UDC 538.913

CCD camera in a neutron imaging system for real time and tomography investigations

B. Muhametuly[1,*], A. Duysebayev[2], Zh. Toksaba[1]

[1]*Al-Farabi Kazakh National University, IETP,al-Farabi 71, 050040 Almaty, Kazakhstan*
[2] *Institute of Nuclear physics, Ibragimov 1, 050032 Almaty, Kazakhstan*
[*]*e-mail: bagdaulet_m@mail.ru*

The report describes the research contract proposal concerning the development of a neutron imaging system for real time and tomography investigations that is based on LiF-ZnS scintillator and Charge Coupled Devices (CCD) camera like light-electrical signal converter. The necessary components of such a type of detector: scintillating screen, aluminized mirror and CCD camera with proper lenses are presented. It is intended to use the imaging system with large scale objects under static and dynamic investigations under various neutron fluencies obtained from Annular Core Pulsing Reactor (ACPR) in steady state and pulsing mode.

Key words: CCD camera, neutron radiography, neutron imaging, real time, neutron tomography.
PACS: 07.68. tm, 28.20

1 Introduction

The new dry neutron radiography facility from Institute for Nuclear Research is placed at the tangential channel of the ACPR and will enlarge the applications of neutron radiography, will diversify the applied methods and will make the neutron radiography easier, in comparison with older underwater facility [1].

The L/D ratio is 86-99 depending on the position of the object on the rotary table with 60 cm diameter. The divergent angle of the collimator is 3.3^{o}.

The neutron beam at the sample position has a diameter from 270 mm to 290 mm depending on the position of the sample on rotary table of the holder. The sample holder is designed to support objects up to 200 kg and assure 360^{o} rotation (in at least 200 steps), 60 cm transversal movement and 19 cm vertical movement. All movements are remote controlled and will be observed by a surveillance system based on a remote controlled CCD camera.

A major step in the improvement of the neutron radiography activity is the implementation of the neutron imaging system for tomography and real-time investigations. The utilization of an imaging system based on a scintillator, a front coated mirror, lenses and CCD camera is a guarantee of more reliable and accessible images and a progress for neutron radiography imaging [2,3].

The work in the field of neutron radiography at INR Pitesti has the goal to spread the neutron radiography nondestructive control technique for various scientific studies and industrial applications. This technique is helpful for improvement of the quality assurance in the top level activities of research and development in the nuclear field and industry.

2 Imaging System Based on CCD Camera

The components of the imaging system are placed in an aluminum light tight box (1274 mm×634 mm×564 mm) sustained vertically by a holder fixed on the metallic frame of the neutron radiography facility. The box has the possibility to be rotated, moved forward back (300 mm) and rotated horizontally for storage. The schematic design of the neutron imaging detector is shown in Fig. 1. In Fig. 2 there is an outer view of the detector.

For this project, in fact, two scintillators are used (Fig. 3), one ^{6}LiF-ZnS scintillator for neutrons, one of the preliminary series from PSI, Switzerland with 0.3 mm thickness of converter-fluorescent layer and one Kodak Lanex regular (Gd2O2S) for gammas, each with 300 mm×300 mm dimensions and green light emitters. The position of the scintillators in the main window of the detector is changed by a remote controlled step by step motor. The presence of the gamma radiation in the neutron beam offers the opportunity to perform, complementary, nondestructive investigations with gamma radiations.

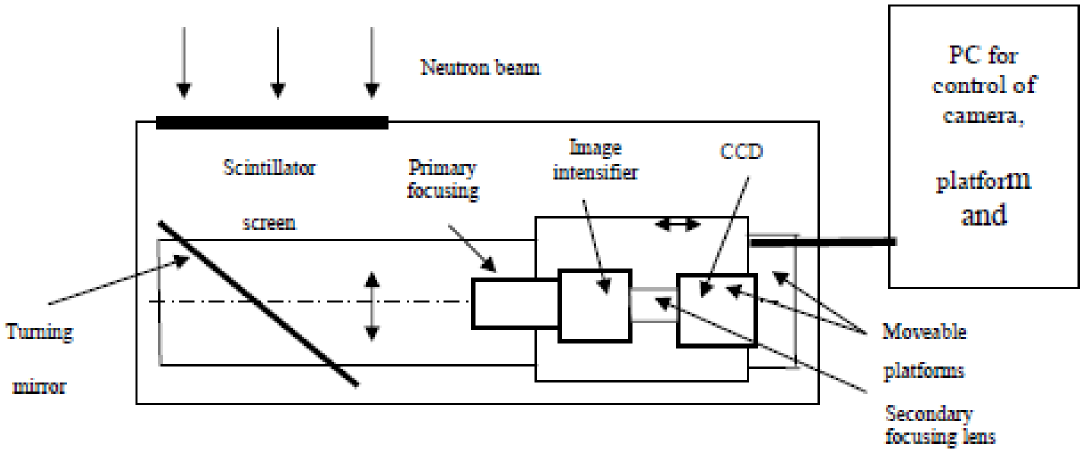


Figure 1 – Schematic diagram of neutron imaging components.

