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[1,2]*Chuprakov I.,
PhD, ORCID ID: 0000-0002-0592-1680,
*e-mail: igorchuprakov@gmail.com
[1,2,3]Nazarov K.,
PhD, ORCID ID:0000-0003-4637-2486,
e-mail: k.nazarov@inp.kz
[1,2,3]Mukhametuly B.,
PhD, ORCID ID: 0000-0003-1474-8354,
e-mail: bagdaulet_m@inp.kz
[1,2,3]Bekbayev A.,
PhD, ORCID ID: 0000-0003-4800-357X,
e-mail: a.bekbayev@inp.kz
[1,2,3]Arynbek Y.,
Master, ORCID ID: 0000-0002-6942-8211,
e-mail: yersultan@jinr.ru
[1,2]Kenessarin M.,
Master, ORCID ID: 0000-0001-5680-0769,
e-mail: muratkenessarin@inp.kz
[3]Bazarbayev Y.,
Master, ORCID ID: 0000-0001-9374-3847,
e-mail: yerik.bazarbayev@gmail.com
[1,2,3]Myrzabekova E.,
Master, ORCID ID: 0000-0002-7710-7418
e-mail: e.myrzabekova@mail.ru
[1,2]Nazarova A.,
PhD, ORCID ID: 0000-0003-1724-5322,
e-mail: assel.makhambet@gmail.com
[2]Abdurakhimov B.,
PhD, ORCID ID: 0000-0001-6087-973X,
e-mail: bekhzod@jinr.ru
[2]Zel I.,
Cand. Phys.-Math. Sc., ORCID ID: 0000-0003-0424-7142,
e-mail: zel@jinr.ru

[1]Laboratory of Neutron Physics, Institute of Nuclear Physics, Almaty, Kazakhstan
[2]Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna, Russia
[3]Al-Farabi Kazakh National University, Almaty, Kazakhstan

IMAX – A COMPACT X-RAY MICROTOMOGRAPHY INSTRUMENT FOR MATERIAL RESEARCH

Abstract

As the methods, instrumentation, and resolution of three-dimensional spatial analysis have improved over the past twenty years, it is now possible to image the internal microstructure of multiphase materials in detail in three dimensions. Three-dimensional X-ray microtomography offers a unique opportunity for high spatial resolution imaging that can be achieved in compact desktop systems using X-ray microfocus sources. Recently, a modern desktop cone-beam X-ray microtomography system for quantitative analysis of materials in three dimensions was installed at the Institute of Nuclear Physics of the Ministry of Energy of the Republic of Kazakhstan. This paper presents the design, description of the main components, and technical parameters of this X-ray microtomography system, called IMAX. This system is designed to acquire, process, store X-ray images, and reconstruct three-dimensional data from angular projections for the study of internal structures and non-destructive testing of materials. The system consists of a microfocus X-ray source providing an X-ray energy range from 35 to 80 keV, a flat panel scintillation detector system allowing high-resolution digital imaging, optomechanical platforms for sample positioning, and radiation shielding. The first results of test measurements using this X-ray system are presented.

Key words: x-ray beam; imaging; tomography; non-destructive testing.

Introduction

Currently, in the Neutron Physics Laboratory of the INP ME RK, a neutron radiography and tomography installation, TITAN, operates on the 1st horizontal channel of the WWR-K reactor [1, 2]. The neutron beams from this instrument are used to solve a wide range of problems in materials science and engineering research [3, 4]. However, in some experiments, difficulties arise when studying small details with good resolution or objects with low contrast for neutrons, necessitating the use of another method to reduce ambiguity, such as X-ray tomography, to solve problems [5, 6]. These imaging methods are complementary to each other [7, 8]. X-ray imaging is implemented in large installations such as synchrotron sources [9], free electron lasers and in laboratories using micro or nano focal X-ray tubes [10, 11]. Recently, experimental installations have been developed where measurements are carried out simultaneously with both types of radiation [12, 13]. X-ray imaging elements are installed on the neutron beam line, and they can be located coaxially or perpendicular to each other [14, 15]. Implementing the X-ray imaging mode at the TITAN installation was complicated by the presence of a thermal neutron beam from the reactor's radial channel, which created unwanted background, and by the difficulty in combining the resulting images with different exposure times and beam geometries (X-ray cone beam and neutron parallel beam). Therefore, it was decided to create a new freestanding tabletop X-ray imaging instrument as a complementary method to neutron imaging.

