

THE PROTOTYPE OF RECORDING SYSTEM FOR SHOCK AND DETONATION WAVE INVESTIGATION WITH APPLICATION OF SYNCHROTRON RADIATION

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ABSTRACT

A new version of the prototype of multichannel recording system for shock-wave and detonation processes investigations on synchrotron radiation beams of VEPP-3 storage ring is described in this report. The requirements set to this system, its structure and features of operation are considered.

In addition, the opportunities of the flat charge method application for improvement of time resolution in small-angle X-ray scattering experiments are considered and the estimations of attainable accuracy of shadow radiography are given.

KEY WORDS

Applications, synchrotron radiation, explosion, nanodiamonds, detectors

1. Introduction

Nowadays synchrotron radiation (SR) is demonstrated to be an effective instrument in short-time process investigations (first of all, shock-wave and detonation ones) [1, 2].

A prototype of recording system [3], providing the measurement of radiation intensity at SR flash repetition rate, was previously developed for studying of the possibilities of these techniques. The experience obtained during the exploitation of this prototype allowed to start the designing of a new, functionally wider, version of the recording system.

Synchrotron radiation is an X-ray radiation produced by the relativistic electrons moving in a strong magnetic field. This radiation has a high intensity, low angular divergence, and a broad spectrum [4]. For the SR source of VEPP-3 storage ring (the energy of electrons 2GeV, magnetic field 2T), the emission spectrum is from 5 to 50keV, the divergence angle of the SR beam is $\sim 0.01^\circ$,

the intensity in the point of registration is about 10^8 photons/cm² per flash; the SR flash rate is 4MHz, the duration of a flash is less than 1ns.

2. The Experimental Schemes and Detectors

The two main schemes of SR application to the short-time processes investigations are shown on Fig.1. Here 1– electron bunch, 2– SR beam, 3– investigated sample (an explosive) with shock (detonation) wave 4; 5– an array of the high-speed X-ray detectors, 6– collimator, 7– scattered radiation.

The scheme on Fig.1A corresponds to a shadow radiography experiment for determination of the absorbing material quantity in a beam. In this case, depending on the orientation of the linear detector array, either X-ray tomography (for axially symmetric objects) or sufficient temporal resolution improvement (due to self-scanning of the process) is attainable.

The scheme on Fig.1B corresponds to a small angle X-ray

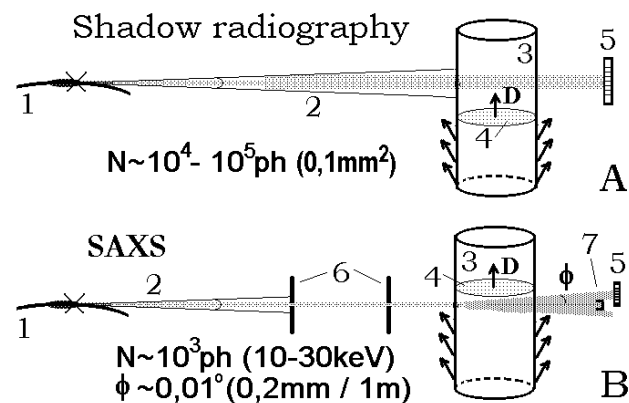


Fig.1 Registration schemes of shadow radiography (A) and SAXS (B) on SR beam; N- typical number of incident photons on a detector element per SR flash, phi- typical SAXS angles; the rest designations are in the text.

