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Development of fast one-dimensional X-ray detector for imaging of explosions

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Abstract

Investigation of fast dynamic processes (explosions) with the help of synchrotron radiation allows to understand properties of matter at very high temperatures and pressures. Detector for such studies has to be able to detect X-ray photons from each electron bunch separately with position resolution of about 0.1 mm.The prototype of detector for imaging of explosions at SR beam (DIMEX) is described in the paper. Spatial resolution of ~300 μm (FWHM) and time resolution of ~100 ns is demonstrated with SR beam from 2 T wiggler at VEPP-3 and electron beam energy of 2 GeV.Results of the first experiments on projective imaging and small angle scattering (SAXS) are presented.

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Keywords: Detector; Explosion; Time resolution; Synchrotron radiation

1. Introduction

Synchrotron radiation has been shown to be a powerful tool to study very fast physical and chemical processes appearing at high temperatures and pressures during explosions [1,2]. Very short pulses of synchrotron light irradiated by individual electron bunches allow imaging of the development of detonation wave as well as evolution of electron density within the volume of the exploding materials.

Such experiments require an exceptional set of parameters from the detector. In order to view independent images from different electron bunches, time resolution of the detector has to be less than bunch crossing time. For VEPP-3 storage ring this time equals 250 ns in single bunch regime. Spatial resolution of ~0.1 mm allows viewing of detonation wave structure in projective imaging experiments. Efficiency of more than 50% for X-rays in the energy range of 15–35 keV is very desirable in order to get good photon statistics. Finally, an efficient imaging at such frame rate requires very high rate capability of 10^{10}–10^{11} phot./s/mm^2. At such photon rate the detector can work only in charge integrating mode. Another restriction comes from the requirement

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of high frame rate. Storage of a frame within ~ 100 ns is quite difficult. Thus, raw data from the detector have to be stored in analog form temporary during the experiment. After the end of the measurement data can be slower digitized and stored in a final storage area.

In the present paper, we introduce a new detector for imaging of fast dynamic processes and explosions with SR beam (DIMEX). The detector is based on ionization chamber with charge collection to a micro-strip structure coupled to the ASIC with integrators and fast analogue memory.

2. Design of the detector

DIMEX consists of a micro-strip structure with 100 μm pitch, put in the gas volume filled with Xe–CO_2 (80–20%) at 7 bar, and high-voltage drift electrode pushing electron component of the primary ionization to the readout strips (Fig. 1). Shielding of the ionic component of primary ionization is performed by Gas Electron Multiplier (GEM) [3], stretched at a distance of 1 mm above the micro-strip structure. The distance between drift electrode and GEM foil is 2 mm.

Narrow beam of SR (up to 1 mm high) either after absorption in an object or after scattering, gets into the conversion volume between the drift electrode and GEM. Electronic component of primary ionization drifts towards GEM, penetrates through it and then induces charge at the strips. Ions drift towards the drift electrode and do not induce any charge to the readout strips. GEM is a micro-structure consisting of regularly

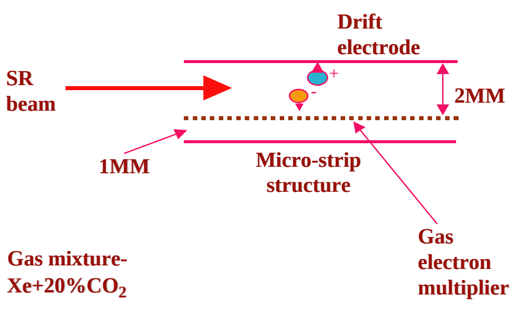

Fig. 1. Design of the detector.

punched holes in an insulating (kapton) foil, double clad with thin copper layers. Foil thickness is 50 μm, holes pitch is 140 μm and holes diameter is ~ 80 μm. By choosing appropriate voltage between the metal layers on GEM sides we can flexibly tune the fraction of charge penetrating through the foil or amplify it.

Readout strips are connected to the input pads of APC128 ASIC [4]. The ASIC consists of 128 channels with low-noise integrators at the input and 32-cell 10 MHz analogue pipe-line. All 128 pipe-lines can be readout in series through analogue multiplexer .

Detector operation includes several stages. An external start signal initiates the measurement sequence. During this stage all channels of each ASIC operate in parallel. Before starting, all pipeline cells are connected to the output of the integrator. After the beginning of the measurement sequence pipe-line cells are disconnected from the integrator one by one, starting from the first cell, under the control of the clock signal. When a pipe-line cell is disconnected, it stores the charge proportional to the output voltage of the integrator at the end of a corresponding clock interval. Clock frequency can be different depending on particular regime. In such a way the frames of an experimental sequence are formed. After storing the signal in all 32 pipe-line cells the measurement sequence is stopped, and the read-out sequence is initiated. During the read-out sequence the input of the integrator is disconnected from the readout strip and connected in series to each pipe-line cell. The output signal of the integrator during this re-read procedure is proportional to the charge stored in a pipe-line cell. More detailed discussion of the advantages of such procedure can be found in Ref. [4]. The output of the integrators is readout through the output multiplexer after the next cell in series is re-read. As the input integrator is used twice, during that measurement sequence and during the read-out sequence, the output signal is reverse proportional to the square of the feedback capacitor.