X-ray tomography (CT) has become a well-established non-destructive diagnostic and three-dimensional imaging technique [16, 17]. The sufficient penetration depth of X-rays into materials allows information to be collected based on the study of a series of 2D projection images that reveal the internal structure of the sample. The use of modern X-ray sources with varying energy and current makes it possible to provide a convenient penetration depth depending on the properties of the sample. These advantages make this method attractive, and today it is used in various fields of science: biomedicine, archaeometry, paleontology, industrial quality control, and materials science.

In X-ray imaging, one of the important parameters characterizing the quality of the image is the spatial resolution and sharpness, which strongly depends on the size of the focal spot of the source [18, 19]. Sources with a small focus reduce the penumbra region and increase the image sharpness. In laboratory conditions, to implement imaging and tomography with good quality, it is necessary to use microfocus sources and highly sensitive X-ray detectors that provide resolution in the micrometer range. Although such laboratory imaging systems are inferior to synchrotron and free-electron laser sources in terms of intensity and collimation, laboratory setups offer significant advantages in ease of access and experimental flexibility.

In this regard, a new compact X-ray microtomography installation was created called IMAX (the abbreviation stands for "IMAging with X-rays"). This article presents a description and the main technical parameters of this installation, and shows the results of the first measurements, demonstrating the main areas of application in various scientific fields.

Materials and Methods

The IMAX experimental setup is a shielded compact tabletop box with dimensions of 100×60×60 cm^3, which houses all instruments except the electronic control system. An actual photograph of the IMAX setup is shown in Figure 1. The box is protected by lead plates and a door is provided for sample insertion and manipulation. In addition, for radiation safety purposes, source blocking switches are installed when the door is opened.

This setup consists of three main components: a microfocus X-ray source, a sample stage, and an X-ray detector. All these components are installed inside the box.

a b

Figure 1 – Real photograph of the IMAX X-ray imaging system: (a) - outside view: radiation protective box with dimensions 100*60*60 cm^3; (b) - inside view: on the left - a flat-panel detector, in the middle - a sample table with a rotational and translation stage, on the right - the location of the X-ray filter. There is a microfocus source behind the wall, not visible in the photo

The source of X-ray radiation is a polychromatic microfocus X-ray generator (Spelmann XRB011) with a minimum source size of about 30 μm [20]. Inside the box it is fixed to the wall and is not visible in Figure 1-b). The microfocus source can operate in a voltage range from 35 to 80 kV, the current can vary from 0–700 μA in a given voltage range. The distance between the focus and the outer window is 32 mm, and the X-ray beam opening angle is 40°. As an additional option, a copper filter with different thicknesses is used to reduce the low-energy part of the source spectrum.

Since the detector system and the source are in fixed positions inside the box, geometric magnification is carried out with moving tables. Sample positioning is performed by two translation stages (linear stage along the beam and rotation stage) installed between the source and detector. The geometric magnification of the IMAX beam in imaging mode can vary from 1 to 8, and in tomographic measurements from 1.2 to 4.5.

The IMAX detector system is based on two-dimensional CMOS photodiode arrays for scanning and reading, directly coupled to a scintillator that converts X-rays into light. This flat-panel X-ray camera (Mark 1215C) with a Gadox scintillator has a matrix of 2280 pixels (H) × 1812 pixels (V). The working field of view of the detector is 114×145 mm, and the size of one pixel is 64 microns. The manufacturer specifies an energy range from 20 to 300 keV which covers the operating range of the x-ray source.

Acquiring and adjusting images (normalization, adjustment, filtering and measurements, etc.), selecting energies and source current is performed by the ImageJ software package written in Python. This program allows control over the tomographic data acquisition algorithm and provides flexibility for specific experimental tasks. Depending on the size of the samples under study, you can select one of the modes such as: medium resolution, high resolution, fast tomography.

Tomography data sets are obtained by rotating the sample with small steps and obtaining one tomographic projection per step. It is possible to improve the quality of images by averaging several frames. Reconstruction of tomographic data is performed in this program using a filtered back projection algorithm for cone beam geometry. After CT reconstruction, three-dimensional volumetric data is visualized using the Visualizer programs, and well-known ImageJ and BoneJ program plugins are used for analysis and calculation.