Figure 2 – A view of the detector with scintillators and CCD camera.

A front aluminum coated mirror on a float glass substrate of 2.3 mm and a surface of 400mm·300 mm is used. The thickness of the aluminum coating is about 100 nm covered with a thin coating of SiO with the thickness of about 3 nm. The optical efficiency of the mirror (reflection) is about 0.915.

Figure 3 – The scintillator for neutrons (left) and the scintillator for gammas (right).

A dual primary lenses, image intensifier, secondary lens and the CCD camera coupled to a PC complete the chain for image acquisition. The optical system was made in collaboration with PROOPTICA Bucharest, a Romanian Research Institute in Optics.

The light of the scintillator screen is reflected at 45 by the mirror and is focused on the photocathode of the image intensifier by the primary lenses. The image of the phosphor of the image intensifier is focused on the sensor of the CCD by the secondary lens. The primary focusing lenses assure two fixed positions to visualize the image of the screen. To protect the photocathode of the image intensifier was considered a common part of the primary lenses and two interchangeable parts to assure the two focusing distances. The change of the optical parts is made manually now but in the future will be used a stepped motor. The principal parameters of the optics are summarized in table 1.

Figures 4 and 5 show the two positions of the primary lenses, first arrangement for the 300 mm field of view and the second for the 100 mm field of view. The image intensifier is a XD-4 type, model XX2051D from DEP. Both the photocathode (Super S-25 with the sensitivity of 600 μA/lm) and the phosphor (P20-AF) have a diameter of 18 mm. The image intensifier has a microchannel electron multiplier plate. The image intensifier assembly includes the high voltage multiplier and oscillator. Two batteries each of 1.5 V or a DC 3 V (minimal 2 V and maximal 3.8 V) are used for operating supply voltage. The gain of the image intensifier at 2×10^{-5}lx is between 8000-12000 cd/m^{2}lx.

Table 1 – Parameters of the optical system

	Field of view (mm)	Distance scintillator-photocathode(mm)	Distance phosphor-CCD sensor(mm)	Effective Focal length (mm)	Working F/#
Primary lens 1	300	860	-	42.85	1.40
Primary lens2	100	526.5	-	96	2.98
Secondary lens	18	-	80.64	15	6.98

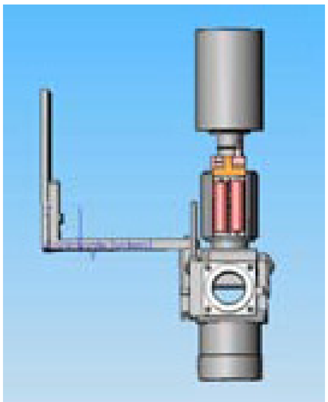


Figure 4 – Visualization of the entire 300 mm x 300 mm scintillator.

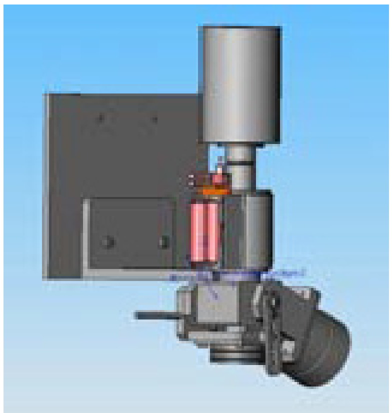


Figure 5 – Visualization of a 100 mm x 100 mm surface of the scintillator

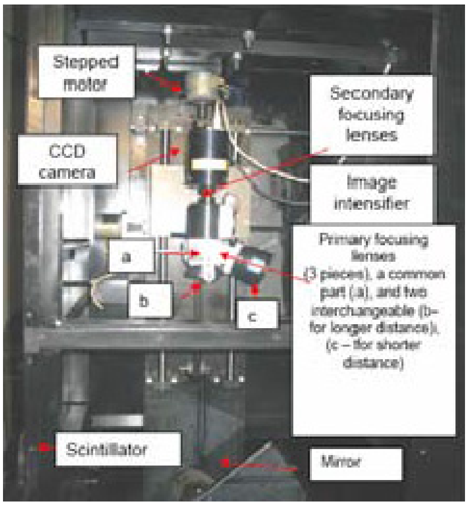


Figure 6 – A view of the components of the detector.

