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Fast Neutron Imaging with CCD Detectors and Imaging Plates

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Various CCD and IP (Imaging Plate) based fast neutron imaging systems have been developed and their operation has been experimentally tested. The detectors allow perform fast neutron radiography with comparatively weak neutron sources like a portable neutron generator. They provide a reasonable spatial resolution of about 1-2 mm within exposure time of several tens of minutes.

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1. Introduction

The development of fast neutron imaging techniques can decidedly broaden potentials of non-destructive testing in a wide range of applications. It is expected that an innovative imaging system conformed to a suitable fast neutron source in combination with a sophisticated software could provide appropriate productivity and achievable results in terms of the quality of testing. At present development of efficient detectors possessing low sensitivity to background radiation is a challenging problem of fast neutron imaging. The development of an efficient imaging detector is of current importance in case of neutron sources with a relatively low neutron output such as a portable neutron generator, for example.

At present two types of fast neutron detectors are mostly used for fast neutrons imaging: CCD detectors and detectors based on usage of Imaging Plates (IP). The paper describes detectors of both types developed in the course of more than ten years at two Moscow institutes: P.N.Lebedev Physics Institute of Russian Academy of Sciences and All-Russian Research Institute of Automatics of Federal Atomic Energy Agency [1-6].

2. CCD detectors

Figs. 1-5 show optical schemes of the CCD type detectors. Each detector contains a luminescent screen to transform fast neutrons into light, an image intensifier, an optics and a CCD-matrix. The most important units of the detectors are screen and input optics. These parts determine the detector efficiency and along with CCD-matrix format its spatial resolution. The detector efficiency depends in most cases on probability of recoil protons production (RPP) in the screen, screen luminosity (SL) and a portion of light (PL) transferred by the input optics to the image intensifier [3]. It is practically impossible to design a detector combining the best technically achievable values of these parameters. That is why the detector design depends on specific tasks to be solved.

The detector #1 [1] (fig. 1) contains the dispersive screen consisting of hydrogenous polymer matrix and embedded powder luminophor (Gd_2O_2S:Tb). Effective thickness of such a screen is limited by its opacity and depends on the linear coefficient of light attenuation (0.77 mm^{-1} [3]). At the same time due to application of a fibre optical taper as the input lens the detector is distinguished by the highest PL parameter.

The detectors #2 [1] (fig. 2) and #3 (fig. 3) contain the same dispersive screen but their sensitive area is greatly larger. Besides, the detector #3 provides two independent optical channels for screen imaging. The additional channel can be used to improve the image quality by summarizing images or to increase spatial resolution obviously at the expense of corresponding losses of sensitive area for this channel. The same optical scheme was used in the detector intended for imaging simultaneously fast neutrons and X-rays emitted by a portable neutron generator. A special combined luminescent screen has been developed for this purpose. Images produced by neutrons and X-rays at the display surface of this screen come into view in different regions of visible spectrum. Corresponding optical filters placed before input lenses allow to separate these images and register them independently of one another.

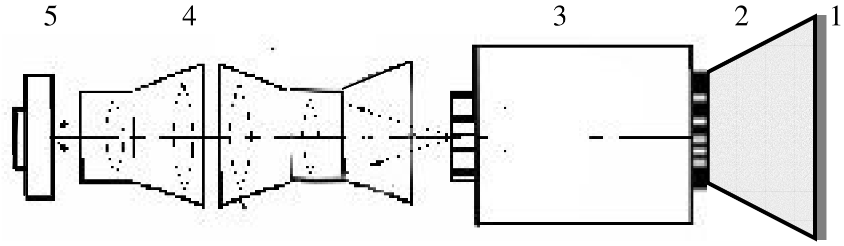

Fig. 1. Optical scheme of the CCD-detector based on usage of a taper as an input lens
1 – screen-converter, 2 – taper, 3 – image intensifier, 4 – scaling lens, 5 – CCD-matrix.

