского излучения с температурой T_{rad}, соответственно потоком W_{rad} за время t_{rad}.
- Падающий поток внешнего источника содержит набор частот. Излучение на более низких частотах поглощается более эффективно, более жесткое излучение проникает глубже в плазму.

The table of simulation examples

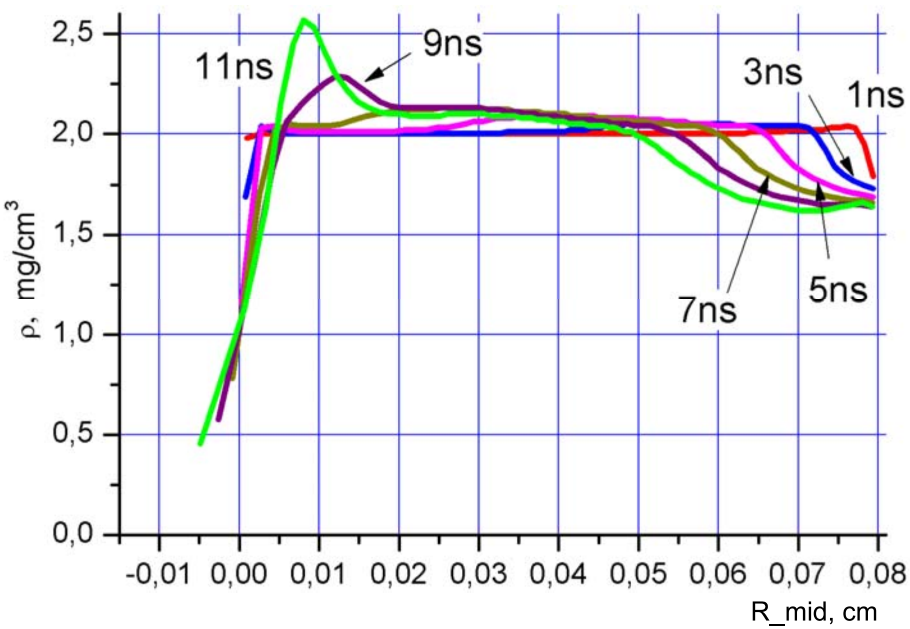
N	T_{rad}, eV	τ_{rad}, ns	W_{rad}, 10^{11} W/cm^2	coef	E_{out} /E_{rad}
169	20	5	0,17	“real”	0.04
172	20	5	0,17	Bremss.	0.95
175	20	5	0,17	1/5* “real”	0.15
176	25	5	0.39	“real”	0.15
171	30	5	0.83	“real”	0.32
174	30	5	0.83	2* “real”	0.10
170	40	5	2.6	“real”	0.64

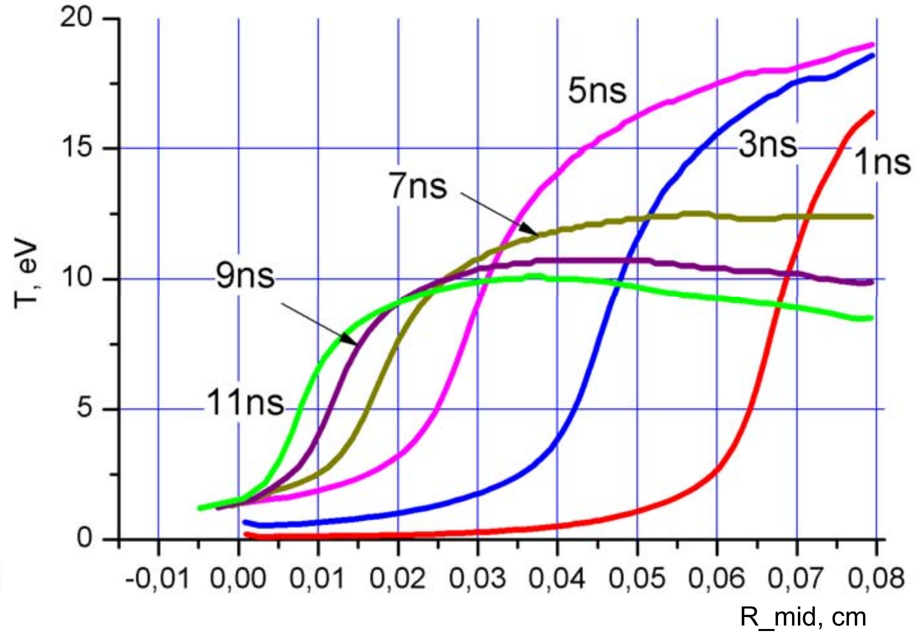


The picture illustrates the results of modeling:
T_{rad}=20eV, W_{rad}=1.7·10^{10} W/cm^2, t=5ns.

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.

Fig.1. The plasma radiation spectra on the right-hand boundary (where the external flux falls) and on the left-hand boundary (opposite side of a laser) at 1 ns and 4 ns. The radiation propagating into the target is shown by a black curve; a green curve shows the irradiation coming from the plasma on the left. The heated plasma is a source of thermal radiation. The spectra of the plasma thermal radiation are also shown: the red curve - from the right-hand boundary toward the incident flux; the blue curve – from the left boundary of the plasma. The self thermal radiation is generated at lower spectral frequencies as compared to the spectrum of the incident flow. This is due to the fact that the plasma temperature is lower than the external source temperature.

