Problems in case of optical measurement of dense plasma heating in laser shock-wave compression

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Introduction

In this work, we discuss the possibility of using pyrometric technique for measuring the temperature of the target material behind the front of the shock wave emerging at the free surface of the target.

The experimental results* obtained by measuring the sample heating in the case of laser generation of shock wave in aluminium are compared with the our results of numerical simulation.

(Apart from the staff of GPI RAS, scientists from JIHT RAS, IPCP RAS, LULI (Ecole Polytechnique, France) and Università di Milano, also participated in this work**)**

***** Batani D., Bossi S., Hall T.A., Mahdieh M., Koenig M., Krishman J., Benuzzi A., Lower Th., in *Advances in Laser Interaction with Matter and Inertial Fusion* (London: Word Scientific Publ., 1997) p. 409.

Dynamic method for EOS determination

From the general laws of conservation of mass, momentum and energy:

$$V = (D - u)V_0/D\ ,\ P = P_0 + D\,u/V_0\,,\ E = E_0 + 0.5(P_0 + P)(V_0 - V)\ .$$

- Measuring any two of the five parameters (usually D and u) it is possible to receive caloric equation of state:

$$\boldsymbol{E = E(P,V)}.$$

For constructing total thermodynamic equation of state

$$\boldsymbol{T = T(P,V)}$$

the solution of a linear differential equation is used:

$$\left[P + \left(\frac{\partial E}{\partial V}\right)_P\right]\frac{\partial T}{\partial P} - \left(\frac{\partial E}{\partial P}\right)_V \frac{\partial T}{\partial V} = T,$$

with at least one experimental value of temperature as a boundary condition.

Experimental details

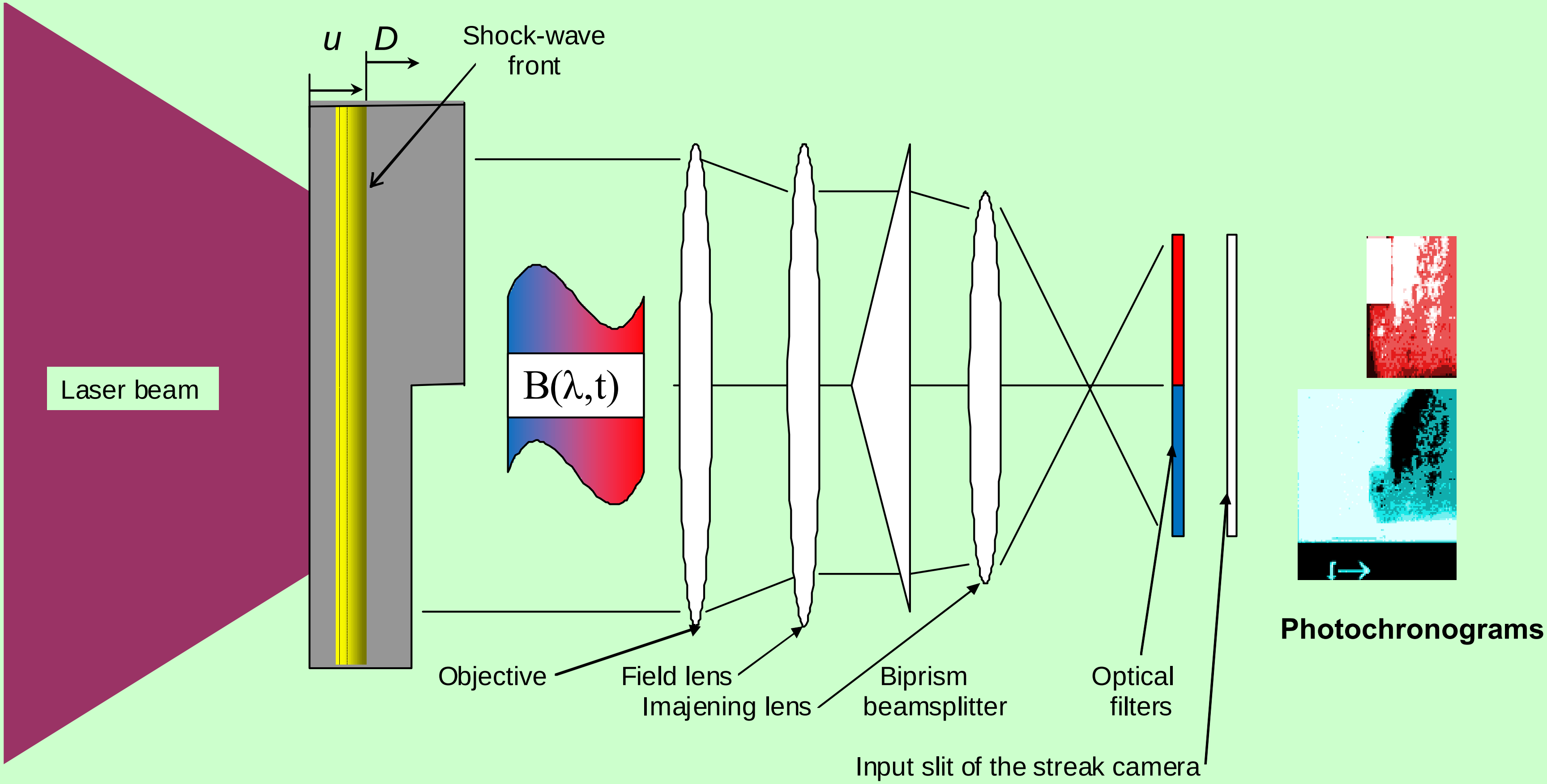
Experiments were performed by using laser radiation at 0.53 μm, 600 ps pulse duration and providing the intensity onto target up to 3×10^{13} W/cm^2.