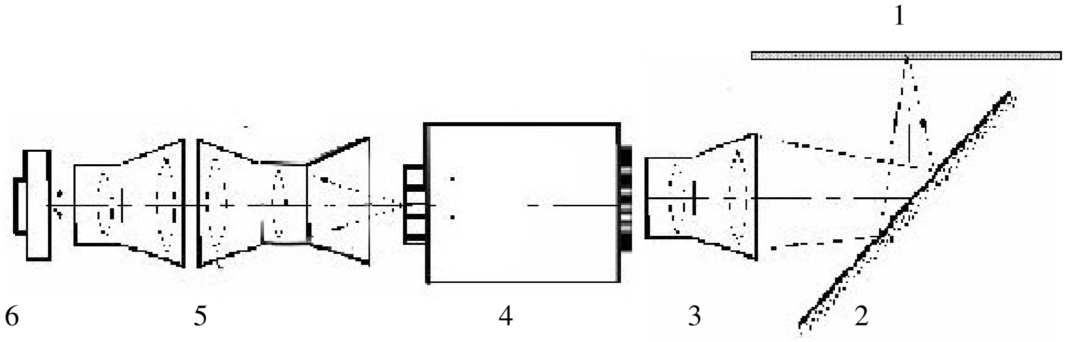

Fig. 2. Optical scheme of the CCD-detector based on usage of projection lens.
1 – screen-converter, 2 – deflecting mirror, 3 – projection lens, 4 – image intensifier, 5 – scaling lens, 6 – CCD-matrix.

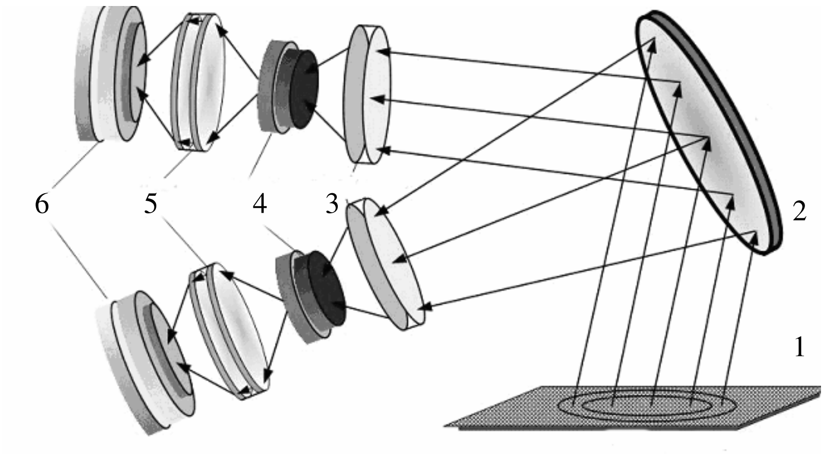

Fig. 3. Optical scheme of the CCD-detector with two channels of registration.
1 – screen-converter, 2 – deflecting mirror, 3 – input projection lens with optical filter (optional), 4 – image intensifier, 5 – scaling lens, 6 – CCD-matrix.

The detector efficiency for fast neutrons can be increased by application of a transparent screen long enough (~ 1cm) in the direction of the neutron beam. This approach results however in a loss of spatial resolution at the screen periphery for a conical fast neutron beam having place in neutron radiography with a portable neutron generator and a "typical" CCD-detector (fig. 2). Two designs were invented to solve this problem (figs. 4, 5). The first one (fig. 4) is based on application of a 60 mm thick slab made of luminescent polystyrene and a special optical condenser. The only difference between the other one (fig. 5) and a "typical" CCD-detector consists in usage of a special fiber optical screen in the form of a truncated pyramid. The condenser and fiber optical screen have been designed to transfer only those light rays which propagate along neutron rays emitted by a point like source placed at a fixed distance from the screen surface. It was 500 mm for both detectors.

Table 1 presents performance attributes of the described detectors.

