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The synchrotron radiation beamline 8-b at VEPP-4 collider for SAXS, WAXS and micro tomography investigation of fast processes at extreme condition of high temperature and pressure with nanosecond time resolution

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Abstract

The main purpose of the beamline design – realization of experiments using explosive charges up to 200 grams of TNT equivalent. To achieve this goal is necessary to use a of hard range of photons in the region of 30-60 keV. Additional requirement - the development of a powerful explosion chamber, and very fast one coordinate detector DIMEX. The fist detonation experiments was made with explosive 40 mm diameter. Test WAXS experiments was made and time resolution of 73 ps was received. SAXS/WAXS experiments was made at accelerators complex VEPP-3/VEPP-4.

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Keywords: synchrotron radiation, SAXS, WAXS, detonation, shock wave, nanodiamond, high pressure, high temperature, time resolved, nanosecond, picosecond, TNT, BTF, RDX

Introduction

The 8-b beamline uses radiation of 7-pole wiggler (five main poles with the field of 1.3 T and the two side, with

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half the field), is aimed for the study of fast processes taking place in the detonation wave and under the shock wave impact. The main purpose of the beamline design – realization of experiments using explosive charges up to 200 grams of TNT equivalent. To achieve this goal it is necessary to use a hard range of photons in the region of 30-60 keV. Additional requirements - the development of a powerful explosion chamber, and very fast one coordinate detector DIMEX (Aulchenko, 2010).

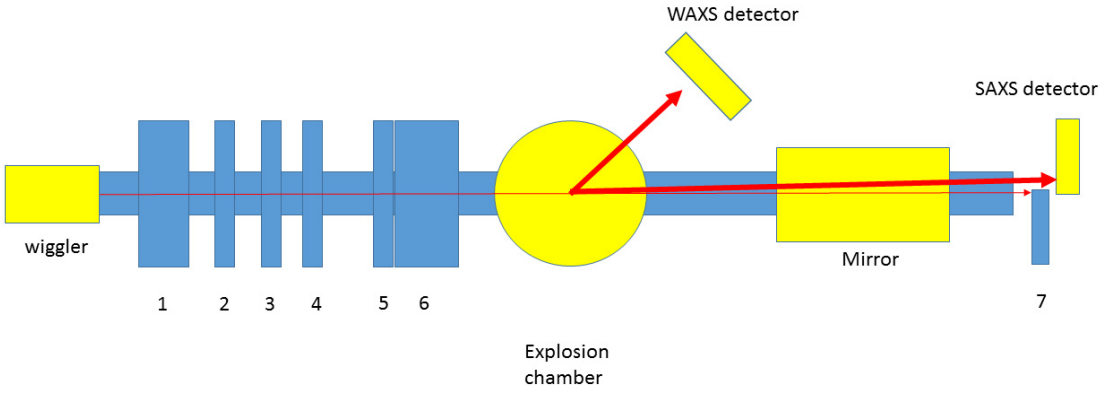

Fig. 1. The scheme of The synchrotron radiation beamline 8-b at VEPP-4 collider for SAXS, WAXS and micro tomography investigation of fast processes at extreme condition of high temperature and pressure with nanosecond time resolution. 1 – X-ray optics unit, 2 – CCD beam position monitor, 3 – position sensitive ionization chamber, 4 - horizontal slit, 5 – fast acting shutter, 6 – Kratky collimator, 7 – beam stop.

Another goal of this project was to obtain high temporal resolution -an exposure time of 0.1 ns with a 600 ns interval and a number of shots of 32 was attained at the station for research on shock-wave processes.

Beamline consists of the following main elements: 1 – X-ray optics unit, 2 – CCD beam position monitor, 3 – position sensitive ionization chamber, 4 - horizontal slit, 5 – fast acting shutter, 6 – Kratky collimator, 7 – beam stop.

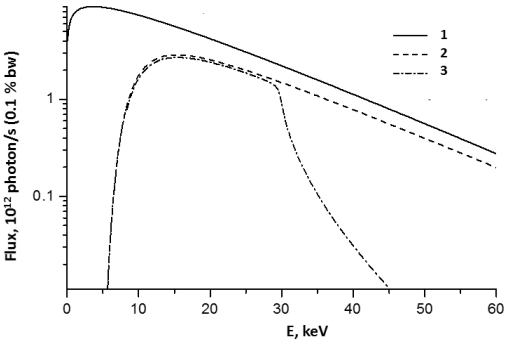

Fig. 2. Spectrum of SR (20 mA, 4 GeV electron energy, the main pole wiggler field 1.3 T, the critical energy of 13.8 keV): (1) from the source, (2) after the Be-foil, (3) after the mirror with nickel plating (angle 2 mrad).