Two interchangeable CCD cameras, one cooled for static acquisition and one for real time image acquisition are intended for use. The image of the detector assembled with the cooled static acquisition camera is presented in Fig. 6.

SXV-H9 camera from STARLIGHT XPRESS, intended primarily for astronomical image acquisitions, is used for static acquisition. The characteristics of the camera are:

– Sony ICX285AL Exview HAD CCD sensor with ultra.

– low dark current.

– Pixel size: 6.45 μm · 6.45 μm with 1392×1040 pixels format.

– CCD image area: 8.98 mm (horizontal) ×6.7 mm (vertical).

– Spectral response: QE max at 540 nm (~65%).

– Readout noise: less than 12 electrons (typical 7 electrons).

– Full well capacity: greater than 27,000 electrons (unbinned).

– Dark current: less than 0.02 electrons/second

– Data format: 16 bits.

– Computer interface: built-in USB 2.0 compatible interface (also works with USB 1.1).

– Images download time: typically 3.5-4 seconds at full resolution using USB 2.0 and 7 seconds with USB 1.1.

– Cooling system: single stage thermoelectric cooler to give a CCD temperature ofapproximately -30C below ambient.

– The thread for lens coupling is M42×0.75 as it is used for photo cameras.

For real time acquisition it is proposed to use in the near future a Basler camera model A201bwith characteristics:

– Sensor size (H×V pixels): 1008×1018.

– Pixel size: 9.0 μm ×9.0 μm.

– Maximum frame rate at full resolution: 30 frames/second.

– Monocolor camera.

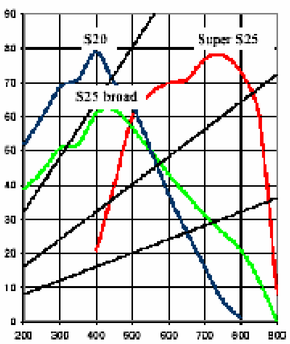
– Data format: 8 bits single pixel or 10 bits dual pixels.

– Synchronization: via external trigger or free-run.

– Channel link output.

The peak wavelength of the emission spectrum of the LiF-ZnS scintillator is at ~ 520 nm and of the Lanex scintillator is at 544 nm. Figures 7–10 show the spectral characteristics of the photocathode and phosphor of the image intensifier and of the sensors of the CCD cameras.

QE=20



Wavelength

QE=5%, QE=10

Figure 7 – The spectral response of the photocathode (Super S25) of the image intensifier.

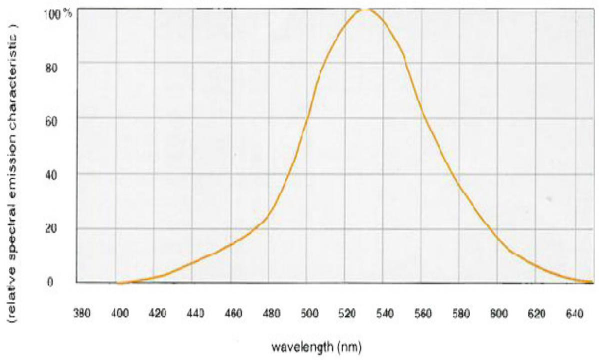


Figure 8 – Spectral emission characteristic of the fluorescent screen type P20-AF of the phosphor of the image intensifier.

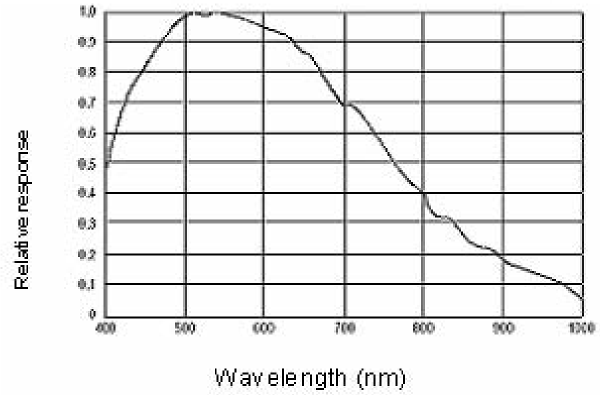
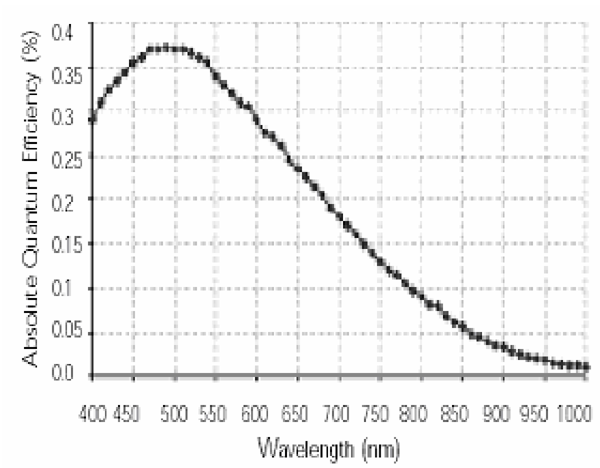


Figure 9 – Spectral Sensitivity Characteristics for sensor ICX285AL of the Starlight Xpress CCD camera.