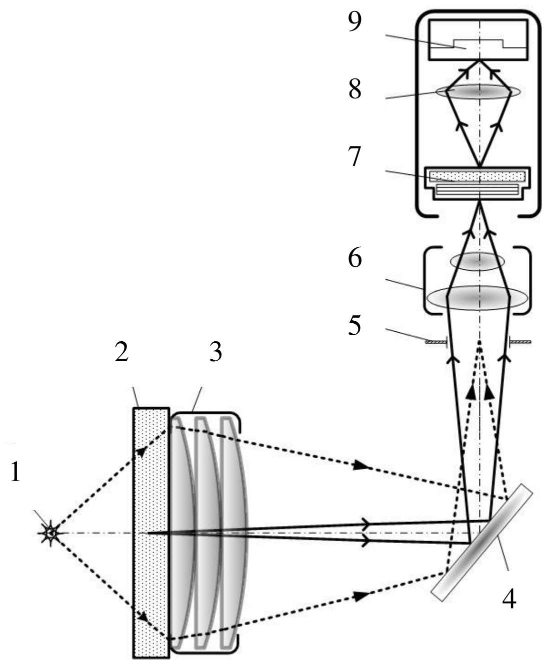

Fig. 4. Optical scheme of the CCD-detector based on usage of a special optical condenser. 1 – fast neutron source, 2 – screen-converter, 3 – condenser, 4 – deflecting mirror, 5 – input aperture, 6 – input projection lens, 7 – image intensifier, 8 – scaling lens, 9 – CCD-matrix.

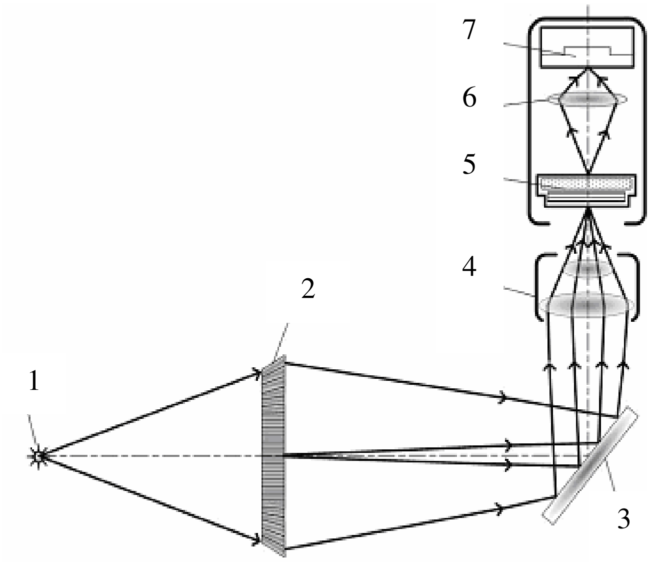

Fig. 5. Optical scheme of the CCD-detector based on usage of a fiber optical screen. 1 – fast neutron source, 2 – screen-converter, 3 – deflecting mirror, 4 – input projection lens, 5 – image intensifier, 6 – scaling lens, 7 – CCD-matrix.

Table 1. Performance attributes of position sensitive CCD-detectors for fast neutrons.

Detector	#1	#2	#3	#4	#5
Sensitive area, mm	40x40	120x120	350x350	∅180	150x150
Screen thickness, mm	1-3	3	3	60	100
Spatial resolution, mm	0.5	1.0	2.0	2.2	2.5
Screen type	dispersive	dispersive	dispersive	polystyrene slab	fibre optical polystyrene
Matrix format	1024x1152	768x576	1024x1152	768x576	768x576
Pixel pitch, μm	10x10	27x27	10x10	27x27	27x27

The scintillating fibre optical pyramid was also used in the detector intended for detection and identification of fast neutron sources (fig. 6). Its optical scheme is analogous to the scheme presented in fig. 1. The taper was replaced by the fiber screen and the dispersive screen was replaced by the thermal neutron luminescent detector (^{6}LiFZnS) performed in the form of a matrix. So, such a composite screen provides imaging not only fast neutrons but also thermal neutrons produced in the screen due to fast neutrons moderation. Matrix form of the thermal neutron screen allows separating signals produced by fast and thermal neutrons. Spatial distribution of the signal produced by fast neutrons is used for detecting position of the source. Fig. 7 shows histograms of fast neutron signal along X-axis at three angular positions φ (fig. 6) of the ING-07 (14 MeV portable neutron generator) with respect to the detector axis: φ=45°, 90°, -90°. The observed fluctuations in the histograms are explained by spatial inhomogeneity of the screen structure.