1. Wiggler

The source of synchrotron radiation for the beamline is the seven-pole wiggler, where two side poles have approximately half the field, and five main poles are in the region of maximum field of 1.3 Tesla.

The emission spectrum of the wiggler for the field 1.3 T, energy of the electrons is equal to 4 GeV, and the current drive of 20 mA, is shown in Fig. 2 for the horizontal angle 1 mrad (by integral vertical angle). Also it shows the spectrum after Be foils of front end (total thickness of 12 mm), and after the mirror (nickel plated angled 2 mrad beam SR).

2. X-ray optics unit

The purpose of X-ray optics is focusing of synchrotron radiation in the vertical plane. Refractive optic is used (Nazmov V.P., 2013.). The LIGA technology was used for production of lens.

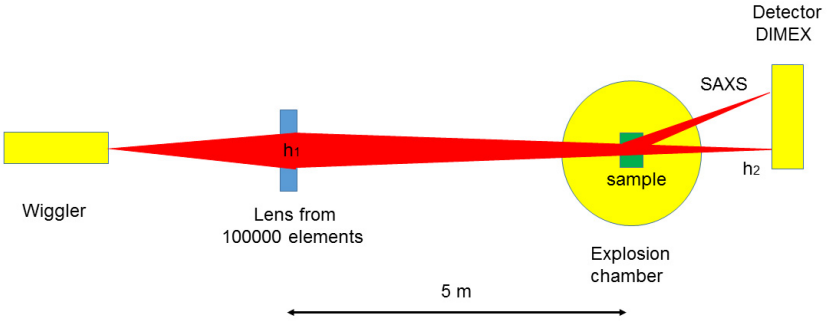

Fig. 3. X-ray optic scheme. The initial vertical size of SR beam is h_1=1 mm, the size after X-ray lens is h_2=0.1 mm. Refracting X-ray lens consists of separate focusing elements in the form of triangular prisms (size 10 micrometers, number 100000) arranged into rows.

Refracting X-ray lens consists of separate focusing elements in the form of triangular prisms (size 10 micrometers, number 100000) arranged into rows. SU-8 plastic was used us lens material. The geometric dimensions, vertex angle and number of elements in each row, as well as the material from which the focusing elements are made vary depending on the selected photon energy in the range from soft X-rays to gamma-rays. The number of focusing elements in different rows is determined by a set of given energies. Each selected energy can match one to several rows of focusing elements. Focusing elements of each row can be made in the form of both right and oblique prisms of different size, with a different vertex angle and with flat or parabolic lateral sides. A beam can be focused in the form of a line or point. The initial vertical size of SR beam is h_1=1 mm, the size after X-ray lens is h_2=0.1 mm.

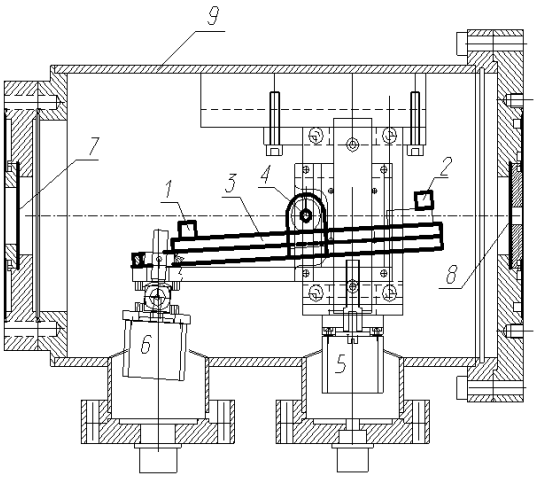

Fig. 4. Structural diagram of the collimator Kratky. 1,2 – high precision parallelepipeds, 3 – glass plate, 4- rotation axes, 5 – vertical movement mechanism, 6 – rotation mechanism, 7,8 – Be window, 9 – vacuum hutch.

3. CCD beam position monitor and ionization chamber

The monitor consists of a phosphor coated on an aluminum plate and CCD camera. To carry out monitoring of

the plate is introduced into the synchrotron radiation channel and image of the SR beam is detected BY CCD camera. The accuracy of determining the position of the beam is 5 microns. The monitor is used only during the equipment preparation for experiment. During the experiment, the phosphor is derived from the beam.