The diameter of the “smoothening” laser spot on the target was 200 μm.

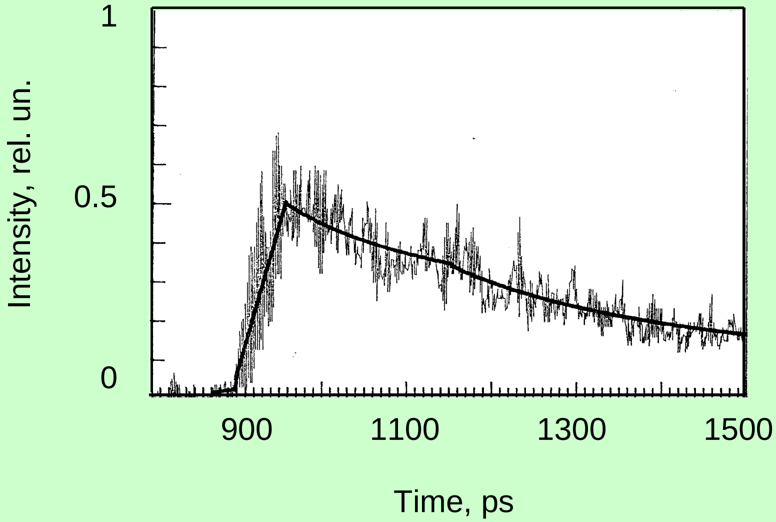
The two-stepped aluminium targets with a base thickness of 9.4 μm and the step height of 4 μm were used.

A streak camera provided 5-ps resolution for the light emission from the rear surface of the target.

A scheme of the experiment set-up to measure light signals in the “red” and “blue’ channels



The observed “red” and “blue” emission on a rear side of the target (*to the left- base surface; to the right- step surface*).



