Table 1. Parameters on the detonation wave front in pressed RDX and TNT.

HE	ρ_N, g/cm^3	ρ_CJ, g/cm^3	τ, μs	Δ, mm	Δ_1, mm	$\frac{\rho_\mathrm{N}}{\rho_\mathrm{CJ}}$
TNT	2.59	2.09	0.1±0.014	0.7±0.1	0.63–0.97	1.24
RDX	2.7	2.15	0.48±0.012	0.4±0.1	0.36–0.6	1.25

size of the compression region because of detonation front curvature.

The detector reading error ΔJ can be taken $\frac{\Delta J}{J} \approx 2\%$ when averaged over three experiments [3].

It is necessary to add the detector reading correction error ($\approx 1\%$) and the error of mass reconstruction along the SR beam ($\approx 0.8\%$) to this value:

$$\frac{\Delta Y}{Y} \approx 1\%, \quad \frac{\Delta F}{F} \approx 0.8\%.$$

In our experiments, the surface of the detonation wave front was considered to be a sphere of a radius R. The error of determination of the compression region sizes (the value d) due to the detonation front sphericity is $\frac{\Delta d}{d} \approx 3\%$.

Therefore, the density determination error in the first channels of the detector

$$\frac{\Delta\rho}{\rho} = \sqrt{\left(\frac{\Delta J}{J}\right)^2 + \left(\frac{\Delta Y}{Y}\right)^2 + \left(\frac{\Delta Y}{Y}\right)^2 + \left(\frac{\Delta d}{d}\right)^2}$$
$$\approx \sqrt{2.0^2 + 3.0^2 + 0.8^2 + 1^2} = 3.8\,\%$$

This estimation is true up to a channel where side scattering of products is registered. At this instant, the spherical front reaches the side surface of the charge (area A in Fig. 4). Later on, the error caused by the geometry of detonation products scatter and uncertainty in the parameters on the side surface of the explosive charge (in area A) is added.

The above estimates demonstrate a good accuracy of density measurement, while spatial resolution is defined by the detector step (h = 0.1 mm) as well as by electric charge spread inside it (reading "smearing").

Conclusion. The obtained experimental data on density on the detonation wave front in hexogen are in good agreement with literature data obtained in other setups [4]. The observed spatial resolution of $\sim$ 100 μm makes it possible to investigate transient processes at initiation of detonation as well as substance parameters on the detonation wave front.

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DENSITY EVOLUTION DURING THE INITIATION OF DETONATION IN POROUS PETN

Pruuel E.R., Kashkarov A.O.*, Lukyanchikov L.A., Merzhievsky L.A.

LIH SB RAS, Novosibirsk,

**kashkarov@hydro.nsc.ru*

The paper deals with the method and results of diagnostics high-velocity nonstationary processes using high-speed X-ray tomography. Investigation of transition from combustion to detonation was performed for porous charges of high explosives (PETN).

As a source of X-ray was used synchrotron radiation. The beam of SR through special windows in the explosive chamber penetrates through an investigated charge and the attenuated radiation gets on the linear detector. Energy of photons much above energy of chemical bonds in substance, therefore influences not chemical structure but only atomic structure of investigated substance. From the linear detector (256 channels with an interval 0.1 mm between them) are taken the data about intensity of the attenuated radiation with an interval in 500 nanosecond (32 shots) at time of an exposition 1 nanosecond. The basic scheme of the detector and research facility is in detail stated in work [1].

The nonstationary flow arising at initiation charge of PETN bulk density in a fragile thin cover was investigated. The size of particles 200–300 micron, charge length 20–30 mm, diameter 16 mm. Charge of HE was initiated by a high-speed flow of products of a detonation of additional HE charge.

Experiments in similar statements were performed earlier repeatedly. Distribution of density in charges and in the field of scattering, deformation and destruction of inert mediums was investigated. Essential difference of experiments in this work is research of detonation in porous HE charge. In this case considerable curvature of front, and a flow essentially nonstationary is observed.