The ionization chamber is designed to monitoring the position of the SR beam. The position sensitive ionization chamber is used during experiment. The accuracy of determining the position of the SR beam is 1 micron.

4. Horizontal slit

The horizontal slit was used for SR beam collimating in horizontal plane. Horizontal size gap is adjustable in increments of 1 micrometer in the range of 0.1 - 60 mm by means of a step motor. The tantalum used as material of slit.

5. Fast acting shutter

A fast acting shutter that opens the SR flux only for the time of an experiment is used to reduce the space charge of positive ions being accumulated in the drift gap (Aulchenko, 2010). The shutter is a disk with a narrow slit, rotating with a period of 18 ms. The shutter opens for 60 μs, which is sufficient for carrying out an experiment. The time between two open shutter phases is enough for positive ions to reach the drift electrode. For the disk position to be determined, there are three closely spaced holes in it. A light guide is located opposite these holes on the one side of the disk, and a photodiode is located on the other side. When the disk rotates, a sequence of three pulses is induced in the photodiode. Based on these pulses, the instant when the slit passes through the optoelectronic couple is determined, and the current disk speed is determined from the time interval between two such sequences. The signal from the optoelectronic couple is processed by the control unit and it calculates the time to the next phase of shutter opening. A certain time is subtracted from this value in order to compensate for the delay in generation of the detonation wave and its propagation to the sample region exposed to SR. On the expiry of the calculated time, a command is issued to the generator of pulses for the detonator.

6. Kratky collimator

A scheme of Kratky (Kratky, 1982) has been selected in the development of the collimator. The scheme is a system of elements as depicted in Figure 4. There are two collimating element - lower labeled number 1 and the top with the numeral 2, mounted on a glass plate 3, which has a high degree of surface finish, as well as a very small deviation from the ideal plane (less than 1 micrometer). The second element is mounted on the plate at a height equal to the height of the first element precisely. It is very convenient as all of these elements use the measures of the sets for the precise measurement of lengths. In particular, measures were chosen with dimensions 8.5 * 8.5 * 29 mm. The measures have a precise desired geometry of faces, and the faces have a smooth surface. Further, the plate 3 mounted thereon is mounted on the plate element basis. The latter has the ability to move up and down across the SR beam. Moving is done by precision guides using the stepper motor 5.

Similarly, in the middle of the faces of collimating elements 1 and 2 is the axis of rotation 4. The drive 6 can change the angle of the base of the glass plate to the camera axis (± 3°). In height is equivalent to ± 6 mm. Thus, the height gap can be changed from 12 mm to 0 mm.

7. Explosion chamber

After the collimator is installed the most important installation - explosion chamber. Explosion chamber is designed for diffraction experiments at the synchrotron radiation beam during the detonation test sample capacity of 200 g of TNT. On chamber's entering shock wave reducer was installed for protection of 2 mm beryllium window.

The camera has five outputs for the diffracted photons from the investigated sample and one output for SAXS photons. The same output is used for primary beam, partly attenuated in the sample for micro tomography.

Explosive camera is mounted on the adjustment device which allows optimum set it relative to the primary beam SR. Special conditions - possibility of carrying out the experiment in an inert atmosphere or in vacuo.

8. Detector

Since SR is emitted by electron bunches in a storage ring, the SR burst corresponding to a single bunch may be very short. Should a detector capable of detecting SR from a single bunch without mixing signals from different bunches be available, it is possible to obtain information on changes in the state of the material in a sample under investigation with a very high time resolution. A detector for imaging of explosions on an SR beam—DIMEX—has been developed by the Budker Institute of Nuclear Physics (Aulchenko, 2010). This detector is a high pressure ionization chamber with a strip readout at a pitch of 0.1 mm. The electron component of primary ionization is collected within 50 ns, which is substantially shorter than the interval of 4 bunches in the VEPP-4 storage ring (300 ns). The DIMEX is filled with a Xe–CO_2 mixture (3 : 1) at an absolute pressure of 7 atm. The spatial resolution of the detector is ~210 μm, and its efficiency for radiation with an energy of 20 keV is ≥50%. The dynamic range of the detector is ~100, which allows one to measure the signal with an accuracy of ~1%. In this case, the maximum flux of X-ray photons, at which the DIMEX operates in a linear region, is ~10^{10} photons/(channels).