The spatial resolution of the X-ray image was measured using a standard sample of 0.05 mm lead on a silicon substrate. Two images were taken with an exposure of 200 ms for two positions of the sample with beam magnification values of 2.19 and 4.1. The results of the MTF measurement of the change in amplitude (i.e. signal brightness) of different spatial frequencies showed 11.25 lp/mm at a magnification of 4.1, and 7.7 lp/mm at a magnification of 2.19. The obtained characteristics and capabilities of IMAX microtomography are at the level of world manufacturers of microtomographic scanners and can be found in the literature [21–24].

Results and Discussion

Tomography of corals

One of the scientific applications of X-ray microtomography is the morphological non-destructive study of the structure of corals, which are considered to be the engineers of reef ecosystems [25, 26]. The advantage of using this method is that a complete three-dimensional image of a complex branching object such as a coral, including the features of the internal structure (internal pores and cracks, shape and growth axis), can be obtained with high resolution.

The IMAX desktop setup was used to perform tomographic measurements of a coral found on the coasts of the Seychelles Islands. The images were obtained with an X-ray source with a tube voltage of 80 kV and a current of 50 μA. The magnification factor was 1.4 and the voxel size was 45*45*45 μm^3 after reconstruction. The tomographic volume was obtained from 900 projections with 5-frame averaging and an angular step of 0.4◦. The exposure time of one frame was 100 ms.

The actual photograph, three-dimensional model and tomographic section are shown in Figure 2. As we can see, the 3D model reconstructed from the X-ray projection set accurately indicates all external pores, and even the internal pores are visible on the tomographic slices. Thus, the internal structure of the corals can be qualitatively assessed, and biologically significant morphological characteristics, such as the distance between branches and the surface-to-volume ratio, can be calculated with good quality.

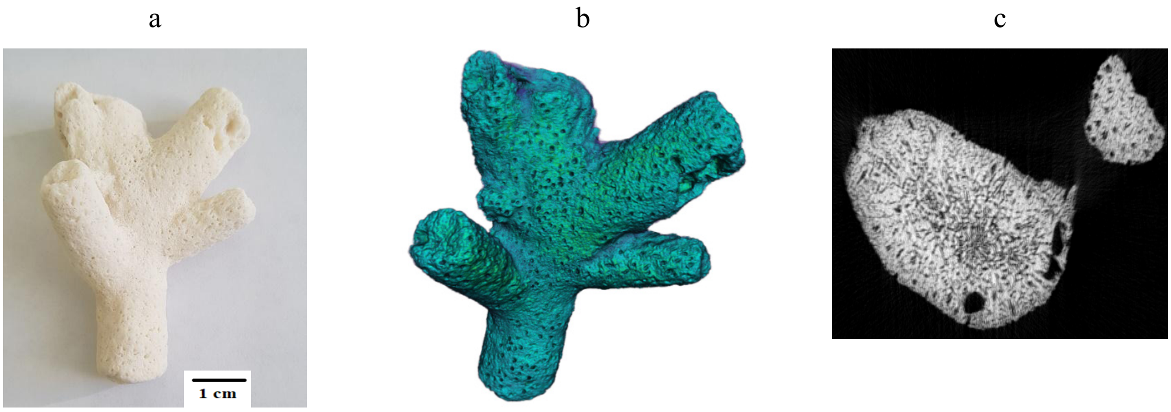

Figure 2 – Real photo (a), X-ray microtomography 3D model (b) and slice (c) of coral found on the Seychelles islands

Metallic foams

The study of the structure of metal foams is the main application area of modern X-ray tomographs due to the strong absorption of X-rays in elements with high density and atomic number. Today, metal foams are a very attractive material that is used in developments for a wide range of applications from lightweight structures to packaging, insulation and collision protection [27–29]. The X-ray tomography method allows for a detailed study of the structural characteristics and changes in the macro/microstructure of metal foams under various external conditions: deformation, pressure, temperature, etc.

To demonstrate the capabilities of the IMAX installation, a tomographic experiment was conducted on copper foam with a porosity of 10 ppi. The projections were obtained by averaging 10 X-ray frames and a source voltage of 75 kV and a current of 35 μA. The magnification factor was 2.2, and the pixel size was 29 * 29 μm2. Figure 3 shows a real photo, a 3D model, and a horizontal slice of copper foam. As can be seen from one of the slices of the 3D foam model, there is good contrast, and all the internal walls are visible. There are cavities and pores inside the walls and we can say about the anisotropy of the distribution of the material during production.