Fig. 2 shows the spectral energy generated up to 1,4, 5 ns. After 5 ns the plasma losses for the radiation are decreasing.There takes place the energy re-distribution over the space coordinate. In this calculation the radiation transmitted energy is 4% of the incident energy.

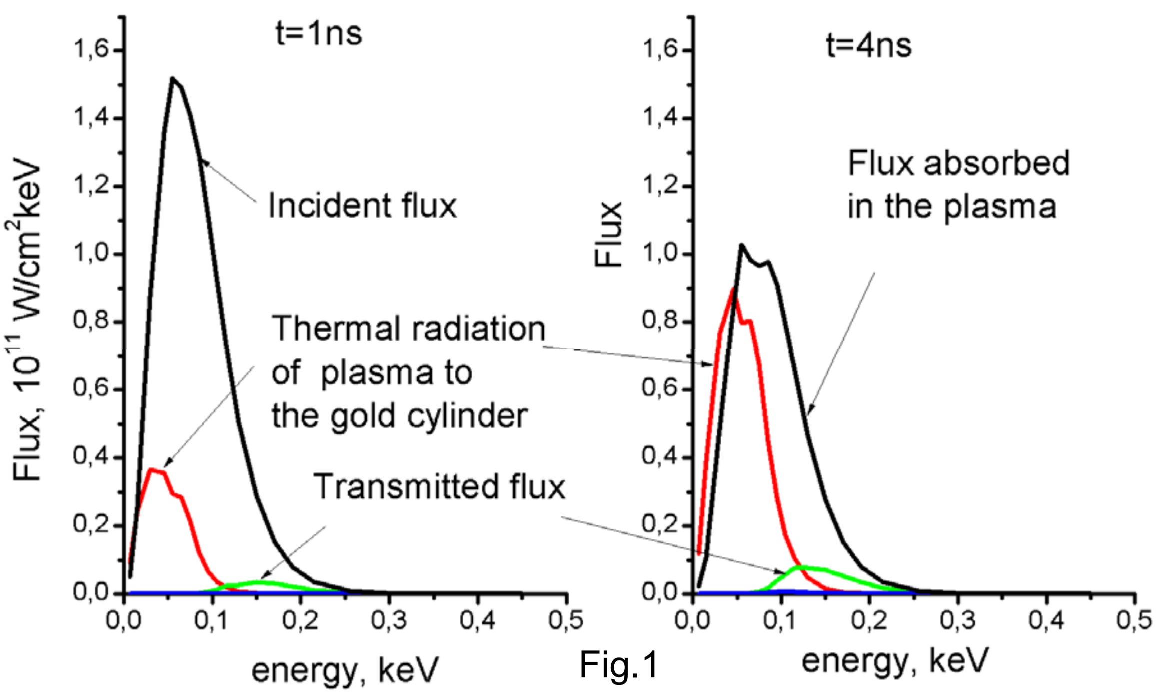


Fig.1

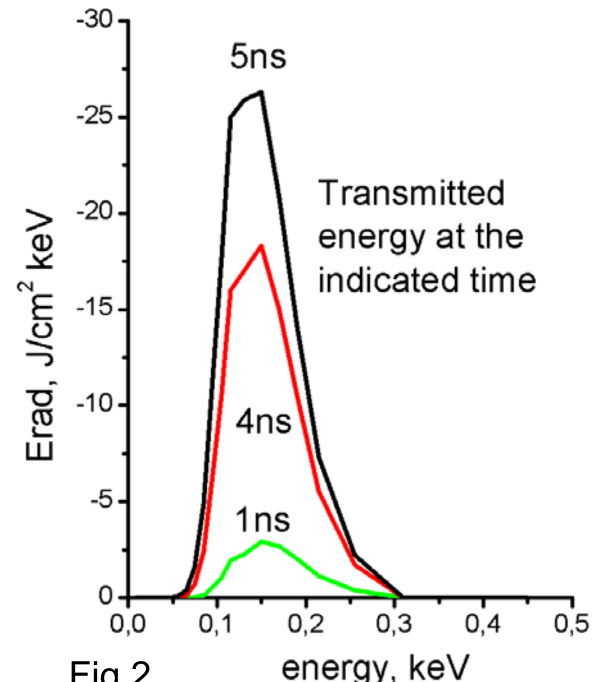
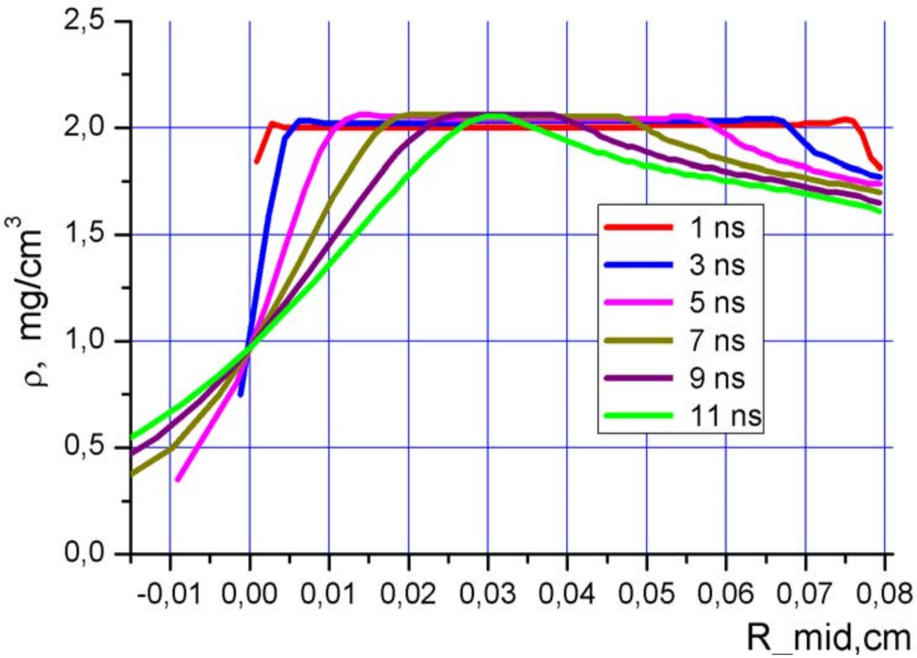