Experiments were made at two various arrangements of HE charge relatively a SR beam: longitudinal and cross-section. The first statement of experiments allows to see the process as a whole from a stage of initiation to development of a stationary detonation in a charge that gives the chance to define dynamics of position and speed of front. The front form and flow structure behind front remain are unknown. The data of cross-section statement is used for tomographic flow visualisation. Sharing of results from both statements allows to reconstruct structure of density distribution in detonation products $\rho(r,z,t)$, where r - radial co-ordinate, z - co-ordinate along an axis of symmetry of a charge, t - time from the initiation moment.

For density reconstruction the solution of the following mathematical problem is necessary: to find function $\rho(x,y,t)$ from the integral equation

$$F(x)=\int_{-\sqrt{R_0^2-x^2}}^{\sqrt{R_0^2-x^2}}\rho(\sqrt{x^2+y^2})dy, \qquad (1)$$

where $F(x)$ - experimental function ρd where ρd - amount of substance on a SR beam $\int \rho dl$. The problem belongs to the class of ill-posed problems of mathematical physics. To obtain the solution of such problem the additional aprioristic information is usually used, allowing to allocate the corresponding physical one. The state becomes complicated that in experiments $F(x)$ function is measured in a finitesimal discrete set of points, thus - with a margin error. Possibility of the solution of the problem is facilitated by that it possesses axial symmetry as the initiation means, the investigated charge and, hence, a developing flow are axisymmetric.

For reconstruction distribution of density the modified method offered in [2] was used. This iterative method is based on use of the additional aprioristic information on the general structure of a realised flow in the investigated phenomenon. Here it was necessary to change the scheme of reconstruction of density proceeding from the assumption of essential curvature of front of detonation, and necessity of merging the data from various areas of a charge, in which arising flow variously in force nonstationary of initiation process.

At first $\rho(r,t)$ reconstructed at $z = const$ by data from one experiment in cross-section statement. It is supposed that a form of shock front in a charge is parabola $t = -\alpha r^2$ with the varied parameter α, outside of a charge border of scattering of detonation products is a straight line. The profile line of shock front has the form of sharp sudden change of compression with the subsequent smooth dispersion. In each knot of a grid initial value of density is set. Varied parameters are distances between knots in time, curvature of front, a scattering corner, initial value of density before front and position of the maximum corresponding to front. Out of flow area initial value of density is necessary equal to zero. The smooth function describing density distribution constructed by means of interpolation given parameters by cubic splines.