Figiure 10 – Spectral Response Sensitivity for A201b Basler Monochrome Camera.

The lenses have the chromatic correction between 0.45 nm and 0.65 nm with the maximum at 0.53 nm. The projection of the round image (the neutron beam has a round section with about 290 mm in diameter) on the CCD sensor is like in Fig.

11. For Starlight camera the top and bottom parts of the image are missing and for Basler camera the image match the sensor.

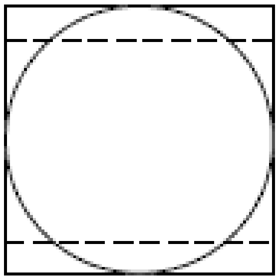


Figure 11 – The projection of the image on the sensor of the CCD cameras (dashed line on Starlight and continuous line on Basler CCD).

A calculation for geometrical resolution of the combination Starlight CCD camera (1392×1040 pixels) and standard lens (PENTACON, TESSAR etc.), without an image intensifier, indicated that should be ~ 0.22 mm when it is visualized the entire scintillator (300 mm) and ~ 0.07 mm when it is visualized only a surface of 100 mm×75 mm of the scintillator [3]. The geometrical resolution is the ratio of the measure of a visualized length and the number of pixels of the CCD sensor on which that length is projected. The detector assures a geometrical resolution for a field of view of 300 mm in concurrence with the geometrical resolution offered by the collimator-object-detector arrangement for a thickness of an object of about 2 cm. Some comparisons of the theoretical geometrical resolutions and experimental geometrical resolutions obtained with the piece of equipment that contains the image intensifier and with one with a standard lens will be done here.

The previous calculation done for a Basler camera (1008×1018 pixels), intended for real time imaging, determines for a field of view of 300 mm and 100 mm the values of ~ 0.3 mm and ~ 0.1 mm for the geometrical resolution.

The final resolution of an image obtained with a detector with scintillator and CCD camera depends on:

– geometrical resolution of the assembly collimator-object-detector;

– the scattering of neutrons on their path in collimator, object and detection system (previous detection);

– intrinsic resolution of the scintillator;

– the piece of equipment lenses-image intensifier – CCD camera;

– other aleatory processes.

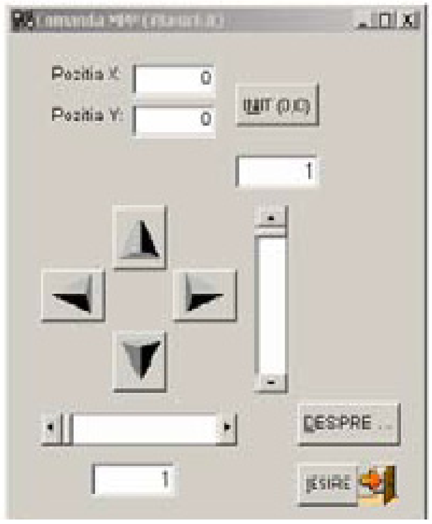


Figure 12 – The user interface of the software for remote controlled step by step motors.

There are three remote controlled stepper motors (GAMMA, ML 330/220K type) inside the tight light box. One motor changes the scintillators and two of them change the distance between scintillator and imaging equipment. The hardware that controls the motors is named SAM 01 and the software was programmed in Visual Basic 6.0. An output of the SAM 01 is now shared on turn between two motors. The window which is used to command the motors is shown in Fig. 12. It is possible to command the movement with an established number of steps or step by step for very fine adjustments.

The SXV-H9 camera from STARLIGHT XPRESS came with its own software for operation, acquisition and analyses of the image, named SXV_H9_USB-HX Camera Image. The acquisition mode (time of acquisition from thousandths to minutes, binning, subframes, single or continousaquisition, auto save, etc.) is selected from the interface window and then the Take Photo button is pushed. The image is saved in diferent formats (tiff, fits, bmp, etc.). The saved images are used subsequently for some adjustments (contrast, luminosity or contour improvements) and some analyses (length measurements, histograms, etc.) and even for tomography reconstruction. An image of the main window and of the interface control is shown in Fig. 13.