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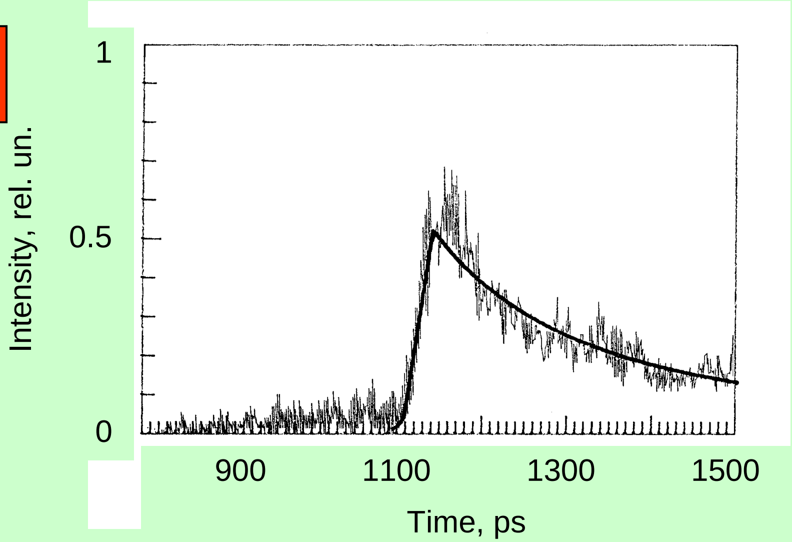