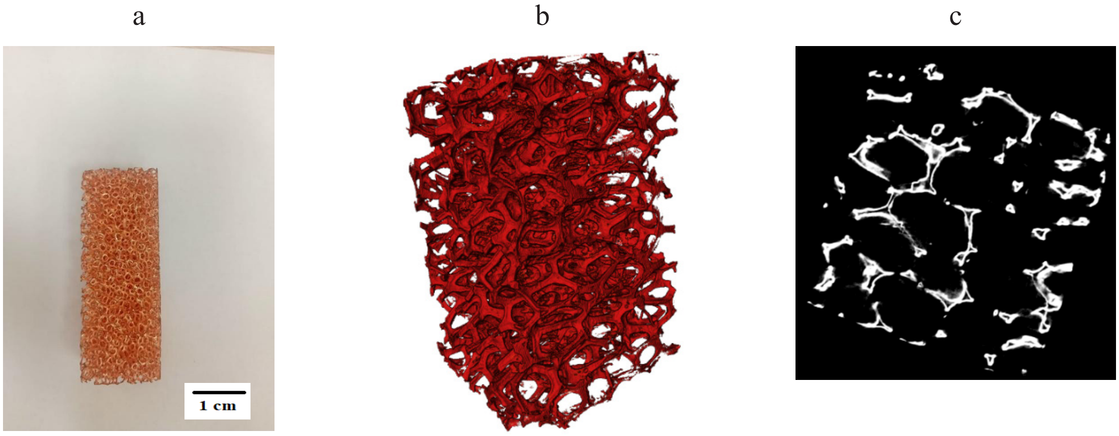

Figure 3 – Real photo (a), X-ray tomography 3D model (b) and slice (c) of copper metallic foam

Archeological objects

One of the important areas of using the X-ray tomography method is the study of the structural features of cultural heritage sites [30, 31]. Because the study of rare, valuable, and unique historical objects as cultural heritage sites always requires the use of modern approaches to ensure their preservation and integrity for future generations. As an example of such works, the results of studies of the ceramic amphora found in the historical region of Dobrudja in Romania are presented [32].

The 3D model and slices of the ceramic amphora after tomographic reconstruction are shown in Fig. 4. As can be seen, there are many elongated cracks at the base of the handle (Fig. 4-c), which may indicate a layered structure of the amphora handle. It should be noted that the attenuation coefficient is more isotropically distributed throughout the entire volume of the sample. In addition to the cavity and crack, large silicate grains (yellow areas in Fig. 4-c-d) and metal inclusions (red areas in Fig. 4-c-d) with high X-ray attenuation coefficients contrast well.

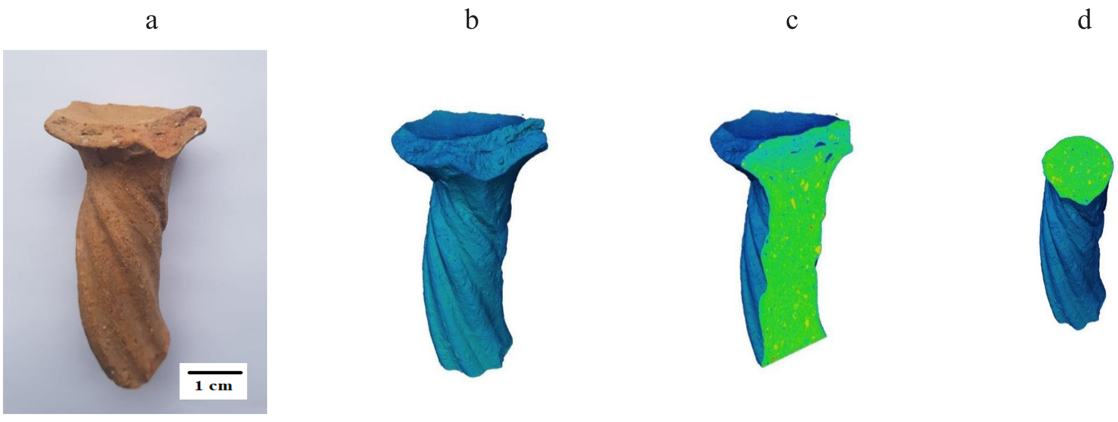

Figure 4 – Real photo (a), X-ray microtomography 3D model (b), and selected longitudinal (c) and transversal (d) virtual slices of the 3D model of the studied pottery fragment. The rainbow-like coloring shows X-ray linear attenuation coefficient degrees from low (blue) to high (red). A scale bar is shown