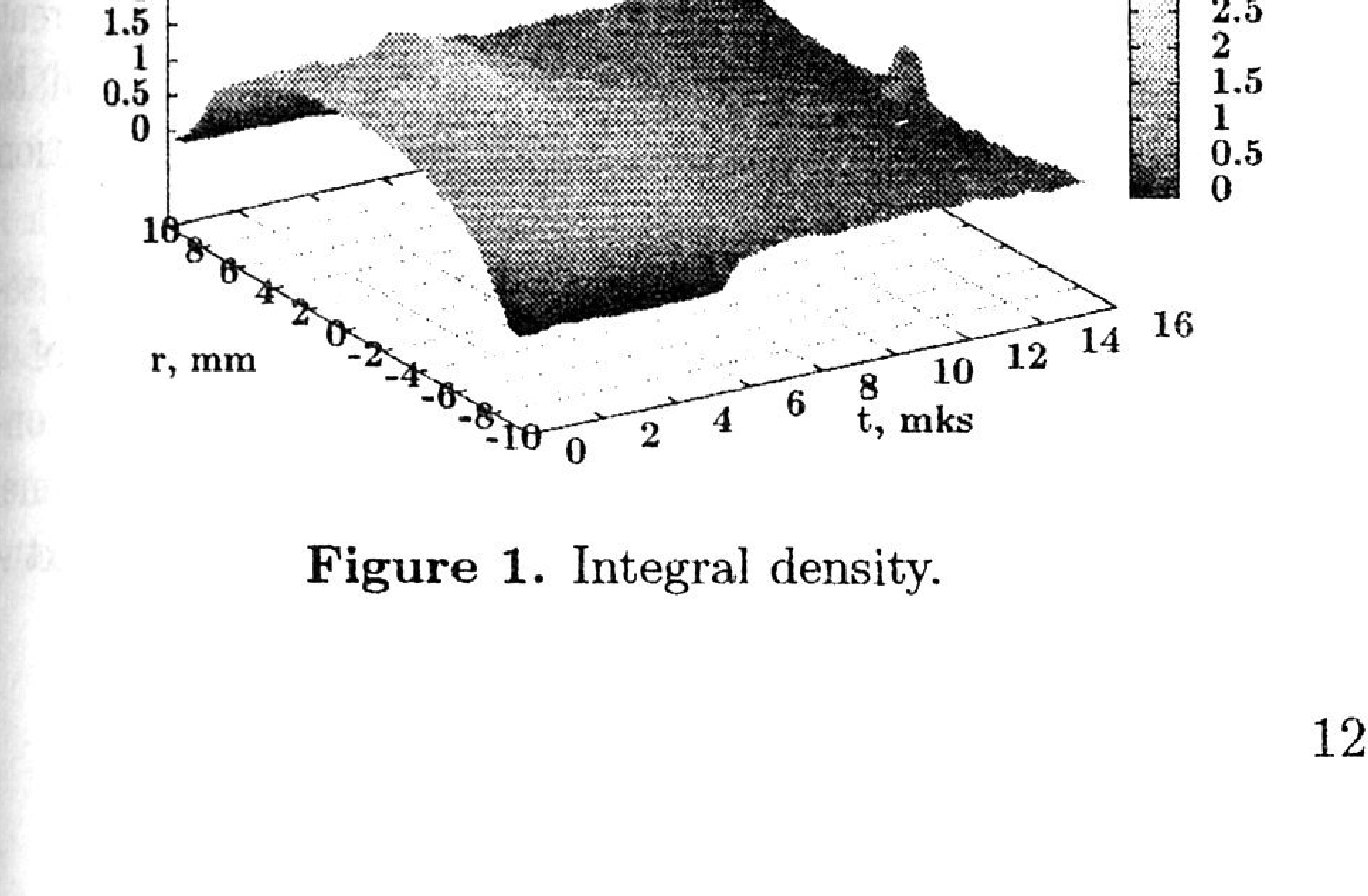

Figure 1. Integral density.