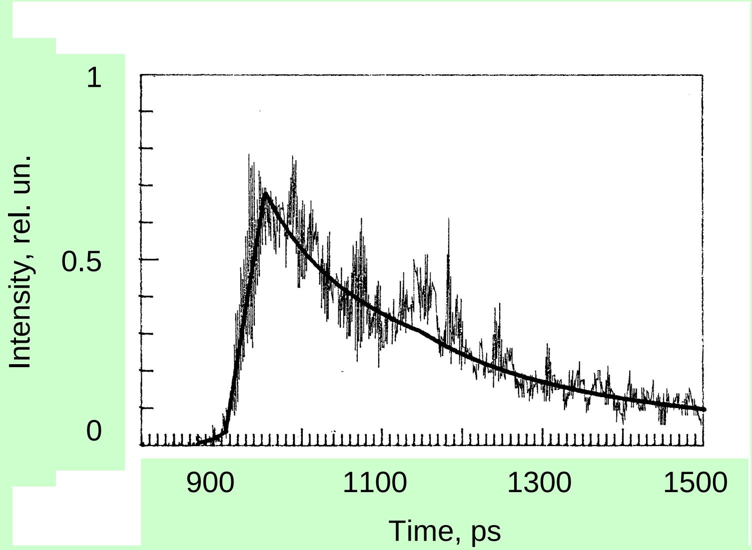

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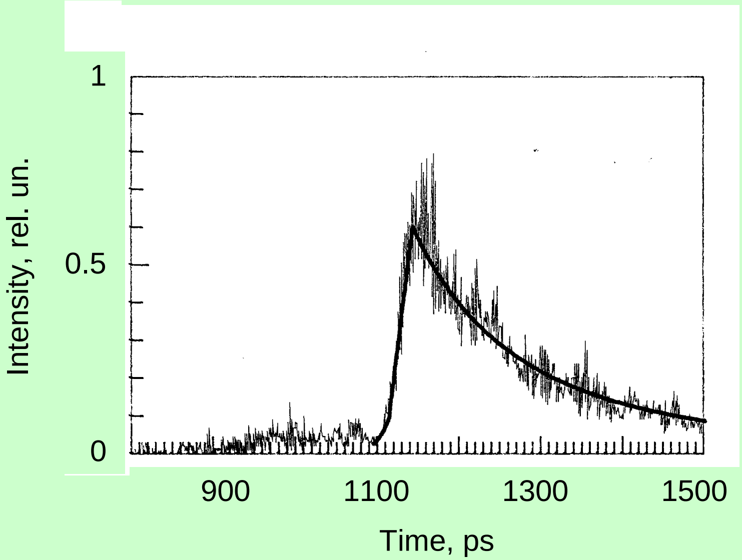
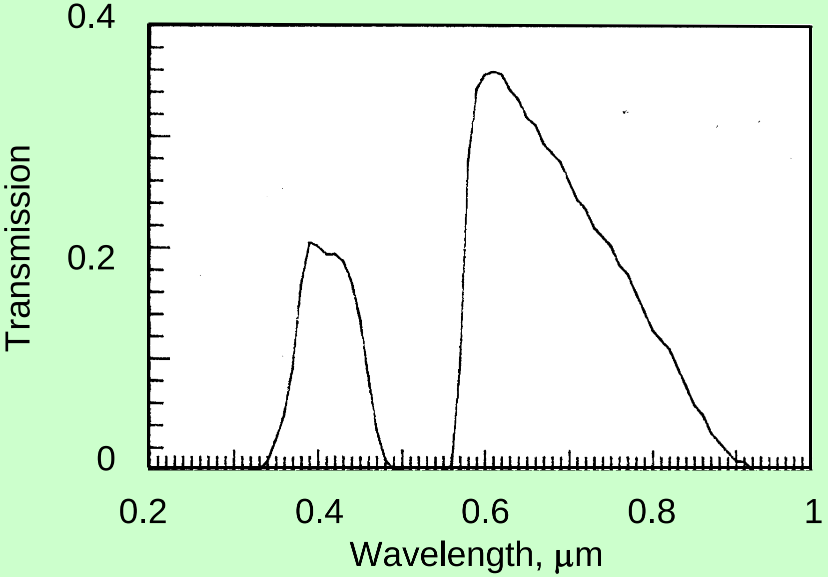
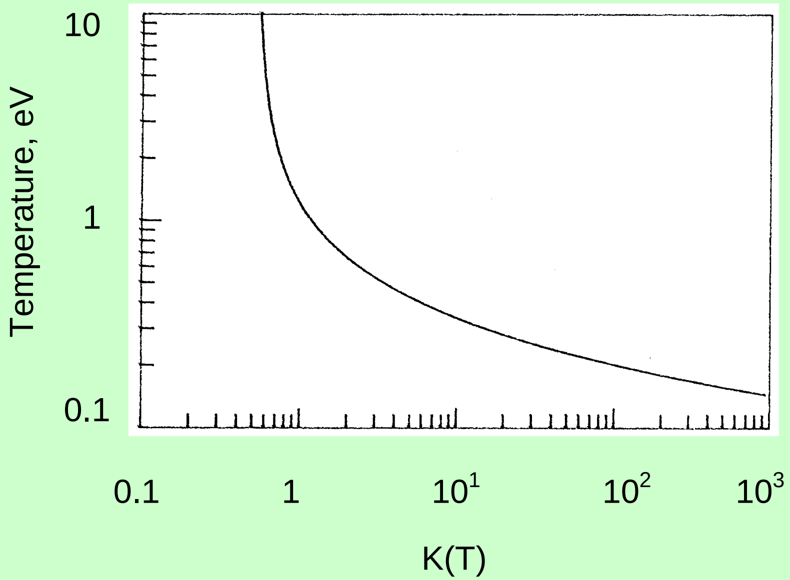