Fig.2

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

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

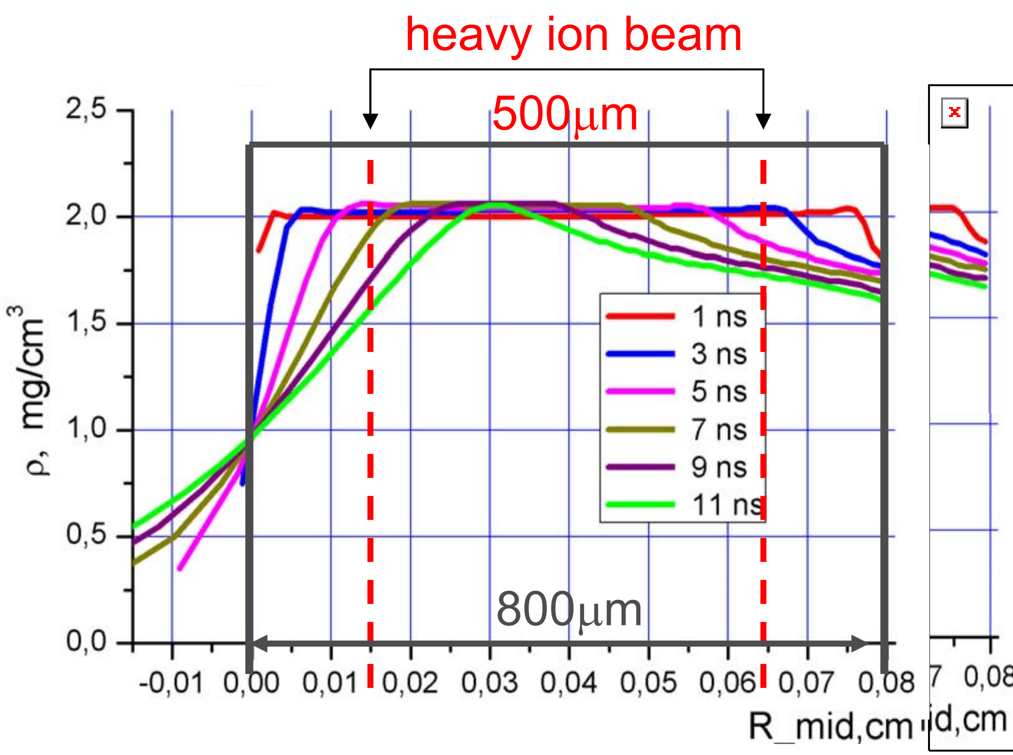


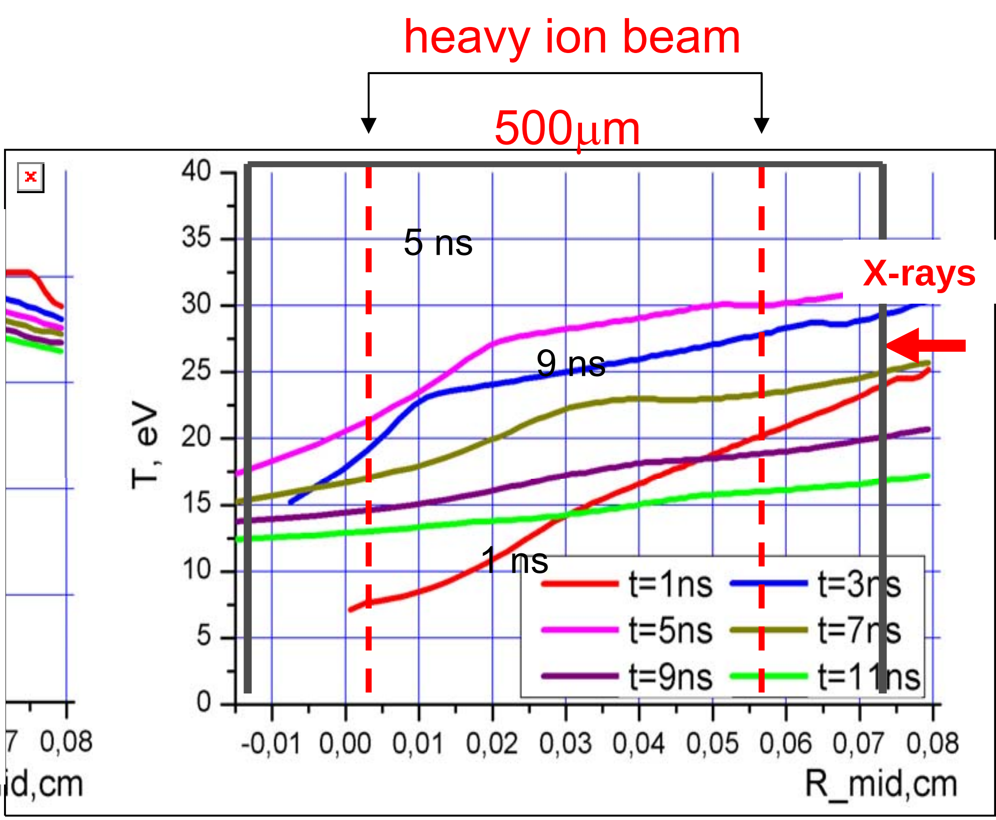
Hydrodynamics of CHO-foam heated by the external X-ray source