Conclusions

This article describes a newly developed desktop compact microtomography system designed for acquiring, processing, and storing X-ray images, as well as for reconstructing three-dimensional data from angular projections. The system was developed in the Neutron Physics Laboratory of the Institute of Nuclear Physics in Almaty, Republic of Kazakhstan. The design of the installation, including a detailed description of the main components and technical parameters, is presented. Additionally, the paper showcases the first results of test measurements using X-ray radiography and tomography, demonstrating the performance and potential of the IMAX system in various scientific and technical applications. These findings highlight the importance and promise of using the IMAX system in both research and industry.

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[1,2]*Чупраков И.,
PhD, ORCID ID: 0000-0002-0592-1680,
*e-mail: igorchuprakov@gmail.com
[1,2,3]Назаров Қ.,
PhD, ORCID ID:0000-0003-4637-2486,
e-mail: k.nazarov@inp.kz
[1,2,3]Мұхаметұлы Б.,
PhD, ORCID ID: 0000-0003-1474-8354,
e-mail: bagdaulet_m@inp.kz
[1,2,3]Бекбаев А.,
PhD, ORCID ID: 0000-0003-4800-357X,
e-mail: a.bekbayev@inp.kz
[1,2,3]Арынбек Е.,
[1,2]Кенесарин М.,
магистр, ORCID ID: 0000-0001-5680-0769,
e-mail: muratkenessarin@inp.kz
[3]Базарбаев Е.,
магистр, ORCID ID: 0000-0001-9374-3847,
e-mail: yerik.bazarbayev@gmail.com

[1,2,3]Мырзабекова Э.
магистр, ORCID ID: 0000-0002-7710-7418,
e-mail: e.myrzabekova@mail.ru
[1,2]Назарова Ә.,
PhD, ORCID ID: 0000-0003-1724-5322,
e-mail: assel.makhambet@gmail.com
[2]Абдурахимов Б.,
PhD, ORCID ID: 0000-0001-6087-973X
e-mail: bekhzod@jinr.ru
[2]Зель И.,
физ.-мат. ғ.к., ORCID ID: 0000-0003-0424-7142,
e-mail: zel@jinr.ru

[1]Ядролық физика институтының нейтрондық физика зертханасы, Алматы қ., Қазақстан
[2]Франк атындағы нейтрондық физика зертханасы, Біріккен ядролық зерттеулер институты, Дубна қ., Ресей
[3]әл-Фараби атындағы Қазақ ұлттық университеті, Алматы қ., Қазақстан

IMAX-МАТЕРИАЛДЫ ЗЕРТТЕУГЕ АРНАЛҒАН ЫҚШАМ РЕНТГЕНДІК МИКРОТОМОГРАФИЯЛЫҚ ҚҰРЫЛҒЫ

Аңдатпа

Соңғы жиырма жылда үшөлшемді кеңістіктік талдау әдістері мен аспаптарының дамуы, сондай-ақ олардың ажыратымдылығының артуы көпфазалы материалдардың ішкі микроқұрылымын егжей-тегжейлі бейнелеу мүмкіндігін кеңейтті. Үшөлшемді рентгендік микротомография ықшам жұмыс үстелі жүйелерінде рентгендік микрофокустау көздерін пайдалану арқылы жоғары кеңістіктік ажыратымдылықпен бейнелеуді қамтамасыз ететін бірегей әдіс ретінде қалыптасты. Жуырда Қазақстан Республикасы Энергетика министрлігінің Ядролық физика институтында материалдарды үш өлшемді сандық талдауға арналған заманауи жұмыс үстелі конустық сәулелі рентген микротомография жүйесі (IMAX) орнатылды. Бұл мақалада аталған рентген микротомография жүйесінің жобалық ерекшеліктері, негізгі құрамдас бөліктерінің сипаттамасы және техникалық параметрлері баяндалады. Жүйе рентгендік суреттерді алу, өңдеу, сақтау, сондай-ақ материалдардың ішкі құрылымын бұзбай зерттеуге және бұрыштық проекциялар негізінде үшөлшемді деректерді қайта құруға арналған. IMAX жүйесінің құрамына 35–80 кэВ энергия диапазонын қамтамасыз ететін микрофокустау рентген көзі, жоғары ажыратымдылықтағы сандық бейнелеуге мүмкіндік беретін жалпақ панельді сцинтиллятор детекторы, үлгілерді орналастыруға арналған оптомеханикалық платформалар және радиациядан қорғау жүйесі кіреді. Жүйенің алғашқы сынақ өлшемдері бойынша алынған нәтижелер ұсынылып, оның ғылыми-зерттеу мақсаттарына сәйкестігі талқыланады.