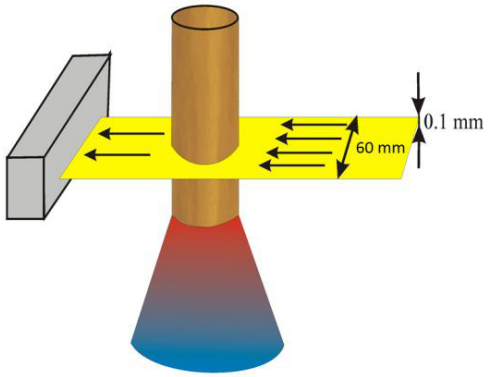

Fig. 5. Experimental setup for density measurement of explosion products in a expansion zone during detonation of explosives after detonation front with using synchrotron radiation. The axis of the sample of explosive is positioned vertically, while wide beam of SR lies in the horizontal plane. Spatial resolution in the vertical direction (the orientation axis of the specimen) of this scheme is 0.7 mm, and in the horizontal - 0.1 mm.

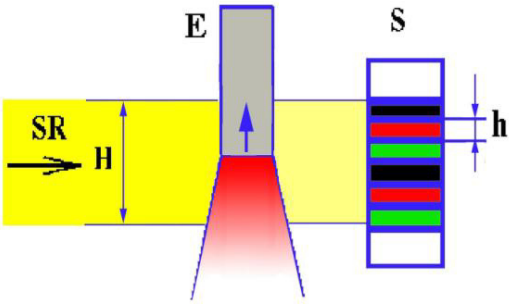

Fig. 6. Experimental setup on SR beam. Beam width H=60 mm, thickness 0,4 mm. Exposure time 0.1 ns. DIMEX-Si detector strip width h=0,05 mm. In this experiment the axis of the sample of explosive is positioned horizontally, while wide beam of SR lies in the horizontal plane: (E) explosives, (S) DIMEX-Si. This scheme is used for the study of the detonation front structure with space resolution near 0.1 mm.

9. Axisymmetric microtomography and introscopy

Tomographic methods for examining the density of static objects have been developed and successfully used. As applied to dynamically changing objects, they are used with lesser success in gas dynamics and plasma physics for determining the temperature and the density and in pulsed X-ray density radiography . In these tasks, it is nearly always impossible to obtain experimental data from different angles with a high accuracy. Therefore, selection of the error tolerant reconstruction algorithm capable of efficiently using a priori information on the sample under investigation is of principal importance for high quality density reconstruction. The use of the VEPP-4 storage ring as a radiation source (with its high X-ray flux) and the DIMEX as a detector offers a chance to conduct explosion experiments with a nanosecond exposure and a spatial resolution of ~100 μm. The procedure of these experiments was described in (Ten K, 2009). To determine the spatial distribution of the density in detonation products of a cylindrical charge of explosive material (EM) in a particular cross section, the X-ray shadow was sequentially recorded with a 0.3 μs interval between frames. The amount of material examined with X-rays along the beam was determined from the X-ray flux attenuation using the appropriate calibration. The method for reconstructing the density by the recorded X-ray shadow from the sample under investigation was developed in the above papers. This method is based on regularization, involves a priori information on the type of the sought function, and provides a means for attaining a high accuracy in reconstructing distribution ρ(r, z). This method was used to reconstruct

spatial density distribution ρ(r, z) of expanding TNT explosion products, which is presented in (Ten K, 2009).

Two schemes of realization X-ray imaging used to install: (1) the axis of the sample of explosive is positioned vertically, while wide beam of SR lies in the horizontal plane (Fig 5.); (2) the axis of the sample of explosive is positioned horizontally. The first scheme is used to for density measurement of explosion products in a expansion zone during detonation of explosives after detonation front. Spatial resolution in the vertical direction (the orientation axis of the specimen) of this scheme is 0.7 mm, and in the horizontal - 0.1 mm. The second scheme is used for the study of the detonation front structure. Spatial resolution in the horizontal direction (the orientation axis of the specimen) of this scheme is 0.1 mm.

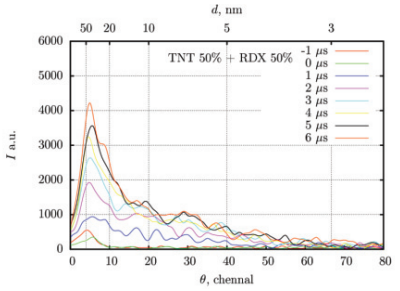

Fig.7. The dynamic of SAXS signal during TNT detonation.