Characteristics of two-channel pyrometer

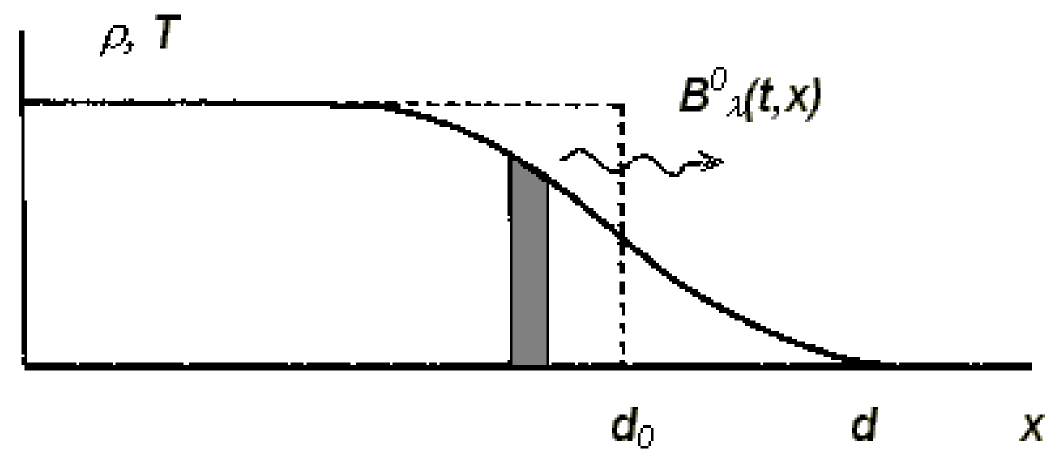




- **To the left** - spectral range sensitivity of each channel $g_{blue}(\lambda)$ and $g_{red}(\lambda)$.
- **To the right** - the curve a result of calculation based on relation:

$$(\int g_{red} B_\lambda d\lambda)/(\int g_{blue} B_\lambda d\lambda) = \mathbf{K(T^*)} = (\int g_{red} B_\lambda^0 d\lambda)/(\int g_{red} B_\lambda^0 d\lambda)$$

Numerical modeling of light emission (*as it is offered in the monography Zel'dovich and Raizer*) with calculation T and ρ profiles at consecutive moments of time with step 5 ps



$$B_\lambda = \int_0^d dx\ B_\lambda^0(T(x,t))\tilde{\chi}_\lambda(x,t)\exp(-\int_0^x \tilde{\chi}_\lambda(\xi,t)d\xi)$$

$$B_\lambda^0 = \frac{2hc^2}{\lambda^5}\frac{1}{\exp(hc\ /\ \lambda kT\ ) - 1}$$

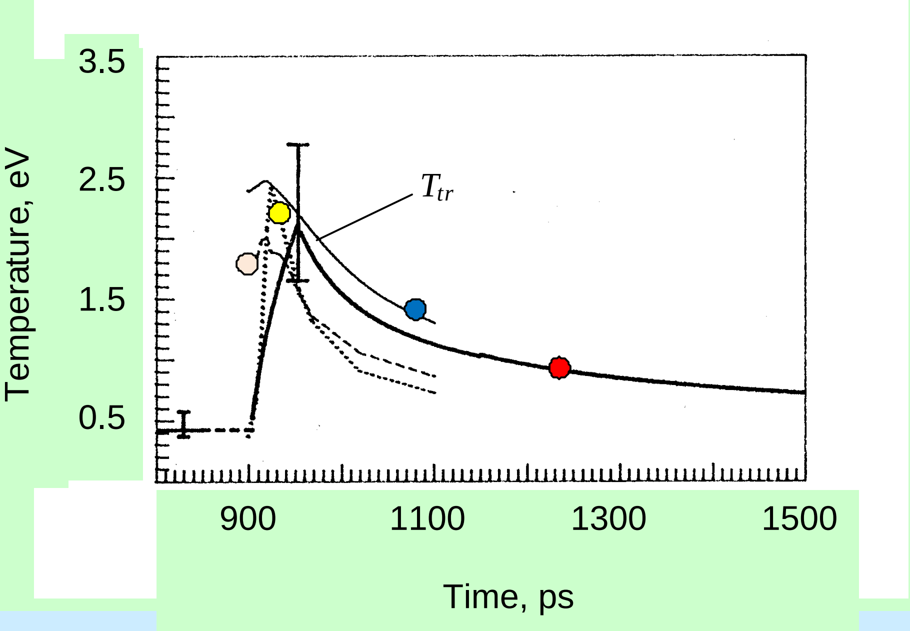
$$\tilde{\chi}_\lambda(x,t) = \chi_\lambda(x,t)[1 - \exp(-hc\ /\ \lambda kT(x,t))]$$