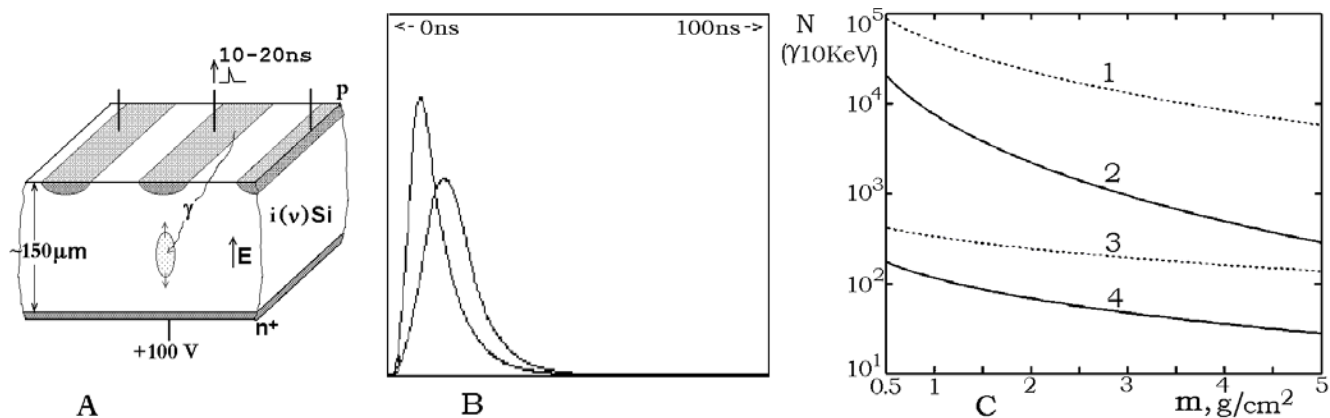


Fig.2 A- schematic cross-section of microstrip detector. B- estimated changes of recorded pulse for variations of the photon absorption depth in microstrip detector. C- calculated signal (1, 2) and quantum noise (3, 4) (in a number of 10-keV photons) versus absorbent quantity m for ideal (1, 3) and microstrip (2, 4) detectors.

scattering (SAXS) registration appearing in presence of nanometer-scale nonuniformities in an object (such as ultradisperse diamonds in detonation plasma).

The principal requirement to the detectors for these experiments is the capability for current mode operation with low pulse response duration (less than 250ns for VEPP-3). From tested semiconductor detectors four types of them are found meeting this condition (subsequently they were used in experiments):

1. phototransistors FTG-3 (material – Ge, pulse response duration is about 150ns, they are used for registration of SAXS hard component);
2. pin-photodiode chips (Si, pulse response $\sim 5 ns$, SAXS and shadow radiography of non-stationary processes);
3. avalanche photodiode arrays, developed in Institute of Semiconductor Physics of SB RAS (Ge-GaAs heterojunction, 16 cells of $100 \times 100 \mu m^2$, pulse response $\sim 50 ns$, shadow radiography);
4. microstrip detector, developed by A. G. Chilingarov [5] (Si, 50 strips each 40mm length and $100 \mu m$ stepped, pulse response $\sim 30 ns$, SAXS and shadow radiography).

The last mentioned detector, having a good surface uniformity at an exceptionally low noise level, provided (despite of reduced quantum efficiency) a high quality registration and further was chosen as the basic detector for the first version of the recording system prototype. The schematic view of the microstrip detector cross-section is shown in Fig.2A.

Also the calculations and a number of measurements for determining of the requirements to the recording system are performed. The calculated (for shadow radiography) signal (diagrams 1 and 2) and quantum noise (diagrams 3 and 4) (both are expressed in a number of 10keV photons) vs. quantity of absorbent m are shown in Fig.2C. The

absorbent is TNT, the detector cell is $0.1 \times 1 mm^2$, diagrams 1 and 3 correspond to an ideal detector ($QE=100\%$), diagrams 2 and 4 – to microstrip detector.

The calculation revealed that registration dynamic range (the ratio of maximal signal to minimum noise) needed for shadow radiography doesn't exceed 1500 and the requirements to system sensitivity are not high.

The experimentally measured SAXS signals were equivalent from 10 up to 1000 photons. It makes the dynamic range of ~ 300 sufficient, but imposes strict requirements on sensitivity.

3. The First Version of the Prototype

The system consists of the block of the detector and preamplifiers (placed in the radiation-isolated experimental hatch) and the module set deposited in a CAMAC crate: 12-channel module of shaping filters, a number of 4-channel 12-bit ADC modules (developed by E.A. Dementyev, BINP), the synchronization unit, the fast electromagnetic shutter control unit and block of "floated" voltage source.

Shaping filters are used to suppress the additional noise component caused by absorption of X-ray quanta in different depth of detector. Having been observed in early experiments, this component is associated with distinction in the drift velocity of electrons and holes, those results in variations of current pulse duration at absorption of a single X-ray photon (Fig.2B).

