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Synchrotron radiation instrumentation for "in situ" investigation of explosion with nanosecond time resolution

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Abstract

A special instrumentation was developed for the investigation of explosions by synchrotron radiation with 250 ns time resolution. It consists of an explosion chamber, detonation front sensors (wire detectors) and X-ray detectors. The time dependence of the absorption coefficient of the explosive material was measured during the explosion. In the same experiments, the SAXS and the diffraction signal were observed. In the first experiments, hexogen-TNT alloy was used to obtain diamond powder as explosion product. In this experiment the SAXS intensity increased sharply for 1500 ns. This is an unusual result, because according to theory, most chemical transformations finish in about 200 ns. The test experiment has shown that it is possible to receive a time resolution of 20 ns.

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1. Introduction

The detonation process has been investigated by many "in situ" methods. However, till now, the usage of X-ray scattering and diffraction methods was impossible. Investigating explosive processes with synchrotron radiation (SR) has been planned for a long time, but we could not overcome the following problems: (1) lack of scattered photons in an exposure time of 1 ns; (2) Problems with Be window stability under the influence of a shock wave; (3) the difficulty of forming stable detonation fronts in explosives with a small diameter, (optimum for scattering and diffraction experiments); (4) strong electrical noise from the electric detonator.

2. VEPP-3 and wigglers

The storage ring VEPP-3 has the following parameters: $E = 2$ GeV, $I = 150$ mA, orbit period

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of 250 ns, single bunch operation mode, bunch length of 30 cm. The three-pole wiggler with a field of 2 T was used in explosion experiments, 3 T will be used in the near future and a 5 T multipole permanent magnet wiggler is now proposed.

It is possible to estimate the photon flux per bunch N_ε at the detector as

$$N_\varepsilon\left[\frac{\text{phot}}{\text{bunch}}\right] = \alpha\gamma n_e \frac{\Delta x}{L}\eta\left(\frac{\varepsilon}{\varepsilon_c}\right)\frac{\Delta\varepsilon}{\varepsilon}A(\varepsilon)D(\varepsilon)$$

where α—fine structure constant, γ—relativistic factor, n_e—the number of electrons in the bunch, Δx—detector size, L—wiggler–sampler distance, ε—SR photon energy, $\Delta\varepsilon$—spectrum width, ε_c—critical energy, $\eta(\varepsilon/\varepsilon_c)$—spectral function, $A(\varepsilon)$—absorption coefficient in all Be windows and the sample, $D(\varepsilon)$—detector quantum efficiency. By using parameters corresponding to the experimental conditions at VEPP-3 for white beam: Δx—2 mm, L—13 m, ε_c—5.32 keV, $\Delta\varepsilon/\varepsilon \sim 1$, $\varepsilon \sim 30$ keV, $D(\varepsilon) \sim 0.5$, the flux estimate is $\sim 10^8$ photons/bunch, $\sim 2\times10^9$ photons/bunch and $\sim 10^{11}$ photons/bunch for 2, 3 and 5 T wigglers, respectively.

These calculations show that the measurement of the explosion process is nowadays possible by using white radiation, thereby overcoming problem no. 1. After installation of the 5T wiggler it will be possible to use monochromatic radiation.

The scheme of the experiment is shown in Fig. 1: the synchrotron radiation beam is transmitted through evacuated tubes from the wiggler to the experimental hall, where the explosive chamber is installed. The radiation is generated in the wiggler every 250 ns, which determines the time resolution of the experiment.

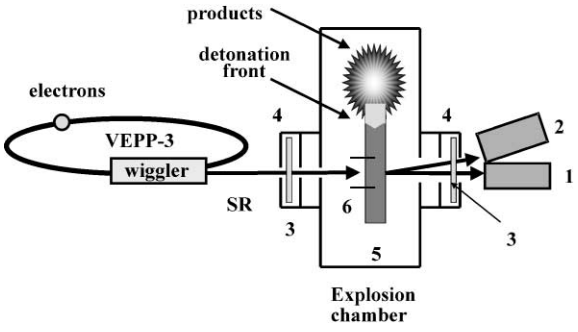

Fig. 1. The scheme of the experiment: 1, 2, 3—transmitted beam and SAXS detectors, beryllium window, 4—shock wave reducers, 5—explosive material, 6—wires detectors as detonation front sensors.

3. Explosion chamber

The explosion chamber is made from 10 mm stainless steel (Fig. 1). There are two slits in the chamber, for the primary and scattered beams. The entrance slit has dimensions of 10 mm horizontally and 3 mm vertically. The exit slit dimensions are 3 mm horizontally and 10 mm vertically. A shock wave reducer (SWR) is installed between the slits and the Be windows to solve problem no. 2. The thickness of each Be window is 2 mm. The explosion chamber can operate with up to ~ 20 g (TNT equivalent) explosive material.

There are four inlets in the chamber body for cables to the wire detectors and detonators. There are also three inlet valves for vacuum, gas and product evacuation systems.

The fast shutter (exposed time 20 ms) was installed in front of the explosion chamber to minimise the radiation damage to the explosive.