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

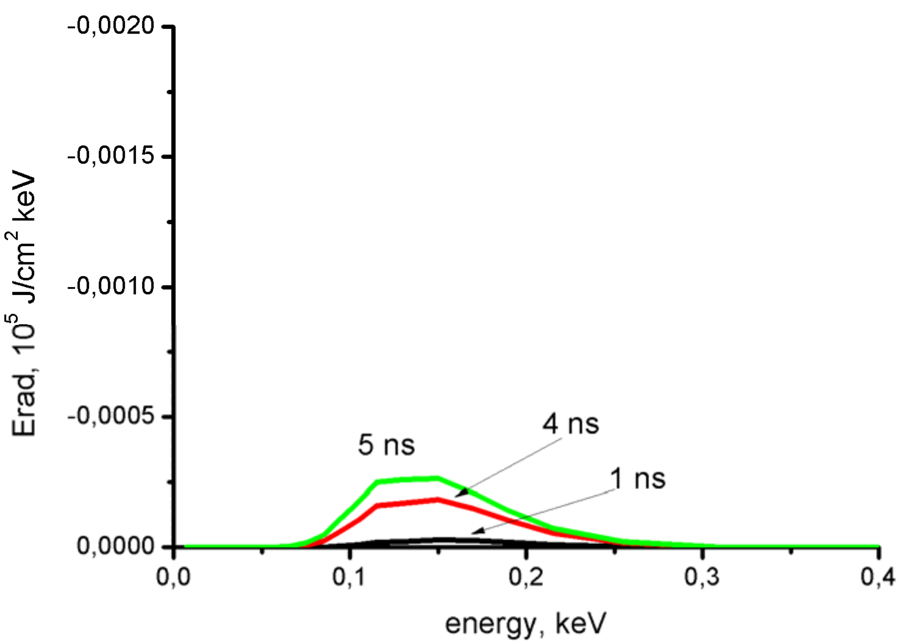




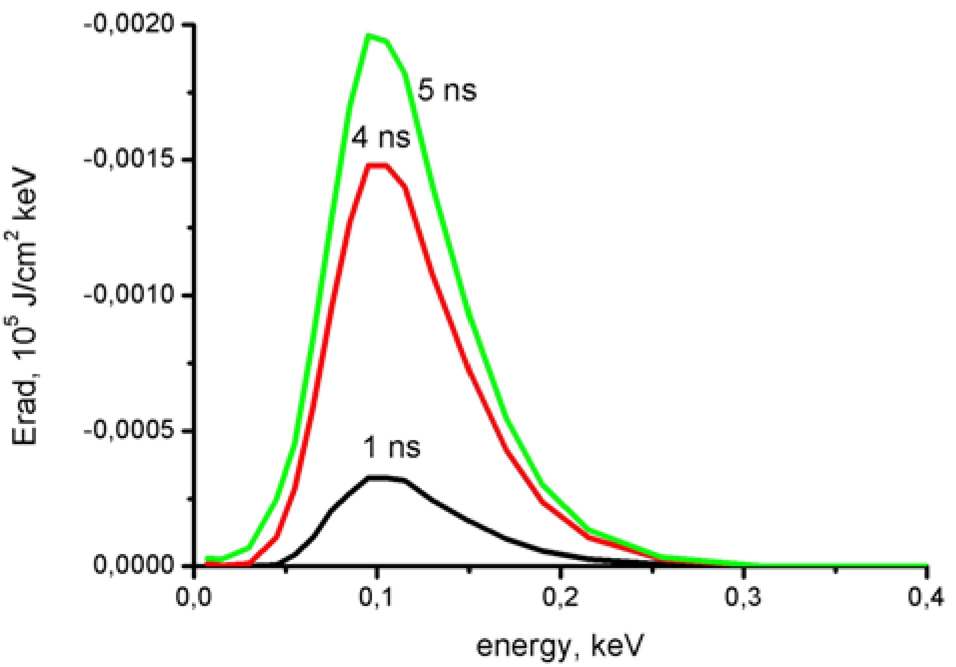
Sensitivity of the calculations results in respect of the optical constants