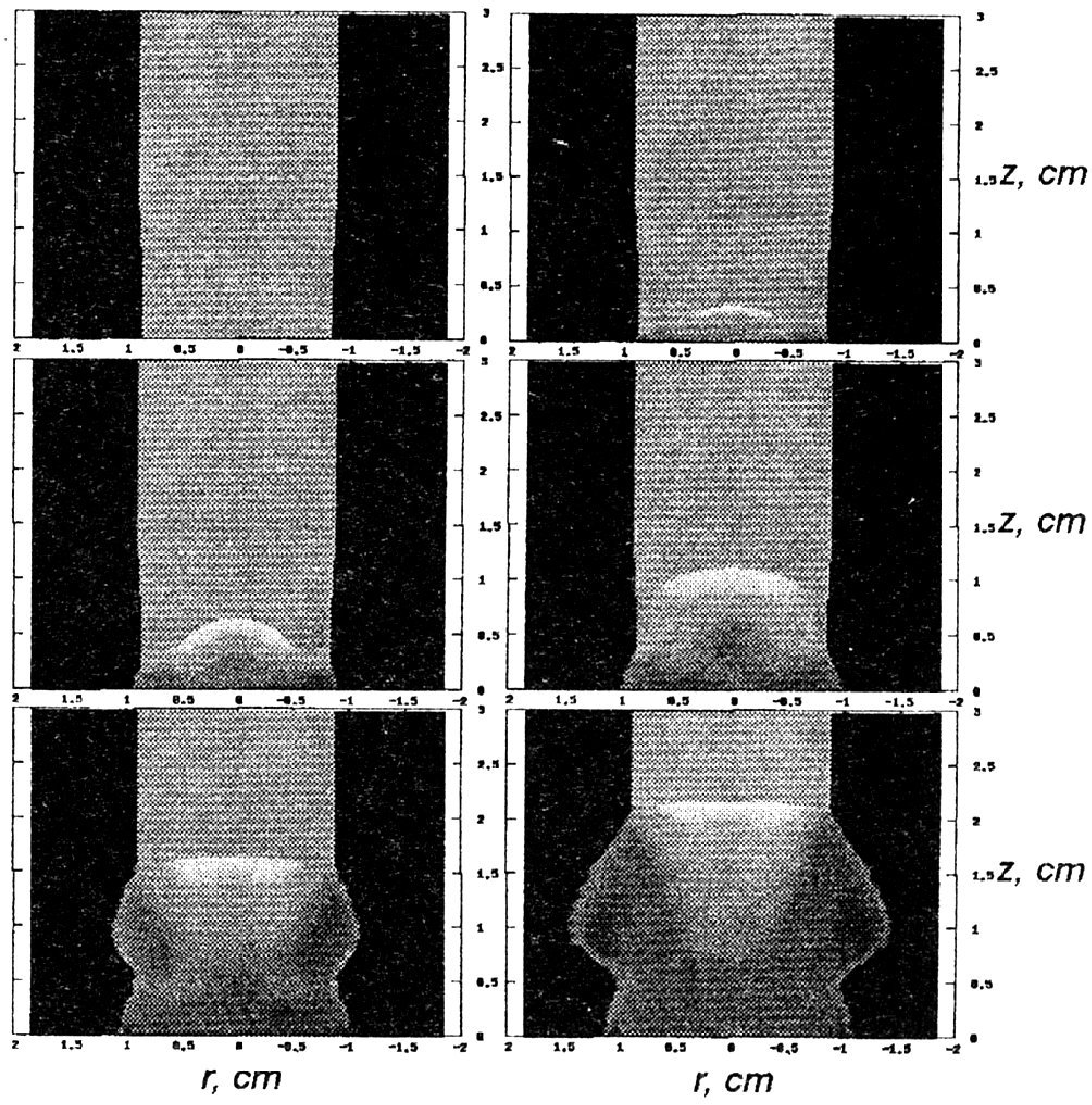

Figure 2. Denisty distribution.

The density in the fixed section z is searched in the form of parametrical function with a set of the parametres described above, for this purpose we numerically solve a minimisation problem of functional root-mean-square deviations between calculated and discrete experimental functions of shades. Thus, for each experimental plane $z = const$ we receive a set of parameters by which temporary distribution of density in the given plane in the form of smooth function $\rho(r,t)$ with discontinuity at the front and charge borders is unequivocally reconstructed. Interpolating the calculated parameters on z, we receive the same set of parameters for any section on z where experiments were not made.

In experiments at longitudinal statement we obtain distribution of $\rho d(r,t)$ in section of a charge Fig. 1. Reconstruction of density distribution on the set of sections gives full $\rho(r,z,t)$. On Fig. 2 density distribution $\rho(r,z)$ is presented at fixed t. For the analysis of density dynamics it is convenient to allocate $\rho(z,t)$ in the charge centre. On Fig. 3 dynamics of a profile of density on an axis of a charge with step of 0.5 mks is presented. Here it is important to notice small rate of compression of substance during the first moments of initiation that testifies to the weak mechanism of initiation. It is possible to assume that the substance warming up not in shock wave front but because of occurrence of a diphasic flow at which the internal surface of pores ignites by gaseous products of burning HE. Increase of pressure of burning products leads to an intensification of the forced filtration and increase amount of reacting explosive in burning front, to pressure increase in a wave of burning and to transition