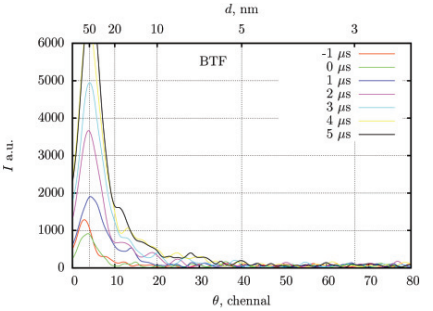

Fig. 8. The dynamic of SAXS signal during BTF detonation.

10. SAXS experiment

Small angle scattering provides information on the distribution of electron density fluctuations in a sample. From the practical standpoint, this is an efficient tool for determining the characteristic particle size and the size distribution of particles in the object of investigation. A spot 0.4–1.0 mm high and 3–40 mm wide is formed at the central part of the explosive charge from the SR beam with the aid of Kratky collimator. In front of the detector, the direct beam is shuttered by beam stop. The scattered SAXS beams are detected by the detector. The distance from the axis of the explosive charge to the detector was L2 = 3432 mm The pitch between the strips of the detector DIMEX was 0.1 mm. Thus, a single channel of the detector DIMEX in these experiments 1 detector channel detector = 0.02914 mrad. In our experiments, the minimum angles of registration amounted to 5 channels or 0.15 mrad, the maximum angle was 120 channels or 3.5 mrad. This measurement range allows detection of the SAXS from particles with a size of 1–200 nm.

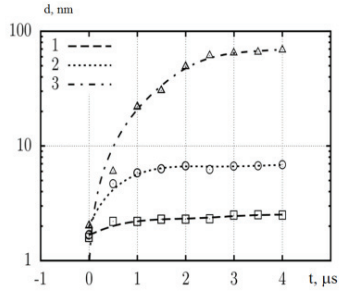

Fig. 9. The growth of the size of nanodiamonds during detonation 40 mm diameter of explosives: (1) TATB; (2) TNT/RDX, (3) BTF.

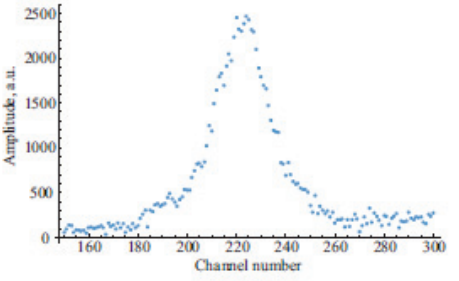

Fig. 10. The test WAXS experiment with exposure time 100 ps - the diffraction pattern (110) from W single crystal. The detector channel width was: 0.3mrad≈ 0.02◦.

The result of one of the experiments aimed at detecting the SAXS is shown in Fig. 7-9 . The figure presents the spatial distribution of the SR photon flux obtained in a set of measurements, in which each next measurement is taken 0.66 μs after the previous one. The measurement corresponding to an instant of 3.0 μs corresponds to passing

of the detonation wave. It is apparent that formation of nanoparticles (nanodiamonds) is initiated during the first μs after passing of the detonation wave and then increases in the next 4 μs interval. The mean size of nanoparticles in the sample can be calculated based on the shape of the SAXS distribution.

SAXS experiments provides information about the number of particles formed, as well as their size and shape. The figure 7 shows the dynamics SAXS TNT / RDX, and figure 8 - BTF. Clearly visible difference between the behavior of the two systems, which indicates the formation of diamond nanoparticles of different sizes. The most expected outcome of this experiment - the dynamics of the parameters of these particles (Fig 9.).

11. WAXS experiment

The test WAXS experiment was made with the diffraction pattern (110) from W single crystal. The minimal exposure time was 73 ps (Fig. 10). The detector channel width was: 1channel = 100 μm≈ 0.3mrad≈ 0.02^{o}. The transparent diffraction scheme was used. 250 μm-thick single crystal was used.

It is also an experiment on laser heating of the same sample was made. A laser with a wavelength of 1.06 micron, an energy of 1 J and a duration of 140 microseconds was used. During heating the diffraction pattern (110) from W single crystal shifted at 0.04^{o}, which indicates the occurrence of thermal stresses in the crystal.

Acknowledgements

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