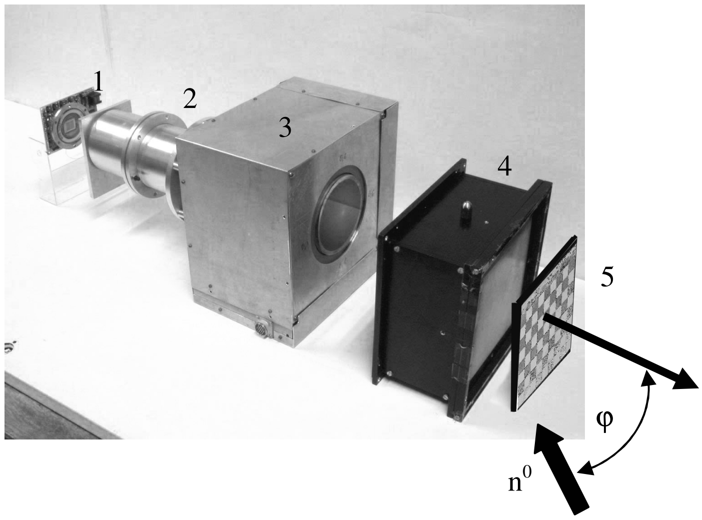

Fig. 6. Device for detection and identification of fast neutron sources
1 – CCD-matrix,, 2 – scaling objective, 3 - image intensifier, 4 – fibre optical screen, 5 – matrix detector for thermal neutrons.

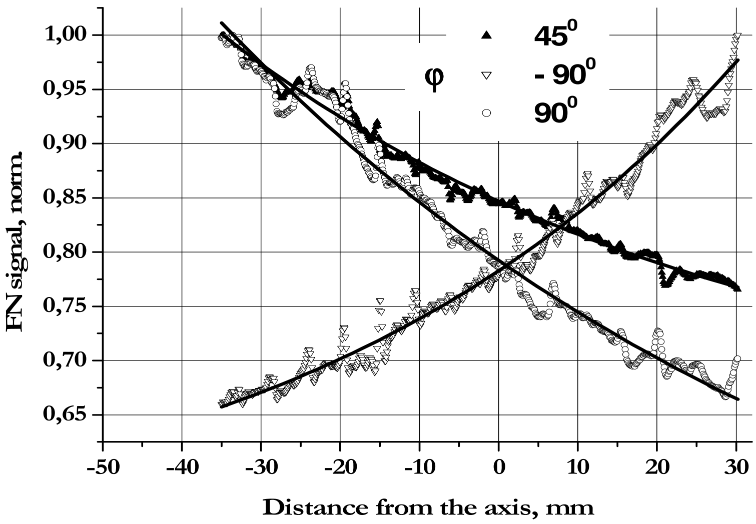

Fig. 7. Spatial distribution of fast (14 MeV) neutrons signal at different angular positions of the portable neutron generator with respect to the detector axis: φ=45°, 90°, -90°.

Ratio of thermal-to-fast neutrons signals registered by the detector depends on the average energy of incoming fast neutrons. That is why its measurement allows discerning between sources with different mean energy, for example, fission spectra, Pu-Be and 252Cf.

3. IP detectors

The "Imaging Plate" (IP) is a film like radiation two-dimensional sensor [7]. Two imaging systems utilizing "direct" and "transfer" methods with IP have been developed for fast neutron radiography [6]. Some of their characteristics are presented in Table 2. Copper and polyethylene sheets were used to convert fast neutrons into charged particles registered afterward by IP.

The transfer method is practically free of the impact of background radiation while images obtained by the direct method are influenced by background related to X-rays emitted by the neutron generator and gammas of inelastic scattering. The direct method is characterized by a higher efficiency. Theoretical estimation of detective quantum efficiency for 14 MeV neutrons gave values of about 1% for PE converter and about 0.3% for Cu converter.

Spatial resolution of the detectors was measured in two ways: by converter and test sample edges imaging. Intensity distribution in the edge image was fitted by sigmoidal function and differentiated afterwards resulting in Line Spread Function (LSF). Resolution was estimated as a FWHM of this function. It should be noted that sample edge imaging takes into account effects of the neutron source size and source-to-detector distance. At the same time converter edge imaging can essentially provide with intrinsic detector resolution. Table 2 shows that resolution for IP type detector is higher than for CCD type and amounts to about 1 mm.

Table 2. Spatial resolution of IP fast neutron detectors.