Recently, the well known Octopus tomography reconstruction software developed at Gent University in Belgium for the images obtained by neutron radiography also, now in version 8.1 was bought. Octopus works with a modular approach. This means that the user can access a number of modules from the main window (Fig. 14), which are opened in separate floating windows. Next to the menus, a selection of buttons makes it possible to easily access the most common modules. These are, from left to right: *Wizard-Select data set – Crop images – Spot filter – Normalize – Sinograms-Parallel reconstruction – Fan reconstruction – Cone reconstruction-Image viewer – Delete temp files – Manual – Update*

Full dynamic range of the CCD camera will be used the for tomography reconstruction.

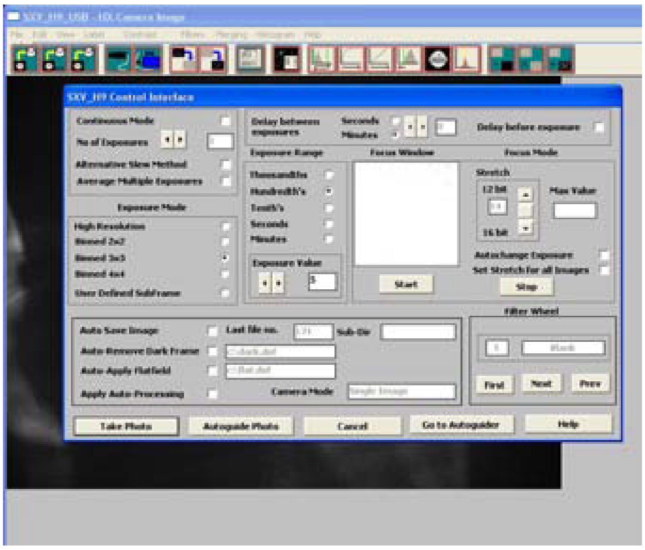


Figure 13 – The main window and the control interface of the software for SXV-H9 camera.

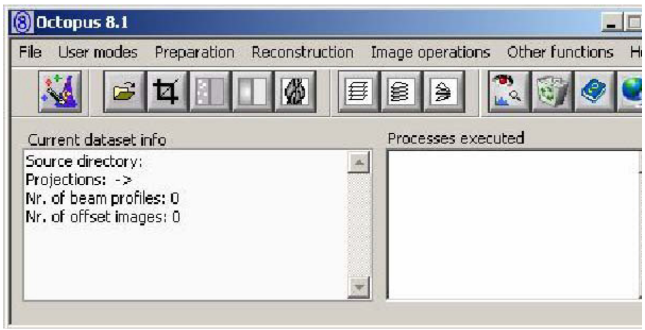


Figure 14 – The main window of the Octopus 8.1 software for tomography reconstruction.

3 Holder for Nuclear Fuel

For the investigation of the fresh nuclear fuel a special holder with 8 positions was built (Fig. 15). It is proper for TRIGA and CANDU nuclear fuel pins. It can be adapted for other types of nuclear fuel pins also. The fuels are rotated simultaneously using a remote controlled stepper motor. The image of the nuclear fuel can be acquired on film with dysprosium or indium (more indicated because the epithermal neutrons penetrate better nuclear fuel and indium has a higher cross section for epithermal neutrons than dysprosium) foils. With the detector based on scintillator and CCD camera a faster investigation can be done with a reasonable geometrical resolution (0.1 mm) using the 100 mm field of view offered by the system. It is intended to do tomography reconstructions for the TRIGA-LEU nuclear fuel pins that will be fabricated at INR Pitesti, for a better characterization of the gaps between pelletclad, pellet-pellet and soldering rings.

Figure 15 – Holder for nuclear fuel put on the sample holder.

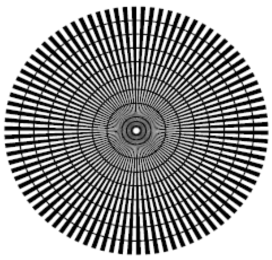


Figure 16 – The pattern used to establish the resolution of captured images with the imaging system.

4 Pattern for Geometrical Resolution Control

For the characterization of the geometrical resolution of the images acquired with the imaging system based on CDD camera was printed on paper a special pattern to be visualized (Fig. 16). The pattern is 270 mm in diameter and has 180 alternative equidistant triangle black-white parts. Between two black parts there is a distance of 0 mm in the centre of the pattern and 4.7 mm at the edge. Other concentric circles mark the position where image has a certain geometrical resolution (table 2) and also characterizes the aspect of the image concerning to possible distortions. The inner part of pattern inside the first circle with 6 mm in diameter was removed. Based on pattern image there are established the alignments and working distances for best images for scintillator-mirror-imaging system.