For restoration of the valid amplitudes of signal (and also for system low-frequency noise suppression and detectors slow time constants compensation) an algorithm of digital correlated double sampling is used. The signal measurement (analog-to-digital conversion) is made twice for every pulse – at "maximum" and at "zero"; the real

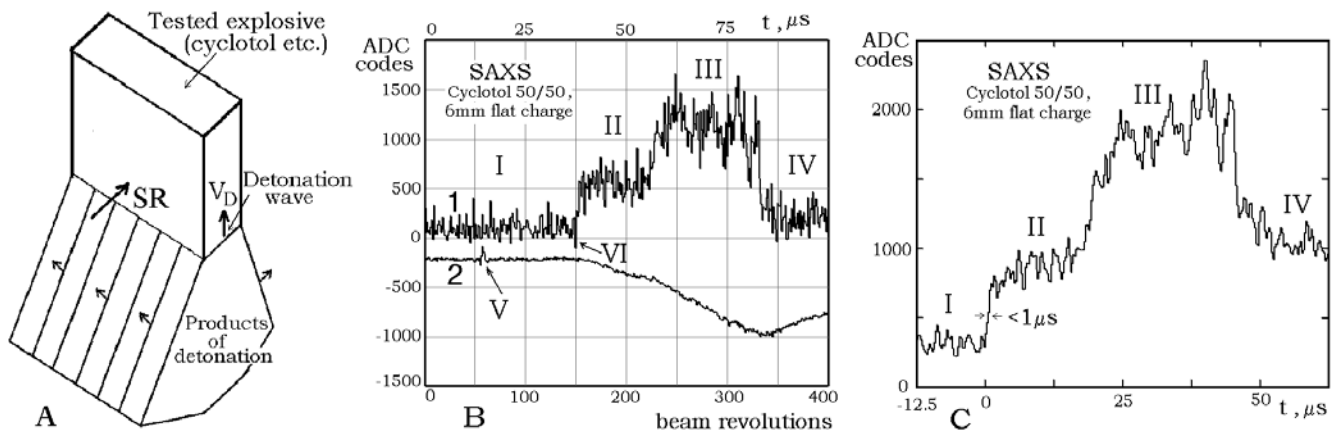


Fig. 3 A- a placement scheme of the flat charge of explosive in SAXS experiments. B- a fragment of the signal recorded in the one SAXS channel ($t=0$ corresponds to the start of experiment). C- the fragment of the same signal after computer processing ($t=0$ corresponds to the detonation wave pass); obviously, the generation time for ultradisperse diamonds doesn't exceed $1\mu s$. The rest designations for B, C are given in the text

amplitude value is obtained during computer processing as a difference between these two samples.

An example of a recording SAXS signal produced by ultradisperse detonation diamonds (UDDs) is shown on Fig.3 (this experiment was performed in a context of a team-work of Institute of Nuclear Physics, Institute of Hydrodynamics and Institute of Solid-State Chemistry [6]). The peculiarity of geometry of the experiment was application of a flat charge of explosive (cyclotol 50/50), that is explained on Fig.3A. This geometry makes possible to keep constant the intensity and spectrum of the passed direct beam (within 20-30 μs after detonation wave).

Fig.3B corresponds to a part of signal recorded by one ADC channel, Fig.3C is the same after computer processing ("zero" subtraction and some quantum noise suppression). Part I of diagrams corresponds to a scattering in initial sample; part II is the scattering on UDDs with conservation of substance quantity in a beam (expansion along the beam); part III is the reduction of absorption in the detonation products (influence of lateral expansion); part IV corresponds to UDDs leaving the beam and burning out in secondary flame. Readout interference V ("zero" line 1 on Fig.3B) is caused by a blasting machine discharge, dip VI on SAXS samples (line 2 in the same figure) caused by density growth and homogenization of the sample in detonation wavefront.

The alignment of the recording system to the experimental conditions is realized by replacement of preamplifiers and/or changing of shaping filter channels. For these three variants the electrical parameters of the system were equivalent to $4 \cdot 10^4/15$, $4600/3$ and $100/1.5$ (the numerator is maximum number of 10keV photons per a flash, denominator is rms of system noise, recalculated to 10keV photons). The maximum recording time is 4ms (16000 SR flashes).

Though the achieved parameters met the experimental requirements, the complexity of sensitivity adjustment and the limited possibilities of increase in the number of channels turned out essential drawbacks. All this (in a combination with a significant progress in microelectronic component industry) made actual the development of the new improved version of the system.

4. A New Version of the Recording System

A new system for recording of the short-time processes is also a CAMAC-prototype, differing from the previous version both by wider functional possibilities and new signal processing algorithms and by better capability of increase in number of channels.

The developed system includes the detector block placed in the radiation-isolated (experimental) hatch and modules deposited in a CAMAC crate: a number of special-purpose 12-channel ADCs, the synchronization unit, the fast electromagnetic shutter control unit and block of "floated" voltage source.