Kramers-Unsold formula for absorption coefficient:

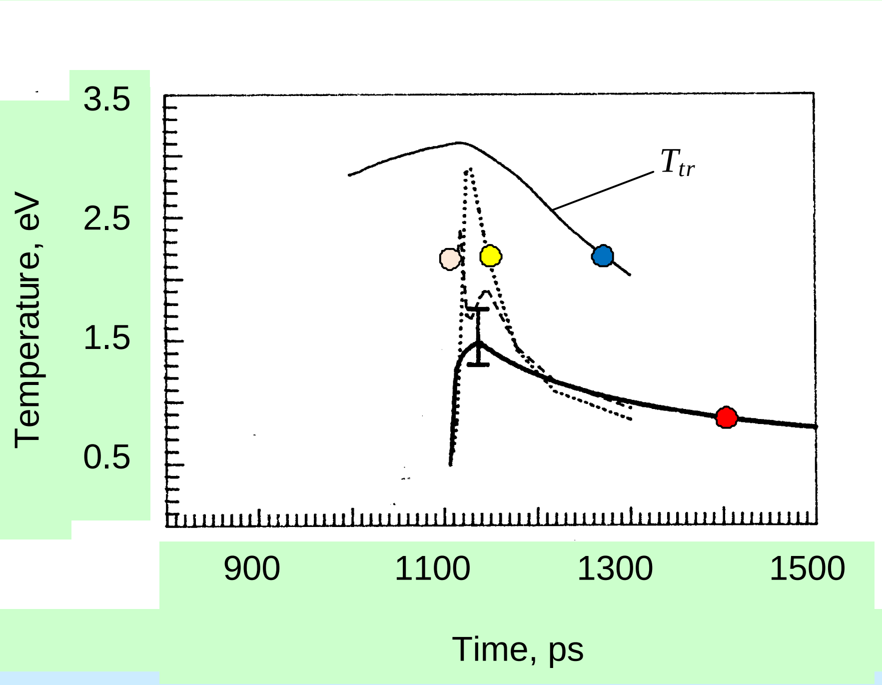
$$\frac{1}{\chi_\lambda}[\text{мкм}] = \frac{1.2\cdot 10^{-3}}{\lambda^3\rho T}\exp\left(\frac{5.99 - \dfrac{1.24}{\lambda}}{T}\right)$$

$$(\int g_{red}B_\lambda d\lambda)/(\int g_{blue}B_\lambda d\lambda) = \mathrm{K(T^*)}\ = (\int g_{red}B_\lambda^0 d\lambda)/(\int g_{red}B_\lambda^0 d\lambda)$$