Table 2 – Levels of geometrical resolution dicated by concentric circles of the pattern.

Radius(mm)	3	5	10	15	30	45	60	75	90	105	120
Resolution(mm)	0.1	0.175	0.350	0.52	1.04	1.57	2.09	2.62	3.14	3.66	4.18

5 Characterization of the Geometrical Resolution

The control pattern was placed on the Lanex scintillator inside the tight light box. Were established the geometrical resolutions of the images of the pattern obtained for two fields of view, 300 mm and 100 mm as the imaging system will be used. The tests were done with the imaging system that contains the image intensifier and supplementary with the Starlight CCD camera and a TESSAR 2.8/50 CARL ZEISS JENA lens with M 42×0.75 mm thread. The aim was to establish the geometrical resolution offered by imaging system (Figs. 17 and 18) and to compare it with that obtained without image intensifier (Figs. 19). The acquisition time of the image was 1s, exception the image from Fig. 17, with 2s (better result). The light permitted to enter into box to illuminate the pattern was sure different. The theoretical assumptions regarding to geometrical resolution (chapter 2) are verified in the case of image acquisition with TESSAR lens. Using image intensifier with 18 mm diameter there is a loss of resolution, which becomes 1.65 times worse than resolution with standard lens.

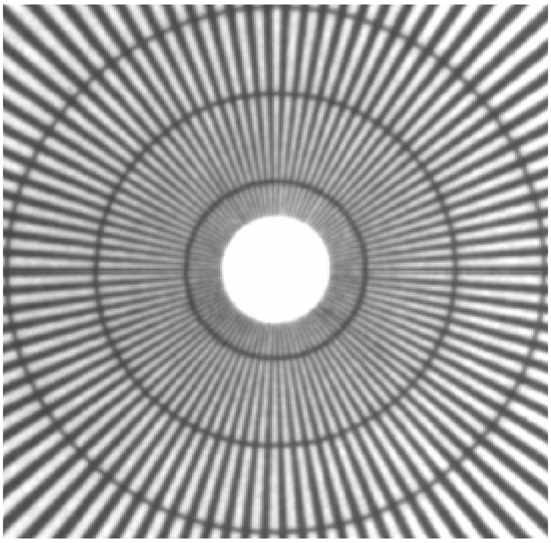


Figure 17 – Central detail of the image of the pattern (100 mm field of view) obtained with the imaging system with geometrical resolution ~ 0.33 mm.

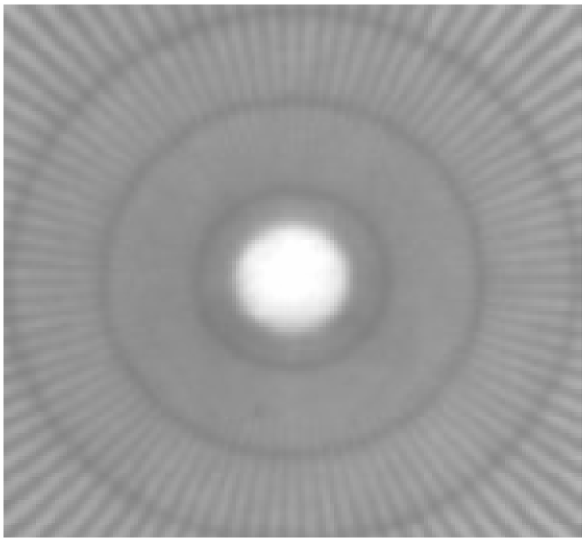


Figure 18 – Central detail of the image of the pattern (300 mm field of view) obtained with imaging system with geometrical resolution ~ 0.1 mm.

