Measurements of detonation propagation in the plastic explosive in charges of small diameters using synchrotron radiation

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Abstract. During the detonation of charges of plastic explosives based on PETN and RDX, the spatial structure of the arising flow and the degree of compression of the matter behind the detonation front were obtained using the synchrotron radiation facilities. The experiments were carried out with charges of small diameters, which made it possible to control the symmetry of the undisturbed charge of the explosive and the flow behind the detonation front. In addition, the advanced detector was used to increase the frame rate by 4 times in comparison with the authors’ earlier works.

1. Introduction
Registration of fast processes accompanying explosive phenomena by using the synchrotron radiation (SR) as the source of X-ray pulses is the efficient method used to the study of detonation and the shock wave phenomena for more than ten years. The authors of this article use and continuously modernize the experimental station at the Siberian Synchrotron and Terahertz Radiation Centre at the Budker Institute of Nuclear Physics \cite{1, 2}. This station enables to obtain a multi-frame slit X-ray film with a frame exposure time of about 1 nanosecond and a spatial resolution of 0.1 mm. The similar station for recording the SR during high-speed processes was created by colleagues at the Argonne National Laboratory in 2012 \cite{3, 4}.

The way of obtaining information about the structure of the flow behind the front of the detonation wave is based on the registration of the SR beam passing through the detonating charge. The identity of the X-ray pulses of the SR by the spectrum and the intensity distribution in the beam during the experiment makes it possible to calibrate the detector and obtain the distribution of the compression of matter along the beam for the process being studied. Also, an important feature is the fact that the registration of the distribution of the compression of substance in a detonating charge of an explosive does not introduce perturbations into the arising flow. This circumstance is especially important for studying the detonation process in charges of small diameters. In this case the use of contact sensors can lead to catastrophic changes in the observed phenomenon.
To register the radiation passing through the expansion area of the detonation products, the new detector was launched (2017) and used in this work. Compared with the previous detector [5], the time resolution was improved by 4 times. Now, the interval between frames is 124 ns. The number of frames during the experiment was also increased up to 100. Thus, it is possible to trace the detonation process starting from the unperturbed state of the material to the late stages of expansion of the detonation products.

2. Experimental setup and reconstructing distribution of compression of substance

In this work, we measured the detonation parameters in cylindrical charges of plastic explosives based on PETN and RDX with diameters of 5, 10, and 15 mm. The measurement of the flow, which arises behind the front of the detonation wave, was carried out in the cross section of the charge as shown in figure 1. The intensity distribution of the SR beam passed through the detonating charge of high explosive is recorded by the one-coordinate multichannel detector. The amount of substance along the SR beam was calculated from the measured intensity distribution using the previous calibration of the detector. For this purpose the attenuation of the intensity for the known amount of the mass of the investigated explosive along the SR beam is determined in the static regime. The integral current in the accelerator ring completely determines the spectrum and the intensity distribution of the synchrotron radiation beam, so the calibration can be carried out regardless of the time of the experiments. However, the detonation products and fragments of experimental assembly that reach the windows of the explosive chamber during an explosion can affect the data recorded, so the calibrating just before each experiment considerably improves results.

The charge was initiated by the generator of plane shock wave. The measurements was carried out at the distance from the face of the initiation that sufficient to establish the stationary detonation regime. The assumption of the stationary detonation front should be made to compare the experimental data for the charges of different diameters and explosive compositions.

Charges of small diameters can be completely placed in the region of registration of the SR beam, which makes it possible to control the symmetry of both the undisturbed charge and the flow arising behind the detonation front. The relative amount of mass for the charge of the explosive based on PETN of 10 mm in diameter is shown in figure 2. The cylindrical symmetry of the mass distribution is of fundamental importance, since it gives the possibility to set the task of tomography of the compression of substance in the process using only one shot. For the tomography problem, it is necessary to smooth out the noisy experimental data. However, there are natural discontinuities at the detonation front and at the charge edge, typical for the
explosion process. To solve the tomography problem is used the method [6] developed earlier by the authors of this work. This method based on the use of a priori information to smooth experimental data. The essence of the method is set out below.