The sensitivity and thus the dynamic range of the ASIC can be changed by connecting additional feedback capacitor to the integrator. Reduction of the sensitivity in this case can widen the dynamic

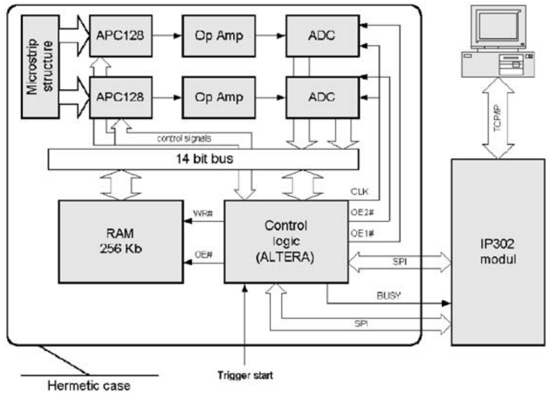

Fig. 2. Block-diagram of the detector electronics.

range by 3.1 and 9.7 times (additional capacitor can be connected only for the measurement or for all the time).

Electronics is assembled in the gas volume. In case of DIMEX prototype, it includes two APC128 chips, two 14-bit ADC, 256-kbyte RAM and PLD ALTERA PF10K20, that controls all the elements and provides connectivity with the network module IP302 outside the hermetic case (Fig. 2).

3. Experimental set-up and results

3.1. Experimental set-up

For the main experiments the white SR beam from 2 T wiggler at VEPP-3 storage ring was used with energy spectrum having maximum around 17 keV and FWHM of about 10 keV. The set-up consists of three chambers. The first chamber contains collimators that form the necessary beam shape. The second is the chamber where the sample was exploded. It had beryllium windows with reducers that protected the beam line from the detonation wave. The third chamber contained the detector with the second collimator and additional shutter for SAXS experiments.

Two main types of experiments were performed using DIMEX. In order to investigate the structure and velocity of detonation wave in an explosion, as well as density distribution inside and around the exploding sample, the projective absorption experiments were realized. In these experiments, the collimated line-shaped beam passed through the sample and the distribution of X-ray flux after the sample was measured with the detector. In our case, the beam was $\sim$12 mm wide and 1 mm high. The samples were 12.5 mm diameter and 100 mm cylinders made of a mixture of hexogen and TNT. The sample was positioned with its axis either parallel to the beam plane, or perpendicular to it. The starting moment of the measurement sequence could be synchronized with the detonation within $\sim$0.5 μs.

Small-angle scattering (SAXS) experiments allowed investigation of the distribution of electron density in an object. The evolution of SAXS image gave information about the amount of particles with different dimensions in an object.

3.2. Results and discussion

In Fig. 3 the calculated efficiency of DIMEX as function of energy is shown for several values of the dead zone before the sensitive region for 7 bar Xe–CO_2 (80–20%) mixture. The sensitive region is 30 mm long. In the prototype, the dead zone is 3 mm long and efficiency is close to 60% in the energy range around 20 keV.

Spatial resolution (line spread function) for the main experimental conditions is shown in Fig. 4. It was measured using edge technique with subse-

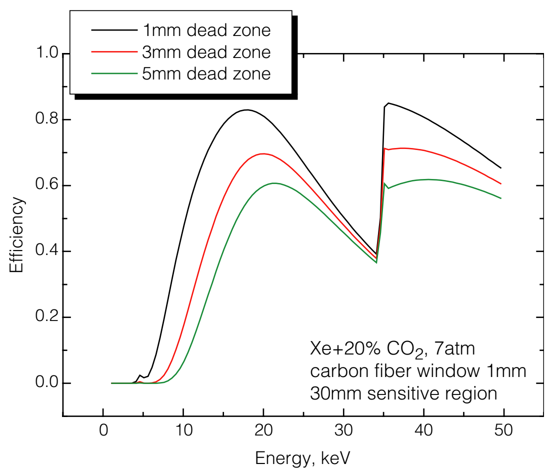

Fig. 3. Efficiency as a function of energy for DIMEX (calculation).