The measured and calculated temporal evolution of the temperature



Base surface

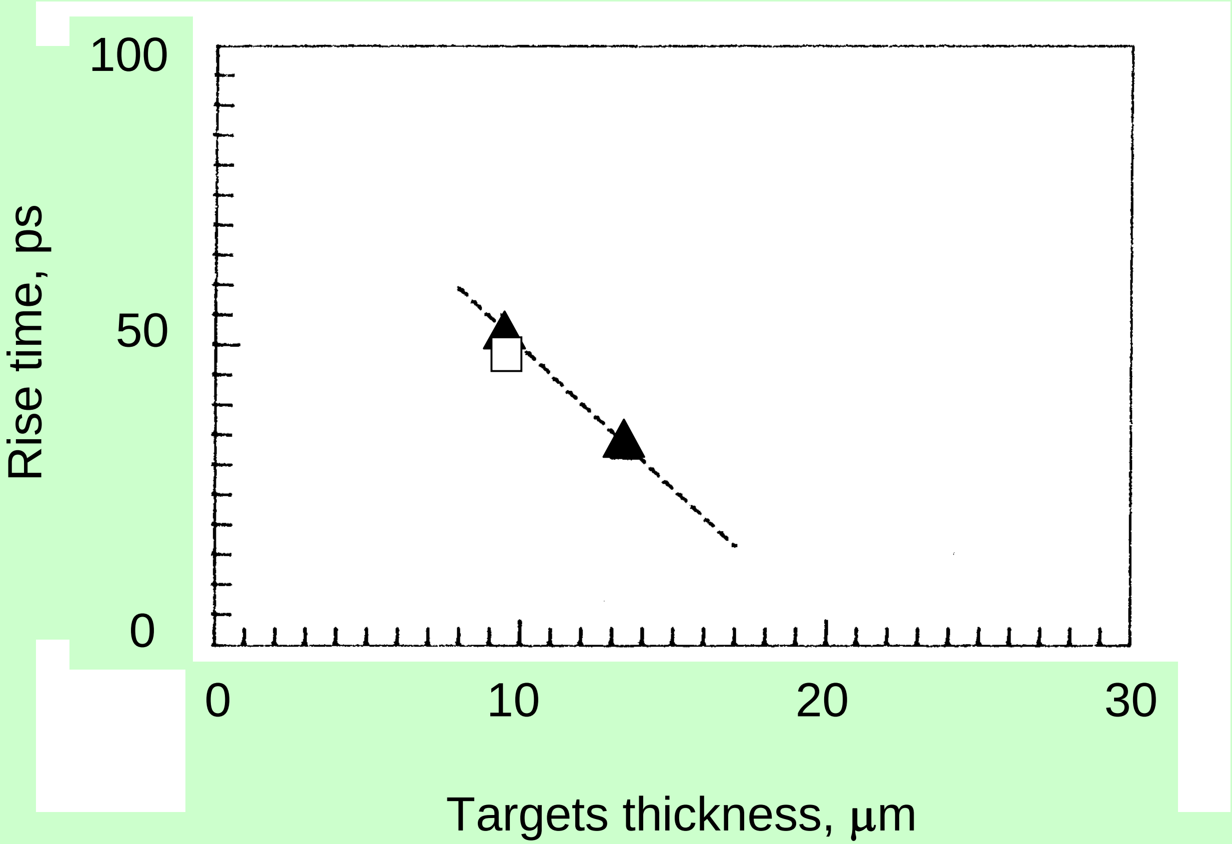


Step surface

- ● Solid thick line- the experimental results
- ● Solid slim line- the calculated maximum value of the true temperature
- ● Dotted line- the semiempirical model for the opacity calculation
- ● Dash line- the Kramers-unsold formula for the opacity calculation