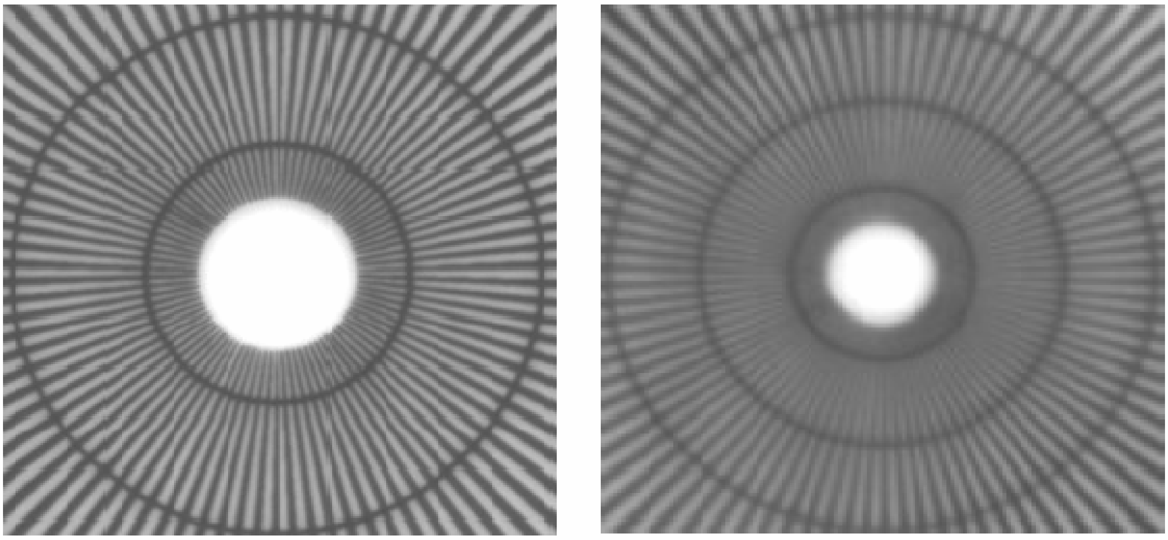


Figure 19 – (Left) Central detail of the image of the pattern (100 mm field of view) obtained with the TESSAR lens with resolution better than 0.1 mm; (Right) Central detail of the image of the pattern (300 mm field of view) obtained with the TESSAR lens with resolution ~ 0.2 mm.

The geometrical resolution becomes 0.1 mm using TESSAR lens, for a field of view of about 165 mm.

6 Neutron Radioscopy Tests

First images with the new detector for neutron imaging were acquired for an object composed of two taps for vacuum, arranged as in Fig. 20. The object contains metals and organic materials [4,5].

The images were taken for entire 300 mm field of view with both types of scintillators, LiF-ZnS for neutrons and Lanex for gammas.

The image from Fig. 21 (Left) was taken with bismuth monocrystal filter (3 cm thickness) put in the mixed beam of radiations (neutrons and gammas) and that from Fig. 21 (Right) with bismuth filter raised (remote steel cable). The neutron intensity passing the box of the detector was measured in both situations (the output is a dose rate) and the ratio was 1.6 in concordance with the ratio of integration times on the sensor of the CCD to obtain good images, 60 s, respectively 40 s.

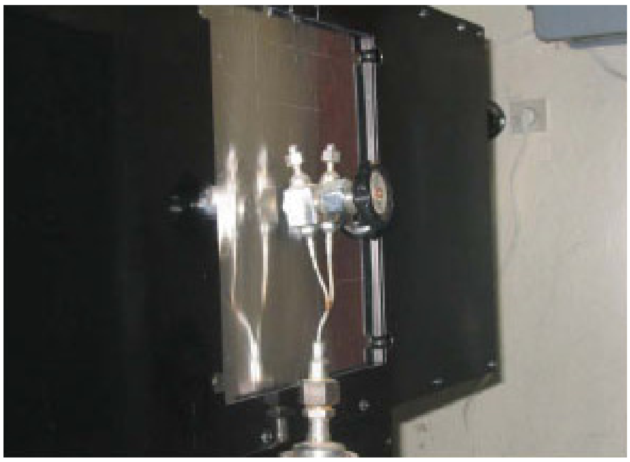


Figure 20 – The test object placed in front of the scintillator screen of the neutron imaging system with CCD camera.

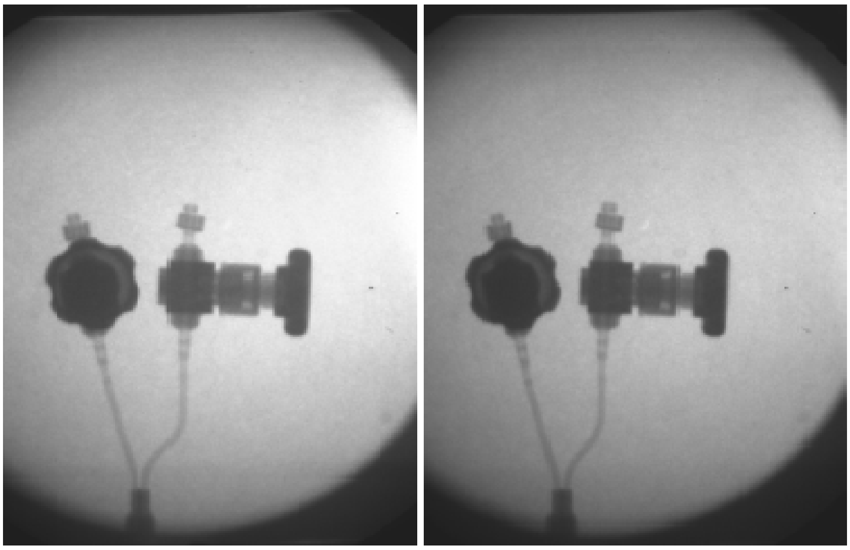


Figure 21 – (Left) The image of the test object obtained with LiF-ZnS scintillator. Integration time: 60 s; (Right) The image of the test object obtained with LiF-ZnS scintillator. Integrationtime: 40 s.