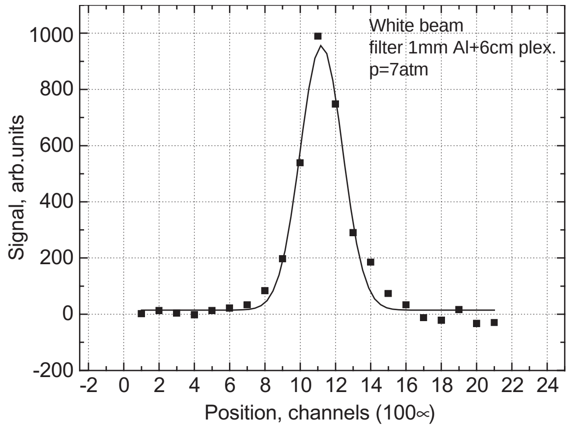

Fig. 4. Line-spread function measured with X-ray beam from 2 T wiggler, using edge technique.

quent differentiation of the experimental result. FWHM of the experimental curve is $\sim 300\,\mu m$.

The most critical parameter of the detector is time resolution. In order to have really independent images from individual electron bunches, time resolution has to be better than bunch crossing time.

In order to measure time resolution, the detector was operated at 125 ns clock period, that is equal to half-bunch crossing time. In such a case, the detector is irradiated only within one out of two successive clock periods. With such short clock period DIMEX can be operated only in the regime without the reset of the feedback capacitor, as the latter cannot be fast and needs ~ 150 ns. Thus, in an ideal case, the dependence of the signal versus time must look as "steps" with the width of 2 clock periods. The difference with this picture gives information about the real time resolution. An example of such measurement is shown in Fig. 5. For electric field in the gaps higher than 1.5 kV/cm the fraction of charge collected within 125 ns after bunch crossing exceeds 0.75. If we assume that charge collection follows exponential law: $Q/Q_0 = \exp(-t/\tau)$, where τ is collection time constant (i.e. time resolution), then the charge fraction collected in 250 ns will be not less than 0.93. Substituting $Q/Q_0 = 0.75$ and $t = 125$ ns and resolving the above-mentioned equation, we get $\tau = 90.2\,\text{ns} < 100$ ns.

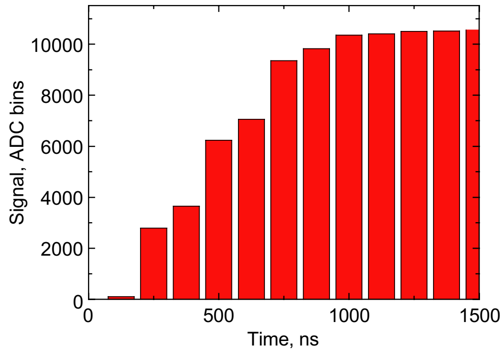

Fig. 5. Time structure of the signal from DIMEX in case of 125 ns clock period. Regime without the reset of feedback capacitor. This is an example of measurement, used for the calculation of time resolution.

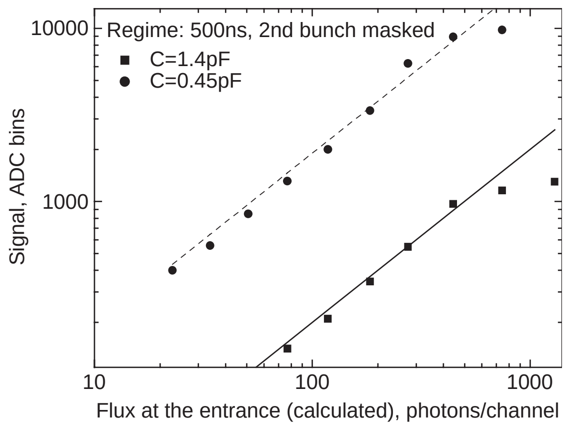

Fig. 6. Signal as a function of X-ray flux at the entrance window of the detector.

One of the main problems of DIMEX is saturation of the signal due to space charge in the conversion region. In Fig. 6 the dependence of signal versus input photon flux is plotted for low and high feedback capacitance. The clock period was 500 ns (frame size) and the second bunch in the frame was masked by the reset signal during the measurement. The saturation of signal in both regimes occurred at approximately the same photon flux of ~ 400 photons per channel. This value was strongly affected by the electric field, that indicated the space charge nature of the effect. Slow ions were accumulated in the conversion gap and distorted the field such that electrons could not be effectively transported.

For the regime with low feedback capacitance and higher sensitivity, the noise before saturation is determined by statistics of photons and, thus, for maximum number of detected photons of 200 (assuming 50% average efficiency), effective dynamic range is limited to ~14.

However, real experiments can be performed with the present prototype even in spite of very moderate dynamic range. The result of a series of projective absorption experiments is shown in Fig. 7. In order to improve the precision, the results of 10 measurements were summed with proper synchronization. Horizontal axis of the figure is position perpendicular to the axis of the sample. Time axis is in vertical in units of 500 ns.The figure clearly shows the detonation wave and the reaction zone with very high density just after the detonation front.