- Decrease in the optical constants leads to decrease in average temperature of the plasma and increase in the plasma reradiated energy.
- Maximum of the spectral intensivity is shifted to a softer region.

Run # 169: T_{rad}=20eV; ”real”



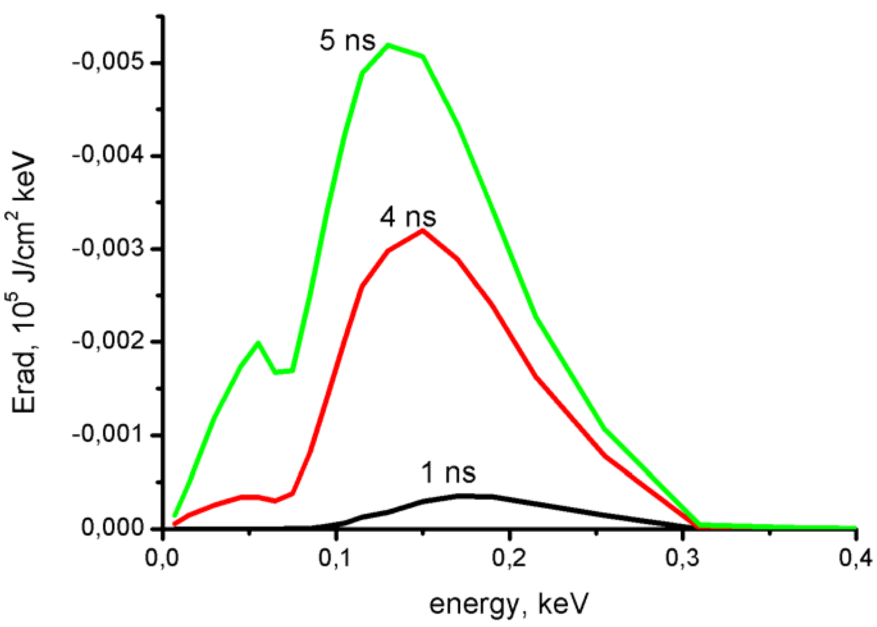
Run # 175: T_{rad}=20eV; 0.2*”real”



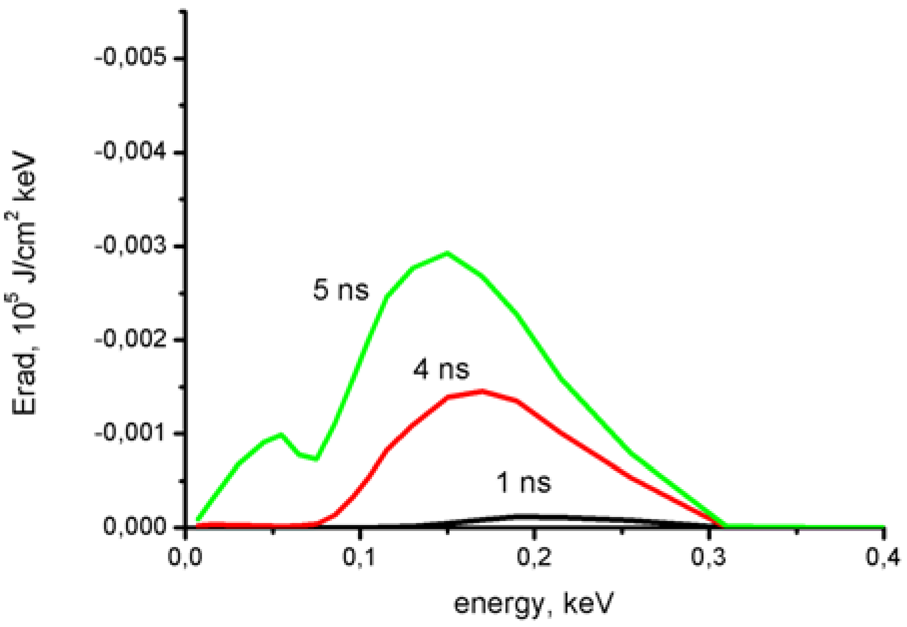
Sensitivity of the calculation results in respect of the optical constants

- Growth of optical constants leads to increase in average temperature of the plasma and decrease in the plasma reradiated energy.
- Maximum of the spectral intensivity is shifted to a harder region.