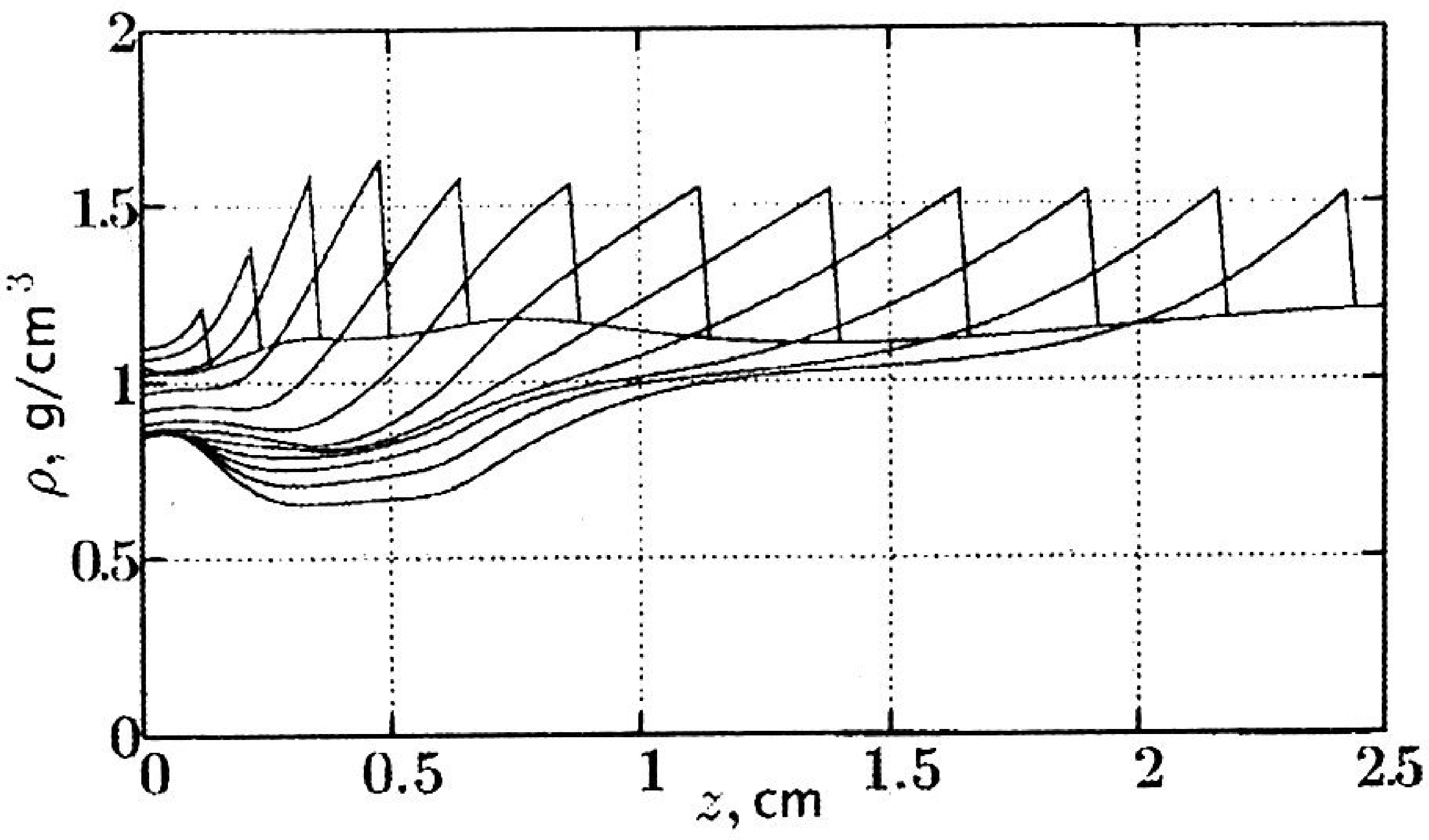

Figure 3. Density evolution on an axis of a charge.