The detector block (designed individually for a given detector) contains a detector and a number of low-noise preamplifiers set into the connectors of the block cross-board. The signals from the detector sensitive elements pass to the preamplifiers and then – via coaxial cables – to the special-purpose ADC modules. In order to provide voltage supply of the preamplifiers and the bias voltage for the detector the block of special-purpose "floated" voltage sources is used.

A cardinal new developed element of the system is a 12-channel ADC module. The structure of a single channel of this module is shown on Fig.4. Each channel includes the input amplifier PGA0 (with capability of signal inversion and gain switching), the correlated double sampling

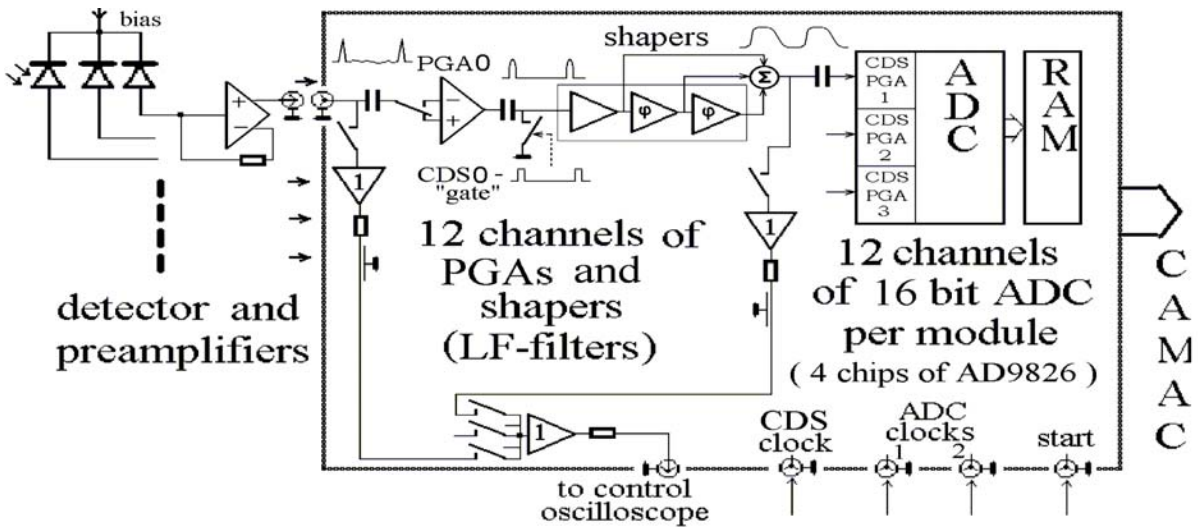


Fig.4 Block-diagram of a single channel of the ADC module. Designations are in the text.

circuit CDS0, the shaping filter SHAPER and analog-to-digital converter (itself ADC).

The latter are represented by the chips of 3-channel 16-bit videoADCs AD9826. The operating speed of these chips is high enough to provide 8MHz signal recording that makes possible the conduction of the experiments in 2-bunch operation mode of VEPP-3. The input circuits of videoADC contain built-in circuits CDS of correlated double sampling and programmable-gain amplifiers PGA. In combination with PGA0 these provide 60-fold sensitivity tuning range of each channel, and combined with CDS0 circuits – the effective reduction of low-frequency noise of detectors (and pre-amplifier drifts) and slow time constants.

The CDS0 circuits also perform “time gate” function; it passes through only short signal pulses and cuts off the high-frequency noise component in the pauses between.

The distinctive feature of the new recording channels is the application of shaping filters (low-pass filters) with the rectangle-approximating impulse response. Such a filter, built on a basis of active delay line, provides effective integration of short pulses but (in contrast to conventional integrator) doesn't require precise time synchronization. These shaping filters are supposed to suppress both some detector specific noise components and element-to-element capacitive interference.

In a similar way to the previous version, shaping filters are supplied with a number of analog commutators and buffer amplifiers that make possible the observation of input and output signals of filters via a control oscilloscope.

Constructively the 12-channel ADC is placed in a 2M CAMAC module that enables placing more than 100 recording channels in a single CAMAC crate.

Synchronization of all ADCs may be provided by a common synchronization unit, start of recording produces by the electromagnetic shutter control unit (simultaneously starting the blasting machine to initiate detonation). The maximal recording duration of the investigated process corresponds to approximately 5400 SR flashes, that makes 1.3ms (single-bunch mode of VEPP-3) or 0.64ms (two-bunch mode). These durations may be multiplied by factors 1.5 or 3 by using ADC modules in 8- or 4-channel modes.

5. Experiment Perspective Configurations

Wide functional possibilities of the new system are expected to simplify pre-starting procedure and execution of experiments with increasing of recorded data amount.

