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Methods of research of the detonation and shock wave processes with the help of SR. Possibilities and prospects

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Abstract

The existing research methods are insufficient for investigation of the detonation physics because of very high pressure, rapidity and aggressiveness of explosion. Therefore, new methods allowing direct experimental investigation with the help of SR are of great interest. This paper suggests and describes realization of a new method for remote investigation of the detonation and shock wave processes with the help of SR. Presented below is a description of the experimental facility at which the first studies on the measurement of the passed radiation and small-angle X-ray scattering (SAXS) at detonation of condensed explosives were conducted.

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1. Introduction

At an explosion (detonation), the explosive passes consecutively through several stages of transformation. Firstly, it is compressed and heated in the shock wave. After that a reaction with liberation of high energy occurs, followed by the spread of the explosion products. The physics of detonation of processes is under intense investigation for a long time but has not been investigated sufficiently. Lack of information on detonation parameters is caused by the limitation of physical research methods at such high pressures (≈ 500 kbar) and short times (≈ 0.1 μs).

Synchrotron radiation (SR) application allows obtaining a new method for remote investigation of fast processes, thanks to the combination of the unique properties of SR as well as to the high quality of the created recording equipment, providing recording in the nanosecond time range.

Such important features of SR as (a) high intensity of the X-radiation, (b) broad spectral range, (c) small angular divergence, (d) high time periodicity and (e) short time of exposure allow obtaining high time and spatial resolution in the experiments. In particular, SR permits getting

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information on the local density change dynamics as well as on the growth dynamics for new formations, including the crystal ones in detonation flows. The most interesting from this point of view is the study of the kinetics of the carbon crystal phase synthesis (including the ultra-dispersed diamonds) in detonation waves.

Explosion experiments with the SR application were performed at the experimental station mounted at the SR channel of the VEPP-3 electron accelerator (with an electron energy of 2 GeV).

After passing the 2 T wiggler the SR beam has an energy of 10–30 keV and duration about 1 ns. Time between pulses is determined by the electron rotation period and is 250 ns.

2. The station for explosion experiments

The station consists of the specialized explosion chamber for 15 g of a high explosive (HE), system for synchronous initiation by detonators without primary explosives, SR beam adjustment system, X-radiation detectors, synchronization system and CAMAC rack for recording of the signals received. The layout of the facility is presented in Fig. 1.

The explosion chamber is made of stainless steel and has: (1) the inlet and outlet windows for the SR, (2) the high-voltage input for detonator initiation, (3) the four cable outlets for the synchronizing signals, (4) the exhaust duct for outlet of gases (detonation products), (5) the two taps for connection to the vacuum system and filling with gases.

To make the X-radiation losses minimal, the inlet and outlet windows for SR were made of 2 mm thick beryllium.

Phototransistors with fast amplifiers were used as detectors. The measurement frequency was 125 ns, i.e. two measurements per revolution. Odd measurements were made at the instant when the radiation from the wiggler arrived and even measurements were performed between them, to measure the detector's background. The total number of measurements was 4000, so, the total interval of measurements was 512 μs, which is enough for the investigation of the detonation processes.

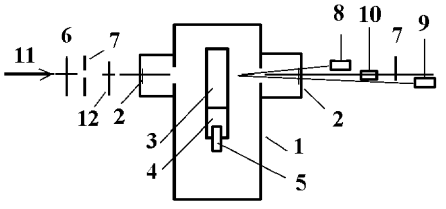

Fig. 1. Arrangement of the experiments. 1—the explosion chamber, 2—the beryllium window, 3—the explosive sample, 4—the HMX powder, 5—the detonator, 6—the vertical knife, 7—the horizontal knife, 8—the SAXS sensor for 1–10 keV, 9—the SAXS sensor for 15–30 keV, 10—the transmission sensor, 11—the SR beam, 12—the electromagnetic shutter.

3. Arrangement of the experiments

The relative disposition of the explosive charge and SR beam is shown in Fig. 1. The irradiation zone on the explosive charge (the SR beam "spot") was 0.2–1.5 mm high and 5–6 mm wide. The diameter of the cast and powder charges was 10 mm. The pressed charges were 12.5 mm in diameter. To ensure solid excitation of detonation in the trotyl-hexogen and trotyl charges, a booster charge of powder HMX was used. The length of the charges varied from 25 to 80 mm. Shooting of similar charges with the X-ray device PIR-600 showed that the detonation front is rather flat for a charge length more than 30 mm. The distance between the wire contact sensors L was 19–21 mm in different experiments.