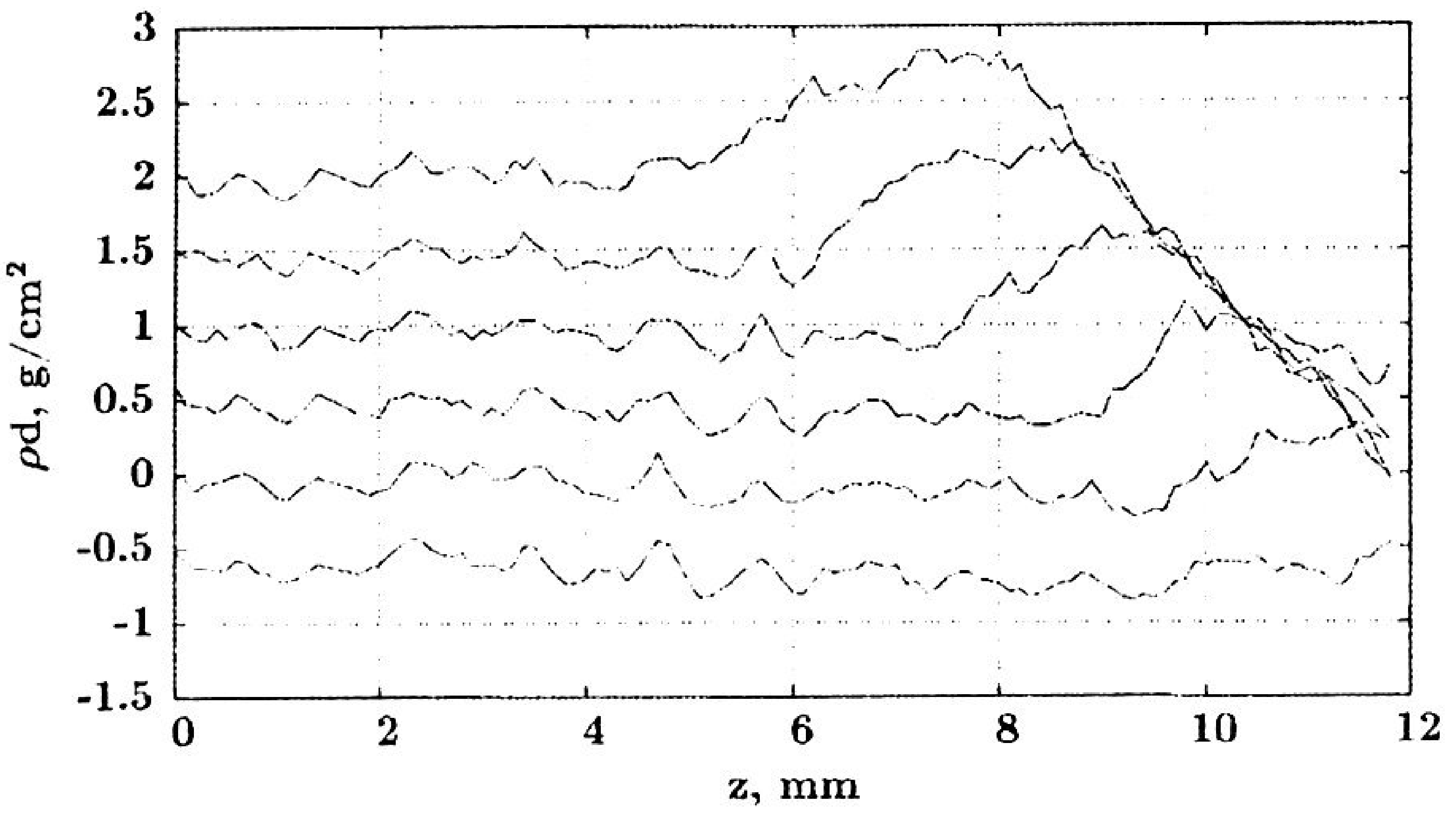

Figure 4. Integral density dymnamics in an inert powder.