Converter type	**Converter thickness, mm**	**Resolution (FWHM), mm**	
		By sample edge	**By converter edge**
Cu	0,25	-	0,5
Cu	0,5	0,9	0,7
Cu	0,75	-	0,9
Cu	1,0	-	1,0
PE	5	1,3	-

Both direct and transfer methods give possibility to use a stack of IP based detectors to enhance image quality by numerical summation of individual images [3]. This technique allows to soften the requirements to neutron flux and to broaden capabilities of portable radiographic equipment. Fig. 9 shows experimental set up and radiographic images of test objects obtained by means of direct method with two stacks composed of 7 IP detectors. As one can see there is noticeable difference between single and summed images.

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4. Radiographic images

Images in figs. 8, 9 demonstrate imaging abilities of the portable equipment developed at VNIIA for fast neutron radiography and tomography. A portable neutron generator of ING-07 type was used as a fast (14 MeV) neutron source. Neutron output was about $1x10^9$ n/s. Presented images were obtained with CCD detector #3 and by the direct method using IP. Exposures were tens of minutes. Radiographic images are quite contrasting for objects made both from light and heavy materials or objects consisting of both types of materials. Observed spatial resolution for some objects attains several millimeters. It is seen that the equipment provides also imaging of objects screened by heavy metals. Fig. 9 shows that even objects inside a 5 cm thick lead container can be visualized.

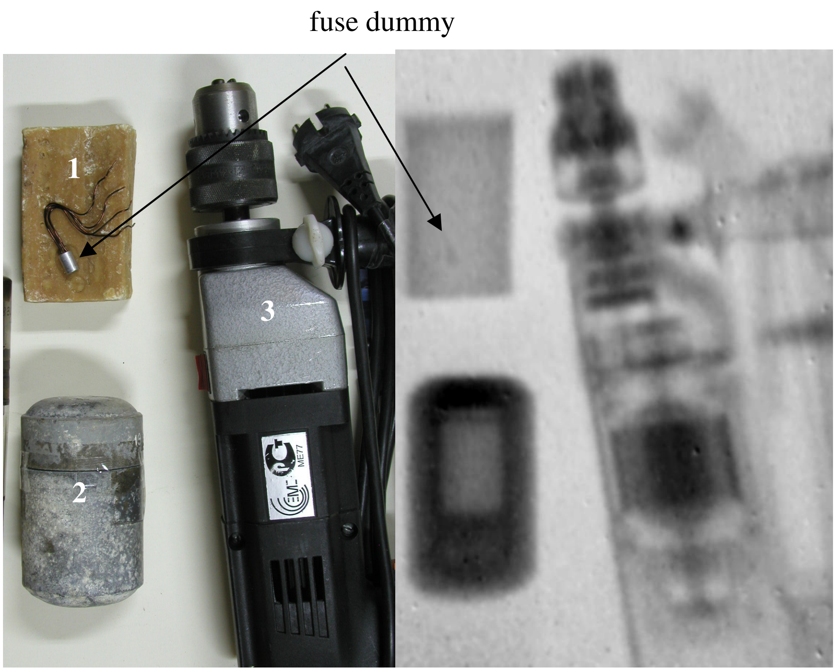

Fig. 8. Photo (left) and radiographic image (right) of test objects obtained with CCD-detector #3.
1 –soap, 2 – lead container with microporous resin and water inside, 3 – drill machine.