4. Results of the experiments

Adjustment of the optical system before the experiments was performed with the use of a charge cast made of paraffin with a 6% addition of the saved detonation products (the soot). The soot was gathered after explosion of the 50/50 trotyl/hexogen charge in the explosion chamber. It is known that 80% of the soot composition are ultra-dispersed diamonds [1]. If the SAXS signal from

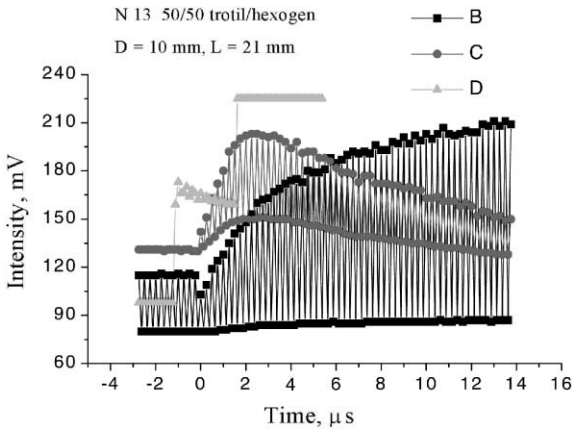

Fig. 2. Experimental results of 50/50 trotyl/hexogen detonation. The intensity of the passed beam (B) and integral SAXS intensity (C) and contact sensors (D) versus time.

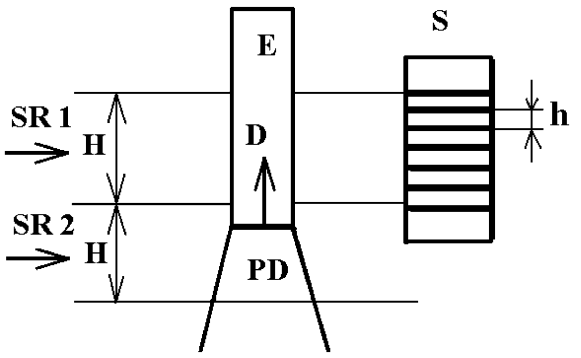

Fig. 3. Scheme of the density measurement with the help of a pile of detectors. SR-1—the SR beam position, SR-2—the next SR beam position in the time t, H—the SR beam height, X—the linear distance between the two SR pulses, E—the explosive charge, D—the detonation front position, PD—the spreading detonation products, S—the microstrip SR detector, h—the distance between the strips.

the paraffin cast exceeded the background level by 3–5 times, then the adjustment was optimal.

The 50/50 trotyl/hexogen alloy was the first to be studied. Among the widespread HE, this alloy has the highest output of ultra-dispersed diamonds (UDD) [1]. Fig. 2 shows records of the passed radiation through the 50/50 trotyl/hexogen (B), SAXS (C) and signals from the wire sensors at $L= 21$ mm (D). The measurements were made in $t= 250$ ns. Between the measurements the amplifiers' "background" was measured.

Therefore, the valid signal for the passed radiation and SAXS is obtained from the difference of the upper and lower points. The detonation rate was $D = 7.5$ km/s.

4.1. Density measurement

One can see clearly in the recording, a compression on the detonation front and spread of the detonation products after the explosion. The density increase on the detonation front is $\approx 30\%$. At this detonation rate the linear resolution is $X = D$, $t= 1.875$ mm. The VEPP-3 storage ring allows a double increase of the SR pulse frequency rate when two electron bunches are used, which means a double increase of the linear resolution. The resolution can be increased principally via the use of a pile of detectors (a microstrip detector) instead of one detector. Fig. 3 shows the scheme of the experiment performance. When density is measured with one sensor, the linear distance between two pulses is $X= 1.875$ mm. If a microstrip detector of more than 1.9 mm height is used, then the linear resolution is determined by the strip step (width) h. The experiments were performed with the use of a detector with the strip step $h= 100$ μm. In doing so, the time resolution could be $\Delta t = h/D= 13.3$ ns. Only three channels were used in the first stage of the experiments (strips spaced by 400 μm were output from the detector to the three ADC channels). A record of these three channels at detonation of the 80/20 trotyl/ammonium nitrate alloy (TNT/AN) is shown in Fig. 4.

When a detector with the step $h= 7.5$ μm is used, the time resolution will be $h/D= 1$ ns. In doing so, the number of the recording channels shall be 1875 μm/7.5 μm = 250.