The example of the image from SAXS experiment with explosion is shown in Fig. 8. *X*-axis is position in detector channels, *Y*-axis is time in units of 250 ns. There is clear maximum in SAXS image that appear at ~1 μs after the detonation. In earlier work [2], where SAXS signal was measured with single channel detector, similar maximum in the signal integrated over a certain range of angles, was interpreted as the sign of diamonds formation out of free carbon in the explosion products. With the present technique this process can be studied in much more details.

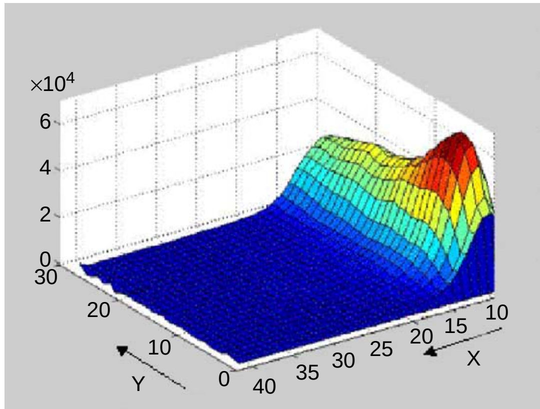

Fig. 8. Result of SAXS experiment. *X*-scale is position in 0.1 mm channels. *Y* scale is time.

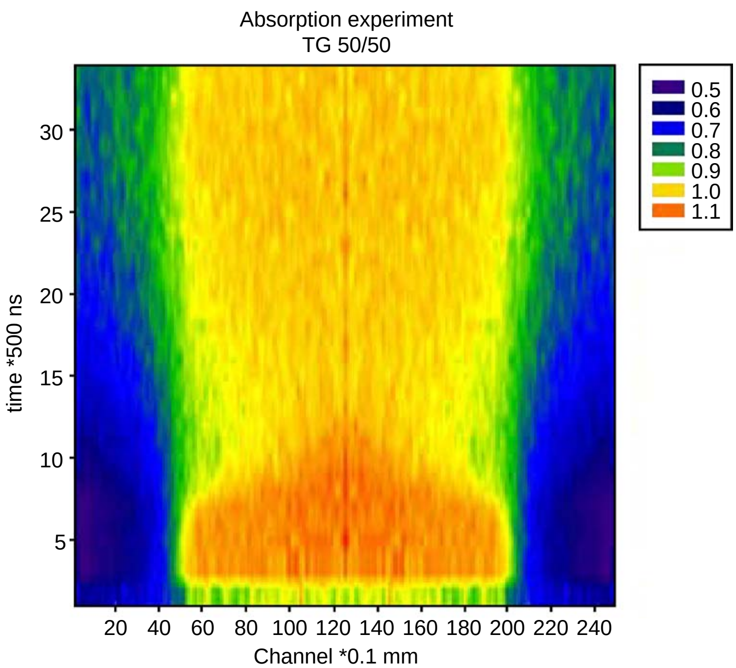

Fig. 7. Projective image of an explosion. Vertical scale is time in units of 500 ns. Horizontal scale is position in 0.1 mm channels.

4. Conclusions

In the present work, we demonstrated that the concept of a very fast detector for imaging synchronously with SR flashes from individual bunches can be realized. The first prototype of DIMEX have been shown spatial resolution of $\sim 300\,\mu m$ (FWHM), time resolution of $\sim 100\,ns$ and dynamic range of ~ 14. Maximum detected photon rate before saturation has been ~ 200 photons per channel per bunch. This value corresponds to photon flux of $\sim 10^{10}$ phot./mm^2/s. The dynamic range and maximum photon flux are limited by space charge effect. Solution of this problem can allow improvement of the dynamic range up to ~ 50 and maximum photon rate up to ~ 2000. These values are determined only by APC128 properties and further improvements will be possible only through development of a new ASIC.

Even with the present moderate dynamic range the first experiments with exploding samples have shown great potential of the techniques. By performing several experiments with identical conditions and synchronization we could improve accuracy adding the results together. Projective absorption experiments have shown the ability of the method to improve significantly the information needed for the precise hydrodynamic model. For the first time SAXS experiments have been performed with such object, demonstrating that we can really get information about the electron density of exploding material. The technique of very fast imaging opens an opportunities in an area of fast dynamic SAXS and WAXS (wide-angle X-ray scattering) studies of an objects under the influence of either different external factors like temperature, pressure, light, etc., or internal metastable or exited states. We believe that this will start a breakthrough in the research and development in the fields of material science that were not available for studies before.

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