Run # 171: T_{rad}=30eV; ”real”

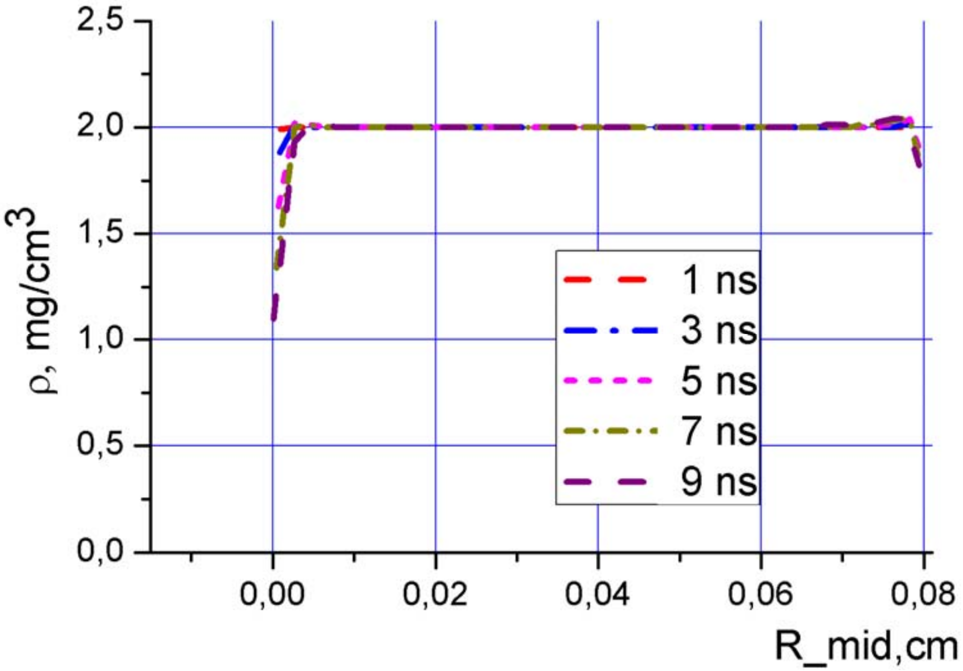


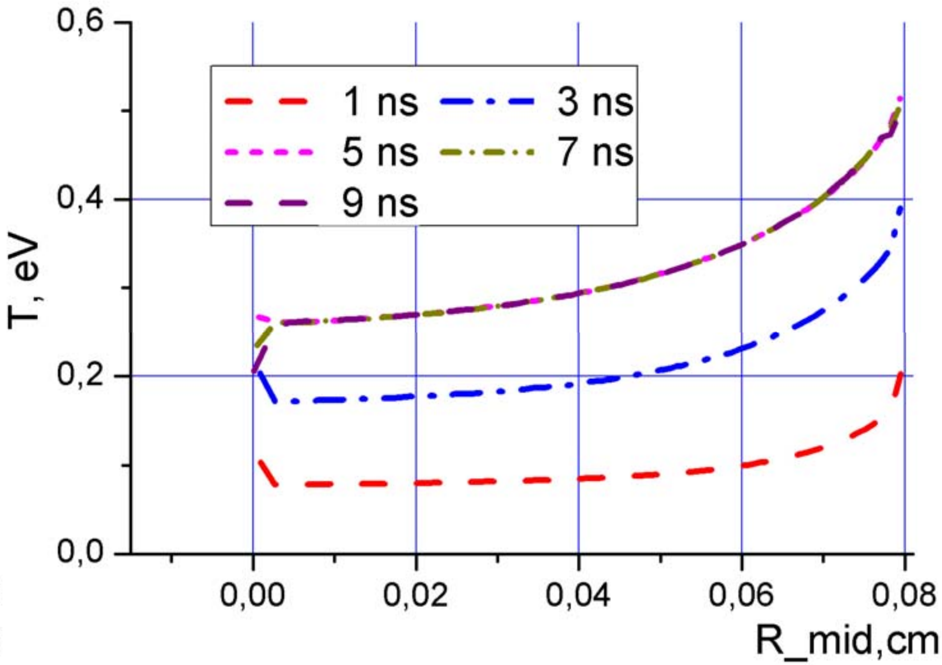
Run # 174: T_{rad}=30eV; 2*”real”



The results of simulation: Bremsstrahlung coefficient; T_{rad}=20eV, W_{rad}=$1.7\cdot10^{10}$ W/cm^2, t=5ns.

We use Bremsstrahlung coefficient of absorption for simulation of thin plasma. In this case plasma is optically transparent for external radiation. Plasma absorbed only 5% incident energy.