4.2. SAXS measurement

The SAXS signal starts increasing during compression in the detonation wave and lasts for 1.75 μs. The decay lasts for hundreds of microseconds. The SAXS signal gives the density fluctuation value for the spreading detonation products. Its maximal value exceeds by a factor of

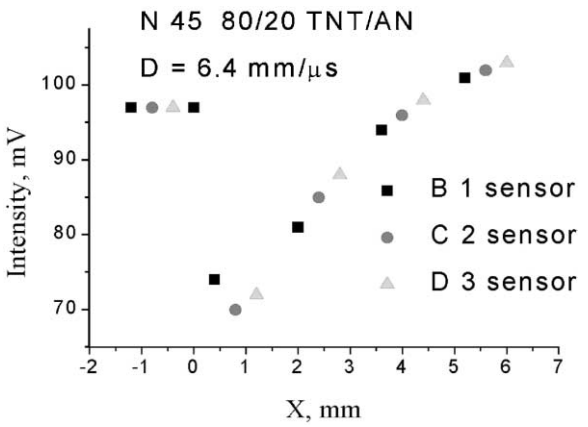

Fig. 4. Sample of 80/20 TNT/AN. The intensity of the passed beam from the three strips of the microstrip detector. The distance between the strips is 0.4 mm.

2.5 the signal from the soot, which consists of diamonds mainly. So, we think that the SAXS signal received is determined basically by the concentration of the crystal phase in the detonation products. Eighty percent of this phase, in turn, are UDD, which are synthesized at detonation of the HE. Previous study of the diamond synthesis at explosion allowed making a conclusion that UDD appear in the narrow zone beyond the detonation front in less than 0.1 μs [1,2].

Therefore, these data give a base for a deeper understanding of the model for formation and growth of the crystal phase (including diamonds) at detonation of an explosive.

5. Possibilities and prospects of the method

Let us specify in brief the main parameters of the detonation and shock wave processes that can be studied experimentally with the SR application.

5.1. Density measurement

Density measurement is done by the measurement of the direct beam absorption and, consequently, by the determination of the variation dynamics of density of the explosives and detonation products. It seems to be more appropriate to use a pile of detectors, e.g. a microstrip detector oriented either along or across the detonation spread (the charge axis). In the first case, that allows increasing the ultimate time resolution (at the expense of the self-development of the stationary detonation process), in the second one, determination of the profile of the compression and rarefaction waves on the base of, for instance, the axial symmetry of a cylindrical or tube charge.

Besides that, measurements of the direct beam absorption can be used in the study of reflection of shock waves, unload (discharge of the detonation products into vacuum or an assigned medium), dynamics of motion of inert additions (powders). If SR-absorbing marks (foils or admixtures of a heavy element, bismuth, for instance) are introduced into the explosive, these measurements can be used for the study of mass flows directly in the charge.

5.2. Determination of the dynamics of growth of condensed phase particles beyond the detonation front

The SAXS signal that is recorded in such setting allows estimation of the total number of particles beyond the detonation front. The quantitative dependence of the particle number and size on time can be obtained with the use of a monochromator. It is also necessary to use a pile or matrix of detectors instead of one radiation detector. By now, a significant restriction is the insufficient intensity of the SR from VEPP-3. One of the ways to increase the intensity is to install a wiggler with more powerful magnets. A more principal way would be a conversion to more powerful storage rings (e.g. VEPP-4 or Spring-8).

The time resolution in the above-described experiments is determined by the period of electron rotation in the VEPP-3 storage ring. The VEPP-4 accelerator now permits stable rotation of bunches with the minimal time interval $t = 5$ ns. The linear resolution $X = 38$ μm corresponds to this time at the detonation rate $D = 7.5$ km/s.

Another way to increase the linear and time resolution is to use devices with charge memory (linear and matrix charge coupled devices, CCD).

Information recorded in them is read to the ADC consequently, therefore one recording channel will be enough for the experiments. Such consequent reading, however, leads to a long total time of full output of the information from the CCD. This time is about 0.1–100 ms, so, signals from all the elements cannot be read during one revolution of a bunch (250 ns). A "superposition" of the signals and overload of the CCD occur.

This restriction can be overcome by using the "parallel" scheme that was described in detail in [3,4]. The spatial resolution of such scheme is assigned by the matrix element sizes and is. $\approx 10\,\mu m$

With high-sensitive matrix CCD working in the mode of X-ray spectrometers being used, it is possible for such a setting to obtain for the local charge region the spatial distribution of the diffracted photons and simultaneously to determine their energies. That will allow determination of the instantaneous structures and concentration of crystal inclusions in this region.

Another way of recording diffraction signals is to use integrating detectors of large area and high time resolution. In doing so, the diffraction signals are recorded at each passing of a bunch, similar to the SAXS signals in the experiments performed.

Registration of the X-ray scattering in large angles permits investigation of the destruction and formation of different crystal inclusions (melting and evaporation of crystals of explosives and metal particles, crystallization of solid oxides, etc.). Besides that, recording of the diffraction pattern with a sufficient angle and X-ray quantum energy resolution will help in identification of different crystal phases and in determination of their state (pressure, temperature and particle sizes). The main restriction on performance of such experiments at present is the insufficient intensity of the diffracted radiation. This restriction could be overcome by using more powerful SR sources.

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