Тірек сөздер: рентген сәулесі, бейнелеу, томография, бұзбайтын тестілеу.

[1,2]*Чупраков И.,
PhD, ORCID ID: 0000-0002-0592-1680,
*e-mail: igorchuprakov@gmail.com
[1,2,3]Назаров К.,
PhD, ORCID ID:0000-0003-4637-2486,
e-mail: k.nazarov@inp.kz
[1,2,3]Мухаметулы Б.,
PhD, ORCID ID: 0000-0003-1474-8354,
e-mail: bagdaulet_m@inp.kz
[1,2,3]Бекбаев А.,
PhD, ORCID ID: 0000-0003-4800-357X,
e-mail: a.bekbayev@inp.kz

[1,2,3]Арынбек Е.,
магистр, ORCID ID: 0000-0002-6942-8211,
e-mail: yersultan@jinr.ru
[1,2]Кенесарин М.,
магистр, ORCID ID: 0000-0001-5680-0769,
e-mail: muratkenessarin@inp.kz
[3]Базарбаев Е.,
магистр, ORCID ID: 0000-0001-9374-3847,
e-mail: yerik.bazarbayev@gmail.com
[1,2,3]Мырзабекова Э.,
магистр, ORCID ID: 0000-0002-7710-7418,
e-mail: e.myrzabekova@mail.ru
[1,2]Назарова А.,
PhD, ORCID ID: 0000-0003-1724-5322,
e-mail: assel.makhambet@gmail.com
[2]Абдурахимов Б.,
PhD, ORCID ID: 0000-0001-6087-973X,
e-mail: bekhzod@jinr.ru
[2]Зель И.,
к.ф.-м.н., ORCID ID: 0000-0003-0424-7142,
e-mail: zel@jinr.ru

[1]Лаборатория нейтронной физики института ядерной физики, г. Алматы, Казахстан
[2]Лаборатория нейтронной физики им. Франка Объединенного института ядерных исследований, г. Дубна, Россия
[3]Казахский национальный университет имени аль-Фараби, г. Алматы, Казахстан

IMAX - КОМПАКТНЫЙ РЕНТГЕНОВСКИЙ МИКРОТОМОГРАФИЧЕСКИЙ ПРИБОР ДЛЯ ИССЛЕДОВАНИЯ МАТЕРИАЛОВ

Аннотация

С учетом того, что методы, оборудование и разрешение трехмерного пространственного анализа значительно улучшились за последние двадцать лет, теперь стало возможным подробно изображать внутреннюю микроструктуру многокомпонентных материалов в трех измерениях. Трехмерная рентгеновская микротомография предлагает уникальную возможность для получения изображений с высоким пространственным разрешением, что может быть достигнуто в компактных настольных системах с использованием рентгеновских источников микрофокусировки. Недавно в Институте ядерной физики Министерства энергетики Республики Казахстан была установлена современная настольная рентгеновская микротомографическая система с конусным лучом для количественного анализа материалов в трех измерениях. В этой статье представлены конструкция, описание основных компонентов и технические параметры этой системы рентгеновской микротомографии, названной IMAX. Система предназначена для получения, обработки, хранения рентгеновских изображений и реконструкции трехмерных данных с угловых проекций для исследования внутренних структур и неразрушающего контроля материалов. Система состоит из рентгеновского источника микрофокусировки, обеспечивающего диапазон энергии рентгеновских лучей от 35 до 80 кэВ, сцинтилляционного детектора с плоской панелью, который позволяет получать цифровые изображения высокого разрешения, оптомеханических платформ для позиционирования образцов и радиационной защиты. Представлены первые результаты испытаний, проведенных с использованием этой рентгеновской системы.

Ключевые слова: рентгеновский луч, визуализация, томография, неразрушающая тестирование.

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