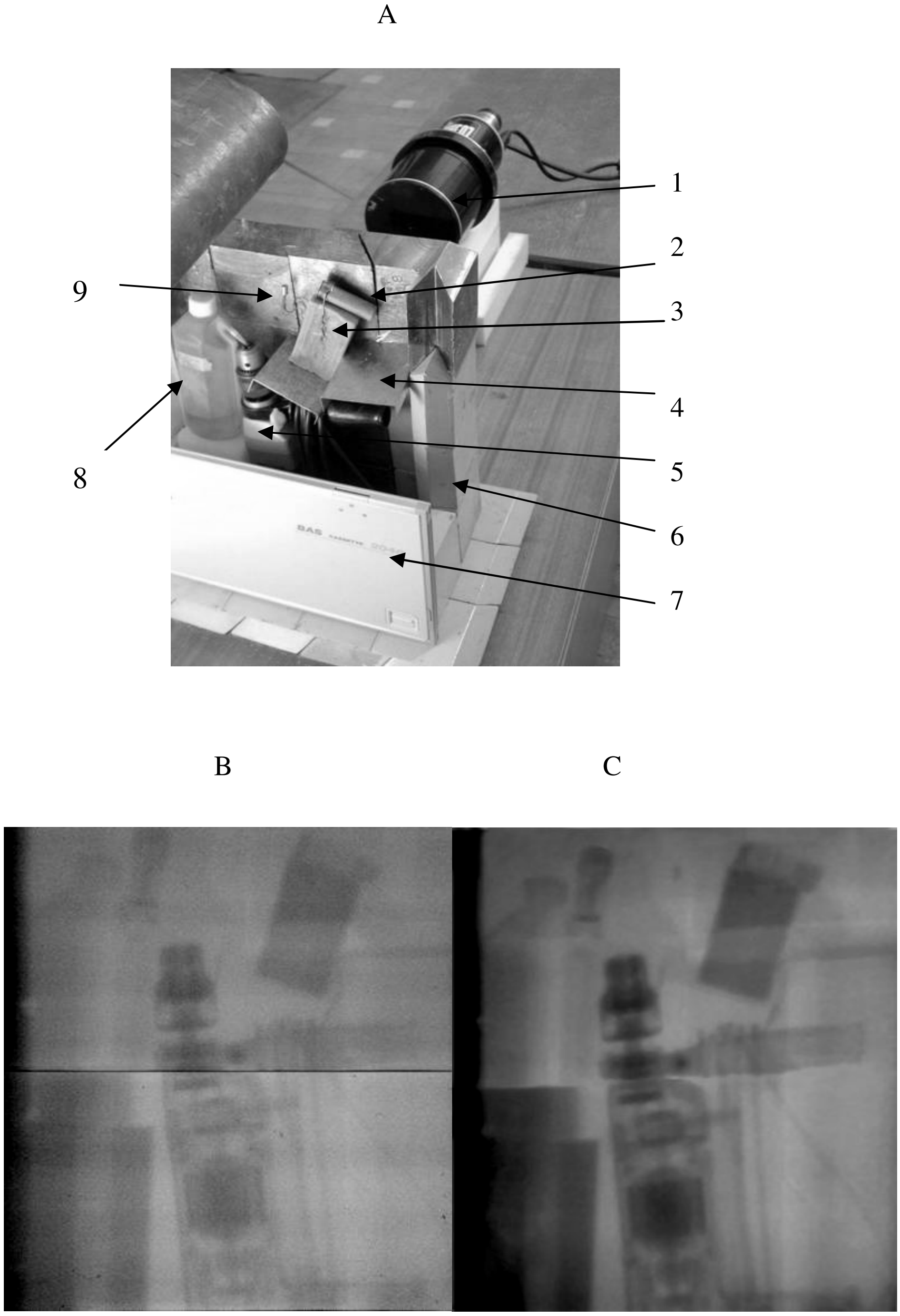

Fig. 9. A – photo of generator and objects arrangement, B – single radiographic image, C – results of seven images summation.
1 – ING-07, 2 – cartridge, 3 – soap, 4 – 2 mm thick tin plate, 5 - drill machine, 6 – lead bricks, 7 – cassette with a set of IP detectors, 8 – plastic bottle with alcohol, 9.- fuse dummy.

4. Conclusions

Various CCD and IP based fast neutron imaging systems have been manufactured and their operation has been experimentally tested. The detectors allow perform fast neutron radiography with comparatively weak neutron sources like a portable neutron generator. Even in this case they provide a reasonable spatial resolution (1-2 mm) during acceptable exposure time.

The most efficient detector is a stack of IP detectors with polyethylene converters. Efficiency of such a detector does not depend on sensitive area which can be easily enlarged. A disadvantage of this detector is loss of time while reading out and superimposing images before their summation. The other drawback is technical difficulties of tomography realization.

CCD detectors have indisputable preference first of all for a “real” time imaging and neutron tomography. They can be used for detection and identification of fast neutron sources as well.

At present prospect of further improvements of CCD detectors concerns with the development of image intensifiers or CCD-matrixes with a larger sensitive area. This will help to reduce photons losses in the input optics and to enlarge detection efficiency. Development of new luminescent materials with higher luminosity is desirable as well.

The presented results are of importance for development of portable equipment intended for non-destructive implant and on site testing with fast neutrons.

Acknowledgements

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