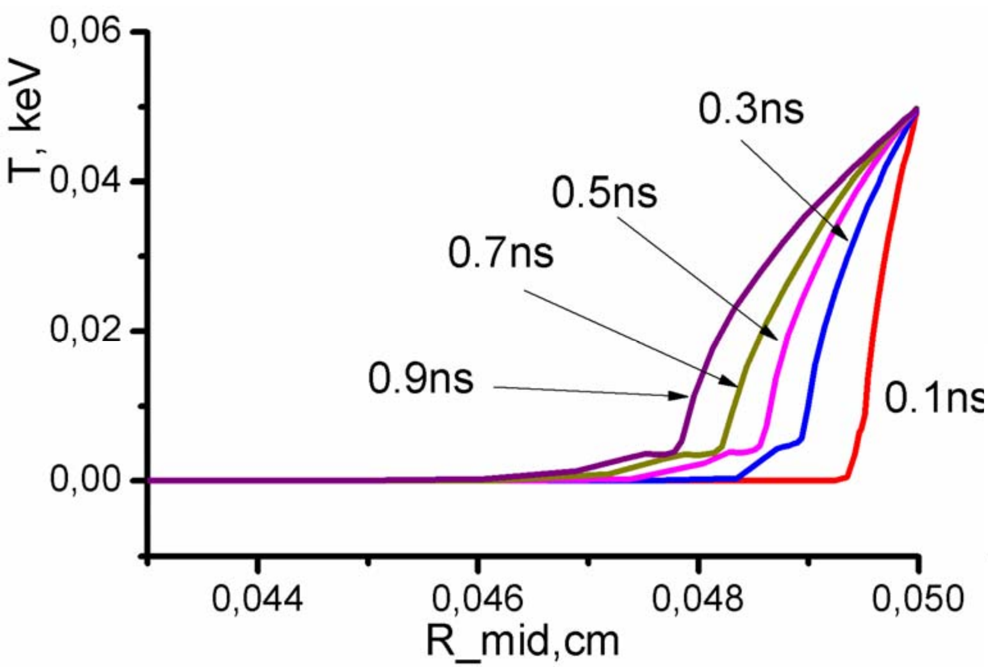
External source has narrow spectral range.

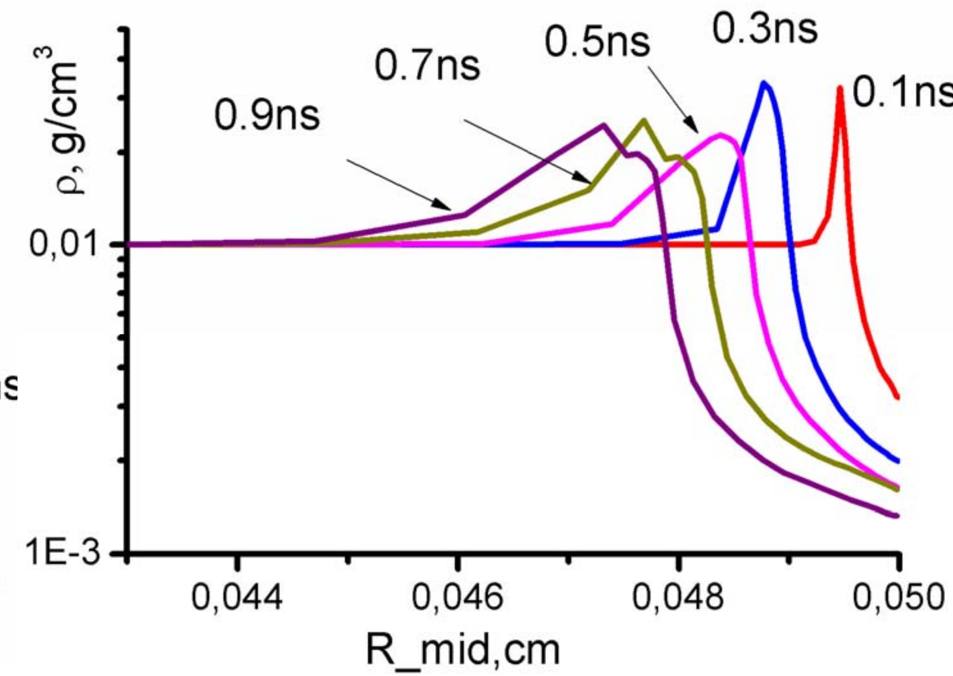
Suppose that an external radiation source is not a “black body” and radiates in a more narrow spectral range. Then energy absorption takes place in a more narrow spatial region of the plasma corresponding to that spectral range. In our calculations we simulate this case as a single spectral group radiation. The energy is absorbed in a relatively narrow spatial region. A shock wave is formed in the 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 an 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.