Measuring the amount of mass along the SR beam during detonation of a cylindrical charge of explosive, we should obtain a distribution of the typical form shown in figure 3. First, we register the unperturbed state of the charge of the explosive, then we see that the detonation front passes through the registration cross section, and later the side expansion of the detonation products proceeds. After a while, the detonation products go outside the registration area of the SR beam. This distribution of mass is equivalent to the distribution of the compression of the substance, obtained by setting the corresponding values in the nodes of the grid shown in figure 4. For this purpose, the spline function is calculated through the grid nodes along each line shown in figure 4 starting from the detonation front down. The spline function gives us the values not only at the grid nodes but also between the nodes. In the experiment the mass distribution is measured in the horizontal cross-sections of the grid (one of them is indicated by a dashed line). This mass distribution can be obtained with use of the another spline function, which is calculated along the dashed line inside the region filled with the explosion products. The geometry of the grid is determined by the curvature of the front and the border of the region filled with the explosion products. Thus, none of the splines intersects the discontinuities. Minimizing the deviations between the experimental and calculated data by varying the grid parameters, we obtain the distribution of the compression of the substance corresponding to the X-ray shadow observed in the experiment.

For the compositions under study, the curvature of the detonation front is very large. For charges of small diameters, the detonation front pass the observation cross-section in only tens of nanoseconds, while the time interval between frames is 124 nanoseconds. This circumstance leads to the impossibility of the reliable determination of the curvature of the front directly in these experiments, and so the curvature was determined in the separate experiments. The similar situation arises with the determination of the state of substance in the von Neumann spike, since the typical width of the chemical reaction zone for the considered explosives is also tens of nanoseconds [7]. Therefore, at best, the first frame behind the detonation front will show the mass distribution close after the Chapman-Jouguet state.

When the detonation front passed through the explosive charge, the detonation products quickly exceed the border of the registration area, due to intensive side expansion. The considered method of reconstructing the flow structure allows one to obtain data in this case due to the requirement of smoothness of the solution, but the error will substantially increase. Previously, it was usually possible to register no more than one frame before the expand of detonation products outside the observation area. The 4-fold decrease in the interval between
frames to 124 nanoseconds significantly increases the accuracy of determining the structure of the compression of substance behind the detonation front.

3. Results
The solution of the tomography problem results in the radial function of the dynamics of the compression of substance in the detonating charge for each experiment. This function can be shown as a three-dimensional surface (figure. 5) or a map (figure. 6) that allows us to compare the flow structures behind the detonation front for the explosive compositions investigated.

The non-constant magnitude of the compression of substance in the undisturbed region of the charge is related both to the quality of the production of the charges and to the experimental error in measuring the amount of substance along the SR beam. This error does not exceed 5% for static objects. This value agrees well with the obtained compression of the substance before the detonation front. It is expected that the total error for the dynamic flow region will be of the similar order.

![Figure 5. The distribution of the substance compression of RDX-based charge. Diameter 5 mm.](image)

![Figure 6. The distribution of the substance compression of PETN-based charge. Diameter 10 mm.](image)

Figure 7 shows the diagrams of the compression of substance along the charge axis for various explosive compositions and diameters. The quantitative difference in the flows behind the detonation front are obvious. For clarity, the profiles were shifted in time to align detonation fronts. It should be noted that the moment when the detonation front passed through the observed cross section of the charge is determined with an accuracy not exceeding 124 ns. This is due to the frame rate and the almost flat shape of the detonation front.

![Figure 7. Compression of substance on the charge axis.](image)

Measurements show that the degree of compression of substance behind the detonation front for charges based on PETN is smaller, and the subsequent reduction of compression occurs faster. However, the obtained value of the maximum compression of substance can hardly be referred to the state at the von Neumann spike or at the Chapman-Jouguet point. The values obtained
for the maximum compression of the substance are rather referred to later states behind the detonation front.

4. Conclusions
The paper presents quantitative data on the dynamics of compression of substance in the area of expansion of the detonation products. This allows to compare the detonation processes in charges consisting of various explosives. It was necessary to make a number of approximations to obtain the data. First of all, we had to consider detonation stationary, that is valid for charges of sufficient length. Further, we had to assume that the arising flow is axisymmetric. The validity of the last approximation was checked during the experiment for charges of small diameters.

On the other hand, obtaining the compression distribution of the substance entails smoothing out the experimental data, and this can lead to partial loss of the data. Therefore, in order to calibrate numerical models, the comparison of the calculated mass distribution along the SR beam with the experimental one will give better results than the use of the compression distribution of the substance for these purposes.

In [8] authors used the VISAR technique and the laser-geterodyne technique (PDV-technique) to study the plasticized PETN of close compositions. They recorded time profiles having the near-front peak and the plateau behind the detonation front with the follow-on dip. According to the authors, the near-front peak corresponds to the Chapman-Jouguet state. In this paper, we do not observe any specific features on the compression diagrams that could indicate the presence of this plateau.

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