The size of the irradiated spot on the sample is: 0.1–1 mm in vertical and 5 mm in the horizontal direction. The diameter of the sample was 10 mm for melted and 12.5 mm for powder explosive. The choice of explosive was critical in overcoming problem no. 3, as it was necessary to choose material with a small critical diameter. Sample length could vary between 25 and 80 mm. Octogen was used as a buster explosive. The distance between the wire detectors was 20 mm. In order to reduce electric noise from the detonator and solve problem no. 4, the distance from detonator to irradiated spot was increased until the time between detonator explosion and the arrival of the detonation front at the irradiated spot reached 5 μs.

4. Detectors

A germanium phototransistor (2×5 mm^2), silicon p-i-n photodiodes (1×1 mm^2) and an Si

microstrip detector (10 μm strip steps) were used in the explosion experiments. The first and third types of detectors give information about the scattering of photons with energies between 15 and 30 keV, the second type for photons with energies between 5 and 15 keV.

An 850SK ADC [1] was used to digitize the signal after amplification. This ADC has 4096 memory cells and a sampling time of 125 ns, so it is capable of taking data for 512 μs, the full duration of the experiment.

Digital correlated double sampling (DCDS) was used for noise reduction and drift compensation of all electronic components. Two measurements for DCDS were made per electron bunch orbit: the first one when photons reach the detectors, and the second one with 125 ns delay, when no photons are generated.

The recorded fluxes at the detectors were: 10^4, 10^3 and 15 photons/bunch for the Si direct beam detector, the Ge SAXS detector and the Si SAXS detectors, respectively.

5. Previous experimental results

The sample detonated in the top part. The velocity of the detonation front was nearly 7 km/s. When the front reaches the position where the SR beam is, the intensity of the transmitted beam decreases sharply (Fig. 2) by about 30%. This signifies that pressure in the explosive increased up to 300 kbar. At the same time the signal at the SAXS detector appears.

The change in density of the explosive in the SR beam trajectory after the detonation front has passed determines the transmitted intensity behaviour versus time, and the experimental data from our experiments agree well with the existing theory of detonation processes in solid explosives. The SAXS intensity has not previously been observed, but obviously SAXS appears when electron density fluctuations appear. In the explosive the atomic density is initially very homogeneous. Therefore the electron density fluctuations are small and the SAXS intensity is small too. In contrast, the atomic density of the explosion products is not uniform and the electron density

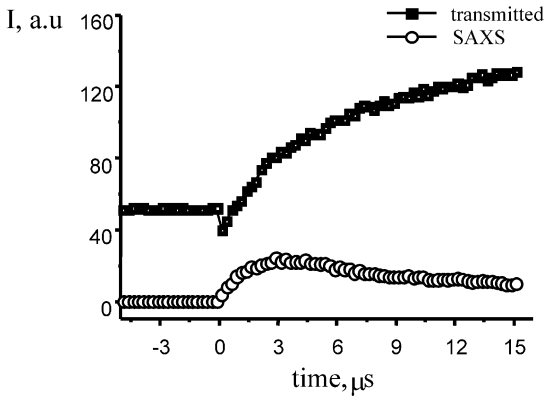

Fig. 2. Experimental results of trotyl detonation. The intensity of the transmitted beam and integral SAXS intensity versus time.

fluctuations are large. These fluctuations will give a high scattering intensity.

When TNT is used as explosive, the SAXS intensity increased for 2.5 μs and then decreased. It is a very interesting and surprising result because theories of detonation affirm that all chemical reactions are finished in 10–100 ns after the detonation front has passed. The behaviour of the SAXS intensity versus time shows that the formation of the products of reactions occurs in a few microseconds.

We have made a lot of experiments with different explosives and have found a correlation between the amount of free carbon in explosion products (solid products) and the maximum intensity of SAXS (in time scale) — the greater the amount of solid products, the bigger is the maximum intensity. The SAXS maximum intensity of those explosives, whose product of reaction contains diamonds (for example TNT-hexogen 50/50 alloy) are much bigger than from other explosives. Our experiments let us conclude that the electron density fluctuations are associated with the existence of carbon particles (graphite, diamond) or a carbon liquid spray.

6. How to improve time resolution and to receive more information

We plan to use the multibunch operating mode of VEPP-4 for the experiments. The time resolution

will be equal to the time interval of 5 ns between the bunches.

The other proposal is to use self-scanning properties of detonation processes. This means that the process of detonation develops simultaneously in space and in time and it is therefore possible to make a conversion between time and space by using a photodiode array or a microstrip detector. For this scheme we have achieved time resolutions of 60 ns and have a plan to achieve a resolution of 20 ns.

After some improvements of the detectors the SAXS/WAXS data versus angle of scattering will be obtainable with the same time resolution. This will provide information on phase transformations behind the detonation front.

7. Conclusion

We have solved all the problems which we had at the initiation of the work (see introduction): (1) increased the number of scattering photons by using wide spectrum range of SR; (2) reduced the influence on Be windows by using SWR; (3) used explosive materials in which critical diameter is smaller than 10 mm; (4) extended the time interval between detonator explosion and measurement time by using a long specimen and also the DCDS method.

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References

[1] A.M. Batrakov, V.P. Kozak, M.E. Kruglyakov, ADC 850SK, Preprint of the Institute of Nuclear Physics SB AS USSR, No. 88–98, Novosibirsk, 1988, p. 22.