to detonation. The measured rate of compression of substance in detonation front well agreed with model of an ideal detonation of Chapman-Jouget $\frac{\gamma+1}{\gamma}$ where γ for condensed HE is close to 3.

For confirmation of the assumed mechanism of development of a detonation the experiments with an inert powder of close density have been made. On Fig. 3 dynamics $\rho d(z,t)$ is presented on an axis of a charge, curves are represented with displacement, true value ρd before arrival of a shock wave of 2 g/cm^2, an interval between curves 0.5 mks. At identical influence on an inert powder the compression rate more than in 2 time exceeding compression in HE, and low speed of a shock wave (about 2 km/s) is observed. It testifies about considerable influence of chemical reactions in explosive already in the first micro second of initiation.

Conclusion. Experiments for a tomography of a nonstationary, not one-dimensional flow of a porous explosive charge arising at initiation are made. The considerable curvature of front changing with development of a detonation in a charge is revealed. The estimation of rate of compression behind detonation front agreed with theoretical data. Density distribution $\rho(r,z,t)$ in all area of a flow from the moment of initiation before development of a stationary detonation is reconstructed. The method is applicable for specification of models of detonation and carrying out of researches of various structures HE with considerable curvature of front.

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HIGH EXPLOSIVES EXAMINATION BY HIGH-RESOLUTION X-RAY COMPUTED TOMOGRAPHY ON THE VEPP-3 SYNCHROTRON RADIATION

Kuper K.E.[1], **Ten K.A.**[2], **Pruuel E.R.**[2]*
[1]BINP SB RAS, [2]LIH SB RAS, Novosibirsk,
**cooper@inp.nsk.su*

Abstract. High-resolution X-ray computed tomography (HRXCT) is a technology ideally applicable to a wide range of materials investigations. It is an express non-destructive method to produce 3D images corresponding to series of slice projections through a sample.

In the present study, HRXCT was applied to high explosives samples with the use of synchrotron radiation from the VEPP-3 storage ring (Novosibirsk, Russia), at the station "X-ray microscopy and tomography". Comparative analysis of internal structure was carried out for different samples pure RDX, TNT and their alloys.

In order to efficiently increase the spatial resolution of the method, X-ray magnification system (Bragg magnifier) was used [1, 2]. The "Bragg magnifier" is based on the diffraction from an asymmetrically cut crystal. Bragg diffraction from an asymmetrically cut crystal produces one-dimensional magnification. Two asymmetrically cut crystals reflecting in mutually perpendicular directions gave a uniform two-dimension magnification. The using "Bragg magnifier" with magnification factor 20 allows achievement 4–5 microns spatial resolution in the registered images.

Introduction. HRXCT gives a detailed three-dimensional imagery of the interiors of high explosives samples, realized in a non-destructive manner. The essence of the method is scanning a sample with X-ray beams that are differently absorbed in its various areas. The attenuation of X-rays along the beam is an integrated characteristic of the density of the object to investigate. The degree of distinguishing different components of high explosives volume in HRXCT data depends on the difference in their linear attenuation coefficients.

The resulting data are reconstructed from a sequence of projections obtained during rotation of a sample as series 2D slices. Collecting a stack of contiguous slices allows reconstruction of a full 3D volume. Our applications include interior examination of textu-

Institutions of the Russian Academy of Sciences
Joint Institute for High Temperatures RAS
Institute of Problems of Chemical Physics RAS

Kabardino-Balkarian State University

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