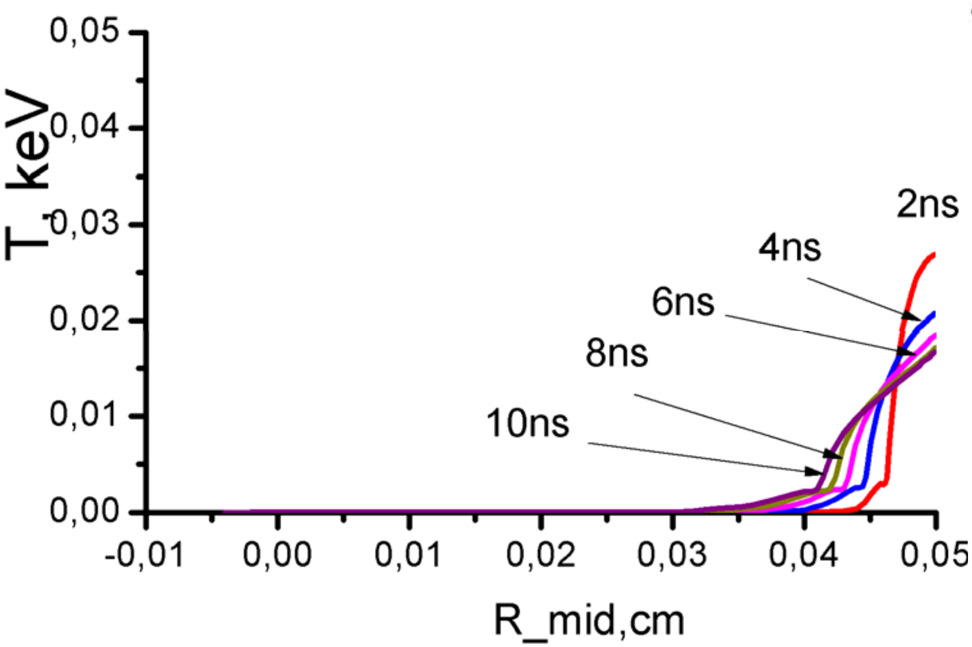
Time is up to 0.9 ns

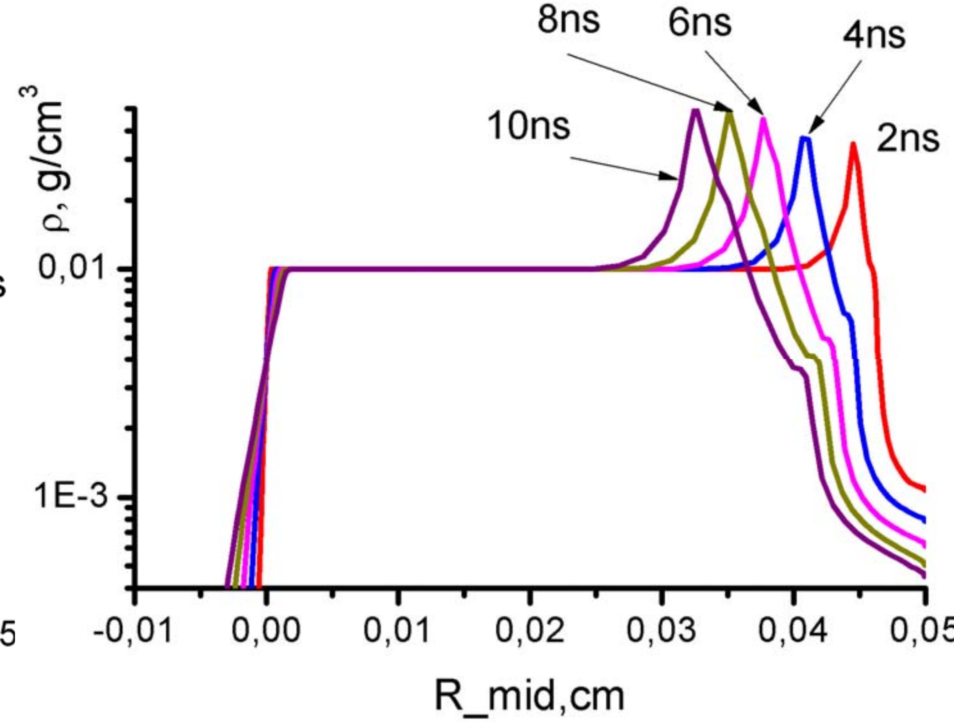




Heating of matter due to a heat transfer from a hot wall (run #117, continued). After 1 ns temperature falls. Profile of density is not uniform. Only 200 μm layer heated.

Time is 1-10 ns





Анализ результатов расчета показывает, что

- Коэффициенты поглощения представляются соответствующими условиям эксперимента.

- Внешний источник мягкого рентгеновского излучения имеет температуру планковского спектра 30 эВ

- Для торможения ионов следует использовать пенные мишени большего размера (1000-1500мкм)Для создания более благоприятной среды

Заключение

- При воздействии внешнего источника рентгеновского излучения, имеющего планковский спектр с T=20-40eV, на низкоплотное пористое вещество (ρ=0.002g/cc) формируется плазма с относительно однородными по пространству профилями плотности и температуры T=15-35 eV.   Поглощение энергии происходит объемно.

- Результаты оказываются чувствительными к значениям оптических констант, используемых в численном моделировании.. Поэтому исследование оптических констант вещества на основании сравнения экспериментальных и расчетных результатов по прохождению излучения через плазму является важной и актуальной задачей.

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 the plasma with density 2 mg/cm^3 and temperature T=15-25eV.
- The calculation results are sensitive to optical constants of the plasma. It is useful to perform preliminary experiments for determination of plasma optical characteristics.

Спасибо за внимание