For example, the application of a set of pin-photodiodes as a detector (in edge-irradiation mode) enables observations of non-stationary detonation processes and combustion-detonation transition (Fig.5A). Application of “multi-spectrozonal” detectors (Fig.5B, C) enables observation of two-phase detonation flows ([7,8]).

At the same time, the ultimate recording opportunities will be strongly limited by capabilities of the SR source. The calculation results of attainable relative accuracy of absorbing medium (trinitrotoluene, i.e. TNT) quantity measurements for the SR source of VEPP-3 storage ring are given in Fig.5D (100mA beam current, 2T present wiggler magnetic field and 4.5T in project).

The approximation of smallest possible error for ideal detector (for the SR source with the energy $E[\text{GeV}]$ of the electrons, their current $I[\text{A}]$, SR flash rate $f[\text{MHz}]$ and with field $B[\text{T}]$) is given by equation [9]:

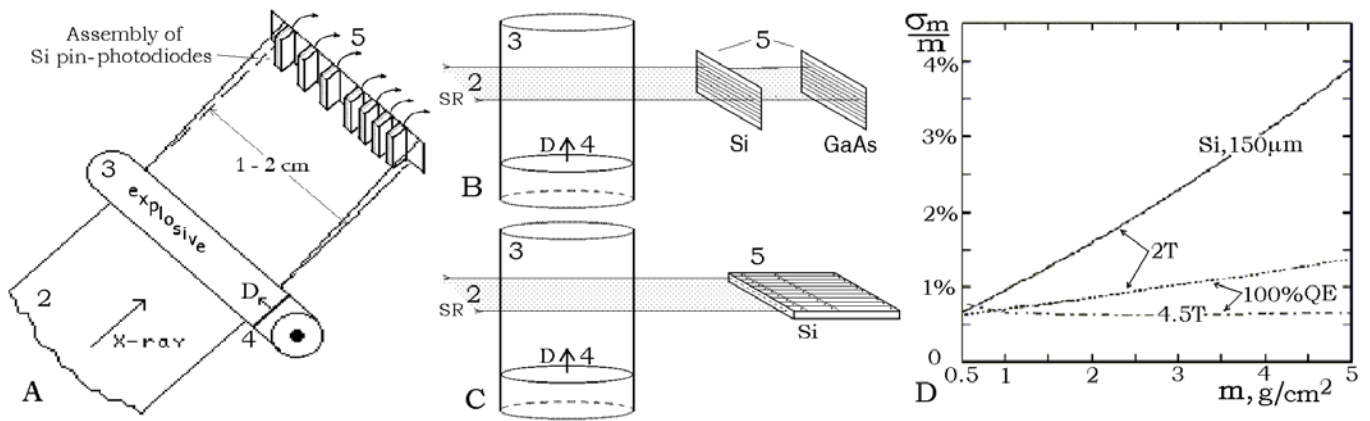


Fig. 5 A, B, C- the possible schemes of shadow radiography: A- with elongated charge (horizontal placement) for observation of combustion-to-detonation transition; B- with multi-spectrozoal detector (an assemblage of conventional microstrip detectors) and improved time resolution; C- with multi-spectrozoal detector (edge-irradiated microstrip detector with segmented strips) for X-ray tomography. Designations for A, B and C are the same as on Fig.1. D- calculated dependencies between the absorbing medium quantity m and the relative accuracy σ_m/m of its measurement for a $0.1 \times 1 \text{mm}^2$ detector; SR source – wiggler of VEPP-3 storage ring; the other designations are in the text.

$$\frac{\sigma_m}{m} = \frac{k+1}{\sqrt{A}} \cdot \left(\frac{k+1}{2\pi E_C E_{ex}} \right)^{1/4} \cdot \frac{\exp\left(\frac{k+1}{2k} \cdot \frac{E_{ex}}{E_C}\right)}{\frac{k+1}{k} \cdot \frac{E_{ex}}{E_C} - \frac{3}{2}}$$

where $E_C [\text{KeV}] = 0.6651 \cdot B \cdot E^2$ is the critical energy of SR source, $E_{ex} [\text{KeV}] = \sqrt{kpmE_C}$ is the energy of spectral maximum of the passing radiation,

$A = 4.9 \cdot 10^{10} \cdot \frac{IS}{BL^2 f}$ (where $S [\text{mm}^2]$ is the detector

pixel square, $L [\text{m}]$ is a distance to the source), and values p and k characterize absorption in the sample material (it is assumed the dependence of the mass absorption coefficient $\mu = p/E_\gamma^k$ on the photon energy E_γ ; for TNT $k \approx 2.32$, $p \approx 844 \text{cm}^2 \text{KeV}^k/\text{g}$).