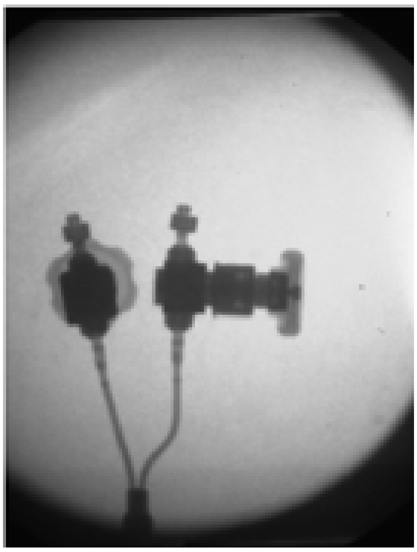


Figure 22 – The image of the test object obtained with Lanex scintillator. Integration time: 40.

The image taken with the Lanex scintillator is shown in the Fig. 22. The bismuth filter is raised and the integration time on CCD sensor is the same like for LiF-ZnS scintillator. As Lanex scintillator contains gadolinium with the biggest neutron capture section among all elements, it is necessary to remove the neutron content with a foil of cadmium, for example, prior to hit the investigated object. In the image from figure 22 the neutrons were not removed, but can be seen differences between images obtained with the two scintillator types. In the image obtained with Lanex scintillator the gamma content of the beam passed the regions with organic material (knobs of the taps) showing clearly the central screw.

The neutron beam intensity is estimated to be ~ 10^5 n/cm^2/s. In the near future the neutron beam will be measured by neutron activation analyses with indium foils after some mprovements of the neutron transfer from reactor core to tangential beam port.

7 Conclusions

The main aim of the project under contract No. 12699 is the development of a neutron imaging system based on CCD camera for static (then for tomography reconstructions) and dynamic imaging and to test the imaging system with large scale objects under static and dynamic mode under various neutron fluencies obtained from ACPR reactor (steady state and pulsing mode). The detector assures these applications through its conception. In addition, it is used for investigations with gamma radiations.

As a first step, the neutron imaging system for static image acquisition with a high resolution CCD camera, image intensifier and proper lenses was commissioned. The decision was taken to use two interchangeable cameras, one for static acquisition and one for dynamic acquisition, each of them with best parameters instead to use one very expensive that covers both situations. The images are acquired with 0.1 mm geometrical resolution for 100 mm field of view of a special pattern. To characterize the resolution of the images obtained from scintillator a special gadolinium pattern with 20 mm diameter must be bought or made so that to be present in every image. With the Octopus software for tomography reconstruction we have the possibility to perform this attractive application.

As the subsequent tests and improvement of neutron beam intensity will demonstrate that the real time imaging can be done, the second CCD camera will be put into operation to complete the desirable task to perform real time imaging. The ACPR reactor is operated when some tests are requested for different experiments and it is not possible to perform tests on a continuous scale, a big disadvantage when it is necessary to have an intensive activity.

As the TRIGA-LEU nuclear fuel will be fabricated and will be ready for testing, the imaging system will be used for neutron radioscopy investigations, as the holder for this application is made.

References

[1] M. Dinca. Development of a new radiography facility with extended applications at the INR TRIGA reactor, Proceedings of the 7th World Conference on Neutron Radiography, Rome-Italy. – 2002. – P. 33-39p.

[2] M.P. Dinca, M.A. Avelescu. Neutron imaging system based on a CCD camera, International Workshop on Neutron imaging using Cold neutron and related topics, Villigen, Switzerland. – 2005. – P. 13–14 p.

[3] M. Dinca, M. Pavelescu. Calculation for a Neutron Imaging System Based on a CCD camera // Romanian Journal of Physics. – 2006.– Vol.51. – P. 363.

[4] M. Dinca, M. Pavelescu. Detector for neutron and gamma radiography based on CCD cameras, 7th World Conference on Neutron Radiography, Gaithersburg MD, USA, 2006.