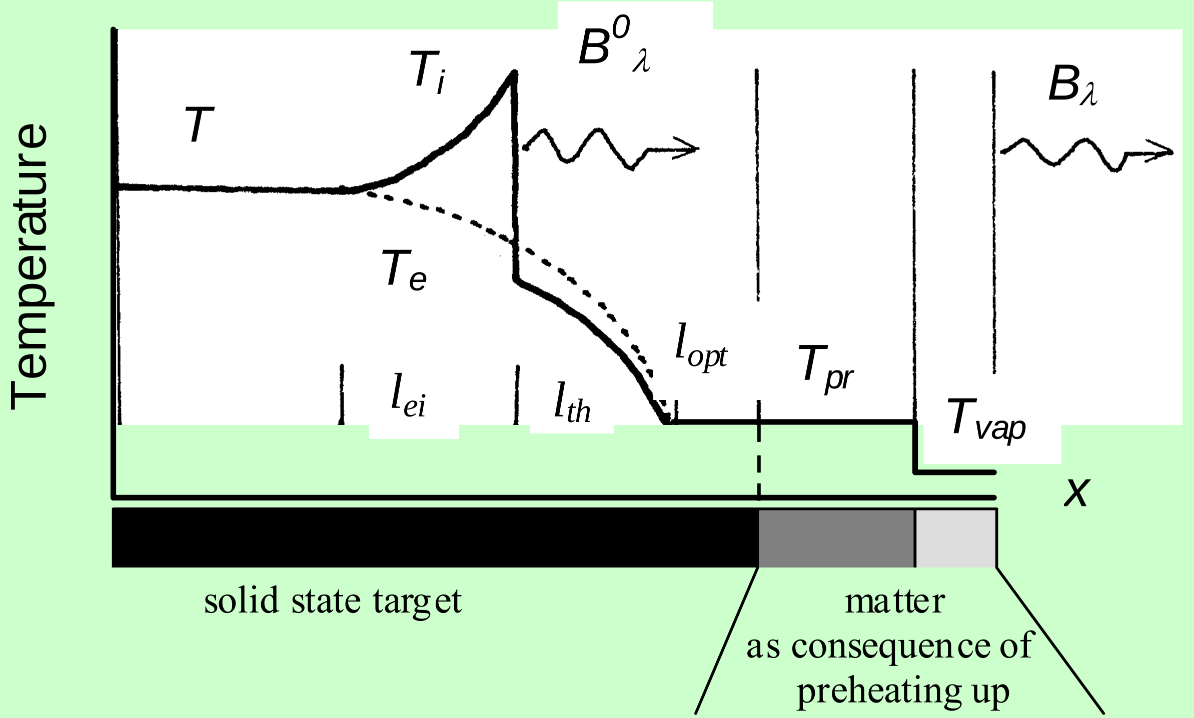
The preheated temperature is 0.45 eV

Comparison of measured (▲) and calculated rise time (□) of an optical signal on the target rear surface as a function of the target thickness



- It is visible, that there is a good consent of the experimental and calculated values

Schemes of the shock-wave front structure (*target is in case of preheating*)



T_i and T_e ion and electron temperatures

T_{pr}- preheating temperature

T_{vap} – evaporated matter temperature

$l_{ei} = t_{ei} D$ – e-i relaxation zone,

l_{th} – electron thermal conductivity zone,

l_{opt} – optical depth

The rise time of optical signal in case of cold and preheated metal target

On base of structure of the shock-wave front* in aluminium cold target, estimation shows that the rise time of optical signals which equal to $(l_{ei} + l_{th} + l_{opt})/D$ does not exceed **1 ps**.

Experimental value of rise time of optical signals on base surface is **52.5 ps**.

According to the numerical calculations made for the case of target preheating (0.45 eV) the total rise time of optical signals is estimated at **50 ps**.

* Ya.B. Zel’dovich and Yu.P. Raizer. 1967 *Physics of Shock Waves and High Temperature Hydrodynamic Phenomena* (Academic Press, New York).

Conclusion

- Problems associated with the temperature measurements in the matter behind the shock-wave front were discussed.

- One of these is the screening of optical radiation from the hot region by matter in the unloading wave.

- Another problem concerns the specific nature of the laser technique used for generating shock wave. Since a high-temperature plasma is formed at the front surface of the target, its radiation may cause a preheating of the target and, consequently, change its initial parameters. It is shown that preheating of the target can significantly affect the parameters of the optical signal detected from the back surface of the target, and hence affect the accuracy of measurements of temperature and pressure of the matter behind the shock-wave front.

The experimental **PHELIX** proposals applied by the GPI and JIHT RAS

Motivation

The measurement of the matter temperature behind the shock-wave front in metals is the actual task in field of constructing thermodynamically full equation of state.

Experimental goal of this project

It is necessary to measure the emission from rear side of target with time resolution equal 1 ps or less (for aluminium targets). In case of lead or bismuth targets this time apparently can be lager.

We intend to find the conditions to prevent the preheating of the targets.

It is supposed in the project to use experiments and numerical modeling simultaneously.

Thank you for attention!