Unfortunately, the future increase in the VEPP-3 wiggler field does not lead to a radical improvement in the quality of shadow radiography.

But with the magnetic field increase SAXS signals will grow significantly. This makes possible detailed studying the dynamics of generation of ultradisperse diamonds under detonation of explosives with negative oxygen balance - including the application of flat charge technique and “multi-spectrozoal” detectors. Nevertheless, a temporal resolution in this technique is also limited by the period of SR flashes (250ns or 125ns for VEPP-3) and solvable duration of generation of the particles - by the time of their contrast change (about 1 μs time of detonation product relief).

The experimental configuration shown on Fig.6A allows preventing particle contrast change during some microseconds after detonation front passage. The flat charge of the explosive under investigation (for example,

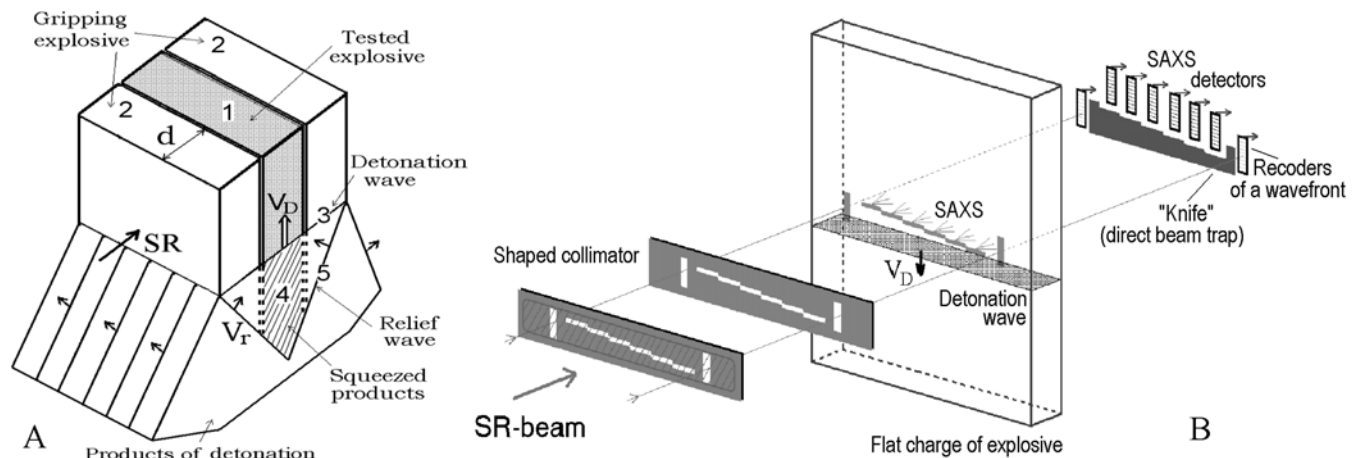


Fig.6 A- configuration with an enhanced time of detonation product compression to observe via SAXS the generation of ultradisperse diamonds. B- experimental configuration with the improved temporal resolution.

cyclotol) is placed between two plates of "gripping" explosive with approximately zero oxygen balance (PETN, nitrocellulose, explosive gelatine, their combinations with ammonium nitrate, etc., producing no solid particles and SAXS during explosion). In the case of coincidence of the velocity and pressure in detonation wave of used explosives, the detonation product density of investigated explosive (and also particle contrast) changes will be delayed by the time necessary for the relief wave pass through the detonation products of "gripping" explosive.

The temporal resolution improvement in SAXS experiment is provided by the configuration of experiment shown on Fig.6B. In this scheme, the shaping collimator forms a graded X-ray beam that passes through a plate of the explosive under study; a set of SAXS detector arrays is placed behind the explosive charge outside main beam. Due to the self-scanning of the process, temporal resolution of the system is determined by the ratio of beam step height to detonation velocity (for example, wave velocity of 5km/s and 5 steps each of 0.25mm provide temporal resolution about 50ns).

6. Conclusion

The launch of the new recording system into operation is expected to facilitate execution of the research of short-time processes with the increase of obtained data amount.

It is also expected that exploitation experience of this prototype will allow to start the development of a functionally complete (placed near the detector) multichannel recording system, connected to a computer via fast standard interface.

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